

Investigation of the $A=7$ systems within the No-Core Shell Model with Continuum

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Motivations

**A=7 systems
(⁷Be and ⁷Li)**

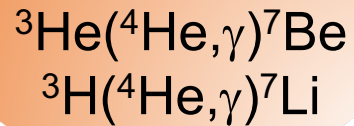
Motivations

Primordial ${}^7\text{Li}$
abundance in the
early universe

PLB **757** (2016) 430

Fraction of pp-chain
branches resulting
in ${}^7\text{Be}$ versus ${}^8\text{B}$
neutrinos

Nuclear Astrophysics



A=7 systems (${}^7\text{Be}$ and ${}^7\text{Li}$)

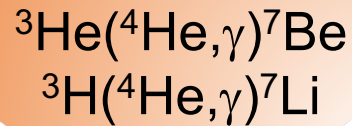
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New experiment in progress at LUNA

Lanzhou Experiment



Possible resonant enhancement near the threshold

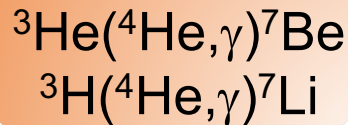
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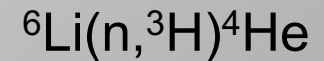
Lanzhou Experiment



Possible resonant enhancement near the threshold

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Tritium breeding



Fusion energy generation (ITER)

Motivations

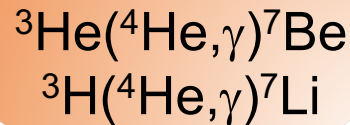
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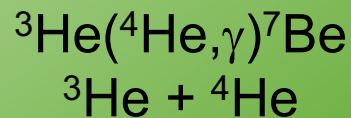
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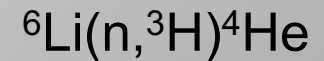
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TRIUMF

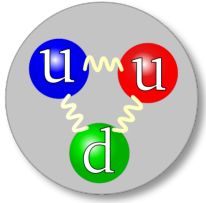


Tritium breeding

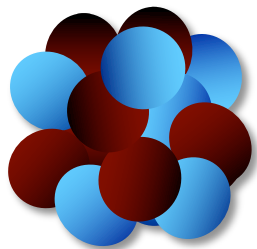


Fusion energy generation (ITER)

