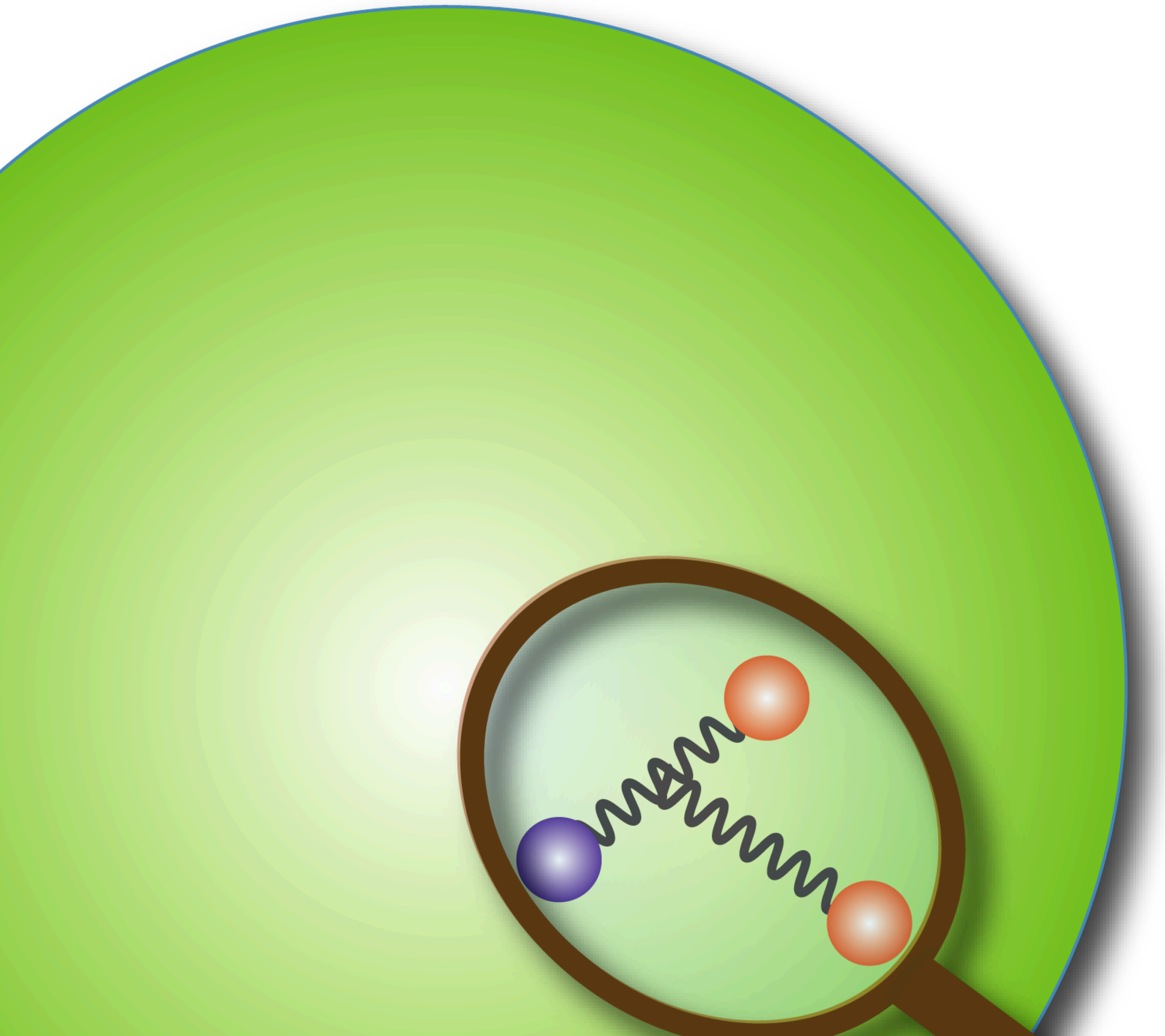
Tokyo Tech

Nucleon-Deuteron Scattering to Investigate Three-Nucleon Forces

Tokyo Institute of Technology
Kimiko Sekiguchi (関口 仁子)

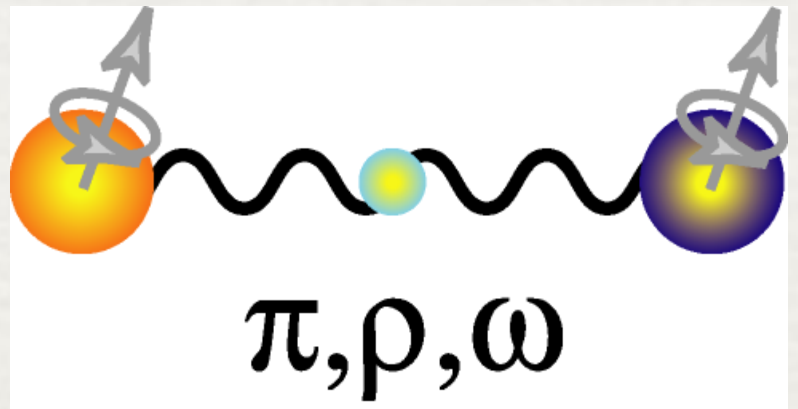


Frontier of Nuclear Force Study

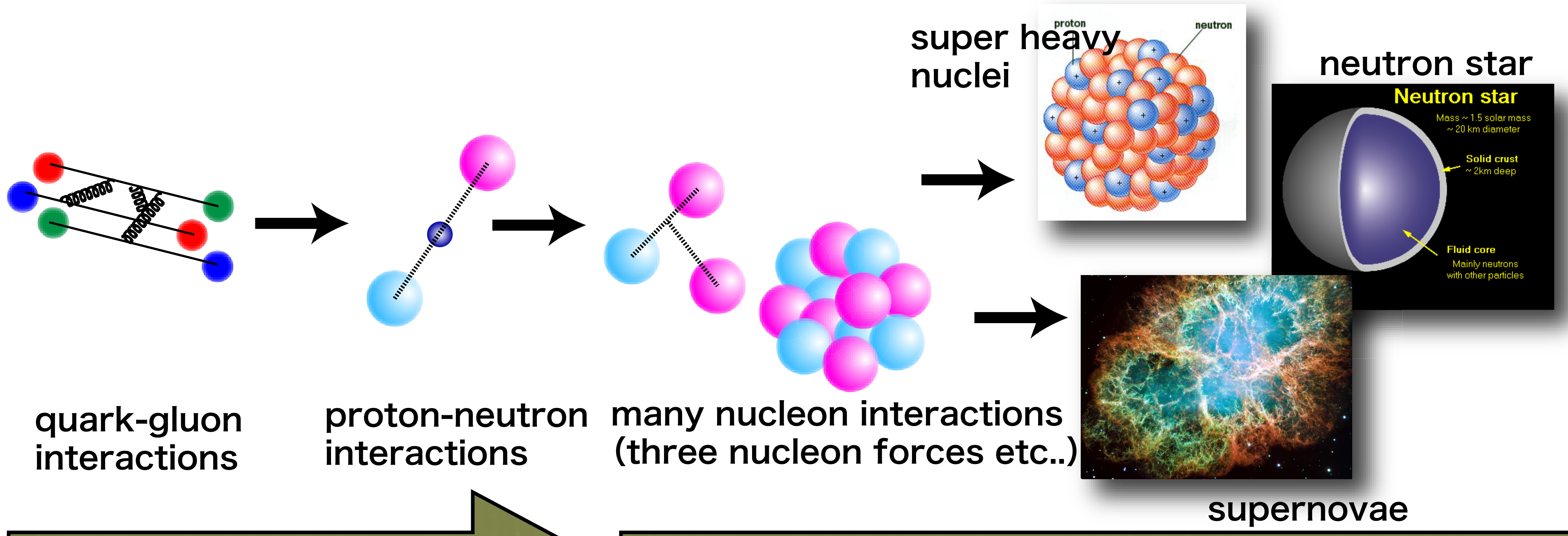
History

1935 Yukawa's meson theory - Two-Nucleon Forces (2NFs)

1990's Realistic Modern Nucleon-Nucleon Potentials (CD Bonn, Argonne v18, Nijmegen)



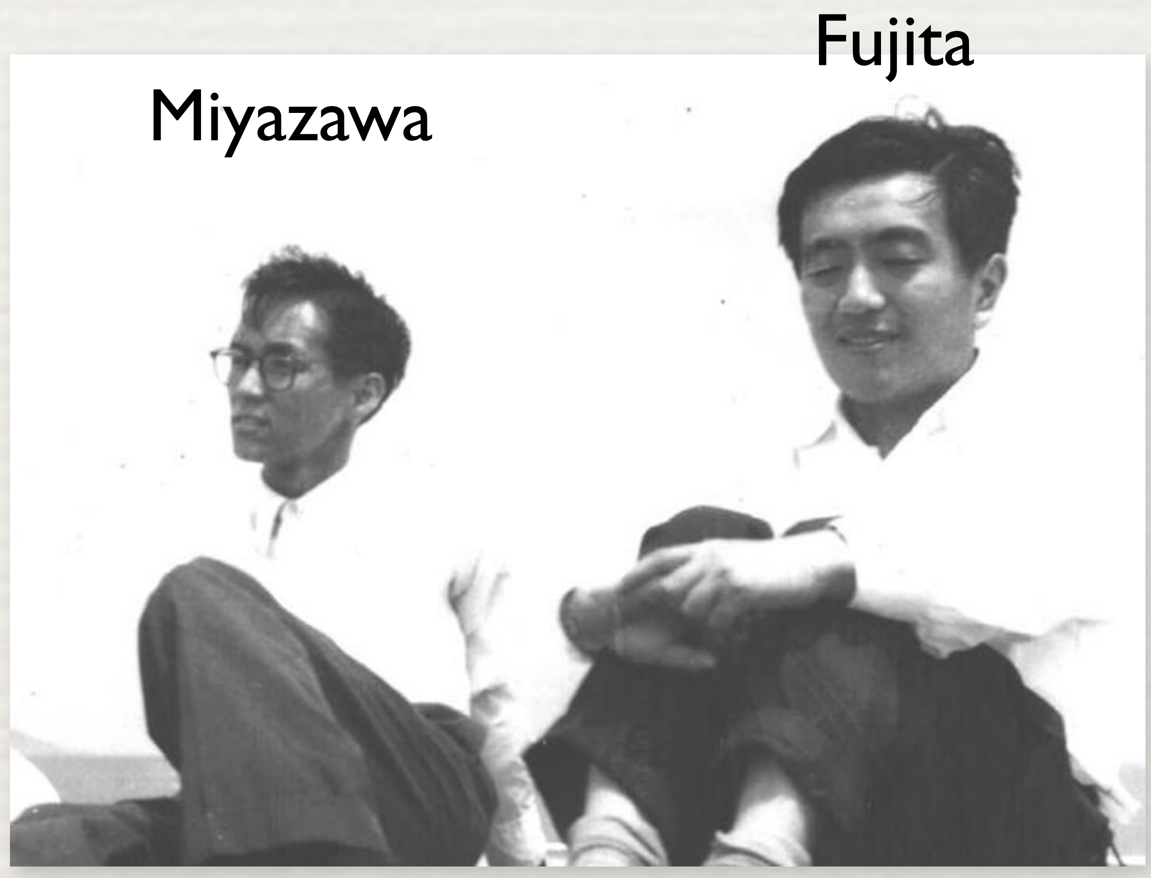
- To understand Nuclear Forces from Quarks ～ Lattice QCD ～
- To understand Nuclei and Nuclear Matter from bare Nuclear Forces ～ with 3-Nucleon Forces ～



Consistent Understanding from quarks to the Universe

Three-Nucleon Force (3NF)

- nuclear forces acting in systems more than $A > 2$ nucleons -

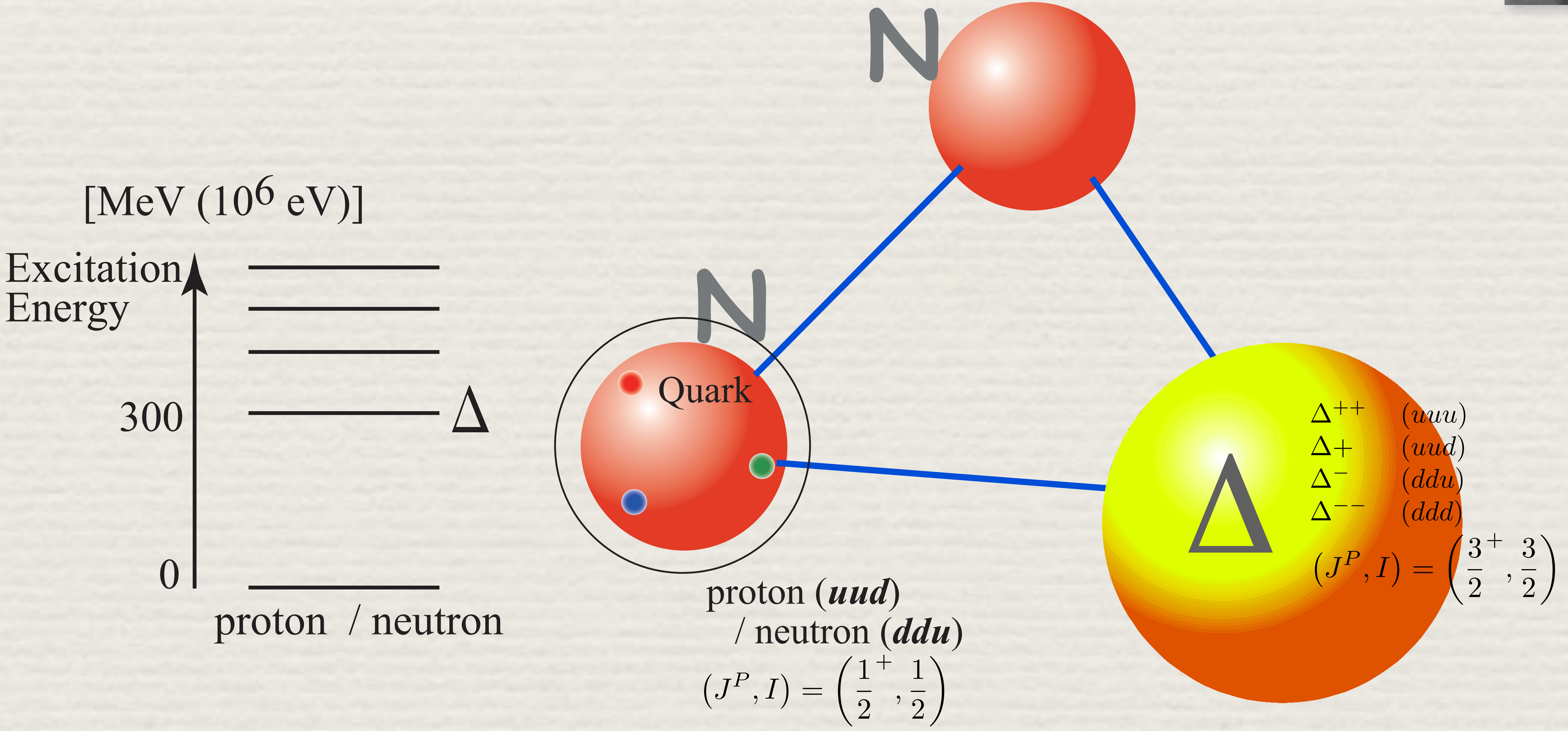


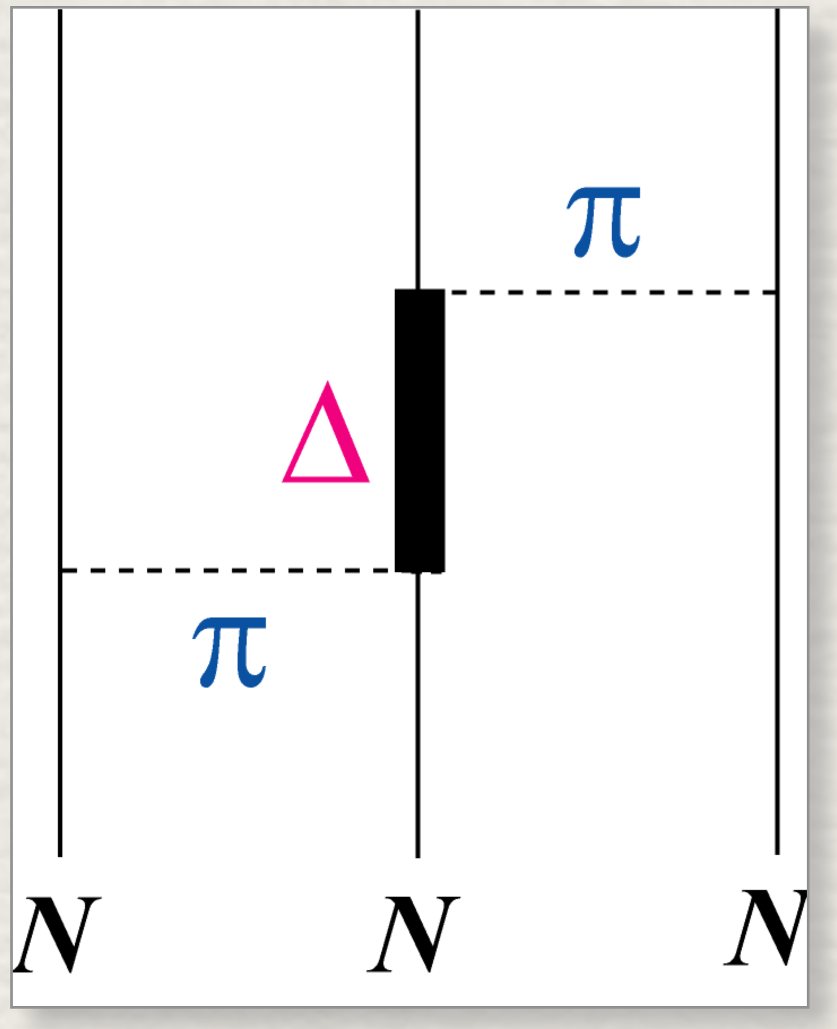
- **2π-exchange 3NF :**

  1957 Fujita-Miyazawa 3NF

  Prog. Theor. Phys. 17, 360 (1957)

  - Main Ingredients : Δ-isobar excitations in the intermediate





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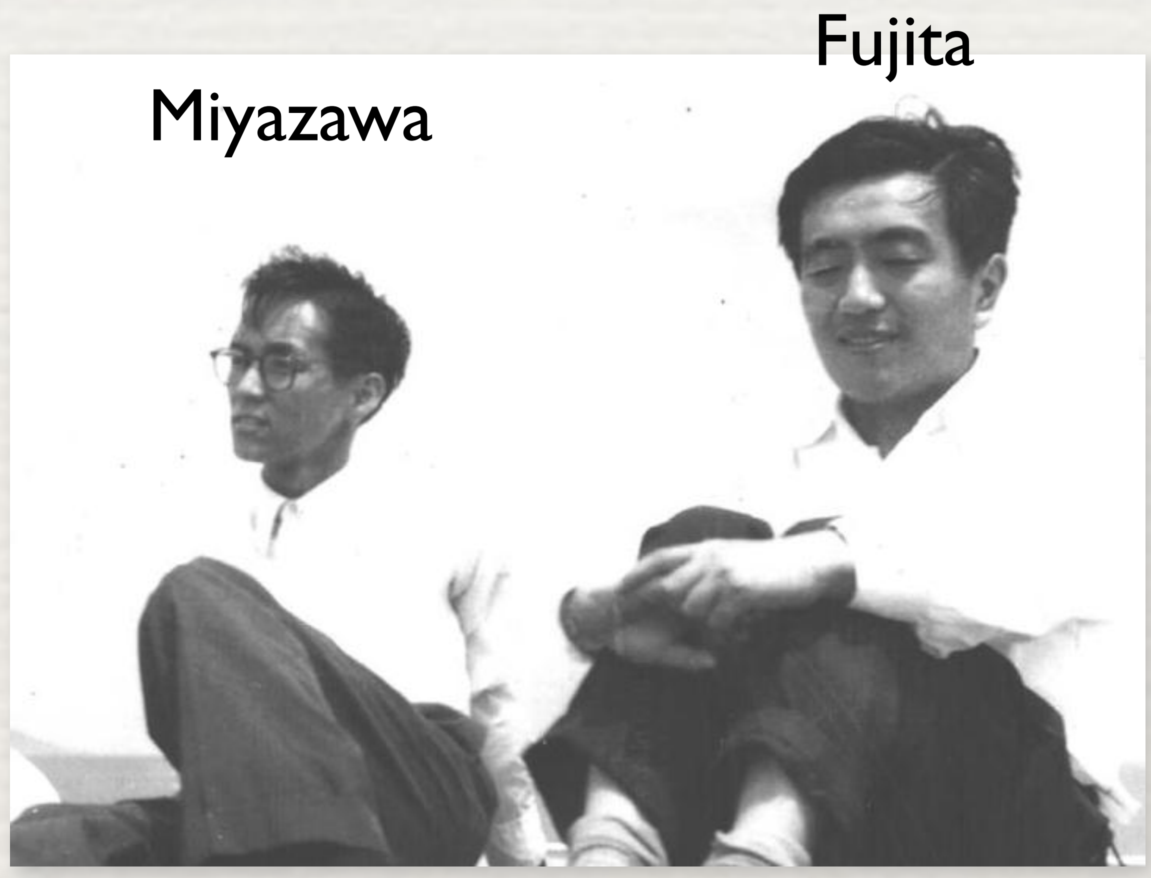
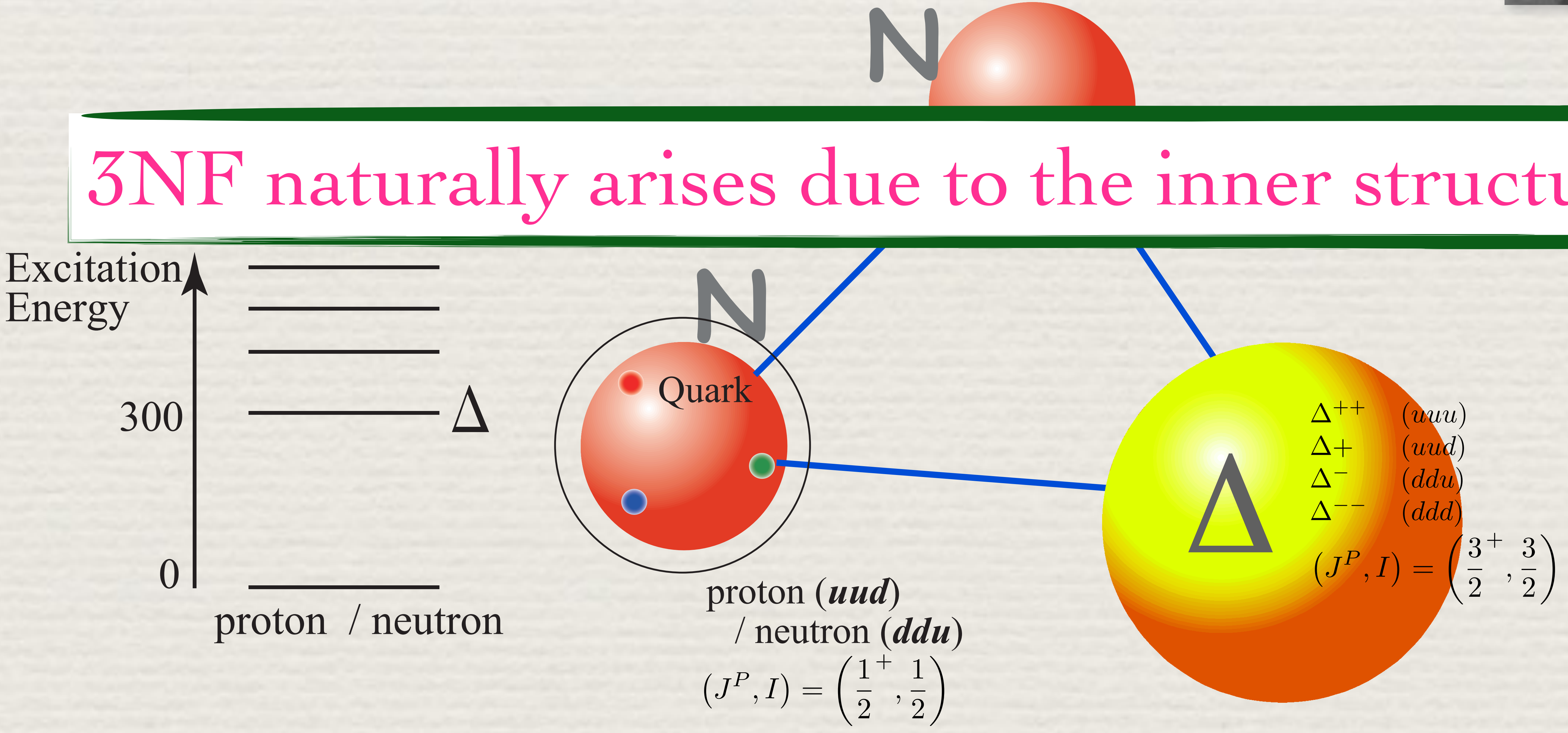
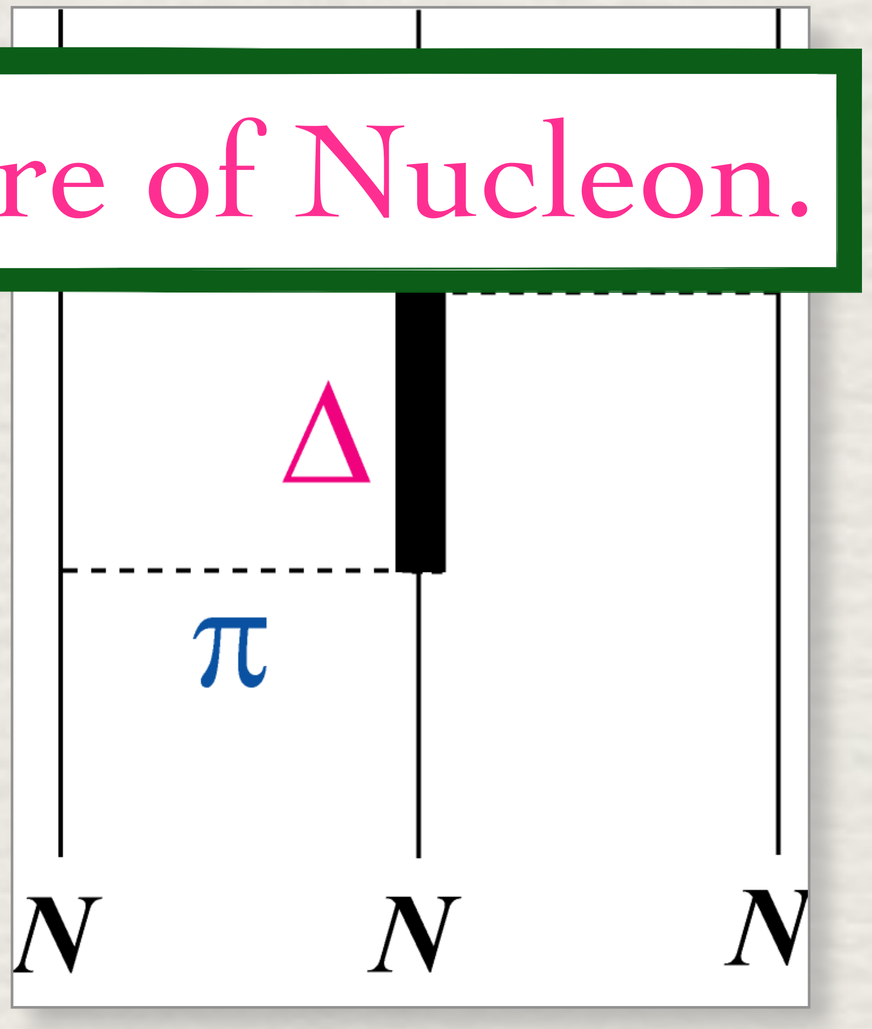


3NF naturally arises due to the inner structure of Nucleon.





