Ab initio study of natural and unnatural parity states of ^{6}Li

NTSE-2014 @ PNU (Khabarovsk) 2014 Jun. 23-27

Rare Isotope Science Project / Institute for Basic Science
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In collaboration with :

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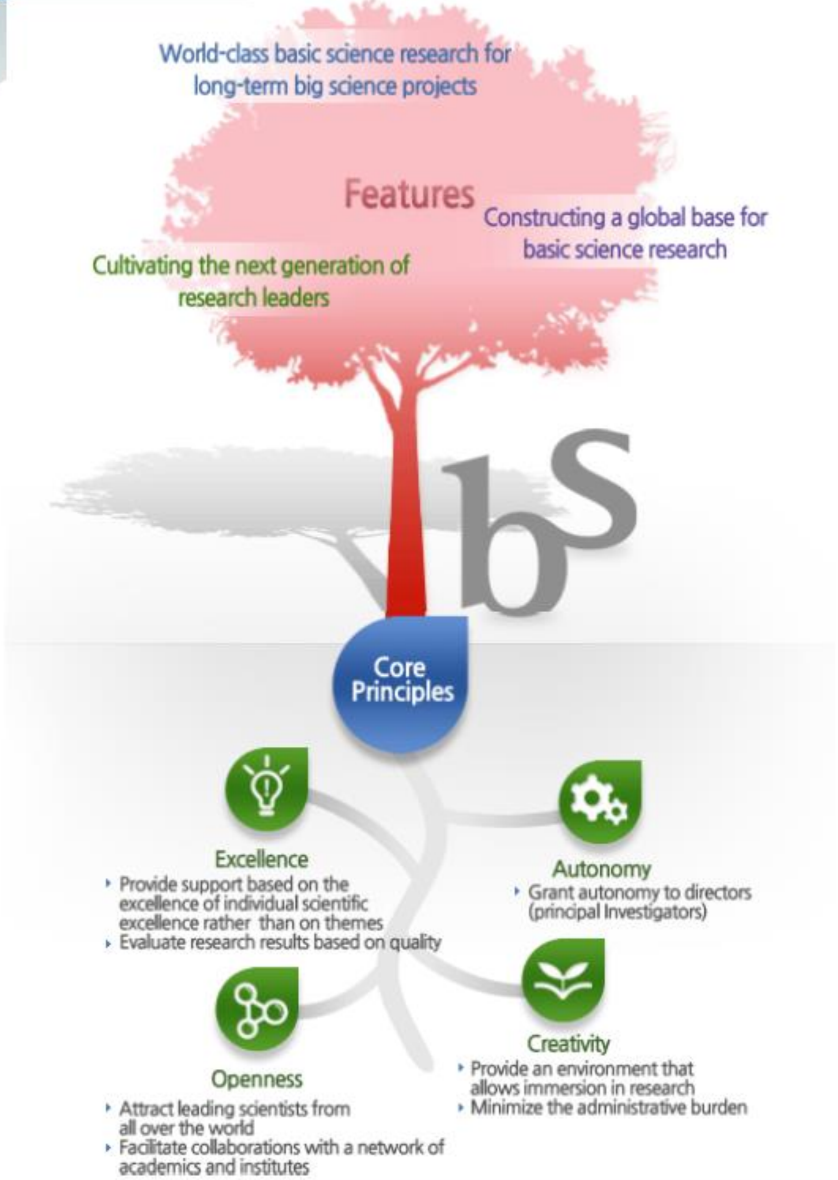
- James Vary, Pieter Maris (Iowa State Univ.)
- Christian Forssen, Jimmy Rotureau (Chalmers Univ. of Technology)

Institute for Basic Science



World-class basic science research for long-term big science projects

Features

Constructing a global base for basic science research

Cultivating the next generation of research leaders

Core Principles

Excellence

- Provide support based on the excellence of individual scientific excellence rather than on themes
- Evaluate research results based on quality

Autonomy

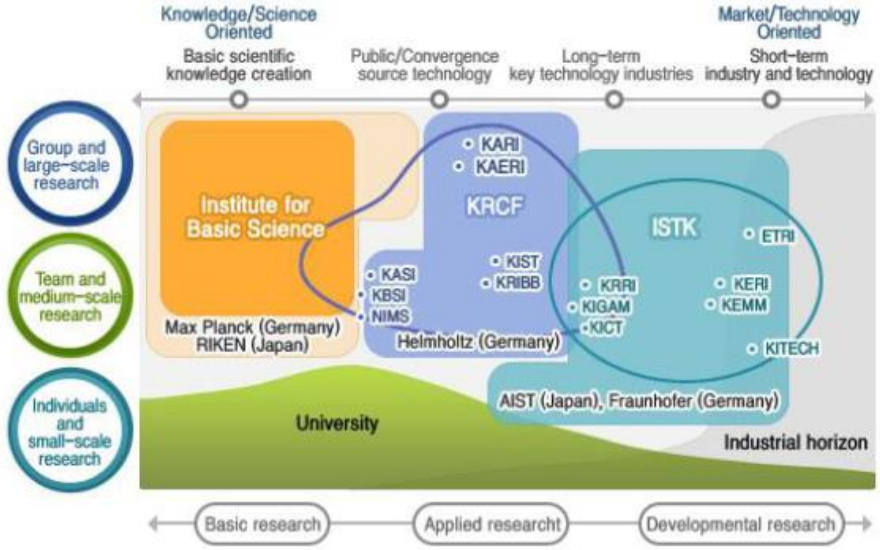
- Grant autonomy to directors (principal Investigators)

Openness

- Attract leading scientists from all over the world
- Facilitate collaborations with a network of academics and institutes

Creativity

- Provide an environment that allows immersion in research
- Minimize the administrative burden

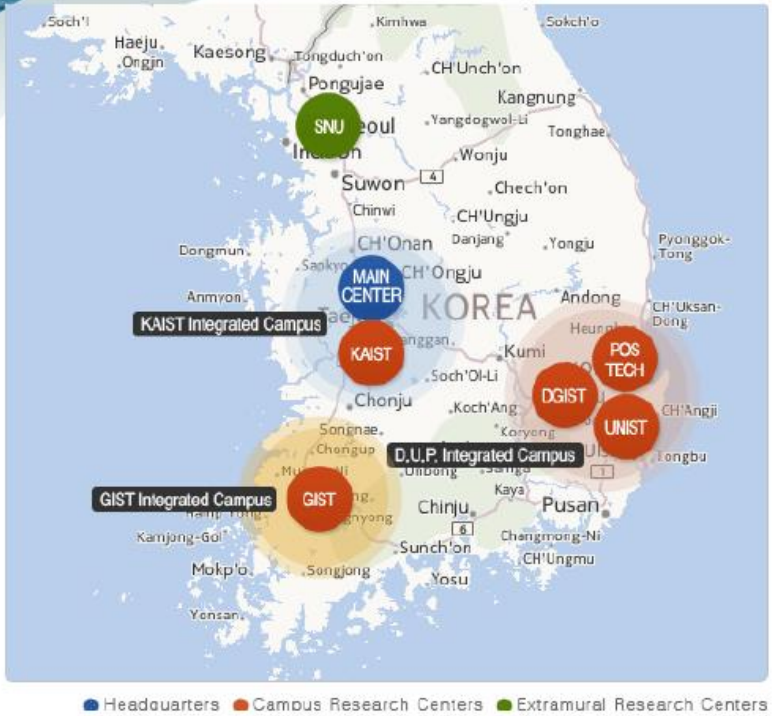


50 Research centers(by 2017) in

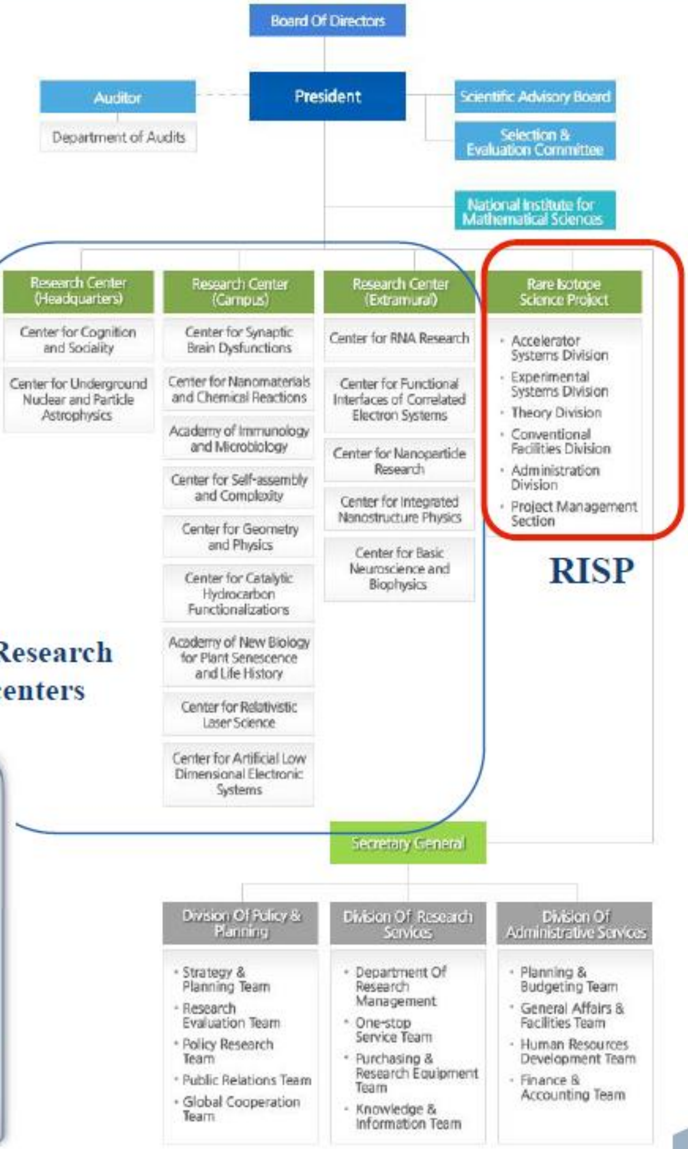
Mathematics
Physics
Chemistry
Life Sciences

- ❖ **PI of the center can be a foreigner**
- ❖ **2-3 centers for research at RAON**

Institute for Basic Science



- 1 Research Center : ~50 staff, average annual budget ~ 9 M USD
- The number of staff: 3,000 (2017, including visiting scientists and students)
- Annual Budget: USD 610 million (2017, including operational cost for the Accelerator Institute)


Board Of Directors

Auditor

Department of Audits

President

Scientific Advisory Board

Selection & Evaluation Committee

National Institute for Mathematical Sciences

Research centers

Research Center (Headquarters)
- Center for Cognition and Sociality
- Center for Underground Nuclear and Particle Astrophysics