From QCD to nuclei



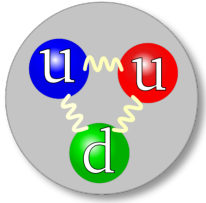
Low-energy QCD



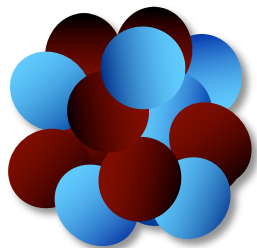
Nuclear structure and reactions



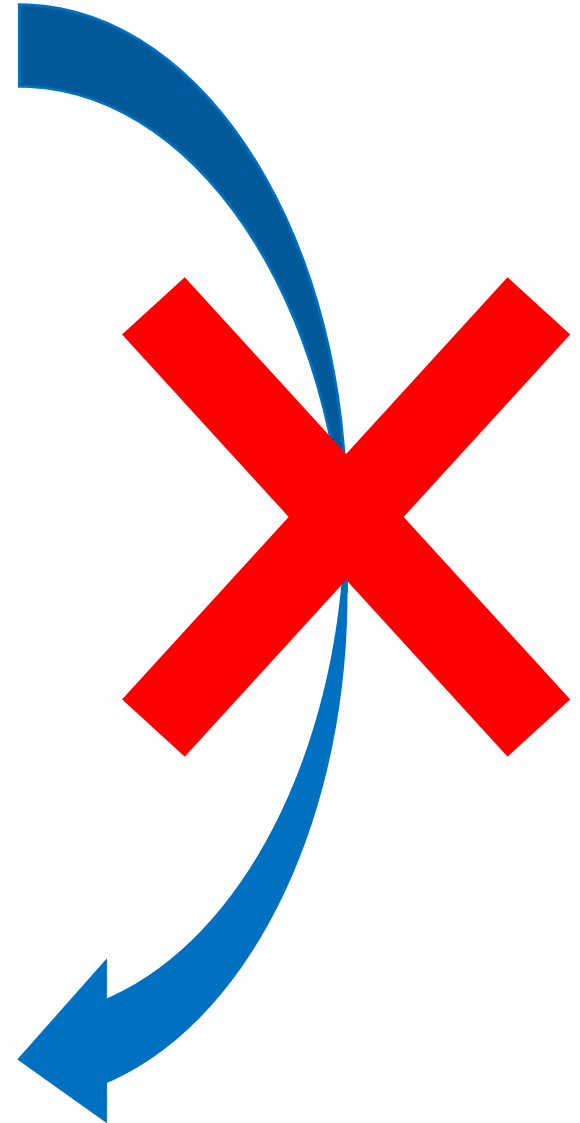
From QCD to nuclei



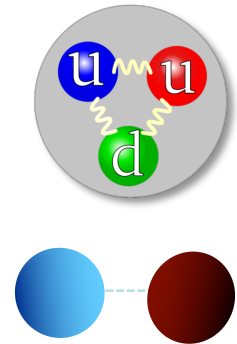
Low-energy QCD



Nuclear structure and reactions



From QCD to nuclei

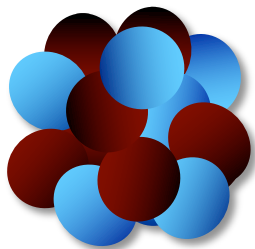


Low-energy QCD



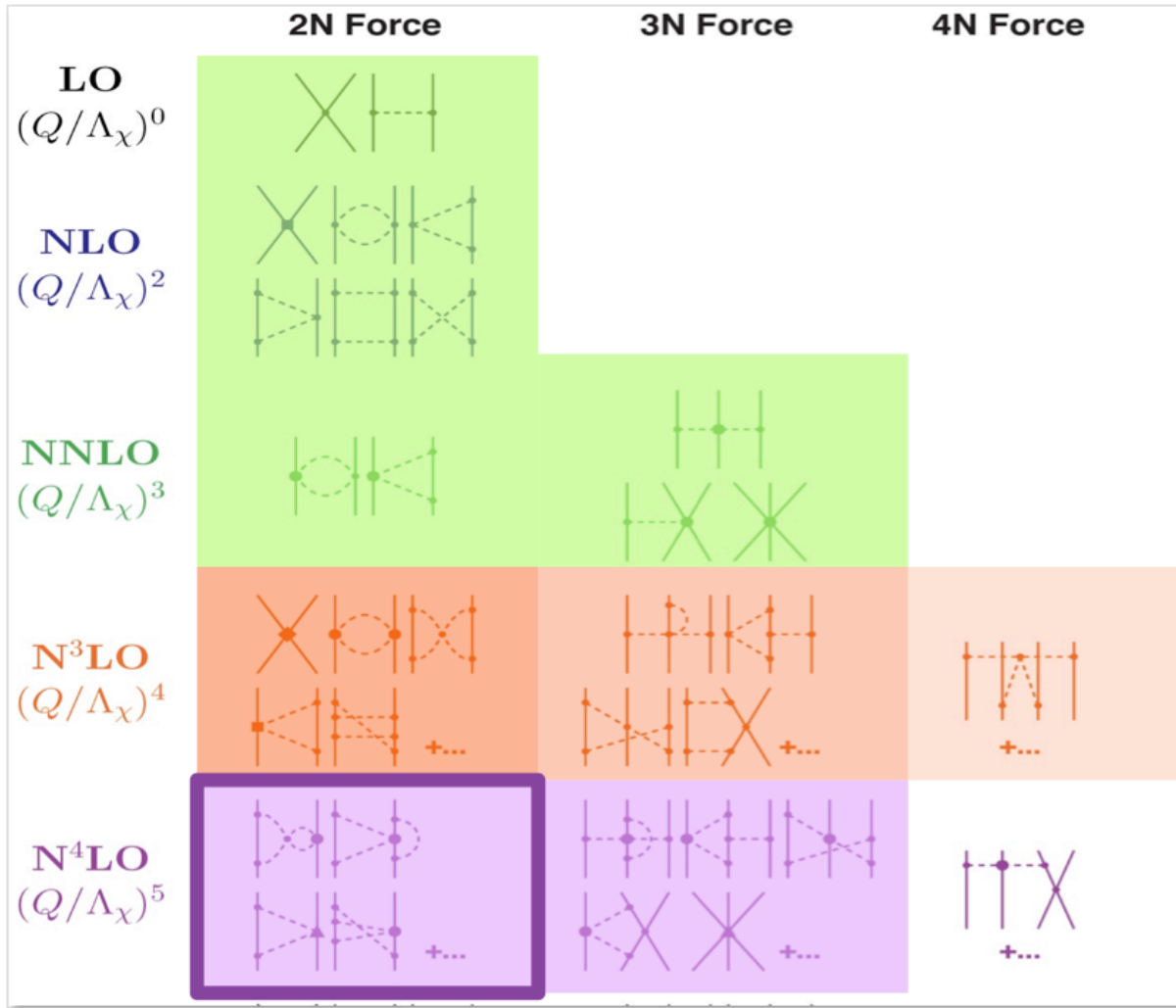
NN+3N interactions
from chiral EFT

...or accurate
meson-exchange
potentials



Nuclear structure and reactions

Chiral interactions



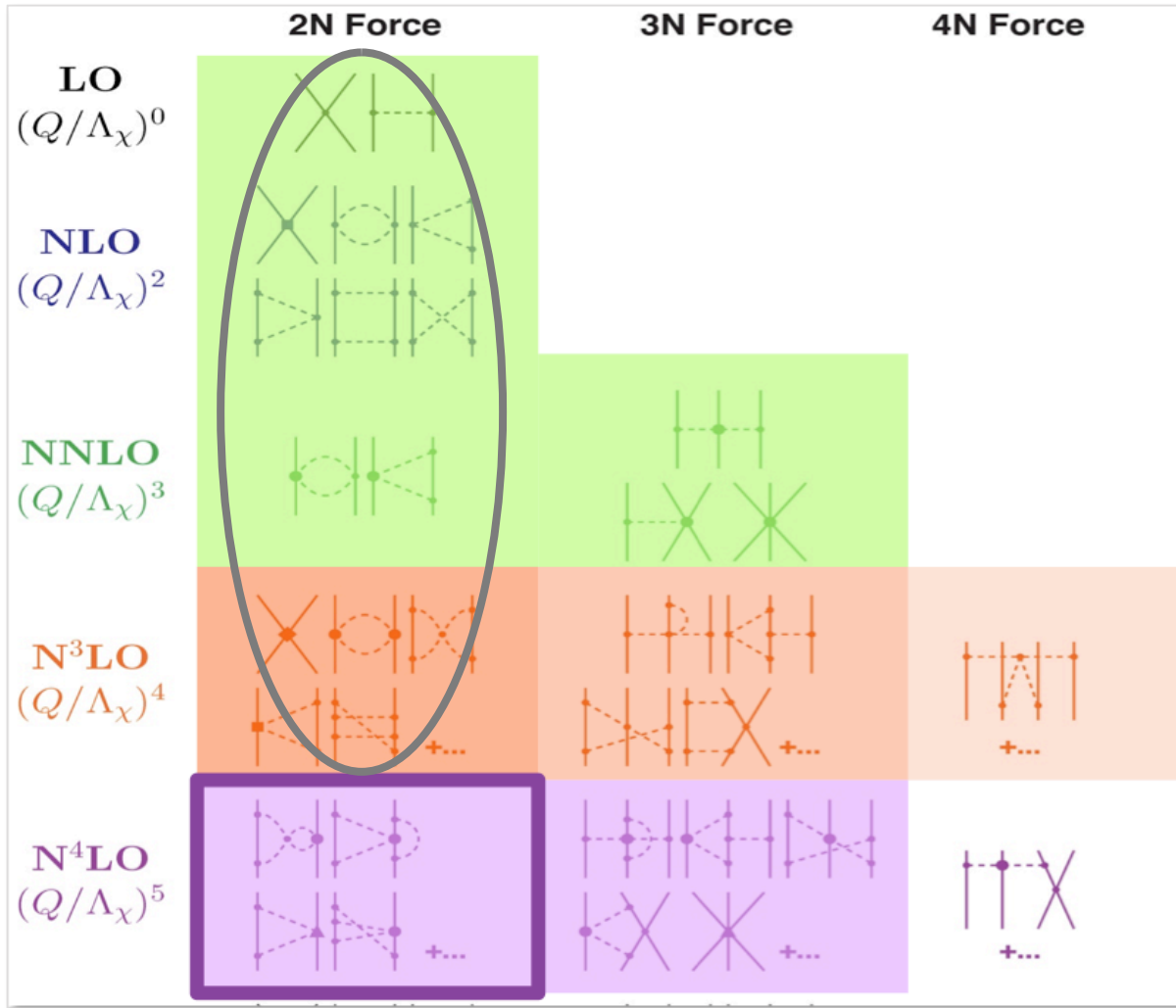
Construction of the most general Lagrangian in terms of **pions** and **nucleons**

Low-momentum expansion of the Lagrangian in powers of Q/Λ_χ

Nuclear forces emerge as a hierarchy controlled by the power ν

Two- and many-nucleon forces are created on an equal footing and emerge in increasing number going to higher orders

