Nuclear experiment approach to the equation of state and condensed phases in nucleonic system

Shinsuke Ota

RCNP, Osaka University

NEWS Colloquium, 2022/08/25, RCNP 6F/Zoom

Self-introduction : Shinsuke OTA

- Born in Dazaifu, Fukuoka, Kyushu
  - famous for God of learning and the present era name “令和 (Reiwa)”

Self-introduction

- D. Sci. in Kyoto (2009)
  - "Low-lying proton intruder state in B-13 via (a,t) reaction" (Gamma-ray spectroscopy with Germanium detector array GRAPE)
  - But stay at CNS from 2002
- Assistant professor at CNS (2009 – 2021.08)
  - DAQ system and position detectors (LP-MWDC, SR-PPAC) for SHARAQ spectrometer and OEDO low-energy beamline
  - Gaseous active target system CAT-S and CAT-M
- Associate professor at RCNP (2021.09 -)
  - Management of Grand RAIDEN
  - Management of Data acquisition infrastructure division
  - Physics, of course, introduced in this talk

Content based on PHANES project

- Overview of microscopic and macroscopic nucleonic matter
- How hard is the nucleonic matter?
  - Equation of state
- What kind of phases exist in the nucleonic matter?
  - Pair condensation phase

Note: Conceptual (near) future plan will be introduced in this talk.

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

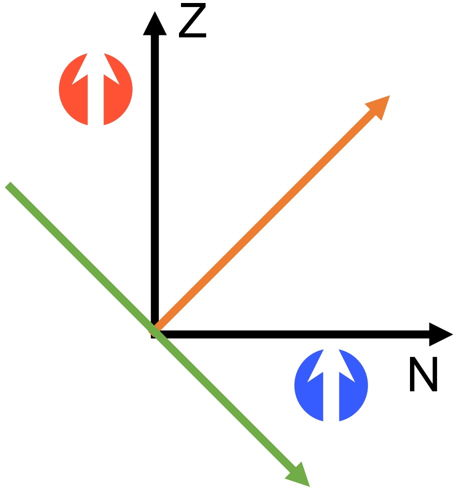
- In the field of condensed matter physics and material science, physical properties are being derived from energy density functional (ex. PHASE https://azuma.nims.go.jp/)
- In the field of nuclear physics, of course, the theoretical researchers estimate the physical properties of macroscopic nucleon 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!

Nucleus and macroscopic nucleonic system

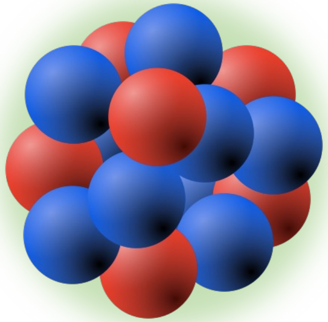
Nuclear chart

Nuclear response ⟺ Mode and property

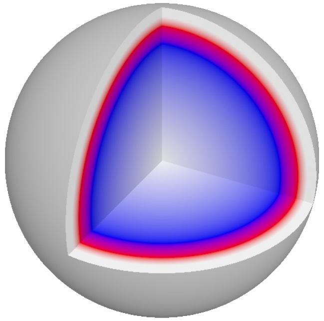
Nucleonic matter



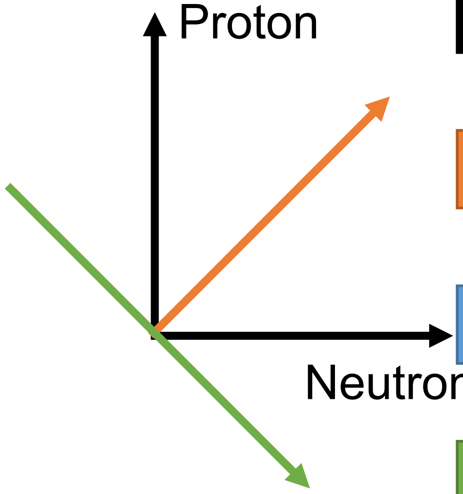
- Quantum
- Mass
- Pair
- Isospin



Nucleus
1 fm
1-300 nucleons



Neutron star
10 km
10^{57} neutrons



- Density
- Number
- Pair
- Asymmetry

Saturation density
Zero Temperature

Spin / orbit angular momentum

Electron system
Pair condensation

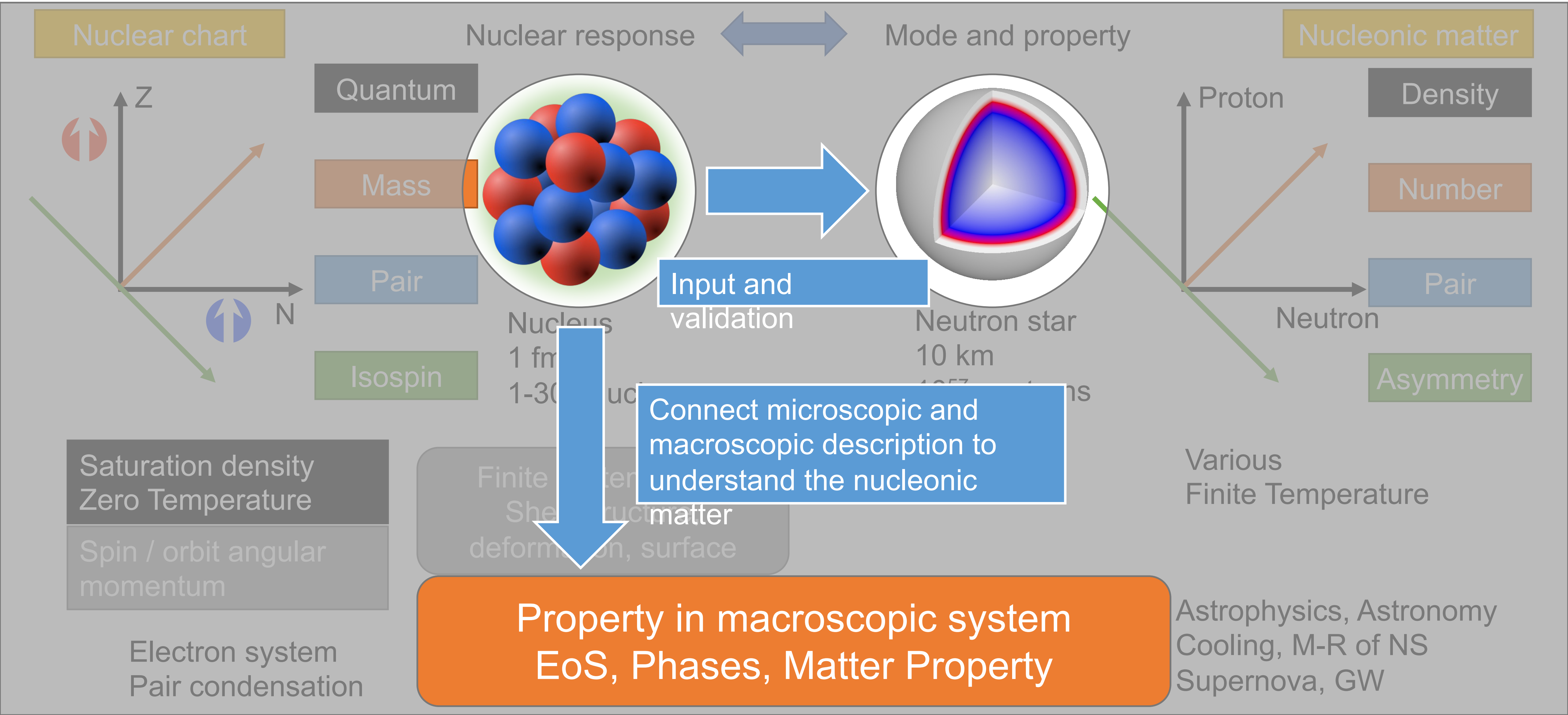
Finite system effect
Shell structure, deformation, surface

Various
Finite Temperature

Property in macroscopic system
EoS, Phases, Matter Property

Astrophysics, Astronomy
Cooling, M-R of NS
Supernova, GW

Motivation



Nuclear chart
Nuclear response
Mode and property
Nucleonic matter
Z
N
Quantum
Mass
Pair
Isospin
Input and validation
Nucleus
Neutron star
10 km
Proton
Neutron
Density
Number
Pair
Asymmetry
Connect microscopic and macroscopic description to understand the nucleonic matter
Saturation density
Zero Temperature
Spin / orbit angular momentum
Electron system
Pair condensation
Various
Finite Temperature
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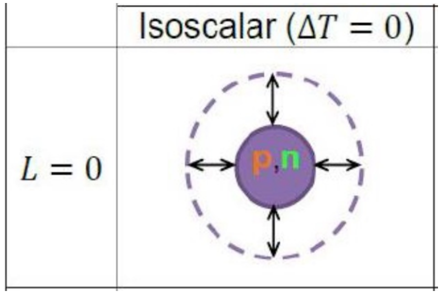
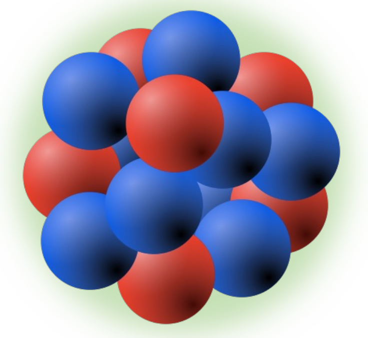
Nucleus and macroscopic nucleonic system

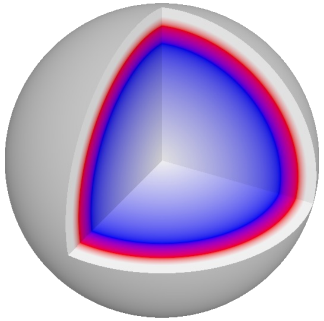
Nuclear response ⟷ Mode and property

Compressional mode in nucleus



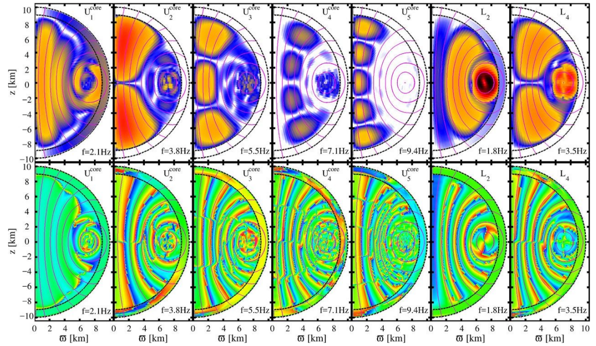


Nucleus
1 fm, 1-300 nucleons

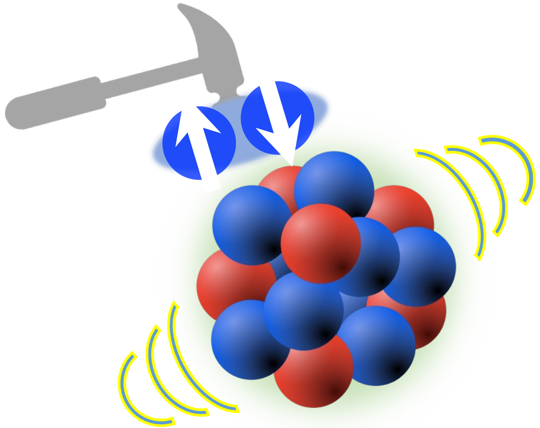


Neutron star
10 km, 10^{57} neutrons

Gabler+2016
Quasi-periodic oscillations



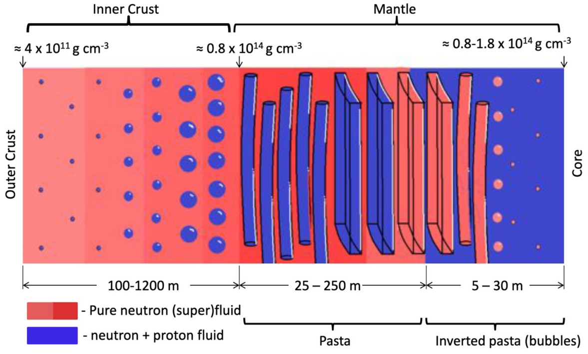
Pair density fluctuation mode
Pair AB mode



Finite system effect
Shell structure,
deformation, surface

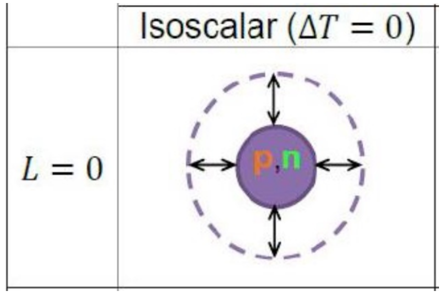
Property in macroscopic system
EoS, Phases, Matter Property

Newton+2013
Superfluidity

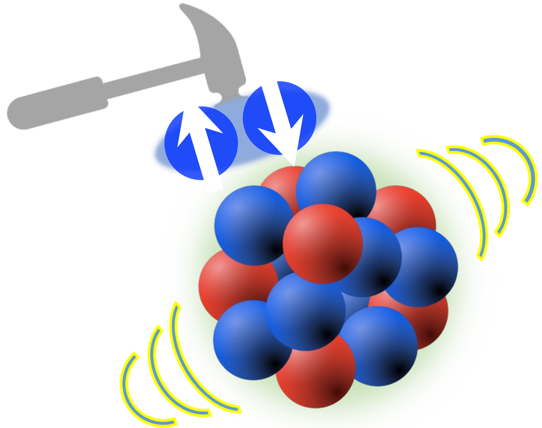


Nucleus and macroscopic nucleonic system

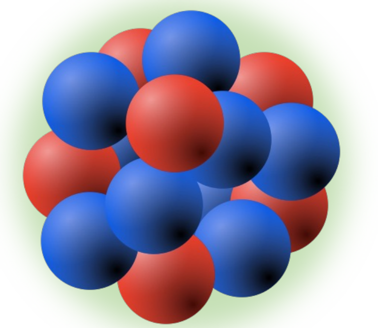
Compressional mode in nucleus



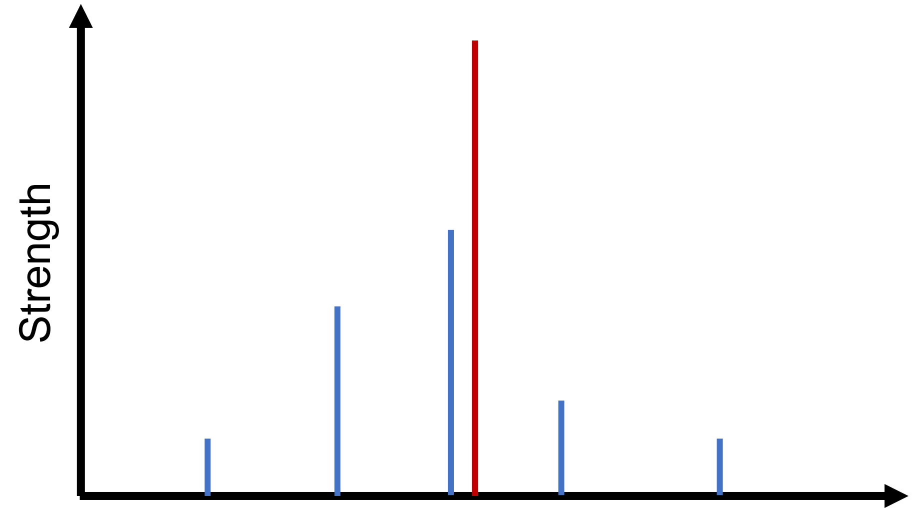
Pair density fluctuation mode
Pair AB mode



Nuclear response



Nucleus
1 fm, 1-300 nucleons



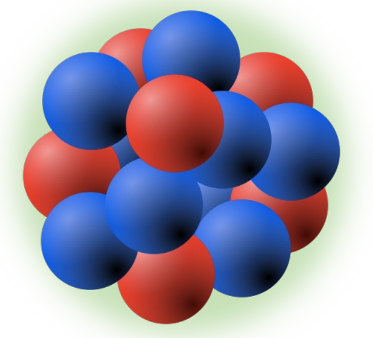
Broadened, fragmented and/or shifted

Finite system effect
Shell structure, deformation, surface

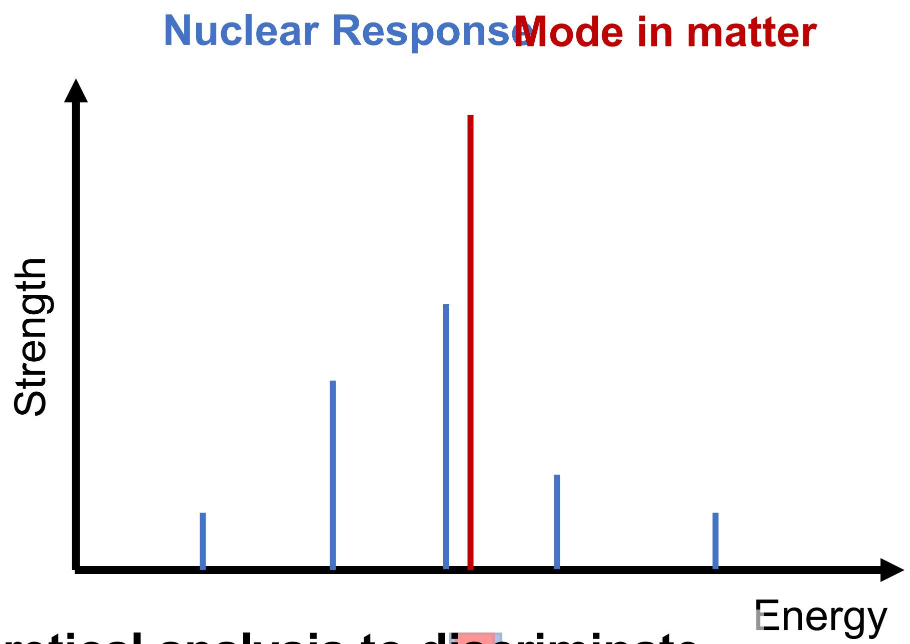
Property in macroscopic system
EoS, Phases, Matter Property

What can we do to extract the matter property?

Nuclear response



Nucleus
1 fm, 1-300 nucleons



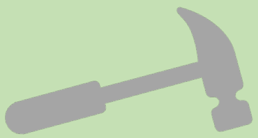
Theoretical analysis to discriminate the matter property from the finite effect

Finite system effect
Shell structure, deformation, surface

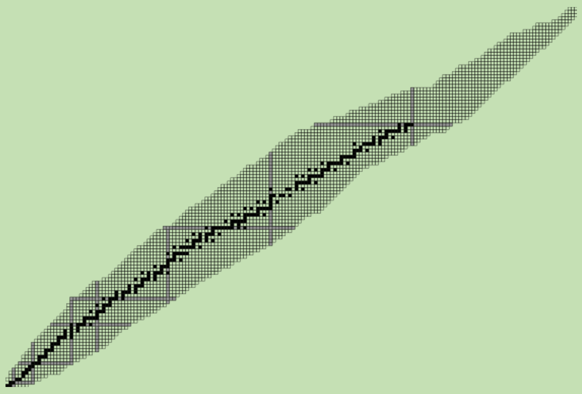
Property in macroscopic system
EoS, Phases, Matter Property

What is important in the experiment?

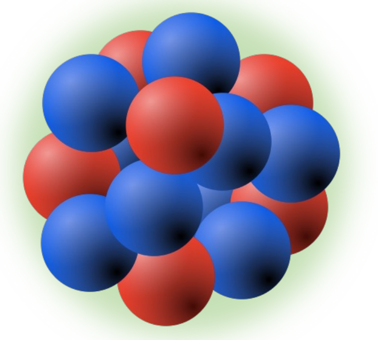
Probe



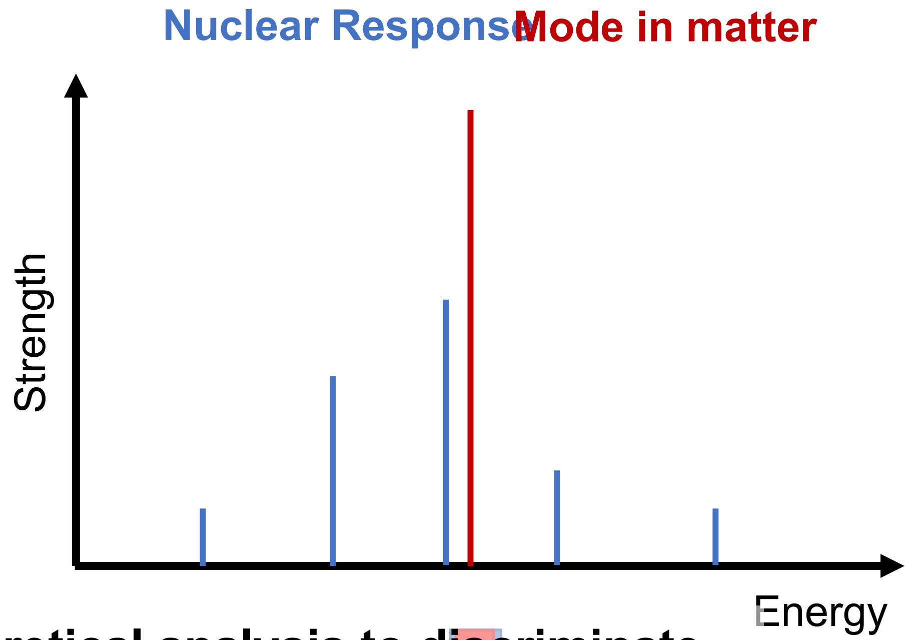
Target



Nuclear response



Nucleus
1 fm, 1-300 nucleons



Theoretical analysis to discriminate the matter property from the finite effect

Finite system effect
Shell structure, deformation, surface

Property in macroscopic system
EoS, Phases, Matter Property

Selection of probe and sensitive property

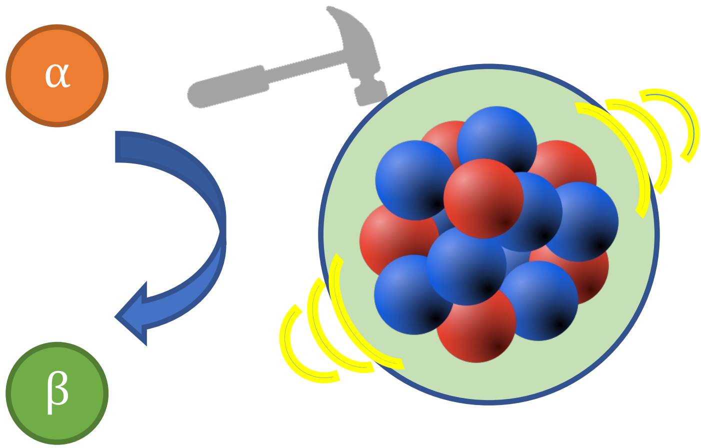
Various quantum changes

- 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

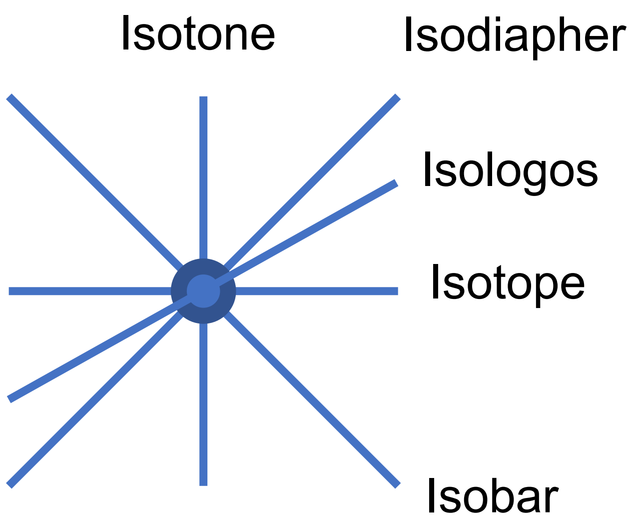
Quantum Change
Mass number ΔA
Spin ΔS
Isospin ΔT
Angular momentum ΔL