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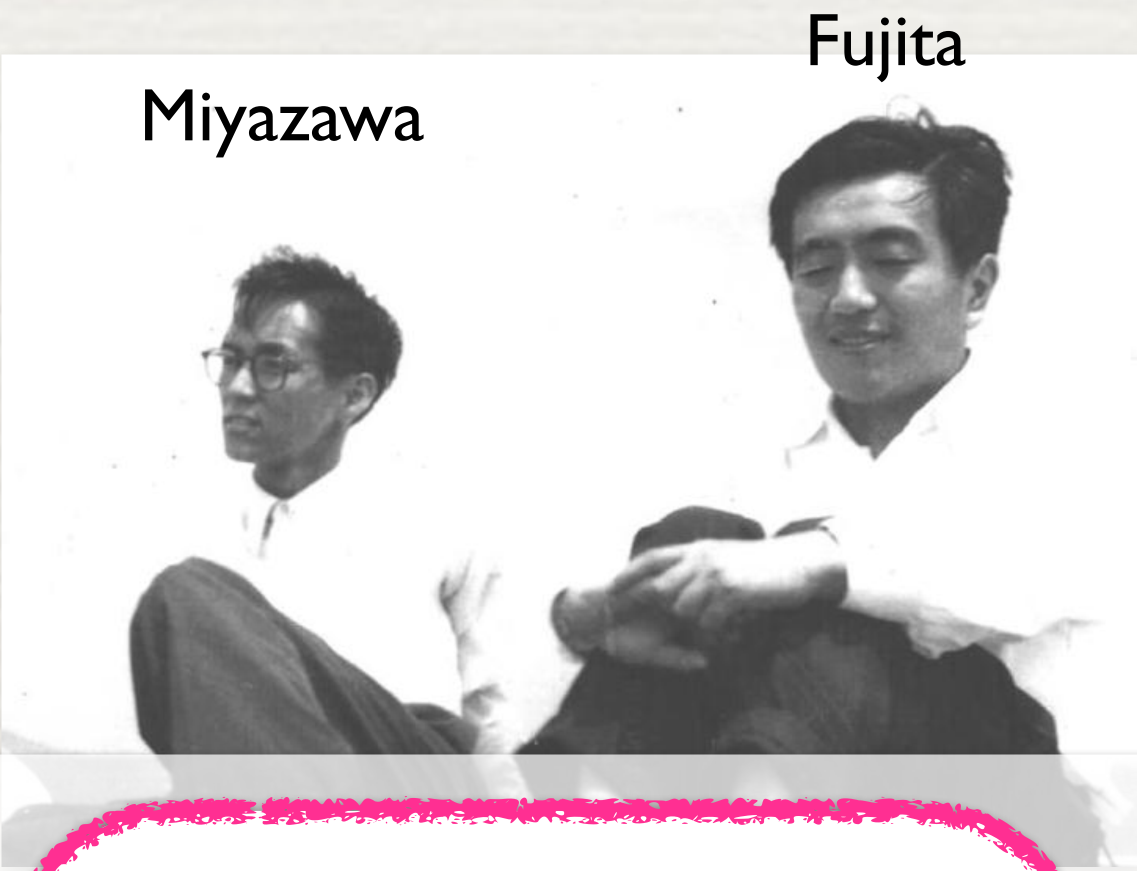
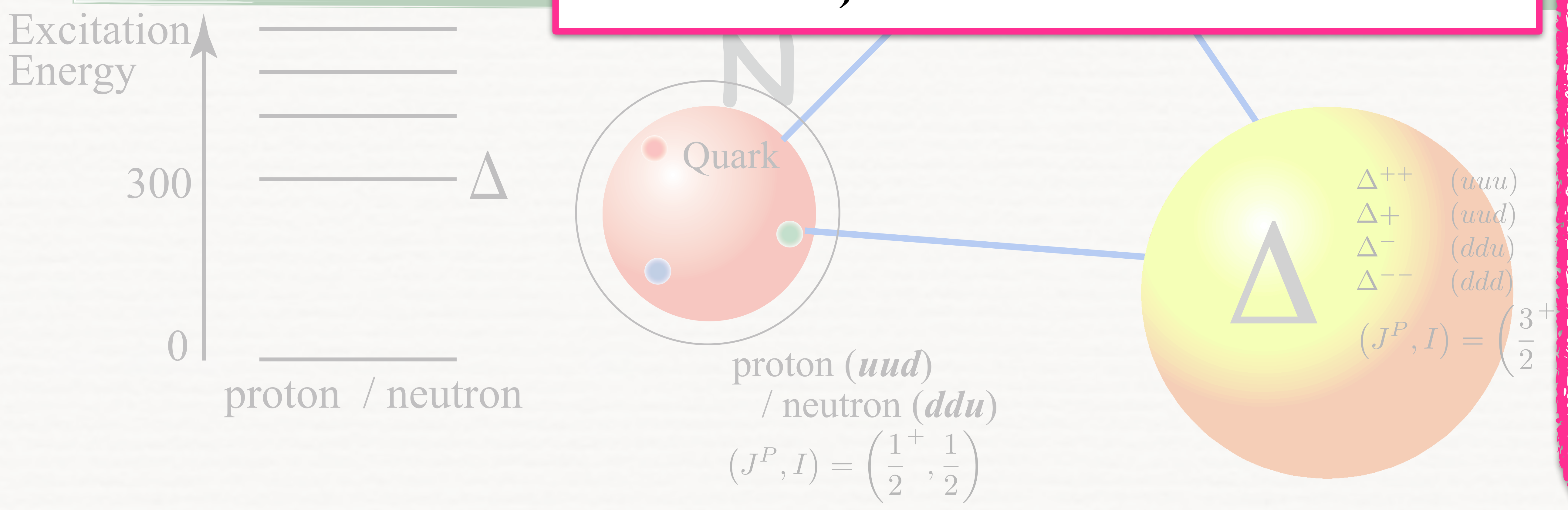
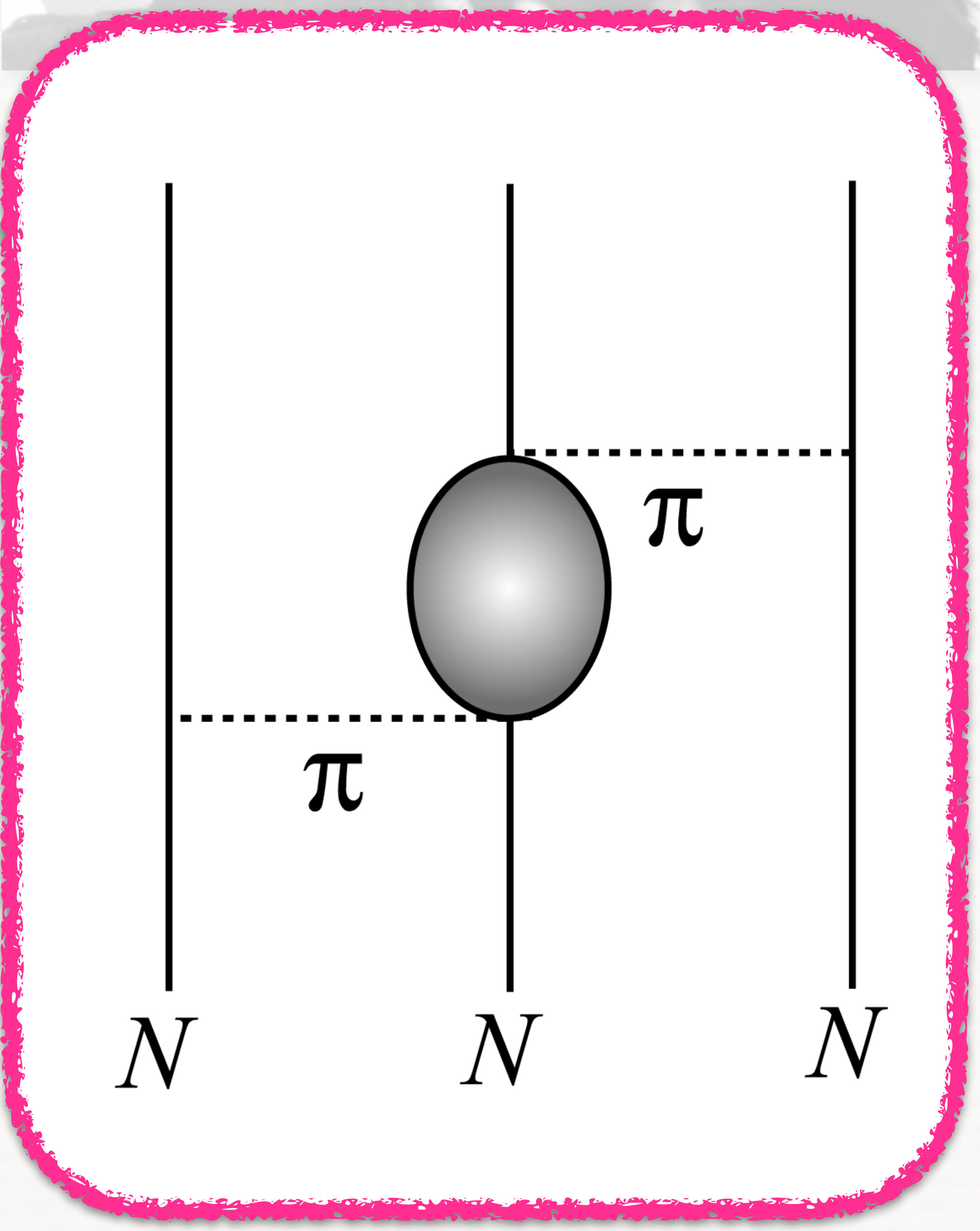


- Tucson-Melbourne (TM)
- Urbana IX
- Brazil, Texas etc…

3NF naturally





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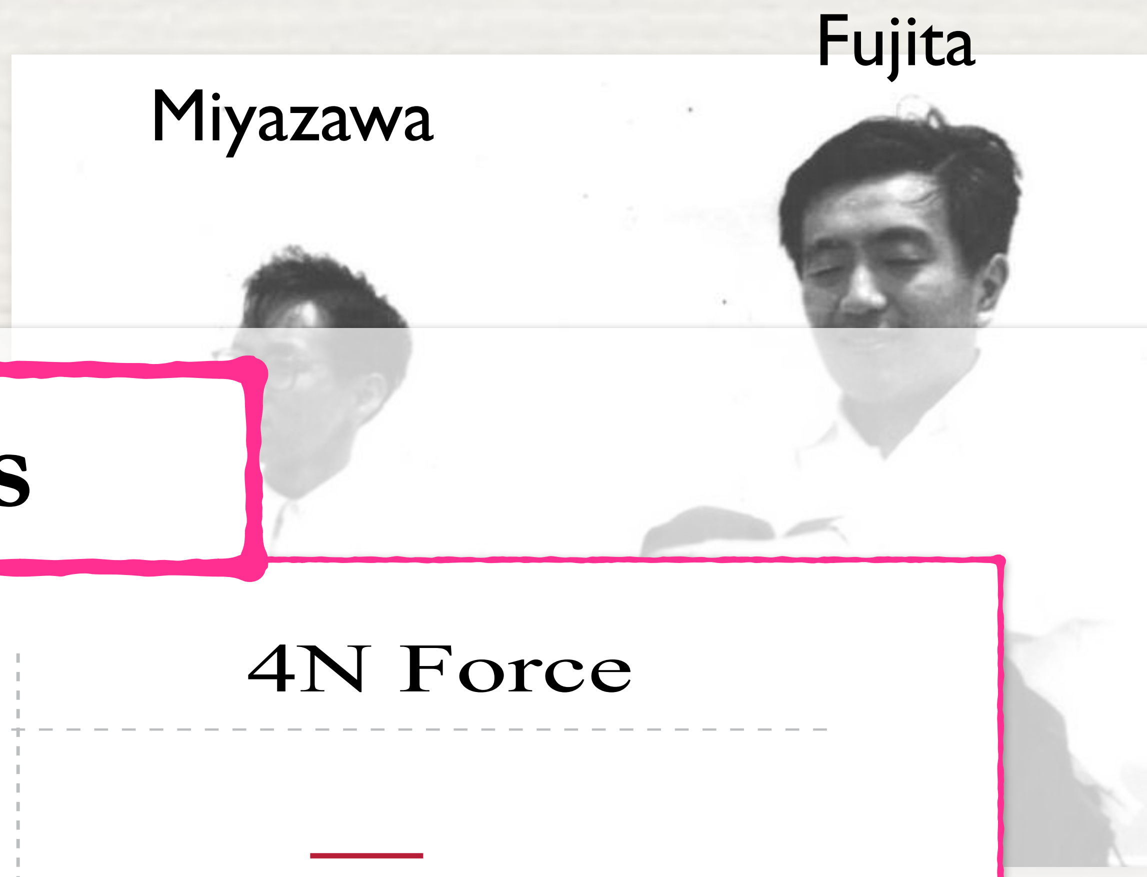
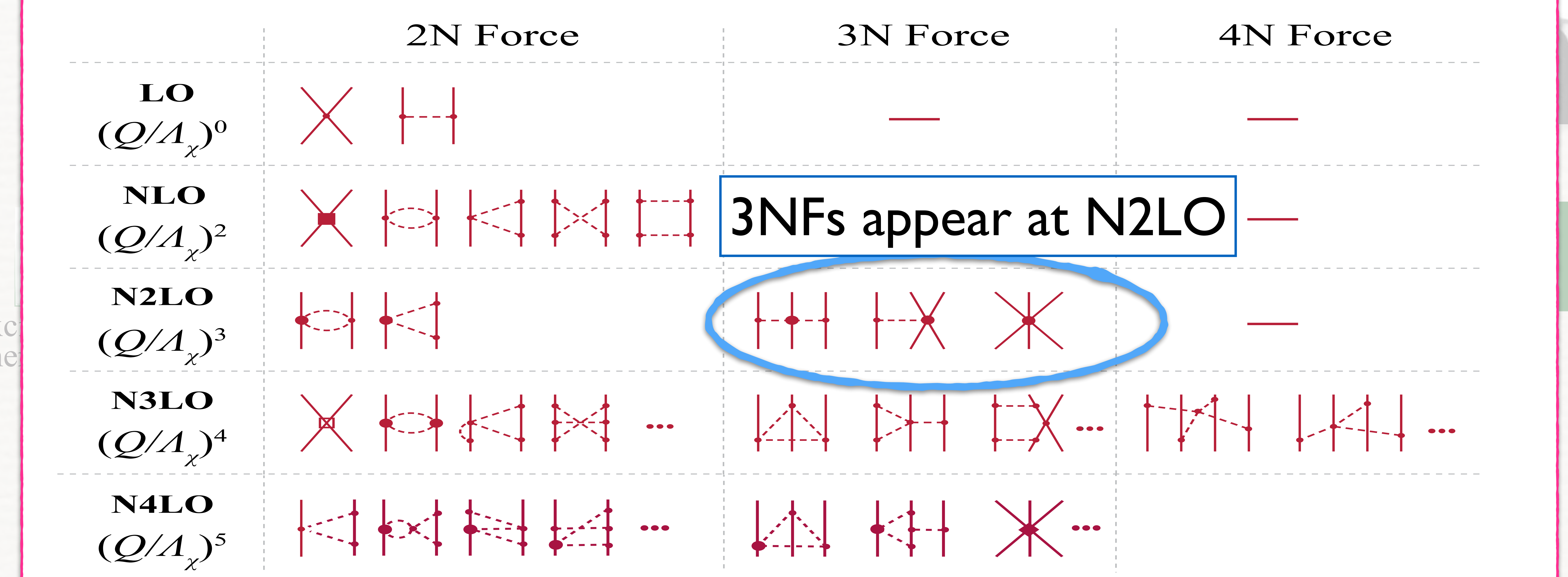


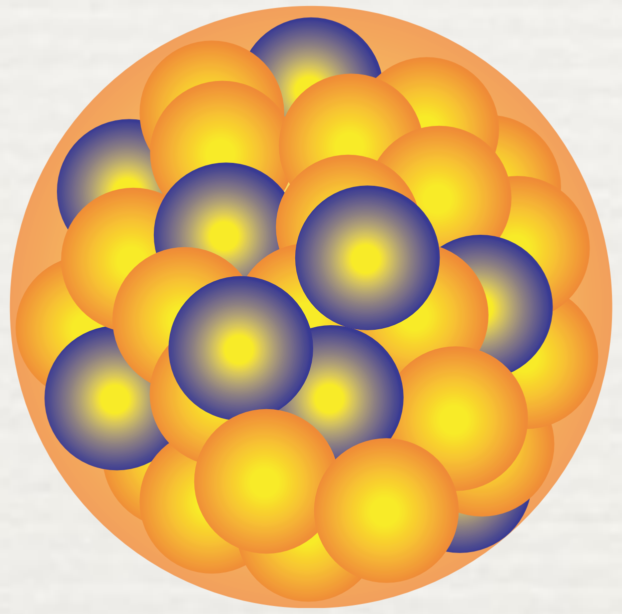
Chiral EFT Nuclear Forces



S. Weinberg, Phys. Lett. B 251, 288 (1990).
U. van Kolck, Phys. Rev. C 49, 2932 (1994).
E. Epelbaum, H.-W. Hammer, U.-G. Meißner, Rev. Mod. Phys. 81, 1773 (2009)
R. Machleidt, D.R. Entum, Phys. Rep. 503, 1 (2011)

Where ?

3NFs in A>3 - ① -



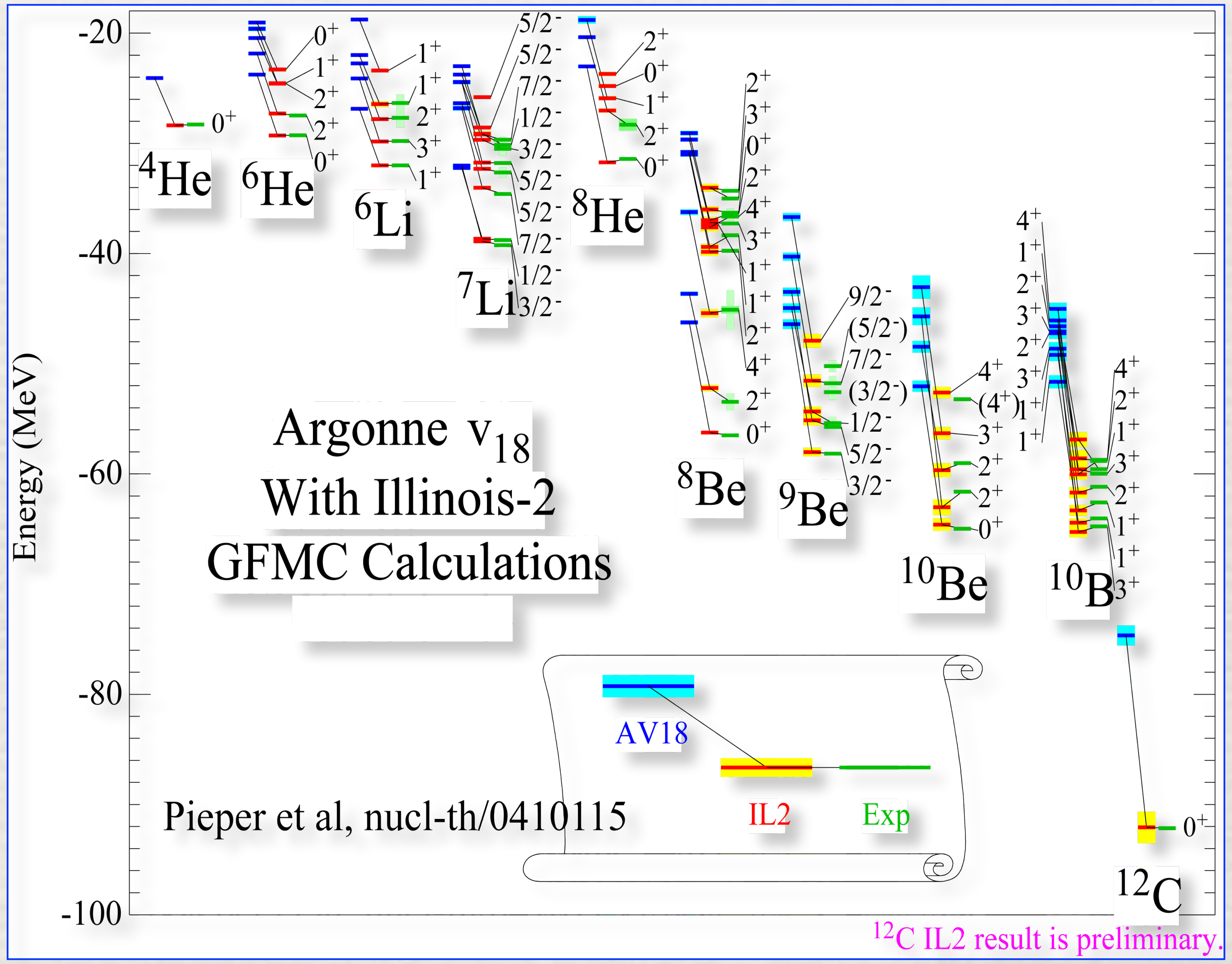
3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei ($A \lesssim 12$) : ^{4}He to ^{12}C

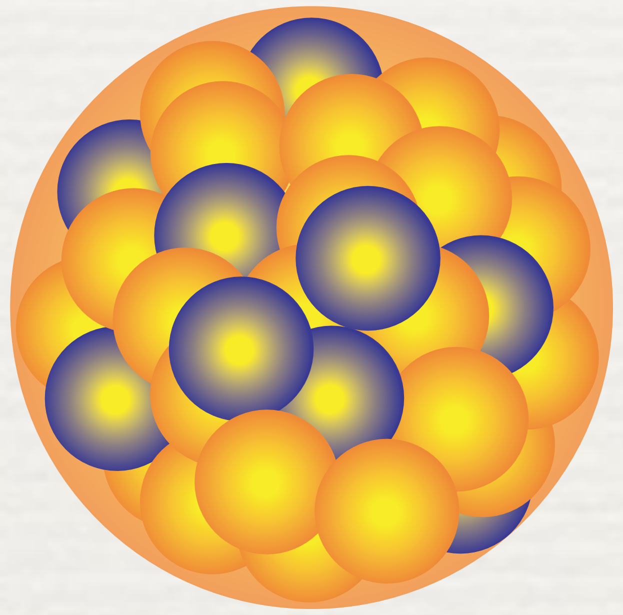
- **Green's Function Monte Carlo**
- **No-Core Shell Model** etc..

- 3NF effects in B.E.
  - 10-25%
  - Attractive

Note :
Isospin T=3/2 3NFs
(three-neutron force)
play important roles to explain B.E.
in neutron rich nuclei.



3NFs in A>3 - ① -



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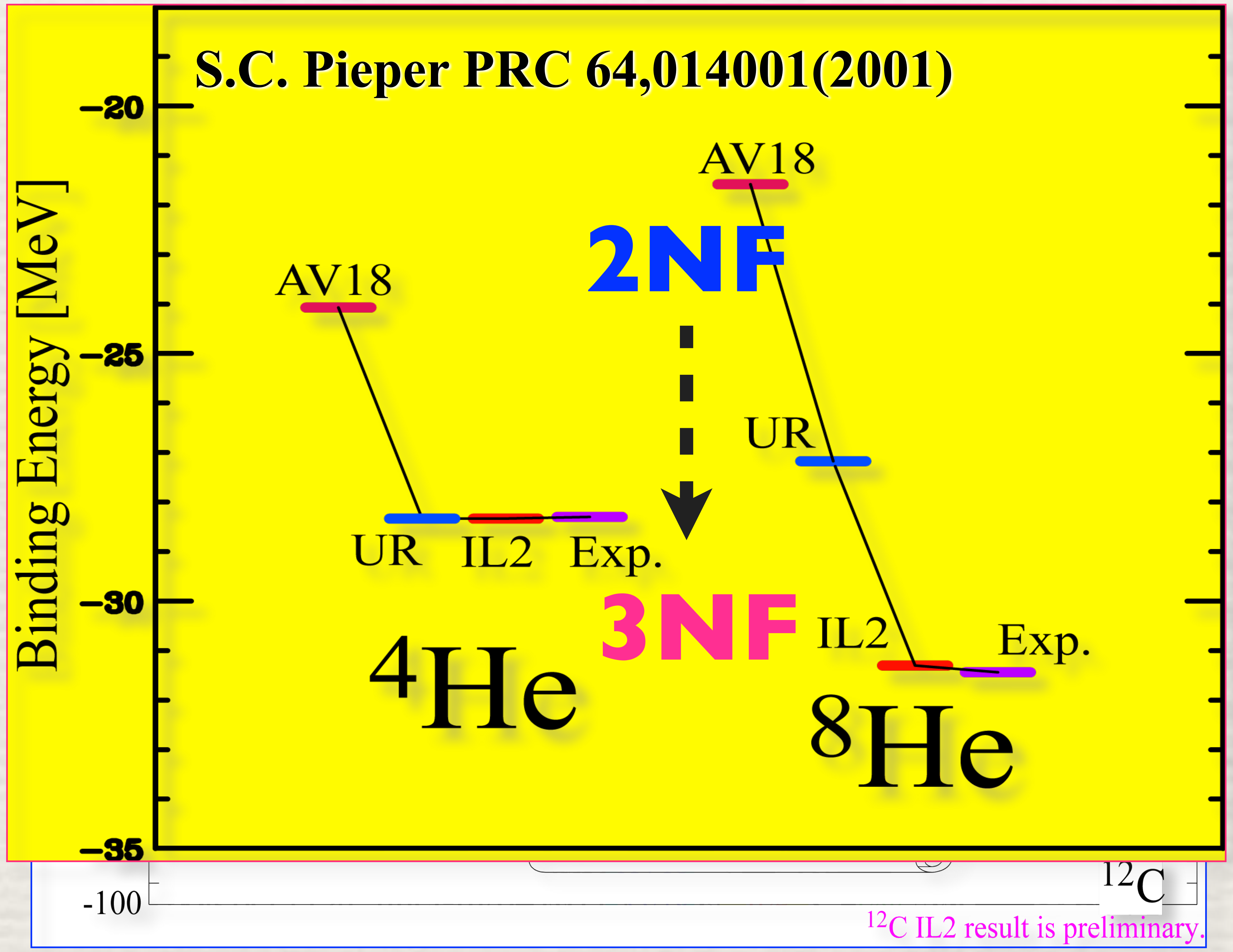
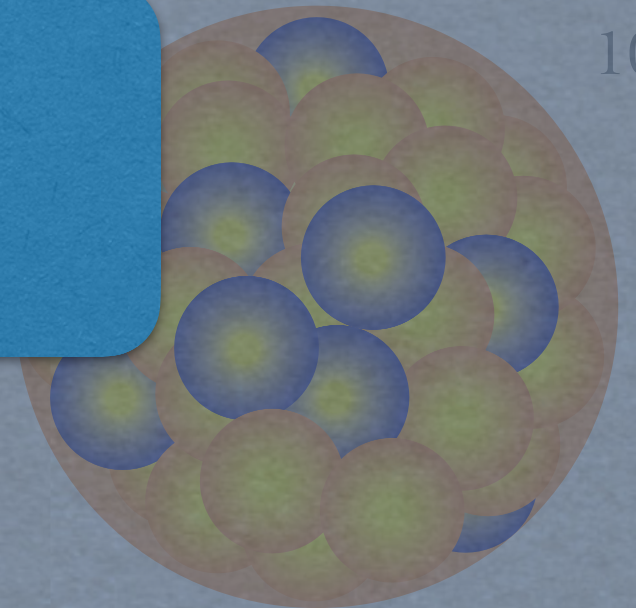


3NFs in A>3 - ① -



3NFs in Finite Nuclei

Ab Initio Calculations for Light Nuclei

$A \lesssim 12$: ^{4}He to ^{12}C

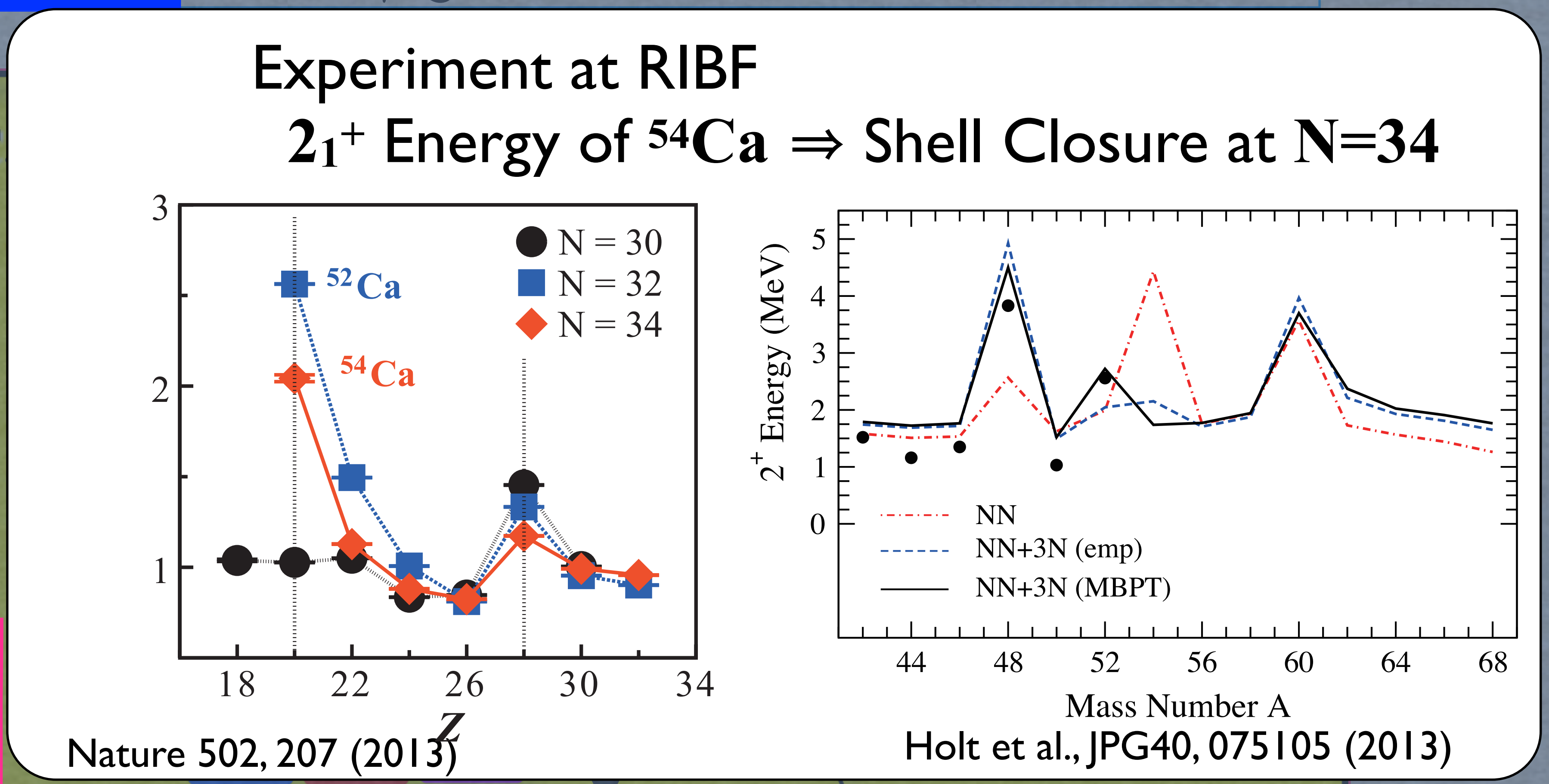
- Quantum Monte Carlo
- No-Core Shell Model
- Coupled cluster theory
- Nuclear Lattice Simulations
- Self-consistent Green's function method

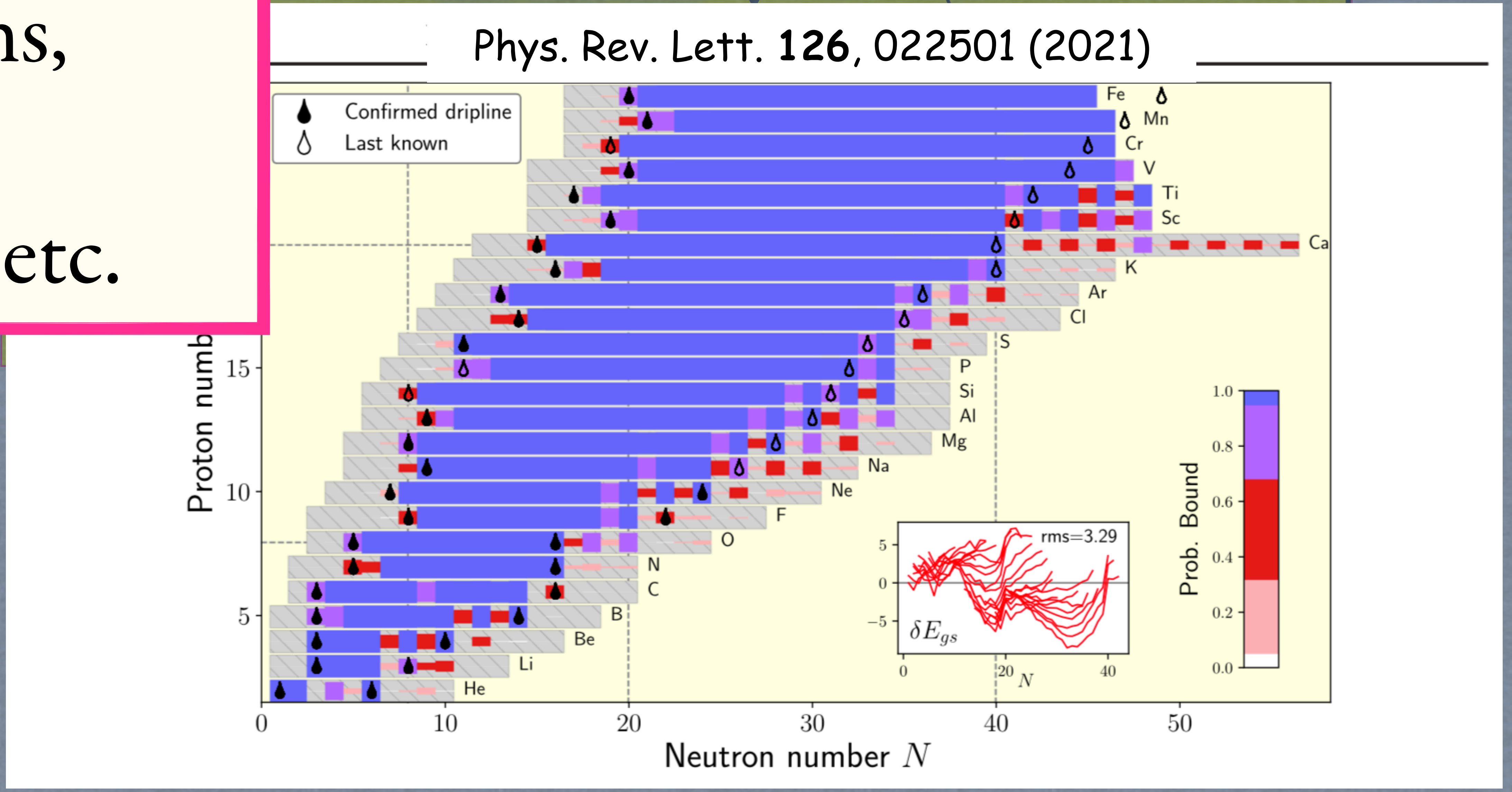
etc.

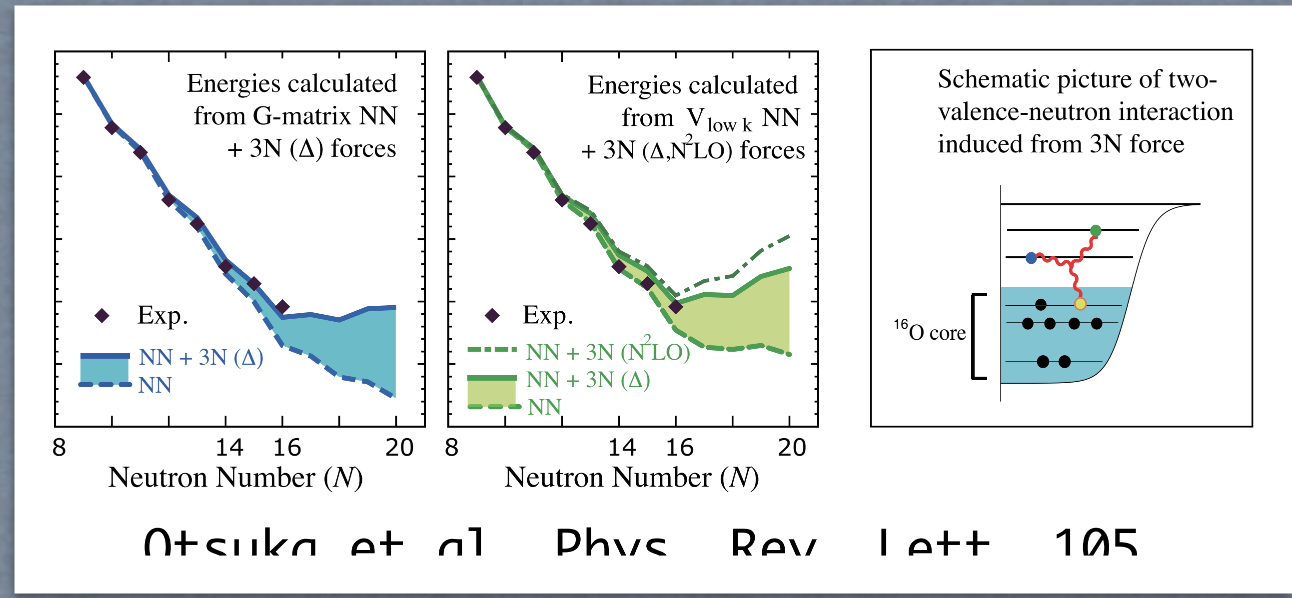
Heavy Mass Nuclei (*up to* ^{208}**Pb**)

3NFs provide key mechanisms,

- Shell-evolution,
- Limits of Atomic Nuclei etc.