Chiral interactions

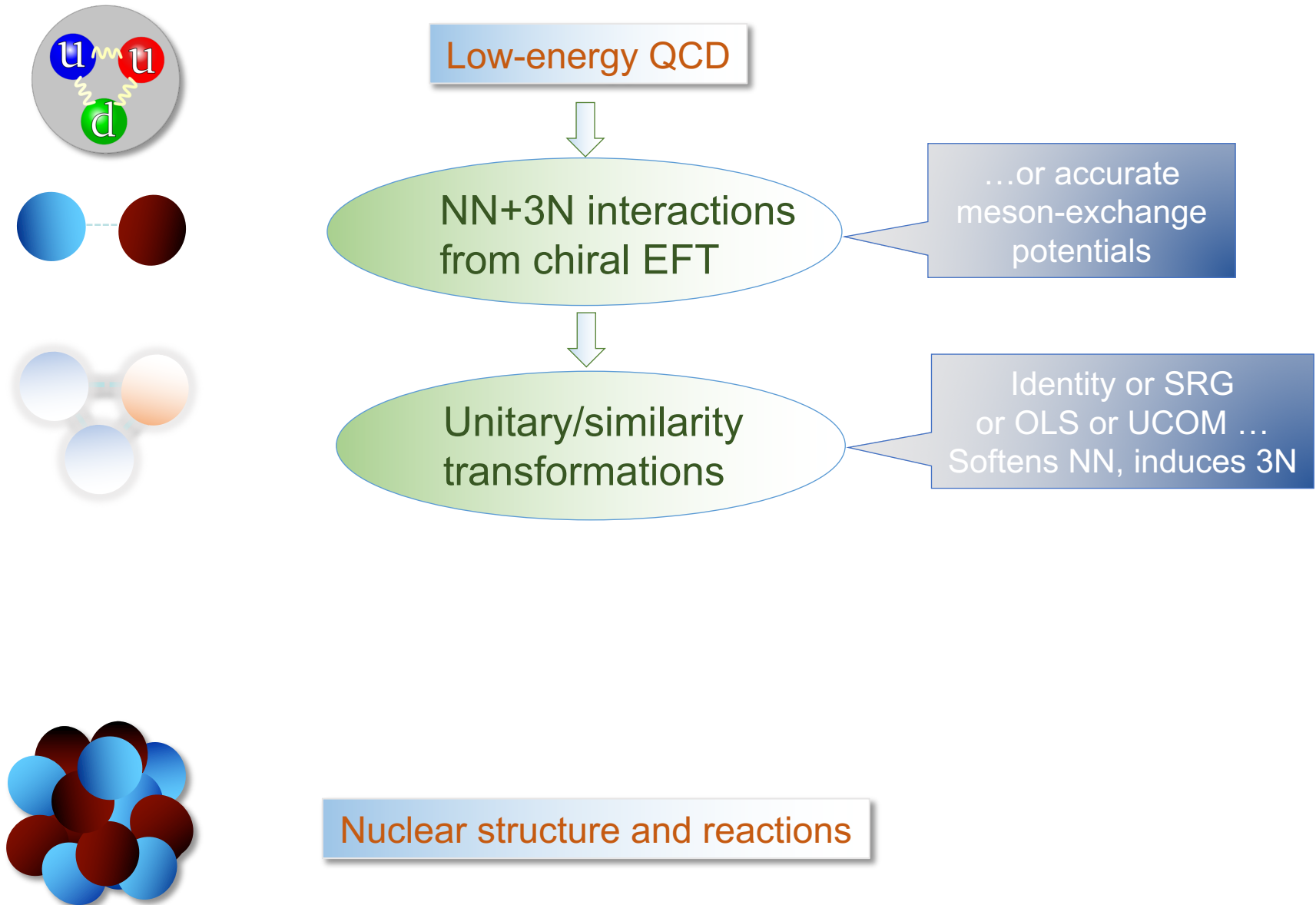


Several choices of two- and three-nucleon forces

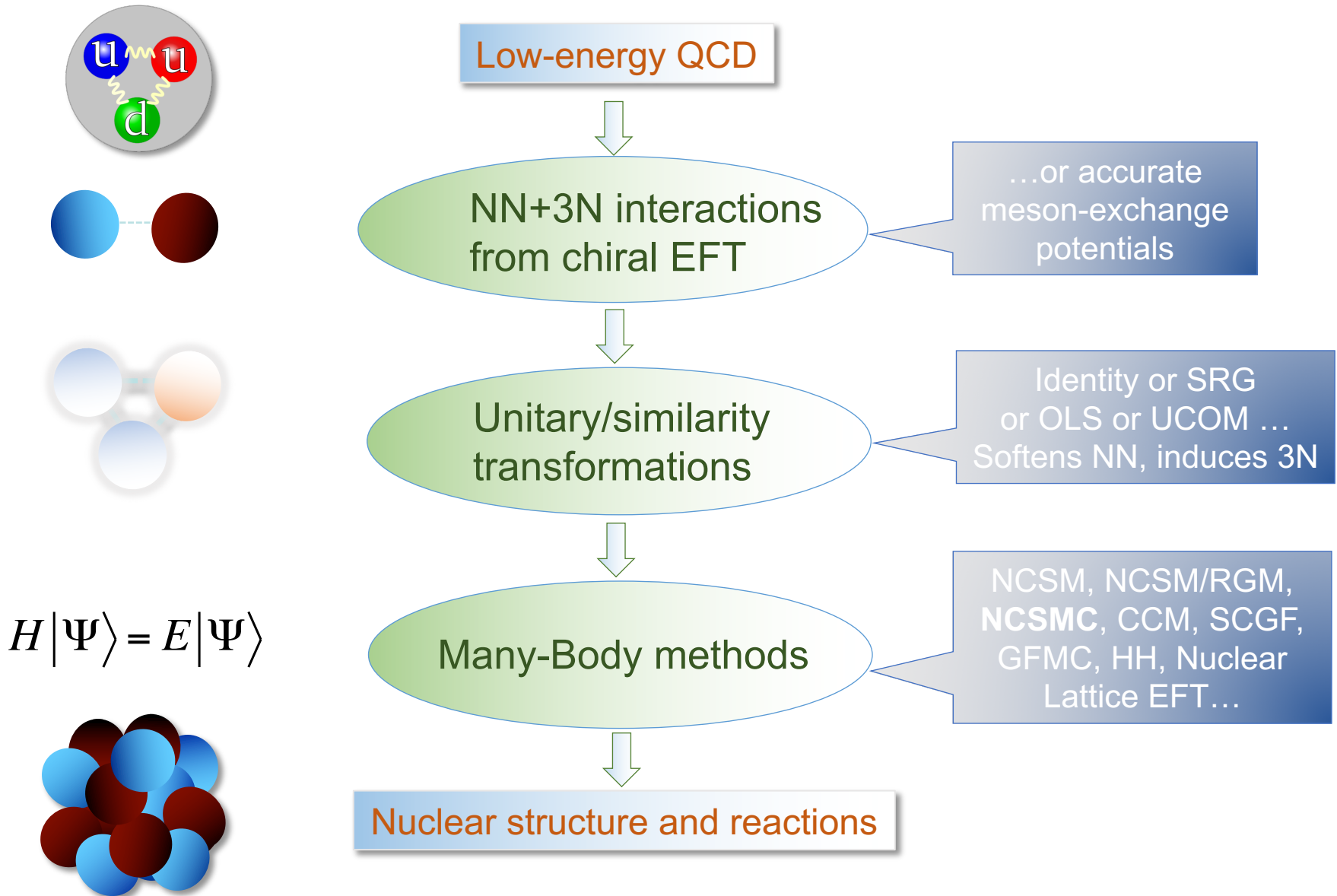
Due to the high computational effort of dealing with a three-body projectile, we only used the NN interaction

NN N³LO Entem, Machleidt

From QCD to nuclei

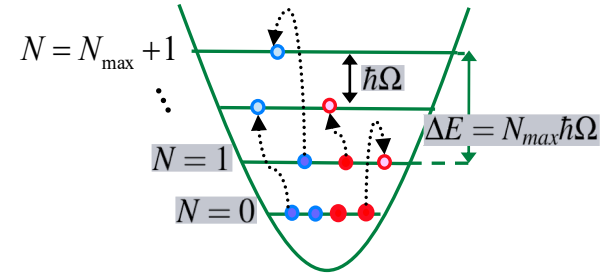


From QCD to nuclei



No-core shell model

- No-core shell model (NCSM)
 - A-nucleon wave function expansion in the harmonic oscillator (HO) basis
 - Short- and medium-range correlations
 - Bound-states, narrow resonances



$$\Psi^A = \sum_{N=0}^{N_{\max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| \begin{matrix} (A) \\ \text{Nucleon Cluster} \end{matrix}, \lambda \right\rangle$$

Unknowns

No-core shell model with RGM

- NCSM with Resonating Group Method (NCSM/RGM)
 - Cluster expansion, clusters described by NCSM
 - Proper asymptotic behavior
 - Long-range correlations

$$\Psi^{(A)} = \sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) \hat{A}_{\nu} \left| \begin{array}{c} \vec{r} \\ (A-a) \quad (a) \end{array}, \nu \right\rangle$$

• Unknowns

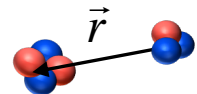
Unified approach to bound & continuum states; to nuclear structure and reactions

- No-core shell model (NCSM)
 - A-nucleon wave function expansion in the harmonic oscillator (HO) basis
 - Short- and medium-range correlations
 - Bound-states, narrow resonances
- NCSM with Resonating Group Method (NCSM/RGM)
 - Cluster expansion, clusters described by NCSM
 - Proper asymptotic behavior
 - Long-range correlations
- Most efficient: *ab initio* no-core shell model with continuum (NCSMC)

NCSM



NCSM/RGM



NCSMC

S. Baroni, P. Navratil, and S. Quaglioni,
PRL **110**, 022505 (2013); PRC **87**, 034326 (2013).

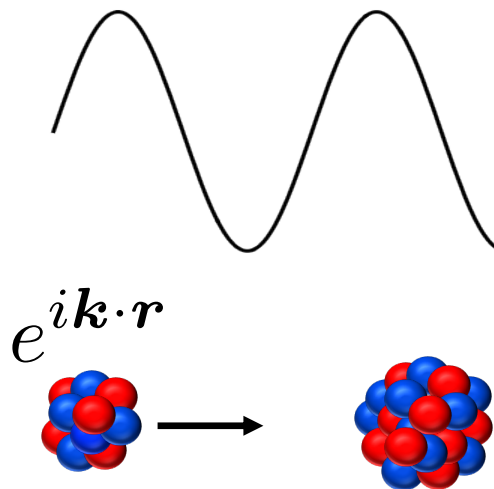
$$\Psi^{(A)} = \sum_{\lambda} c_{\lambda} \left| \begin{matrix} (A) \\ \text{Nucleus} \\ \lambda \end{matrix} \right\rangle + \sum_{\nu} \int d\vec{r} \gamma_{\nu}(\vec{r}) \hat{A}_{\nu} \left| \begin{matrix} (A-a) & (a) \\ \text{Cluster} & \text{Cluster} \\ \nu \end{matrix} \right\rangle$$

Unknowns

Phase shift

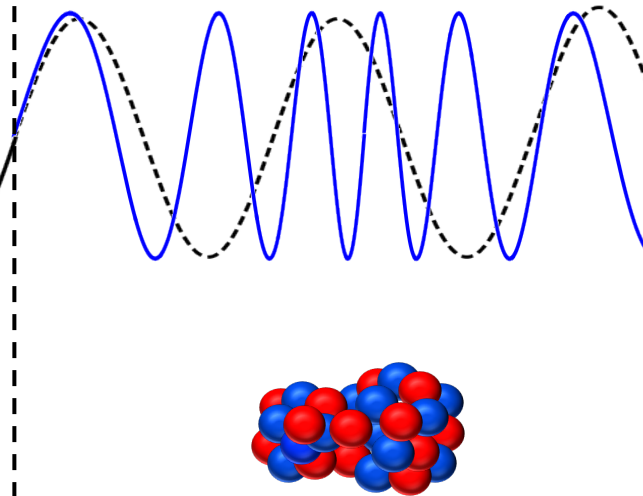
Stage I

The projectile nucleus is moving with a constant momentum against the target nucleus initially at rest. The projectile can be described as a plane wave