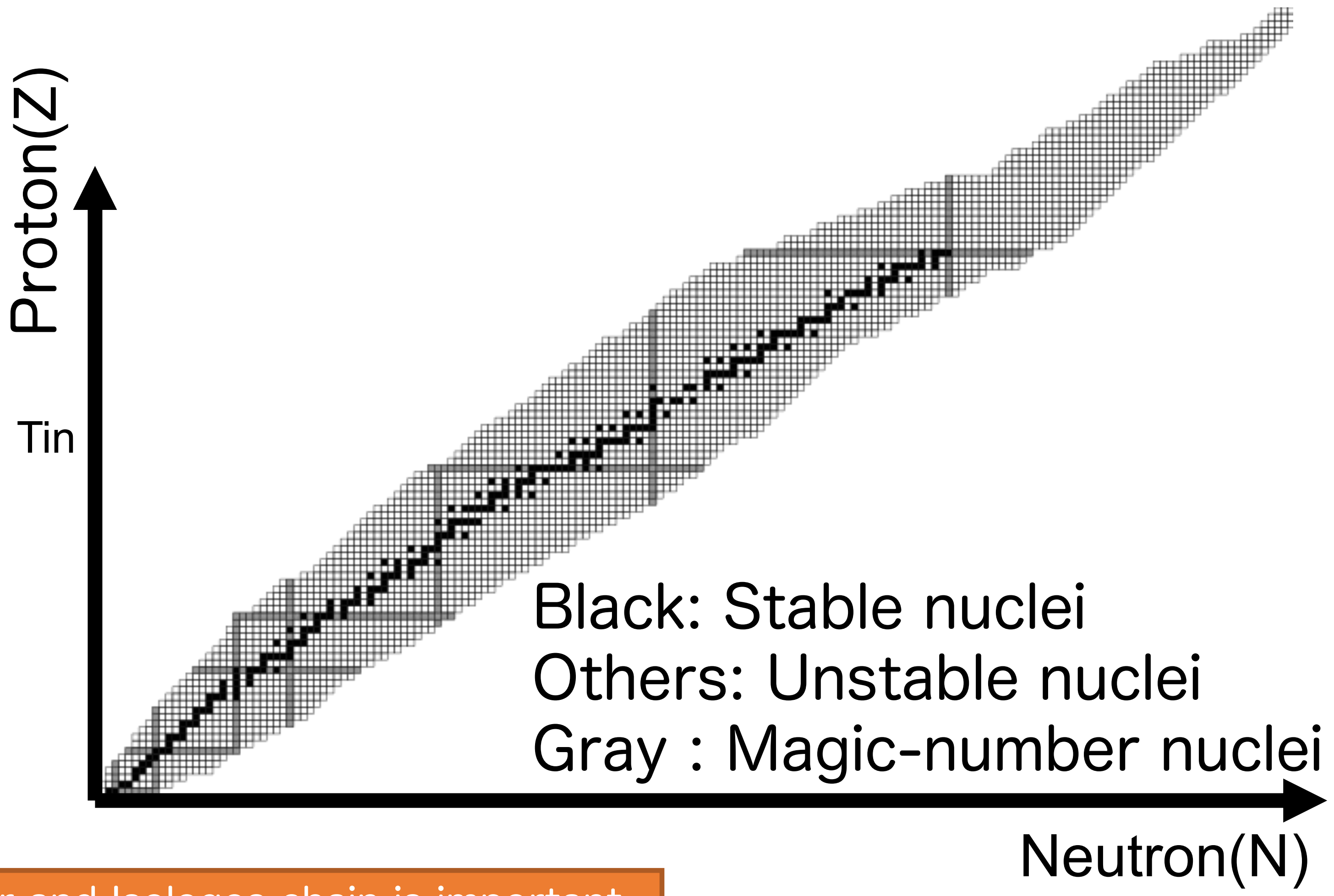
Space-symmetric responses

	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)

Systematics : selection of target



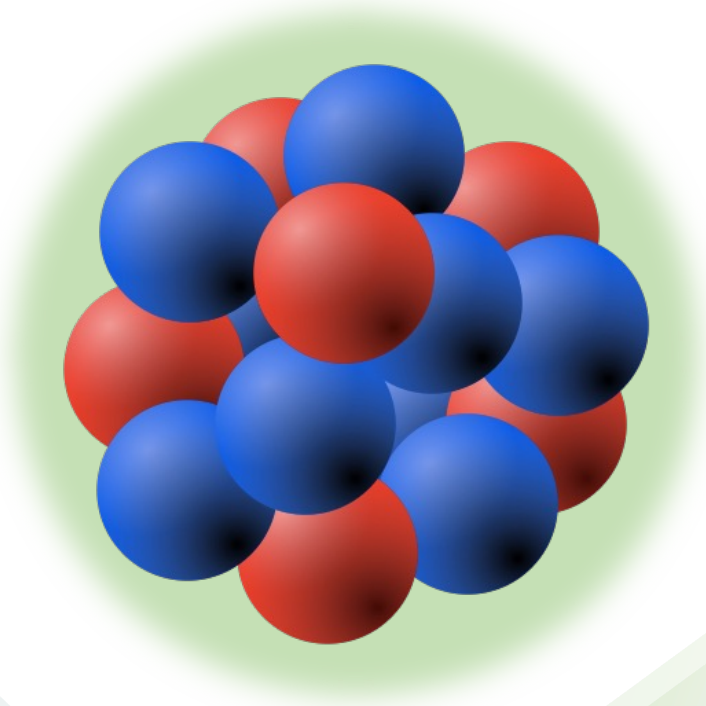
Isotope : Z = const => Neutron
Isotone : N = const => Proton
Isobar : A = const => Isovector
Isodiapher : N-Z = const => Isoscalar
"Isologos?" : (N-Z)/A or A/Z = const => Mass
(neologism)



Systemtics of Isobar and Isologos chain is important.

PHANES Project

- Studying “Phases and Equation of State”, by quantifying the bulk modulus and order parameter of condensations

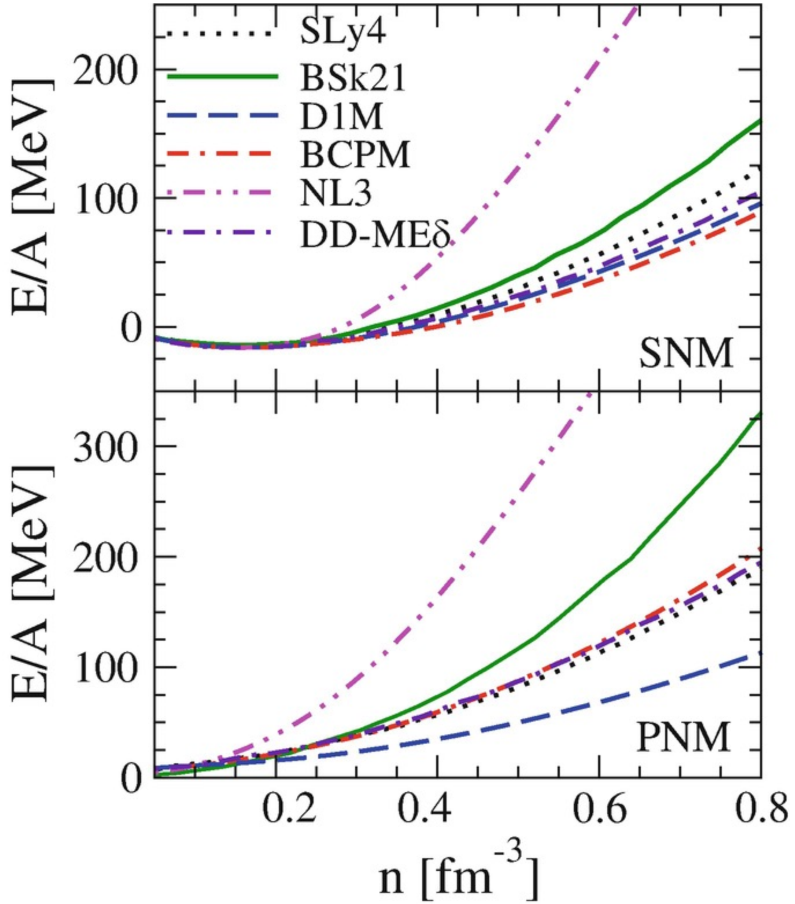


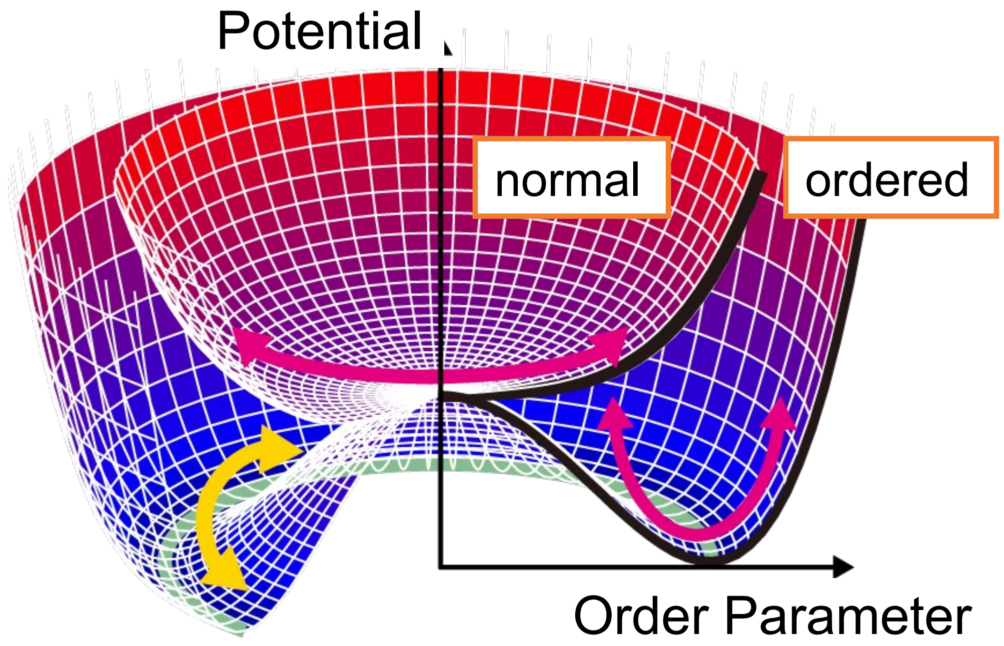
PHANES Project

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

Quantify the bulk modulus and order parameter of condensations

Equation of state
density oscillation mode ⇔ bulk modulus

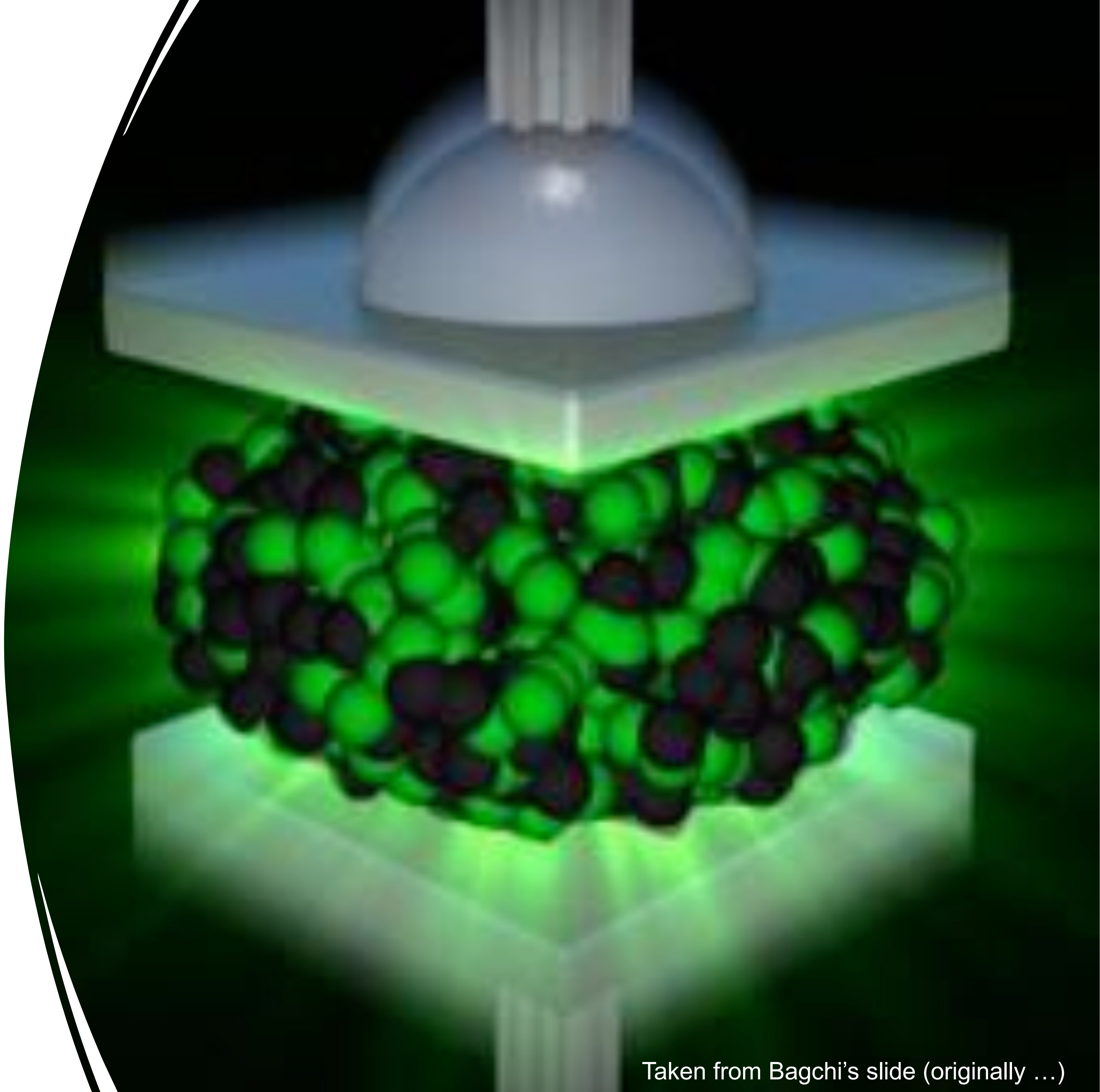




condensed phases (pair, pion, alpha ...)
phase mode and amplitude mode ⇔ order parameter

How hard is the nucleonic matter?

Incompressibility of nucleonic matter



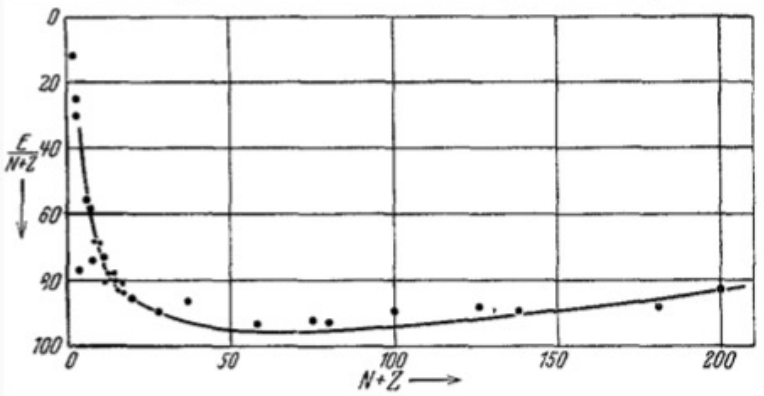
Taken from Bagchi’s slide (originally …)

Nuclear matter equation of state

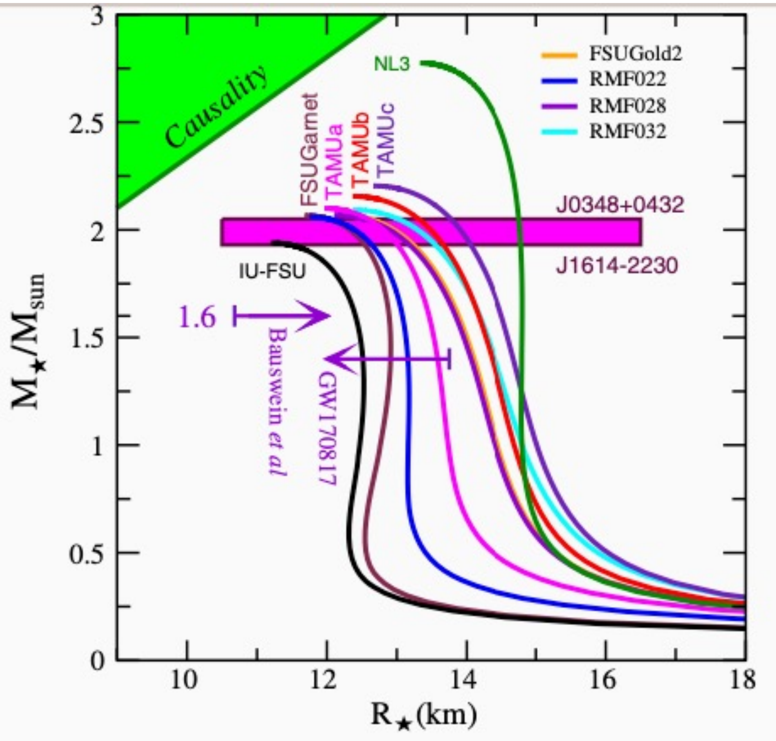
$$E/A - M \equiv \begin{cases} B.E./A(N,Z) & \text{mass formula: } \rho = \rho_0,\ A \lesssim 300? \\ \mathcal{E}(\rho,\alpha) & \text{EoS: any } \rho,\ \alpha, \text{ large } A \end{cases}$$

$\rho_{(0)}$ is (saturation) number density

α is proton-neutron asymmetry



B.E. vs A from Weisäcker1935 ZTK96



M-R relation from Fattoyev+2018 PRL120

Nuclear matter equation of state

connects the worlds of nuclei and astronomical objects

over the discrepancy of 18 magnitude in size and 55 magnitude in nucleon number

Analytic form of the equation of state: a benchmark for the theory

Nuclear matter equation of state

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{SNM}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

$$\mathcal{E}_{SNM}(\rho) = \varepsilon_0 + \frac{1}{2}K_0 x^2 + \frac{1}{6}Q_0 x^3 + \cdots$$

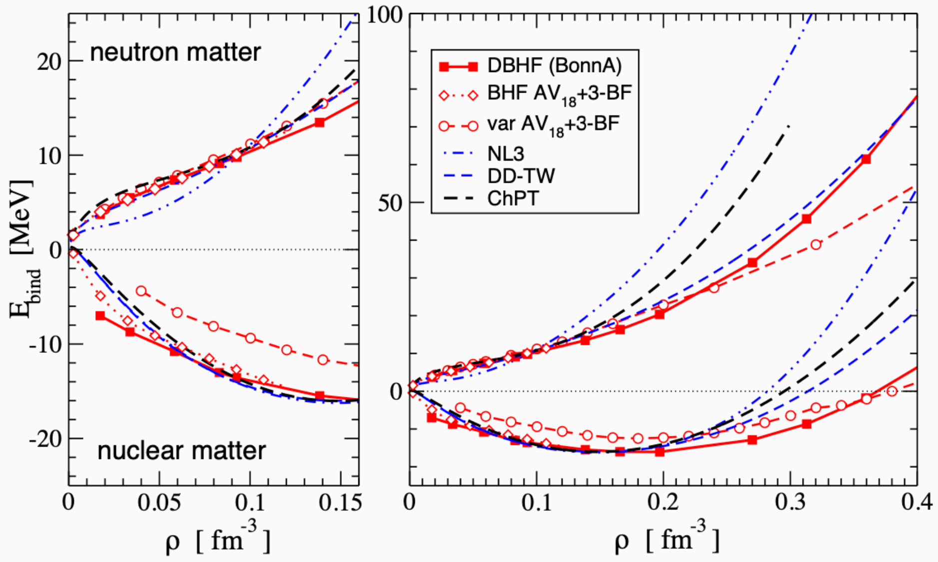
$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sim}x^3 + \cdots$$

$\mathcal{S}(\rho)$: symmetry energy, $x = (\rho - \rho_0)/3\rho$.

Incompressibility

$$K_0(\alpha) = K_0 + \underbrace{K_\tau}_{\text{isospin dep.}} \alpha^2 + \mathcal{O}(\alpha^4)$$

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



Fuchs+2006

A mission of nuclear study

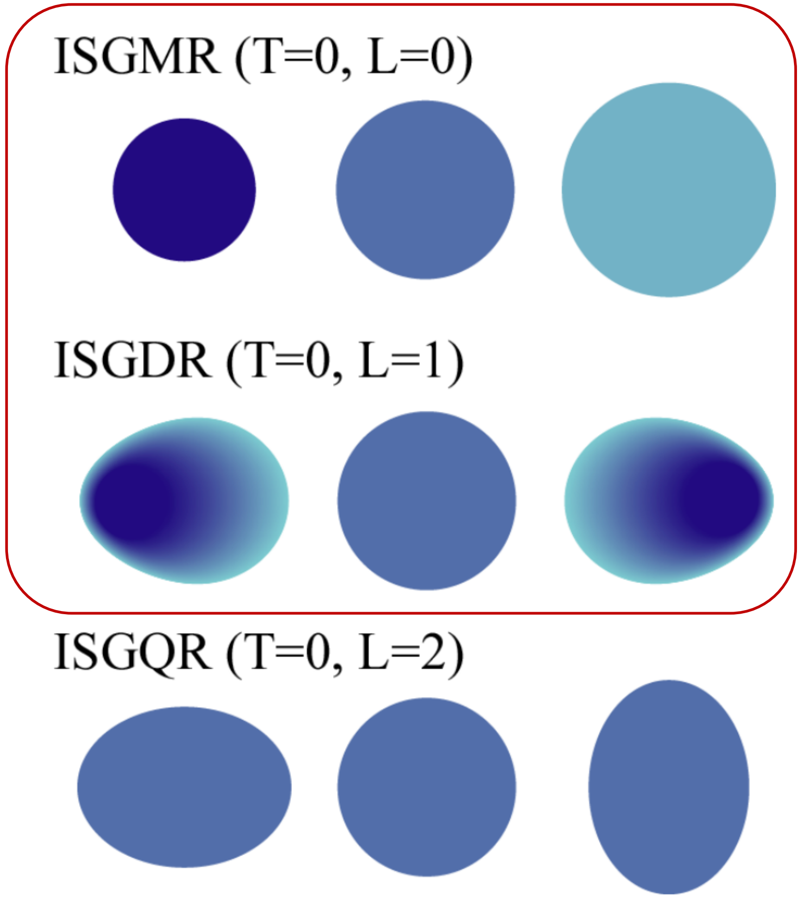
Determine or restrict coefficients of EoS to construct "realistic" interaction

Giant resonance and nuclear incompressiblity

Coherent vibrations of nucleonic fluids in a nucleus => Compression modes: ISGMR and ISGDR

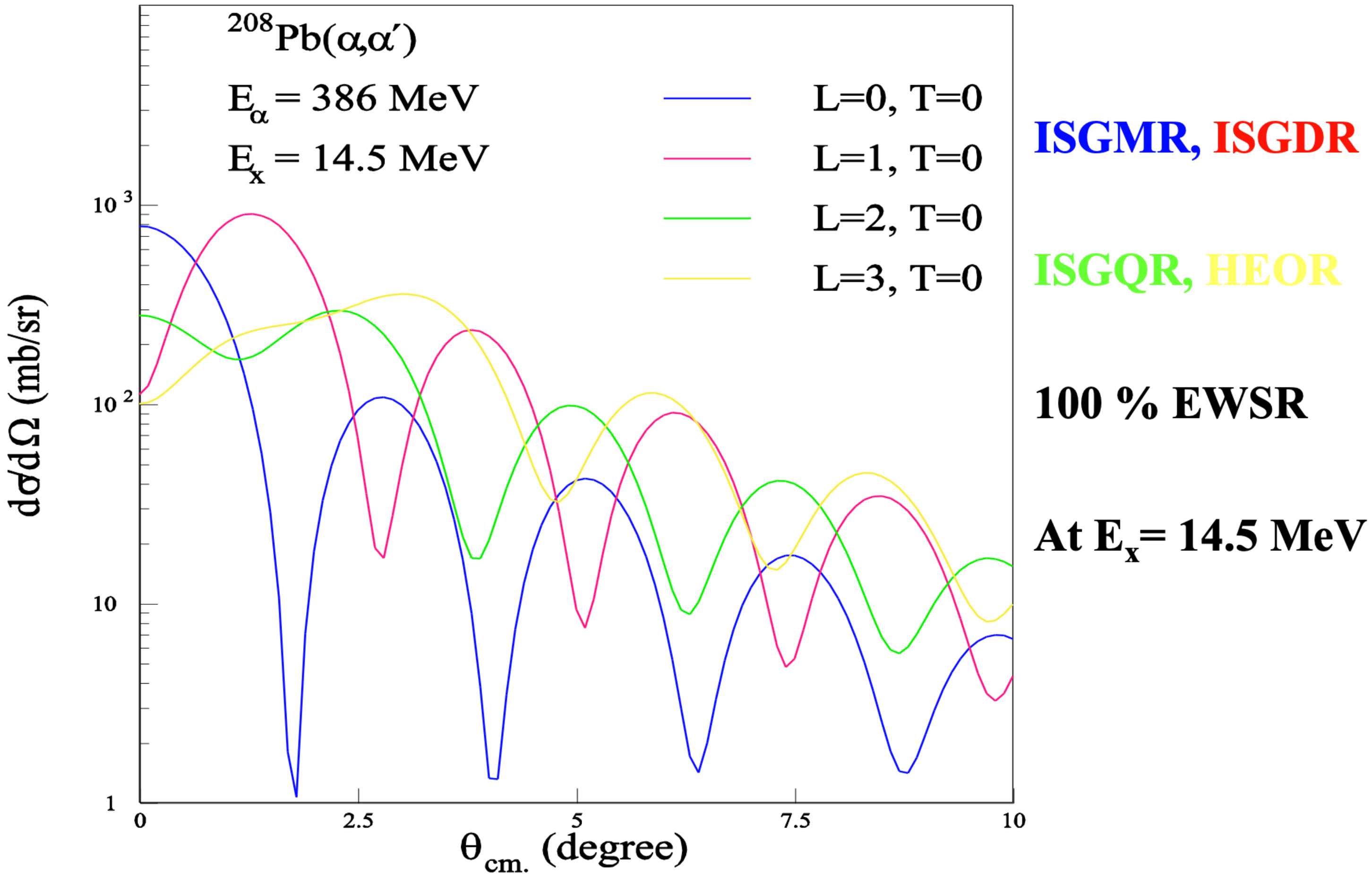
$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$

$$E_{ISGDR} = \hbar\sqrt{\frac{7}{3}\frac{K_A + \frac{27}{25}\varepsilon_F}{m\langle r^2\rangle}}$$