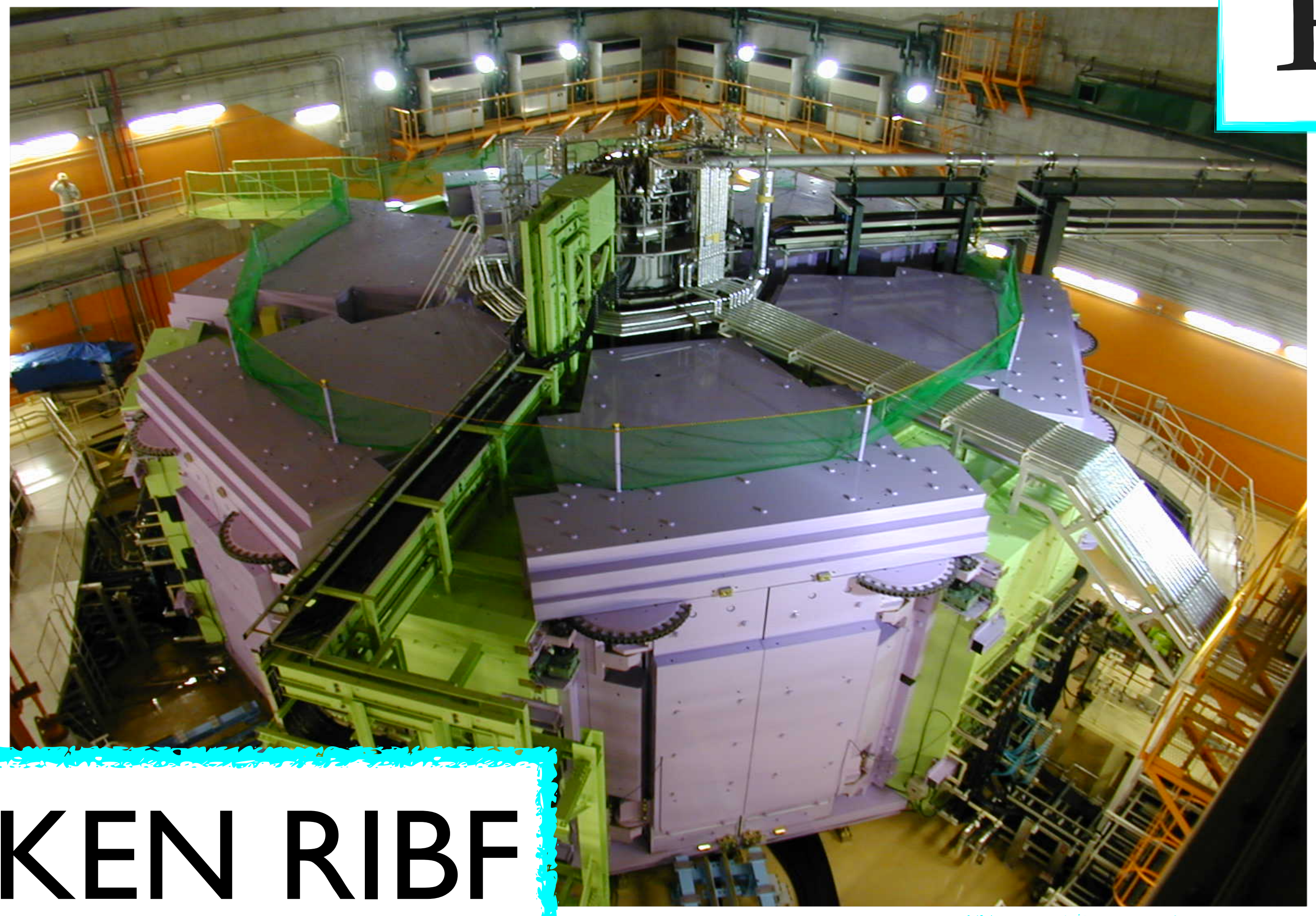




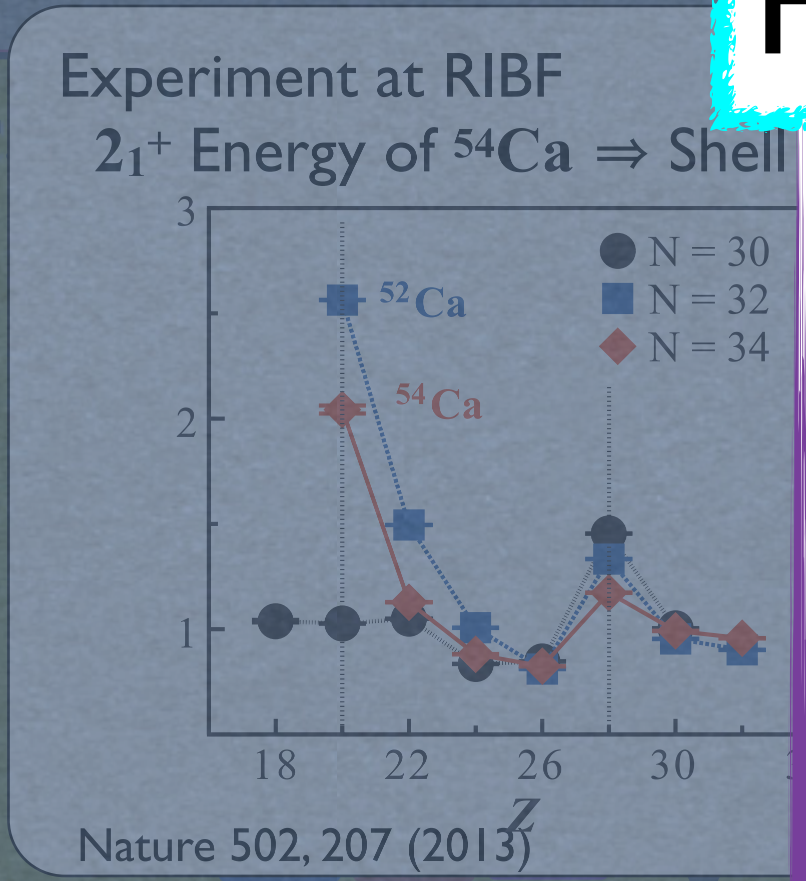
3NFs in A>3 - ① -

3NFs in Finite Nuclei

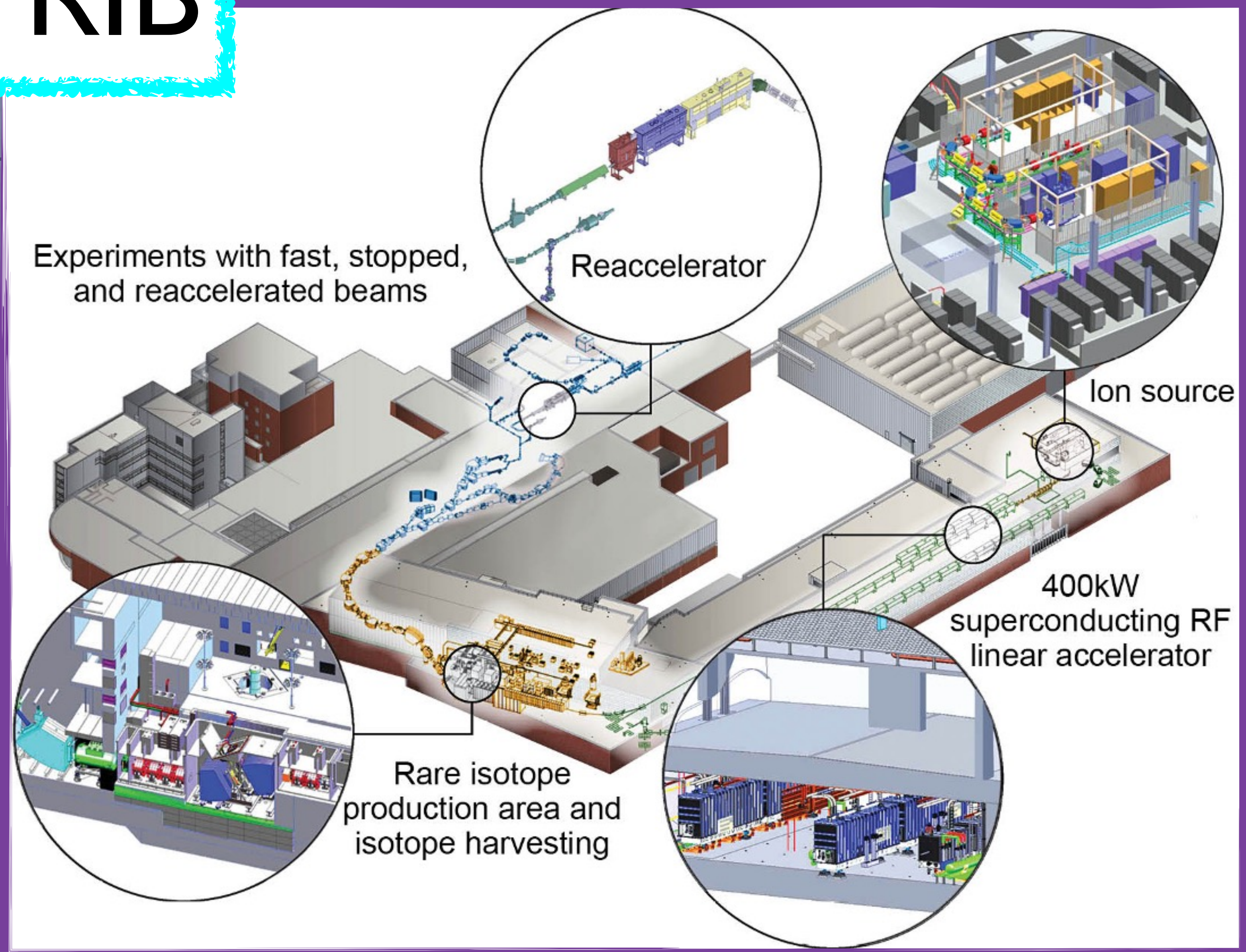
Experiment



RIKEN RIBF

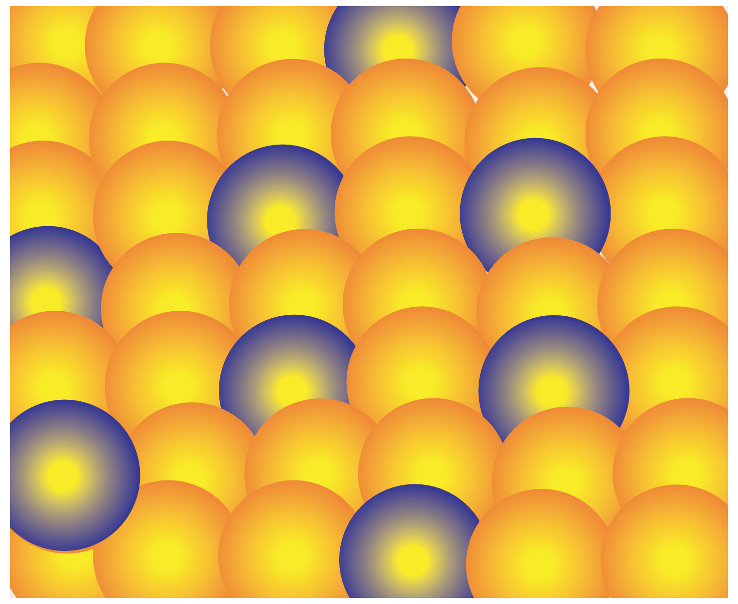


FRIB



IMP / HIAF
RAON
GANIL / ISOLDE
GSI/FAIR
ISAC-I & II
etc.

3NFs in A>3 - ② -

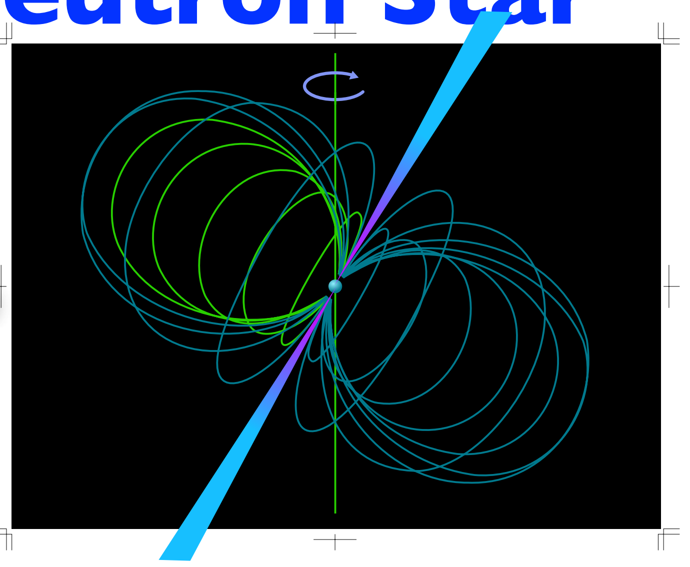


3NFs in Infinite Nuclei - Neutron Star -

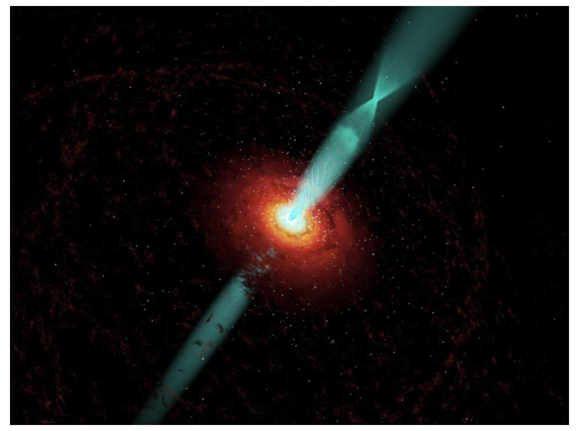
"Endpoint of stellar evolution"

Supernovae Explosion

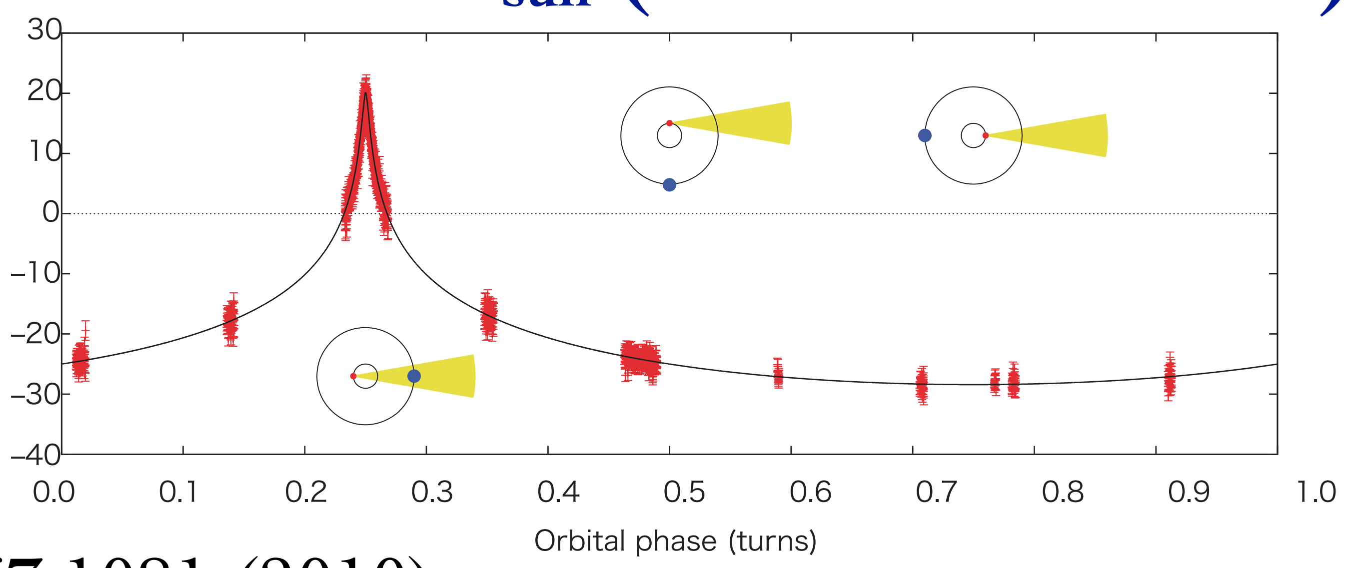
Neutron Star



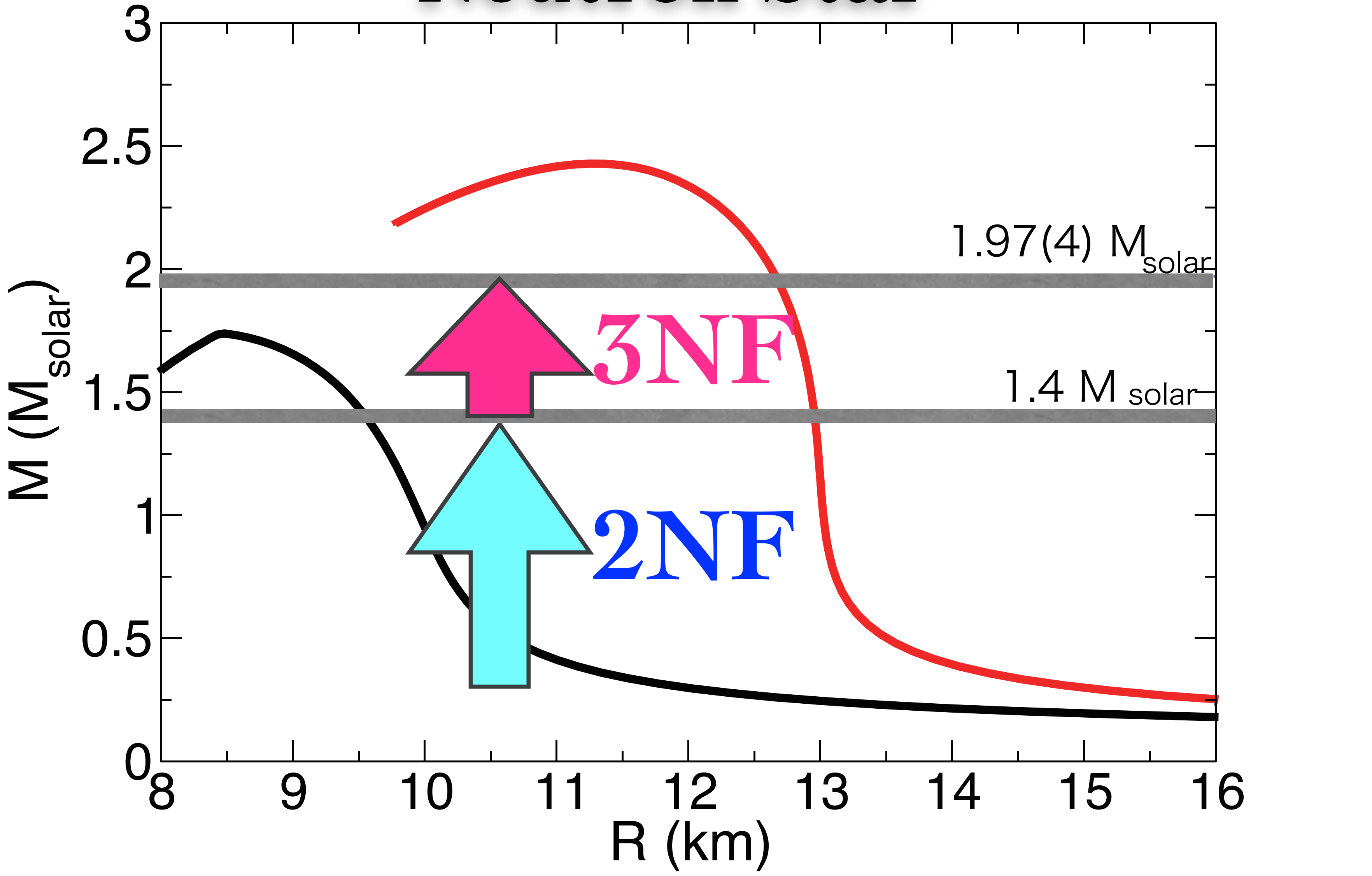
Black Hole



Discovery of Heaviest Neutron Star with 2 solar-mass M_{sun} (PSR J1614-2230)



Nature *467* 1081 (2010)



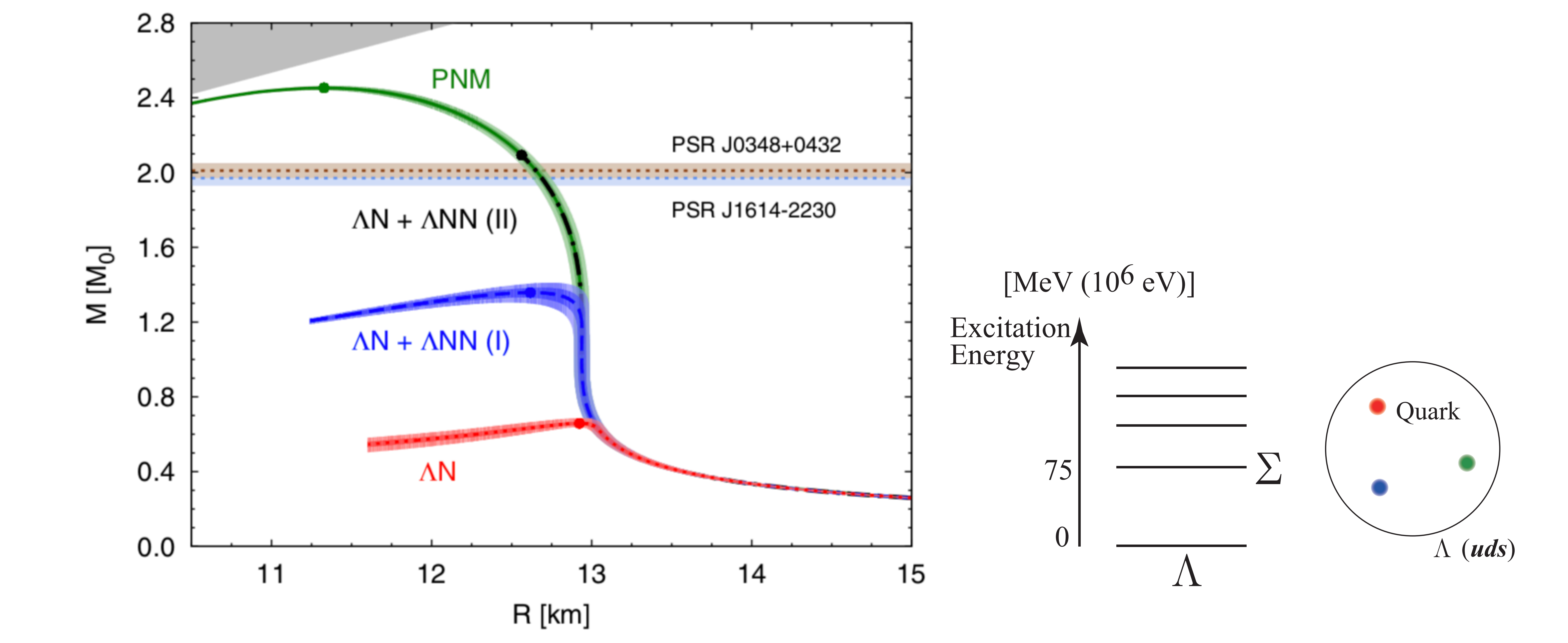
A. Akmal et al., PRC 58, 1804('98)

- 3NF
  - Short & Repulsive
  - Large effects at high density.

3NFs in A>3 - ② -

3NFs in Infinite Nuclei - Neutron Star -

NNN + NNΛ in Infinite Nuclei



D. Lonardoni et al., Phys. Rev. Lett. 114, 092301 ('15)

How ?

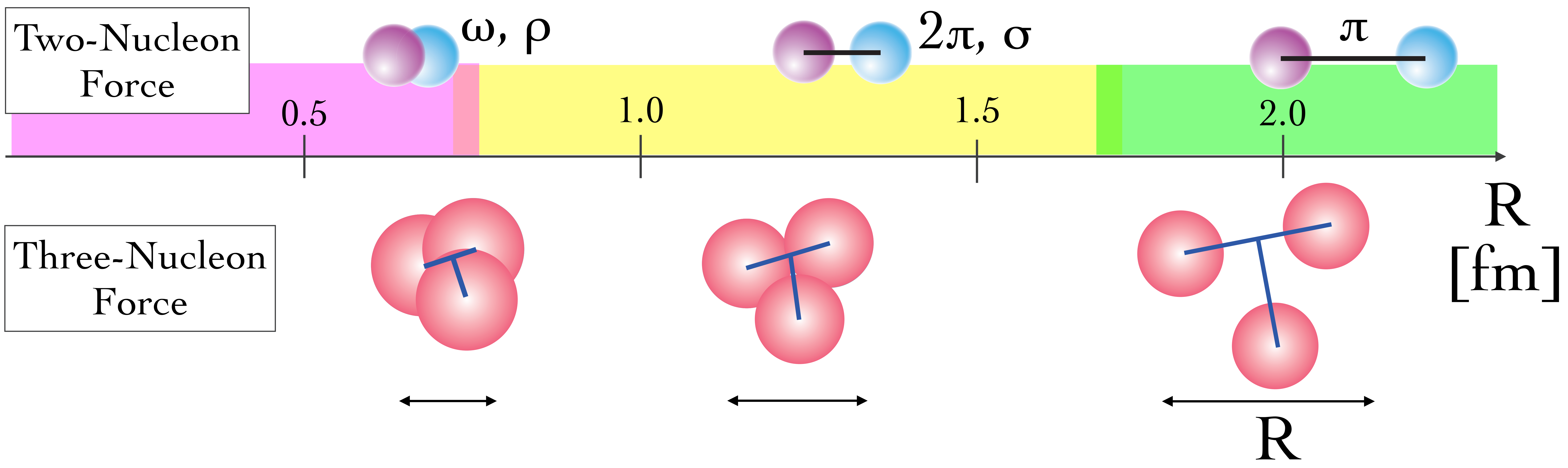
- 3NF is a key to understand nuclear phenomena quantitatively.
- How to constrain the properties of 3NF ?

Two & Three-Nucleon Force

①. Repulsive
-Short Range-

②. Attractive (strong)
-Intermediate Range-

③. Attractive (weak)
- Long Range -



3NFs are momentum, spin, and iso-spin dependent.

Nuclear Matter Neutron Star

Nuclear Structure

Nucleon-Deuteron Scattering

a good probe to study the dynamical aspects of 3NFs.

- ✓ Momentum dependence
- ✓ Spin & Iso-spin dependence

Direct Comparison between Theory and Experiment

- **Theory** : Faddeev / Faddeev-Yakubovsky Calculations

  Rigorous Numerical Calculations of 3, 4N System

2NF Input
- CDBonn
- Argonne V18 (AV18)
- Nijmegen I, II, 93

3NF Input
- Tucson-Melbourne
- Urbana IX

etc..