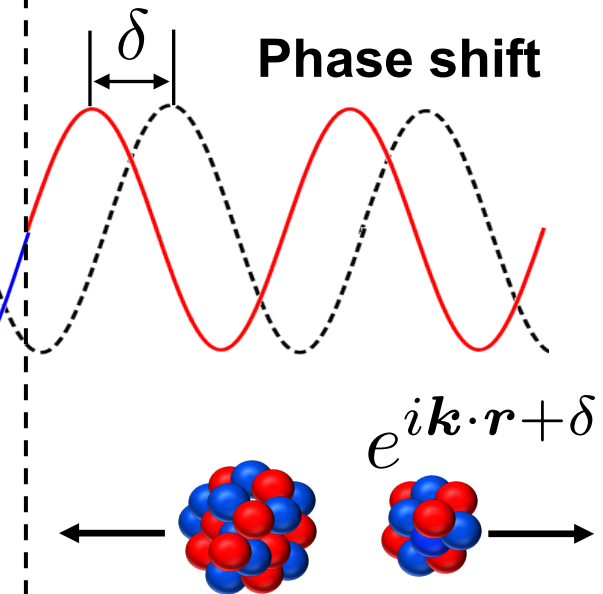
Stage II

During the interaction process the two nuclei form a composite system and the wave function of the projectile starts to oscillate at a different frequency



Stage III

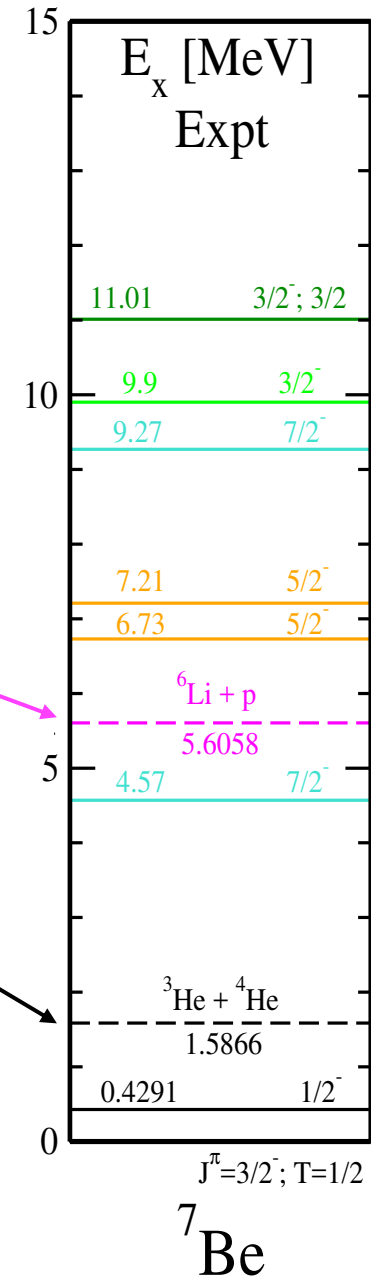
The projectile nucleus can be still described as plane wave, but with a different phase with respect the initial one. The difference δ is called "phase shift"



${}^7\text{Be}$ system

Analyzed mass partitions

- ${}^6\text{Li} + \text{p}$
- ${}^3\text{He} + {}^4\text{He}$

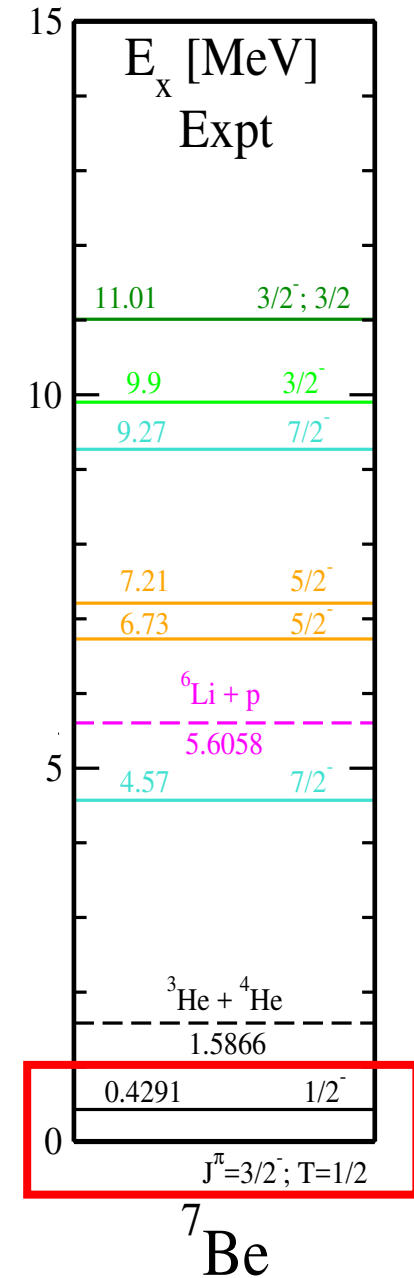


${}^7\text{Be}$ system

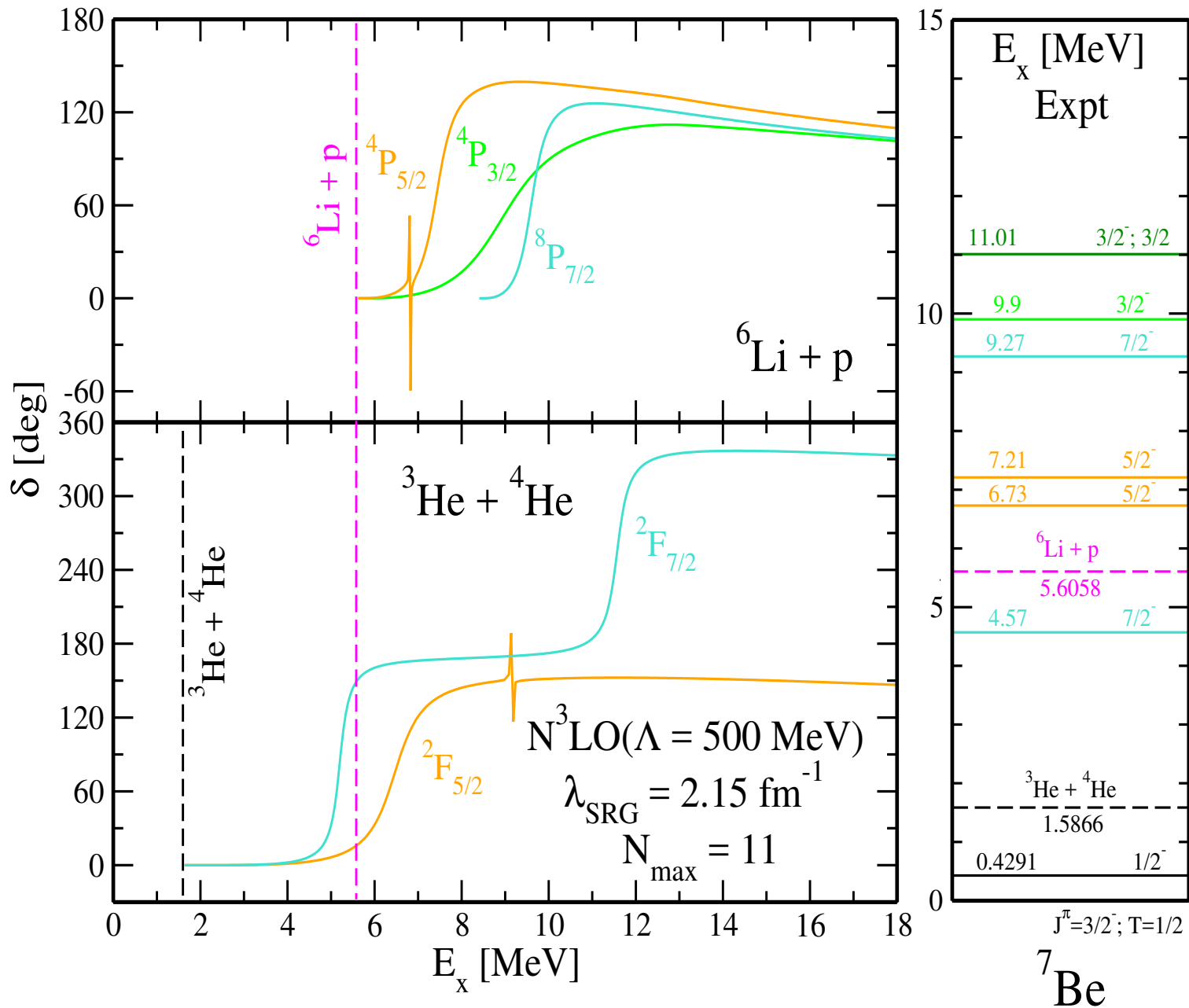
Exp.	$J^\pi = 3/2^-$
E [MeV]	-37.60

${}^3\text{He} + {}^4\text{He}$	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-1.519	-1.256
E [MeV]	-36.98	-36.71