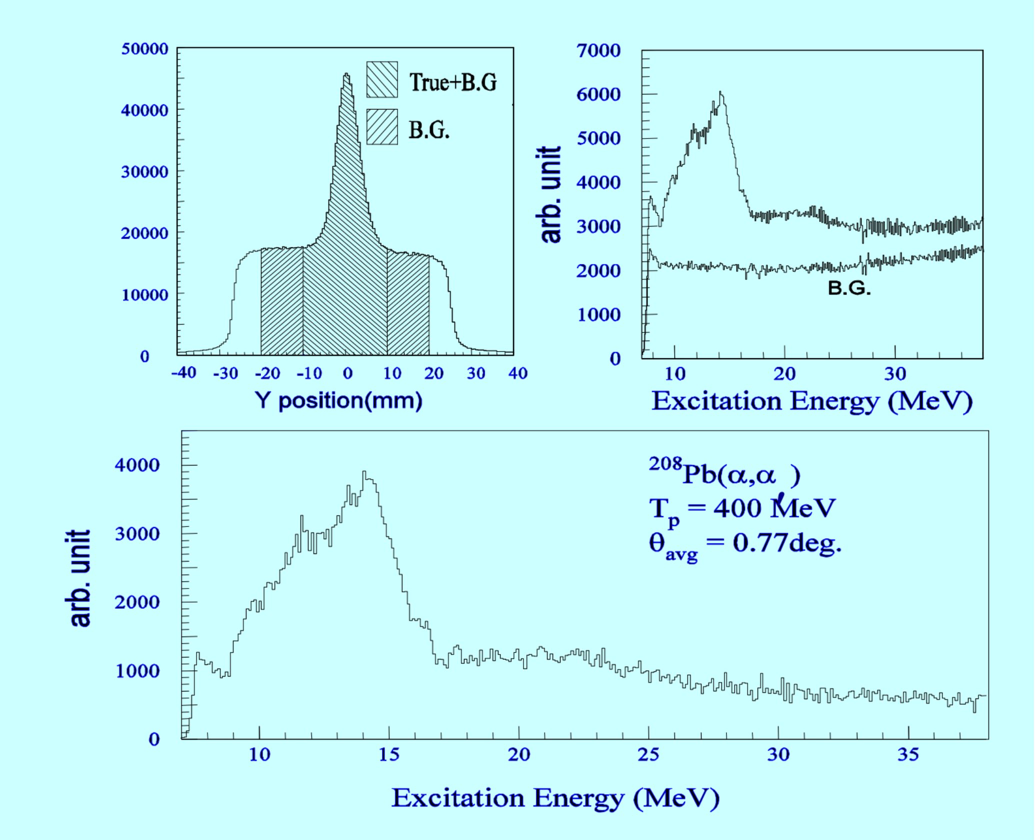


Extraction of ISGMR

- Using the angular distribution in a certain excitation energy range, ISGMR strength are extracted in a corresponding excitation energy bin



Taken from Harakeh's slide.



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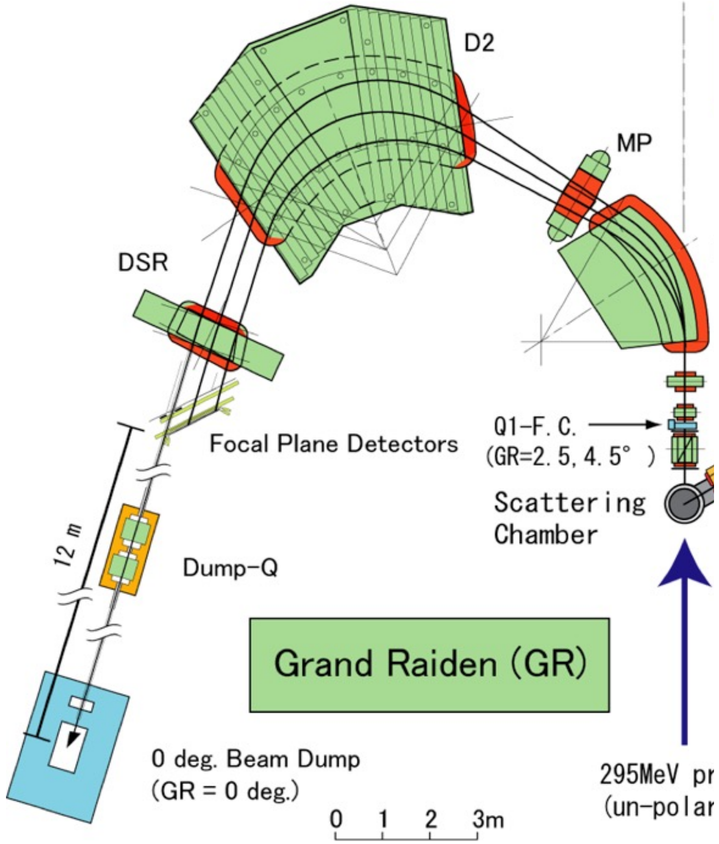


Traditional experiment at RCNP for stable lead nucleus

Connection between nuclear and nucleonic matter incompressibilities

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

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

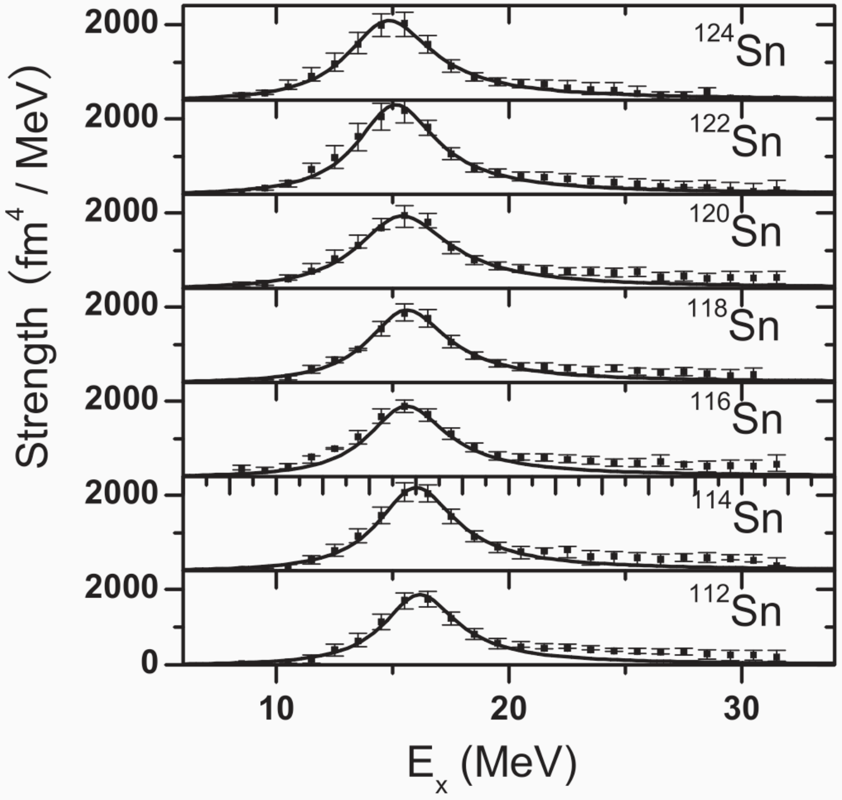
$$K_A = K_{0,V} + K_{0,\mathrm{S}}A^{-1/3} + (K_{\tau,V} + K_{\tau,\mathrm{S}}A^{-1/3})\frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}}\frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

K0 = 240 +- 20 MeV
e.g. Colo+2010

Evaluated using 208Pb and 90Zr
Consistent values from ISGMR and ISGDR and with non-relativistic and relativistic calculation

Ktau => Systematic measurement changing the asymmetry parameter (N-Z)/A

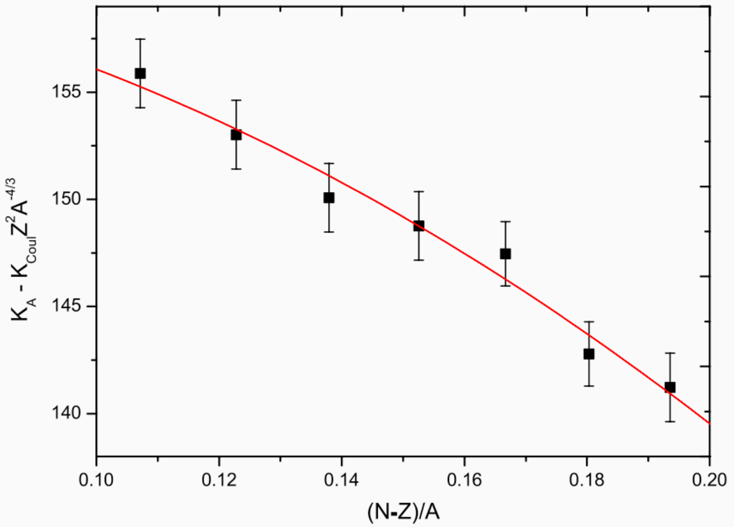
Systematic measurement in Tin isotopes



$^{112-124}$Sn (α,α') at RCNP, E_α = 400 MeV

Multipole decomposition ($L_{\max}$ = 7)

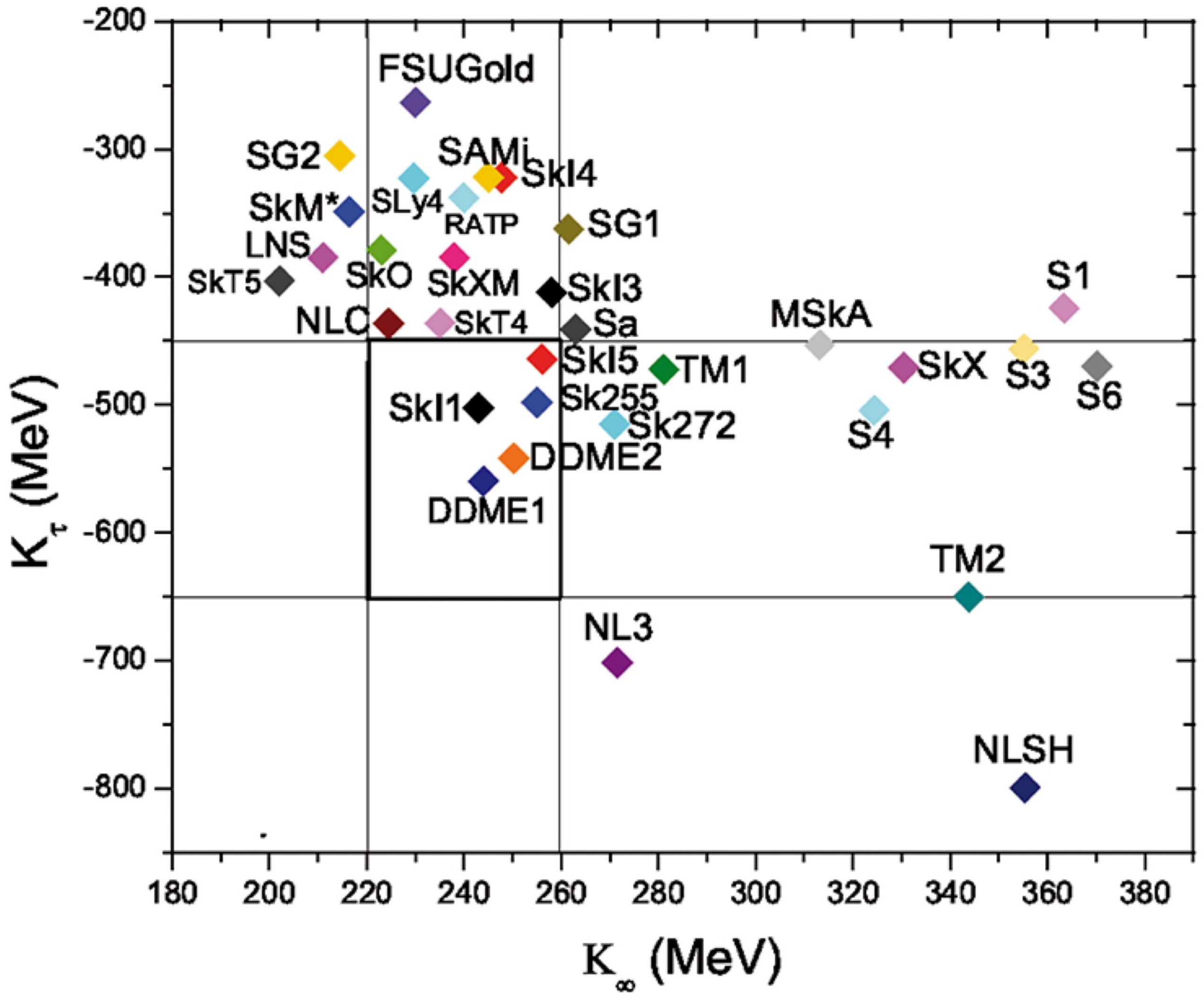
Li+2008 PRL99, Li+2010 PRC81



$K_\tau = -550 \pm 100$ MeV

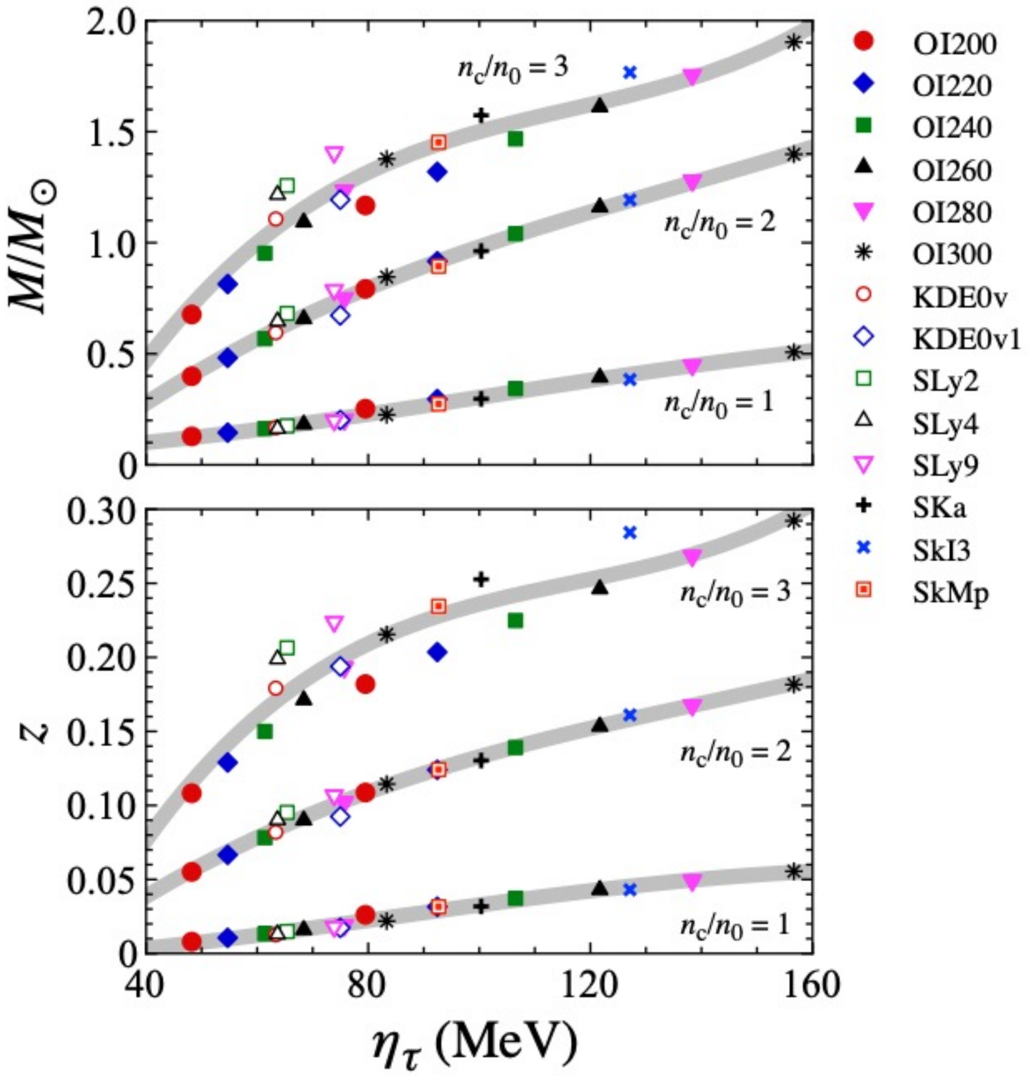
Incompressibility (Colo+2014)

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

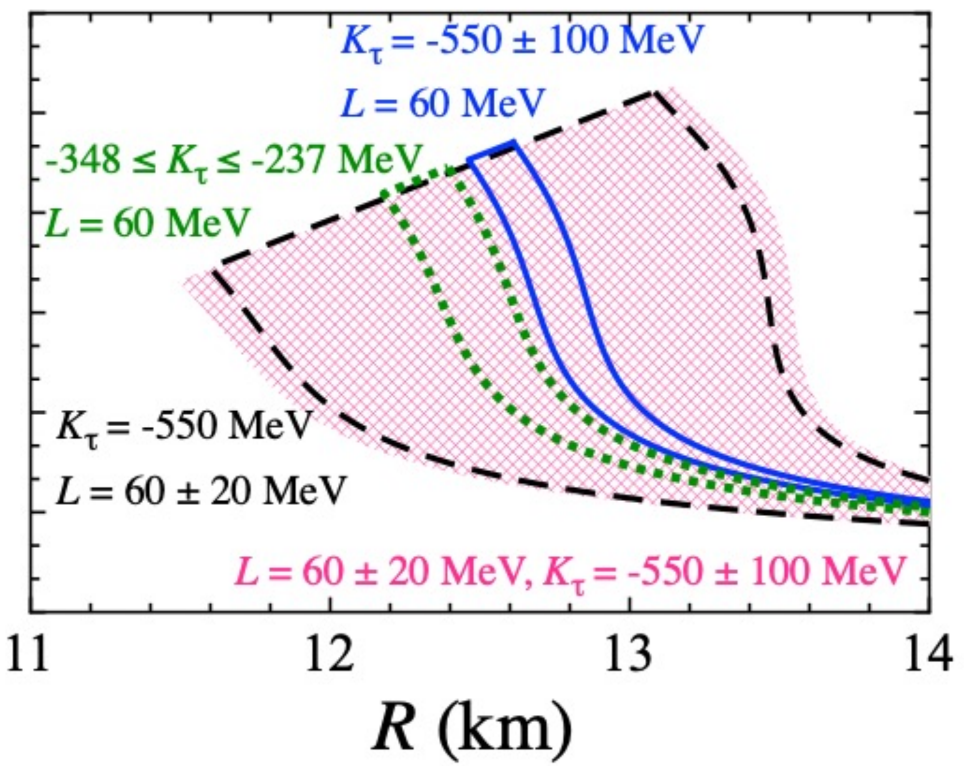


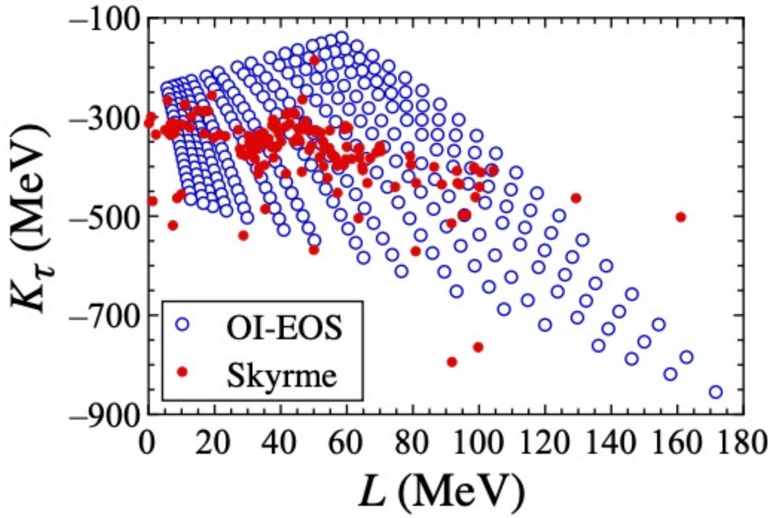
Effect of uncertainty

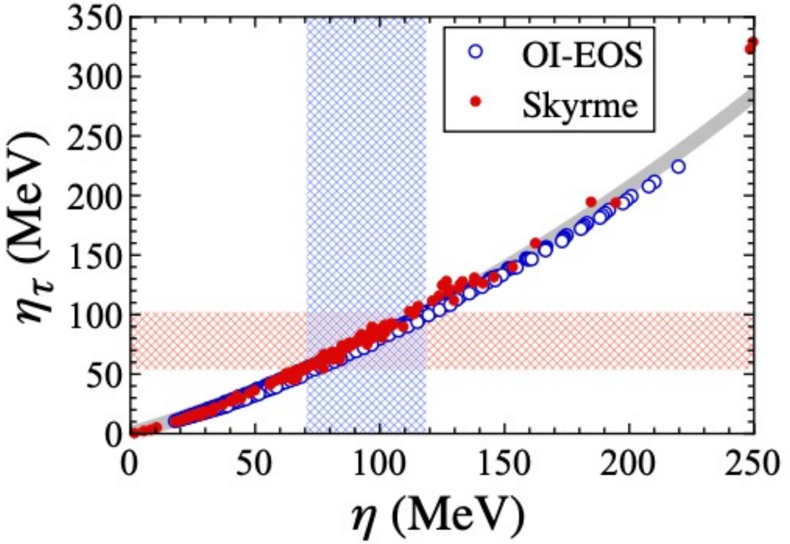
- A new scaling parameter $\eta_\tau = (-K_\tau L^5)^{1/6}$ is suggested in the same manner with $\eta = (K_0 L^2)^{1/3}$ (Sotani+2014 and Sotani+2022)
- In the M-R relation, uncertainty arises mainly from L parameter for now. But uncertainty or accuracy of K_τ



H. Sotani and SO submitted to PRD







Accuracy is more important than precision.