2NF & 3NF Input
- Chiral Effective Field Theory

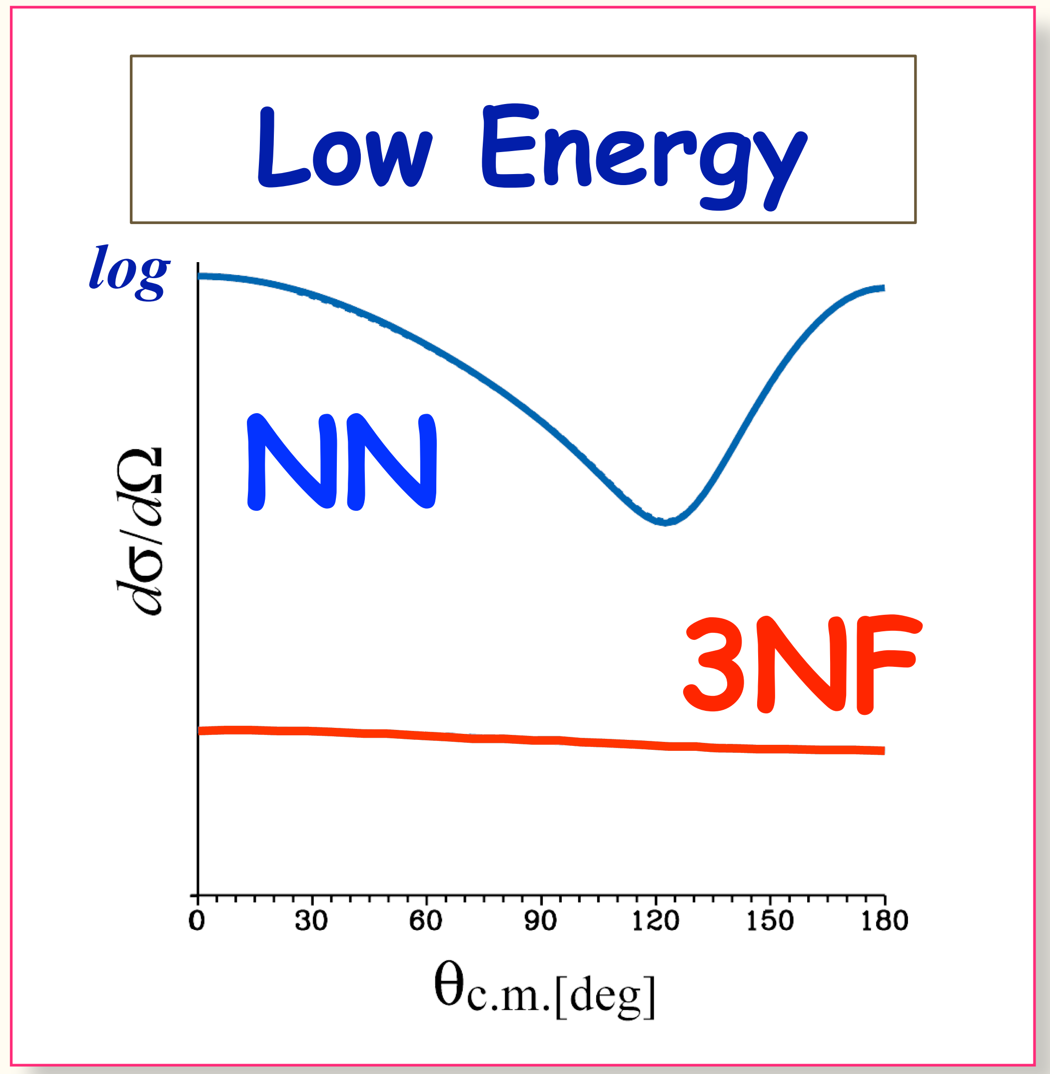
- **Experiment** : Precise Data
  - $d\sigma/d\Omega$, Spin Observables (A_i, K_{ij}, C_{ij})

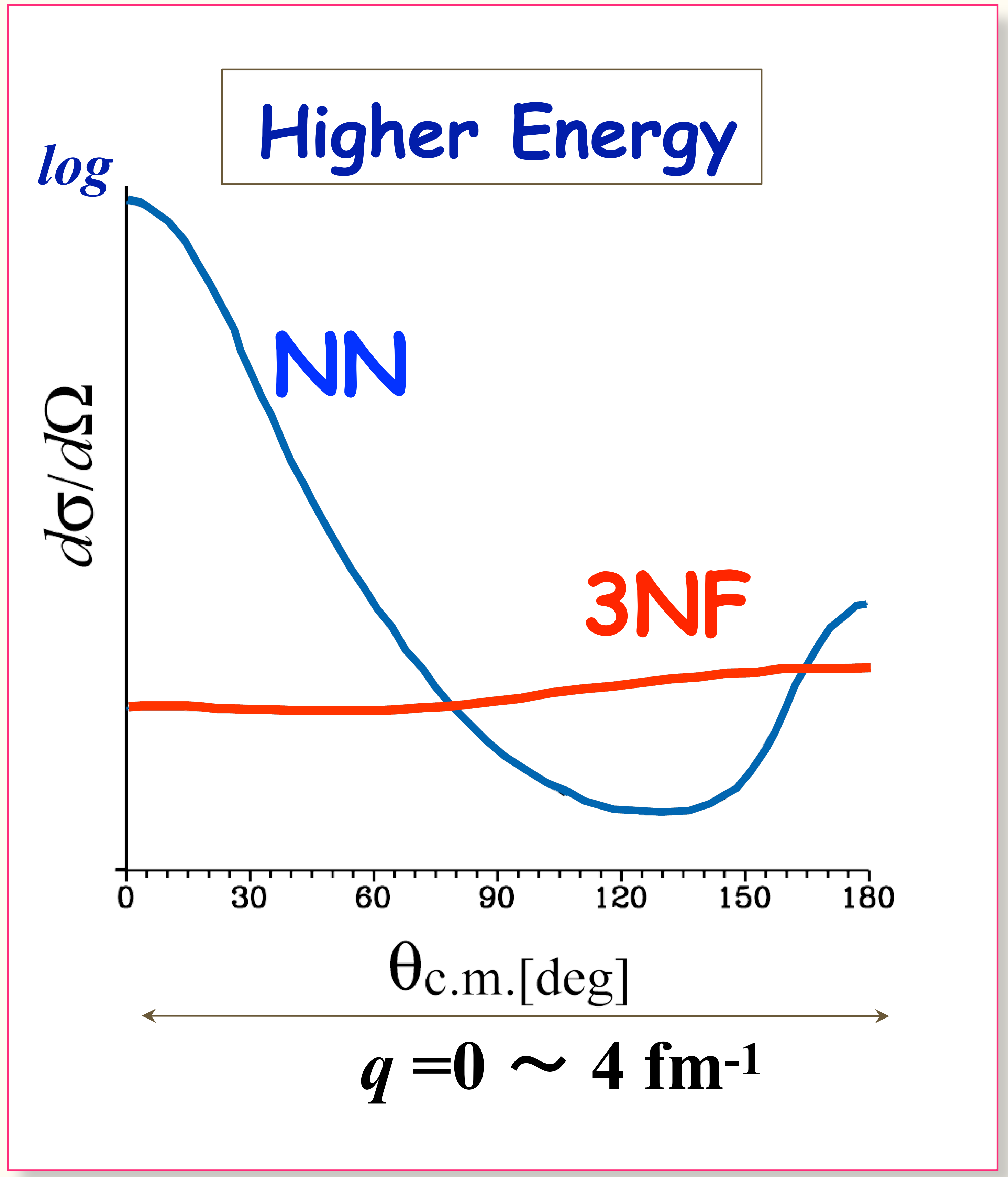
Extract fundamental information of Nuclear Forces

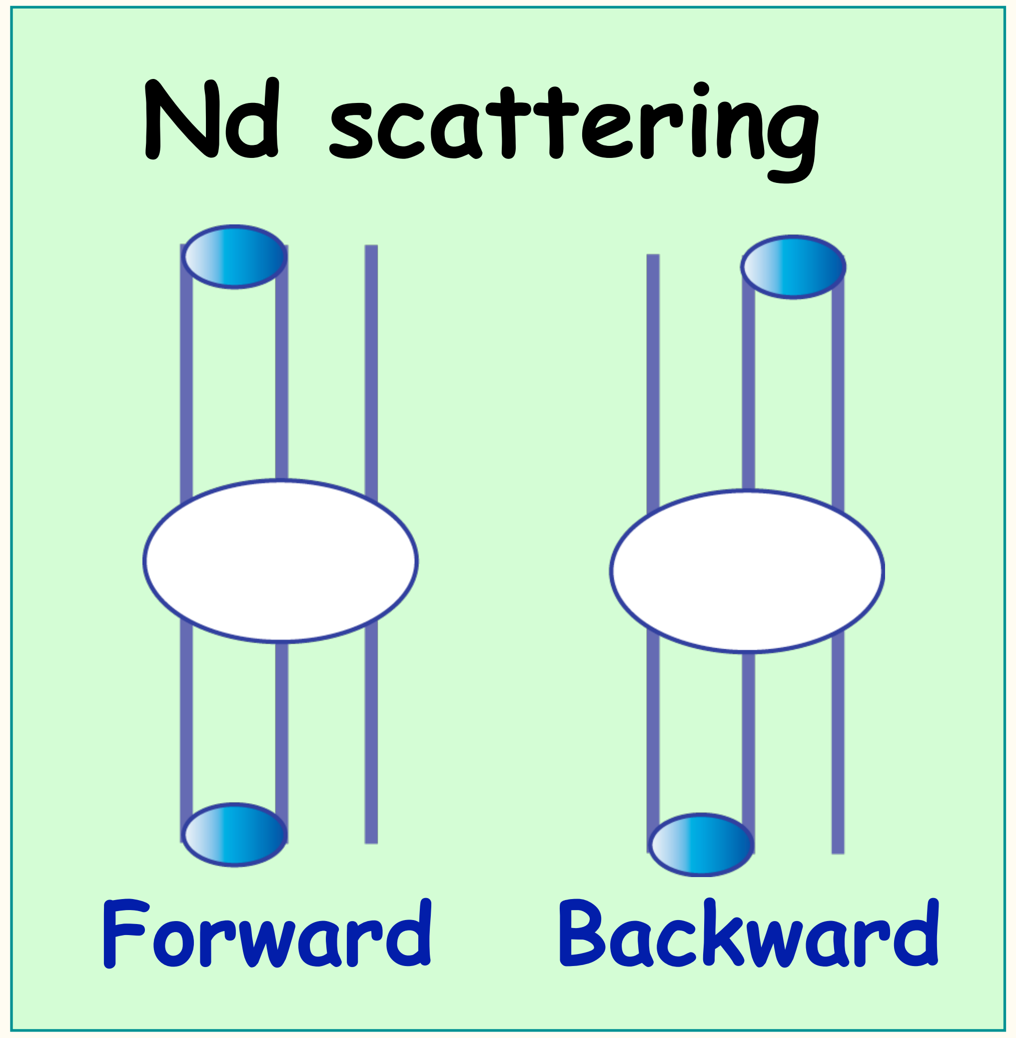
Where is the hot spot for study of 3NFs ?

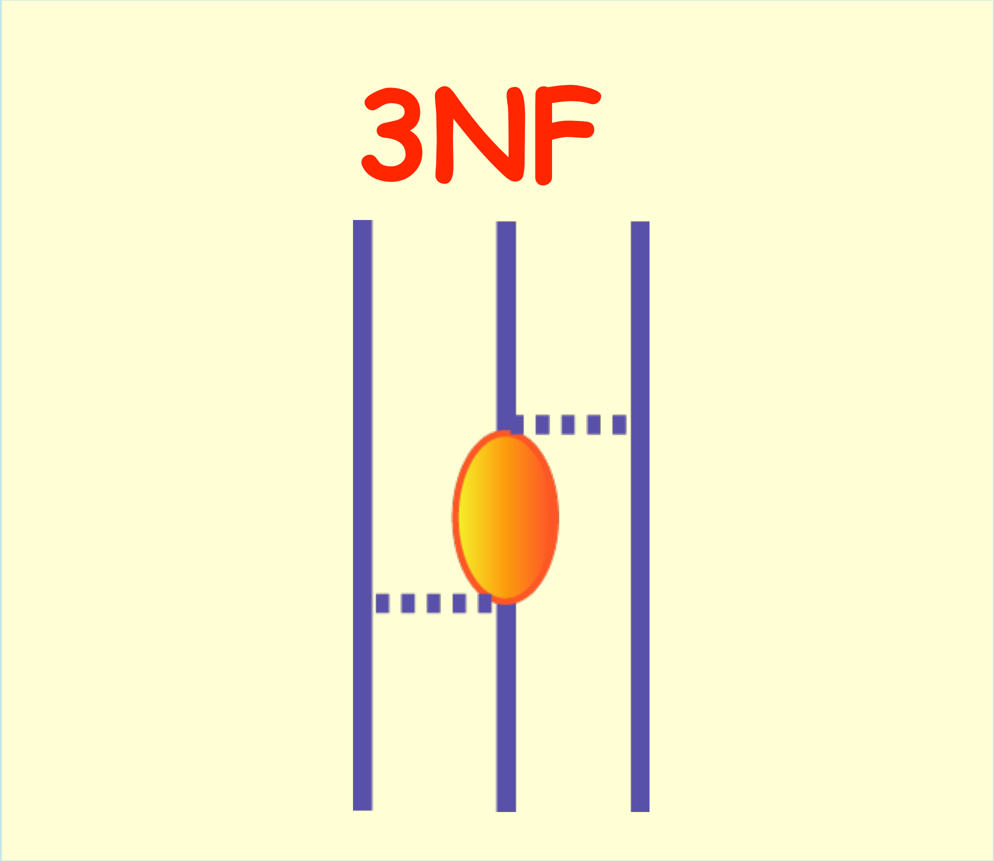
Predictions by H. Witala et al. (1998)

Cross Section minimum for Nd Scattering at ~ 100 MeV/nucleon

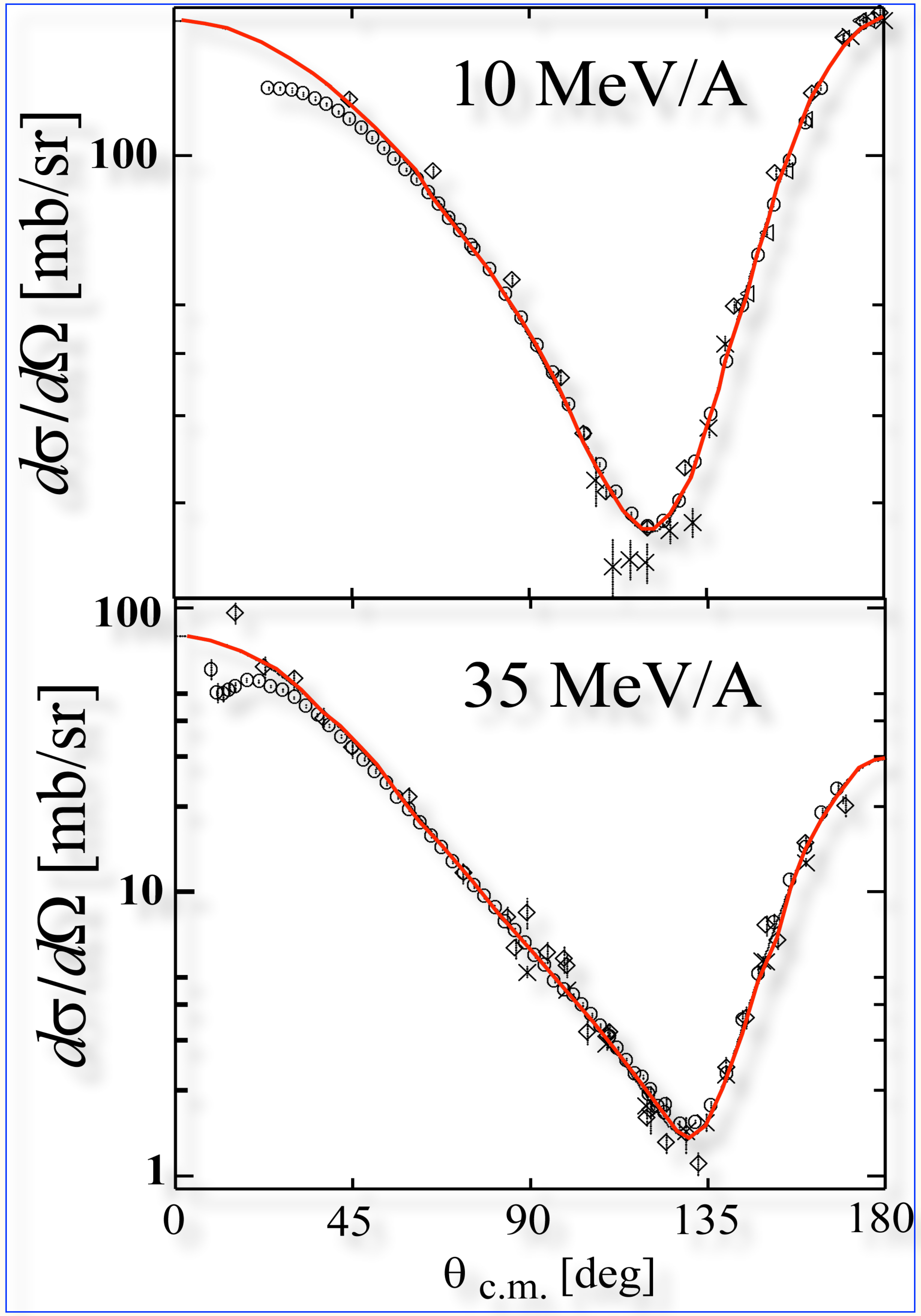








Nd Scattering at Low Energies ($E \leq 30$ MeV/A)



- High precision data are explained by Faddeev calculations based on 2NF.
  (Exception : A_y, iT_{11})

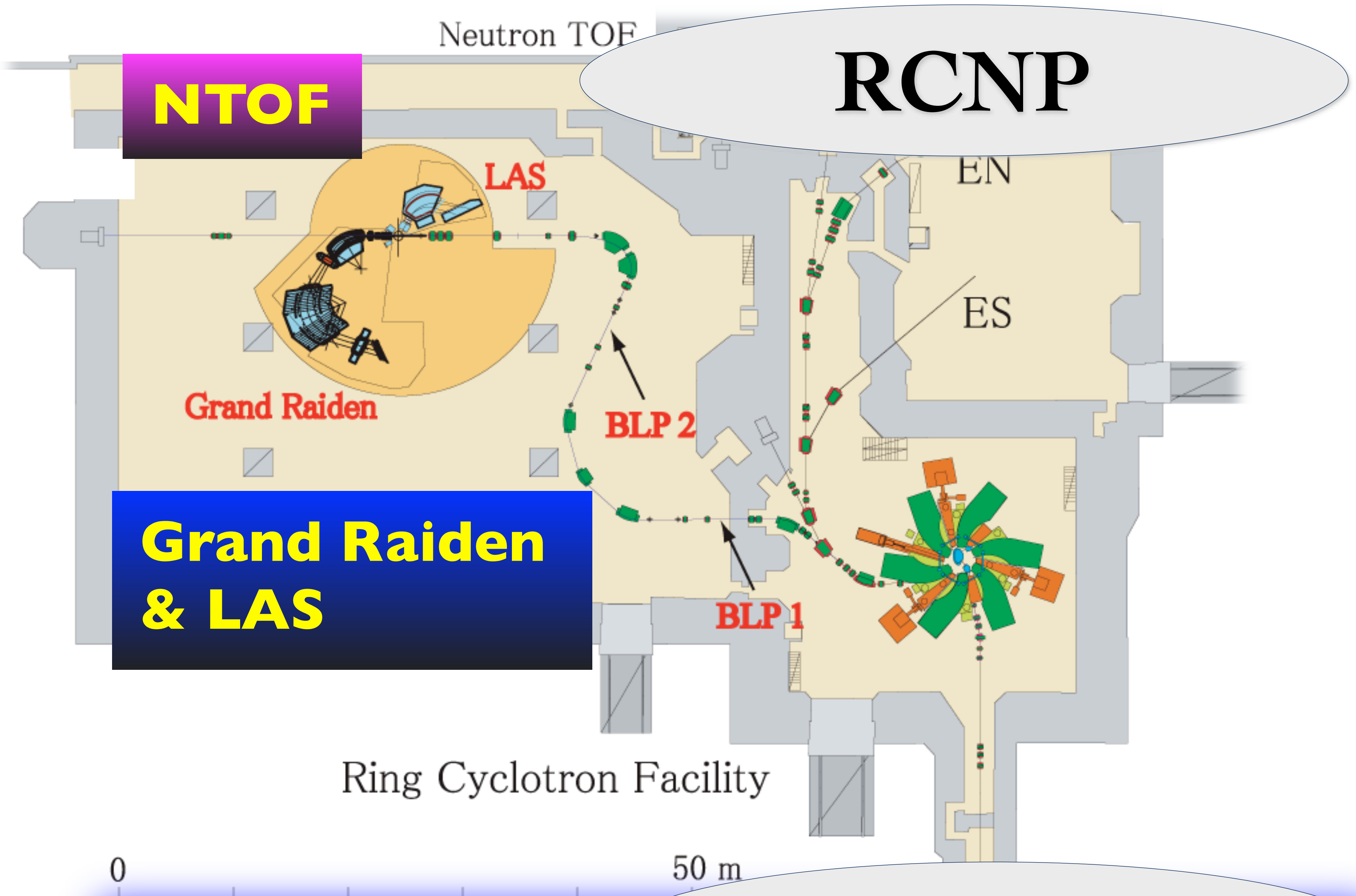
No signatures of 3NF

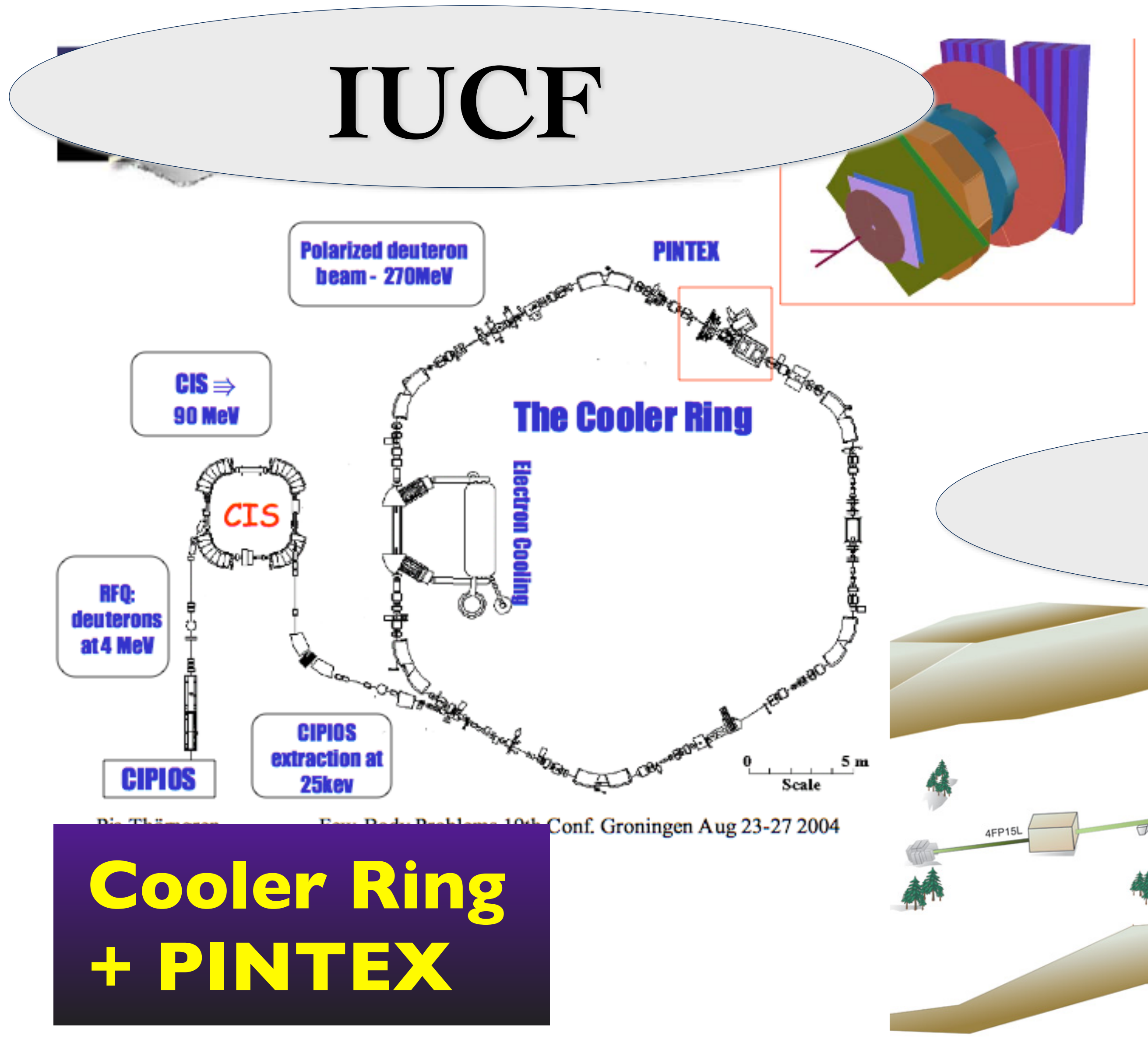
Exp. Data from
Kyushu, TUNL, Cologne etc..

W. Glöckle et al., Phys. Rep. 274, 107 (1996).

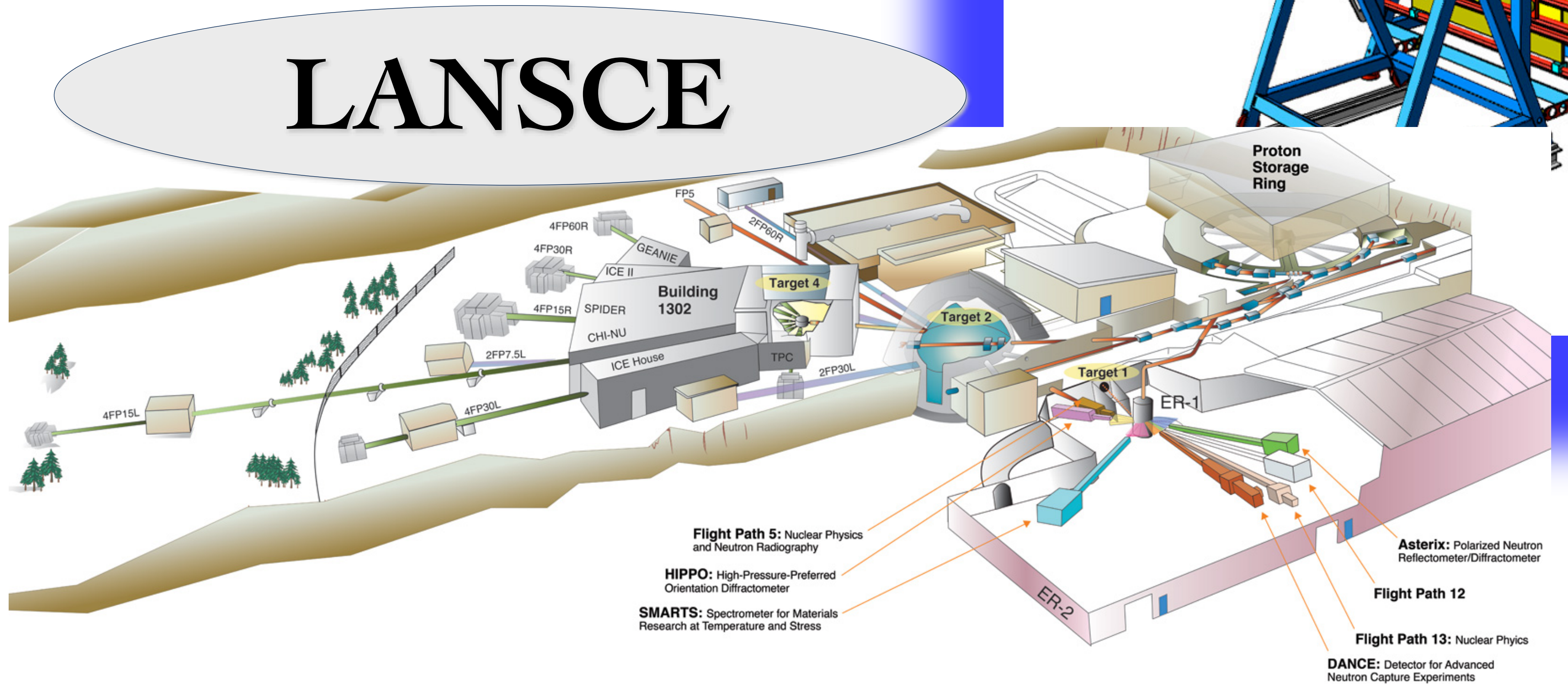
Facilities


RIKEN
magnetic spectrograph
SMART


RCNP
Neutron TOF
NTOF
LAS
EN
ES
Grand Raiden
BLP 2
Grand Raiden
& LAS
BLP 1
Ring Cyclotron Facility
0
50 m


IUCF
Polarized deuteron
beam - 270MeV
PINTEX
CIS ⇒
90 MeV
The Cooler Ring
Electron Cooling
CIS
RFQ:
deuterons
at 4 MeV
CIPIOS
CIPIOS
extraction at
25kev
Scale
5 m
Cooler Ring
+ PINTEX

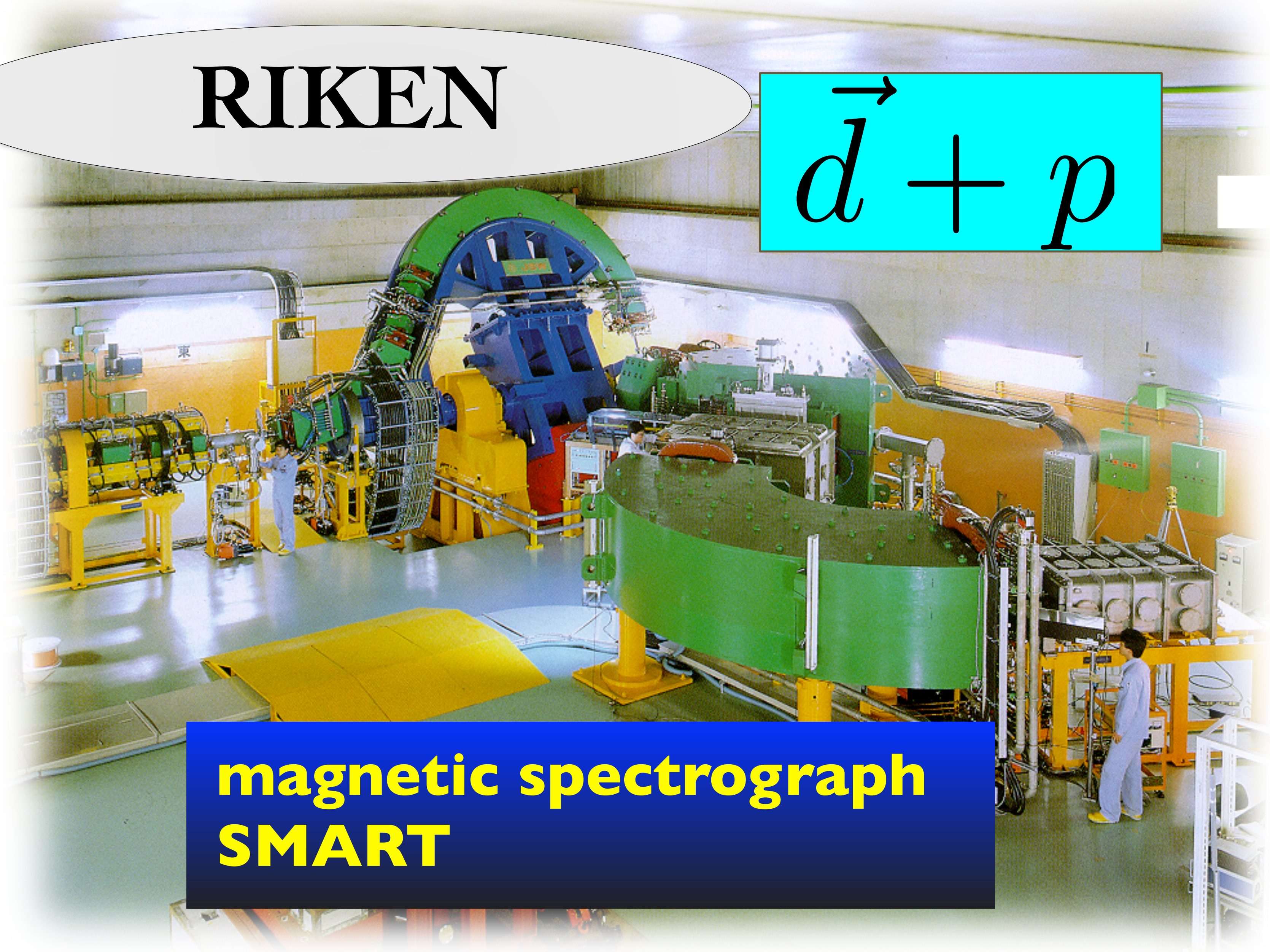

KVI & CCB
BINA
& SALAD
BBS


LANSCE
Proton
Storage
Ring
Building
1302
Target 4
Target 2
Target 1
ER-1
ER-2
Flight Path 12

