Toward Realistic Description of Low energy Fusion for Astrophysics: Application to N-^{4}He and d-^{4}He Scattering

International Workshop XLI on Gross Properties of Nuclei and Nuclear Excitations: "Astrophysics and Nuclear Structure"

Hirshegg, January 29st 2013.

Guillaume Hupin

Lawrence Livermore National Laboratory

Collaborators:

S. Quaglioni *(LLNL)*
P. Navrátil *(TRIUMF,LLNL)*
R. Roth *(TU Darmstadt)*
J. Langhammer *(TU Darmstadt)*

LLNL-PRES-612212

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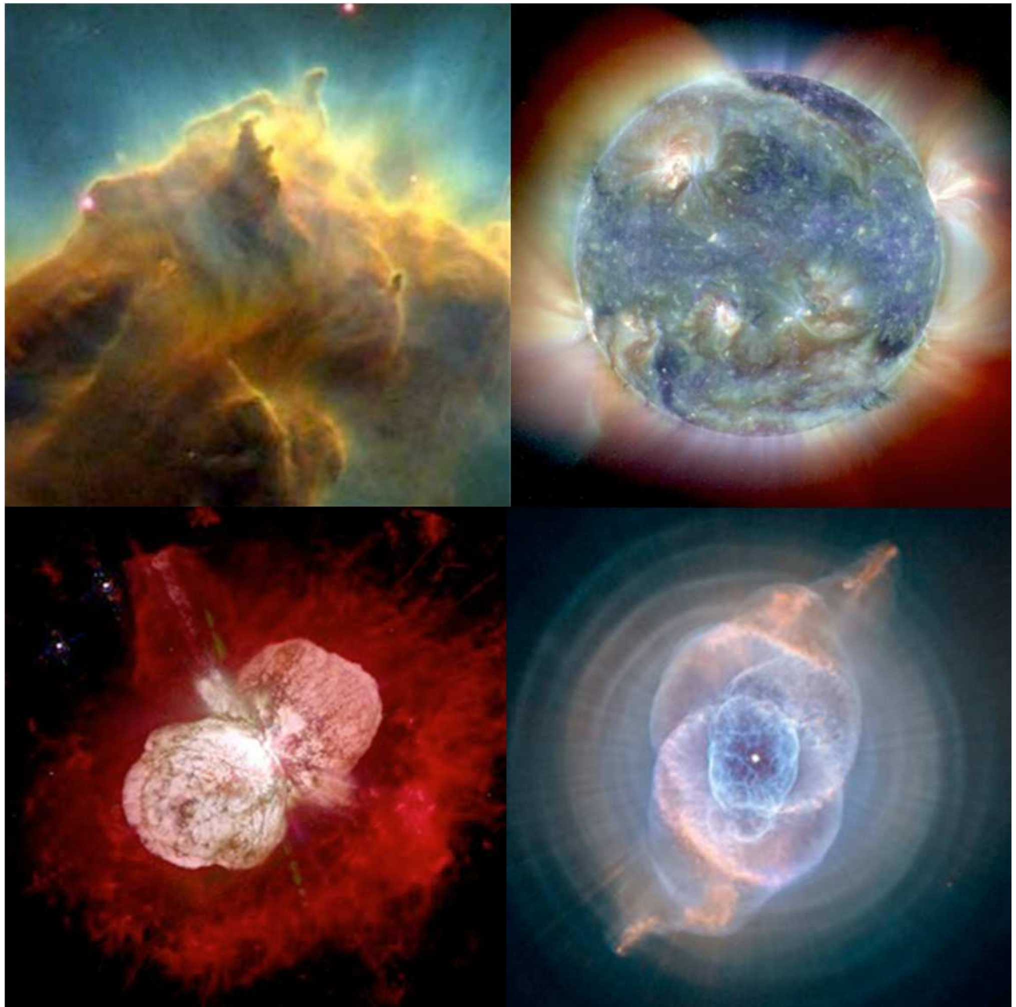
From Stars to Nuclei



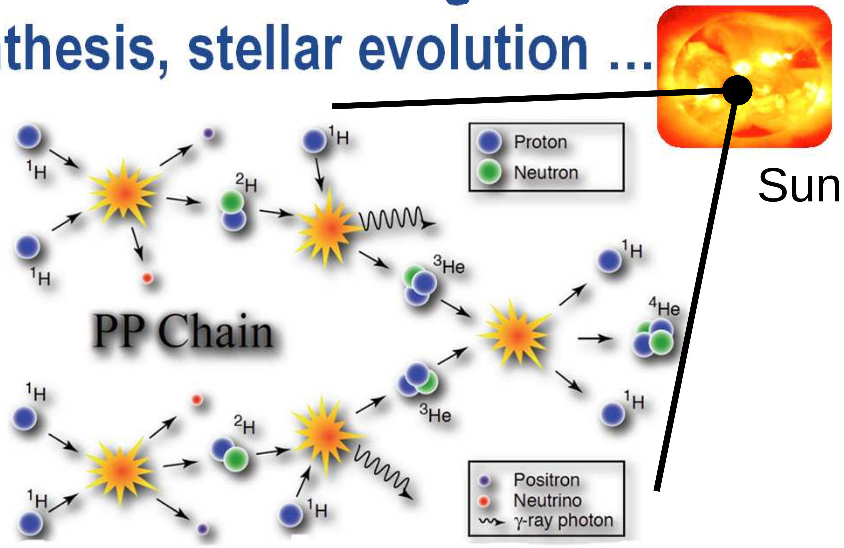
Evolution of stars: birth, main sequence and death

The sun ☉

H	73.46%
He	24.85%
O	0.77%
C	0.29%
Fe	0.16%

Fusion processes play an important role in determining the evolution of our universe: nucleosynthesis, stellar evolution …

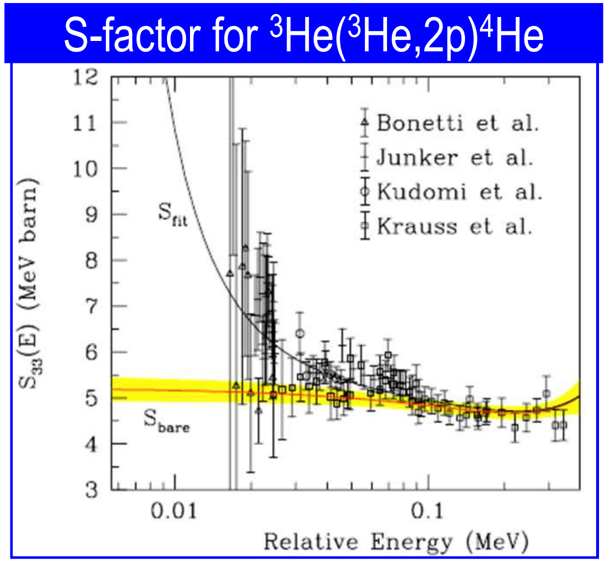
- What powers stars ?
- How long does a star live ?
- …



Nuclear astrophysics community relies on accurate fusion reactions observables among others.

Challenging for both experiment and theory:

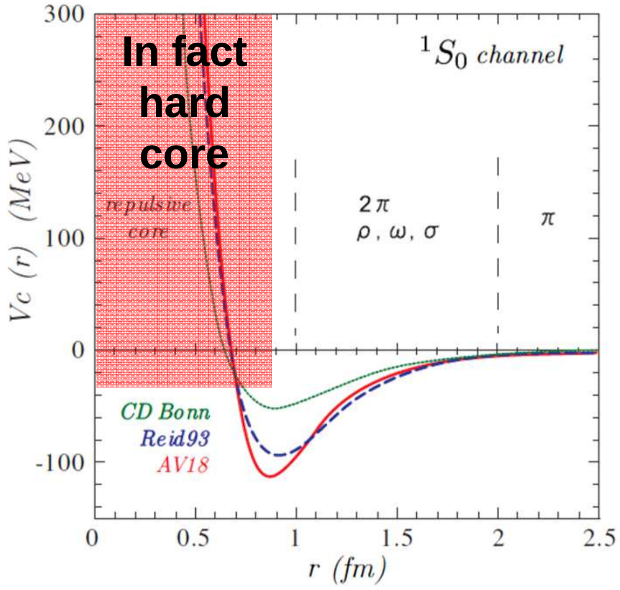
- Low rates: Coulomb repulsion between target and projectile + low energy (quantum tunneling effects).
- Projectile and target are not fully ionized in a lab. This leads to laboratory electron screening
- Fundamental theory is still missing



Some words about the ingredients of an *ab initio* calculation

A high precision nuclear Hamiltonian

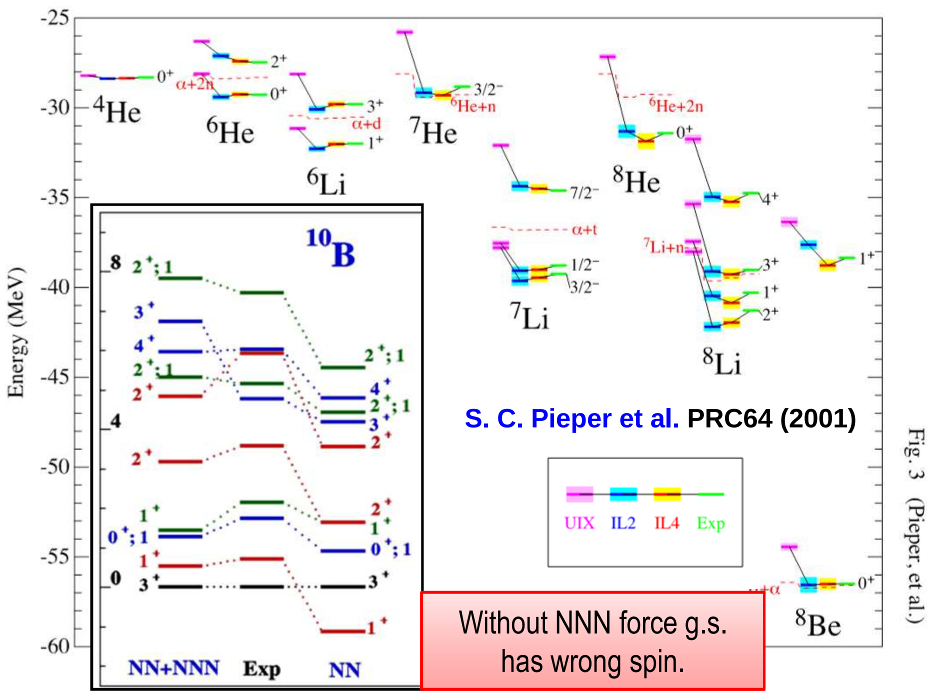
We have a NN interaction…



N. Ishii et al. PRL99 (2007)

The nuclear interaction has a strong repulsive core.
This makes nuclear structure calculation converge slowly.