Scaling using η_τ

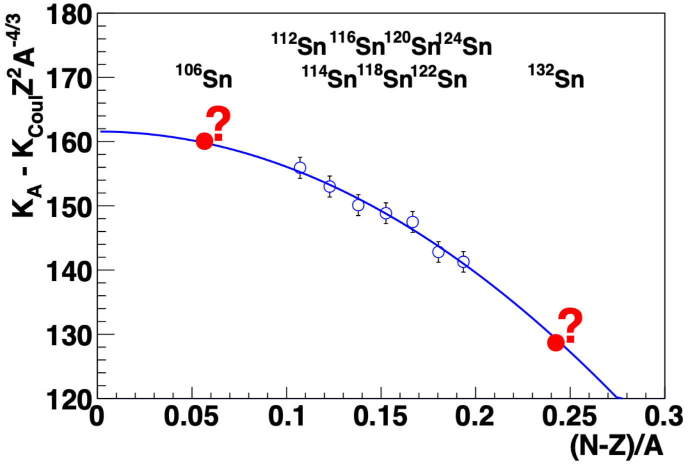
$$\eta_\tau = (-K_\tau L^5)^{1/6}$$

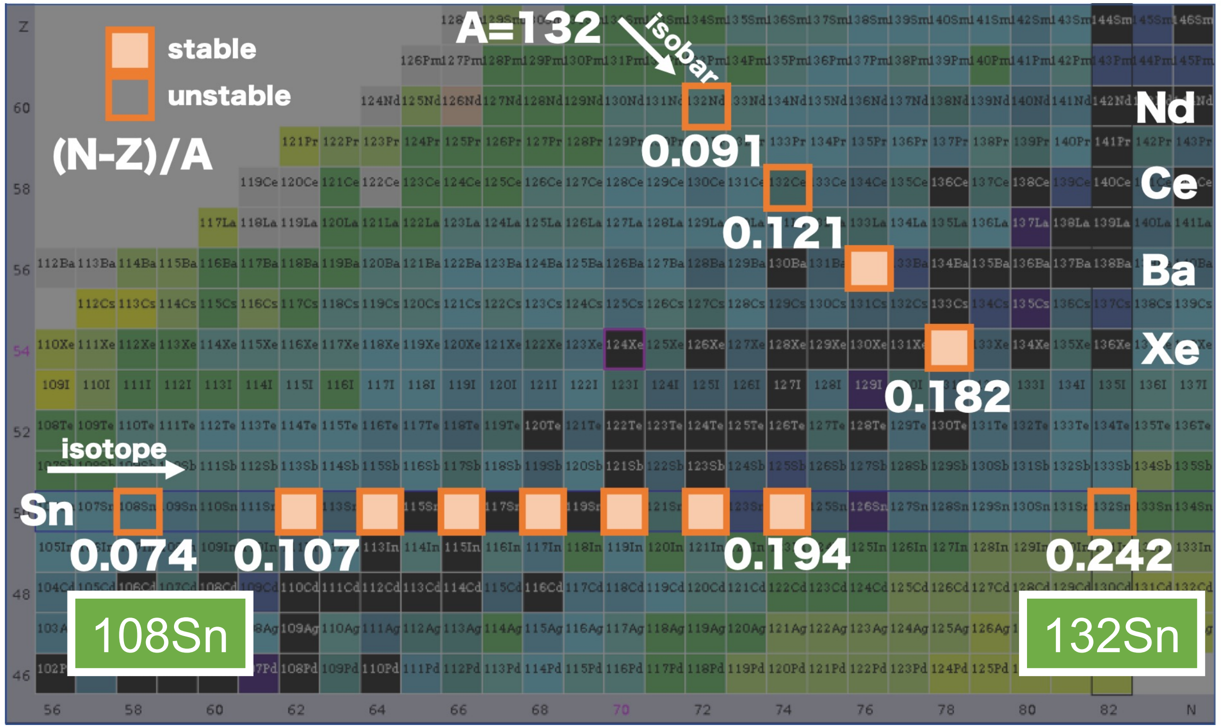
$$\eta = (K_0 L^2)^{1/3}$$

H. Sotani and SO submitted to PRD

Large or small asymmetry term
First attempt of the measurement in unstable nucleus.

The systematics including the unstable nuclei is desired.





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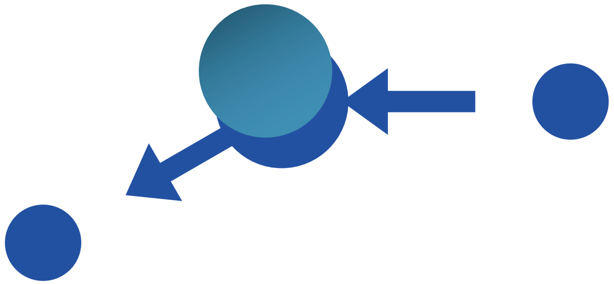
Incompressibility of symmetric matter

Isospin dependence

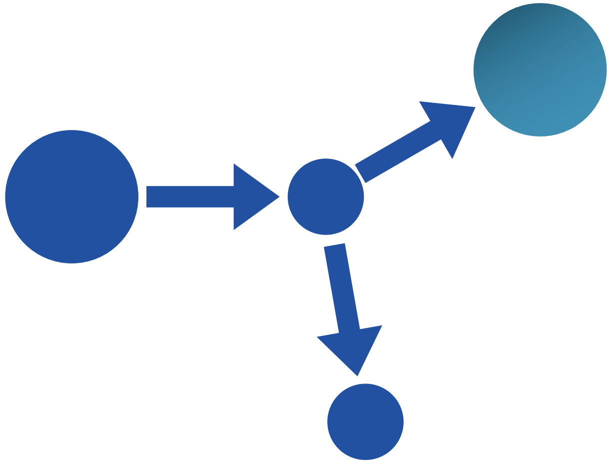
Implementation of nuclear reaction in the laboratory frame



Fixed target

Lorentz boost

In-flight target

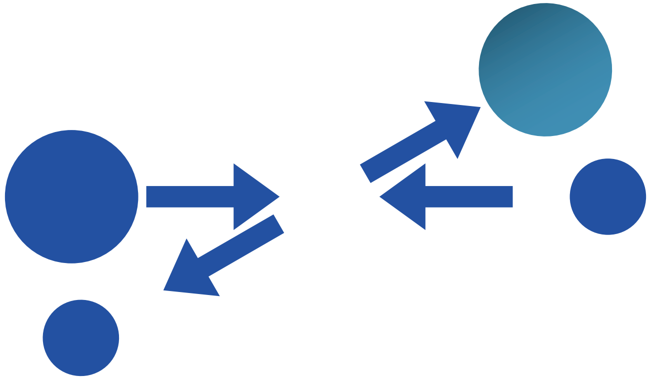


Forward kinematics

- Stable nucleus
- High resolution
  - (w/ spectrometer)

Center-of-mass frame

- Collider experiment

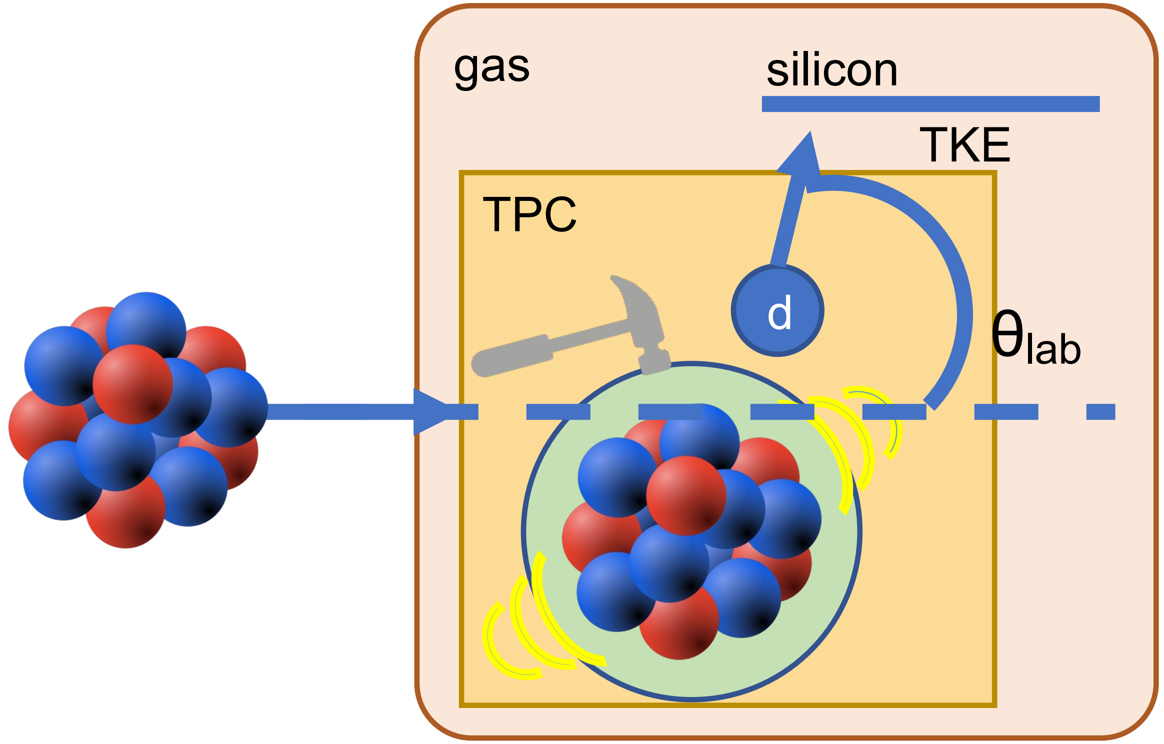


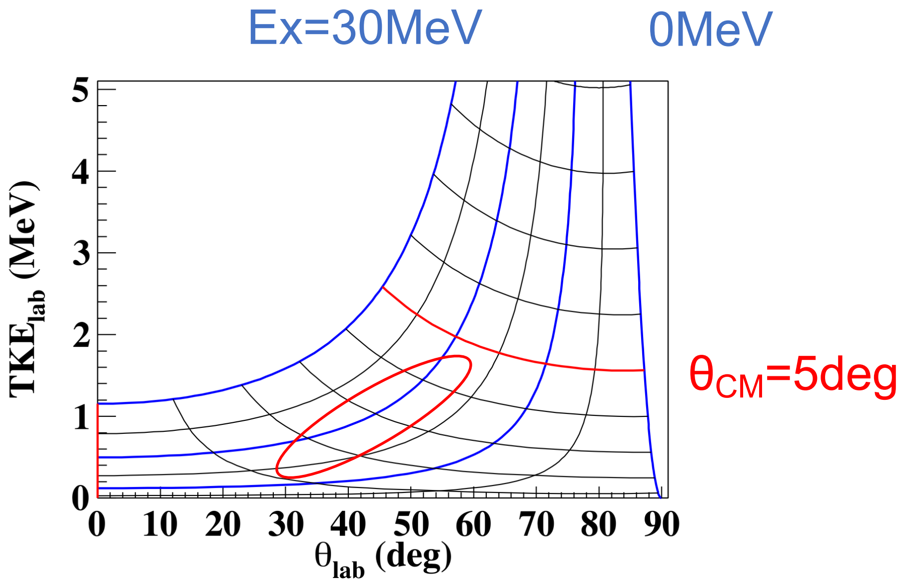
Inverse kinematics

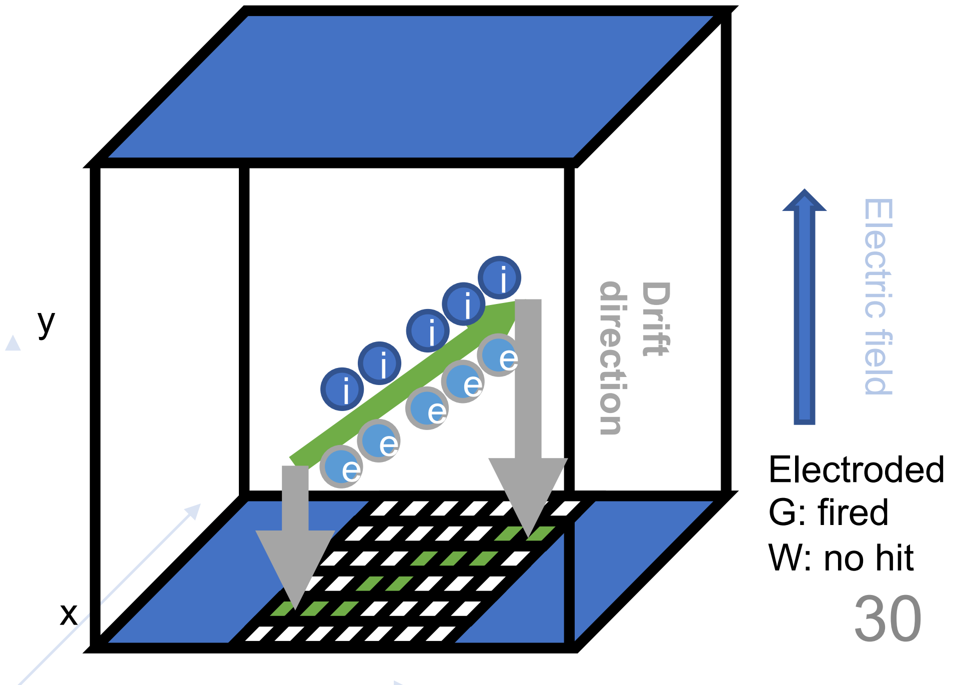
- Unstable nucleus
- Large acceptance
  - Angle
  - Excitation energy
- Decay measurement

Inverse kinematics

Active target = 3D reaction camera
Target gas + Time projection chamber







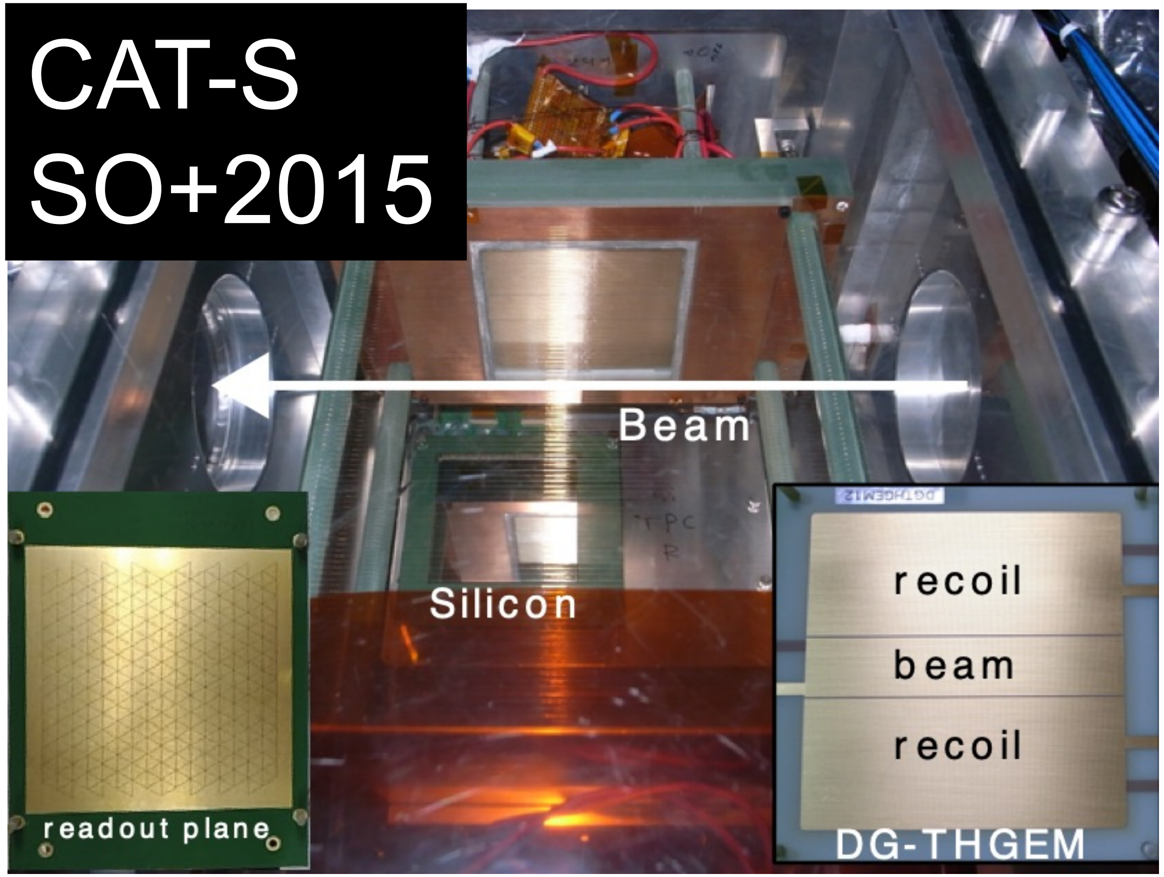
CAT Active target
GMR Measurement with Unstable Nuclei

Gaseous active target for high-Intensity-beam experiments

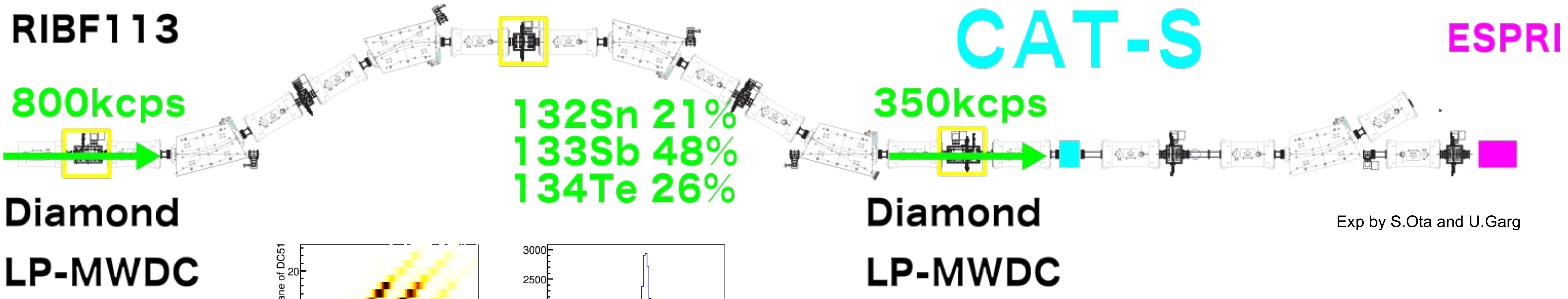
Upto 1 MHz

- Regular triangle shape (416 pads)
- Dual-gain thickGEM
- High-rate DAQ system (V1740)
- Silicon for high energy recoils

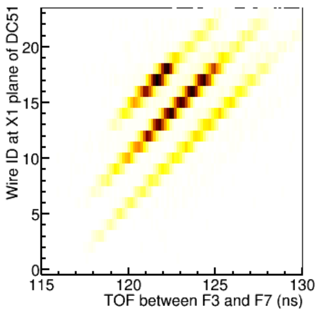
=> Measurement for the Tin isotope

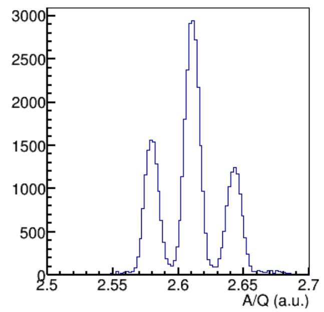


Measurement of 132Sn at RIBF

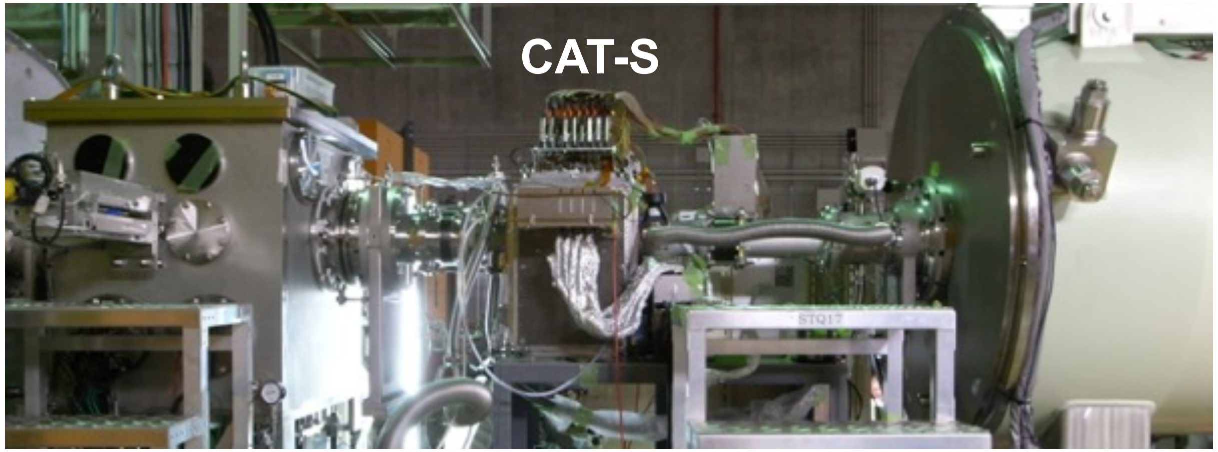


Exp by S.Ota and U.Garg

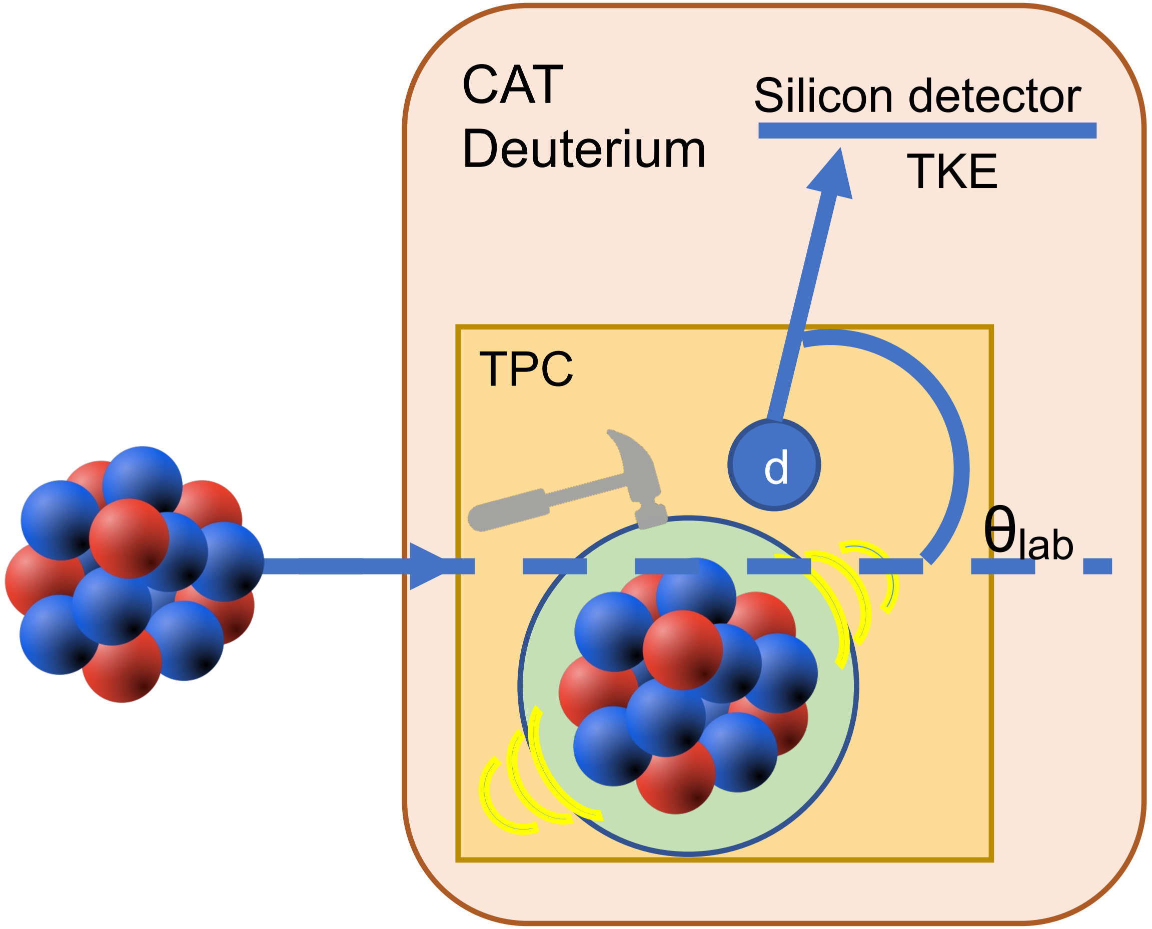


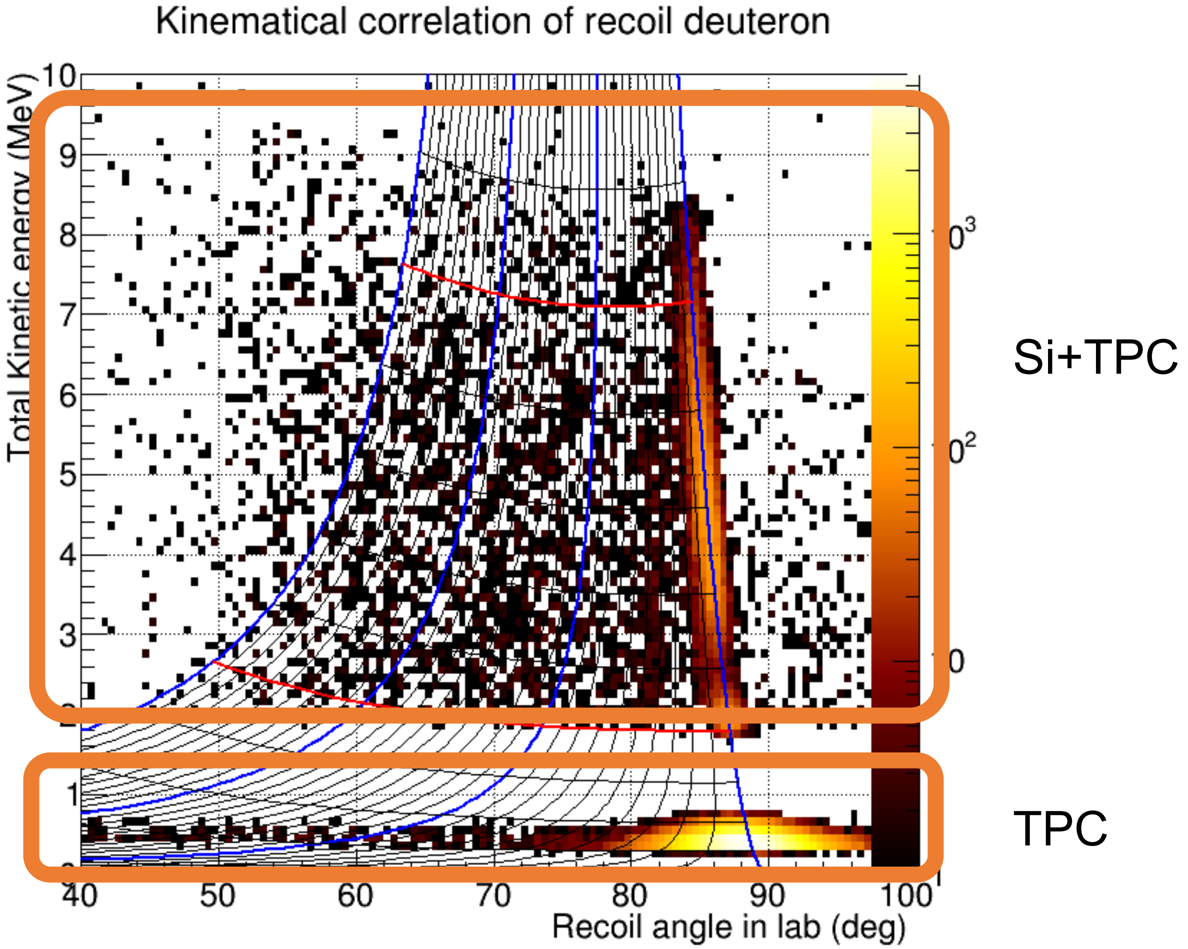


- 350kcps cocktail beam including 132Sn, 133Sb and 132Te
- Particles are analyzed and identified by using BigRIPS Spectrometer
- (d,d’) with CAT-S