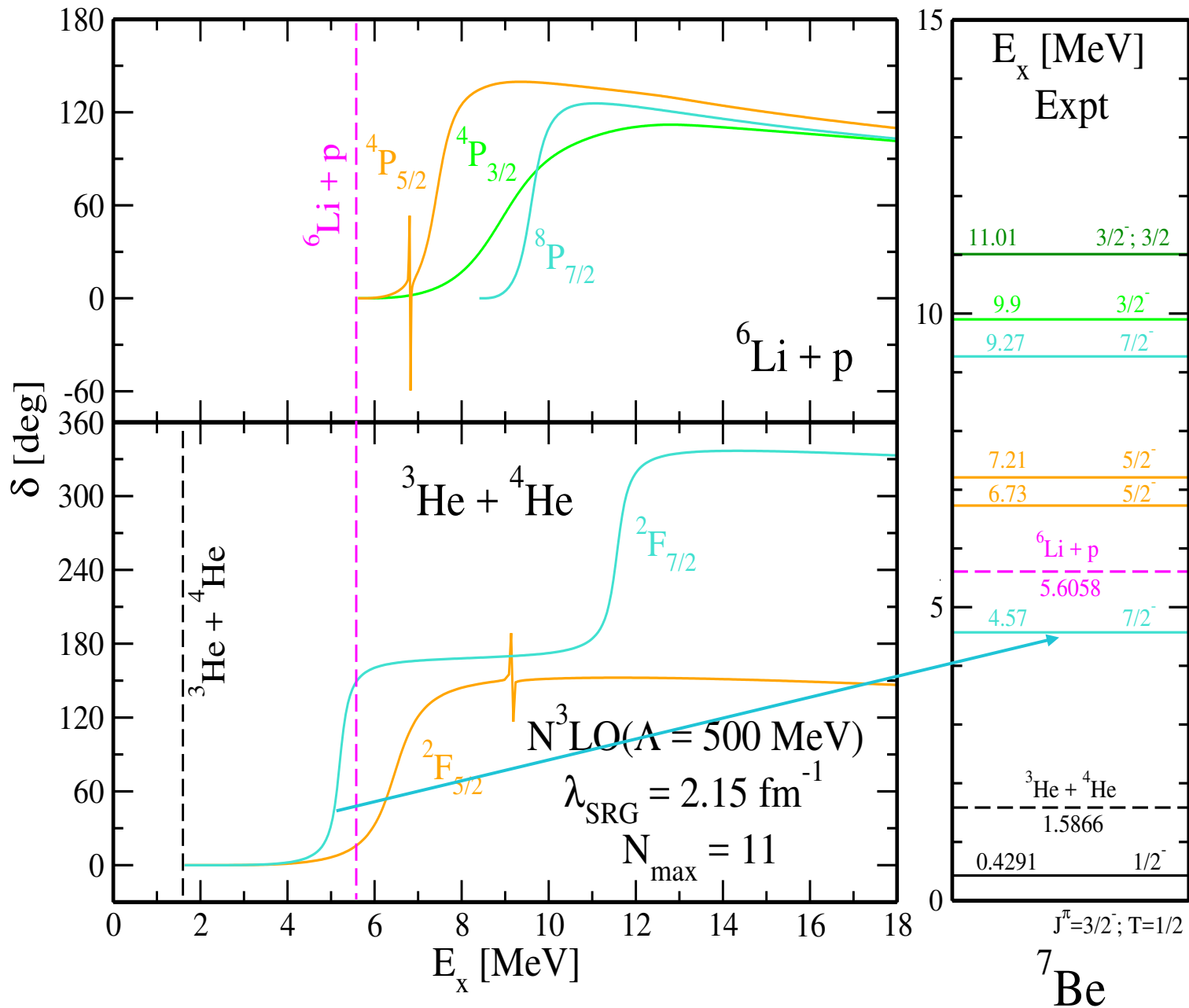
$p + {}^6\text{Li}$	$J^\pi = 3/2^-$	$J^\pi = 1/2^-$
E_{bound}	-5.729	-5.389
E [MeV]	-36.47	-36.13