Research Center (Campus)
- Center for Synaptic Brain Dysfunctions
- Center for Nanomaterials and Chemical Reactions
- Academy of Immunology and Microbiology
- Center for Self-assembly and Complexity
- Center for Geometry and Physics
- Center for Catalytic Hydrocarbon Functionalizations
- Academy of New Biology for Plant Senescence and Life History
- Center for Relativistic Laser Science
- Center for Artificial Low Dimensional Electronic Systems

Research Center (Extramural)
- Center for RNA Research
- Center for Functional Interfaces of Correlated Electron Systems
- Center for Nanoparticle Research
- Center for Integrated Nanostructure Physics
- Center for Basic Neuroscience and Biophysics

Rare Isotope Science Project
- Accelerator Systems Division
- Experimental Systems Division
- Theory Division
- Conventional Facilities Division
- Administration Division
- Project Management Section

RISP

Secretary General

Division Of Policy & Planning
- Strategy & Planning Team
- Research Evaluation Team
- Policy Research Team
- Public Relations Team
- Global Cooperation Team

Division Of Research Services
- Department Of Research Management
- One-stop Service Team
- Purchasing & Research Equipment Team
- Knowledge & Information Team

Division Of Administrative Services
- Planning & Budgeting Team
- General Affairs & Facilities Team
- Human Resources Development Team
- Finance & Accounting Team

Rare Isotope Science Project

- Goal : To build a world class heavy ion accelerator RAON, for rare isotope science research in Korea
- Project period : 2011.12-2020.02
- Budget : 460BWon (1BWon~1M$)
  - include initial experimental apparatus
  - does not include civil engineering, conventional facilities

High intensity rare isotope beam with ISOL and IF methods

- **70MeV, 1mA proton beam, ^{238}U target - 70kW ISOL system**
- **200MeV/u, 8.3pμA, ^{238}U beam and other SI beam - 400kW IF system**
  - **600 MeV for proton**

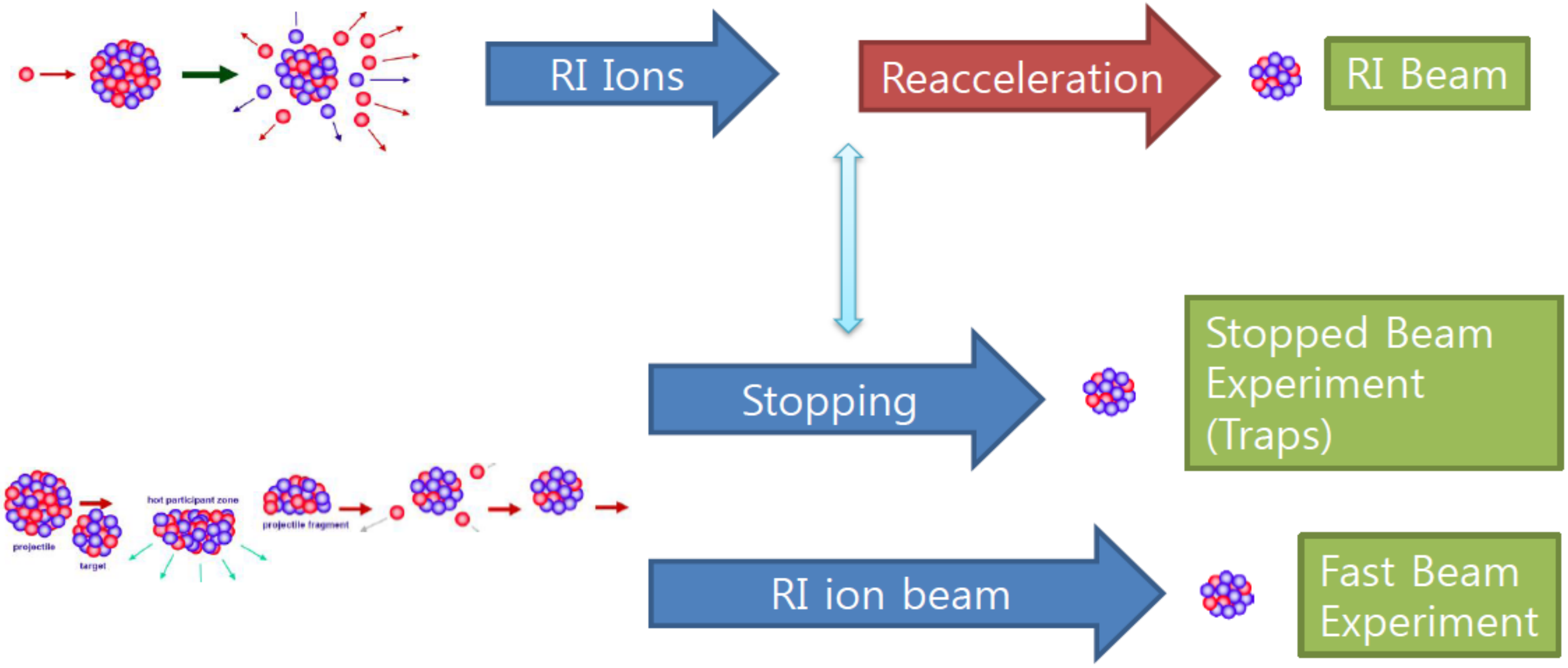
- High current high purity neutron-rich RI beam

  For example, ^{132}Sn : ~250MeV/u, ~ 10^8 pps
- Production of exotic beams combining ISOL and IF methods
- Simultaneous operation of IF and ISOL systems

* ISOL-type facilities: radioactive ions are produced at rest in a thick target either by direct bombardment with particles from a driver accelerator or via fission induced both by fast and thermal secondary neutrons.

* In-flight (IF) facilities: a high energy ion beam is fragmented in a suitable thin target and the reaction products are and then transported to the secondary target.

ISOL(Isotope Separator On-Line)
p → thick target (eg. Uranium Carbide) → target spallation or fission (low energy)



RI Ions

Reacceleration

RI Beam

Stopping

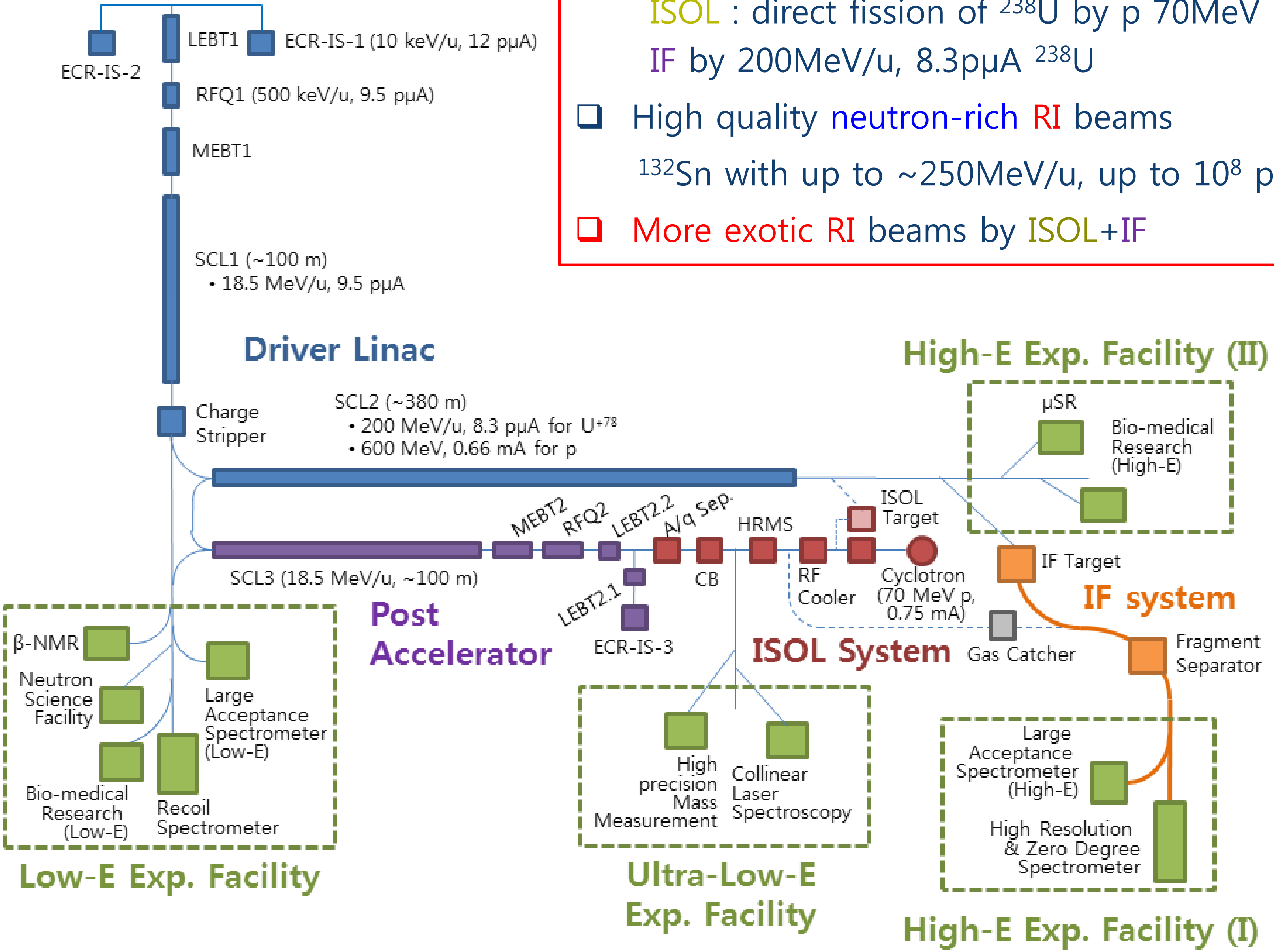
Stopped Beam Experiment (Traps)