Result

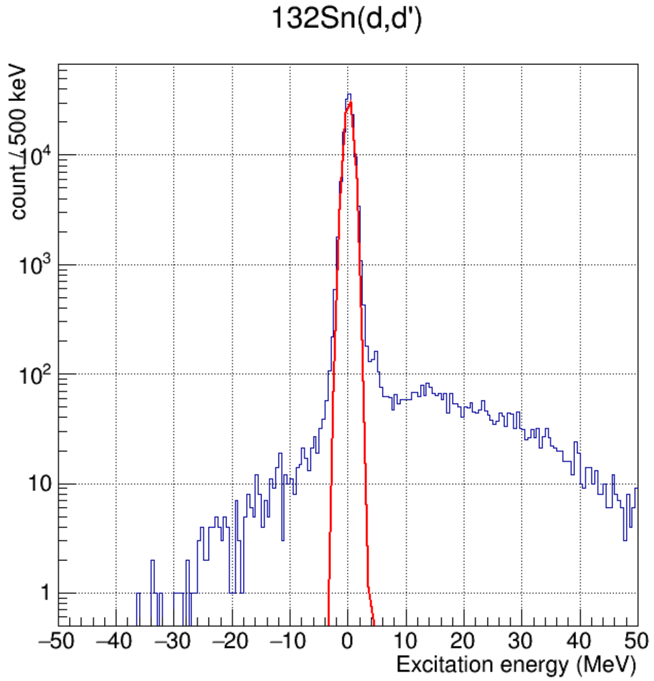




Background by delta-rays are discriminated using pulse height and angular-hough-transform technique

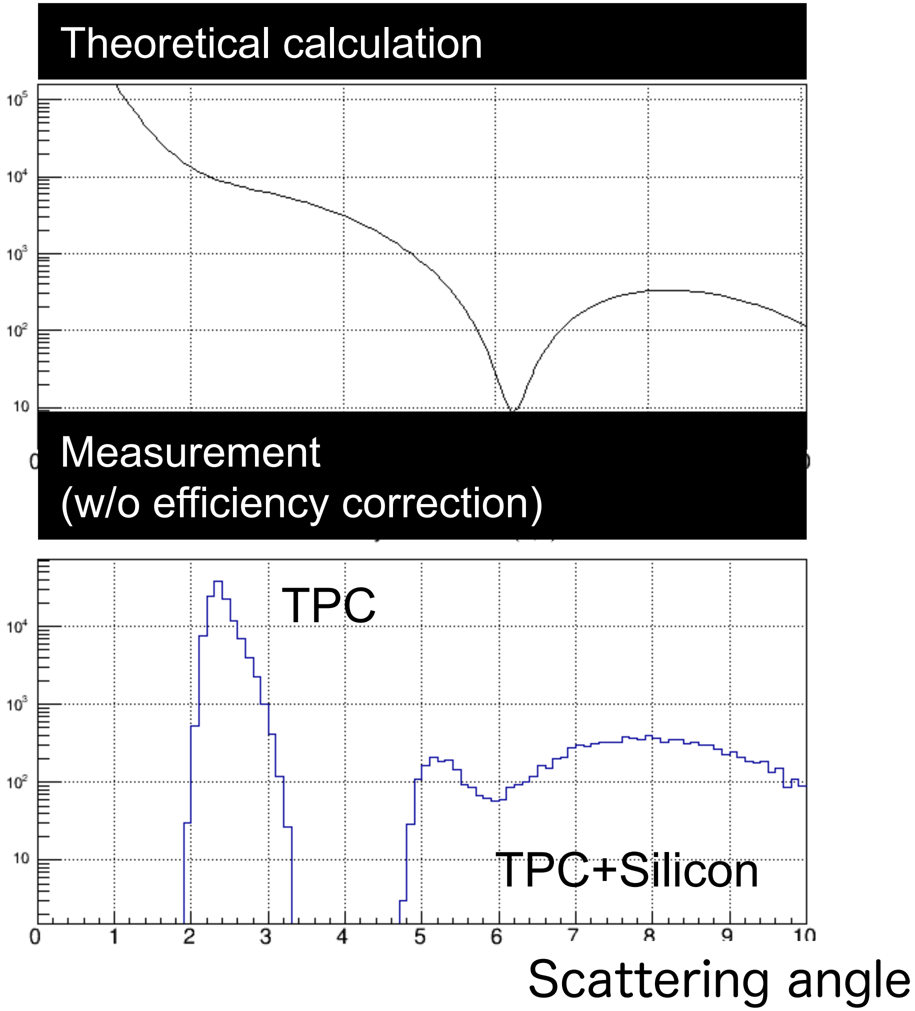
Performance of CAT-S

Excitation energy distribution
0.6 MeV (σ)



Good resolution for the measurement

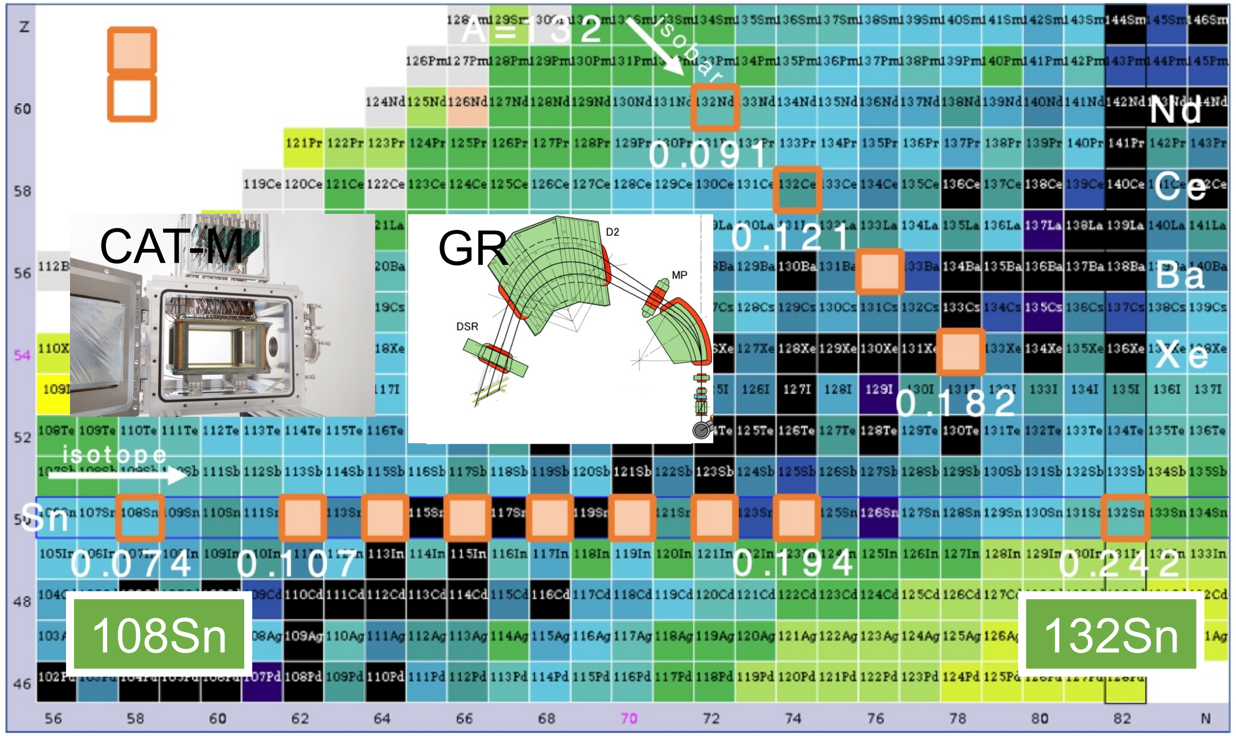
Angular distribution of elastic scattering



For high accuracy and precision determination

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

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

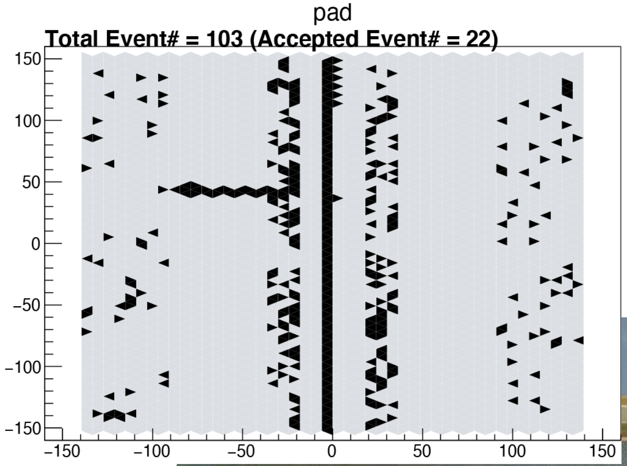
$$K_A = K_{0,V} + K_{0,\mathrm{S}} A^{-1/3} + \left(K_{\tau,V} + K_{\tau,\mathrm{S}} A^{-1/3} \right) \frac{(N-Z)^2}{A^2} + K_{\mathrm{Coul}} \frac{Z^2}{A^{4/3}} + \mathcal{O}(A^{-2/3})$$

CAT-M Active Target

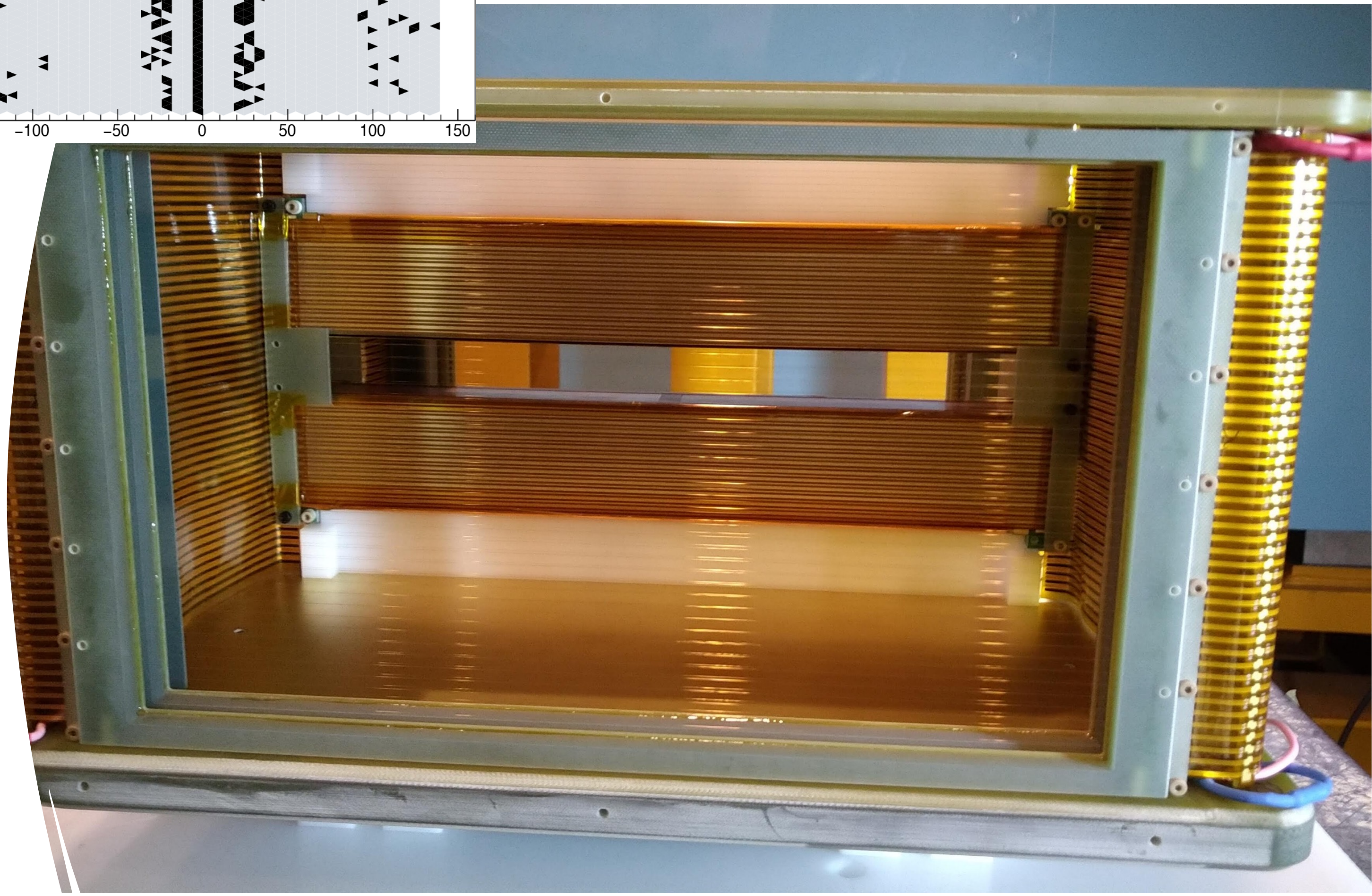
- 10 times larger statistics
- double-layered wire field cage
  - 40x40x20 cm^3
- M-THGEM (or THGEMs)
  - 32 x 28 x 20 cm^3 active volume
- Gas type: Hydrogen, Duterium, He+CO2
- Gas pressure : 0.2-0.4 atm.
- Readout pads
  - Regular triangular shape with 7-mm side
    - Capability of better resolution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

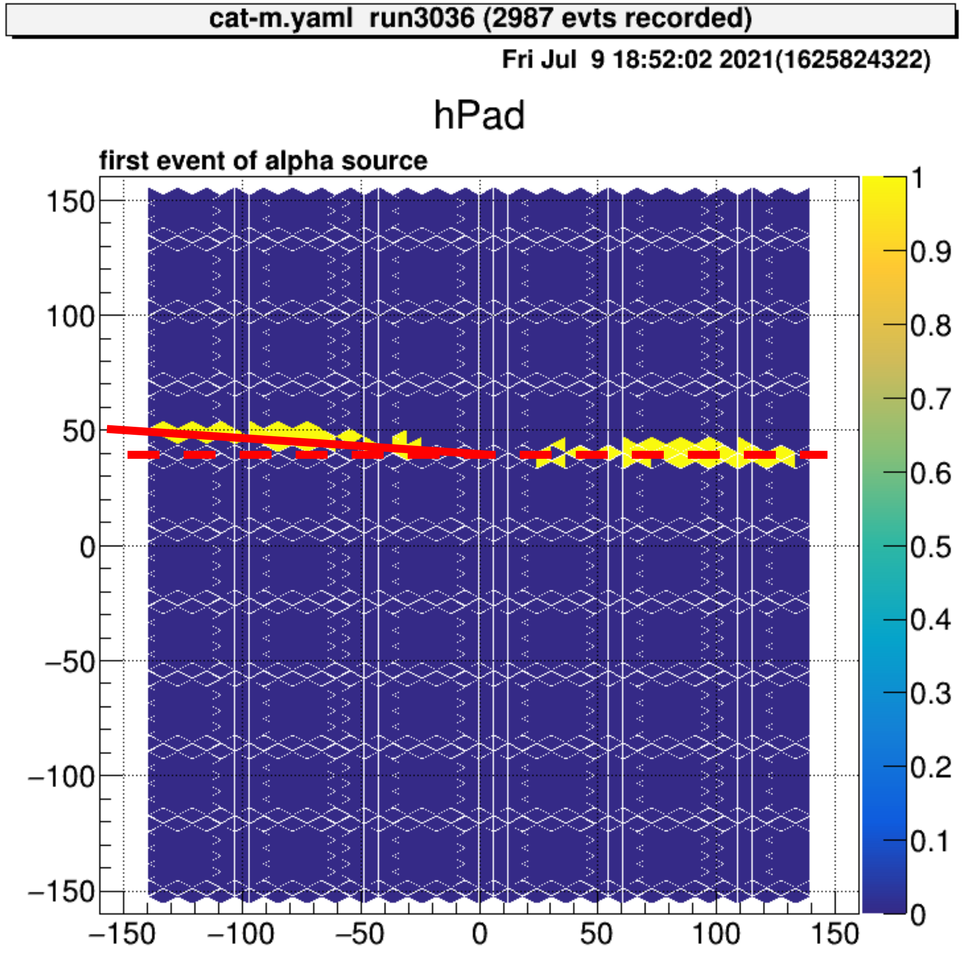


Elimination of noises from delta electrons



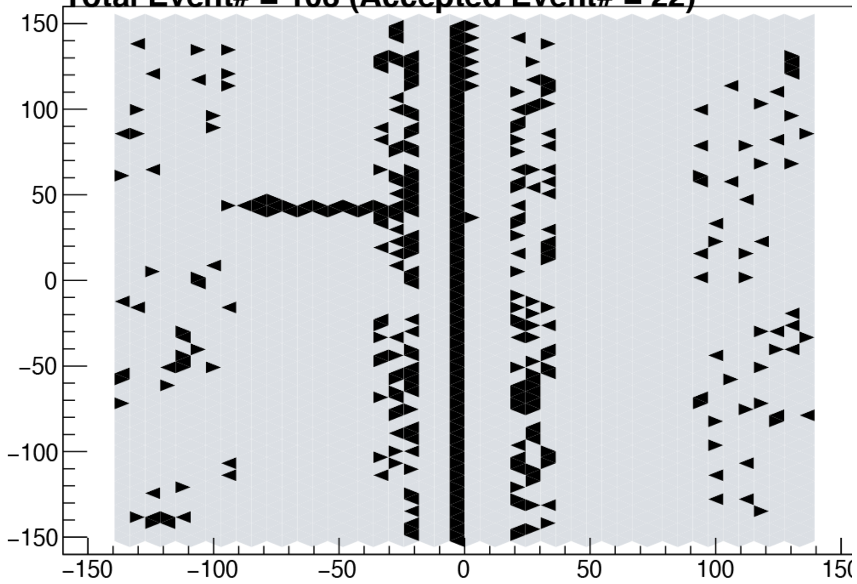
Alpha with magnet

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



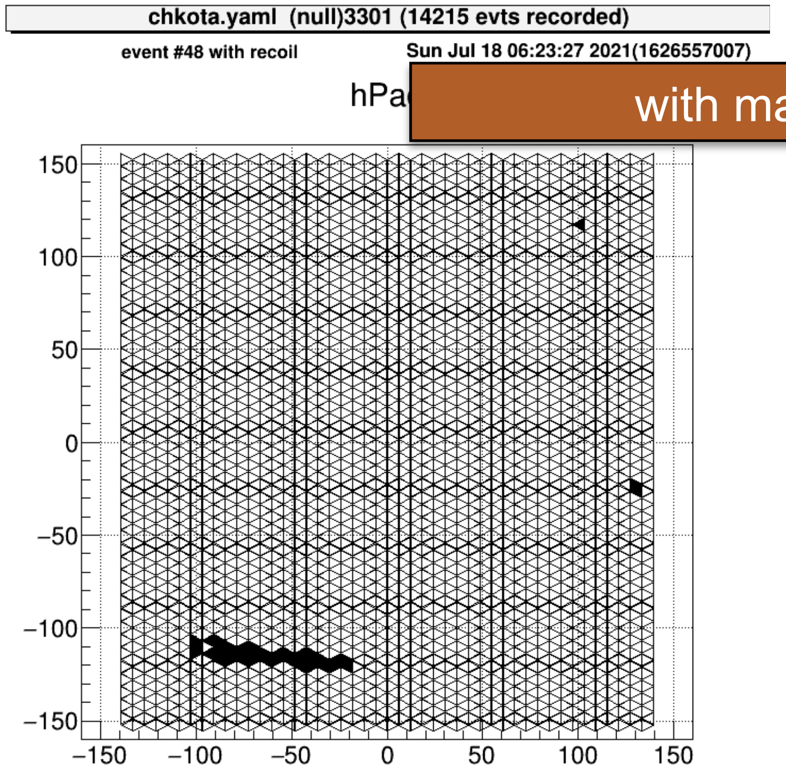
H307-10 (only one event)