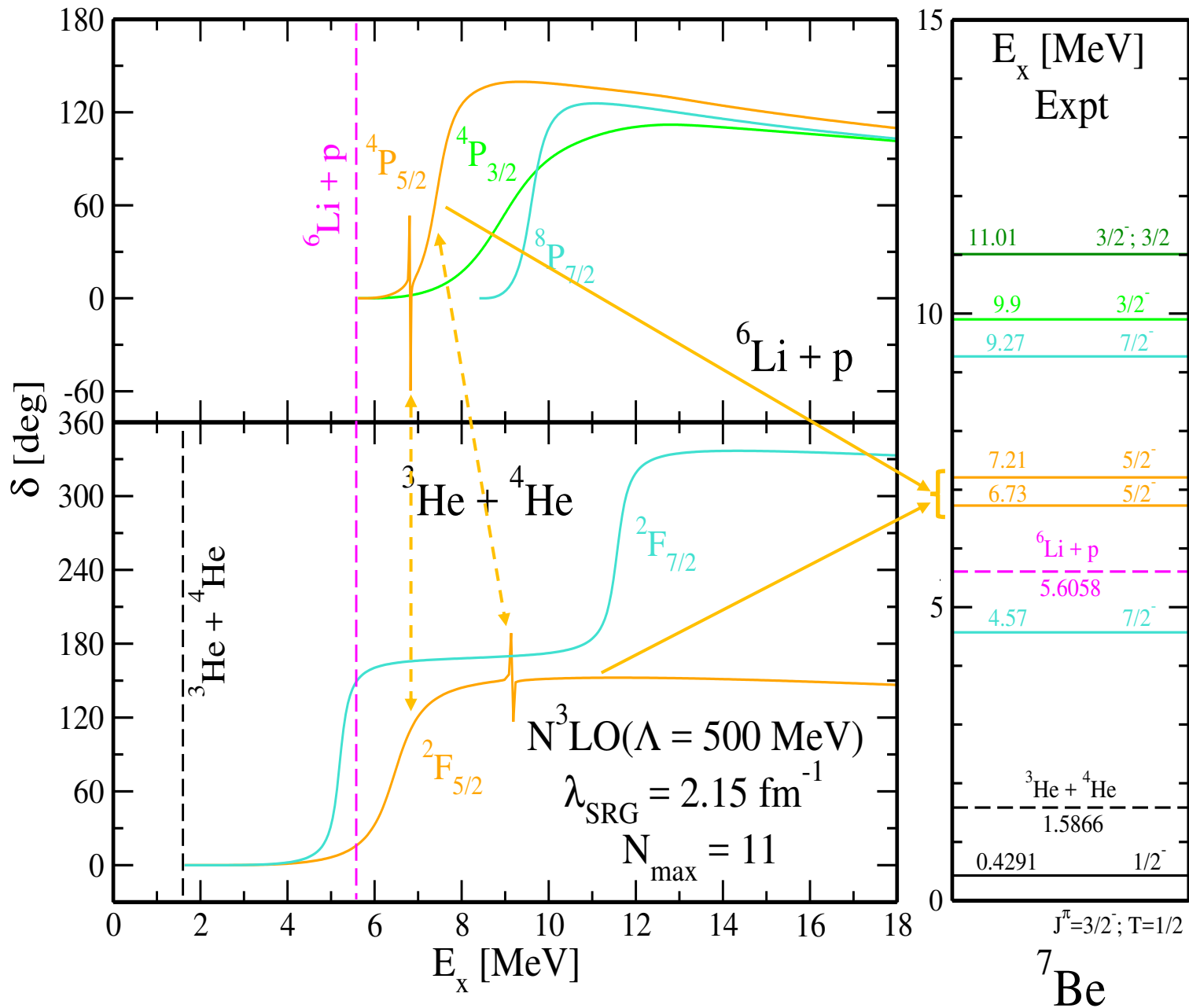
${}^7\text{Be}$ system



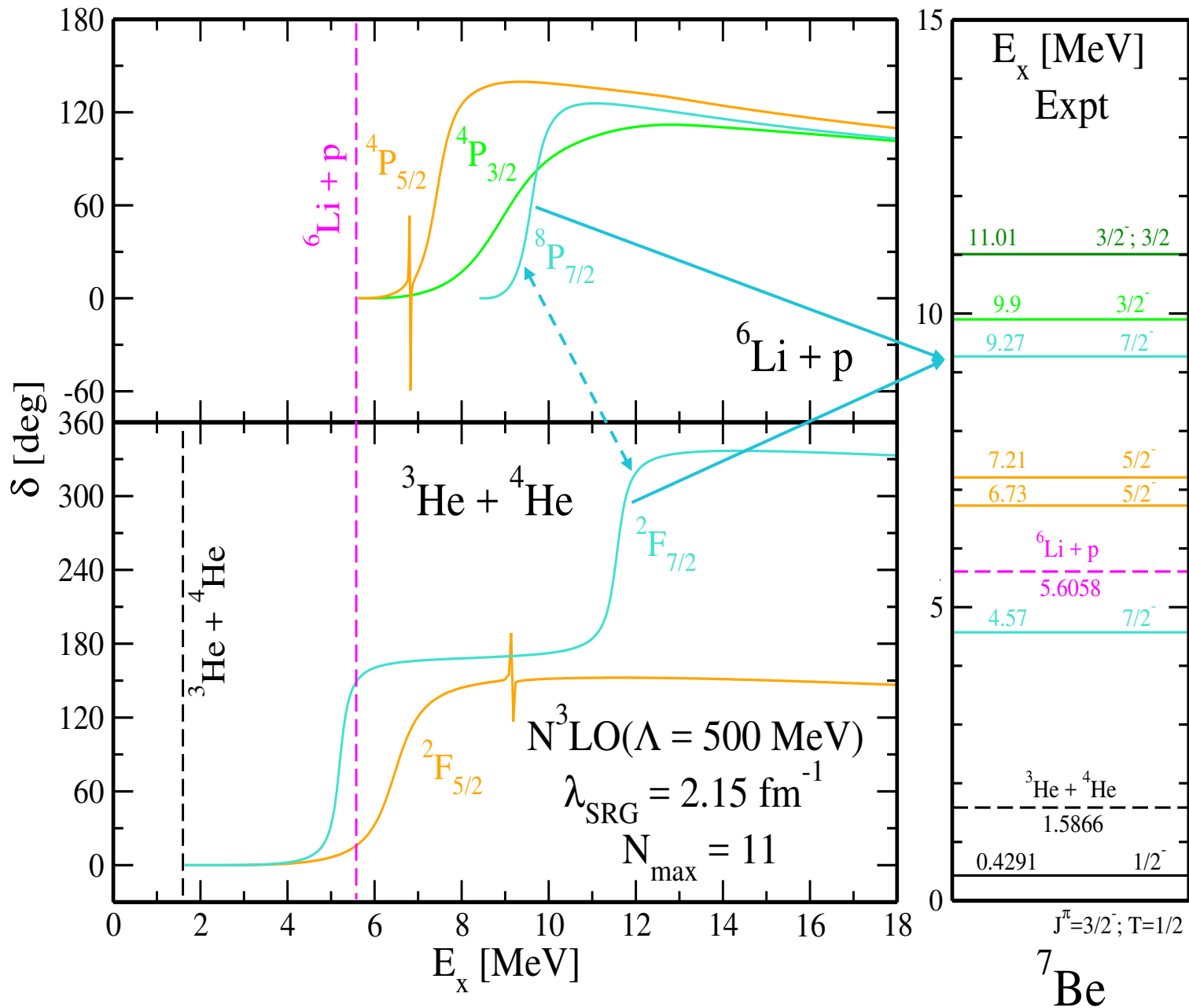
${}^7\text{Be}$ system



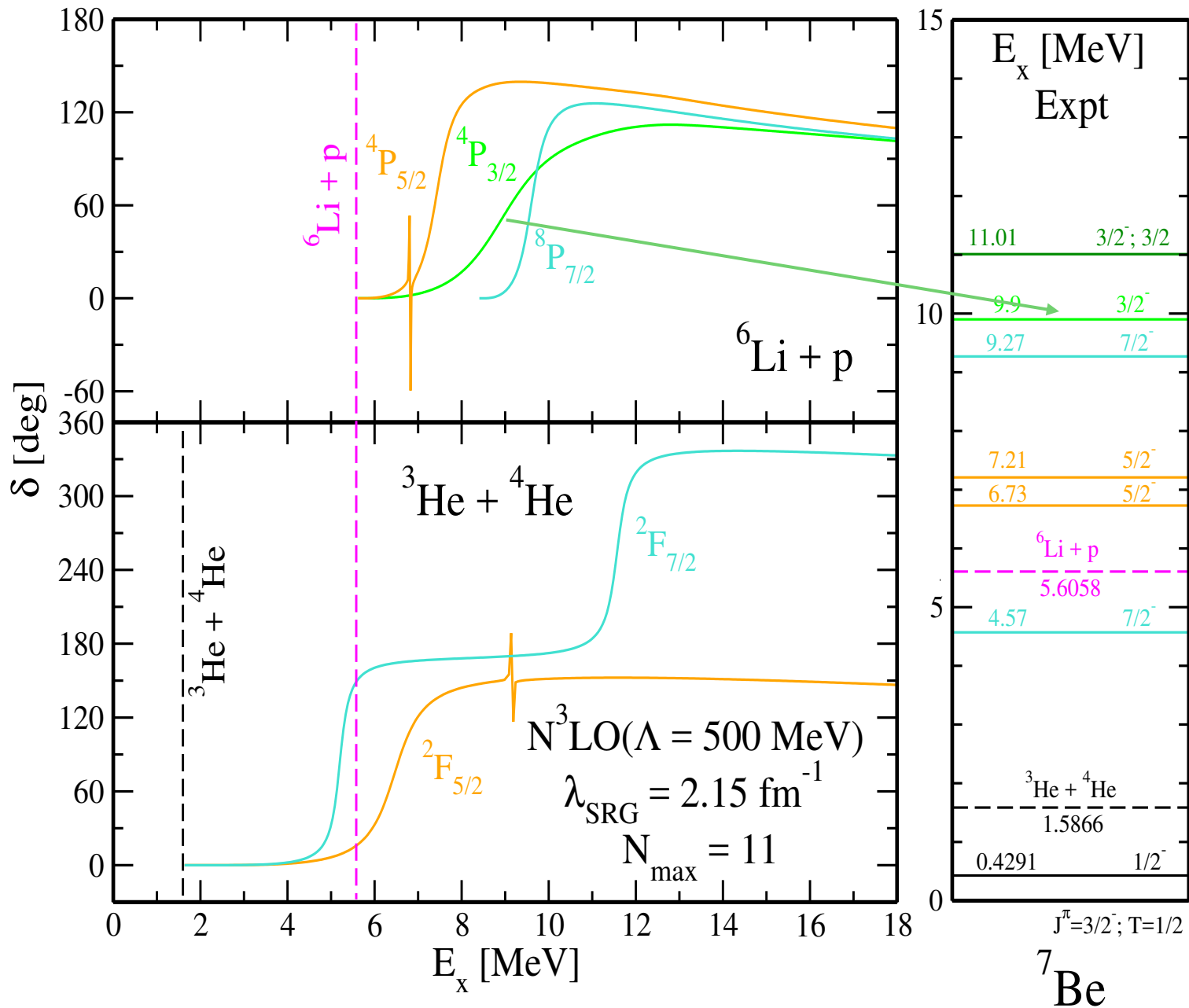
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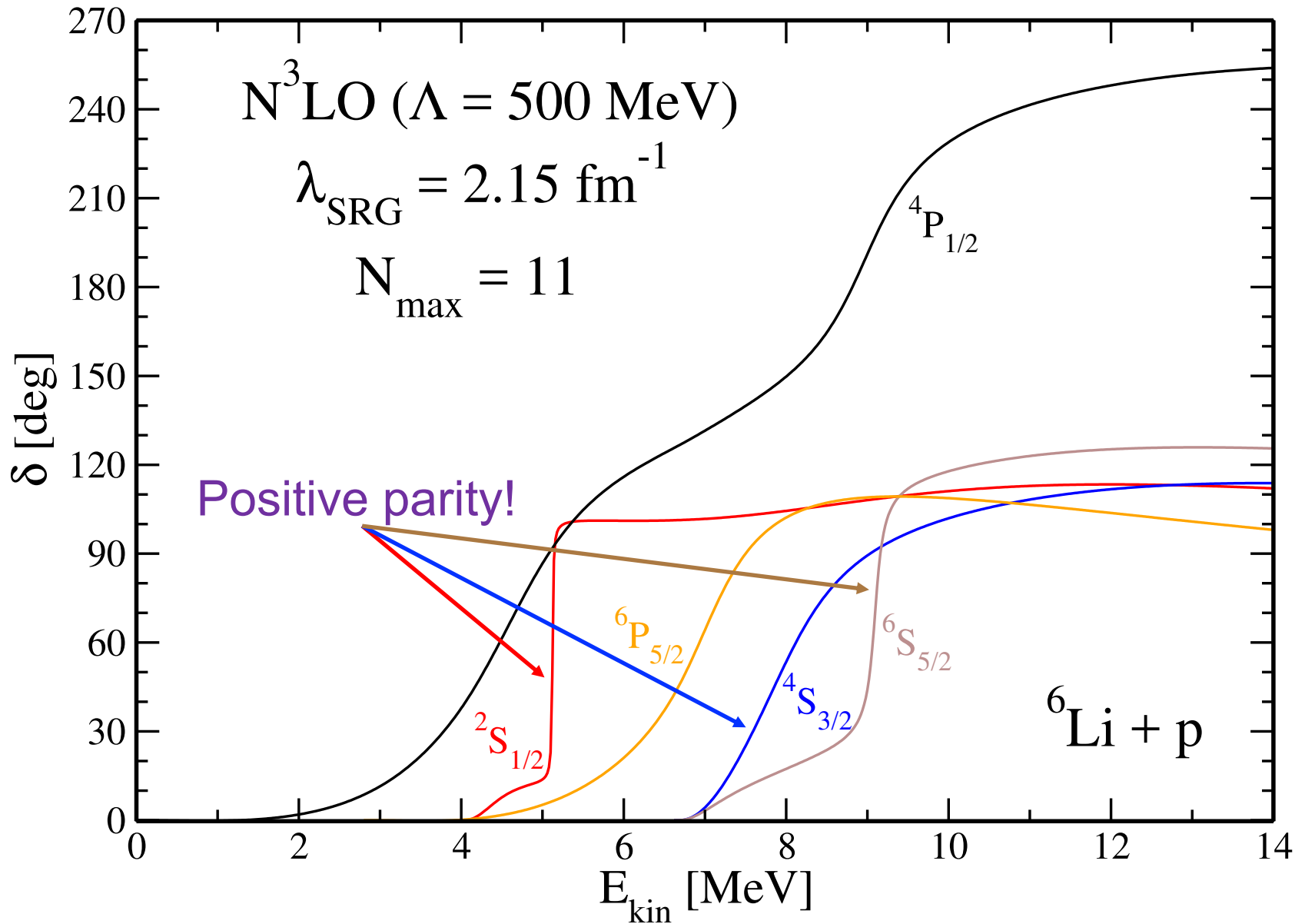
${}^7\text{Be}$ system