Facilities

RIKEN

$\vec{d} + p$



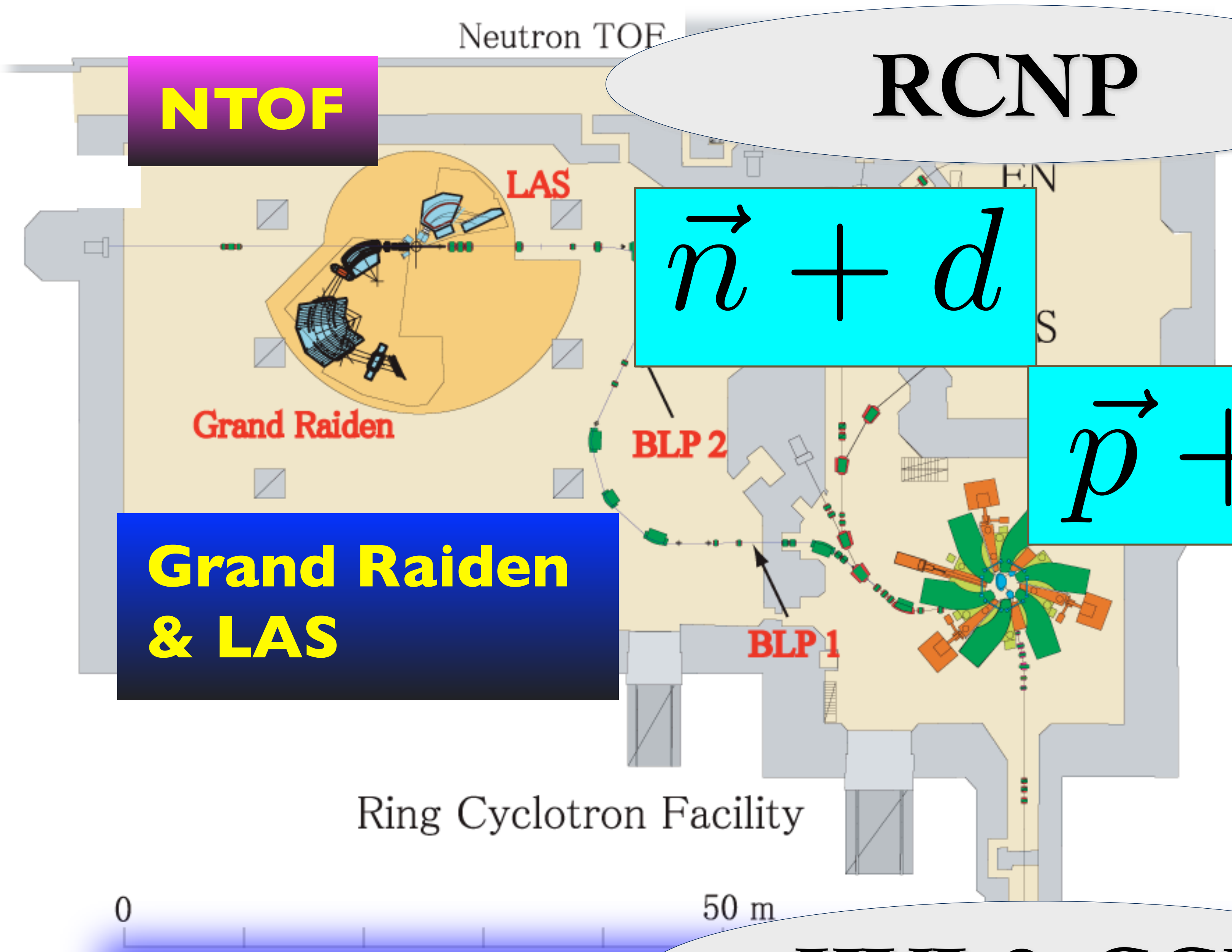
magnetic spectrograph SMART

RCNP

NTOF

$\vec{n} + d$

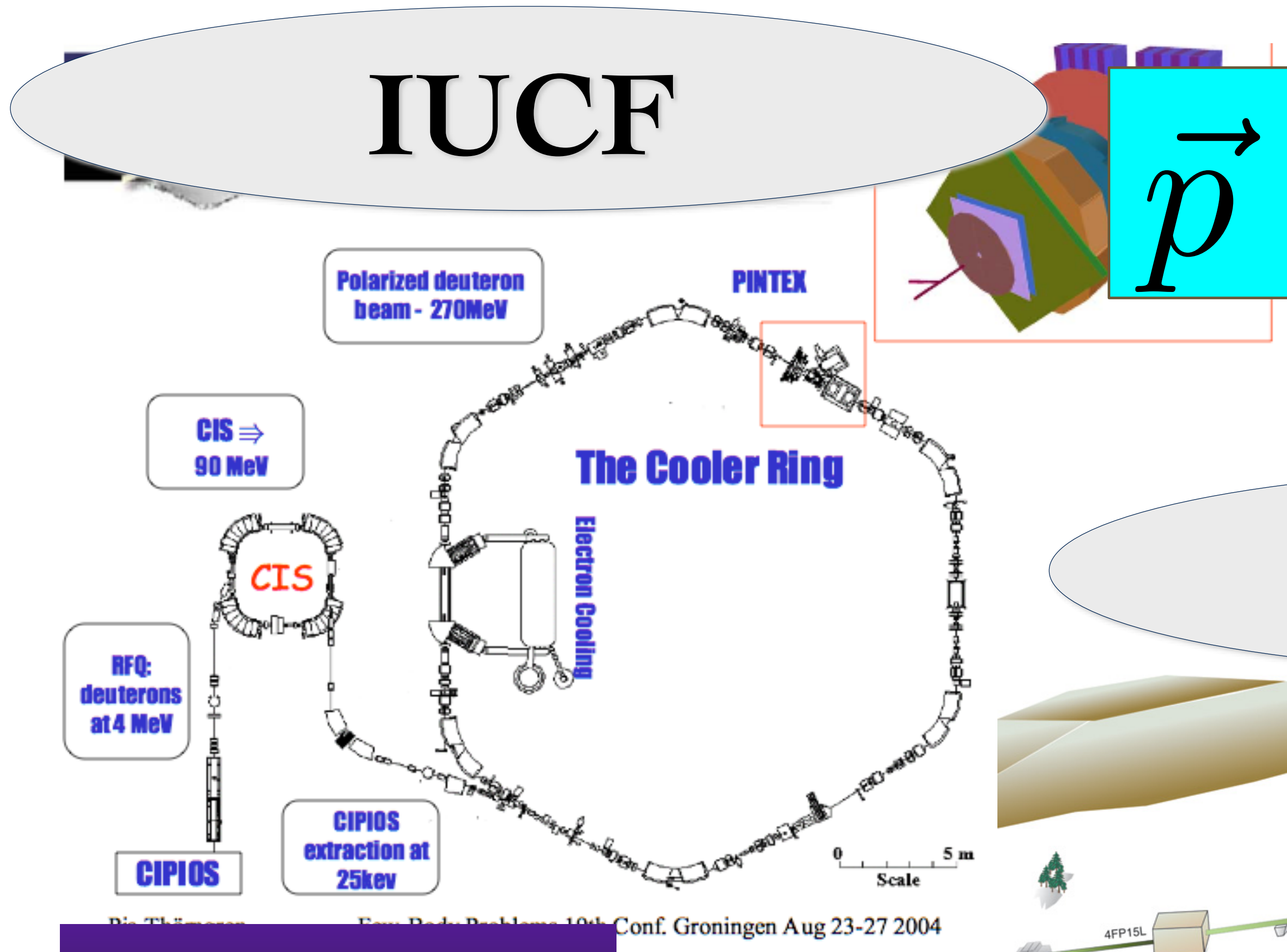
$\vec{p} + d$



Grand Raiden & LAS

IUCF

$\vec{p} + \vec{d}$



Cooler Ring + PINTEX

KVI & CCB

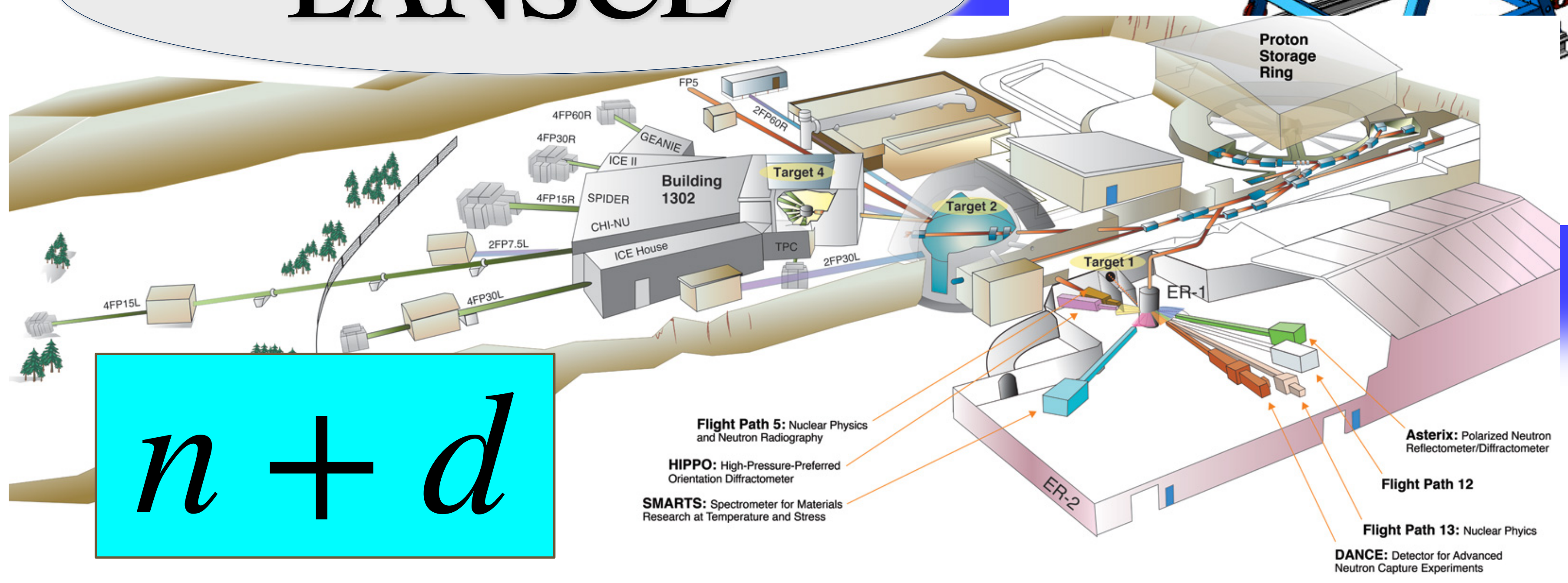
BINA & SALAD

BBS

$\vec{p} + d$

$\vec{d} + p$

LANSCE



$n + d$

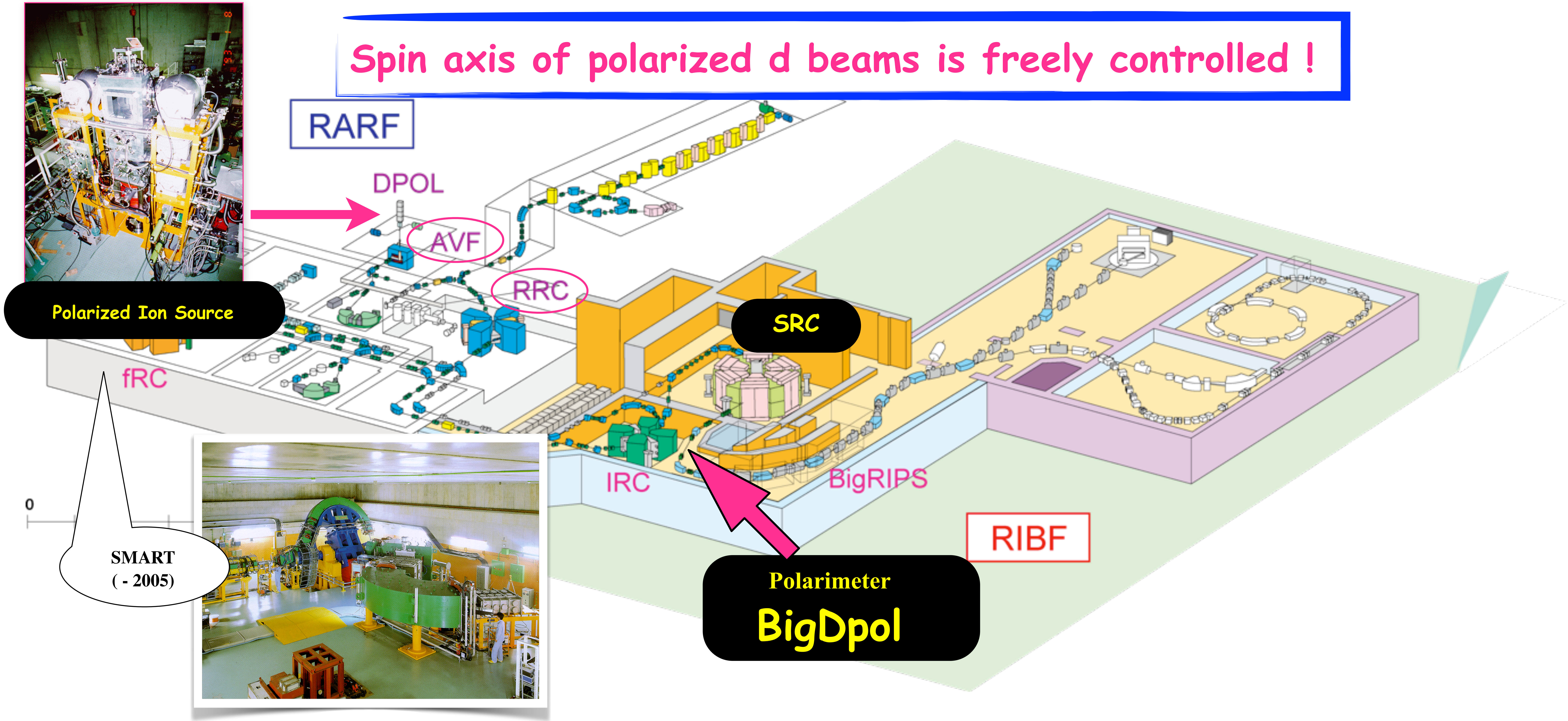
RIKEN RI Beam Factory (RIBF)

Polarized deuteron beam

- acceleration by AVF+RRC : 65-135 MeV/nucleon
- acceleration by AVF+RRC+SRC : 190-300 MeV/nucleon
- polarization : 60-80% of theoretical maximum values

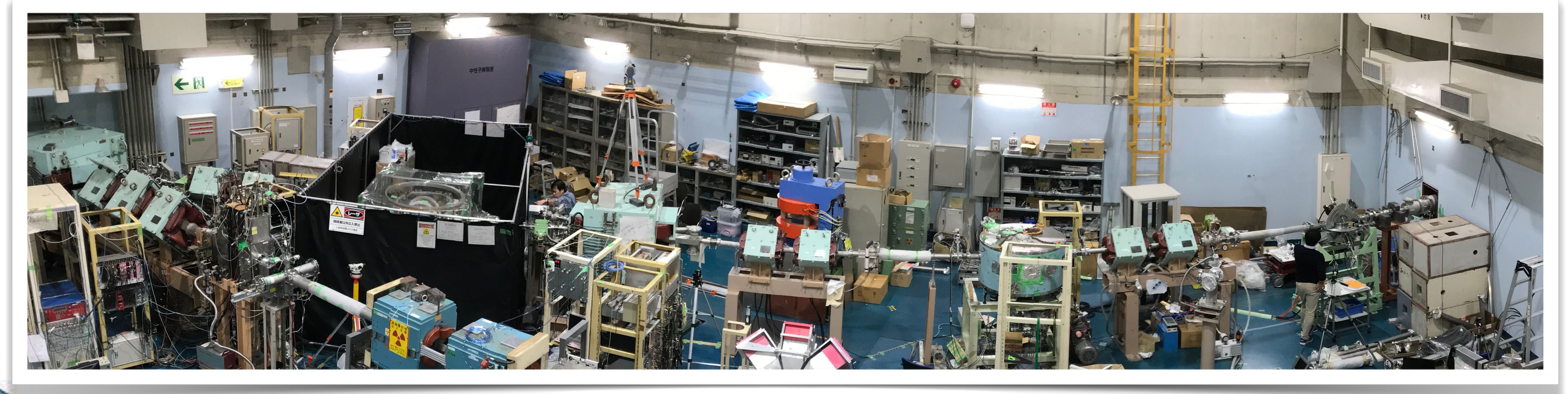
- Beam Intensity : < 100 nA

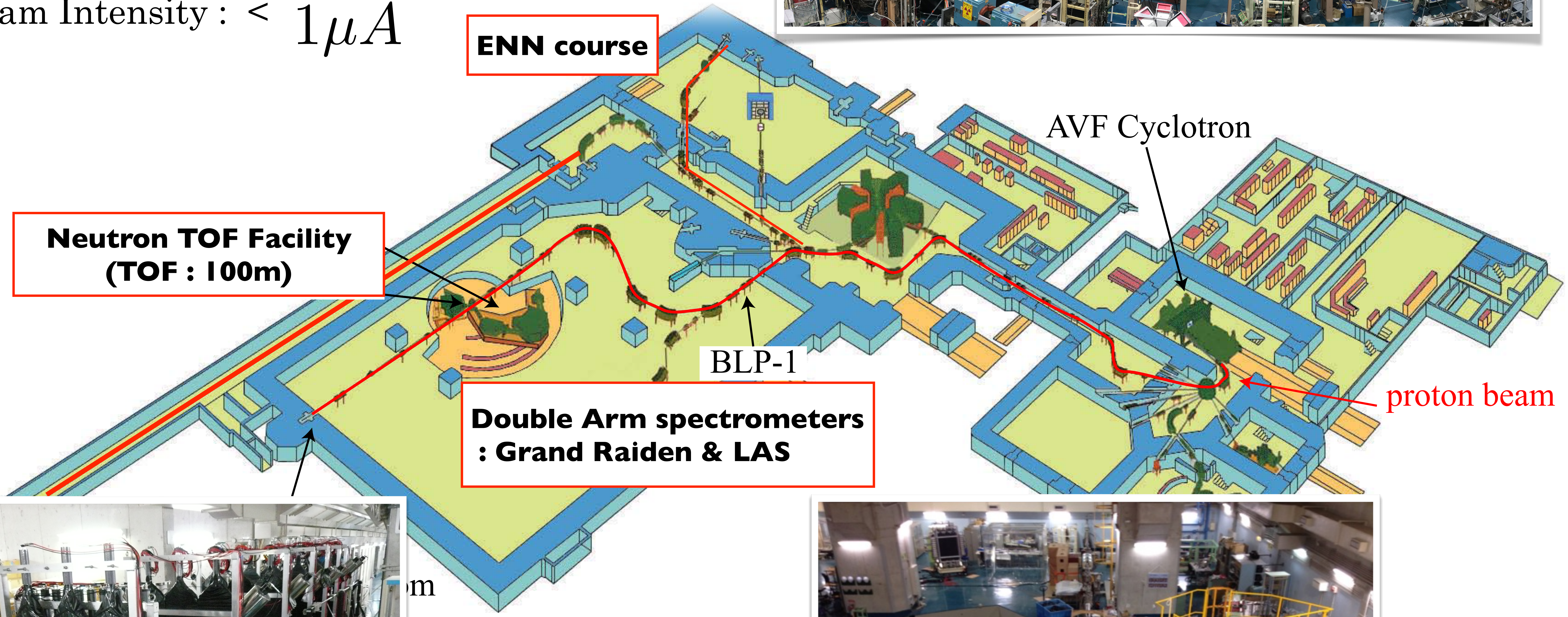
Spin axis of polarized d beams is freely controlled !

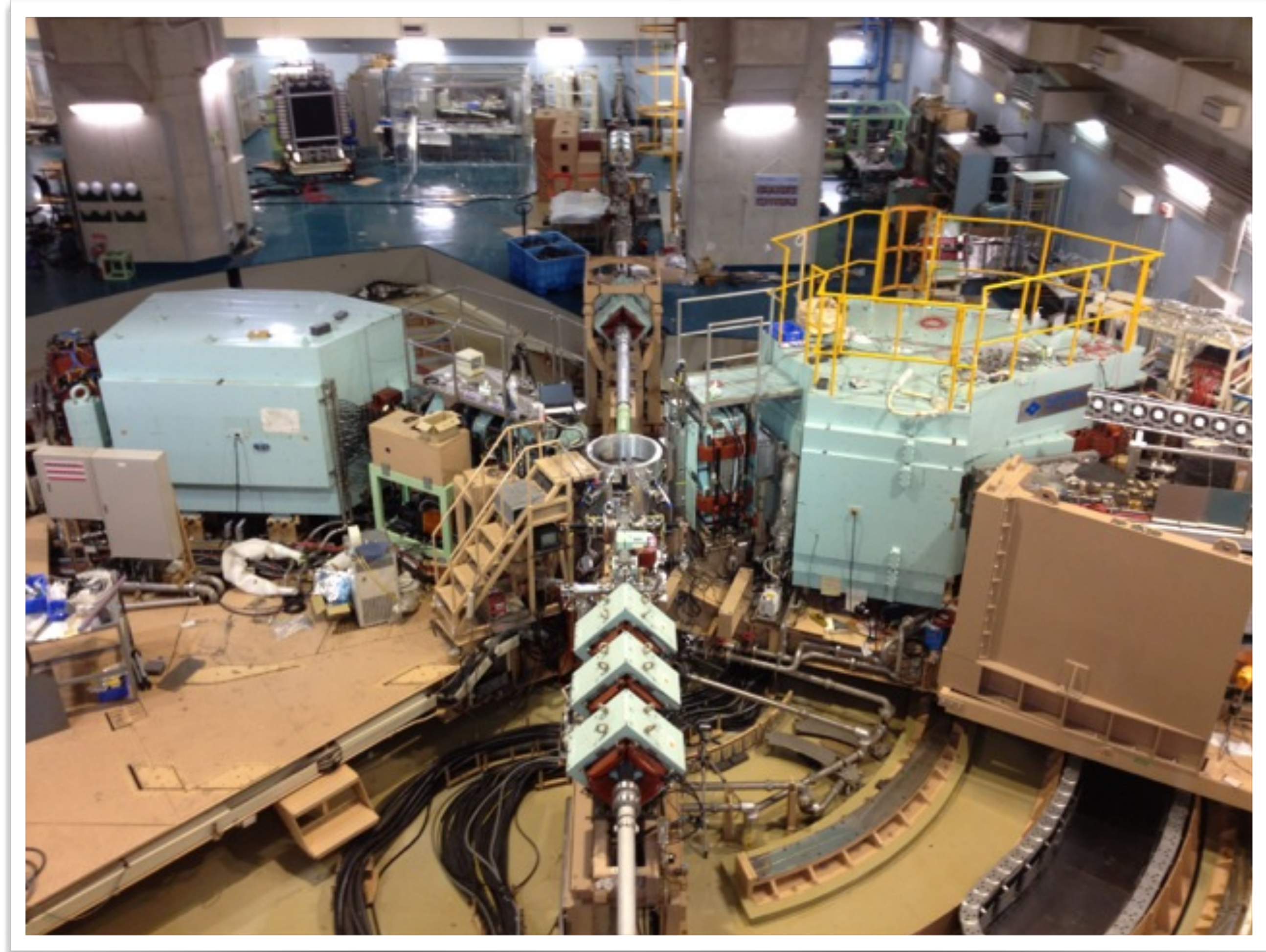


RCNP, Osaka University

- Polarized p beam : 10 - 420 MeV/nucleon
- Polarized d beam : 5 - 100 MeV/nucleon
  - Polarizations : < 70 %
- (pol.) Neutron beams by ^{7}Li(p,n)
- Beam Intensity : < $1\mu A$







Deuteron-Proton Systems

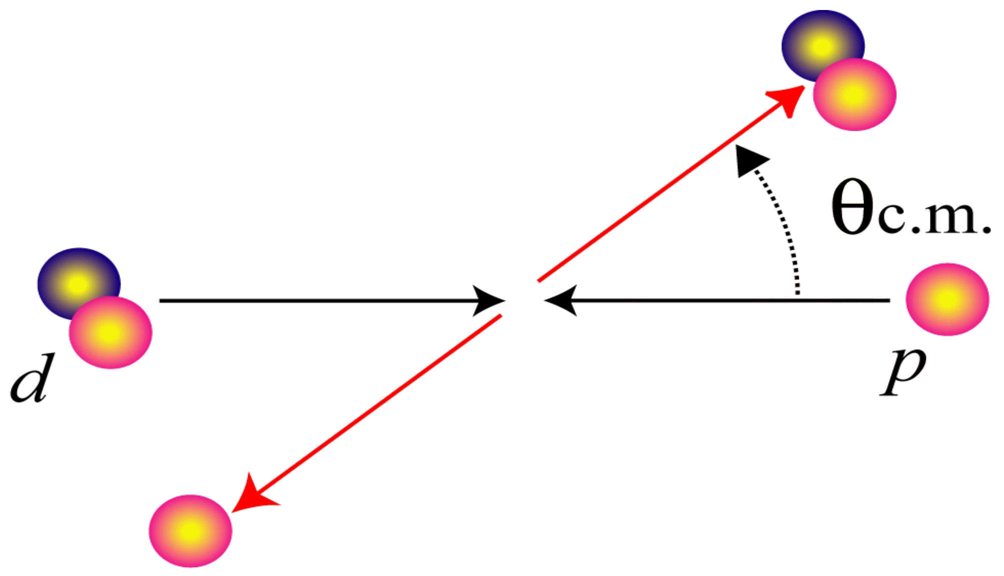
- $d + p \longrightarrow d + p$

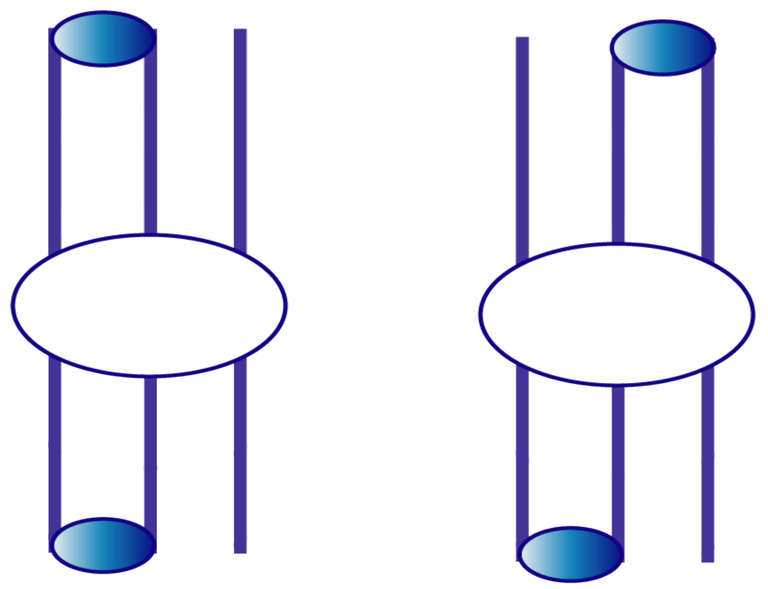
$\theta_{c.m.} = 0^\circ \sim 180^\circ$

Momentum transfer

q **=0 - 3.4 fm^{-1}**

(at E = 135 MeV/A)





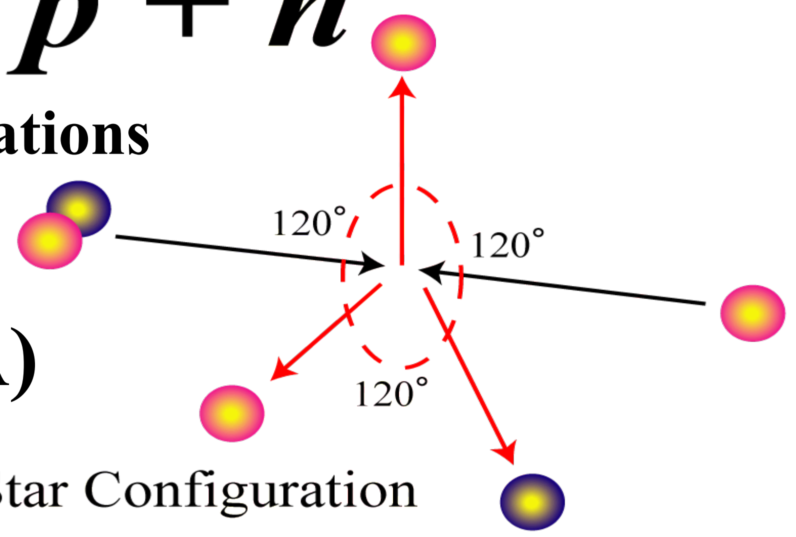
Y. Saito
Parallel 5, on 25th

- $d + p \longrightarrow p + p + n$

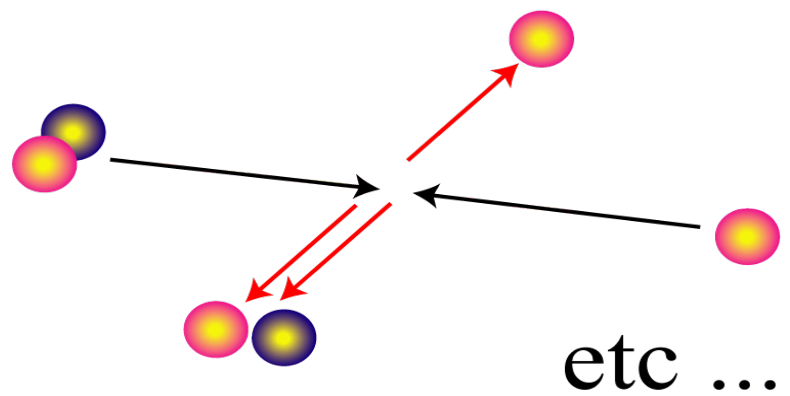
Many kinematical configurations

q **=0 - 3 fm^{-1}**

(at E = 135 MeV/A)

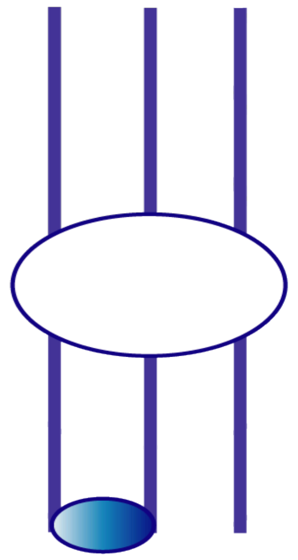


Star Configuration



Final State Interaction

etc ...



Y. Maeda
Parallel 5, on 25th

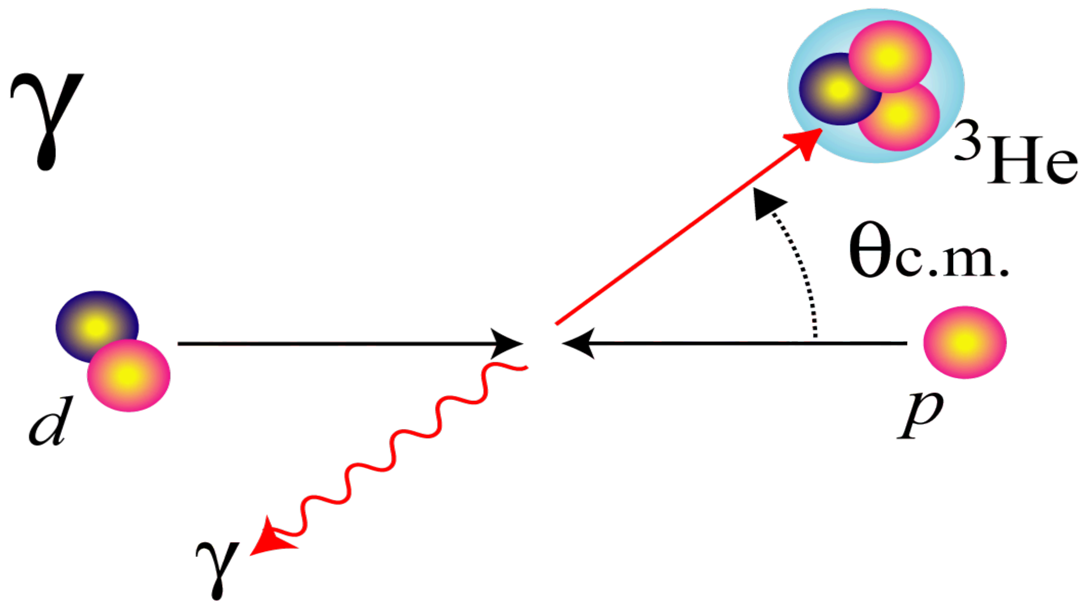
I. Skwira-Chalot
Parallel 6, on 26th

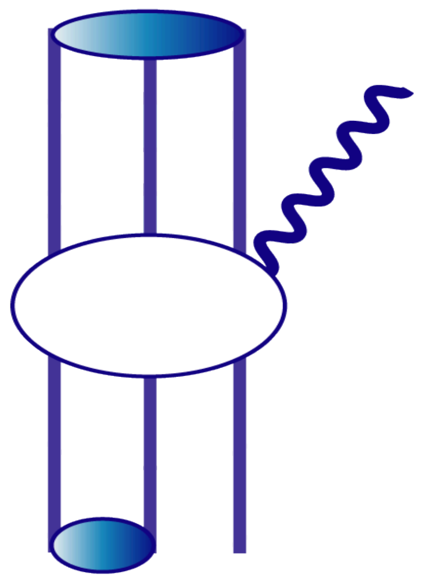
- $d + p \longrightarrow {}^3\mathrm{He} + \gamma$