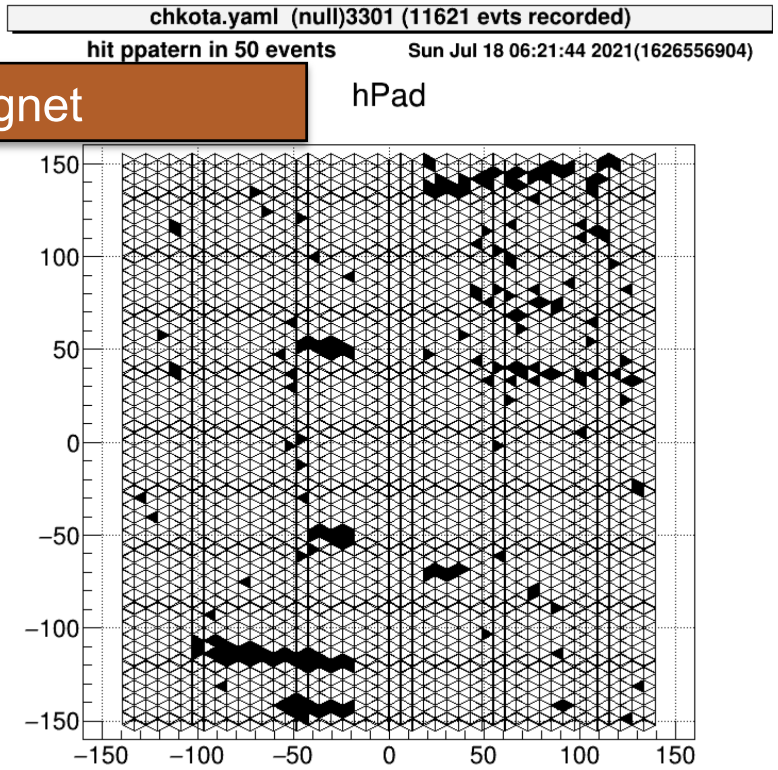
without magnet



30<|x|<90 has higher threshold,
many delta-rays are recorded

with magnet



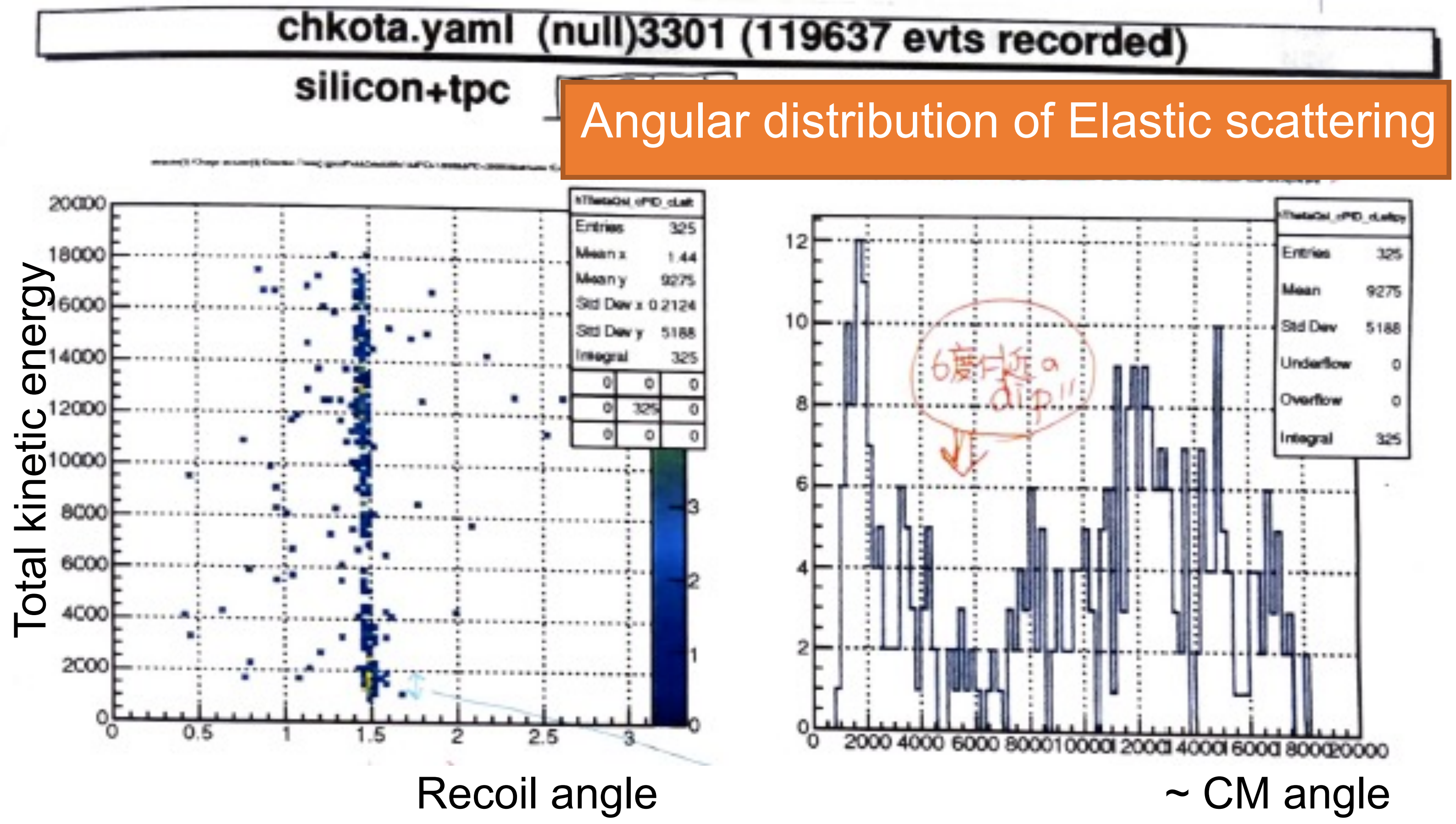


H445-1 : one event (left), 50 events (right)
(30-50) has higher threshold

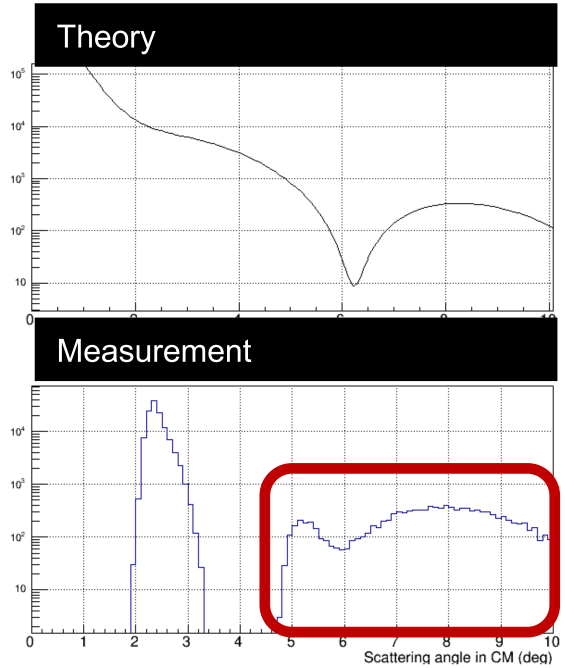
Comparison with / without magnet

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

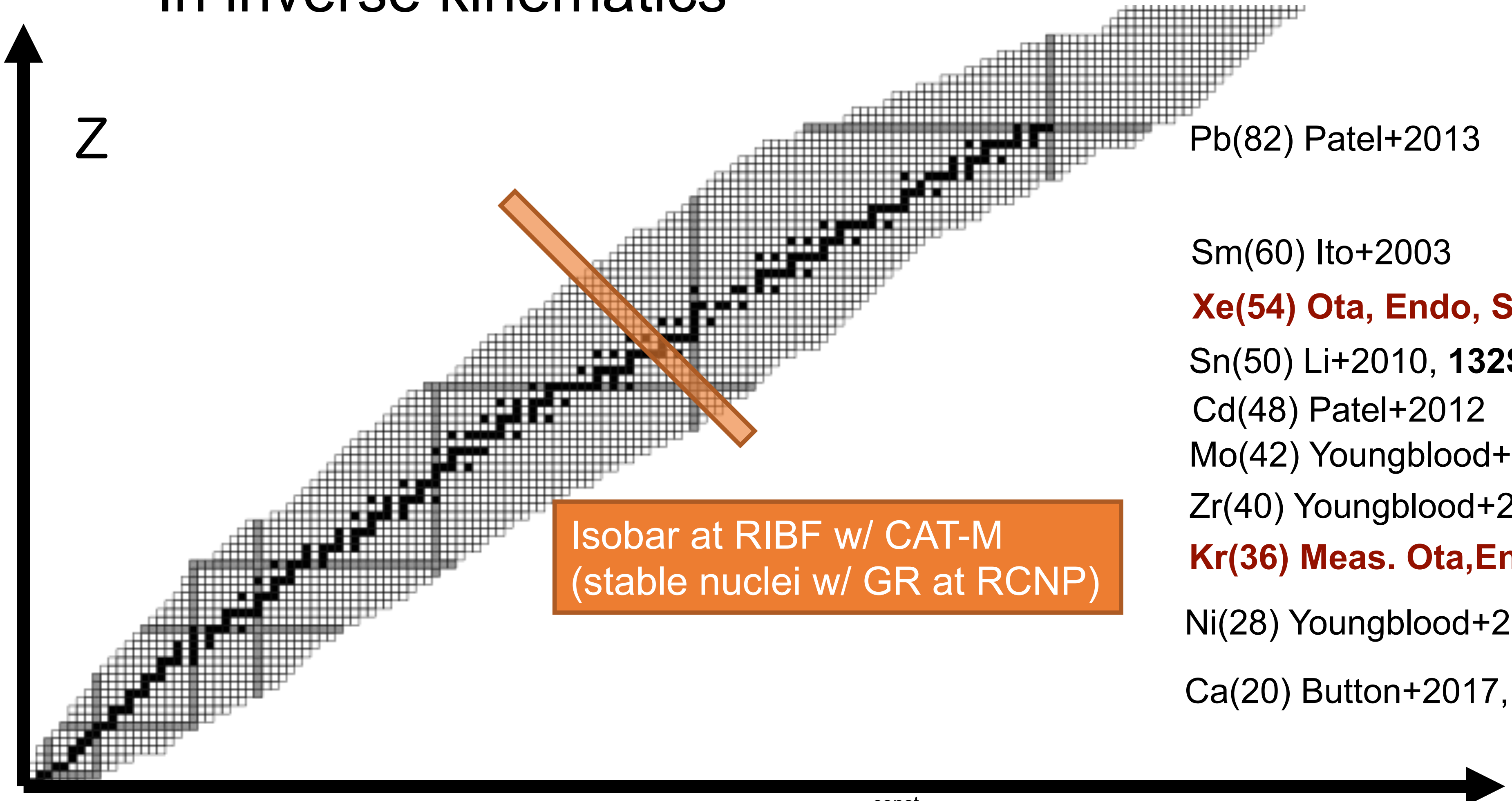
Performance of CAT-M w/ Magnet **10 minutes data**



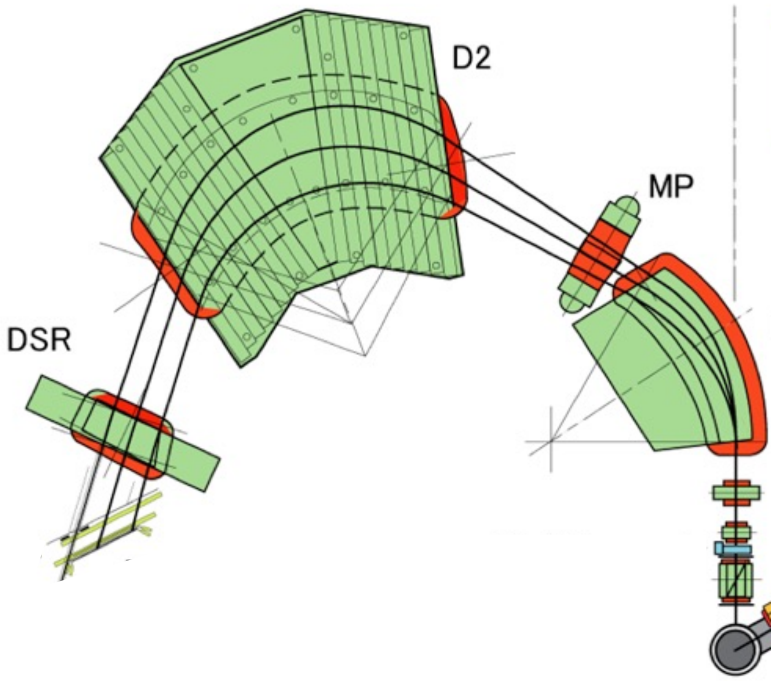
c.f.) 132Sn(d,d) for 5days



Strategy of ISGMR measurement
In inverse kinematics



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

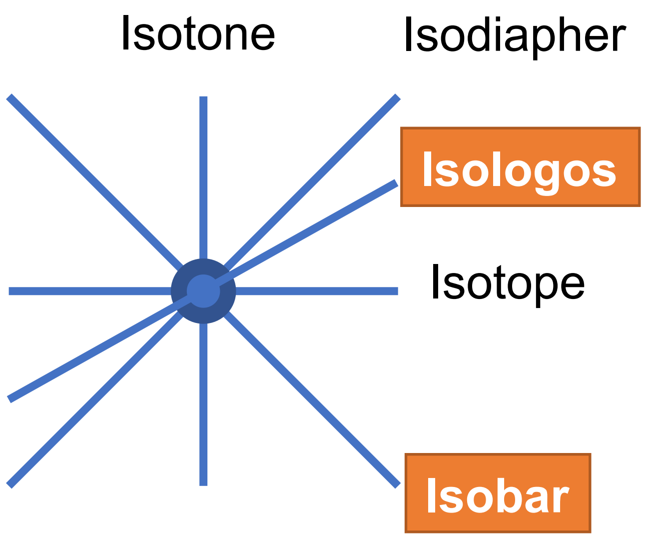


Forward kinematics

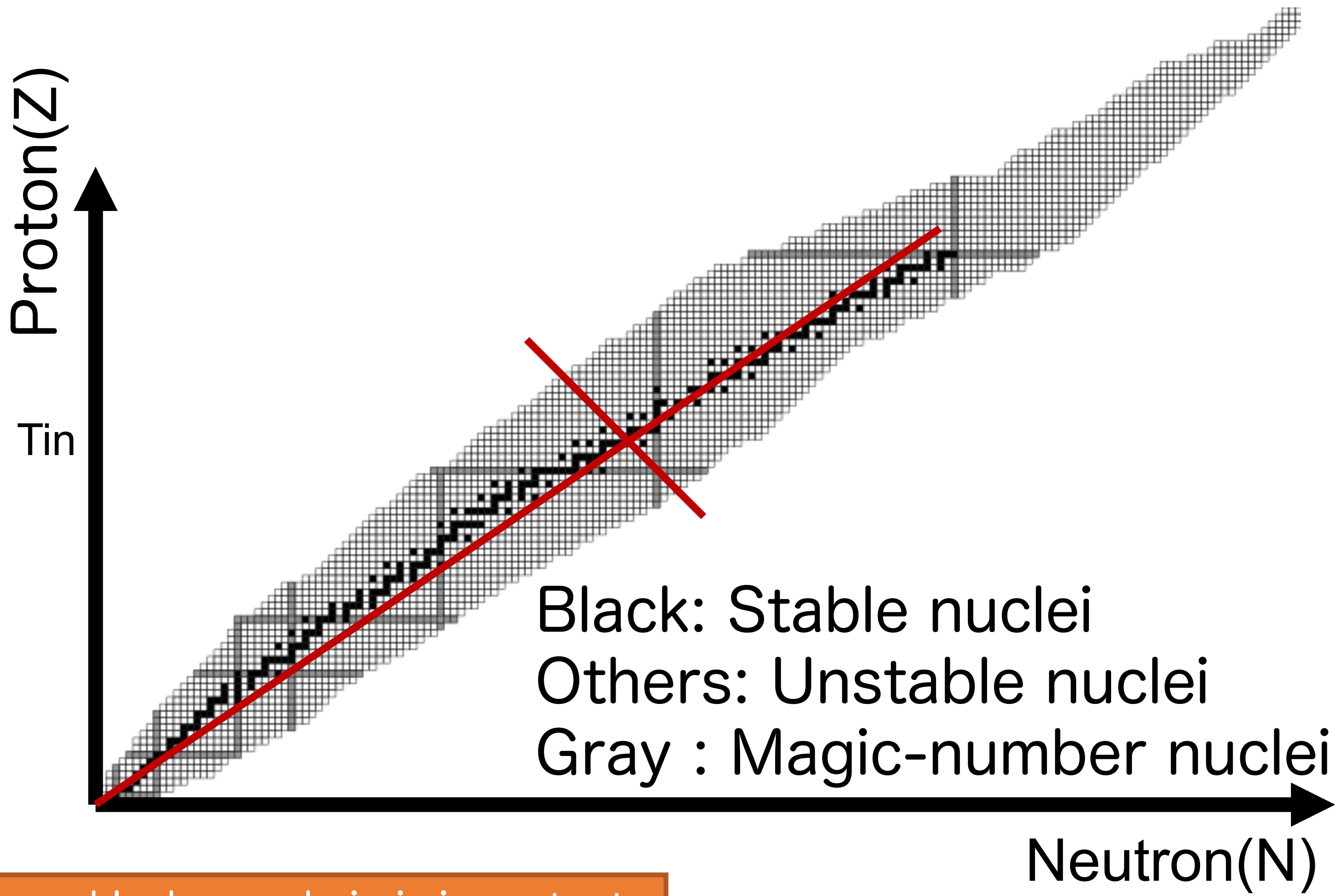
High precision measurement with GRAND RAIDEN

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

Systematics : selection of target for incompressibility

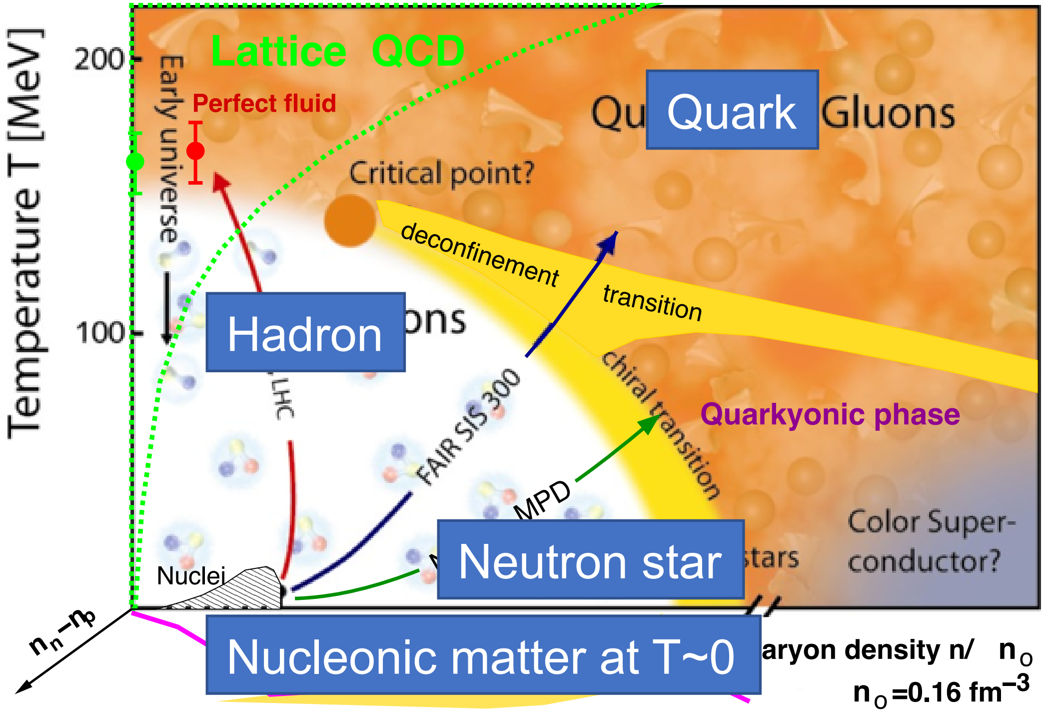


Isotope : Z = const => Neutron
Isotone : N = const => Proton
Isobar : A = const => Isovector
Isodiapher : N-Z = const => Isoscalar
"Isologos?" : (N-Z)/A or A/Z = const => Mass
(neologism)



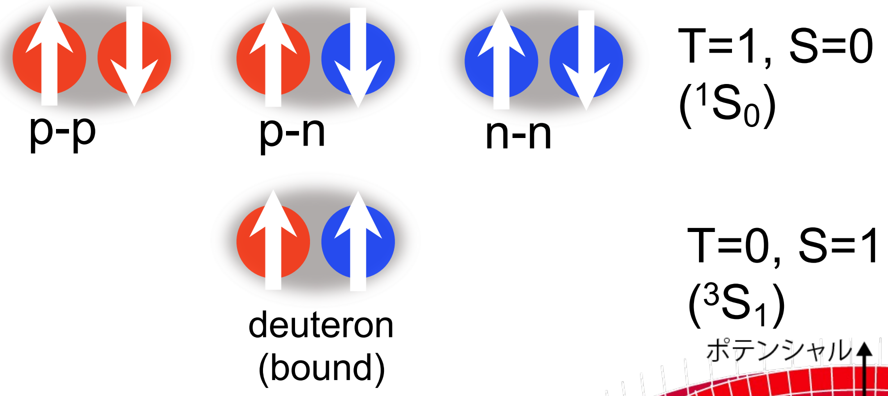
Systemtics of Isobar and Isologos chain is important.

What kind of phases exist in nucleonic matter?



Pair correlation

Spin(S), Isospin(T), Space (L)



Neutron pair condensation

?Spin-triplet pair condensation (nn, pn)

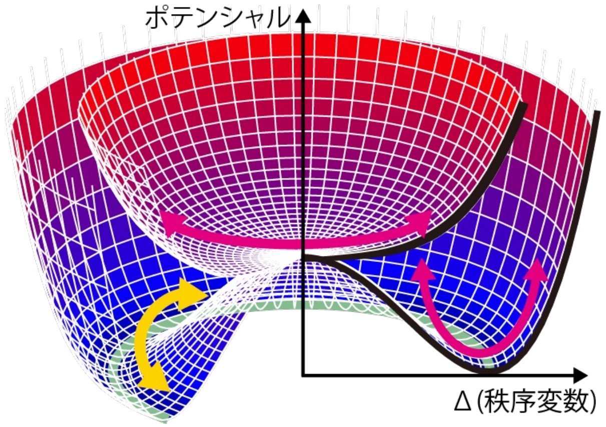
? Proton pair condensation

? Pion, kaon condensation

? Alpha condensation...

? Pasta phase

Order parameter?



Starting from fermion pair condensation

Fermion condensation

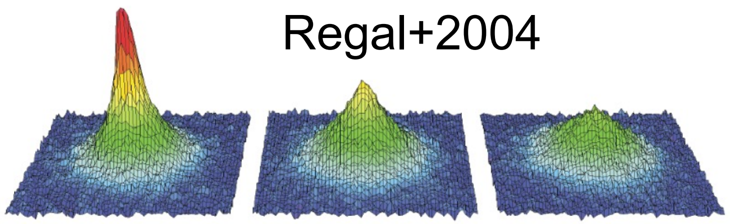
- Superconductor in material
  - BCS State (1957)
  - Beyond BCS
    - FFLO (2009)
    - Spin triplet
    - Parity-non-conserved
    - Time-non-conserved
    - …
- Superfluidity of He-3 (1972)
- Atom pair condensation of K-40 (2004)
- Nucleon pair condensation ?

https://www.jps.or.jp/books/19-11-1.pdf

https://www.jps.or.jp/books/jpsjselectframe/2009/files/2009-11-2.pdf

http://mercury.yukawa.kyoto-u.ac.jp/~bussei.kenkyu/pdf/04/4/0067-044205.pdf

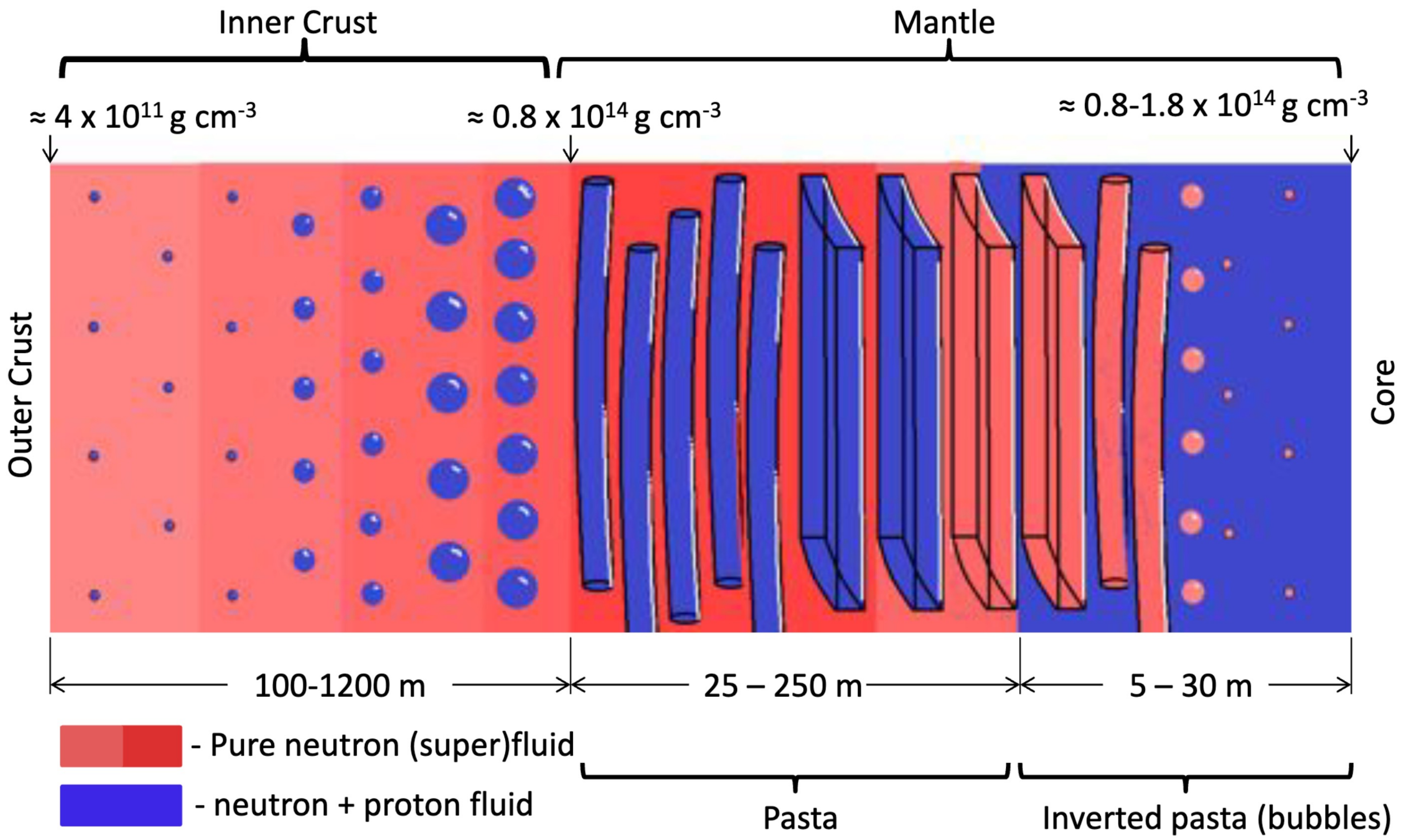
Regal+2004



Structure of neutron star

Superfluid neutron is predicted to exist in neutron stars

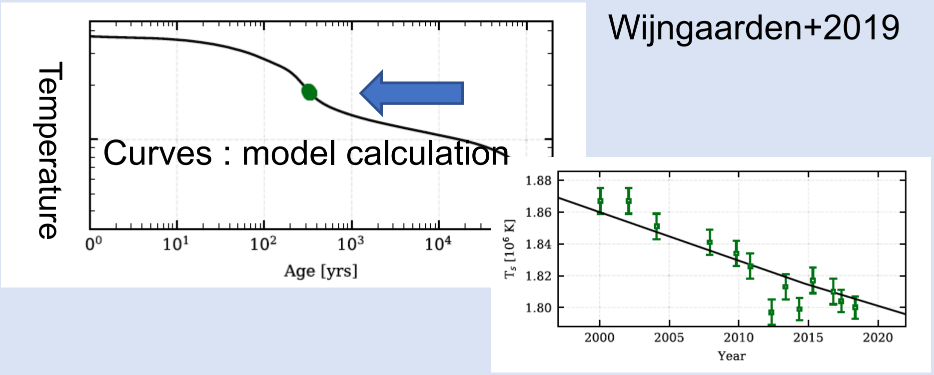
Newton+2013



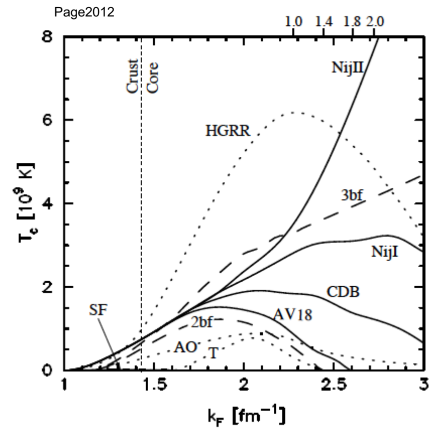
Pairing in Neutron Star Cooling

- Observed temperature change of neutron star in Cassiopeia-A remnant is quite large
  - Thought to be an evidence of phase transition due to the calculation
- Large ambiguities in the used gap models especially for 3P2 gap
  - Nuclear physics have not clarified the existence of P-save pairing