${}^7\text{Be}$ system



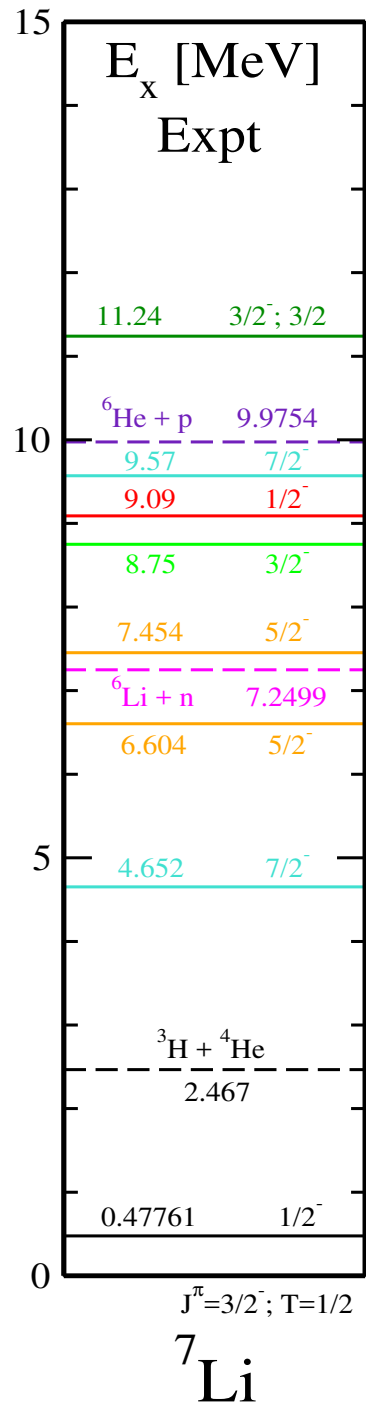
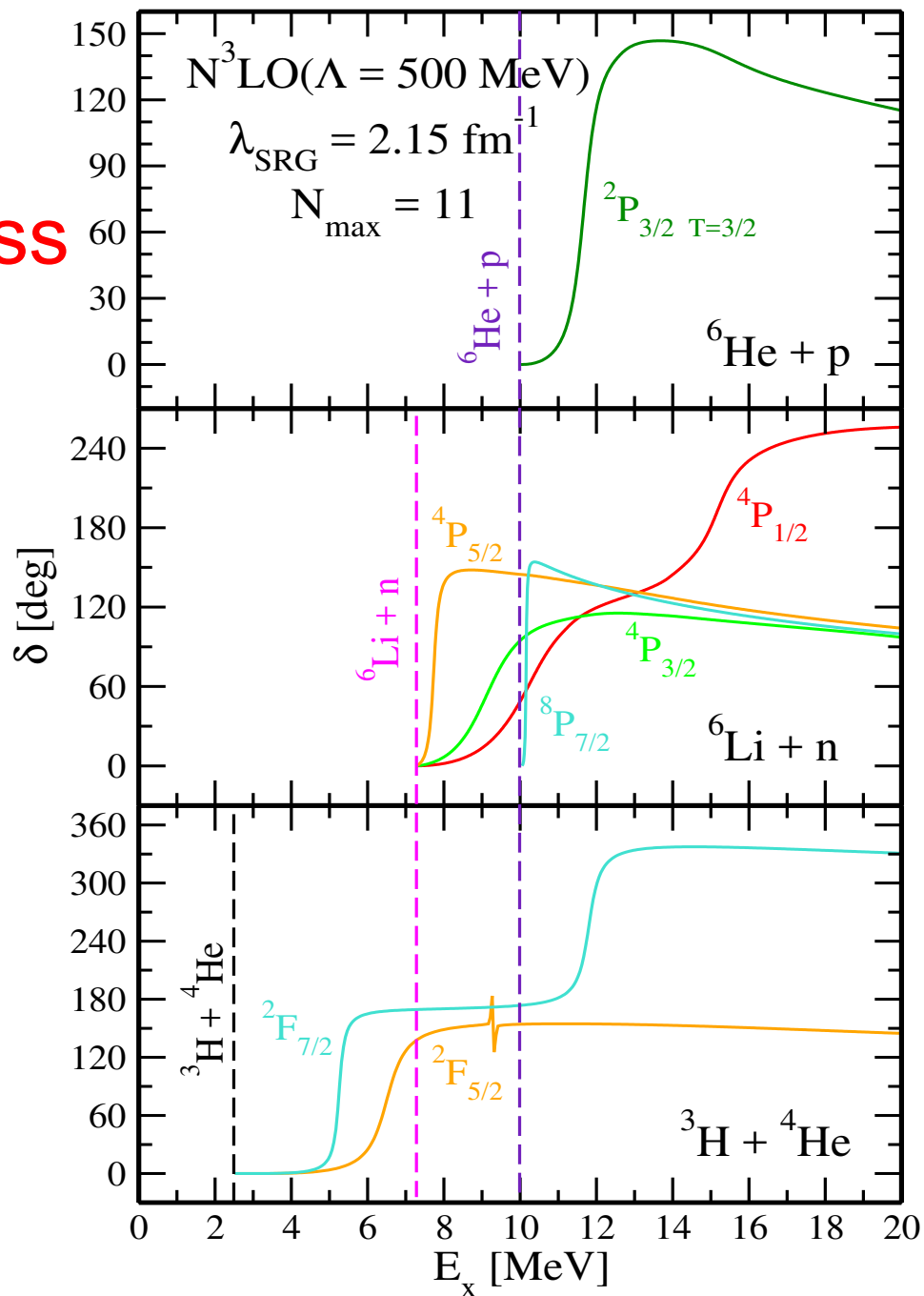
${}^7\text{Be}$ system – New predicted states