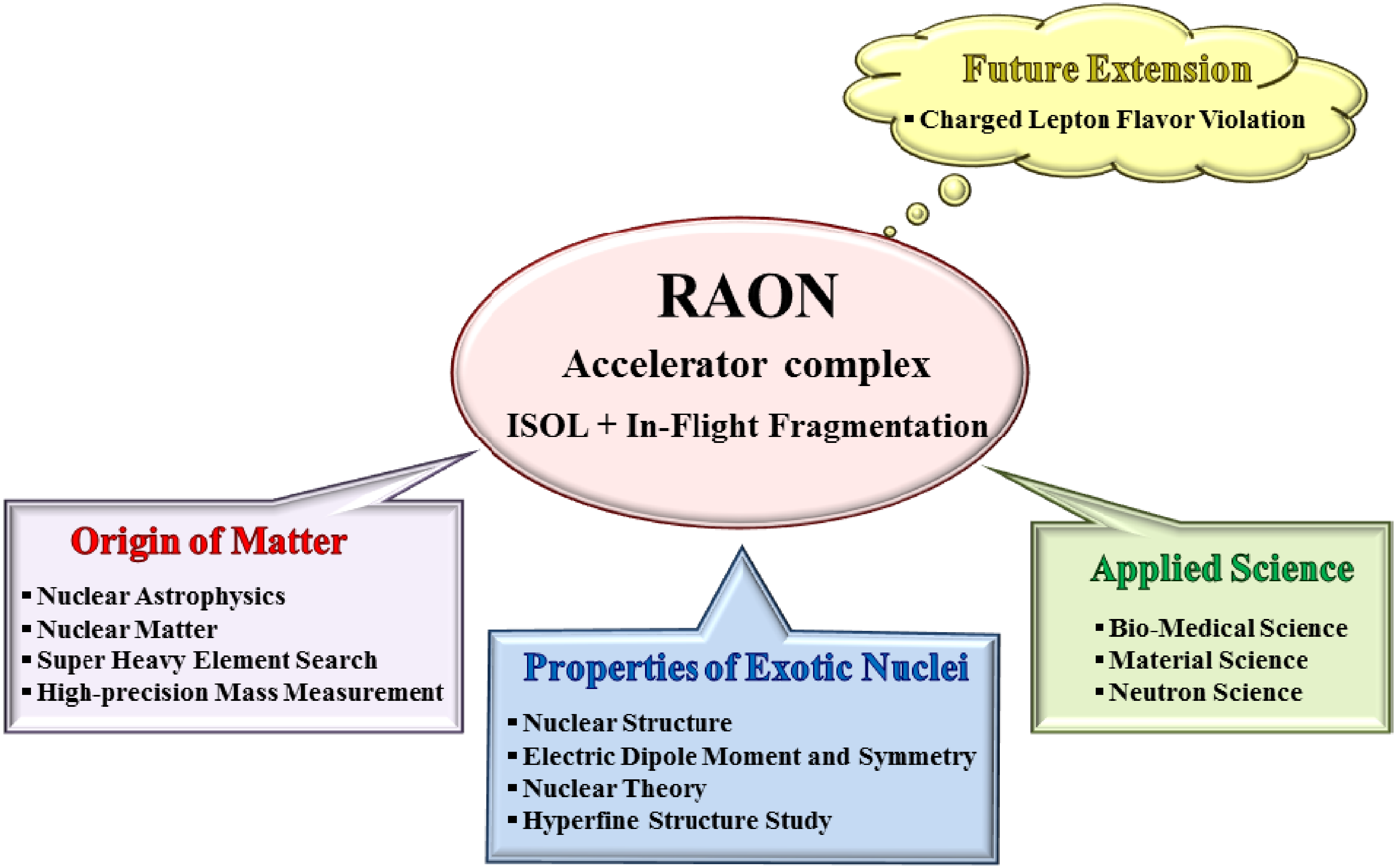
RI ion beam

Fast Beam Experiment

IF(In-Flight Fragmentation)
Stable Heavy ion beam → thin target → projectile fragmentation (high energy)

- ❑ High intensity RI beams by ISOL & IF
  - ISOL : direct fission of ^{238}U by p 70MeV
  - IF by 200MeV/u, 8.3pμA ^{238}U
- ❑ High quality neutron-rich RI beams
  - ^{132}Sn with up to ~250MeV/u, up to 10^{8} pps
- ❑ More exotic RI beams by ISOL+IF




Future Extension
▪ Charged Lepton Flavor Violation
RAON
Accelerator complex
ISOL + In-Flight Fragmentation
Origin of Matter
▪ Nuclear Astrophysics
▪ Nuclear Matter
▪ Super Heavy Element Search
▪ High-precision Mass Measurement
Properties of Exotic Nuclei
▪ Nuclear Structure
▪ Electric Dipole Moment and Symmetry
▪ Nuclear Theory
▪ Hyperfine Structure Study
Applied Science
▪ Bio-Medical Science
▪ Material Science
▪ Neutron Science

- **Highest priority research subjects**
  - Nuclear reaction experiments important to synthesize elements in Universe
  - Search for super heavy elements : $Z > 119$ ($Z \sim 120$)
  - Abnormal nuclear structure of exotic rare isotopes
  - Nuclear symmetry energy at sub-saturation density
  - Precision mass measurement & Laser spectroscopy

- **Important scientific applications**
  - Material science : β-NMR, μSR
  - Medical and bio-science : RI beam irradiation
  - Nuclear data for Gen-IV NPP and nuclear waste transmutation

Science program with beam schedule

Beam schedule	Science program	Exp. facility$^\#$	Beam species on exp. target†		Beam Intensity on exp. (pps) (required/expected)
			Day-1	Extra 2 years	
2018.Q2 ~ from SCL1 (<18.5 MeV/u)	Nuclear structure SHE search, rp-process, Spin physics	RS	^{54}Cr	^{64}Ni ^{26m}Al (^{28}Si), ^{25}Al (^{28}Si), ^{44}Ti (^{42}Ca), ^{14,15}O (^{15}N)	^{15}N, ^{54}Cr ^{28}Si, ^{42}Ca, ^{50}Ti ^{25}Al, ^{26m}Al, ^{44}Ti, ^{14,15}O: ($10^{5\text{-}6}$)
	Pigmy dipole resonance	LAS-L	^{58}Ni	^{40}Ca, ^{112}Sn	($10^{6\text{-}8}$ / <$10^{9\text{-}10}$)
	Biological effects	BM	^{12}C		(<10^{12} / >10^{12})
	New materials, Polarized beam	β-NMR	^{8}Li by (d, n)(n,α) or (p,2p)		^{8}Li (10^{8} / 10^{9})
	Neutron cross section	NSF	n by (p,n) and (d,n)		n (< 10^{12} / 10^{12})
2019.Q4 ~ from ISOL (~5 keV/u)	Hyperfine structure, Mass measurement	Ion Trap LS	^{132}Sn	$^{130\text{-}135}$Sn	^{132}Sn (<10^{5} / 10^{7}) ‡, $^{130\text{-}135}$Sn ($10^{3\text{-}6}$ / $10^{3\text{-}7}$)
2019.Q4 ~ ISOL-SCL3 (<18.5 MeV/u)	r-process	RS	^{132}Sn	$^{130\text{-}135}$Sn	^{132}Sn (10^{6} / 10^{7}), ^{65,66}Ni ($10^{6\text{-}8}$ / $10^{6\text{-}7}$)
	Pigmy dipole resonance	LAS-L	^{132}Sn	$^{50+n}$Ca, $^{60+n}$Ni, $^{106+n}$Sn	
2019.Q4 ~ SCL1-SCL2 (~ hundreds MeV/u)	New materials	μSR	μ^+ by (p, πx)		μ^+ (10^{8} / 10^{9})
	Biological effects	BM	^{12}C		(<10^{12} / >10^{12})
	Baseline experiments, Spin physics	LAS-H	^{40}Ca	^{58}Ni, ^{112}Sn, ^{132}Xe	($10^{6\text{-}8}$ / <$10^{9\text{-}11}$)
2020.Q2 ~ SCL1-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	$^{100+n}$Sn	$^{100+n}$Sn	^{128}Sn ($10^{6\text{-}8}$ / 10^{7}) ^{132}Sn ($10^{6\text{-}8}$/10^{7})‡
	Symmetry energy	LAS-H	^{132}Sn	$^{44+n}$Ca, $^{60+n}$Ni, $^{106+n}$Sn, ^{144}Xe	
2020.Q4 ~ ISOL-SCL3-SCL2-IF(X) (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS	^{132}Sn		^{132}Sn ($10^{6\text{-}8}$ / 10^{7})‡ ^{144}Xe ($10^{6\text{-}8}$ / 10^{6})
	Symmetry energy	LAS-H	$^{106+n}$Sn	$^{133+n}$Xe	
2021.Q2 ~ ISOL-SCL3-SCL2-IF (~ hundreds MeV/u)	Nuclear structure	ZDS & HRS			^{78}Ni (/ <2)

♯ **RS**: Recoil Spectrometer, **LAS**: Large Acceptance Spectrometer, **BM**: Bio & Medical, **LS**: Laser Spectrometer, **NSF**: Neutron Science Facility, **ZDS**: Zero Degree Spectrometer, **HRS**: High Resolution Spectrometer † Beam species **: SI (black), RI (Blue)** ‡ Beam purity >90 % for ISOL, 9% for IF

Ab initio study of natural (and unnatural parity) states of ^{6}Li

Interactions

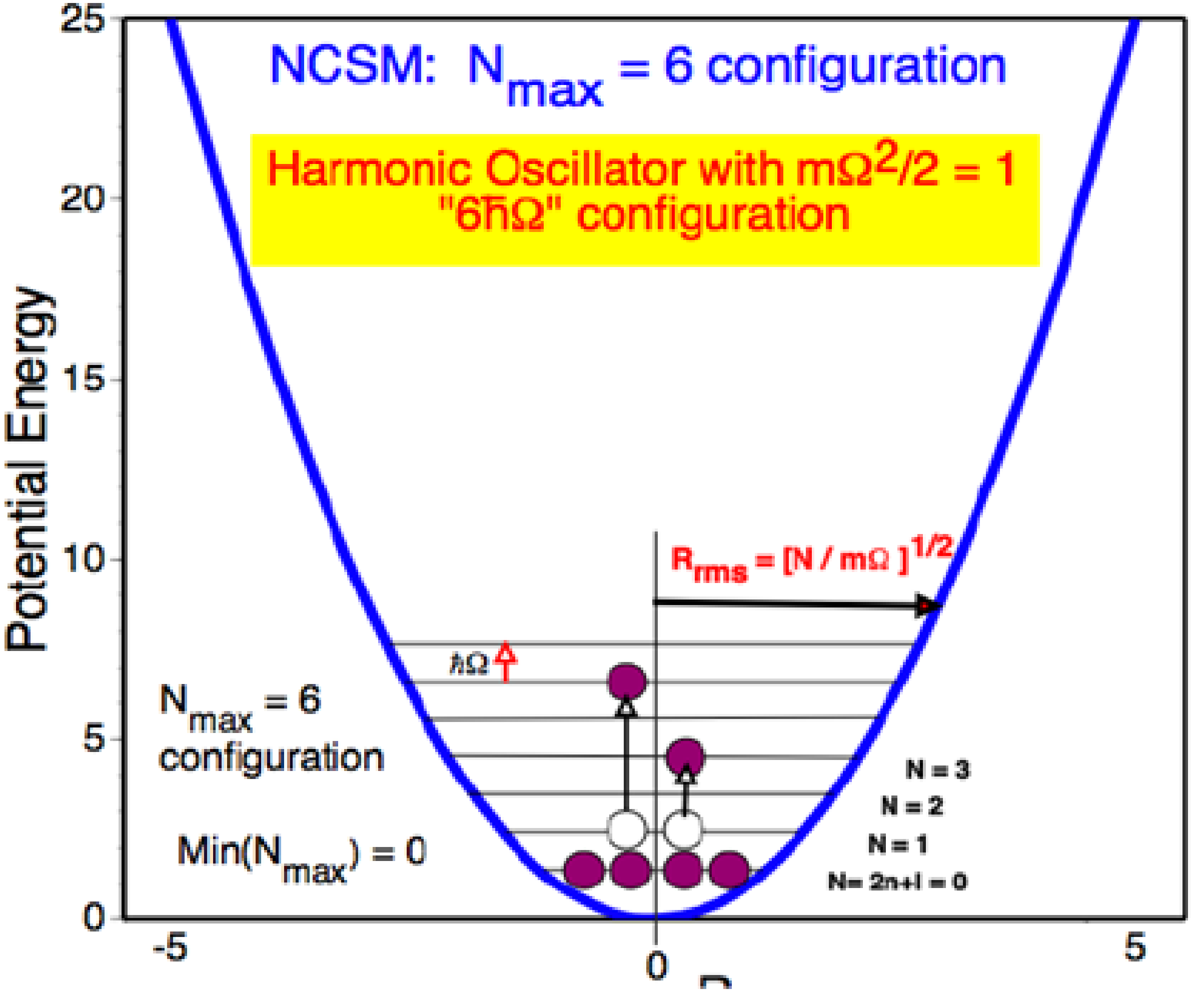
JISP16 [A. M. Shirokov, et al., Phys. Lett. **B644**, 33 (2007)]