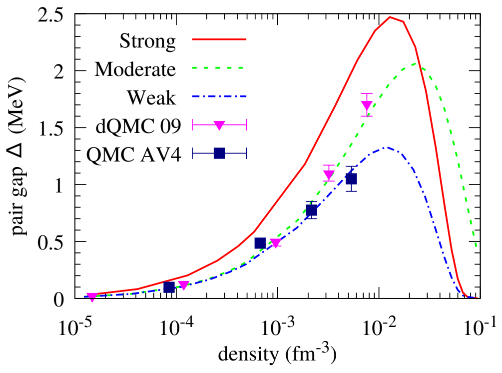
Phase transition in Cassiopeia-A



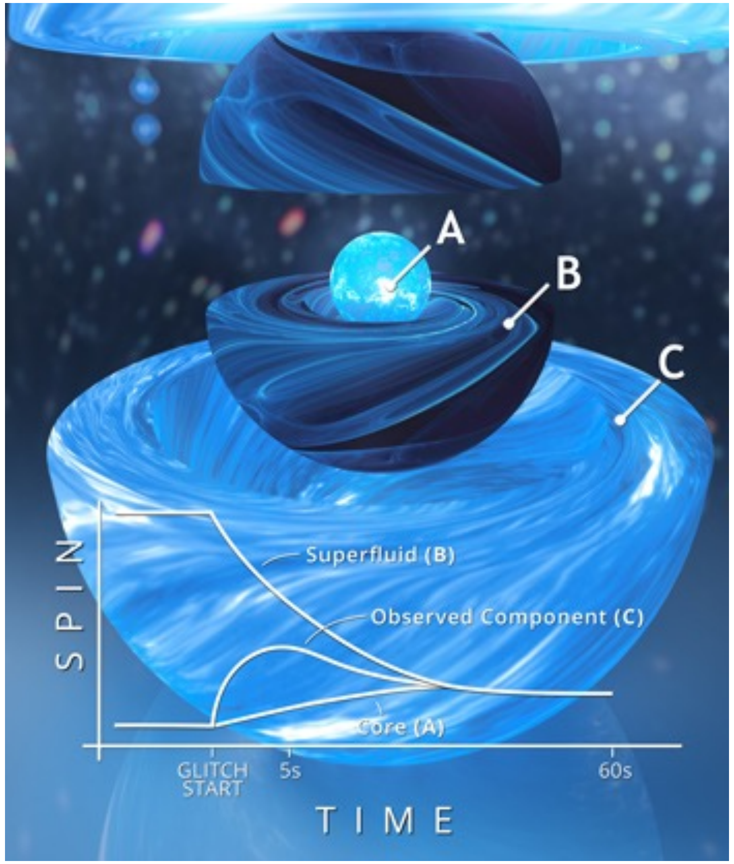
Various 3P2 gap model

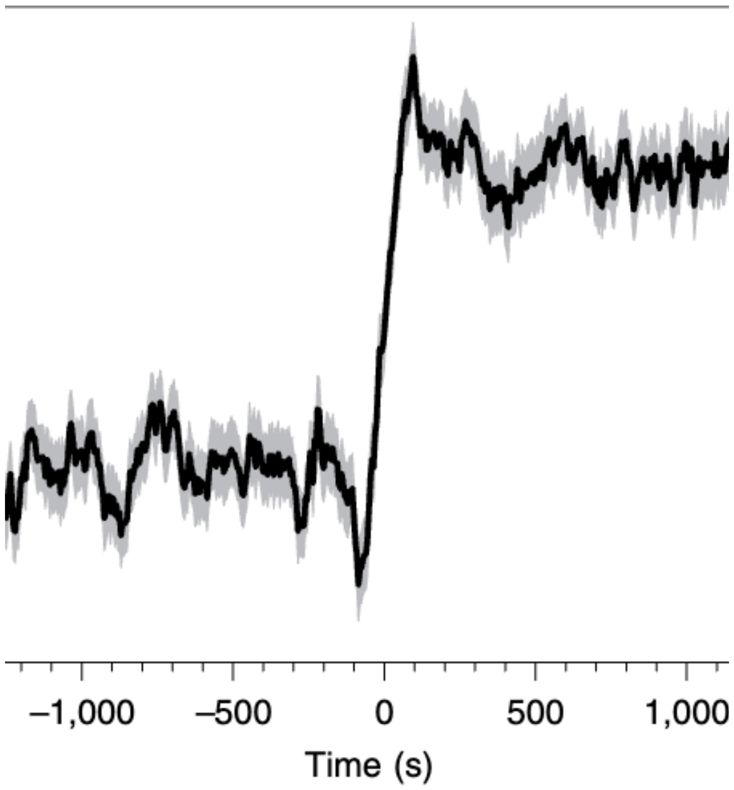


Various 1S0 gap model



Two superfluid phases may exist in neutron star



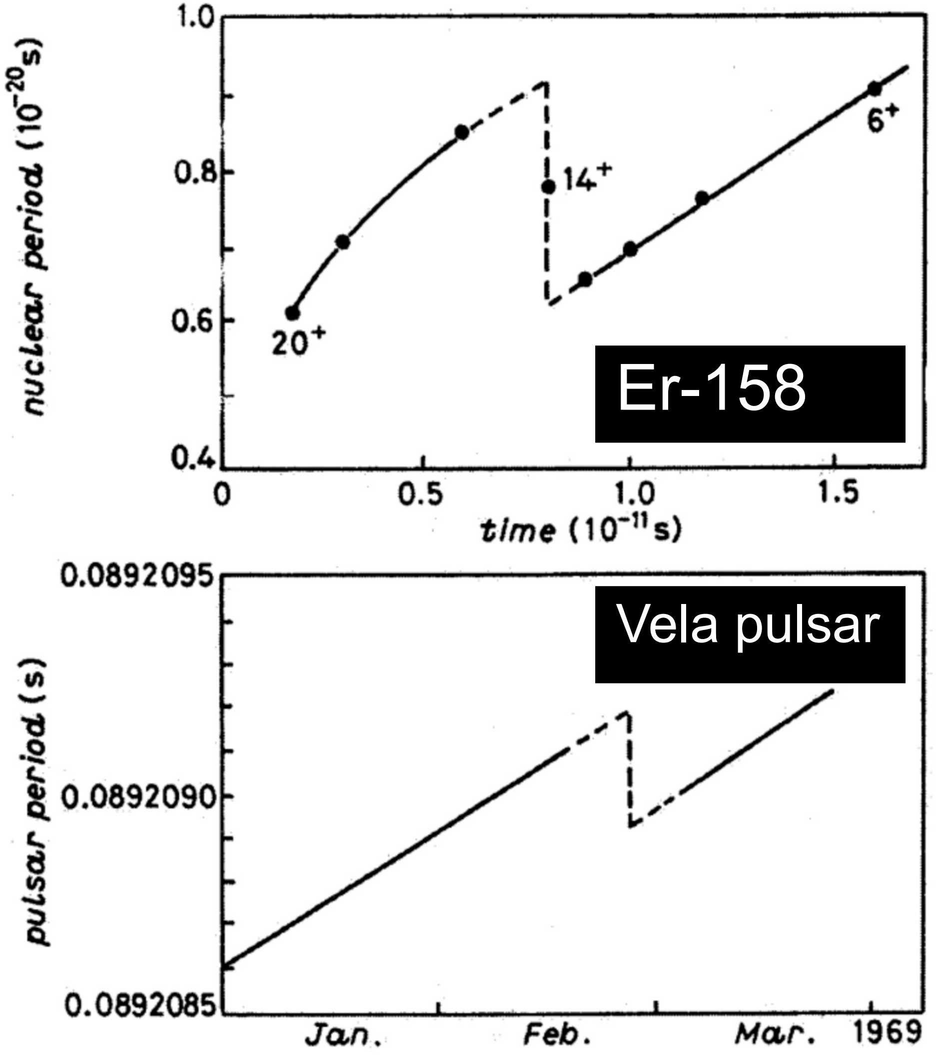


- Rotational evolution of the Vela pulsar during the 2016 glitch (Ashton+2019)
- Extract the rise time and decay time of the pulsar frequency
- Two component model where the inner crust provides the angular-momentum reservoir for the glitch.

Nuclear glitch

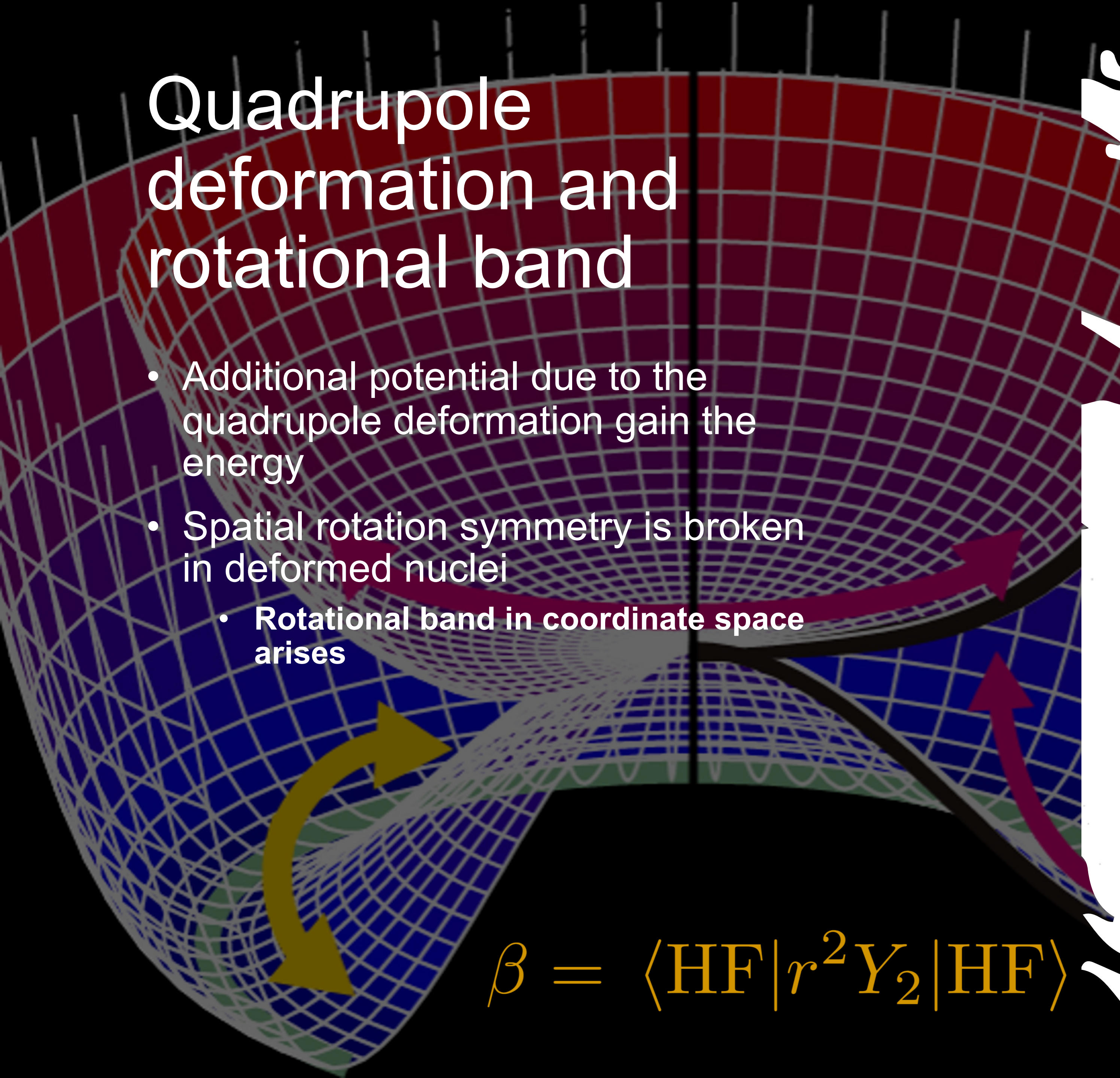
- In deformed nuclei, sudden change of the rotation period against the change of spin is observed (e.g. Er-158).
  - Like the vela pulsar.
- The aligned pair neutron in the high-j orbital carries the intrinsic spin at high spin state
  - Mechanisms of glitches are not exactly same for the moment but based on the nature of pairing.

Nuclear Superfluidity, Brink and Broglia (2005)

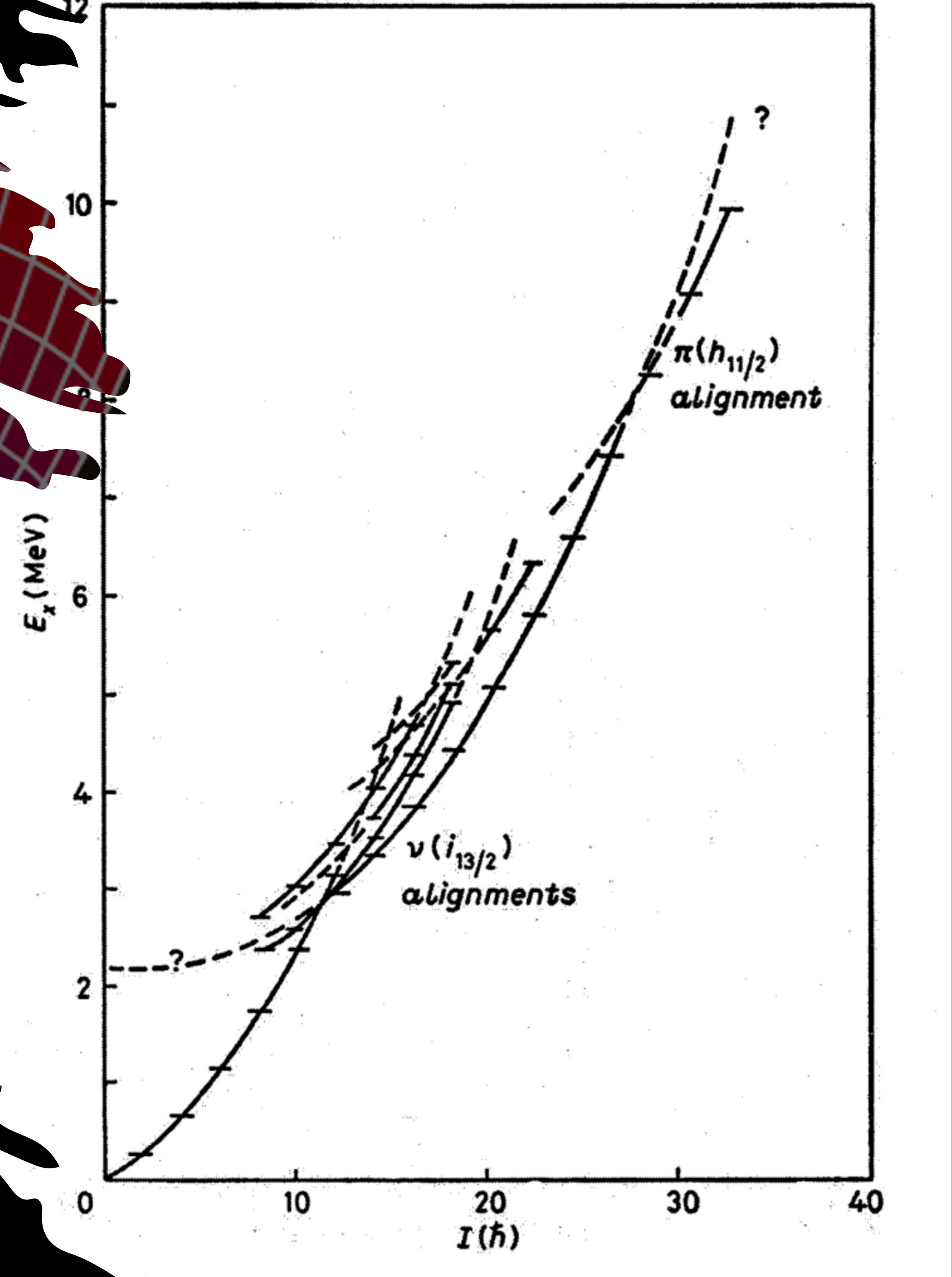


Quadrupole deformation and rotational band

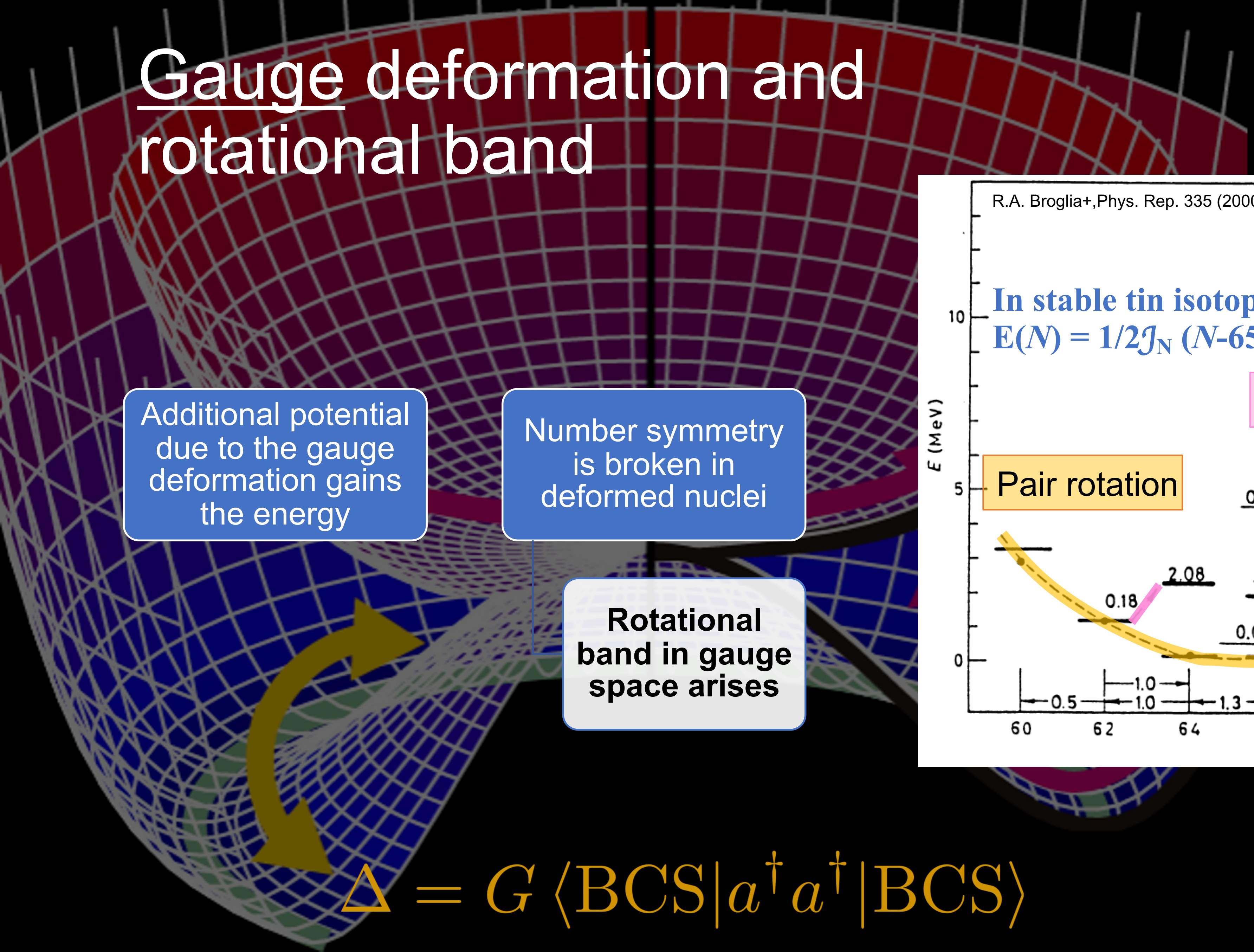
- Additional potential due to the quadrupole deformation gain the energy
- Spatial rotation symmetry is broken in deformed nuclei
  - **Rotational band in coordinate space arises**