…and also NNN interaction

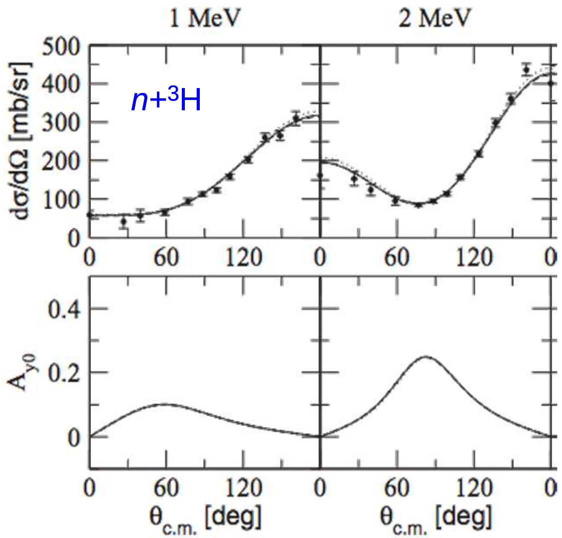


P. Navrátil et al. PRL 99 (2007)

We need a NNN interaction to achieve a high-precision.
This is ~100 times numerically costlier.

Status of nuclear reaction models

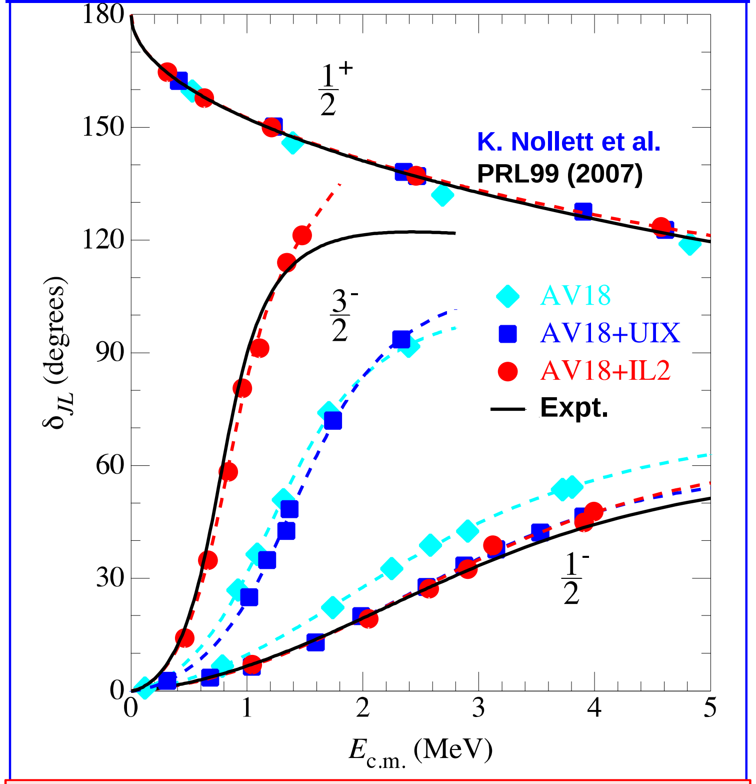
- *Ab initio* nuclear reactions lagging behind structure calculations
  - Exact reaction calculations for very light systems ***A*=3,4**
    - — Faddeev / Faddev-Yacubovsky
    - — Alt-Grassberger-Sandhas
    - — Hyperspherical Harmonics, …



M. Viviani at al.
PRC84 (2011)

  - Now trying to incorporate continuum effects in methods for light nuclei to describe reactions

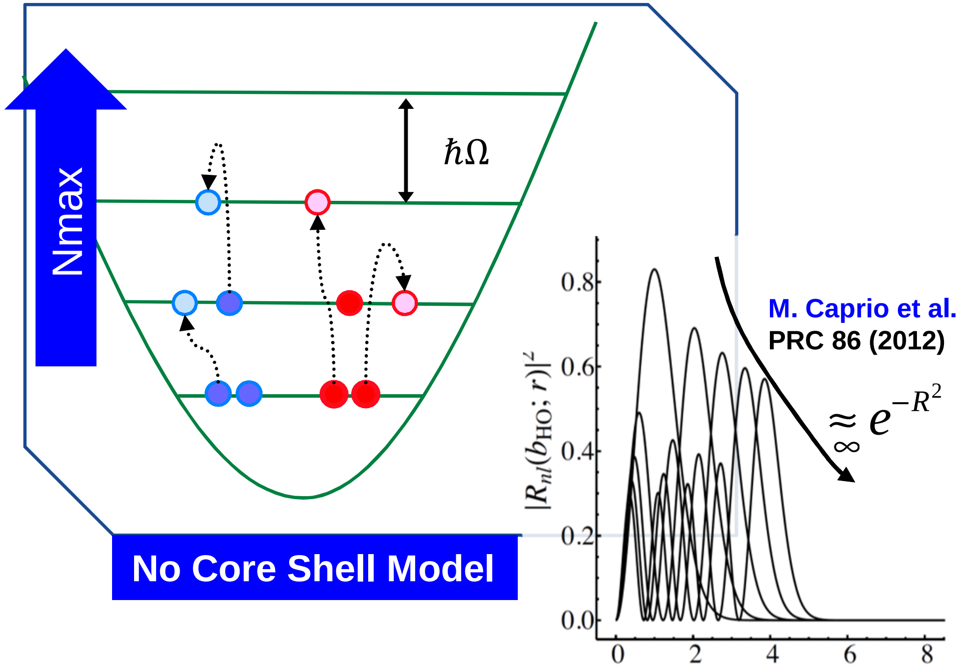
n-α phase-shifts in QMC calculation with/without NNN interaction



Nuclear scattering is sensitive to NNN interaction which plays an important role in the spin-orbit physic

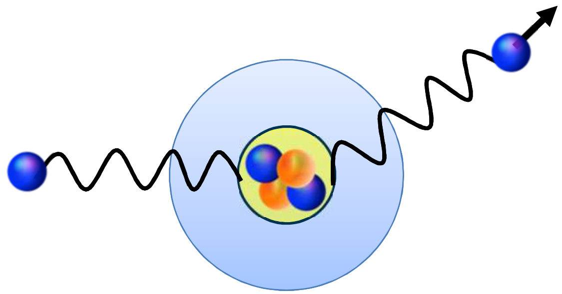
Why is it *hard* to model nuclear reactions?

If we used Harmonic oscillator states…



$$\Psi^{(A)} = \sum_{N=N_{\min}}^{N_{\max}} c_N \Phi_N^{HO}(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)$$

… inbound and outbound waves cannot be described by finite number of basis states



For more information on boundary conditions and R-matrix see
P. Descouvemont, D. Baye *Rep.Prog.Phys.*73 (2010)

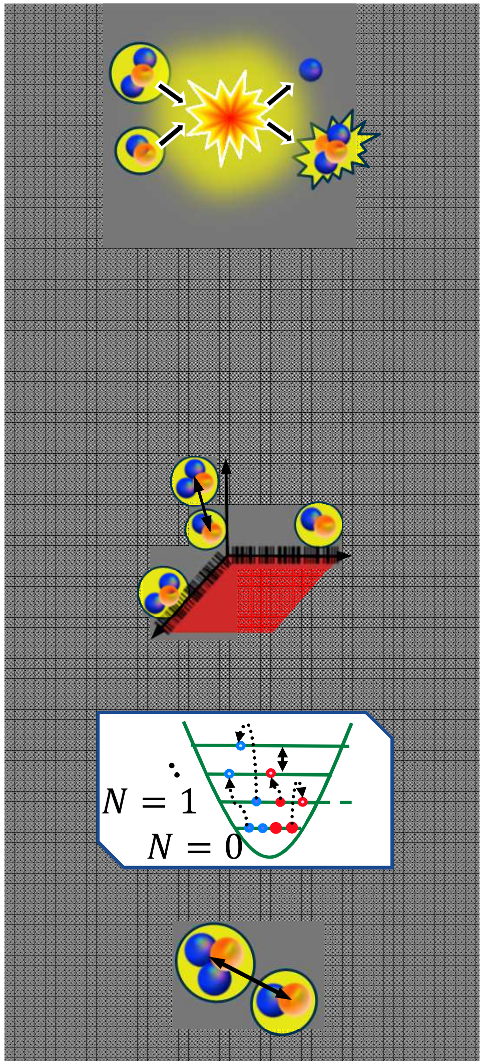
From nucleons to nuclear reactions

- Objective:

  Address static and dynamical properties of light ions and describe fusion reactions.

- Ingredients
  - High-precision nuclear interaction, two- plus three-nucleon, derived within the Chiral Effective Field Theory (EFT).