- J-matrix inverse scattering potential
- *np* scattering data (phase shifts)
- PETs are used to fit properties of some light nuclei

$\mathrm{NNLO}_{\mathrm{opt}}$ [A. Ekström, et al., Phys. Rev. Lett., **110** (2013), 192502]

- Optimized NN interaction at NNLO using POUNDerS
- 3 pion-nucleon couplings and 11 partial wave contact parameters

No core shell model



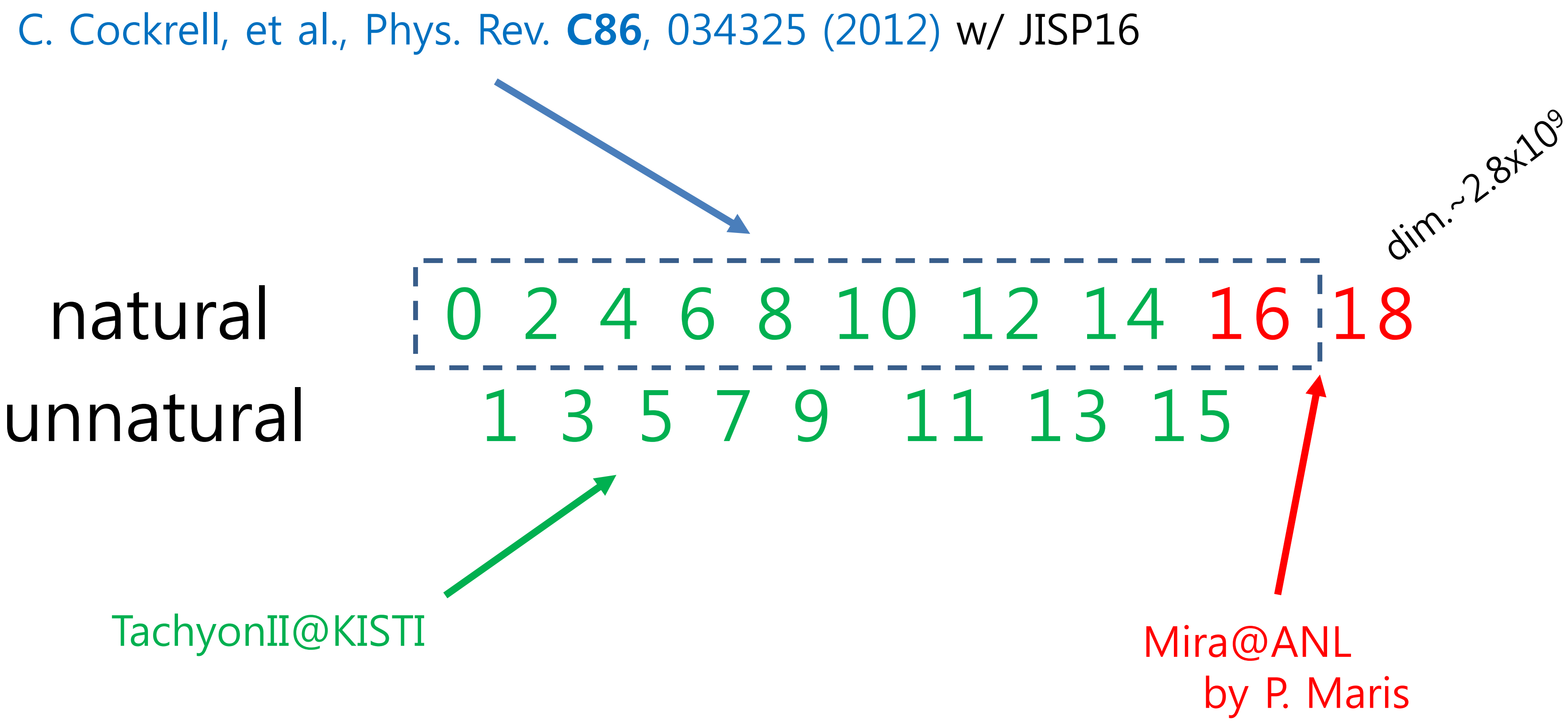
from the talk by J. Vary @ RISP, Mar. 2013

N_{max}

$h\Omega$

MFDn (Many Fermion Dynamics for nuclear structure)