$$\beta = \langle \mathrm{HF} | r^2 Y_2 | \mathrm{HF} \rangle$$



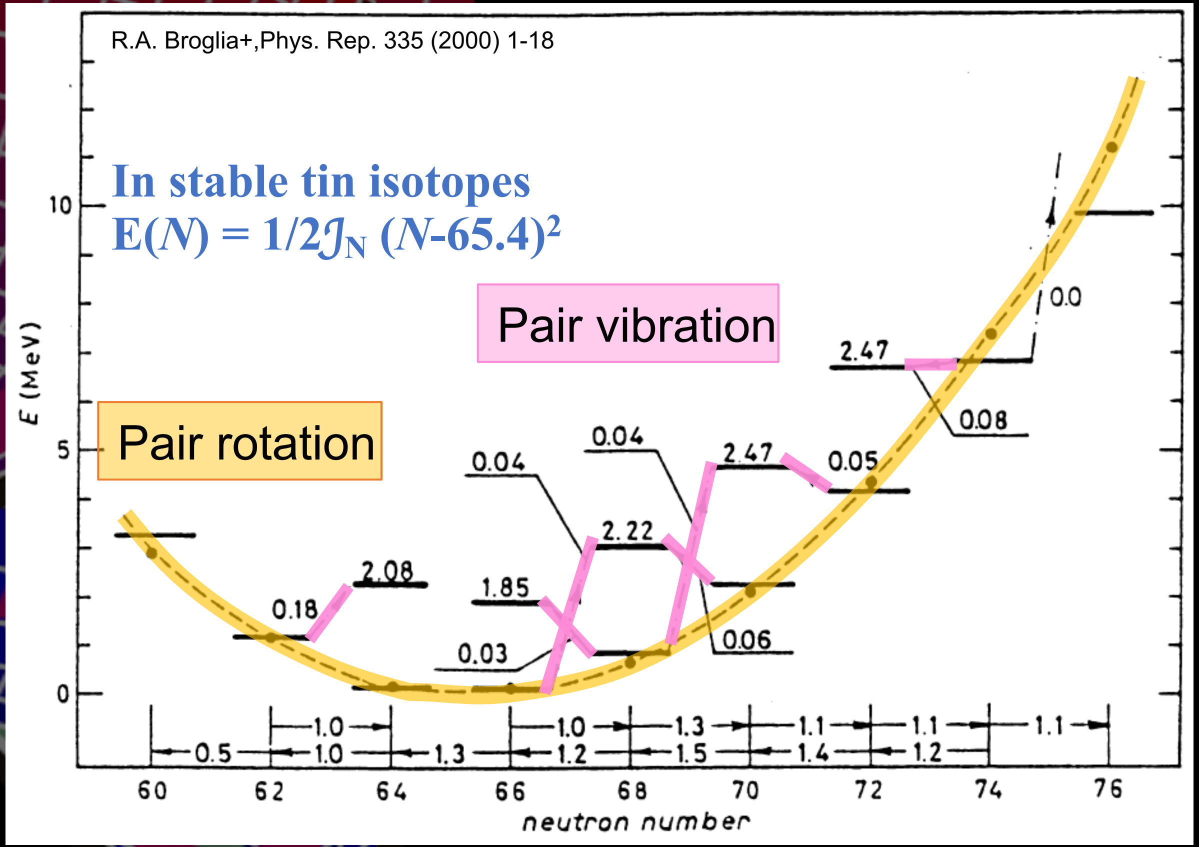
Gauge deformation and rotational band



Additional potential due to the gauge deformation gains the energy

Number symmetry is broken in deformed nuclei

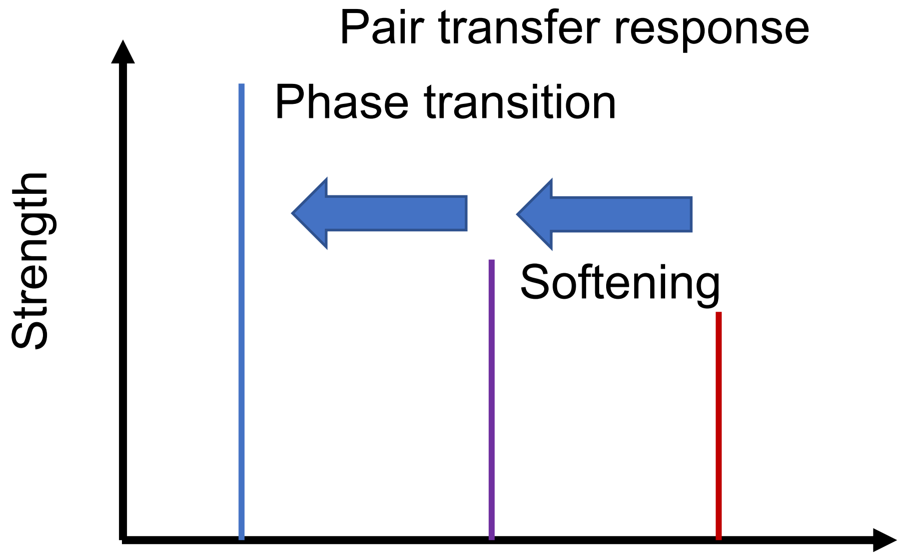
Rotational band in gauge space arises



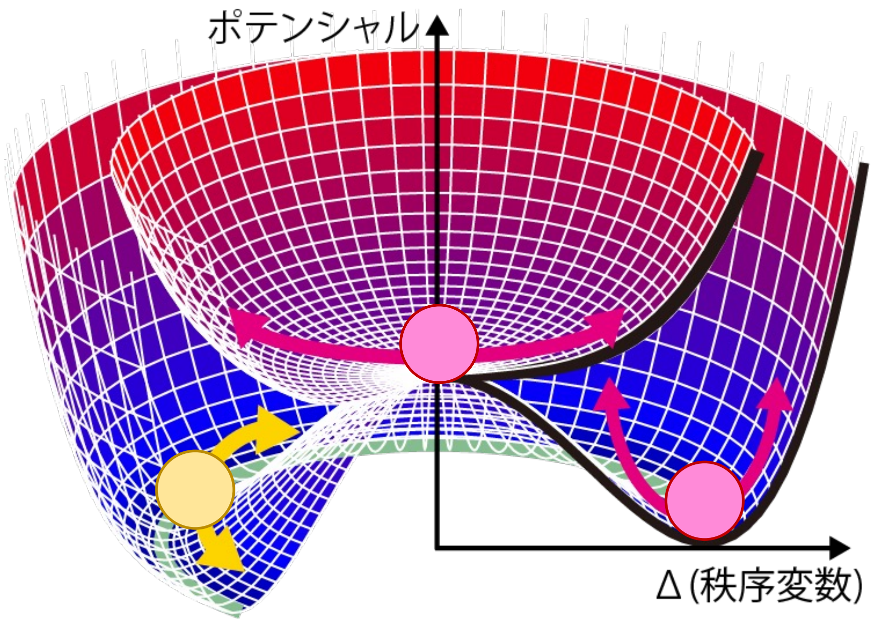
$$\Delta = G \langle \mathrm{BCS} | a^\dagger a^\dagger | \mathrm{BCS} \rangle$$

Nuclear response for condensation

Response to the pair density (order parameter)
=> Pair transfer

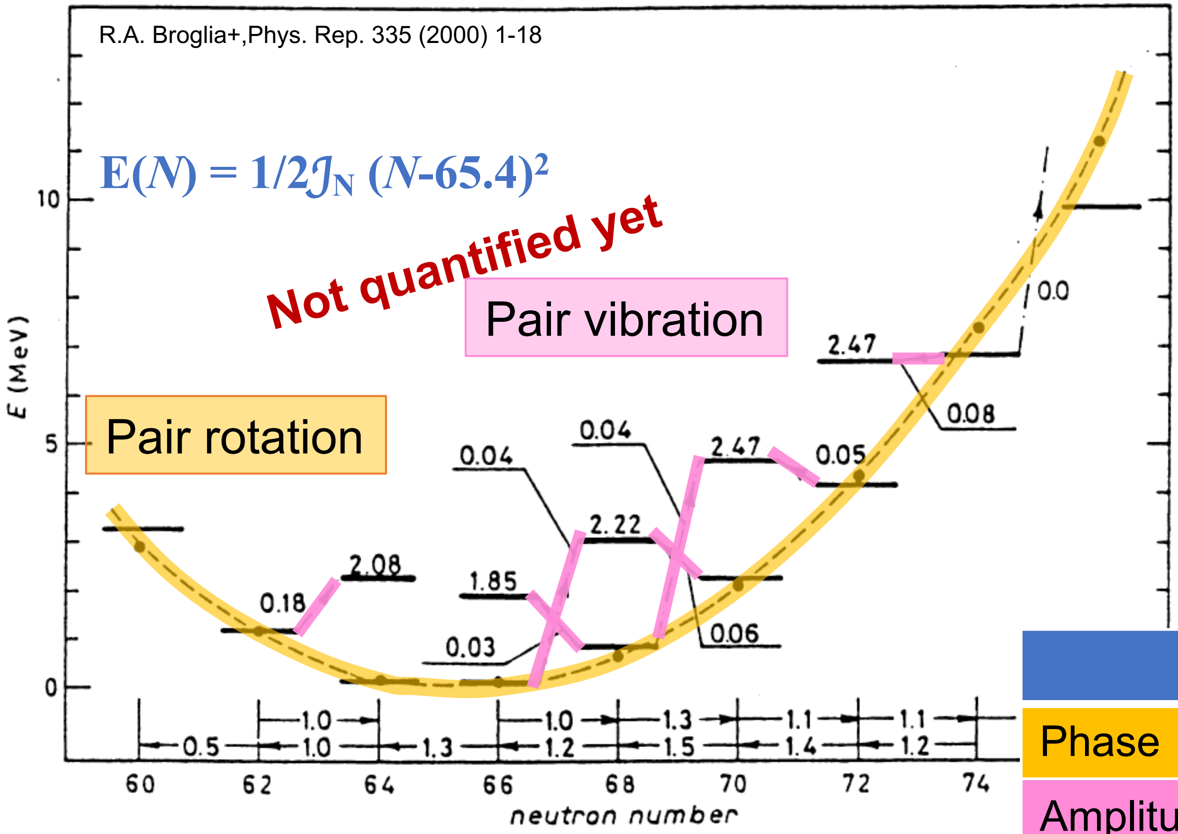


Potential with order parameter (pair density)

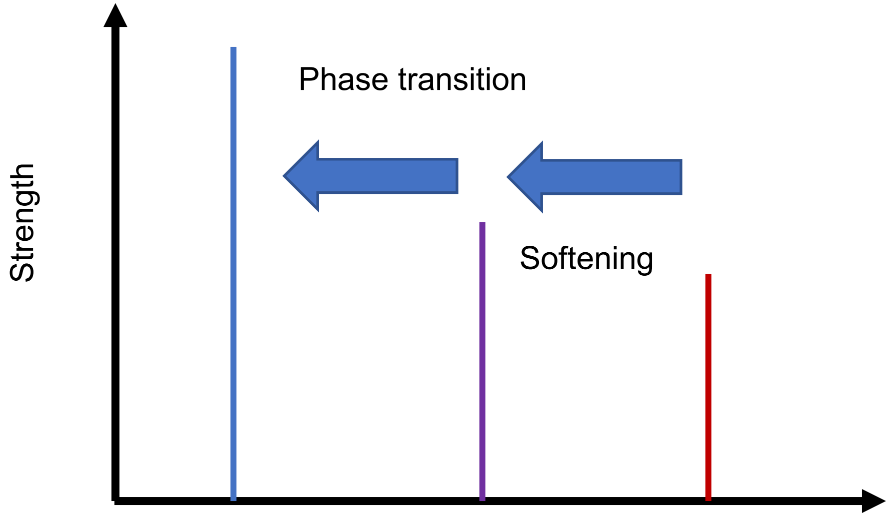


Response to the pair transfer
Phase mode（pair rotation）
Amplitude mode（pair vibration）
⇔ Order parameter

Pair rotation and vibration

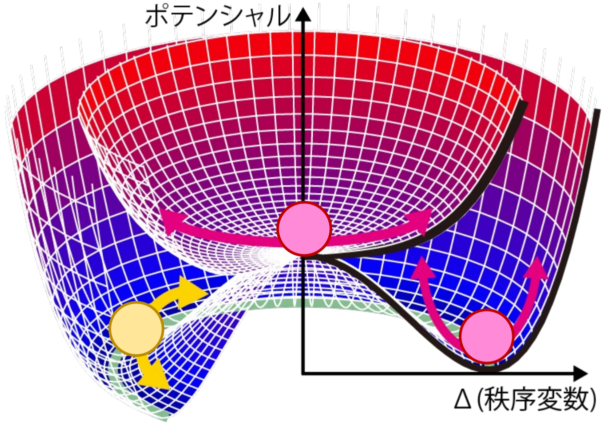


Pair transfer response



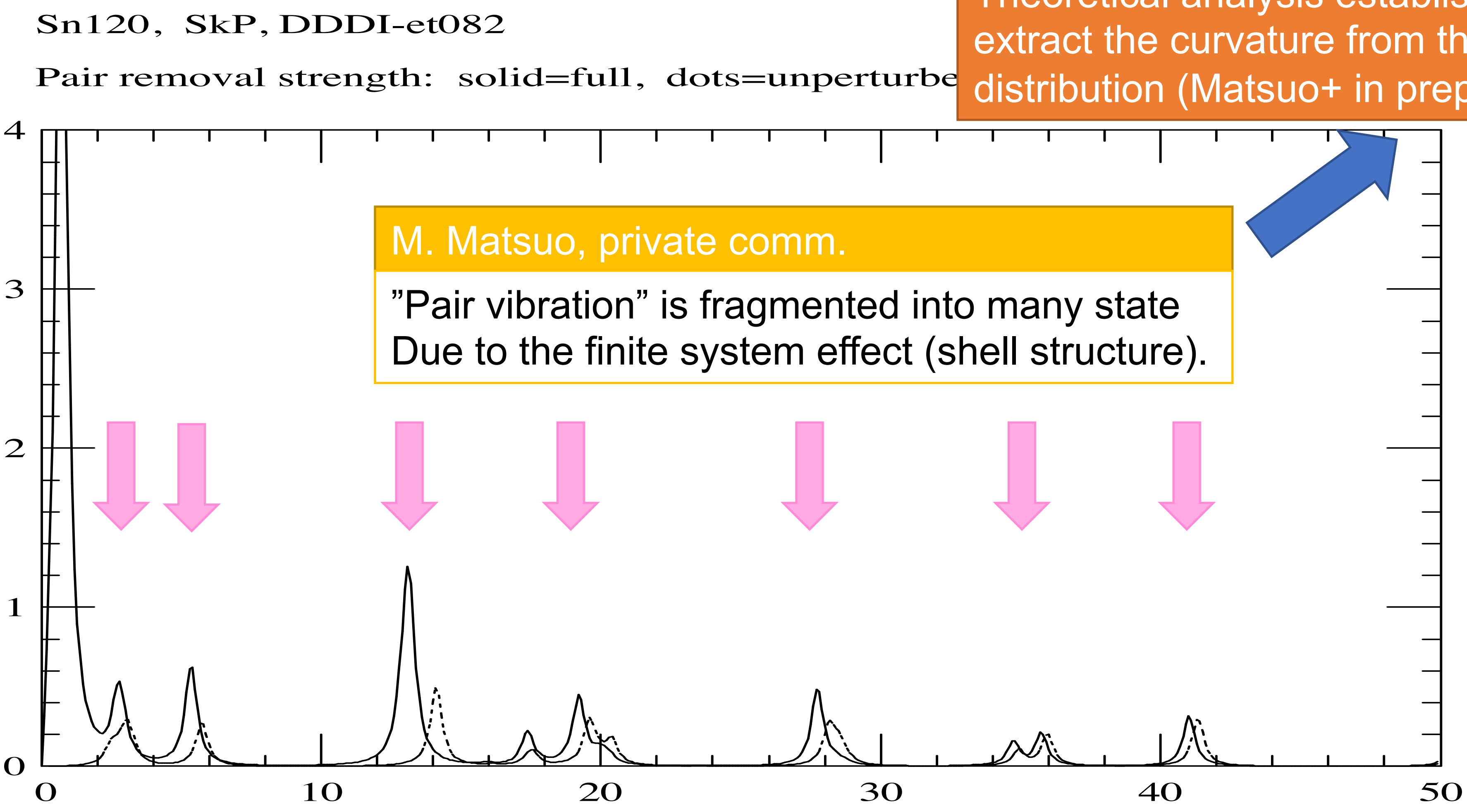
Excitation energy

	Physics	Response
Phase	Gap	Rotation
Amplitude	Curvature	Vibration



How to quantify the curvature?

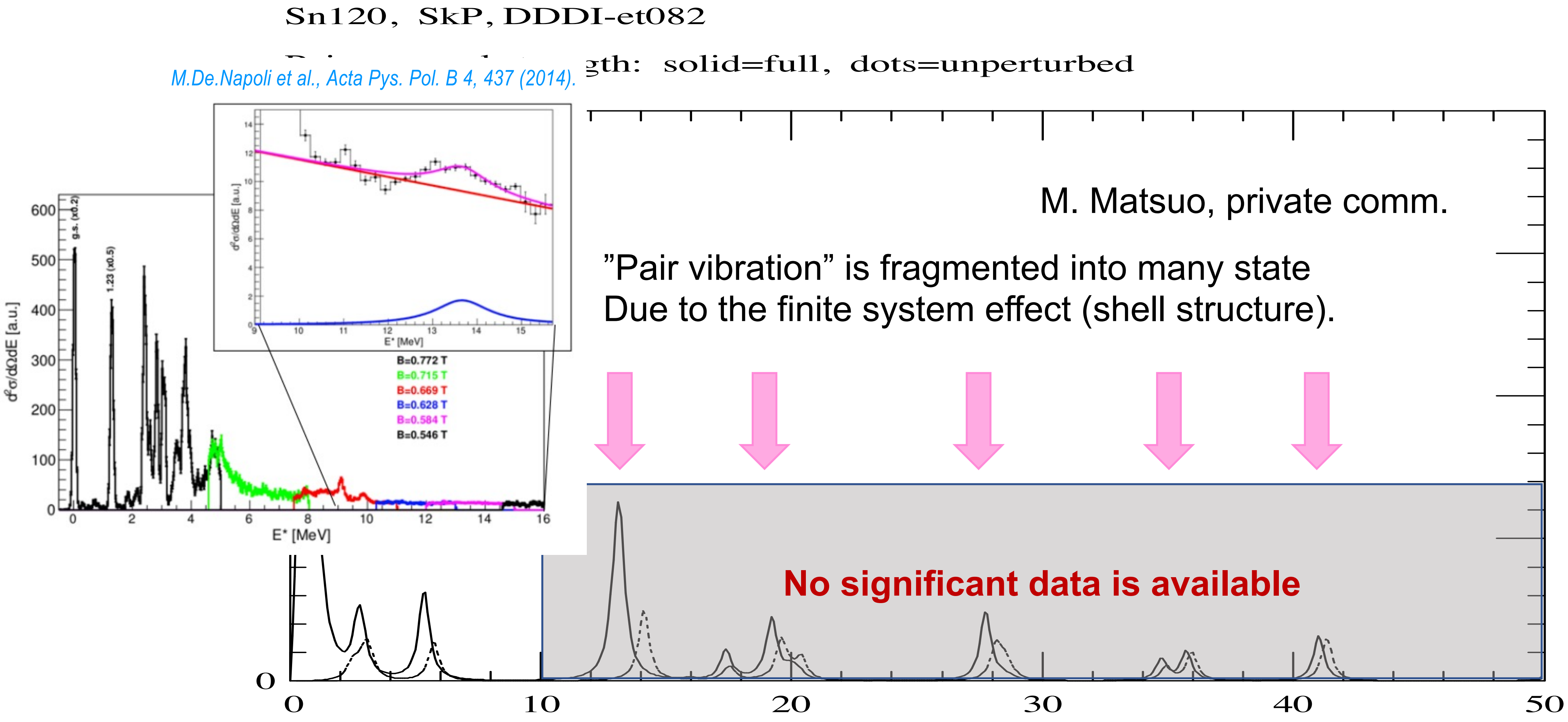
Theoretical analysis established the way to extract the curvature from the strength distribution (Matsuo+ in preparation).



M. Matsuo, private comm.

”Pair vibration” is fragmented into many state
Due to the finite system effect (shell structure).

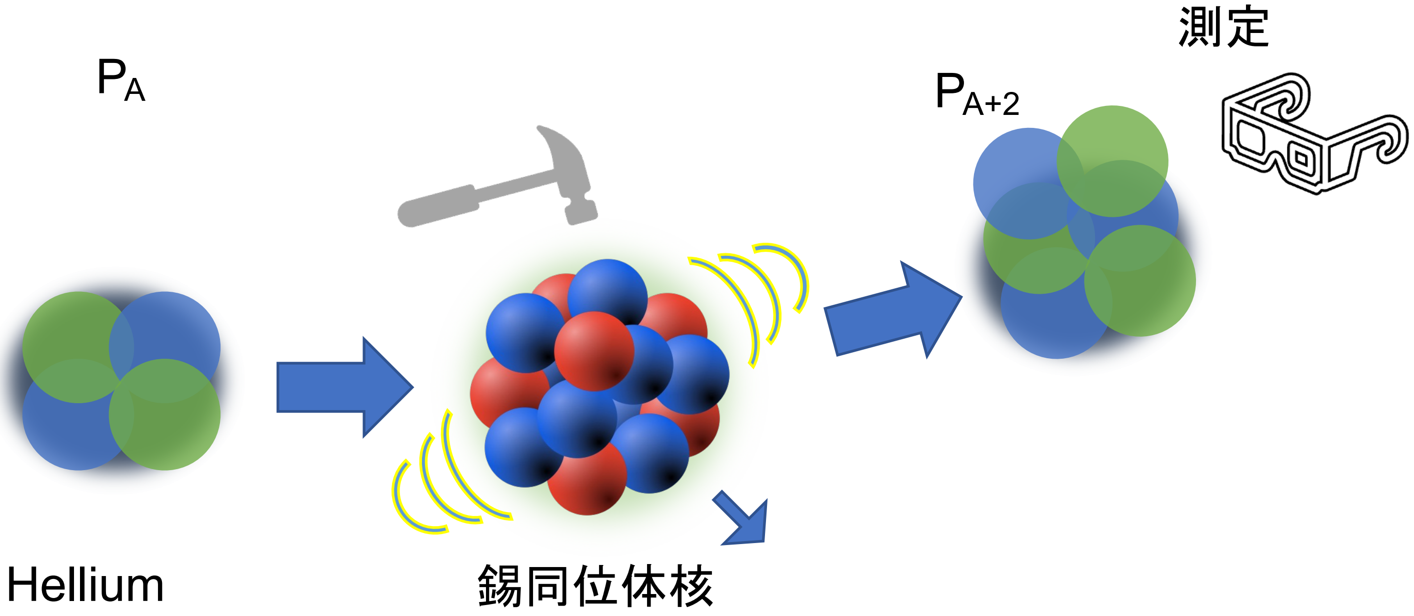
How to quantify the curvature?



Effective tool for highly excited states

Condition for the reaction

- Direct reaction: kinetic energy of incident and outgoing particle should be high
- Recoilless ($P_A=P_{A+2}$) : Two nucleons can easy move from one to the other



Condition for incident energy

$T \sim -(A+2)/2\ (Q – Ex)$

A : Mass of probe

Q : Q-value

Ex : Excitation energy

For example, ^{120}Sn

Ex~ 15 MeV	A	Q (MeV)	Tin (MeV)	Tout (MeV)
(p,t)	2	-7.1	33	11
(a,6He)	4	-14.6	90	60

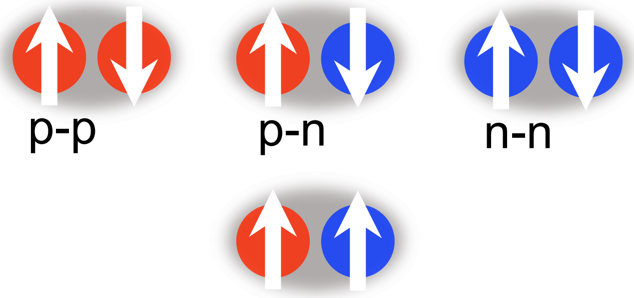
(a,6He) is better for pair removal.

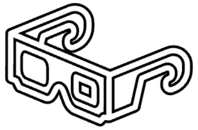
Classification of pair correlation

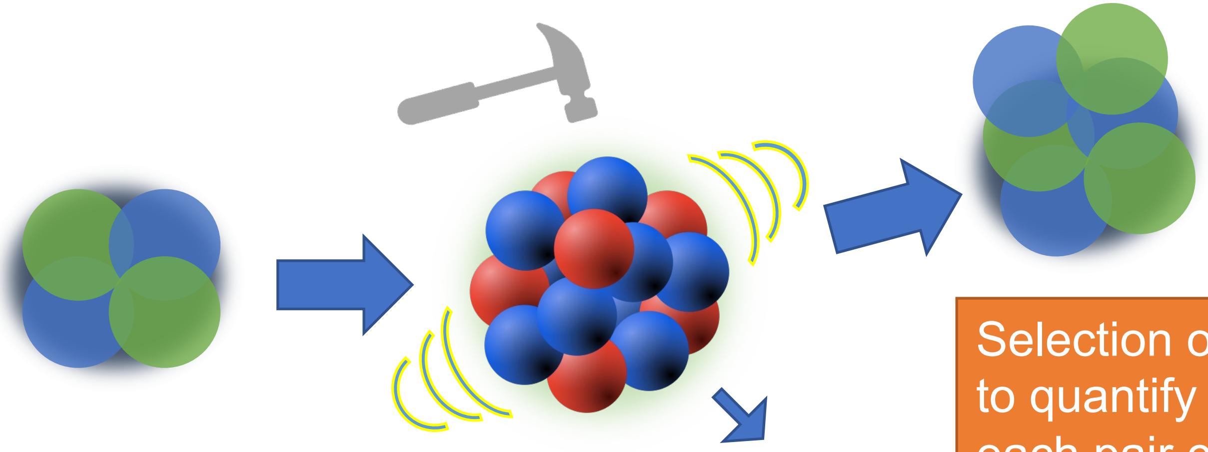
Probe	Pair	Rotation	Vibration
(a,^{6}Li), (a,d)	pn-3S1		
(a,^{6}Li*), (a,$d_{S=0}$)	pn-1S0		
(a,6He),(a,2p)	nn-1S0	◎	△
(3He,n),(n,3He)	pp-1S0		

Quantum numbers of pairing correlation

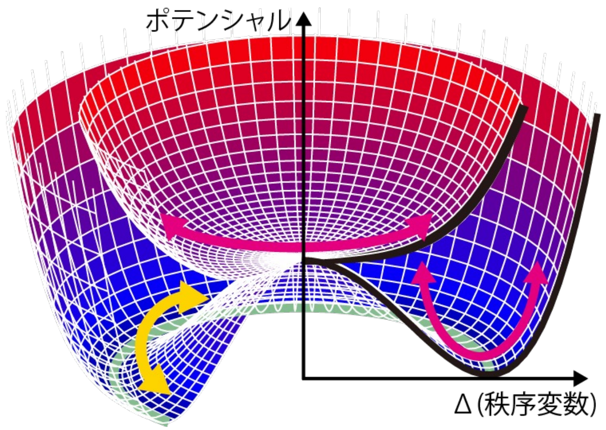
spin(S), isospin(T), space(L)







Selection of probe reaction enable us to quantify the order parameter of each pair condensation.



Summary

- PHANES Project for EOS and matter phases
- EoS : new systematic measurements along isobar and isologos will reveal the finite system effect.
- Pair condensation : Quantification of the order parameter requires the strength distribution of pair transfer upto very high energy.
- Collaborations are very welcome!