- Recipe
  - Solve the many-body Schrödinger equation.
  - Address structural properties. (bound states, narrow resonances)
    - *Ab initio* many-body approaches (A ≤ ~16); No-Core Shell Model (NCSM)
  - Address dynamical properties. (scattering, reactions)
    - Extend No-Core Shell-Model with the Resonating Group Method (RGM)



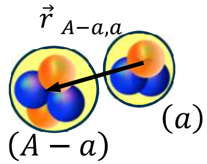
Ab initio NCSM/RGM: formalism for binary clusters

S. Quaglioni and P. Navrátil, Phys. Rev. Lett. 101, 092501 (2008); Phys. Rev. C 79, 044606 (2009)

- Starts from:

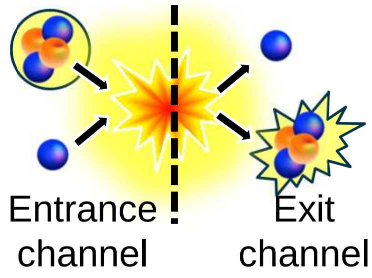
$$\Psi^{(A)}_{RGM} = \sum_{\nu} \int d\vec{r}\; g_\nu(\vec{r})\; \hat{A}_\nu \left|\Phi^{(A-a,a)}_{\nu\vec{r}}\right\rangle$$

Relative wave function (unknown) — Antisymmetrizer — Channel basis



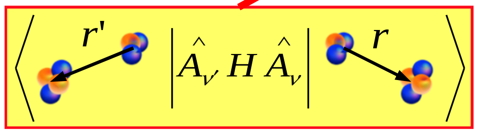
$$\psi^{(A-a)}_{\alpha_1}\psi^{(a)}_{\alpha_2}\delta(\vec{r}-\vec{r}_{A-a,a})$$

Ex: n-^{4}He scattering

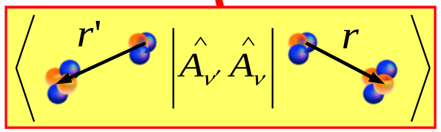


- Schrödinger equation on channel basis:

$$H\Psi^{(A)}_{RGM} = E\Psi^{(A)}_{RGM} \;\Rightarrow\; \sum_{\nu}\int d\vec{r}\left[H_{\nu'\nu}(\vec{r}',\vec{r}) - E\, N_{\nu'\nu}(\vec{r}',\vec{r})\right] g_\nu(\vec{r}) = 0$$



Hamiltonian kernel



Norm (overlap) kernel

$\propto$ NCSM densities

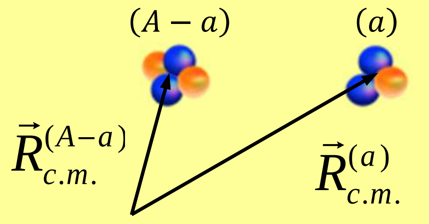
RGM accounts for: 1) interaction (Hamiltonian kernel), 2) Pauli principle (Norm kernel) between clusters and NCSM accounts for: internal structure of clusters

Matrix elements of translationally invariant operators

- Translational invariance is preserved (exactly!) also with SD cluster basis

$$
{}_{SD}\left\langle \Phi^{(A-a',a')}_{f_{SD}} \right| \hat{O}_{t.i.} \left| \Phi^{(A-a,a)}_{i_{SD}} \right\rangle_{SD} = \sum_{i_R f_R} M_{i_{SD} f_{SD}, i_R f_R} \left\langle \Phi^{(A-a',a')}_{f_R} \right| \hat{O}_{t.i.} \left| \Phi^{(A-a,a)}_{i_R} \right\rangle
$$

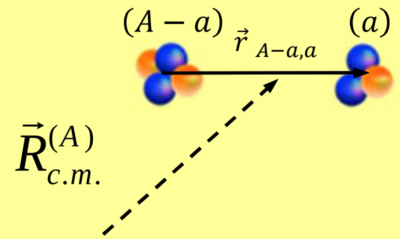
What we calculate in the "SD" channel basis



$$
\left| \psi^{(A-a)}_{\alpha_1} \right\rangle_{SD} \left| \psi^{(a)}_{\alpha_2} \right\rangle \varphi_{n\ell}(\vec{R}^{(a)}_{c.m.})
$$

Matrix inversion

Observables calculated in the translationally invariant basis



$$
\left| \psi^{(A-a)}_{\alpha_1} \right\rangle \left| \psi^{(a)}_{\alpha_2} \right\rangle \varphi_{n\ell}(\vec{r}_{A-a,a})
$$

- Advantage: can use powerful second quantization techniques

$$
{}_{SD}\left\langle \Phi^{(A-a',a')}_{\nu' n'} \right| \hat{O}_{t.i.} \left| \Phi^{(A-a,a)}_{\nu n} \right\rangle_{SD} \propto {}_{SD}\left\langle \psi^{(A-a')}_{\alpha_1'} \right| a^+ a \left| \psi^{(A-a)}_{\alpha_1} \right\rangle_{SD}, \; {}_{SD}\left\langle \psi^{(A-a')}_{\alpha_1'} \right| a^+ a^+ a a \left| \psi^{(A-a)}_{\alpha_1} \right\rangle_{SD}, \; \cdots
$$

Going around the hard core problem

E. Jurgenson, Navrátil, R. J. Furnstahl Phys. Rev. Lett. 103 (2009)

In configuration interaction methods we need to soften interaction to address the hard core
We use the Similarity-Renormalization-Group (SRG) method

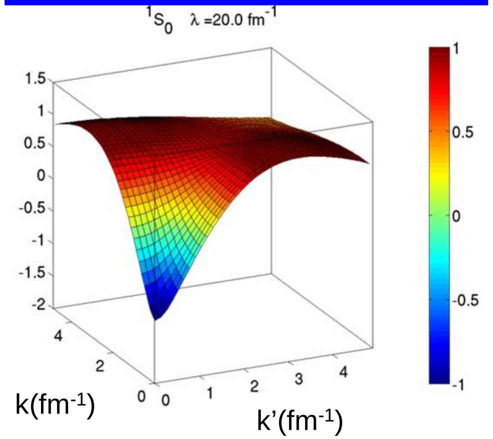
$$H_\lambda = U_\lambda H U_\lambda^+$$

Unitary transformations

$$\begin{cases} \dfrac{dH_\lambda}{d\lambda} = [\eta(\lambda), H_\lambda] \\ \eta(\lambda) = \dfrac{dU_\lambda}{d\lambda} U_\lambda^+ \end{cases}$$

Flow parameter

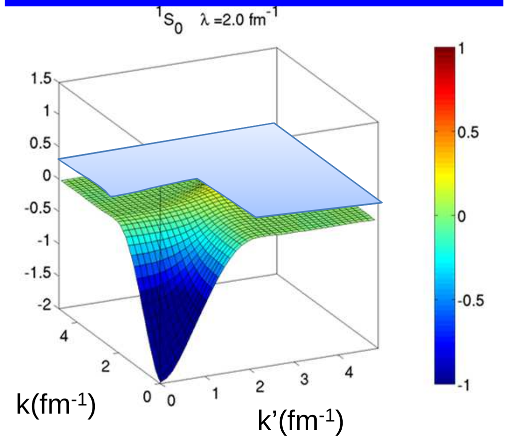
Bare potential



Evolution with flow parameter λ

- Preserves the physics
- Decouples high and low momentum
- Induces many-body forces

Evolved potential



Demonstrated capability to describe binary-cluster reactions starting from NN interactions

☑ Nucleon-nucleus collisions

- ✓ n-^{3}H, p-^{3}He, N-^{4}He, n-^{10}Be scattering with N^{3}LO NN (mod. Lee-Suzuki eff. Int.)
- ✓ Nucleon scattering on ^{3}H, ^{3,4}He,^{7}Li,^{7}Be,^{12}C,^{16}O with SRG-N^{3}LO
- ✓ ^{7}Be(p,γ)^{8}B radiative capture with SRG-N^{3}LO

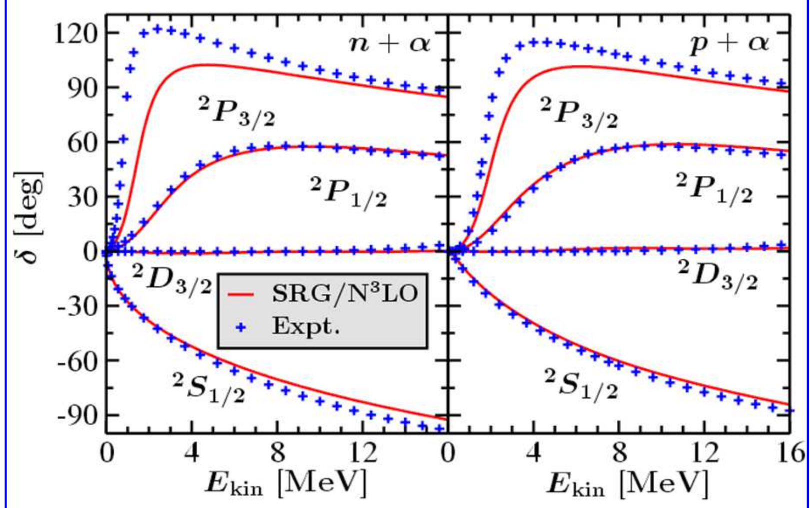
☑Deuterium-nucleus collisions

- ✓ d-^{4}He scattering and ^{6}Li structure with SRG-N^{3}LO

☑(d,N) transfer reactions

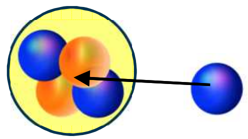
- ✓ ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He reactions with SRG-N^{3}LO