$\theta_{c.m.} = 0^\circ \sim 180^\circ$

q **=1.5 - 2.5 fm^{-1}**

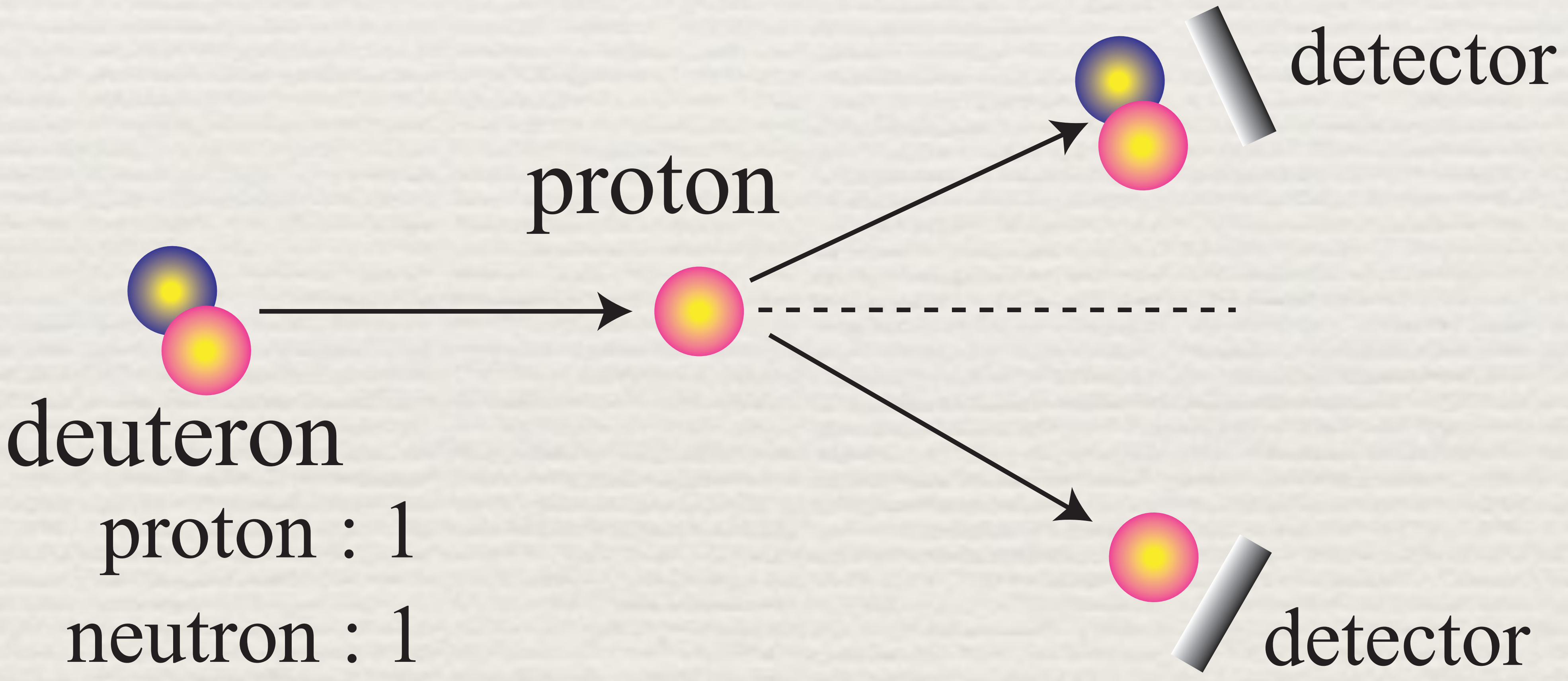
(at E = 135 MeV/A)





deuteron-nucleon scattering

at ∼100 MeV/nucleon



Differential Cross section

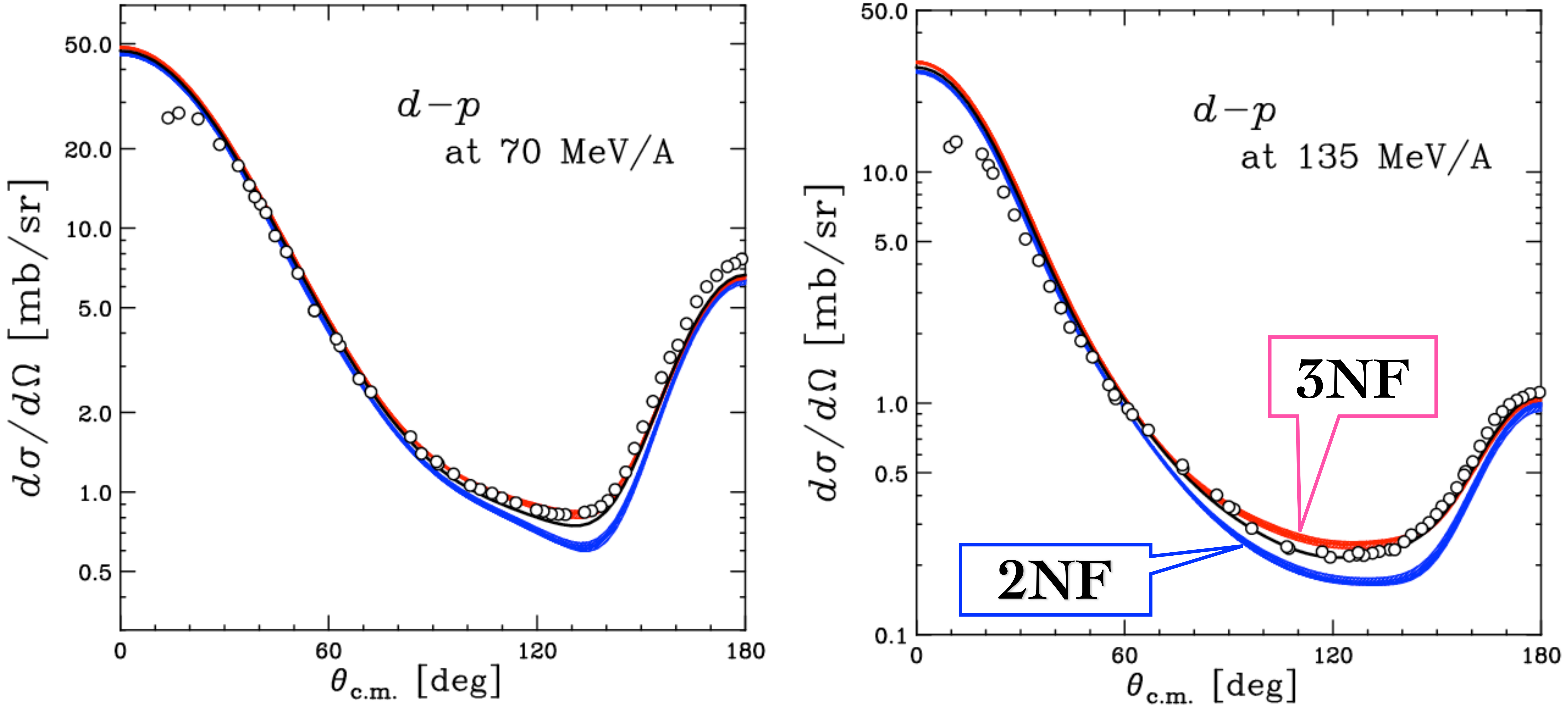
NN (CDBonn, AV18, Nijm I,II)

TM'(99) 3NF +
NN(CD Bonn, AV18, Nijm I,II)

Urbana IX 3NF+AV18

K. Sekiguchi et al. PRC 65, 034003 (2002)
K. Sekiguchi et al. PRL 95, 162301 (2005)

Calculations by Bochum-Cracow Gr.



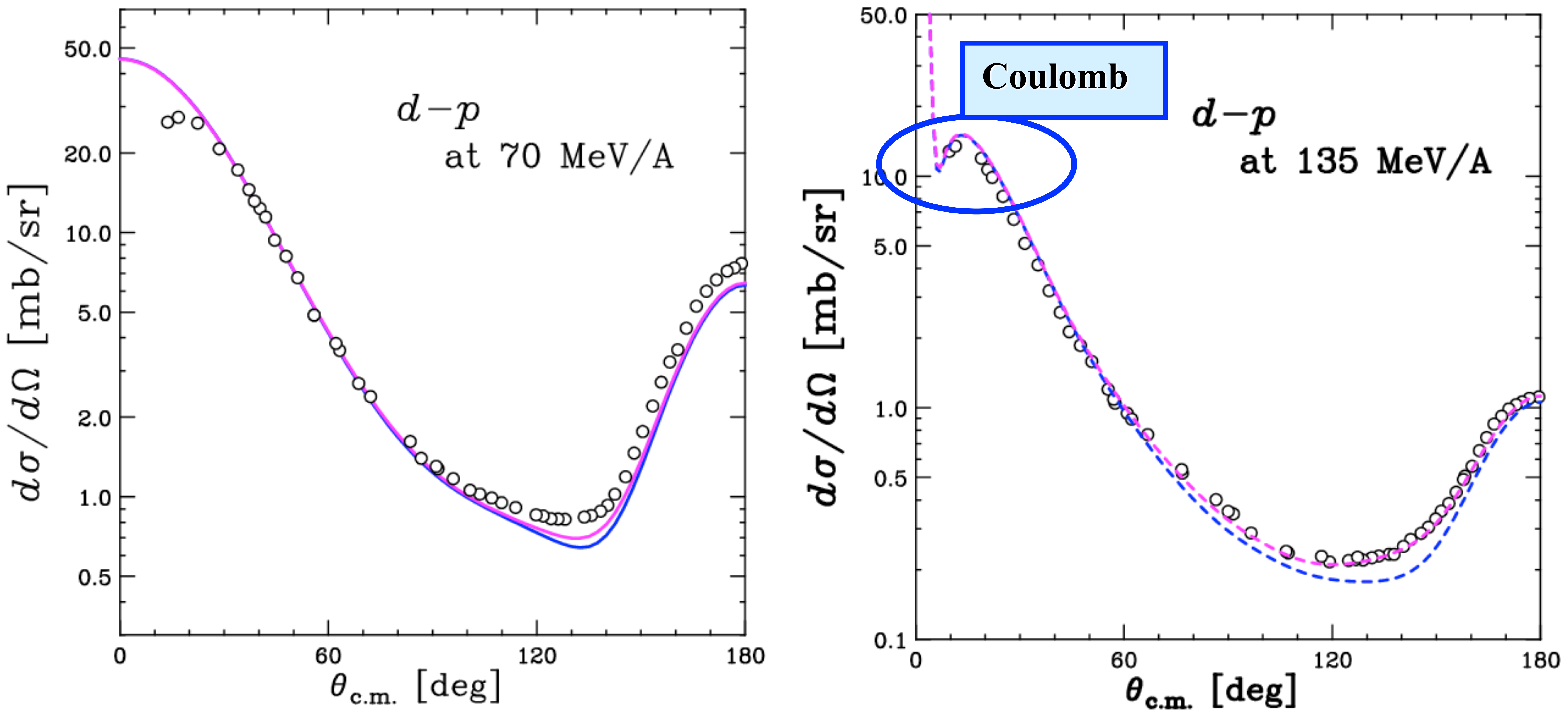
2NF (CDBonn, AV18, Nijmegen I,II)
: Large discrepancy in Cross Section Minimum (~ 30%)

2π-exchange 3NFs (Tucson-Melbourne, Urbana IX) : Good Agreement
: First Clear Signatures of 3NF effects in 3-Nucleon Scattering

CDBonn + Δ-isobar

CDBonnNN pot.

Calculations by Hannover-Lisbon Gr.



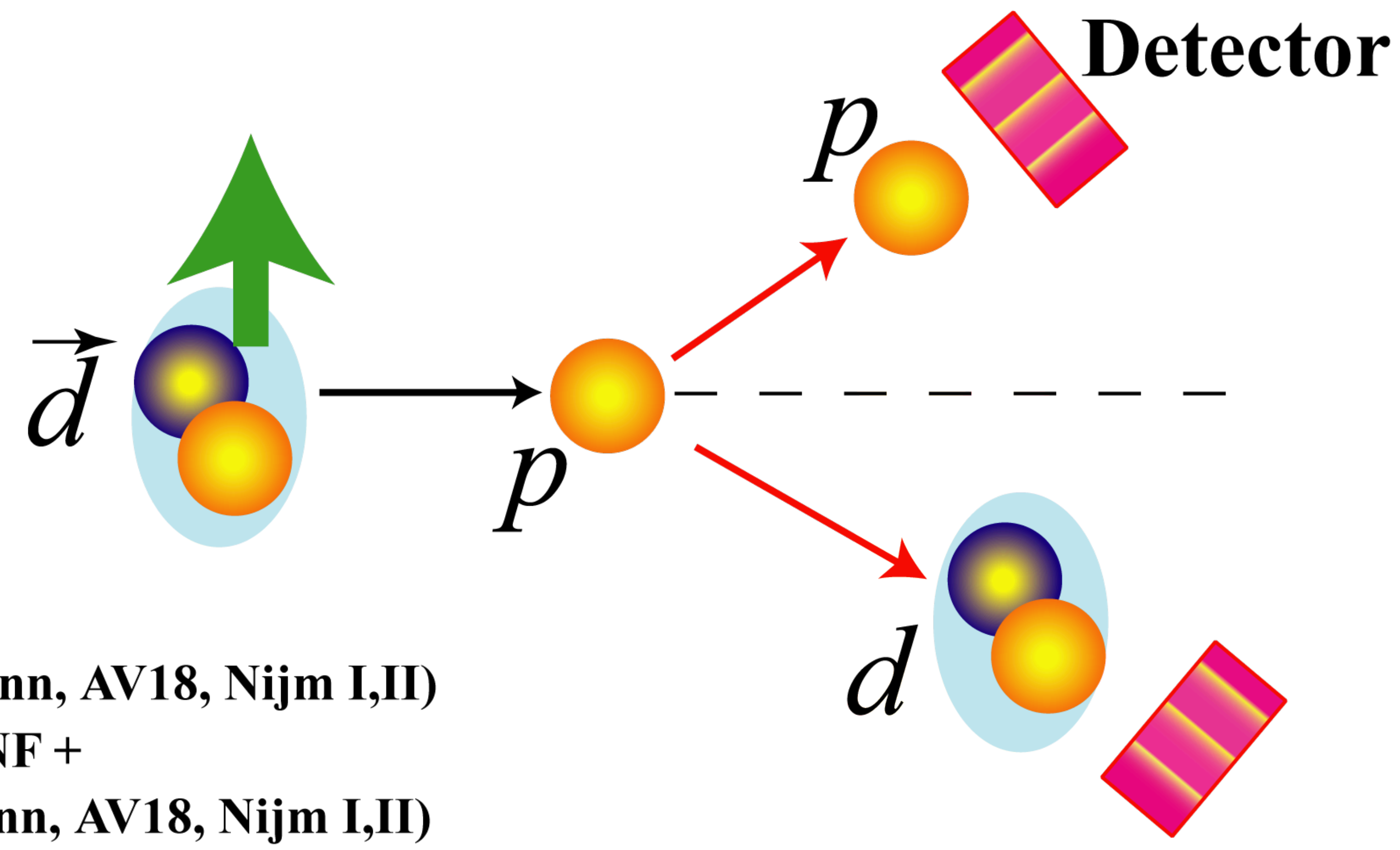
Coupled channel approach with *Nucleon*&Δ-isobar : Good Agreement.

Disagreement at very forward angles : Coulomb effects.

A. Deltuva et al., PRC 68, 024005 (2003)
A. Deltuva et al., PRC 71, 054005 (2005)

Spin Observables

Analyzing Powers



- NN (CDBonn, AV18, Nijm I,II)
- TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
- with Urbana IX 3NF+AV18
- with Δ-isobar + CDBonn

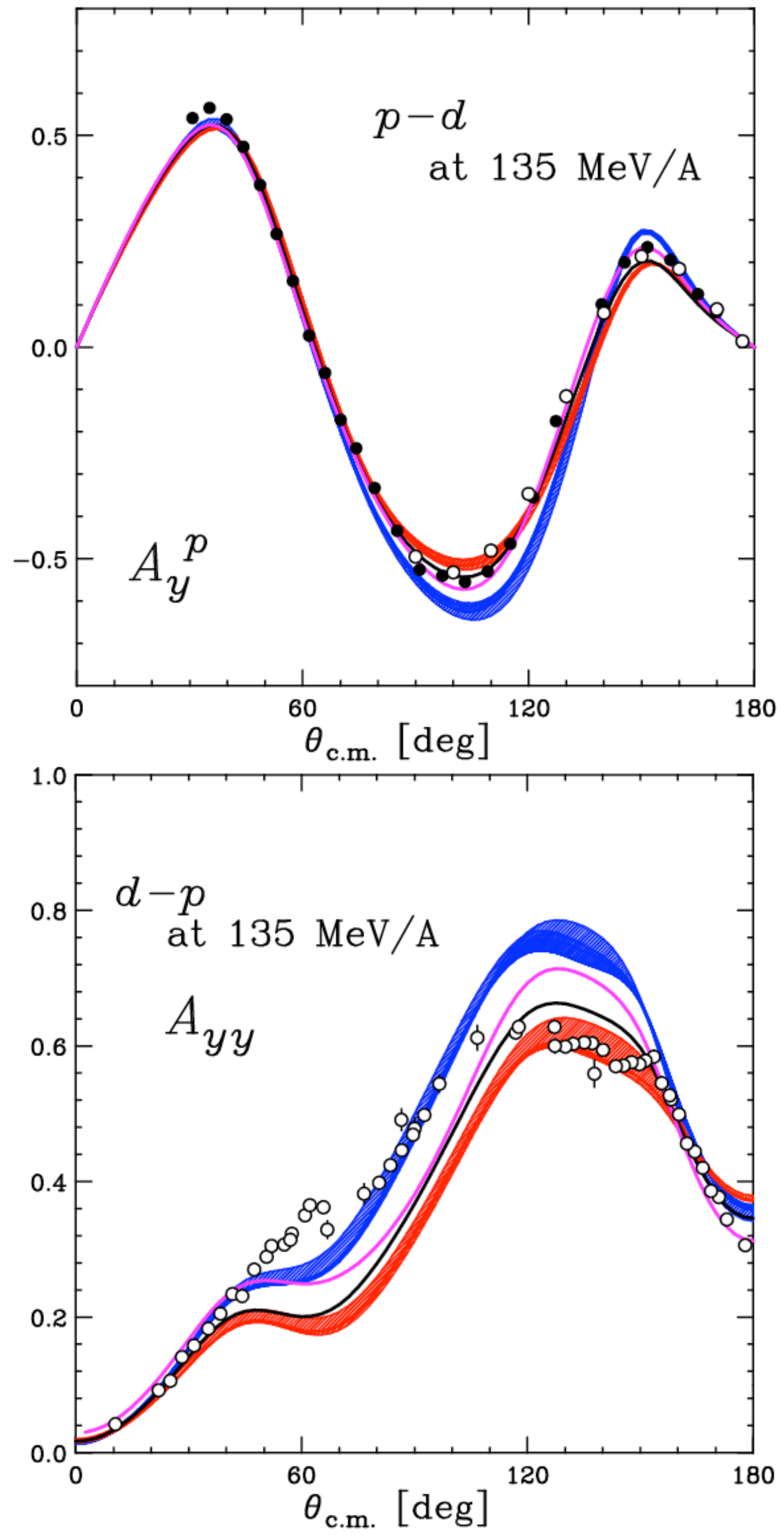
2NF (CDBonn, AV18, Nijmegen I,II) :
Large discrepancy
in Cross Section Minimum

3NF (Tucson-Melbourne, Urbana IX, Δ-isobar) :

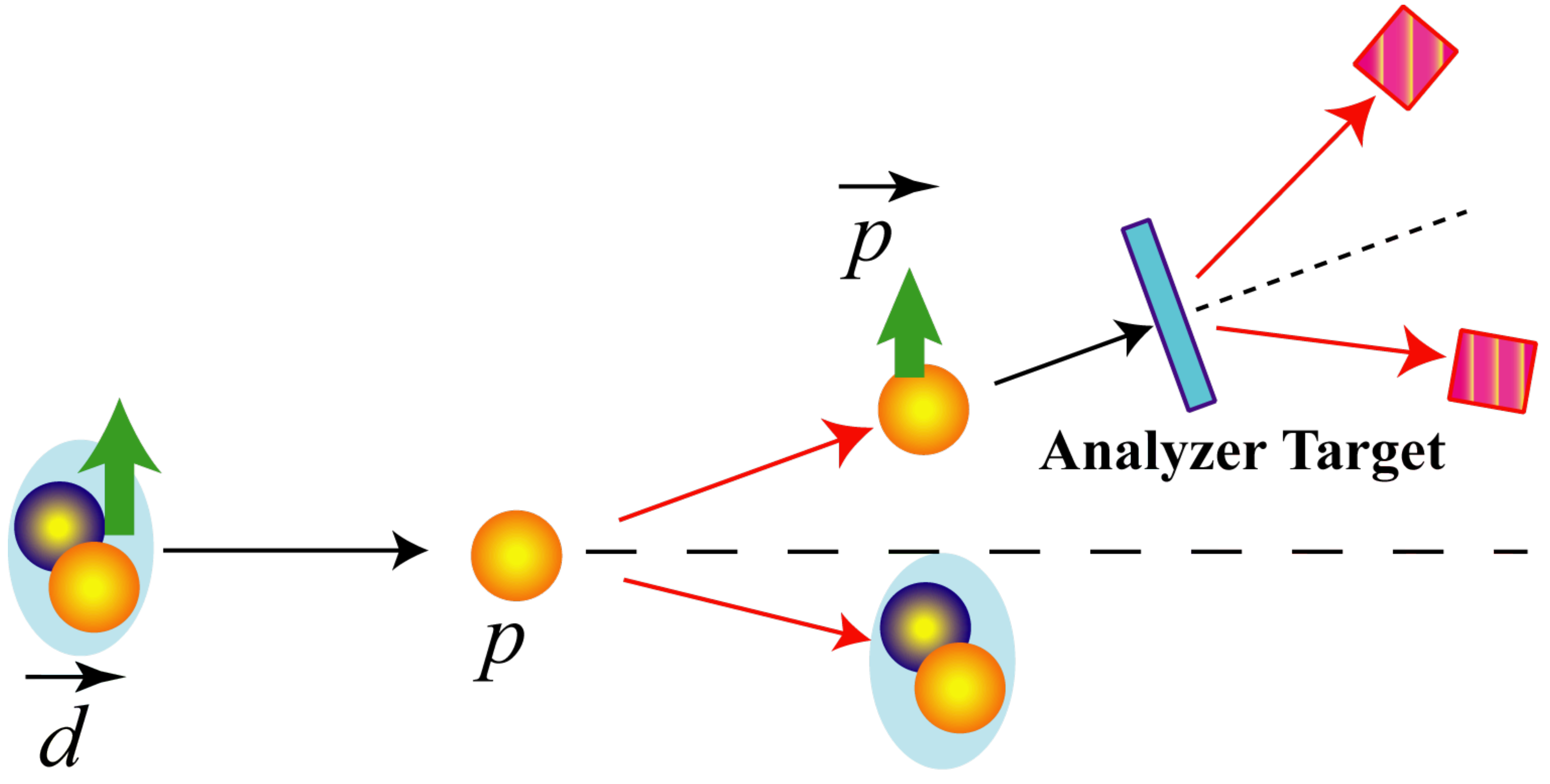
Vector Analyzing Power A_y^p
: Good Agreement

Tensor Analyzing Power A_{yy}
: No superiority

K. Sekiguchi et al. PRC 65, 034003 (2002)



Polarization Transfer Coefficients



3NF :

$K_{xx}^{y'}-K_{yy}^{y'}$: **Good Agreement**

$K_{y}^{y'}$: **Direction : O.K.**

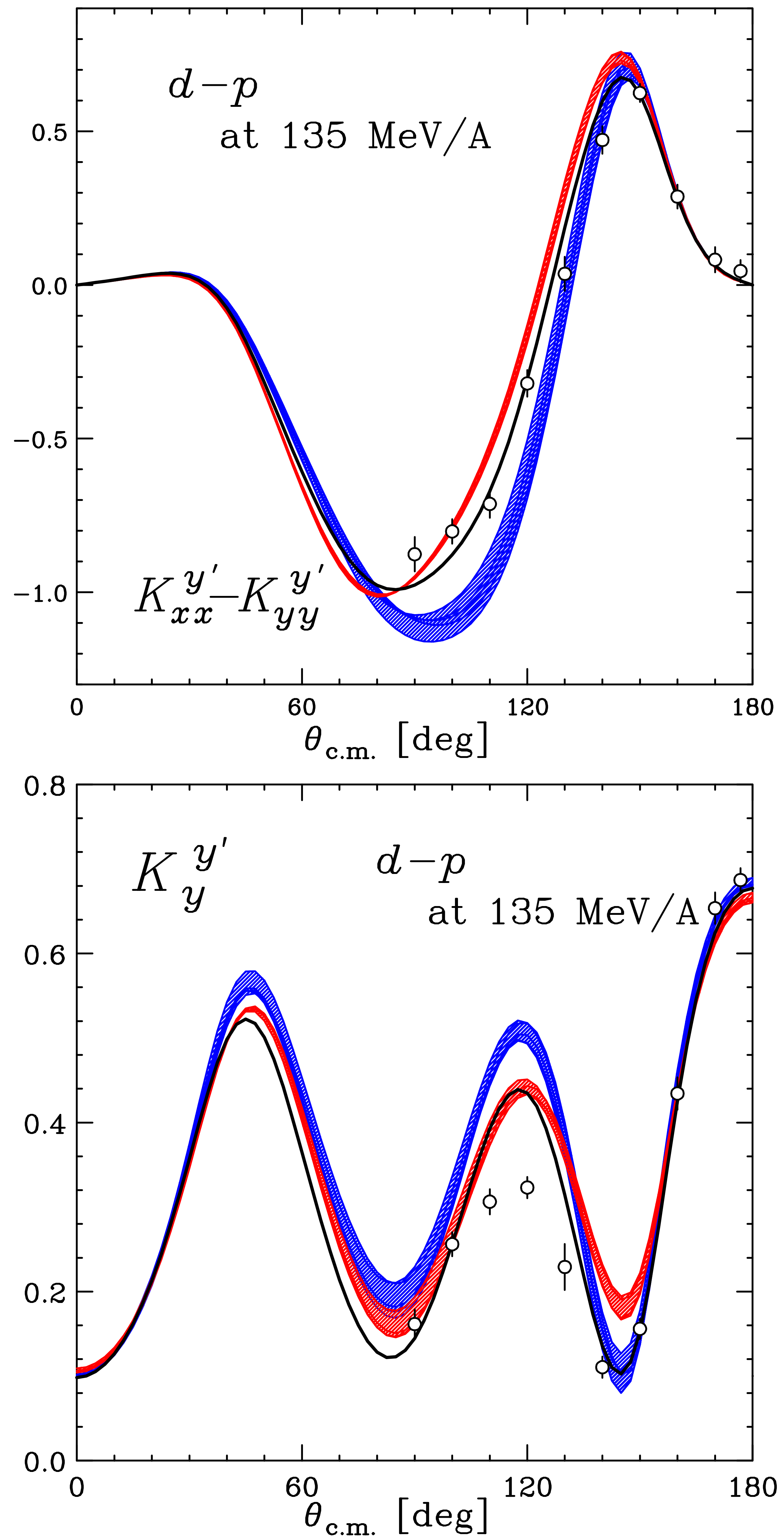
Magnitude : not enough

Spin Observables (A_{ij}, K_{ij}) :

Not always explained by 2π-exchange 3NF

⇒ Defects of spin dependent parts of 3NF

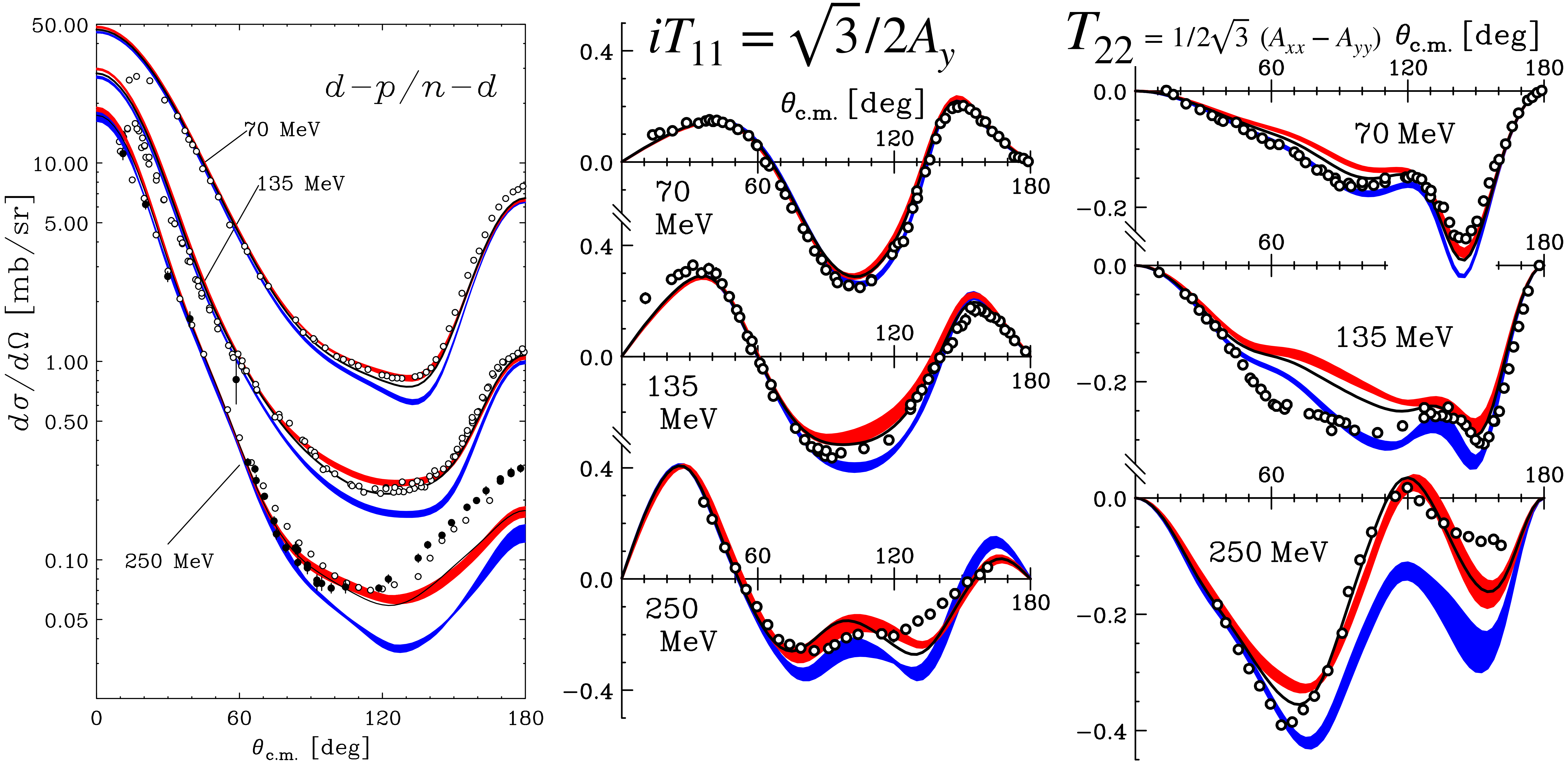
K. Sekiguchi et al. PRC 70, 014001(2004)



Energy Dependence

Energy Dependent Study for *dp* Scattering
- Cross Section & Analyzing Powers -

K. Hatanaka et al., Phys. Rev. C. 66, 044002 (2002)
Y. Maeda et al., Phys. Rev. C 76, 014004 (2007)
K. S. et al., Phys. Rev. C 83, 061001 (2011)
K. S. et al., Phys. Rev. C 89, 064007 (2014)



Serious discrepancies exist at very backward angles.

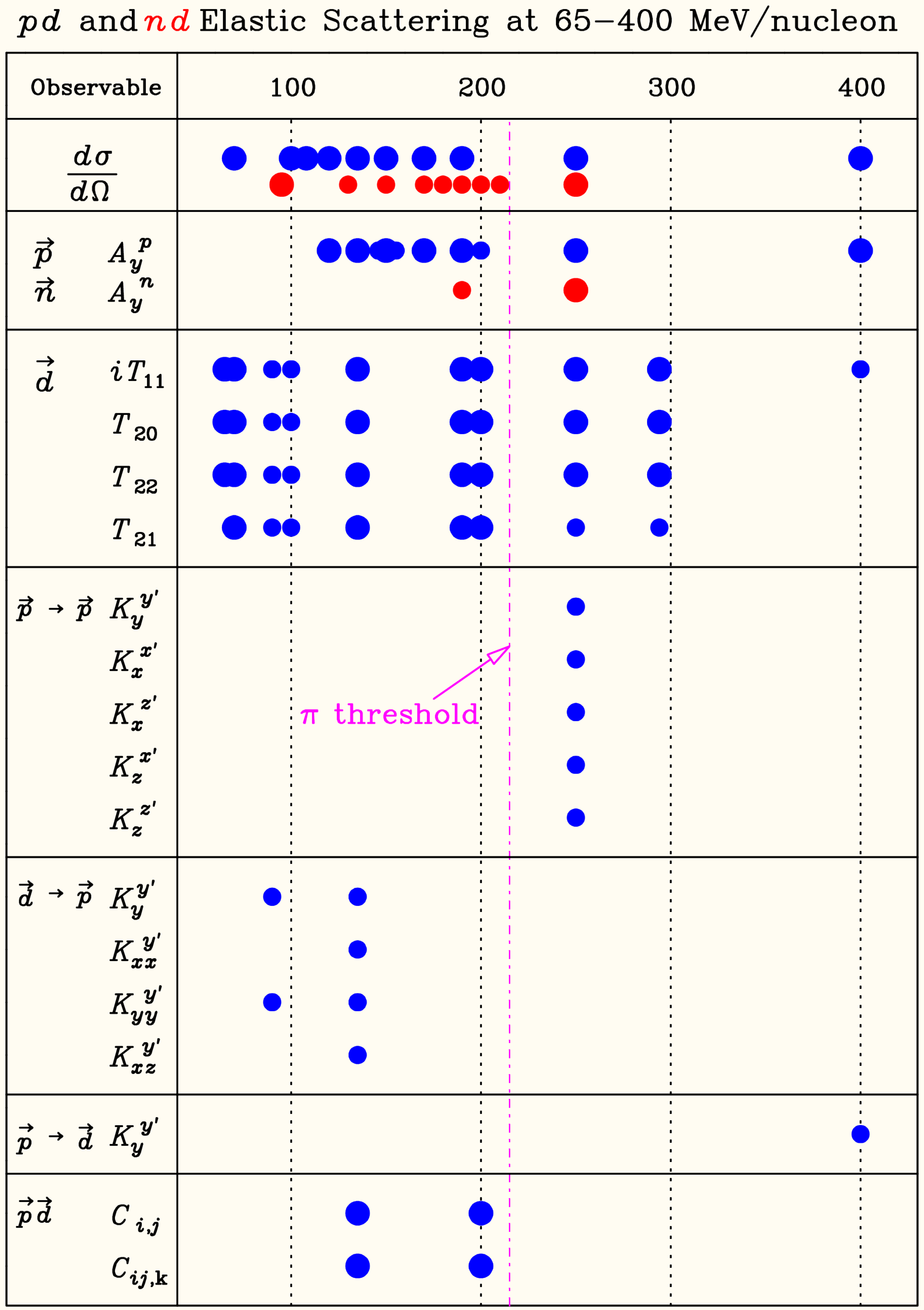
Short Range 3NFs are essential.