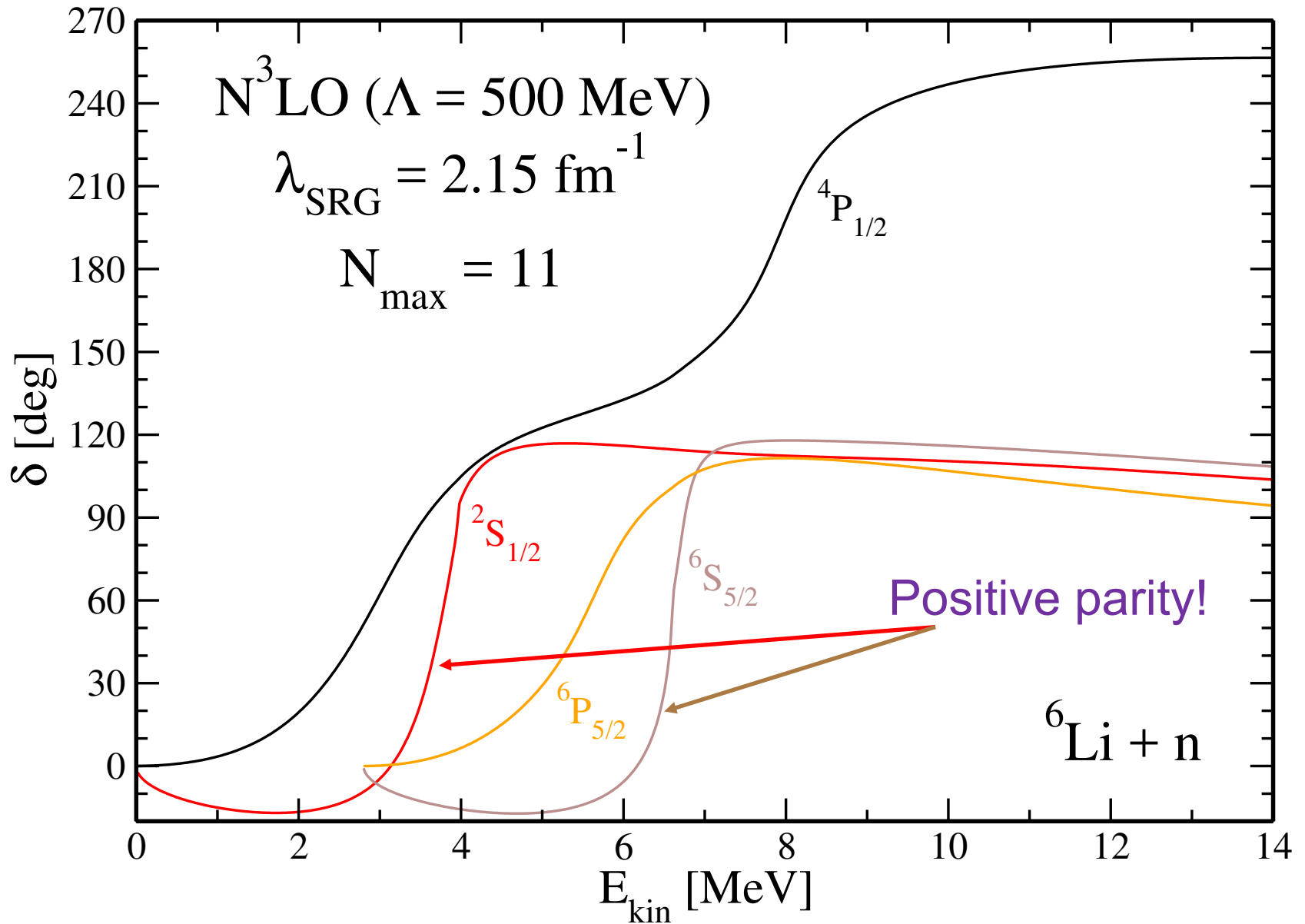
${}^7\text{Li}$ system

Analyzed mass partitions

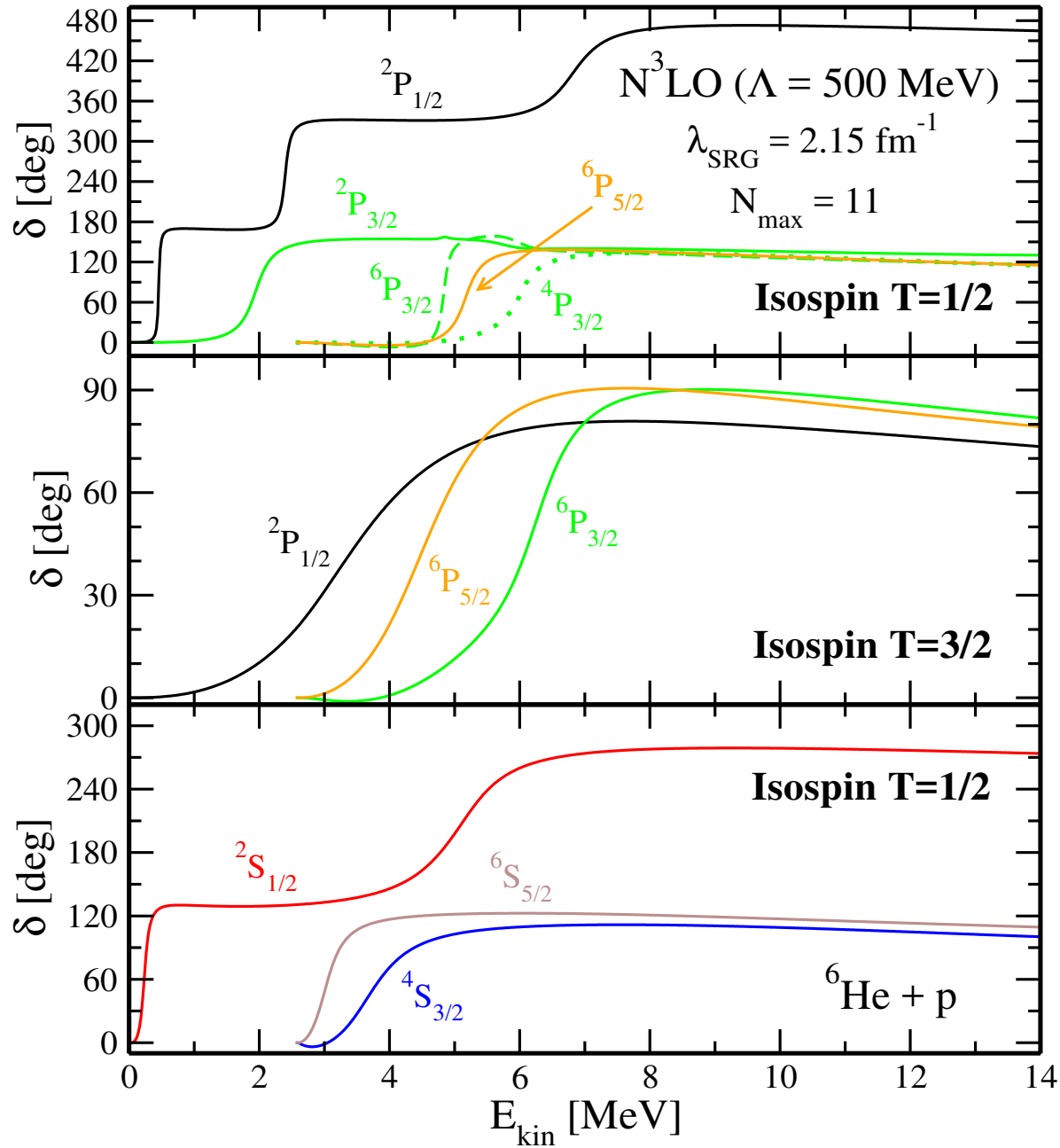
- ${}^6\text{He} + p$
- ${}^6\text{Li} + n$
- ${}^3\text{H} + {}^4\text{He}$



${}^7\text{Li}$ system – New predicted states



${}^7\text{Li}$ system – New predicted states



Summary & Outlook

- Reproduction of the experimental spectrum of ${}^7\text{Be}$ and ${}^7\text{Li}$
 - Predictions for possible new resonant states ($\pi=+,-$)
 - No new resonance found close to the ${}^6\text{Li} + p$ threshold
 - Possible S-wave found above the ${}^6\text{He} + p$ threshold
-
- Coupling between different mass partitions
 - Inclusion of 3N forces