n-He^{4} phase-shift NN only



λ dependent

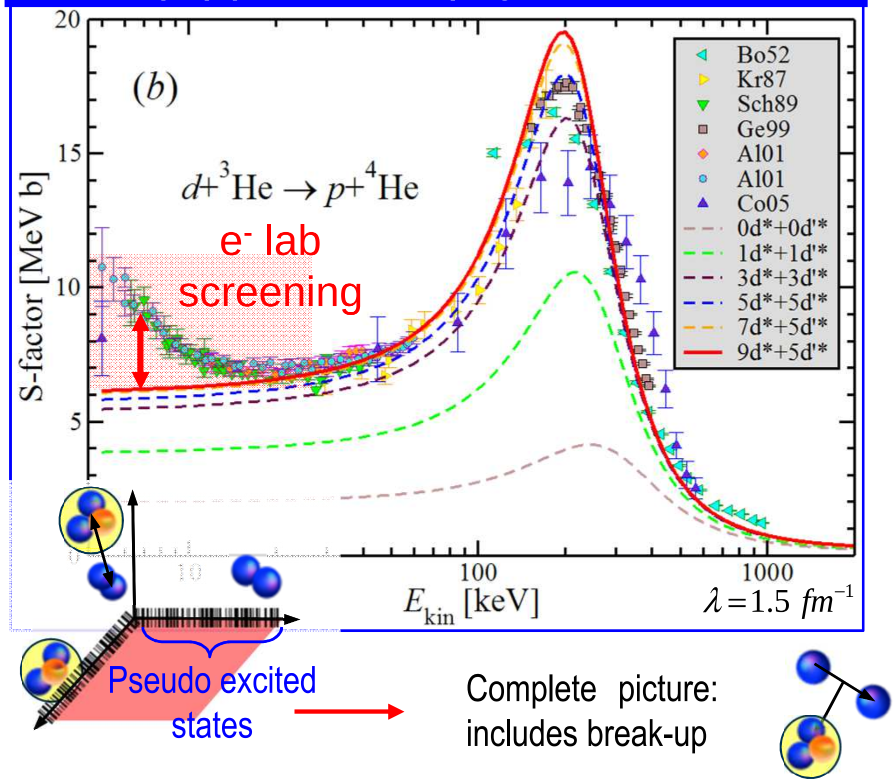
Good reproduction, but still incomplete



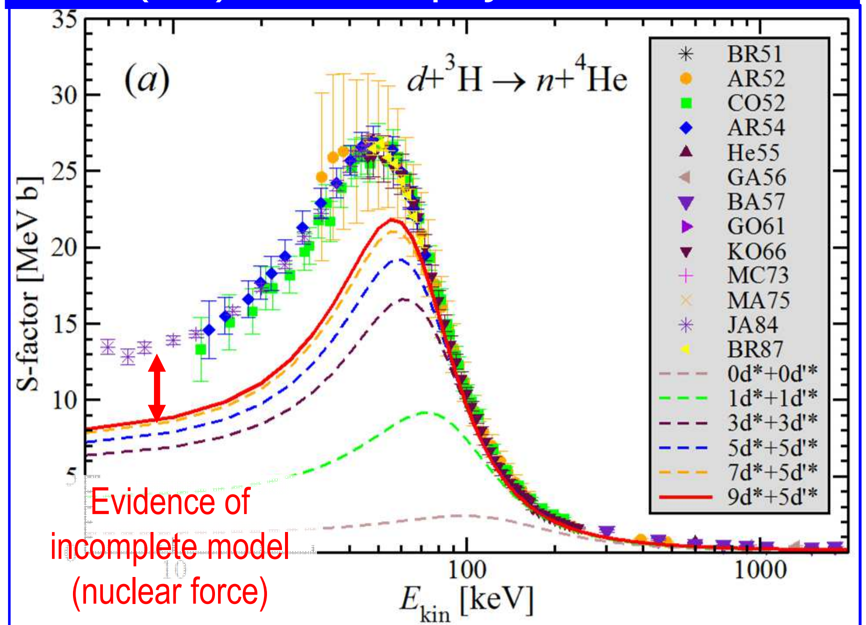
n on ^{4}He scattering

Ab initio many-body calculations of the ^{3}H(d,n)^{4}He and ^{3}He(d,p)^{4}He fusion P. Navrátil, S. Quaglioni, PRL 108, 042503 (2012)

^{3}He(d,p)^{4}He astrophysical S-factor



^{3}H(d,n)^{4}He astrophysical S-factor



NCSM/RGM results for the ^{3}He(d,n)^{4}He astrophysical S-factor compared to beam-target measurements.

Calculated S-factors converge with the inclusion of the virtual breakup of the deuterium, obtained by means of excited $^3S_1$-$^3D_1$ (d^*) and $^3D_2$ (d'^*) pseudo-states.

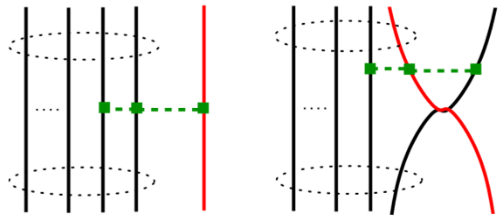
Incomplete nuclear interaction: requires NNN force (SRG-induced + "real")

Including the NNN force into the NCSM/RGM approach

nucleon-nucleus formalism

$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} V^{NNN} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle = \left\langle \overset{(A-1)}{\bullet}\ r' \ \bullet (a'=1) \middle| V^{NNN} \left(1 - \sum_{i=1}^{A-1} \hat{P}_{iA}\right) \middle| (a=1)\ \bullet\ r\ \overset{(A-1)}{\bullet} \right\rangle$$

$$\mathcal{V}^{NNN}_{\nu'\nu}(r,r') = \sum R_{n'l'}(r') R_{nl}(r) \left[\frac{(A-1)(A-2)}{2} \langle \Phi^{J^\pi T}_{\nu' n'} | V_{A-2A-1A}(1-2P_{A-1A}) | \Phi^{J^\pi T}_{\nu n} \rangle \right.$$

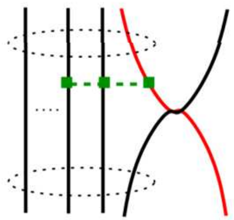


(a) (b)

Direct potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_i^+ a_j^+ a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

$$\left. - \frac{(A-1)(A-2)(A-3)}{2} \langle \Phi^{J^\pi T}_{\nu' n'} | P_{A-1A} V_{A-3A-2A-1} | \Phi^{J^\pi T}_{\nu n} \rangle \right] .$$

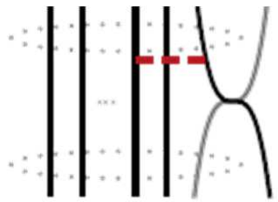


(c)

Exchange potential:

$$\propto {}_{SD}\left\langle \psi^{(A-1)}_{\alpha_1'} \middle| a_h^+ a_i^+ a_j^+ a_m a_l a_k \middle| \psi^{(A-1)}_{\alpha_1} \right\rangle_{SD}$$

We are following two ways of handling the three-body density



$$=$$

- **+** efficient for addressing different projectile
- **+** coupled scheme (makes a good use of Racah algebra)

$$\sum_{\substack{j_0 j'_0 t_0 t'_0 \\ J_0 T_0}} \sum_{\substack{n_a l_a j_a \\ n_b l_b j_b}} \sum_{\substack{n_\alpha l_\alpha j_\alpha \\ n'_a l'_a j'_a}} \sum_{\substack{n'_b l'_b j'_b \\ g' t'_g}} \sum_{\phi'' I_\beta T_\beta} \frac{1}{12}\hat{J}_0 \hat{T}_0 \hat{g}' \hat{t}'_g (- \ldots$$

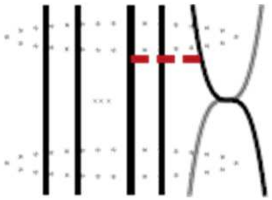
$$\begin{Bmatrix} I_\beta & g' & I'_1 \\ J_0 & j'_0 & j' \\ J_1 & j & J \end{Bmatrix} \begin{Bmatrix} T_\beta & t'_g & T'_1 \\ T_0 & t'_0 & \frac{1}{2} \\ T_1 & \frac{1}{2} & T \end{Bmatrix}$$

$$\langle \phi'^{(A-1)} I'_1 T'_1 \| (a^\dagger_{nlj} (a^\dagger_{n'_b l'_b j'_b} a^\dagger_{n'_a l'_a j'_a})^{j'_0 t'_0})^{g' t'_g} \| \phi''^{(A-4)} I_\beta T_\beta \rangle$$

$$\langle \phi''^{(A-4)} I_\beta T_\beta \| ((\tilde{a}_{n_\alpha l_\alpha j_\alpha} \tilde{a}_{n_a l_a j_a})^{j_0 t_0} \tilde{a}_{n_b l_b j_b})^{J_0 T_0} \| \phi^{(A-1)} I_1 T_1 \rangle$$

$$_a\langle ((n'_a l'_a j'_{a'}, n'_b l'_b j'_b) j'_0 t'_{0'}, n' l' j') J_0 T_0 | V_{3N} | ((n_\alpha l_\alpha j_\alpha, n_a l_a j_a) j_0 t_0, n_b l_b j_b) J_0 T_0 \rangle_a$$

We are following two ways of handling the three-body density



$=$

$$\sum_{jj'}\sum_{M_1 m_j}\sum_{M_{T_1} m_t}\sum_{M'_1 m'_j}\sum_{M'_{T_1} m'_t}\frac{1}{12}(-1)^{I_1+I'_1+}$$

$$\begin{pmatrix} I_1 & j \\ M_1 & m_j \end{pmatrix}\begin{vmatrix} J \\ M_J \end{pmatrix}\begin{pmatrix} T_1 & \frac{1}{2} \\ M_{T_1} & m_t \end{pmatrix}\begin{vmatrix} T \end{vmatrix}$$

$$\sum_{\beta_{A-3}}\sum_{\beta_{A-2}}\sum_{\beta'_{A-3}}\sum_{\beta'_{A-2}}\sum_{\beta'_{A-1}}$$

$$\langle \phi'^{(A-1)} I'_1 M'_1 T'_1 M'_{T_1} | a^\dagger_{nljm_j\frac{1}{2}m_t} a^\dagger_{\beta_{A-2}} a^\dagger_{\beta_{A-3}} a_{\beta'_{A-3}} a_{\beta'_{A-2}} a_{\beta'_{A-1}} | \phi^{(A-1)} I_1 M_1 T_1 M_{T_1} \rangle$$

$${}_a\langle \beta_{A-3}\beta_{A-2} n'l'j'm'_j \tfrac{1}{2} m'_t | V_{3N} | \beta'_{A-3}\beta'_{A-2}\beta'_{A-1} \rangle_a$$