NN (CDBonn, AV18, Nijm I,II)
TM'(99) 3NF + NN(CD Bonn, AV18, Nijm I,II)
Urbana IX 3NF+AV18

Summary of Results of Comparison for *dp* elastic scattering

- Cross section at ~100 MeV/nucleon
  - First clear signature of 3NF effects in 3N scattering
    - Magnitudes of 3NFs is O.K. .
- Spin observables
  - Not always described by 2π-3NFs
    - Defects of spin-dependent parts of 3NFs
- At higher energies …
  - Serious discrepancy at backward angles
    - Short Range 3NFs are required.

Nd Elastic Scattering Data at Intermediate Energies



~2024

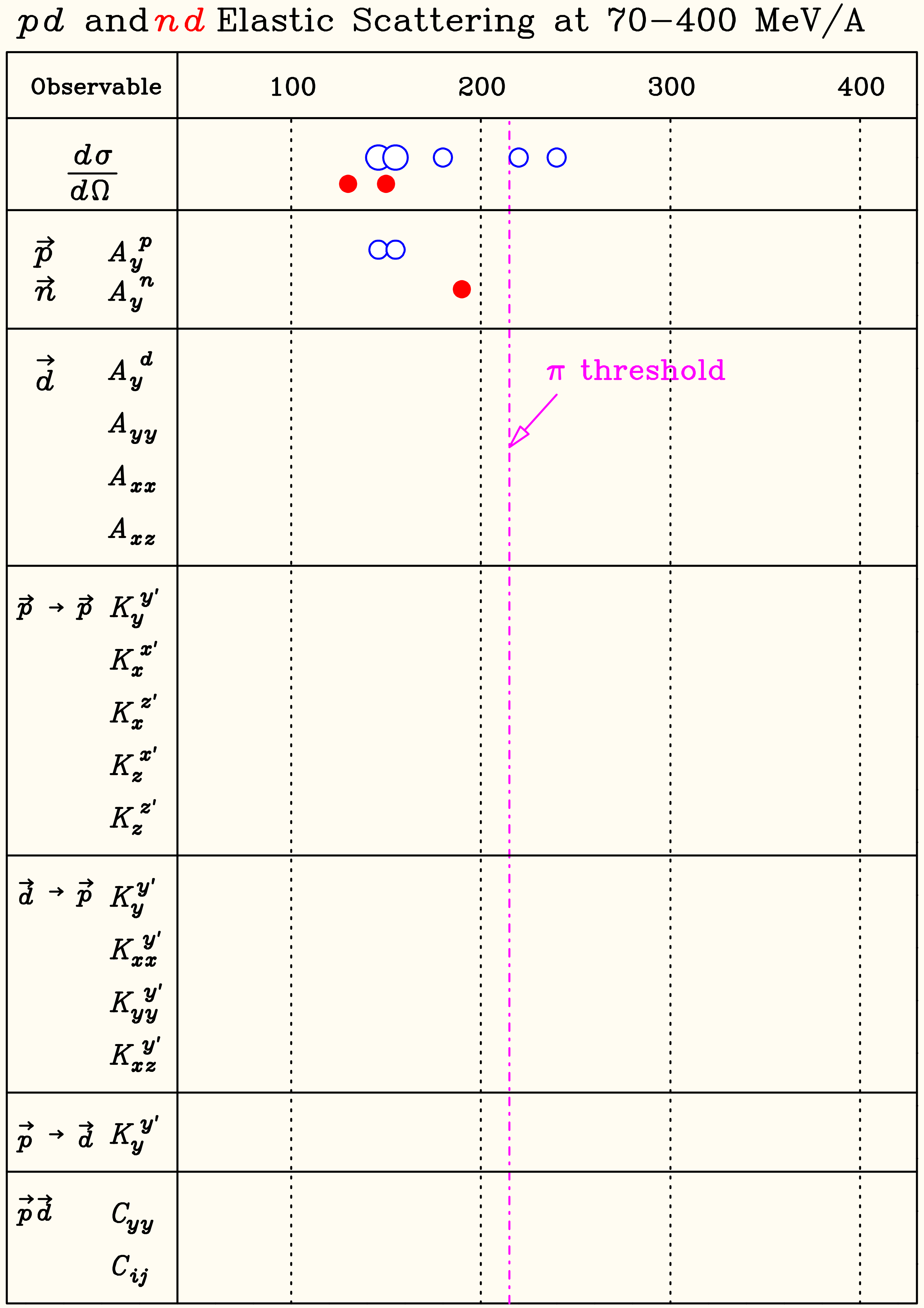
- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**

  from

  RIKEN, RCNP, KVI, IUCF, LANSCE

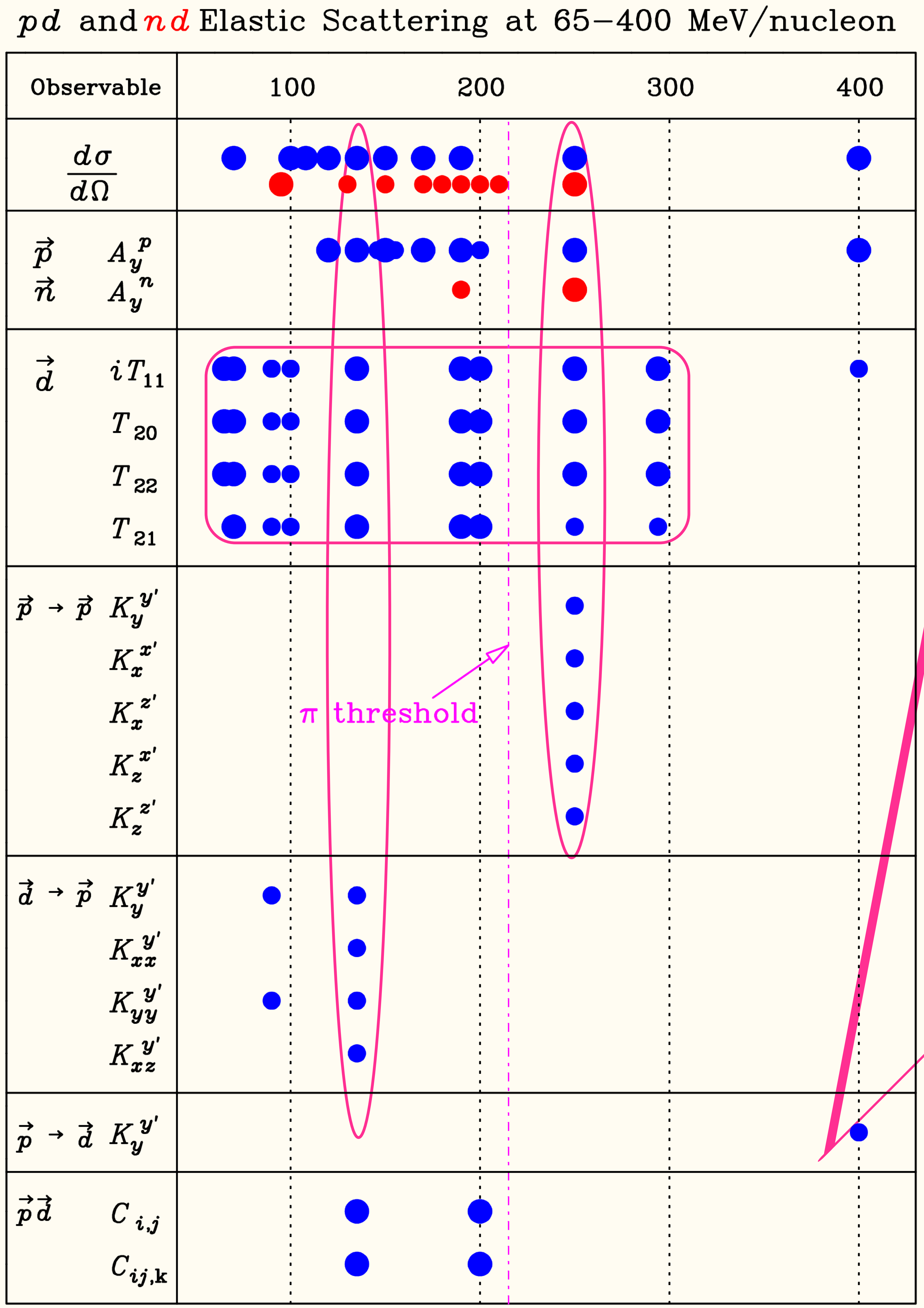
  etc.

Nd Elastic Scattering Data at Intermediate Energies



~1998

Nd Elastic Scattering Data at Intermediate Energies



~2024

- **High precision data set of**
  ***dσ/dΩ* & Analyzing Powers**
  from
  RIKEN, RCNP, KVI, IUCF, LANSCE etc.

After **89** Years of
Yukawa's Meson Thory (1935)
&
After **67** Years of
Fujita-Miyazawa 3NF (1957)

Quantitative discussions on 3NFs start via Theor. & Exp. .

So far …

Nucleon-Deuteron Scattering at ~100 MeV/nucleon

- First Evidence of 3NF effects
- Defects of existing 3NF models

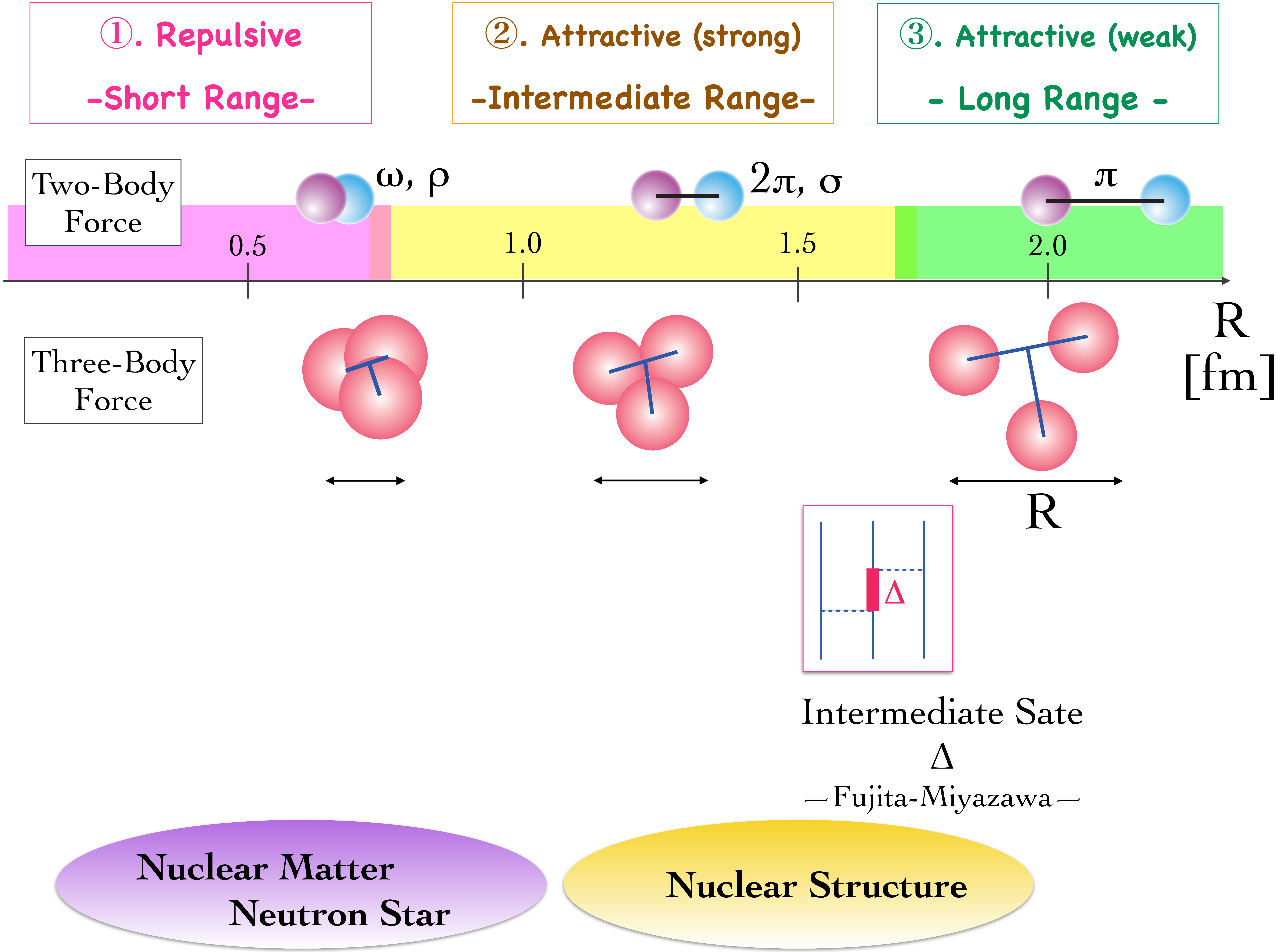
From here

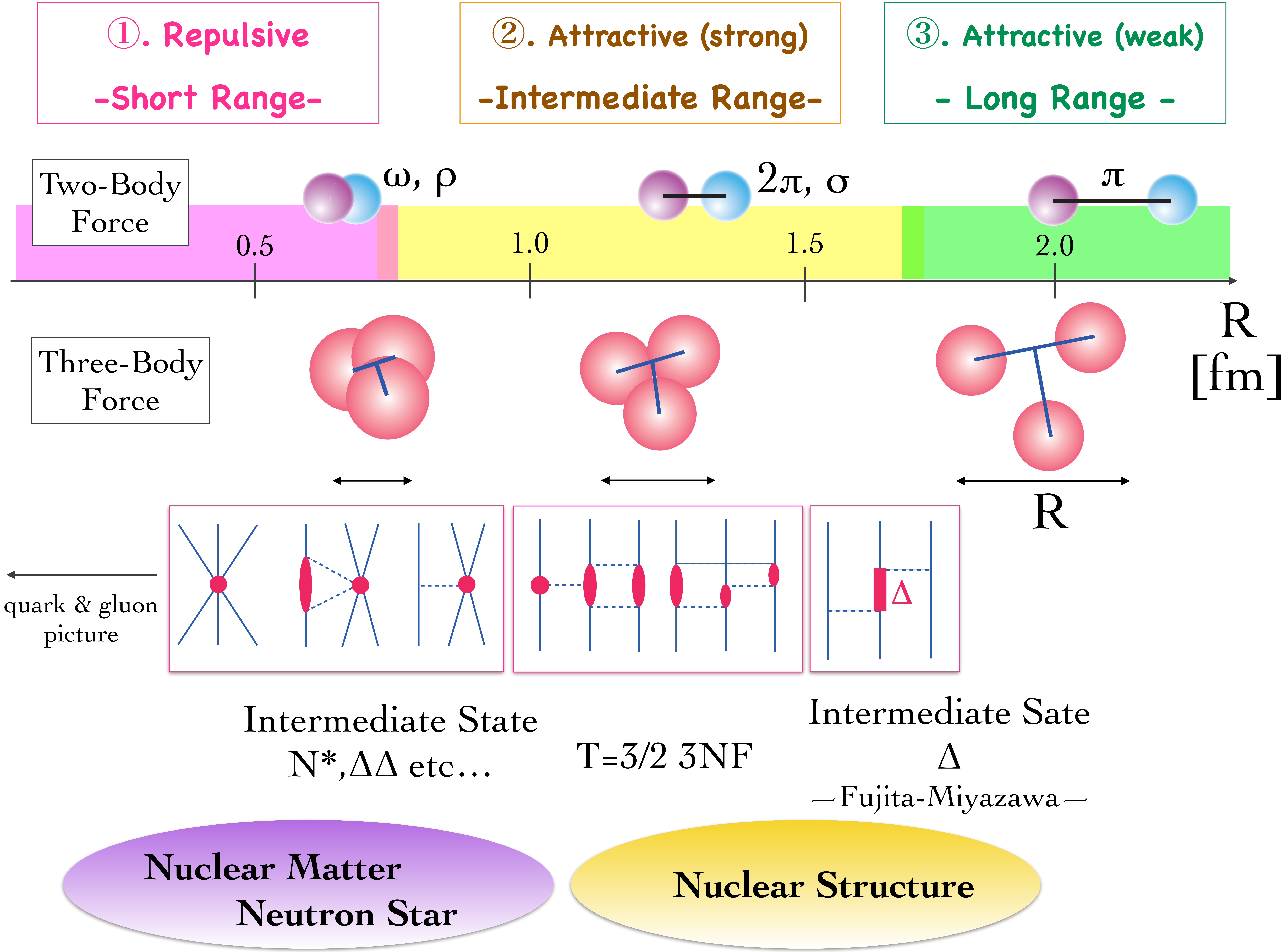
Deuteron-Proton Scattering at ~100 MeV/N : *Golden window of 3NFs*

- Determine 3NFs based on χEFT Nuclear Potential
- High-precision measurement of Spin Correlation Coefficients

Proton-^{3}He Scattering at ~100 MeV/N : *New Probe of 3NF Study*

- 3NFs of isospin channel of T=3/2
- First Step from Few to Many


①. Repulsive
-Short Range-
②. Attractive (strong)
-Intermediate Range-
③. Attractive (weak)
- Long Range -
Two-Body Force
ω, ρ
2π, σ
π
0.5
1.0
1.5
2.0
R [fm]
Three-Body Force
R
Δ
Intermediate Sate
Δ
—Fujita-Miyazawa—
Nuclear Matter
Neutron Star
Nuclear Structure



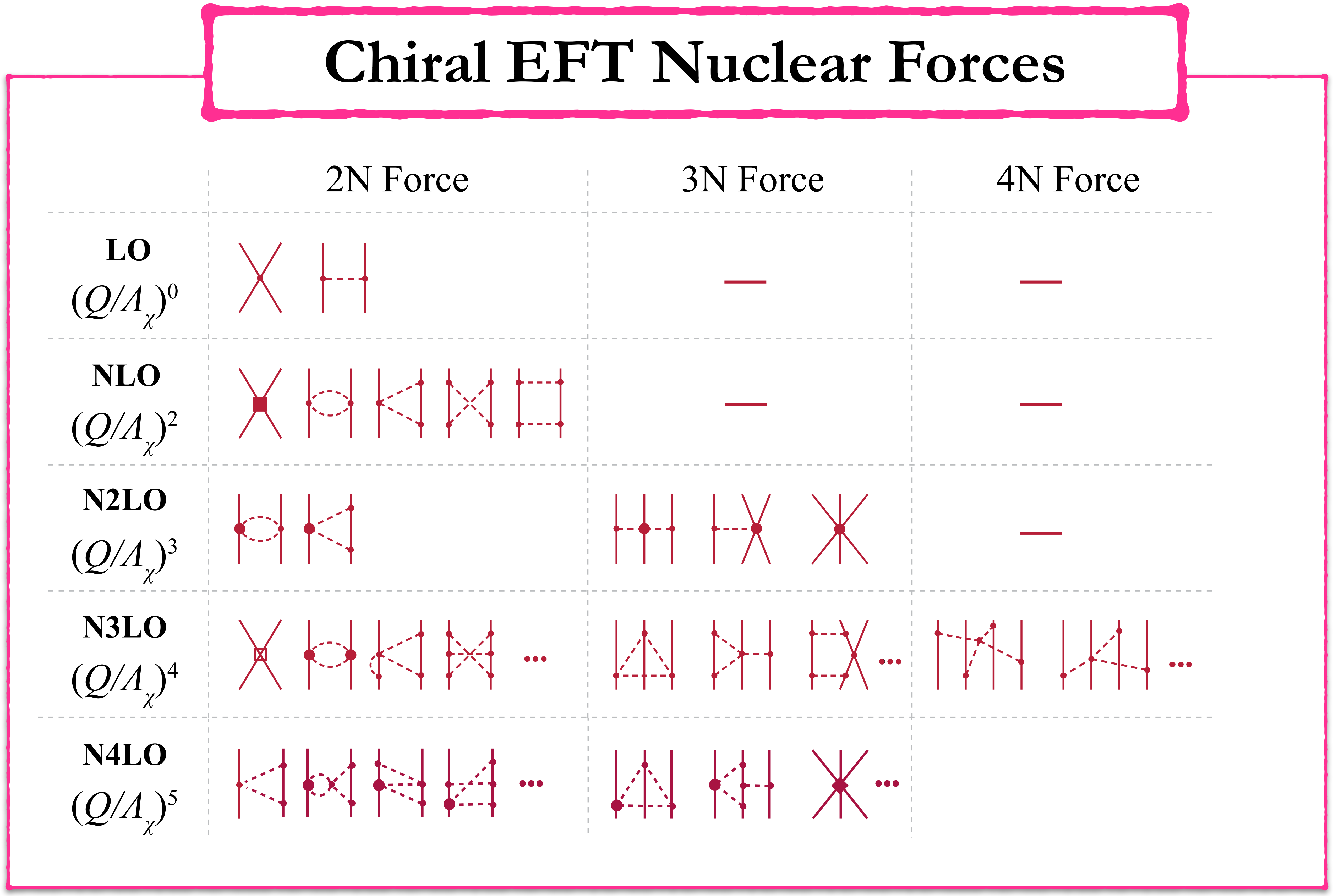
①. Repulsive
-Short Range-
②. Attractive (strong)
-Intermediate Range-
③. Attractive (weak)
- Long Range -
Two-Body Force
ω, ρ
2π, σ
π
0.5
1.0
1.5
2.0
R [fm]
Three-Body Force
R
quark & gluon picture
Δ
Intermediate State N*,ΔΔ etc…
T=3/2 3NF
Intermediate Sate Δ
—Fujita-Miyazawa—
Nuclear Matter
Neutron Star
Nuclear Structure

Chiral EFT Nuclear Force & *dp* elastic scattering

- χEFT 2NFs have achieved to high-precision.

5th order of NN potentials (N4LO+) reproduce pp(np) data with χ^2/datum=1.00

P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)



Chiral EFT Nuclear Force & *dp* elastic scattering

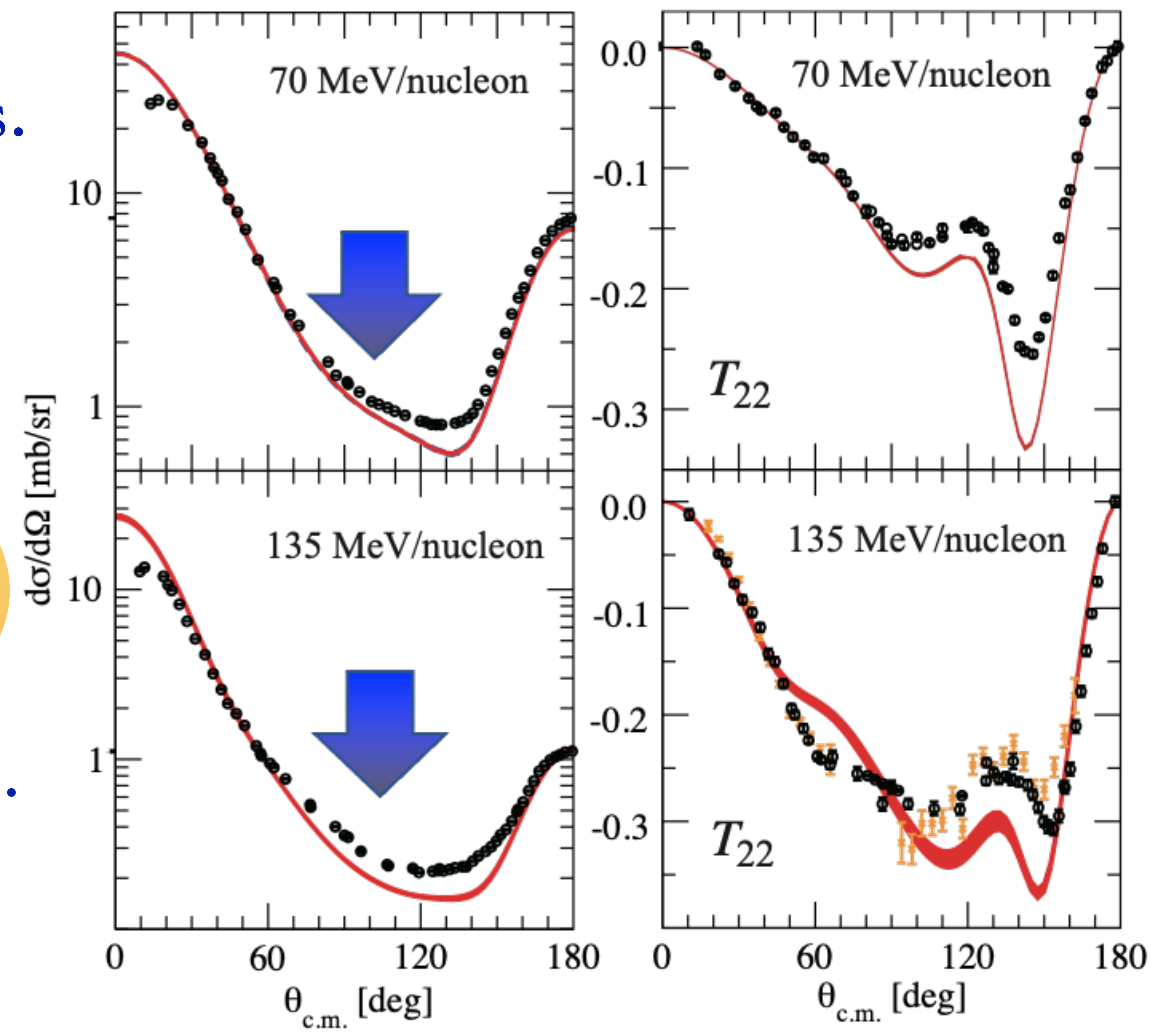
- χEFT 2NFs have achieved to high-precision.

  5th order of NN potentials (N4LO+) reproduce pp(np) data with χ^2/datum=1.00

  P. Reinert, H. Krebs, E. Epelbaum EPJA 54, 86 (2018)

dp scattering & N4LO χEFT 2NFs

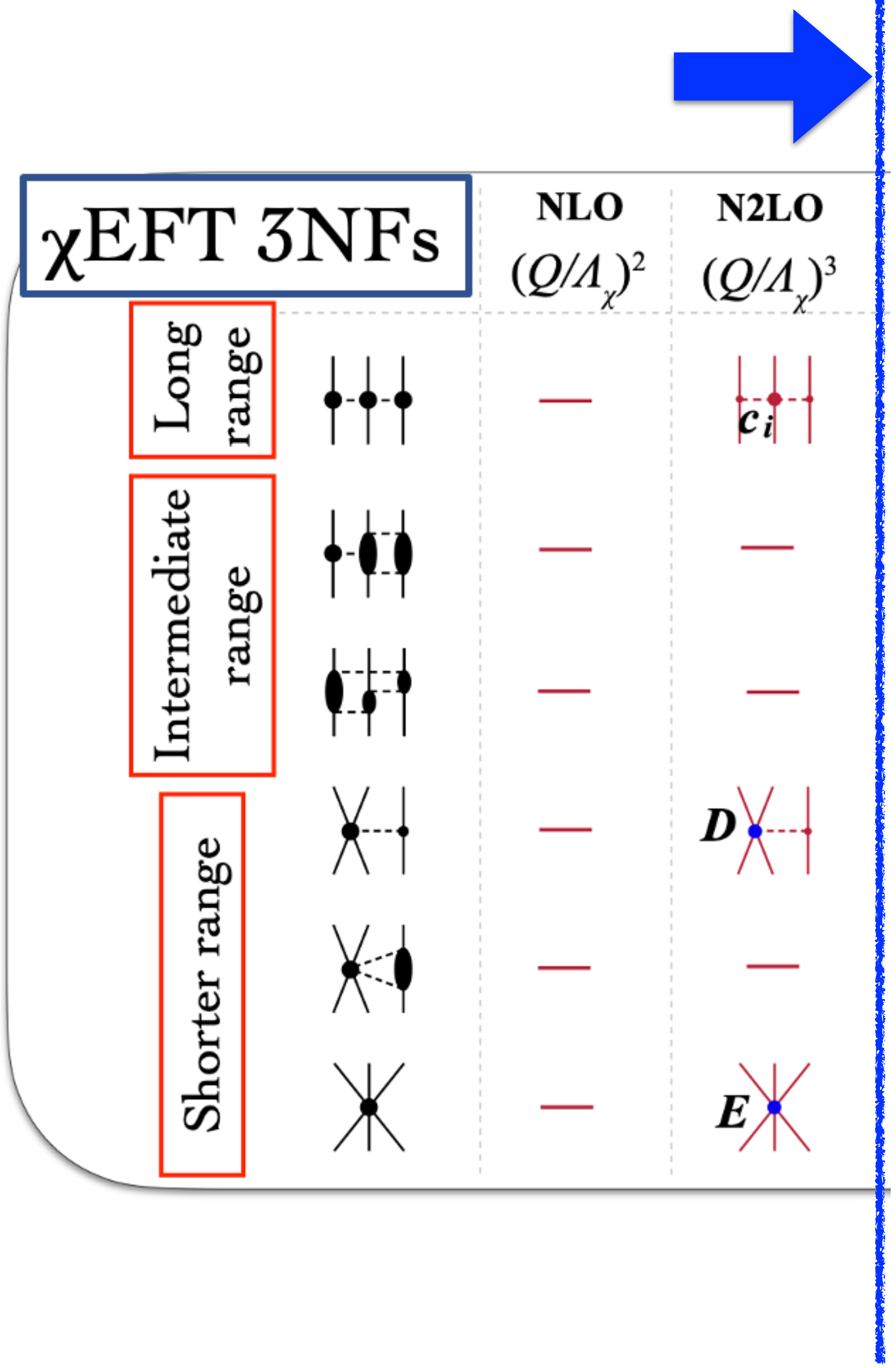
K. S. et al., Phys. Rev. C 96, 064001 (2017)

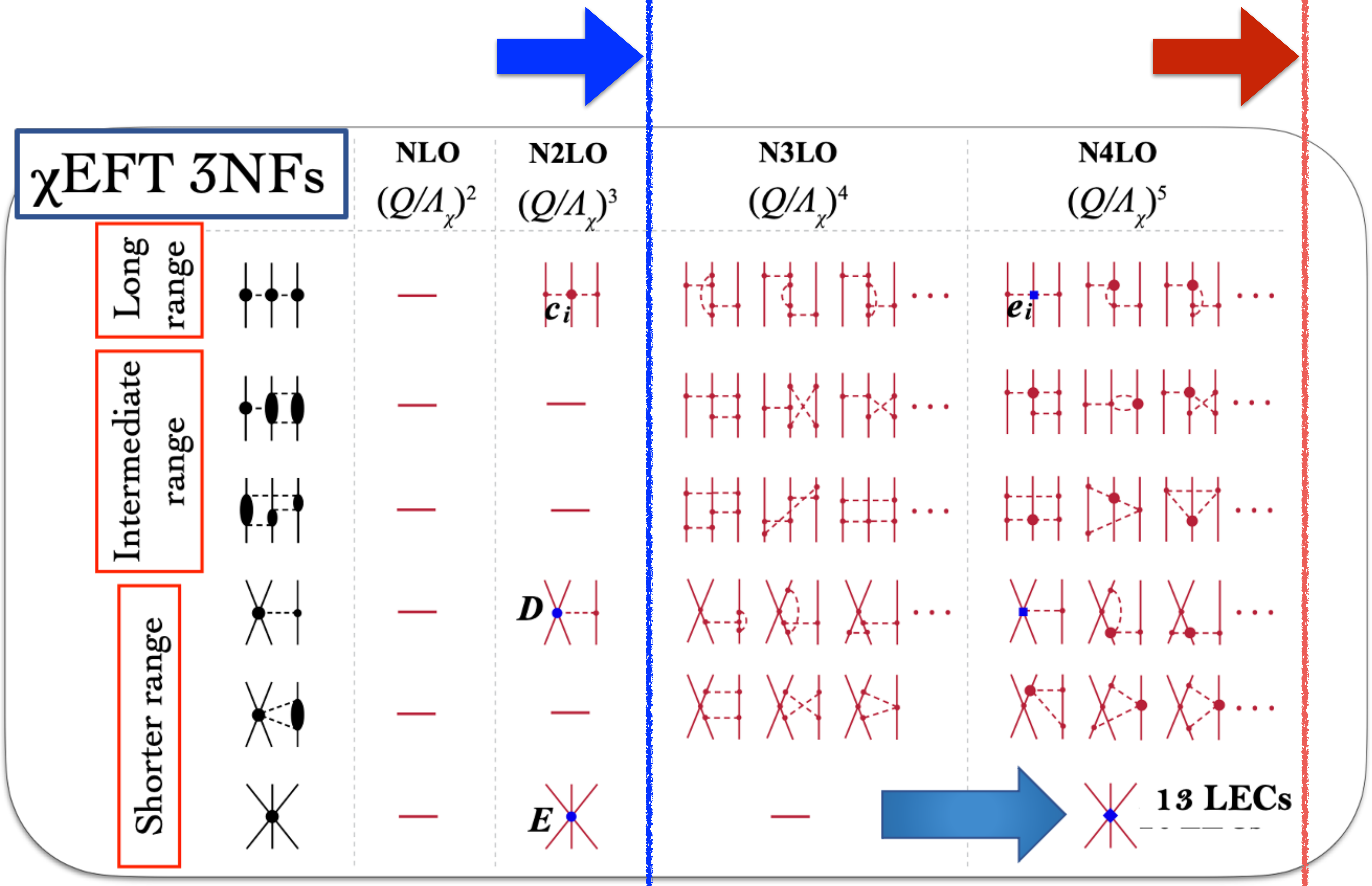


- *dp* elastic scattering data show necessities of the N4LO 3NFs.