$N_{\max}$: many body truncation parameter



C. Cockrell, et al., Phys. Rev. **C86**, 034325 (2012) w/ JISP16

dim.~2.8x10^9

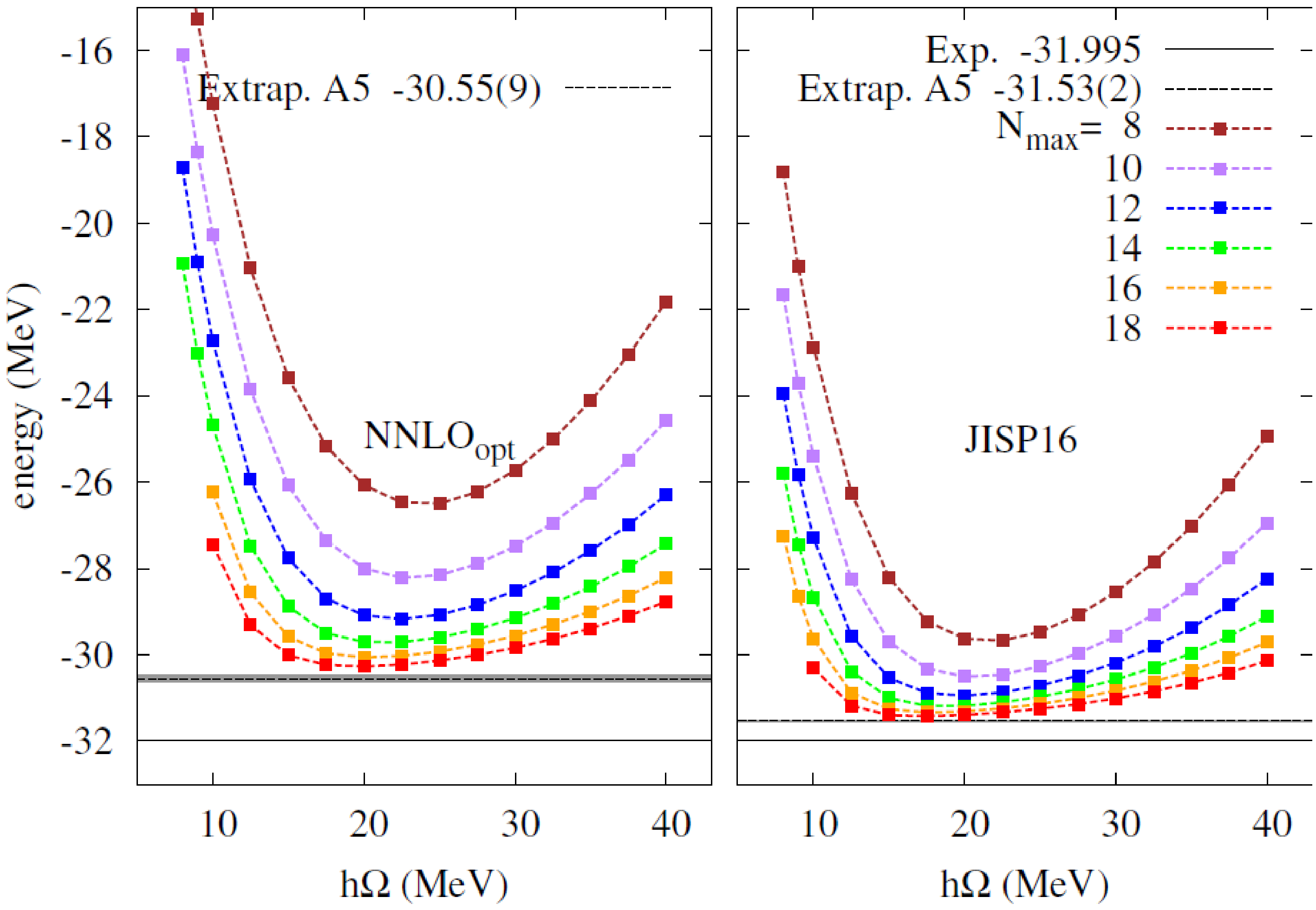
natural 0 2 4 6 8 10 12 14 16 18

unnatural 1 3 5 7 9 11 13 15

TachyonII@KISTI

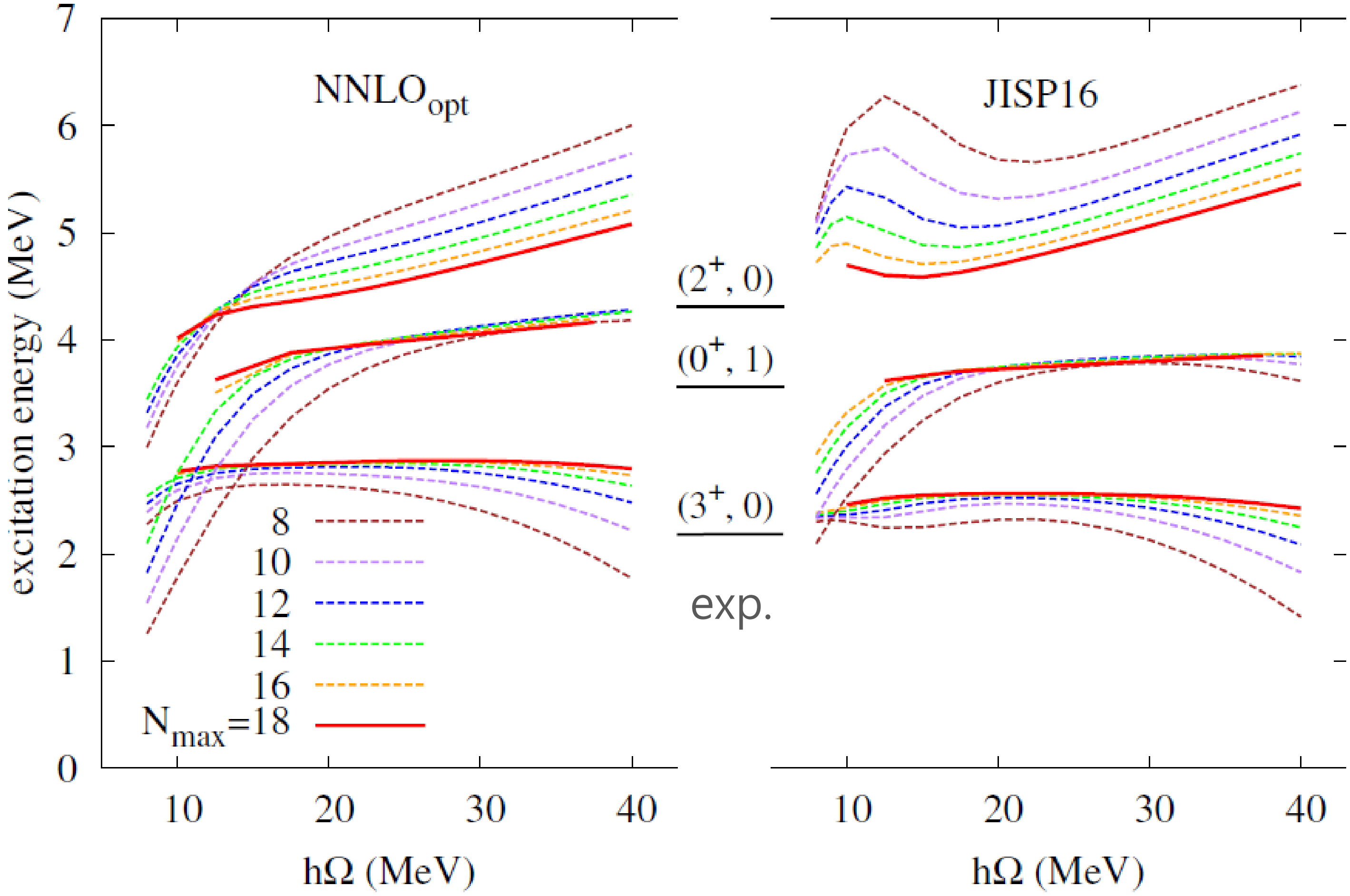
Mira@ANL
by P. Maris

Ground state energy



❖ more underbound and slower convergence compared to JISP16

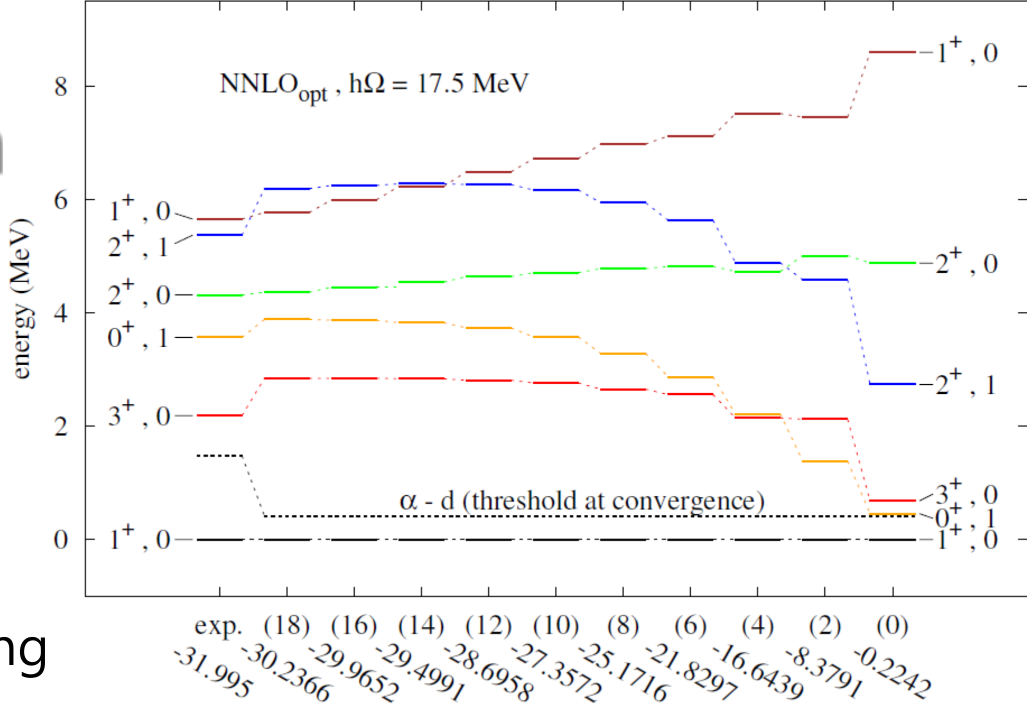
Excitation spectrum

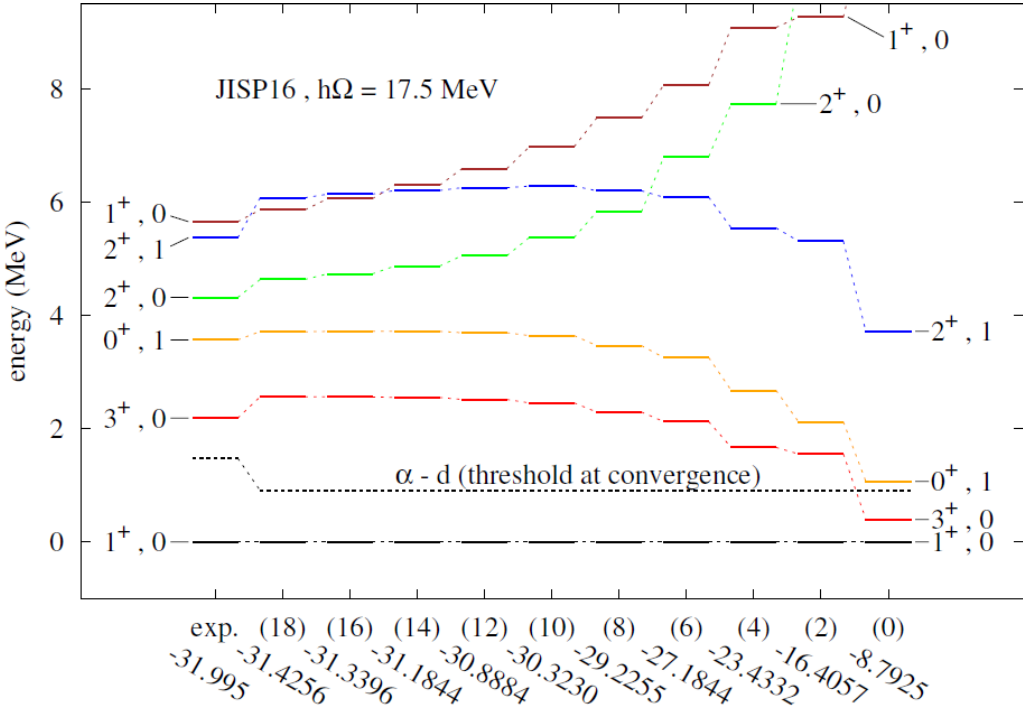


❖ two narrow resonance states converge well for both interactions

Excitation spectrum (natural parity)

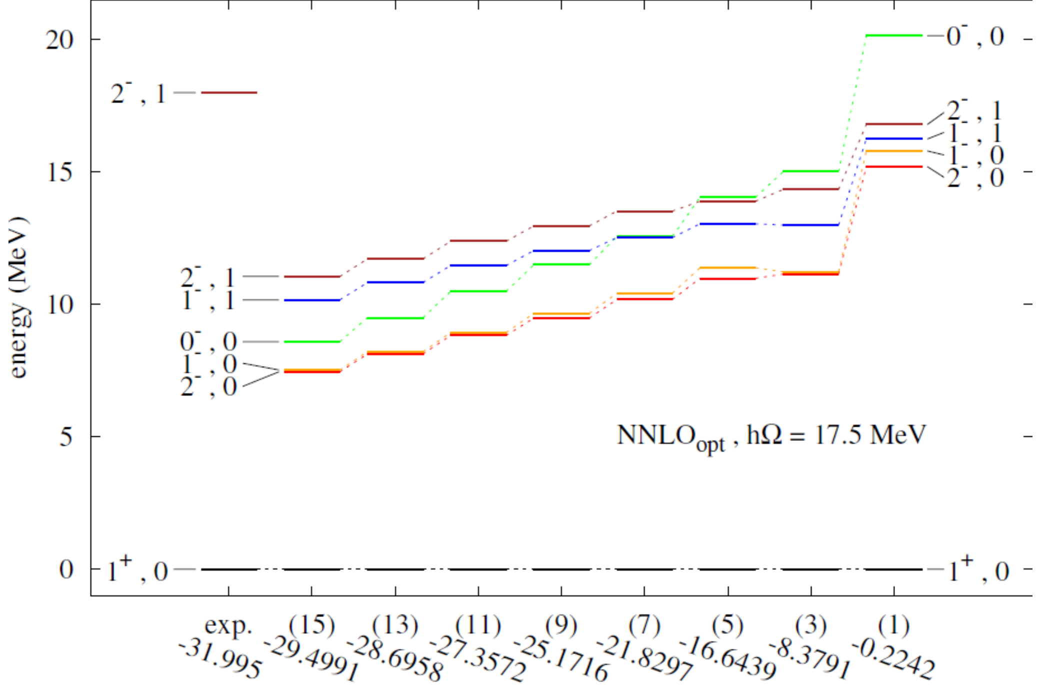
❖ good convergence of low-lying excited states