+ acces to heavier targets
+ no averaged isospin
+ perfectly parallel

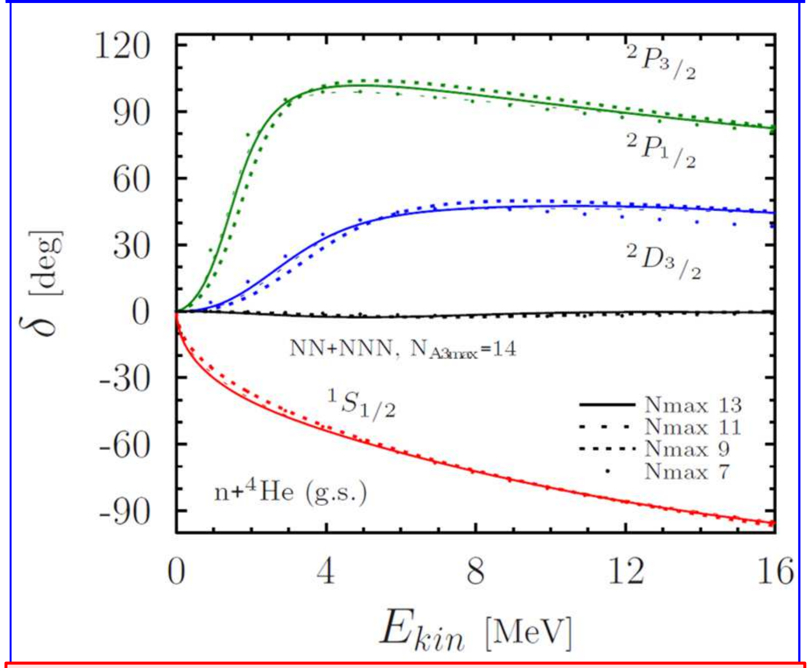
treatment of M_J & M_T q.n.

new computational scheme & infrastructure

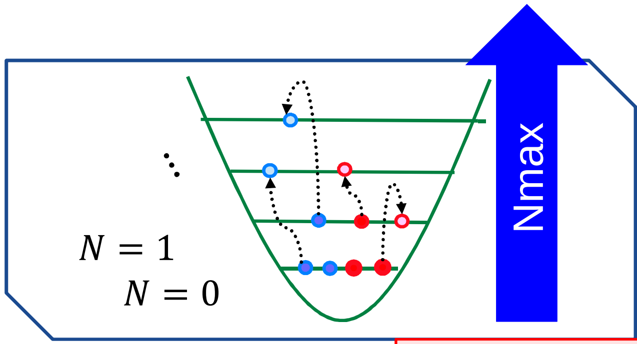
n-^{4}He scattering: study of the model space convergence

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Convergence with respect to the number of HO major shells



Convergence of the phase-shifts as a function of the HO basis size.



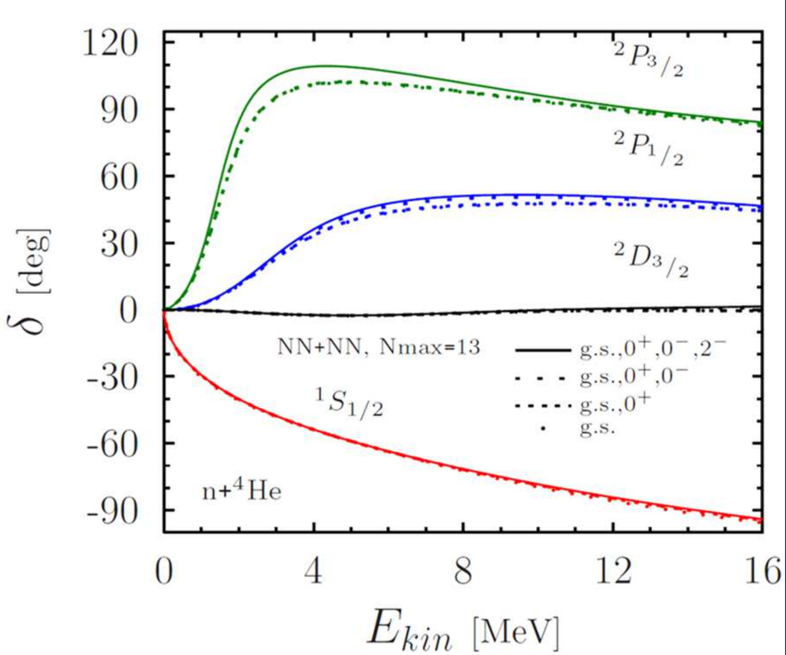
Expanding the size in the HO space.

- Calculations are done using the <u>chiral EFT interaction</u> at N^{3}LO for the NN and N^{2}LO for the NNN.
- For this study, we take ħω=20
- The SRG flow parameter is λ=2.0
- Convergence pattern is good.

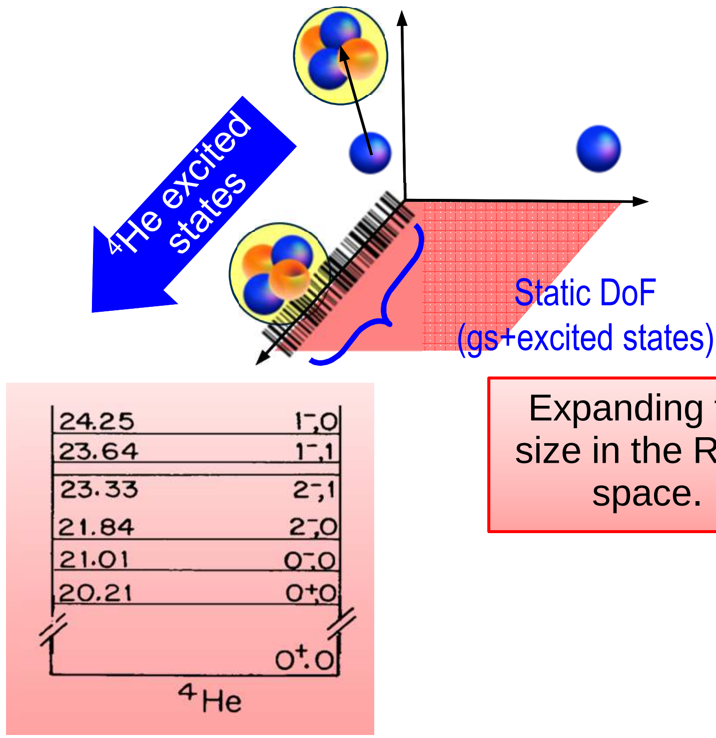
n-^{4}He scattering: study of the RGM convergence in the NNN case

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

NNN case: convergence with respect to the many body space, first excited states



Convergence of the phase-shifts as a function of the ^{4}He excited states.



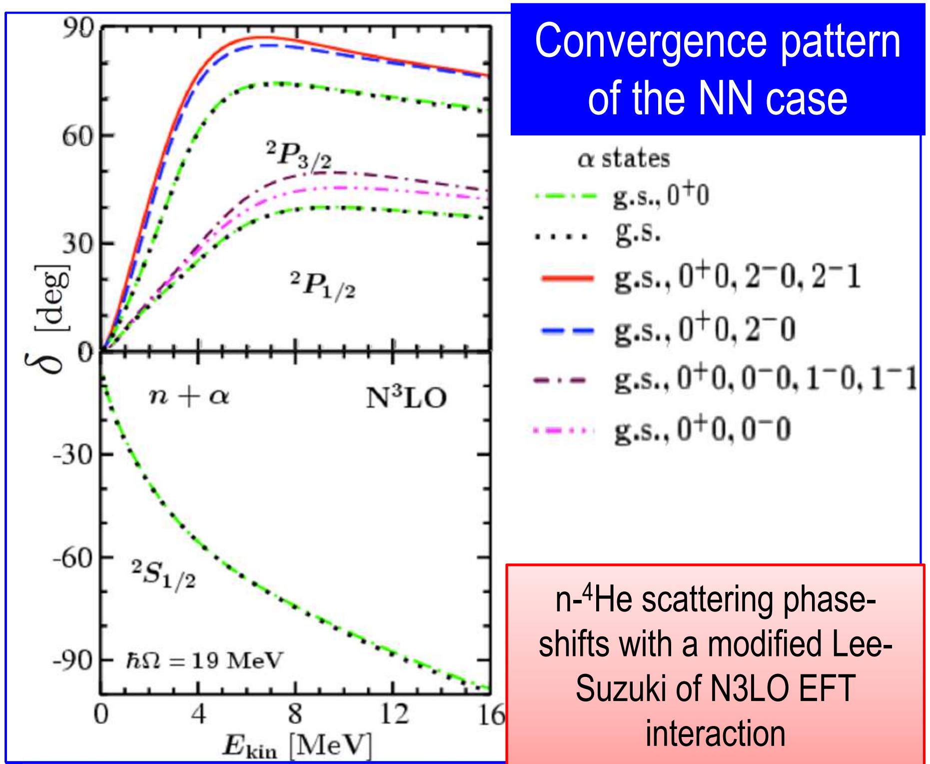
Expanding the size in the RGM space.