Cross section minimum region for *dp* elastic scattering at ～100MeV/nucleon is "Golden window" for the N4LO 3NFs.

LENPIC collaboration,
Phys. Rev. C 98, 014002 (2018)


χEFT 3NFs
NLO
$(Q/\Lambda_\chi)^2$
N2LO
$(Q/\Lambda_\chi)^3$
Long range
Intermediate range
Shorter range
c_i
D
E

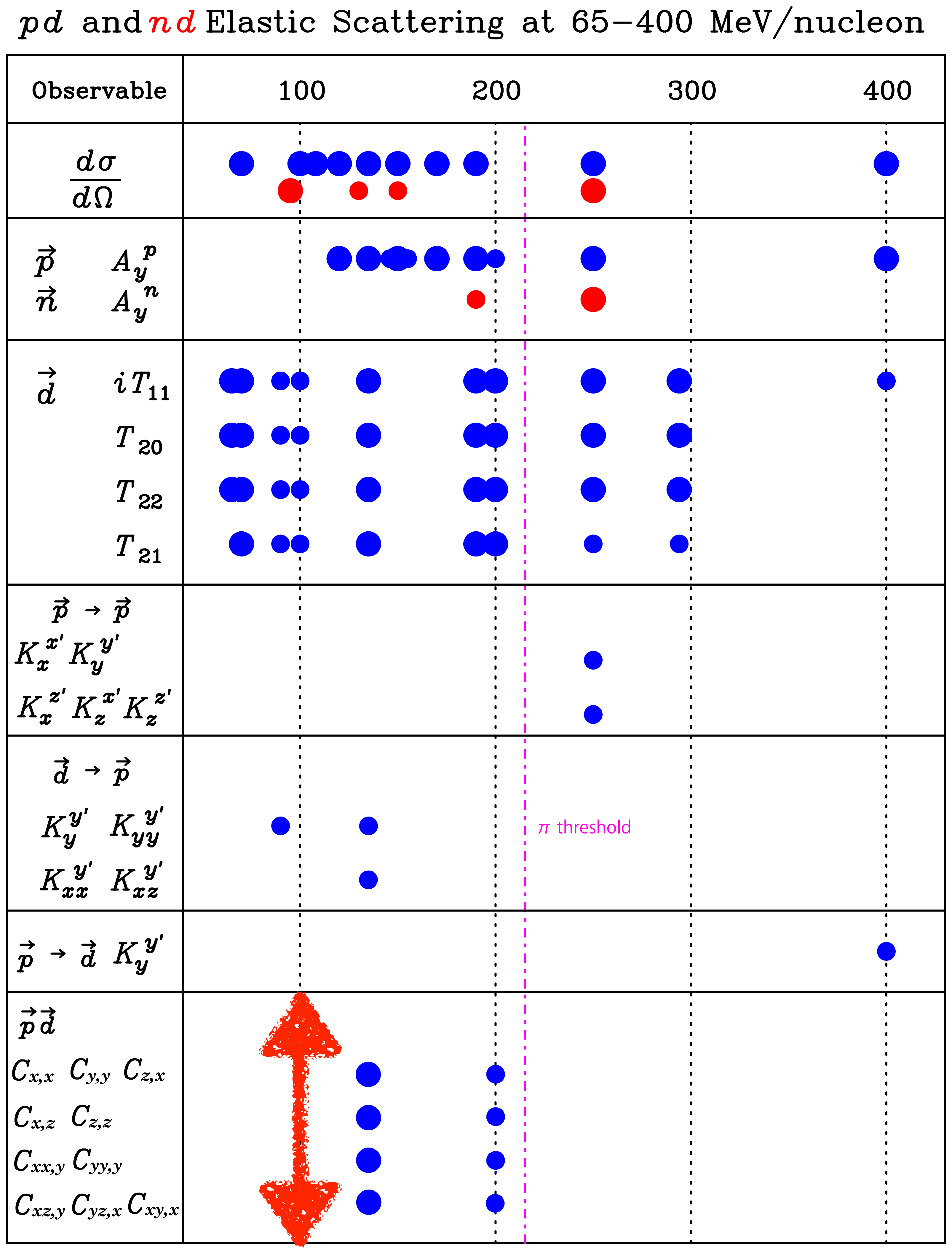


L. Girlanda, et al., Phys. Rev. C 84, 014001 (2011)

L. Girlanda, et al., Phys. Rev. C 102, 019903 (2020).

New Experiment at RIKEN

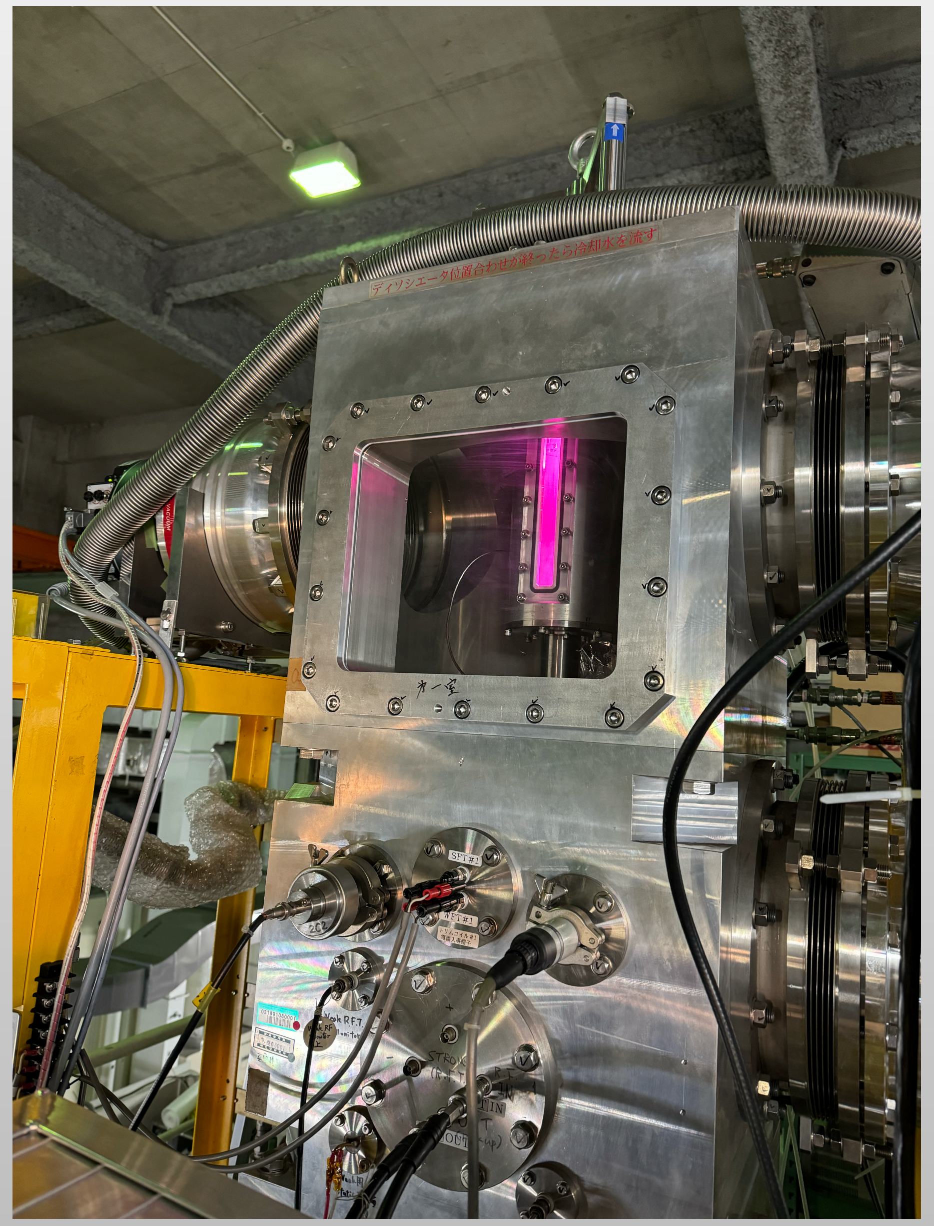
Measurement of Spin Correlation Coefficients for *dp* elastic scattering at ∼100 MeV/nucleon

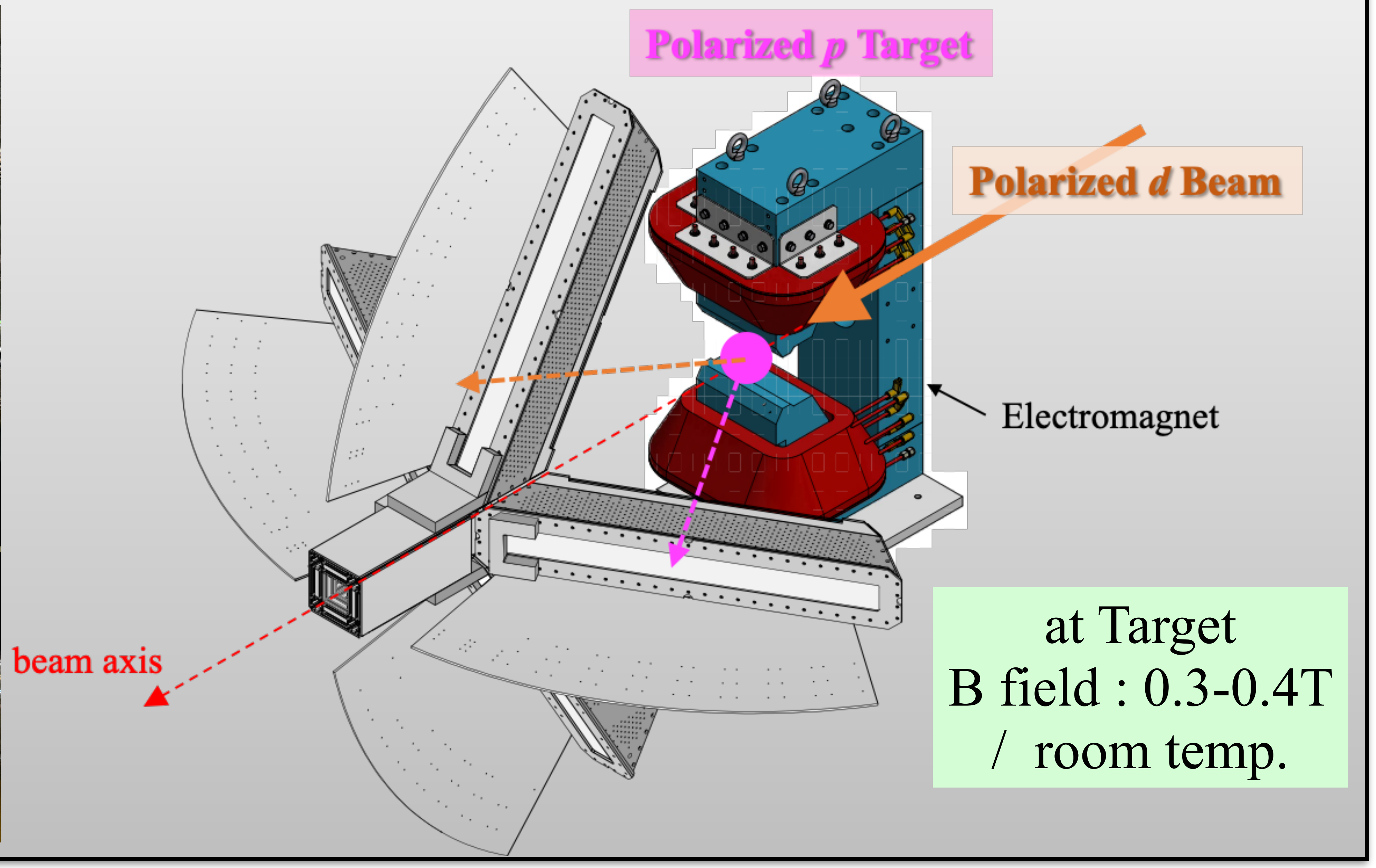


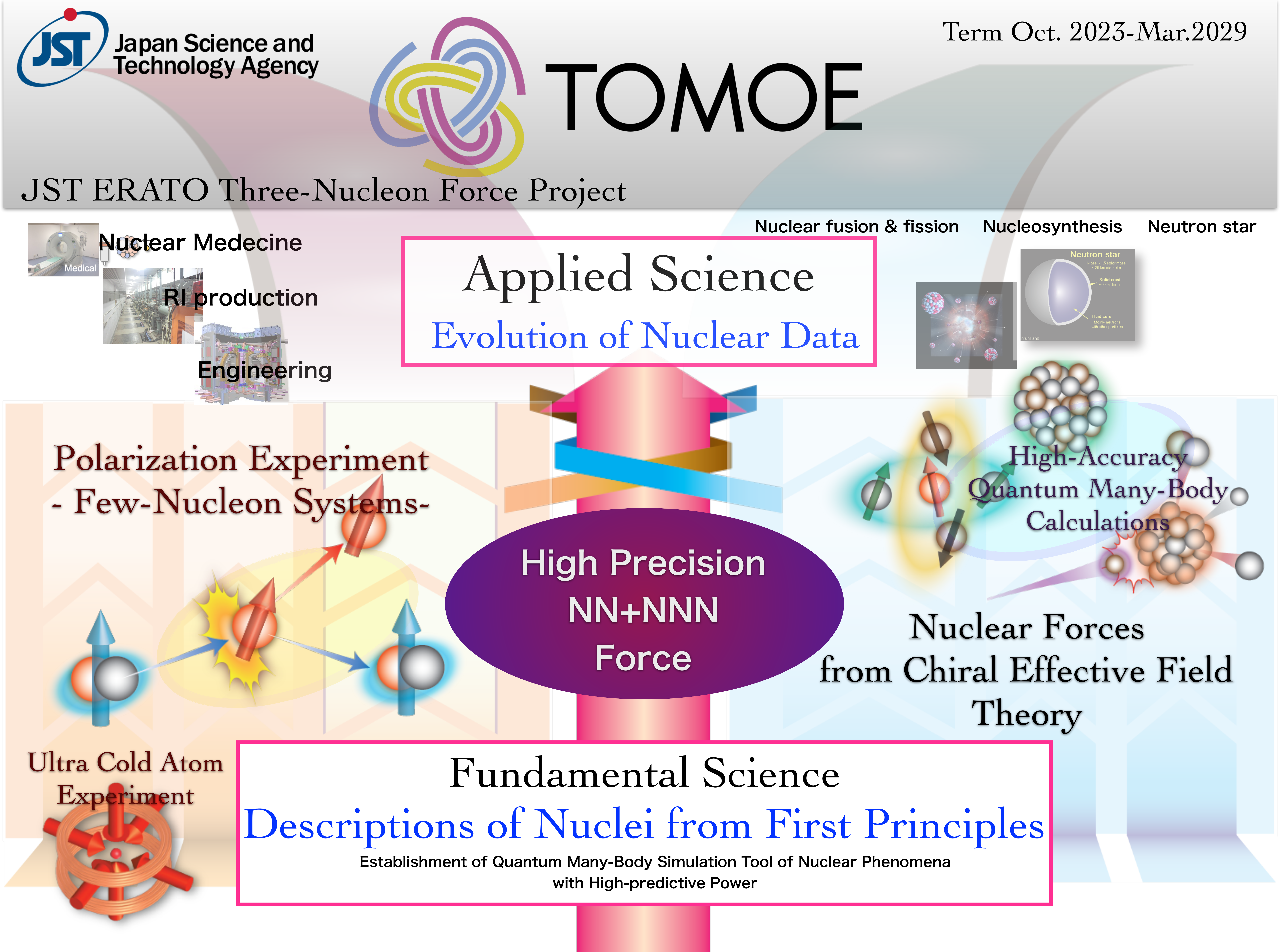
for investigation of N4LO 3NFs

- determination of LECs of N4LO 3NFs from *dp* scattering data

pol.d beam + new pol. p target + new detector system







Japan Science and Technology Agency
TOMOE
Term Oct. 2023-Mar.2029
JST ERATO Three-Nucleon Force Project
Nuclear Medecine
Medical
RI production
Engineering
Nuclear fusion & fission
Nucleosynthesis
Neutron star
Applied Science
Evolution of Nuclear Data
Polarization Experiment
- Few-Nucleon Systems-
High Precision
NN+NNN
Force
High-Accuracy
Quantum Many-Body
Calculations
Nuclear Forces
from Chiral Effective Field
Theory
Ultra Cold Atom
Experiment
Fundamental Science
Descriptions of Nuclei from First Principles
Establishment of Quantum Many-Body Simulation Tool of Nuclear Phenomena
with High-predictive Power

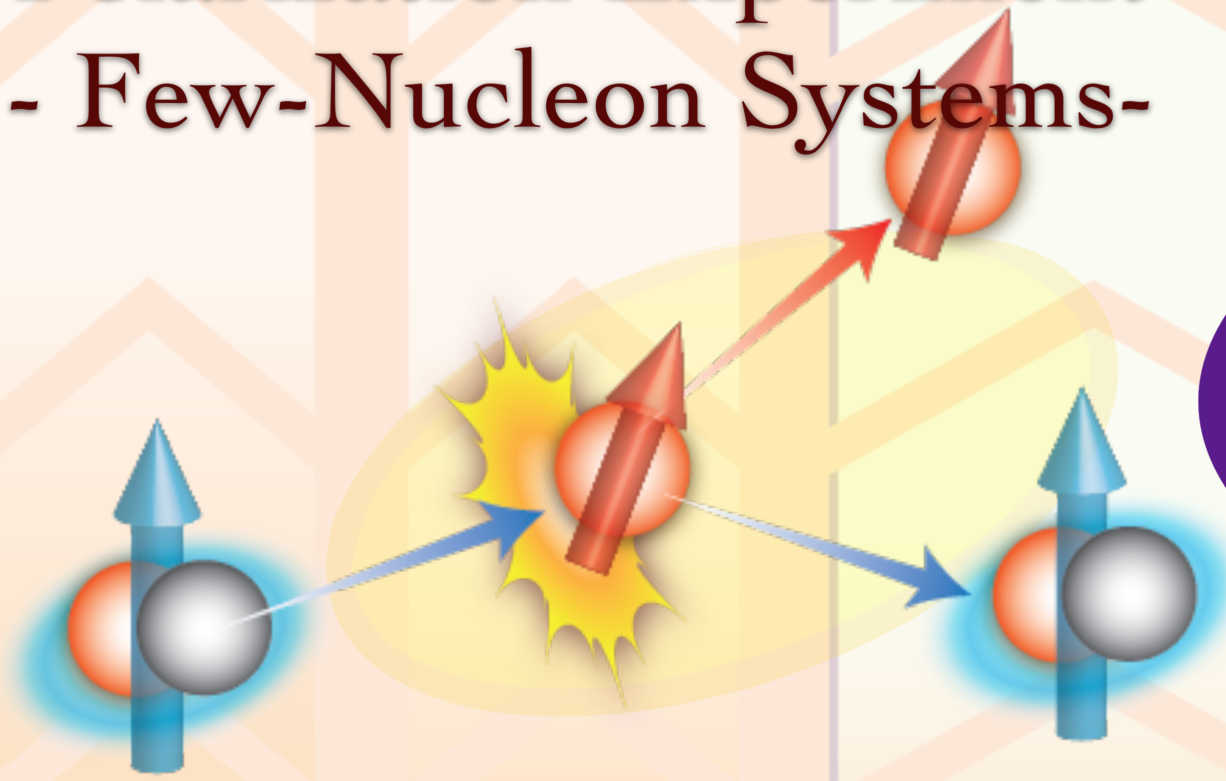
Japan Science and Technology Agency

TOMOE

Term Oct. 2023-Mar.2029

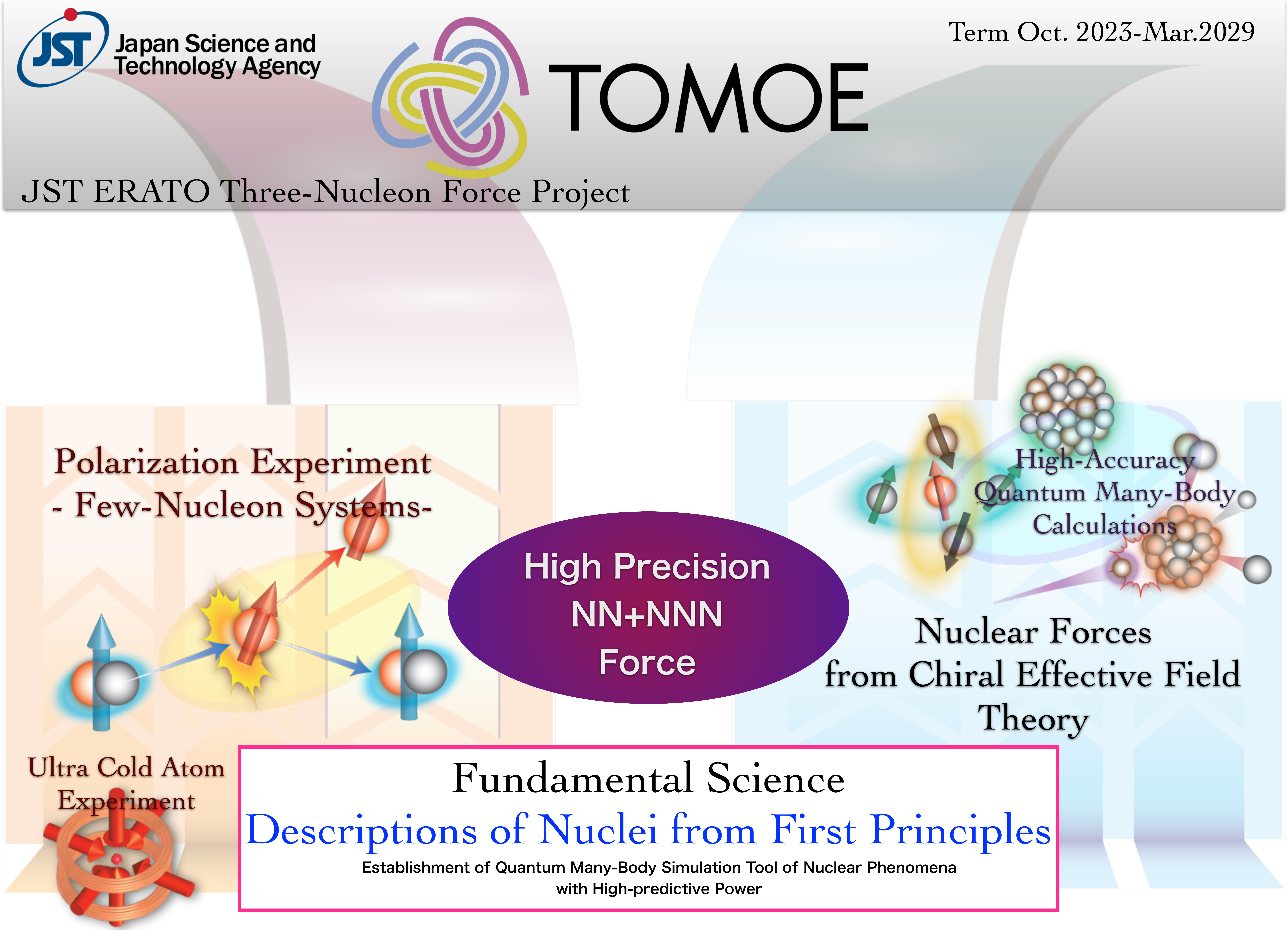
JST ERATO Three-Nucleon Force Project

Polarization Experiment
- Few-Nucleon Systems-



High Precision
NN+NNN
Force

Nuclear Forces
from Chiral Effective Field
Theory


Japan Science and Technology Agency
TOMOE
Term Oct. 2023-Mar.2029
JST ERATO Three-Nucleon Force Project
Polarization Experiment
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High Precision
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Experiment
Fundamental Science
Descriptions of Nuclei from First Principles
Establishment of Quantum Many-Body Simulation Tool of Nuclear Phenomena
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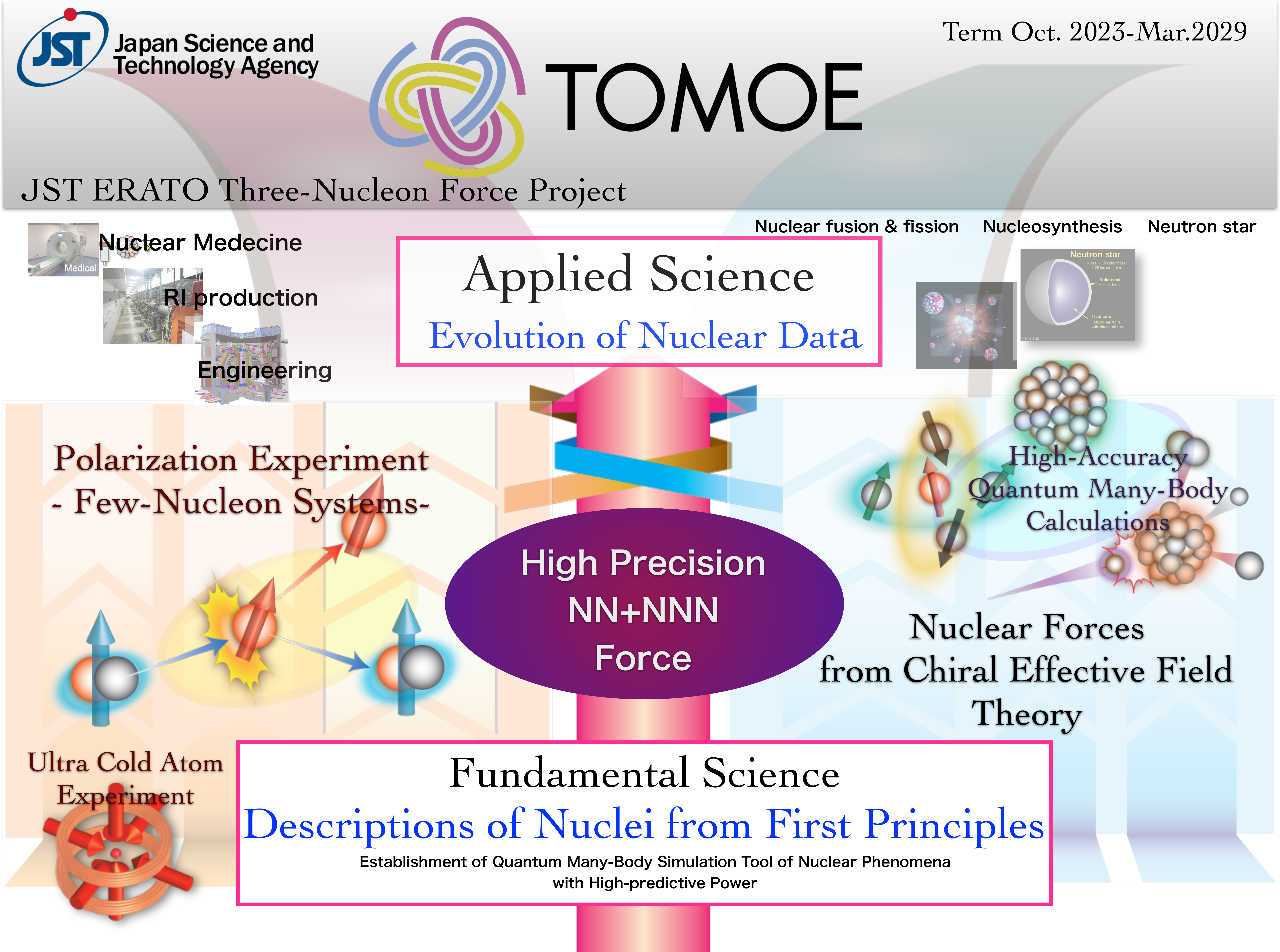
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Summary

To understand nuclear forces is a hot topic of nuclear physics.

Frontiers of nuclear force study
to understand nuclear forces from quarks
to understand nuclei/matter from NN & 3N-forces

3NFs are key elements to fully understand nuclear properties;
- a few, many- and infinite nucleon systems -

deuteron-proton scattering at ~100 MeV/nucleon inspires quantitative discussions of 3NFs.

in Progress

- High precision NN+3N-forces from theory and experiment
- Roles of 3NFs (3BFs) in A > 3

~Consistent Understanding From Quarks to the Universe~

To explore the laws of the nature, step in 1 → 2 → 3 .

道生一
一生二
二生三
三生萬物

道経　第四十二章

老子

Tao produced One,
One produced Two,
Two produced Three, and
Three produced Everything.

"Tao-te Ching", Lao Zi in B.C. 400

RIBF-*d.* Collaboration (2009〜)

Department of Physics, Tokyo Tech

A. Watanabe, K. Suzuki, H. Sugahara, D. Takahashi

Department of Physics, Tohoku University

Y. Saito, Y. Wada, A. Watanabe, D. Eto, T. Akieda, H. Kon,
J. Miyazaki, T. Taguchi, U. Gebauer, K. Takahashi, T. Mashiko, K. Miki,
Y. Maruta, T. Matsui, K. Kameya, R. Urayama

RIKEN Nishina Center

N. Sakamoto, H. Sakai, T. Uesaka, M. Sasano, Y. Shimizu, K. Tateishi

Kyushu University

T. Wakasa, S. Sakaguchi, H. Nishibata,
J. Yasuda, A. Ohkura, S. Shindo, U. Tabata, K. Aradono, K. Hirasawa

Miyazaki University

Y. Maeda, T. Saito, S. Kawakami, T. Yamamoto

CNS, University of Tokyo

K. Yako, M. Dozono, R. Tang,
S. Kawase, Y. Kubota, C.S. Lee

RCNP, Osaka University

H. Okamura

Kyungpook National University

S. Chebotaryov, E. Milman

RIKEN RIBF (2009)

ERATO TOMOE exp. @ RIKEN RIBF (2024)

Theoretical Supports from

Ruhr-Universität, Bochum
E. Epelbaum, H. Krebs, W. Glöckle

Jagellonian University
H. Witała, J. Golak, R. Skibinski

Kyushu Institute of Technology
H. Kamada

Forshungszentrum of Jülich
A. Nogga

Vilnius University
A. Deltuva

Hannover University
P. U. Sauer, S. Nemoto

Lisbon University
A. Sa. Fonseca

Bad Honnef (2006)

Hosei University
S. Ishikawa