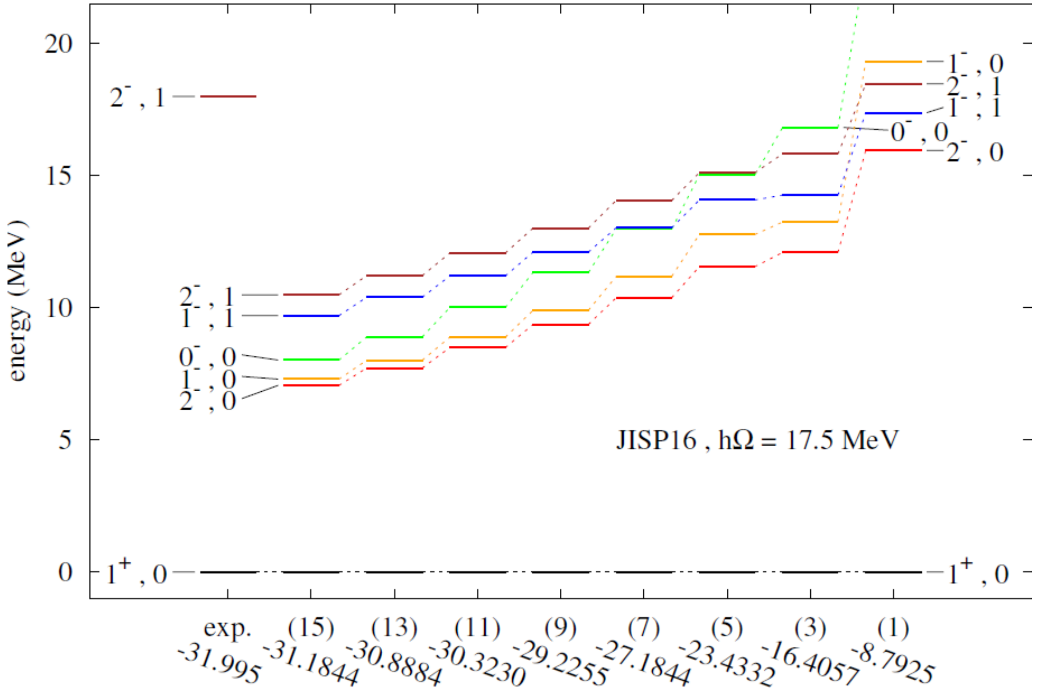




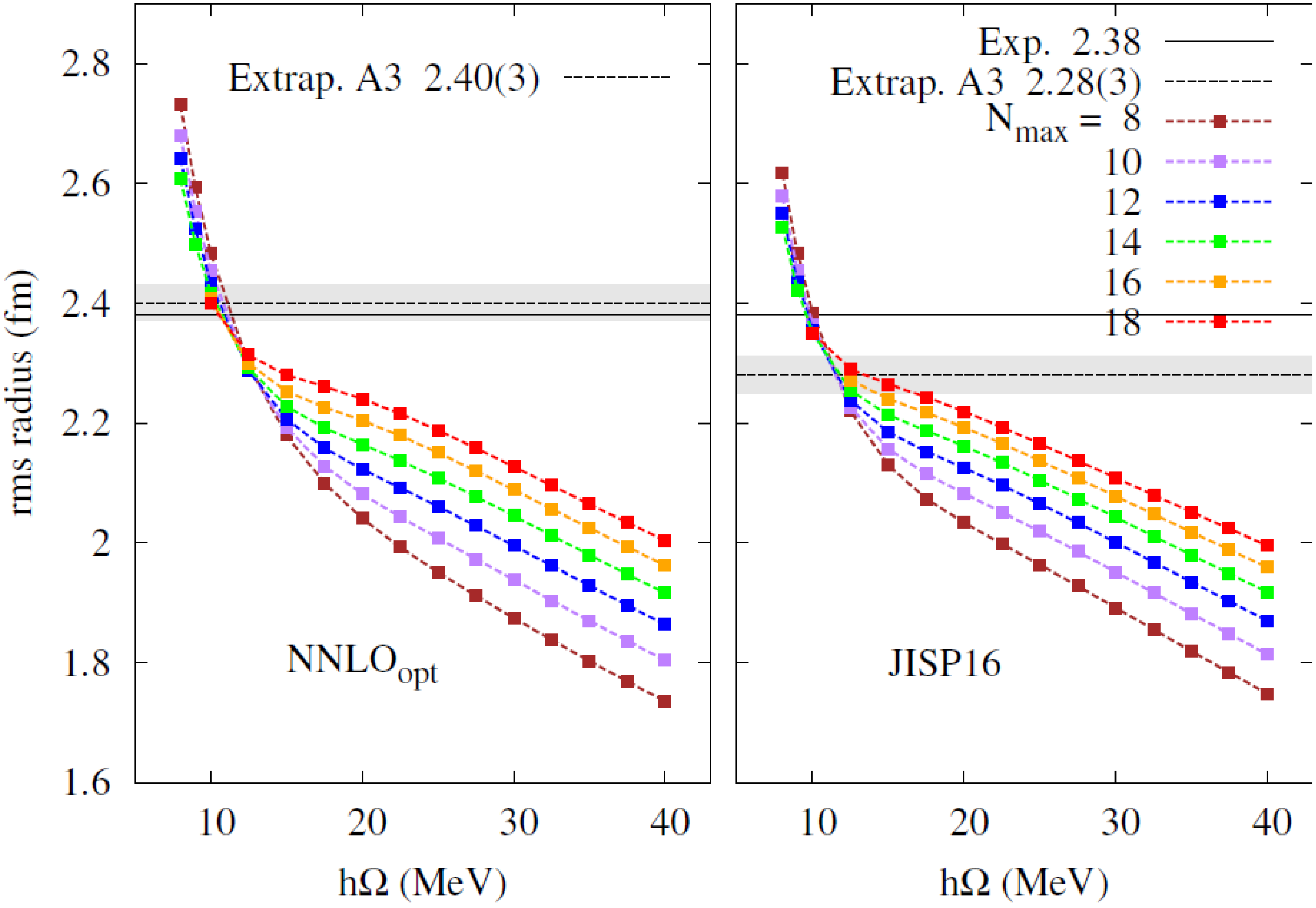
Excitation spectrum (unnatural parity)

- ❖ systematic trend downward indicating continuum (non-resonant) states



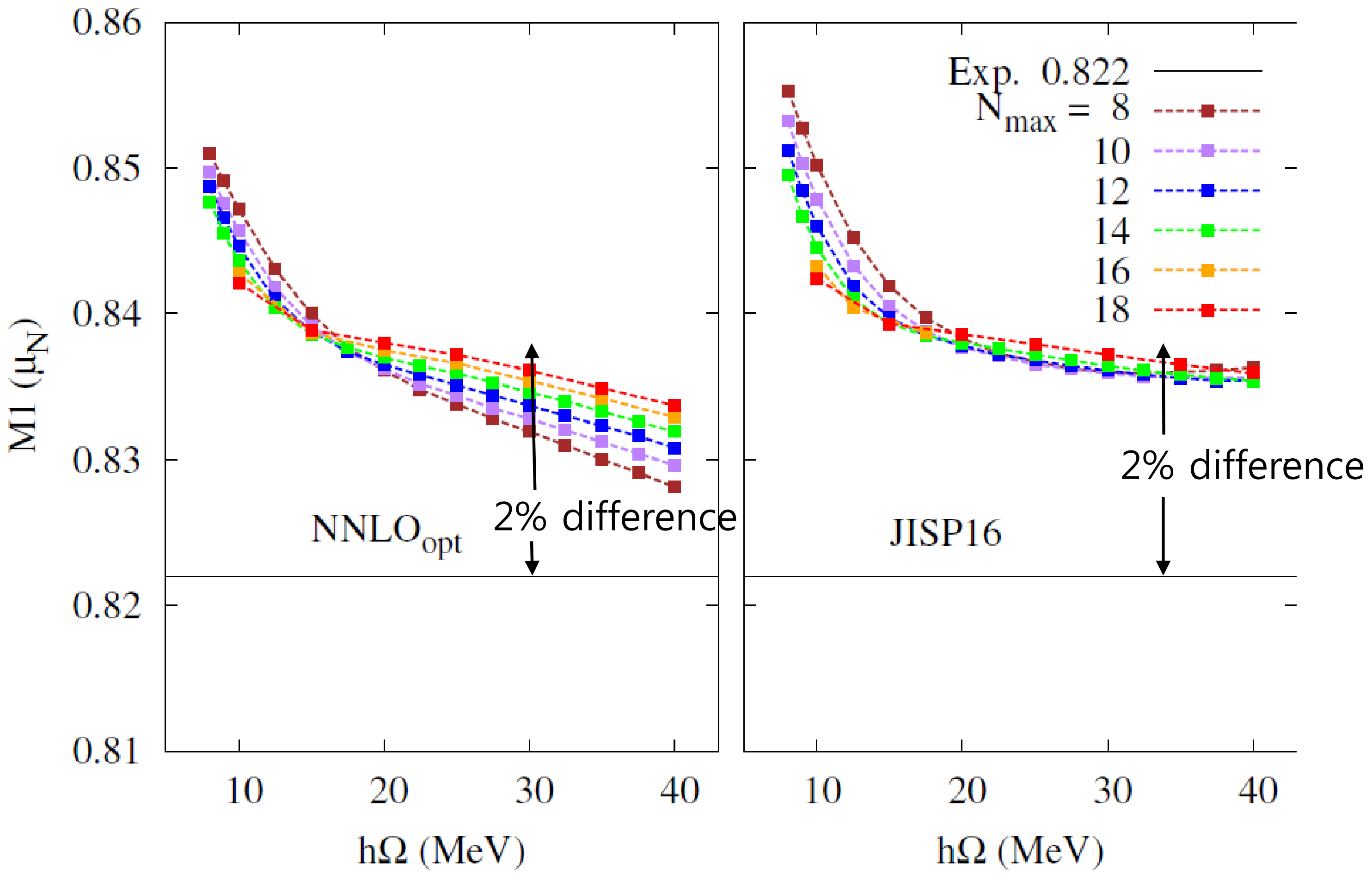


Point-proton rms radius (ground state)



❖ radius converges more slowly than the ground and excited state energies

Magnetic dipole moment (ground state)