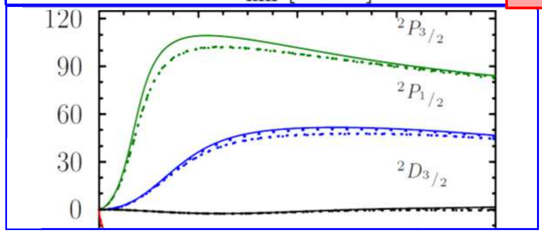
- **A systematic exploration of the Nmax and # of target eigenstates is ongoing.**

n-^{4}He scattering: study of the RGM convergence in the NN case

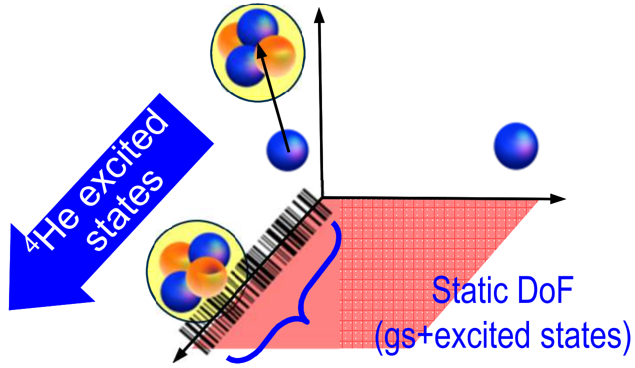
P. Navrátil and S. Quaglioni, Phys. Rev. C 83 044609, (2011)

Convergence pattern of the NN case





n-^{4}He scattering phase-shifts with a modified Lee-Suzuki of N3LO EFT interaction



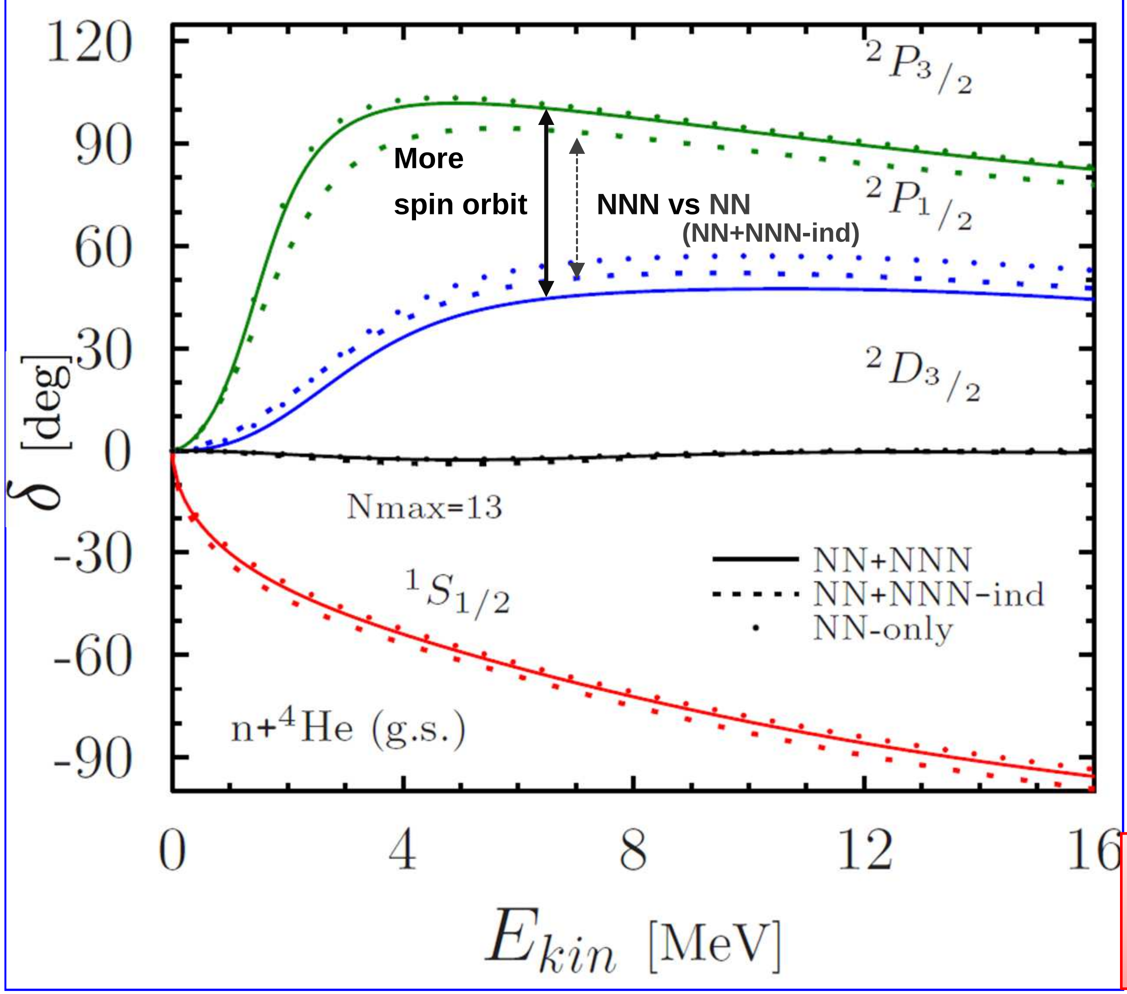
Expanding the size in the RGM space.

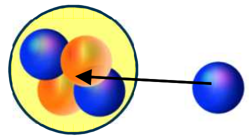
- **The phase-shifts are sensitive to the inclusion of the first six excited states of ^{4}He.**
- **The convergence pattern of the NNN-full is similar.**

n-^{4}He scattering: NN versus NNN interactions, first results

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Nuclear interaction NN→NN+NNN





n-^{4}He scattering

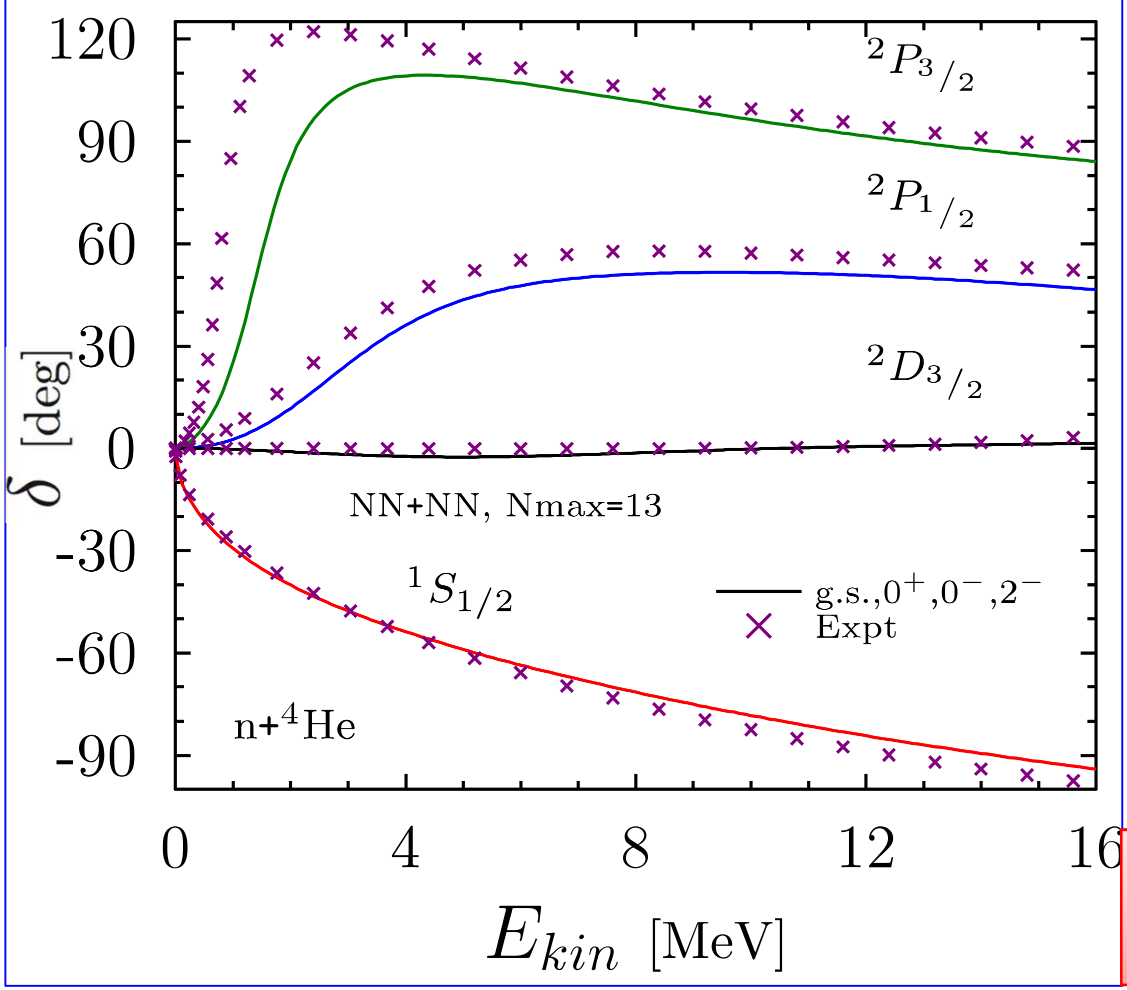
- The largest splitting between *P* waves is obtained with NN+NNN.

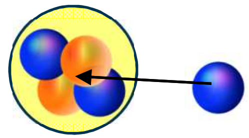
Comparison between NN, NN+NNN-ind and NN+NNN at Nmax=13

n-^{4}He scattering: NN+NNN with the first three excited states

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Nuclear interaction NN→NN+NNN





n on ^{4}He scattering

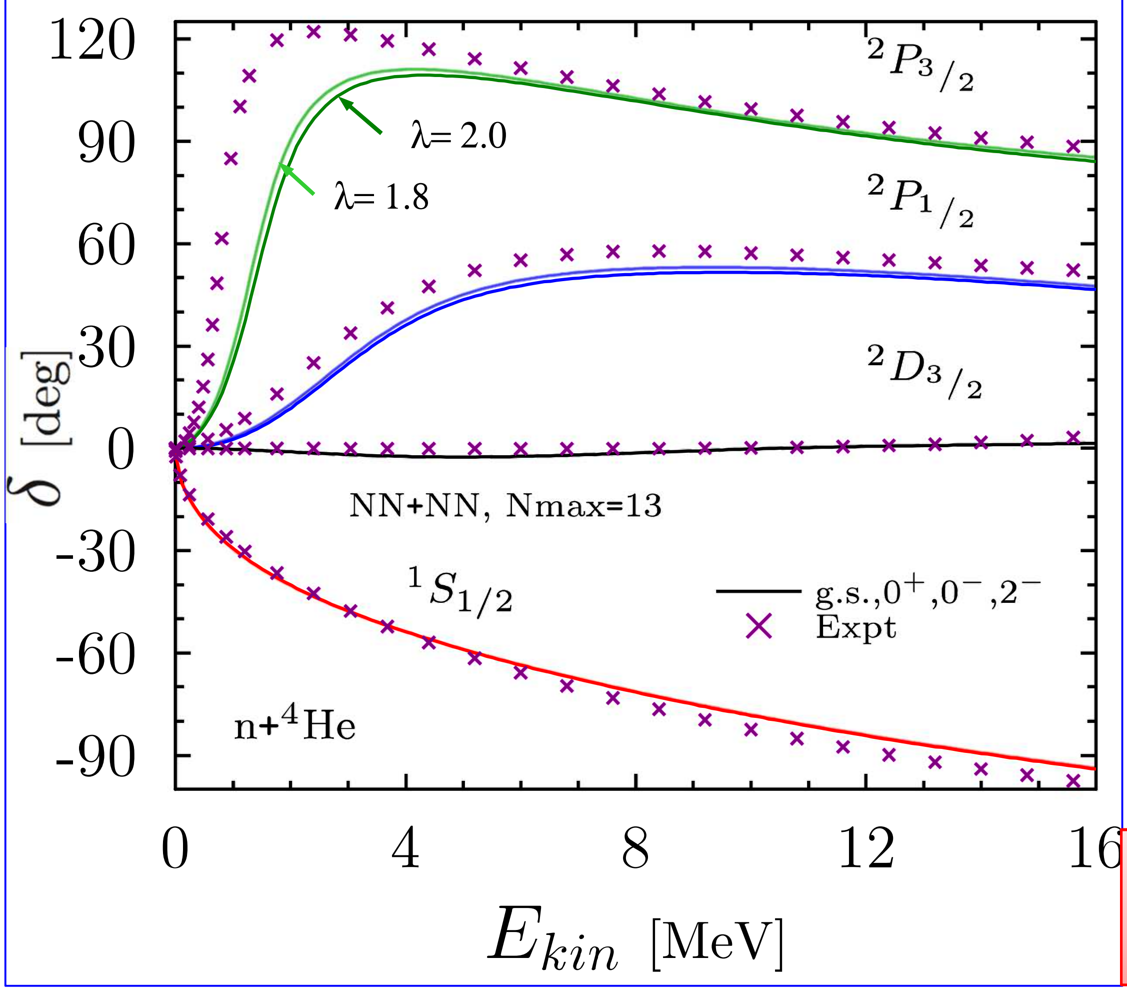
- The largest splitting between *P* waves is obtained with NN+NNN.
- We expect a better reproduction of data when all the first six excited state of ^{4}He included (ongoing study).
- The present NNN force is incomplete (N^2LO only).

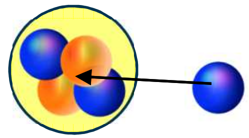
Comparison between NN+NNN and experiment at Nmax=13 and λ=2.0

Preliminary results for the lambda dependence

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

Nuclear interaction NN➔NN+NNN





n on ^{4}He scattering

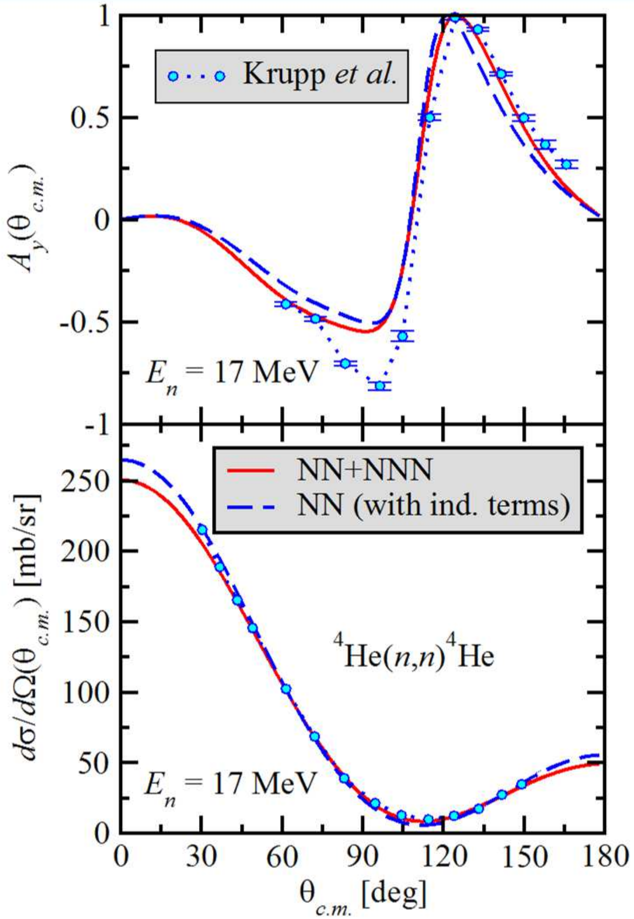
- The SRG evolution is to a good extend unitary.
- A wider range of λ value needs to be explored before a definite conclusion.
- The last sixth excited states of ^{4}He should be included to compare converged results

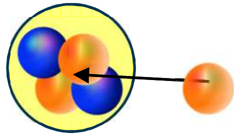
Comparison with NN+NNN at Nmax=13 between λ=2.0 and 1.8