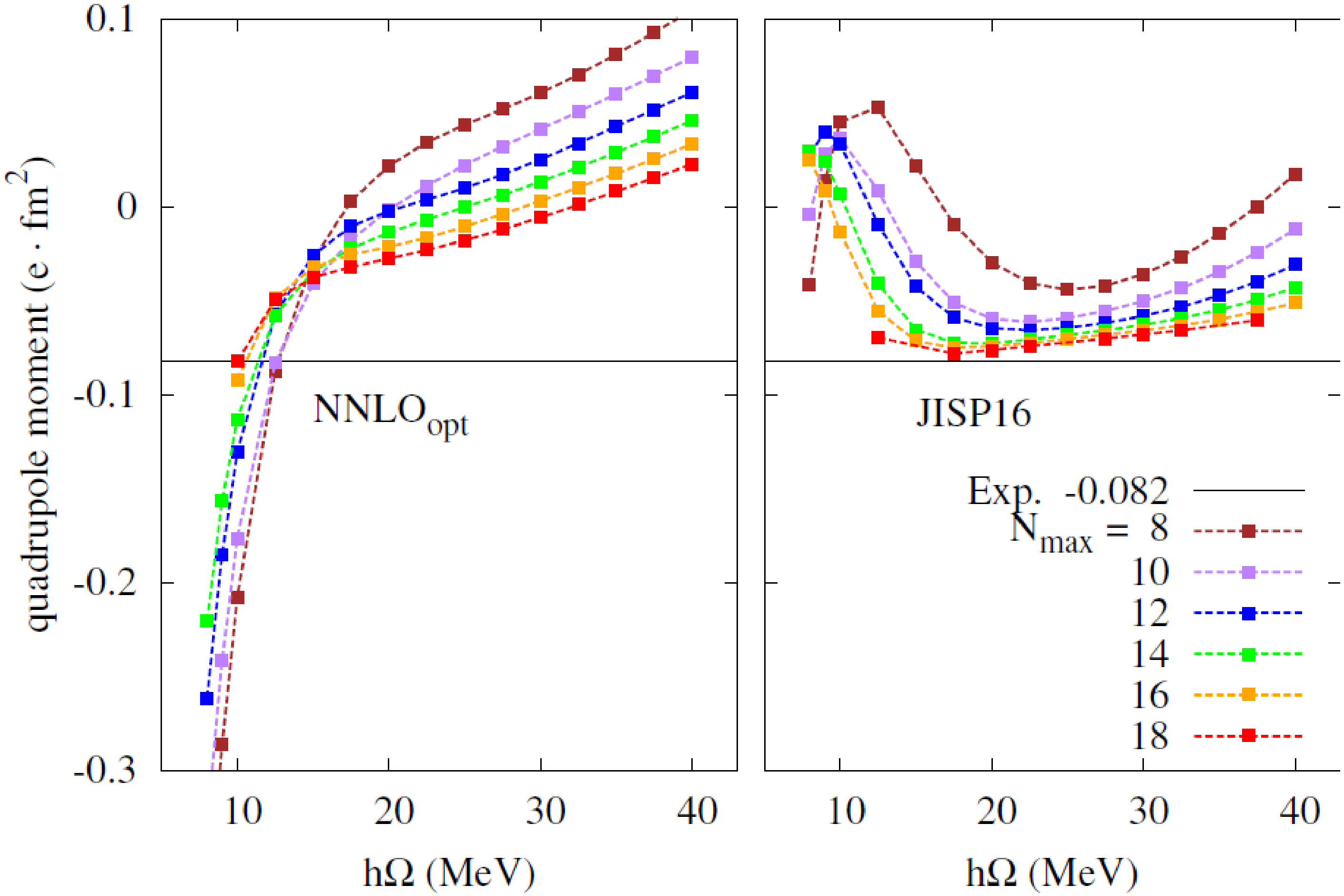


2% difference

2% difference

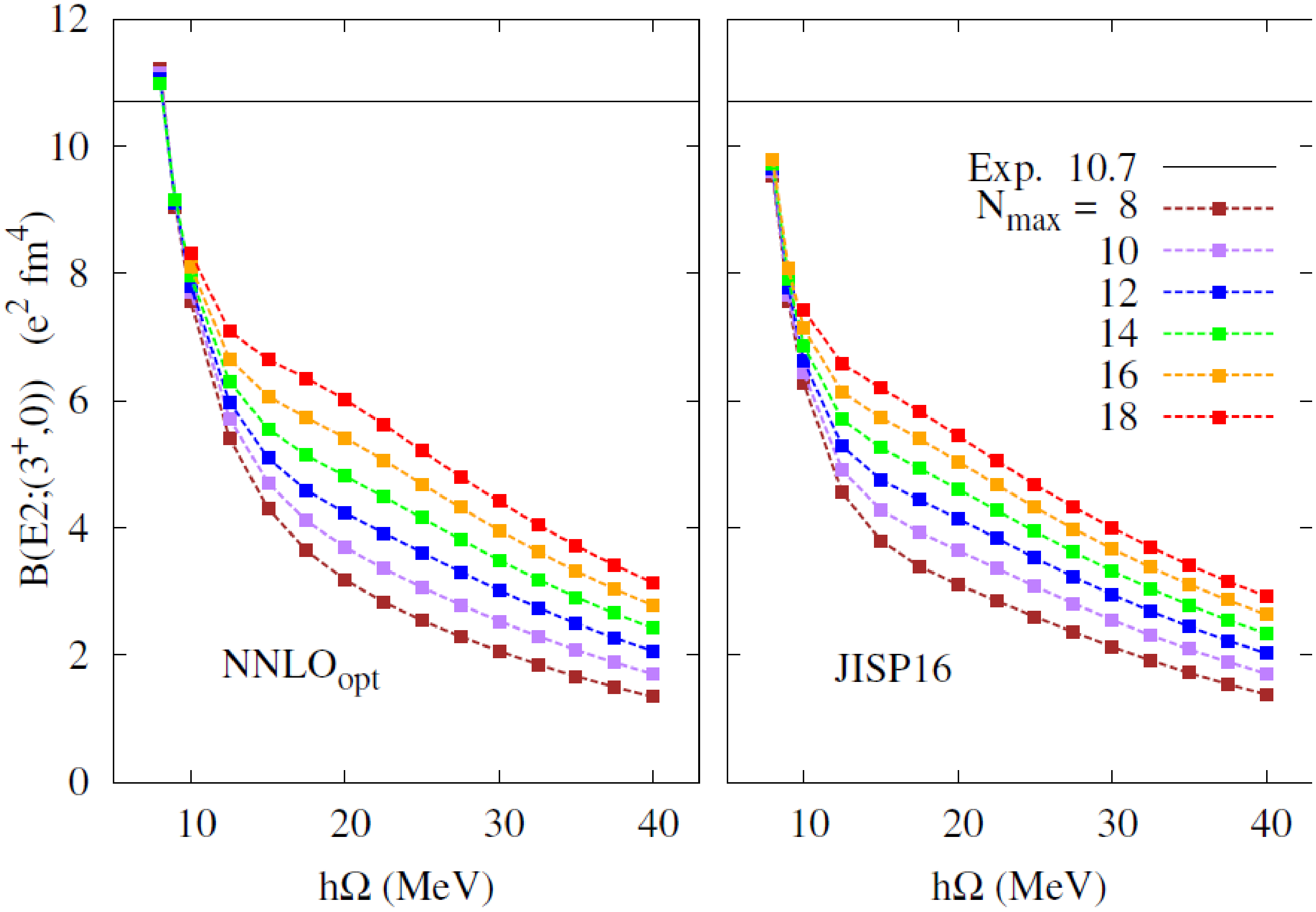
❖ well-convergent behavior and good agreement with experiment

Quadrupole moment (ground state)



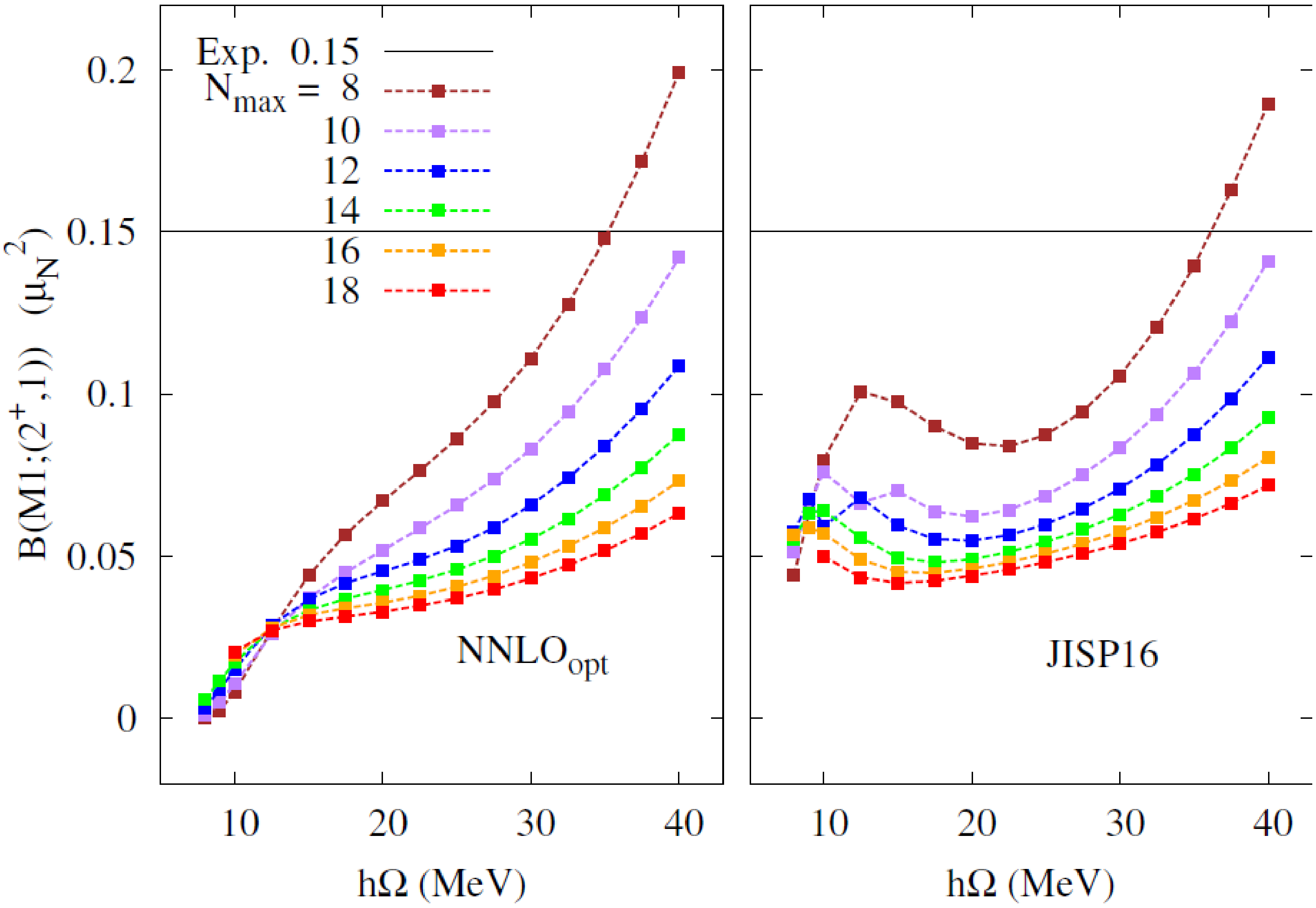
- ❖ good agreement with almost vanishing experimental value
- ❖ drastically different convergence patterns

$B(E2;(3^+,0)\rightarrow(1^+,0))$



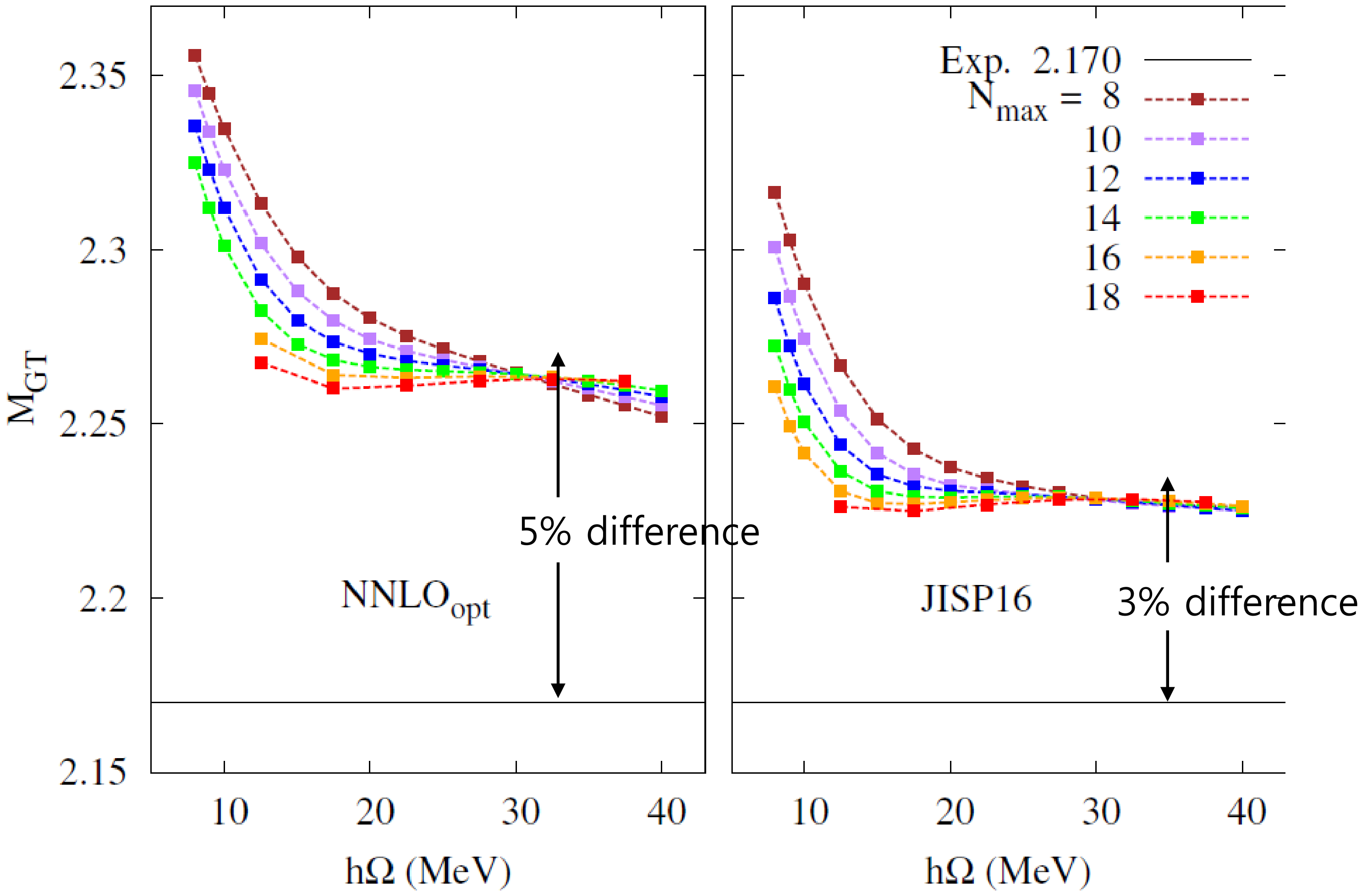
- slow convergence for both interactions

$B(M1;(2^+,1)\rightarrow(1^+,0))$



- ❖ reasonable convergent behaviors
- ❖ different convergence patterns

Gamow-Teller matrix element



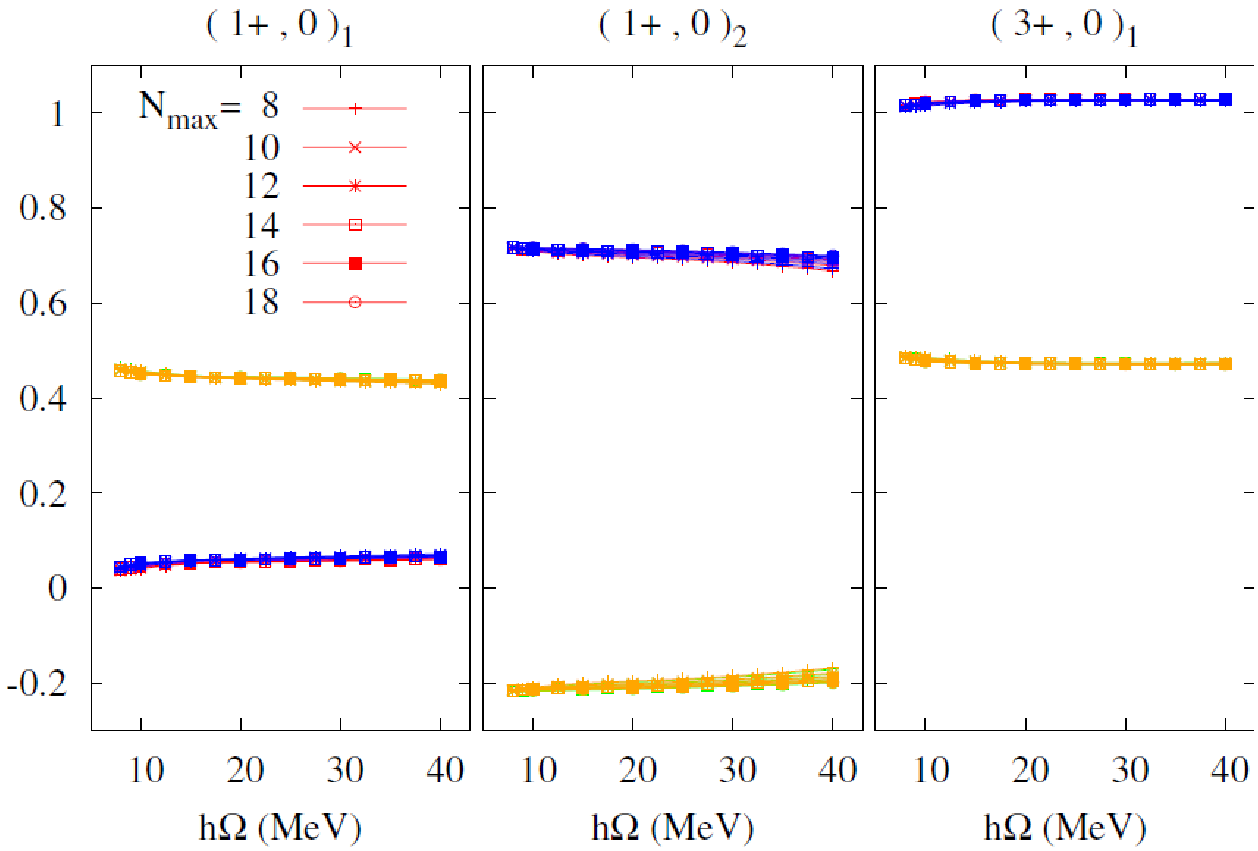
- $(0^+,1)$ of ^{6}Li ~ g.s. of ^{6}He
- well convergent and good agreement with experimental value

Spin decomposition

[P. Maris and J. Vary, Int. J. Mod. Phys. **22**, No.7 (2013) 1330016]

$$J = \frac{1}{J+1}\left(\langle \mathbf{J}\cdot\mathbf{L}_p\rangle + \langle \mathbf{J}\cdot\mathbf{L}_n\rangle + \langle \mathbf{J}\cdot\mathbf{S}_p\rangle + \langle \mathbf{J}\cdot\mathbf{S}_n\rangle\right)$$

- ❖ due to nearly exact isospin symmetry, orbital motions and spin contributions for proton and neutron coincide



Summary

- In general, the ground state energy of $\mathrm{NNLO}_{\mathrm{opt}}$ converges more slowly compared to JISP16.

- excitation energies
  large magnetic dipoles
  large M1 transition
  large M_{GT}
  → reasonably good convergence

- rms radius
  E2 transitions
  → poor convergence (long-range operators)

Future work

- other Li isotopes
- include 3NFs
- investigate convergence in detail,
  e.g. improved extrapolation methods

THANK YOU !

Extrapolation

Extrapolation A5 for ground state energies* (in preparation)

$$E_{gs} = E_\infty + ae^{-c\Lambda_2^2} + E_{IR}(\lambda_t);\ \ E_{IR}(\lambda_t) = de^{-2k_\infty/\lambda_t} = de^{-2k_\infty L_t}$$

$$1/\lambda_t = L_t = L_2 + \Delta L;\ L_i = 1/\lambda_i;\ \lambda_i = \sqrt{\frac{m\Omega}{2(N_i + {}^3\!/_2)\hbar}};\quad N_i = \max(2n+l) + i$$

$$\Delta L = 0.54437b(L_0/b)^{-1/3};\ \ b = \sqrt{\frac{\hbar}{m\Omega}};\ \Lambda_i = \sqrt{\frac{2(N_i + {}^3\!/_2)m\Omega}{\hbar}}$$

Extrapolations A3 for point proton rms radii* (in preparation)

$$A3:\ \ r^2 = \langle r^2\rangle_\infty\left[1 - \left(c_0\beta^3 + c_1\beta\right)e^{-\beta}\right]$$

$$L_t = L_2 + \Delta L;\ L_i = 1/\lambda_i;\ \lambda_i = \sqrt{\frac{m\Omega}{2(N_i + {}^3\!/_2)\hbar}};\quad N_i = \max(2n+l) + i;\ \Delta L = 0.54437b(L_0/b)^{-1/3};\ \ b = \sqrt{\frac{\hbar}{m\Omega}}$$

$$\beta = 2k_\infty L_t;\ \text{"Fit"}\ k_\infty\ \text{ from } E_{gs};\ \text{"SC"}\ k_\infty = \frac{\sqrt{2m\left(E_s + E_c\right)}}{\hbar};\ E_s = \text{proton removal energy};\ E_c = \frac{(Z-1)e^2}{L_t}$$

Based on “Extrapolation A” of P. Maris, J.P. Vary and A.M. Shirokov, Phys. Rev. C79, 014308 (2009)
with improvements for IR region from
S. Coon, M.I. Avetian, M.K.G. Kruse, U. van Kolck, P. Maris, and J.P. Vary, Phys. Rev. C86, 054002 (2012); arXiv:1205.3230
R.J. Furnstahl, G. Hagen, and T. Papenbrock, Phys. Rev. C86, 031301 (2012); arXiv:1207.6100
S.N. More, A. Ekstroem, R.J. Furnstahl, G. Hagen and T. Papenbrock, Phys. Rev. C87 044326 (2013); arXiv:1302.3815