Cross section and p-^{4}He scattering

G. Hupin, J. Langhammer, S. Quaglioni, P. Navrátil, R. Roth, work in progress

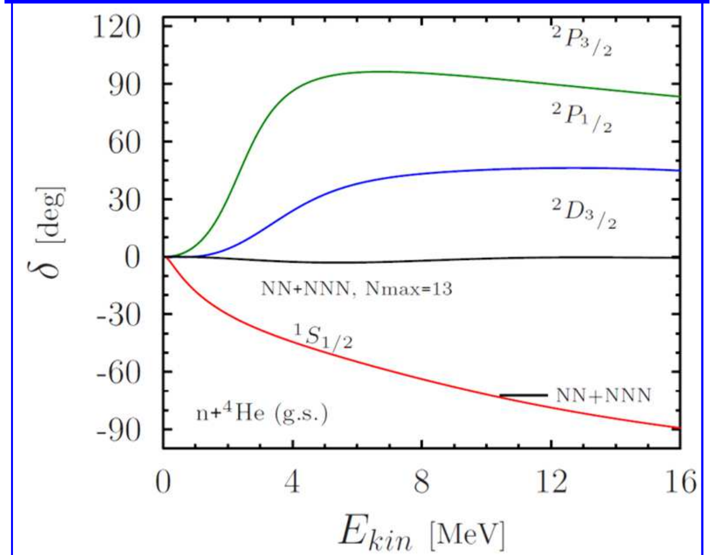
Analyzing power and n-4He cross section





p-^{4}He scattering

p-4He phase-shifts

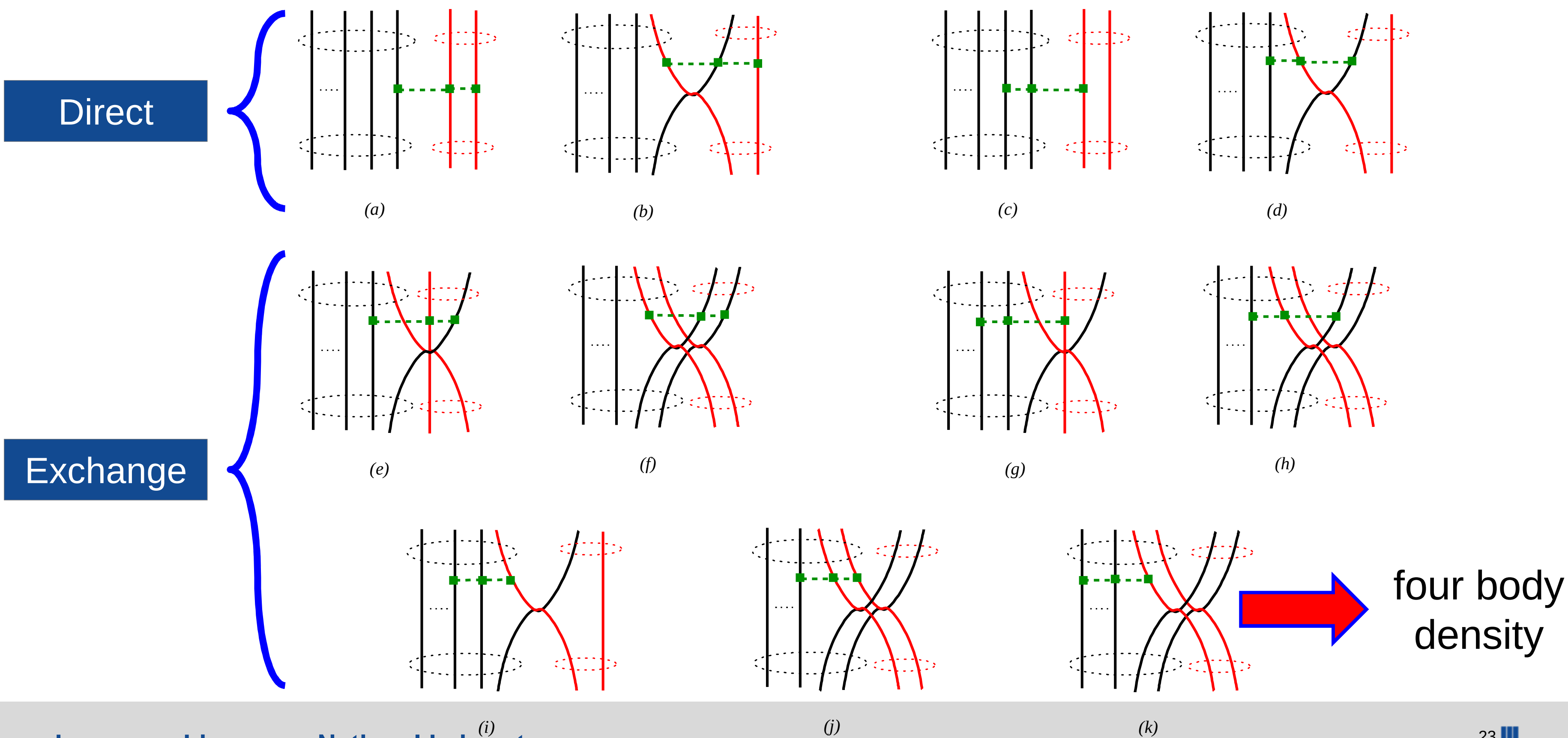


The breaking of isospin symmetry was tested in the p-^{4}He scattering

Including the NNN force into the NCSM/RGM approach

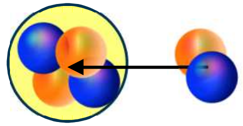
deuteron-nucleus formalism

$$\left\langle \Phi^{J^\pi T}_{\nu' r'} \middle| \hat{A}_{\nu'} V^{NNN} \hat{A}_{\nu} \middle| \Phi^{J^\pi T}_{\nu r} \right\rangle = \left\langle \begin{matrix}(A-2)\\ r' \\ (a'=2)\end{matrix} \middle| V^{NNN} \left(1 - \sum_{i=1}^{A-2} \sum_{k=A-1}^{A} \hat{P}_{i,k} + \sum_{i<j=1}^{A-2} \hat{P}_{i,A-1} \hat{P}_{j,A} \right) \middle| \begin{matrix}(A-2)\\ r \\ (a=2)\end{matrix} \right\rangle$$

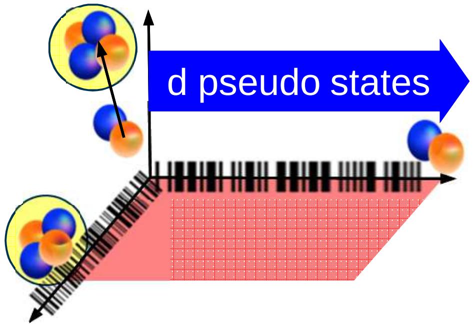


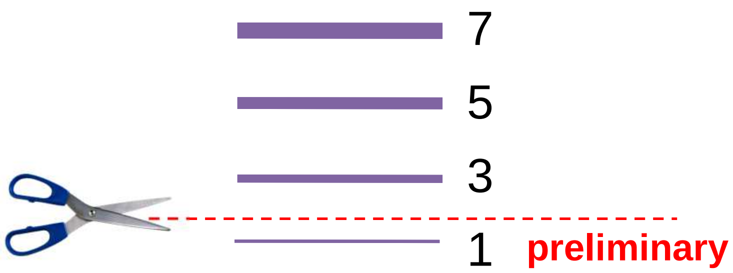
^{4}He(d,d)^{4}He with NN+NNN interaction

G. Hupin, S. Quaglioni, P. Navratil, work in progress



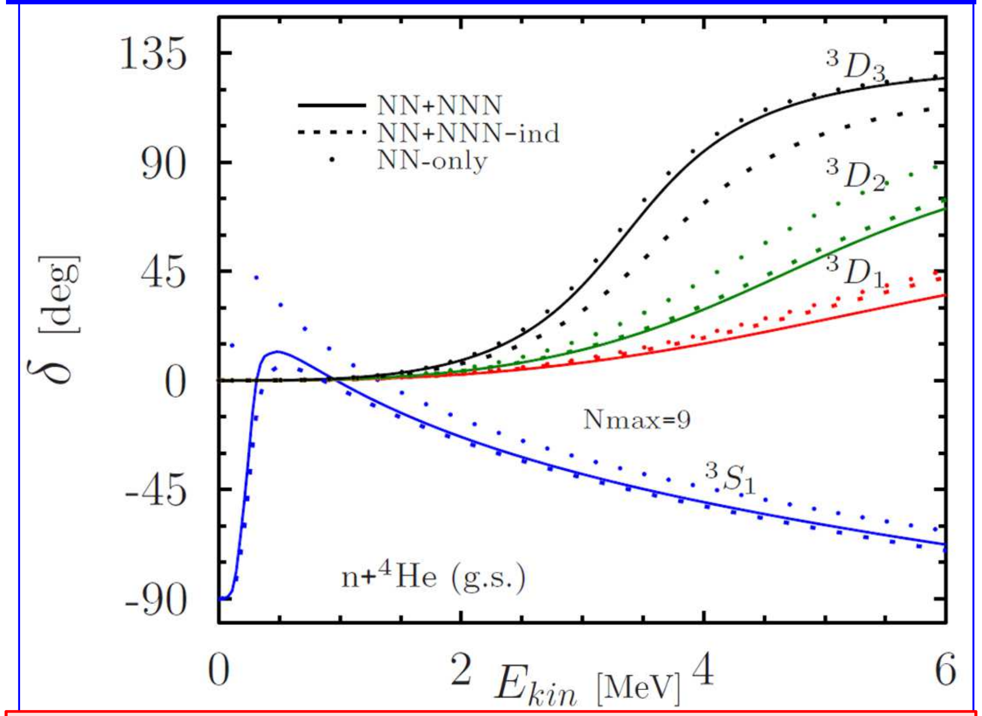
d-^{4}He scattering





Pseudo-states
in each channel
d(g.s., $^3S_1$-$^3D_1$, $^3D_2$, $^3D_3$-$^3G_3$)

Phase shifts with λ= 2 fm^{-1}

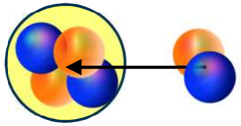


d(g.s.) + ^{4}He(g.s.) scattering phase-shifts for NN, NN+NNN-induced and NN+NNN potential with λ=2 fm^{-1}.

Preliminary results in a small model space and with only d and ^{4}He g.s., look promising

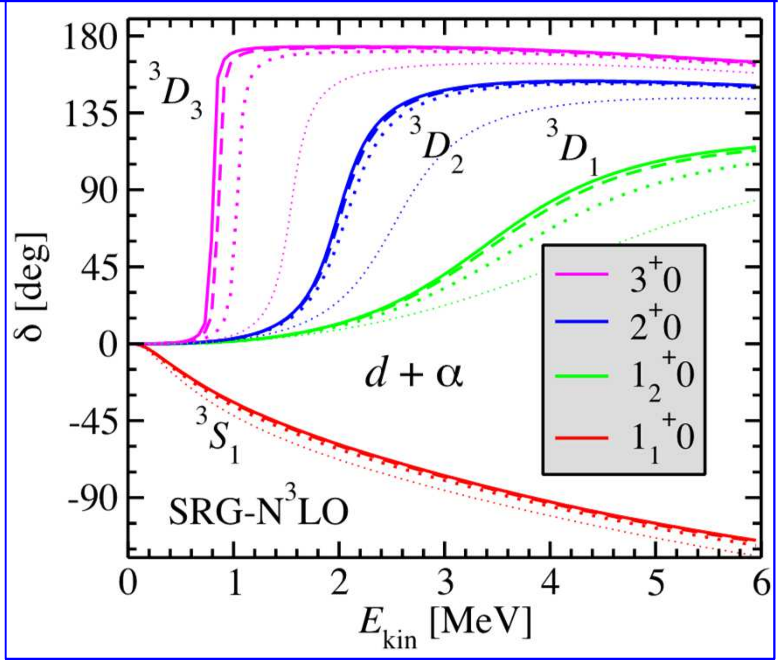
^{4}He(d,d)^{4}He with NN-only

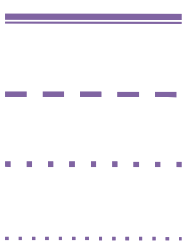
S. Quaglioni and P. Navratil



d-^{4}He scattering

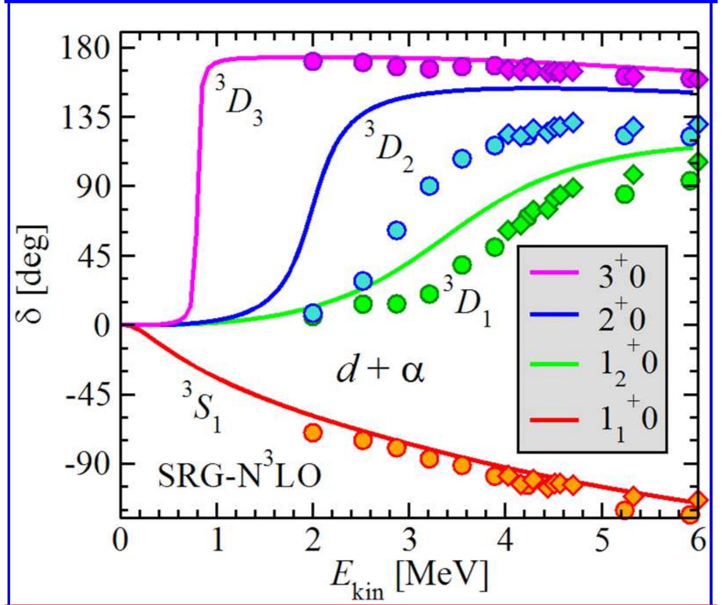
^{4}He(d,d)^{4}He phase shifts





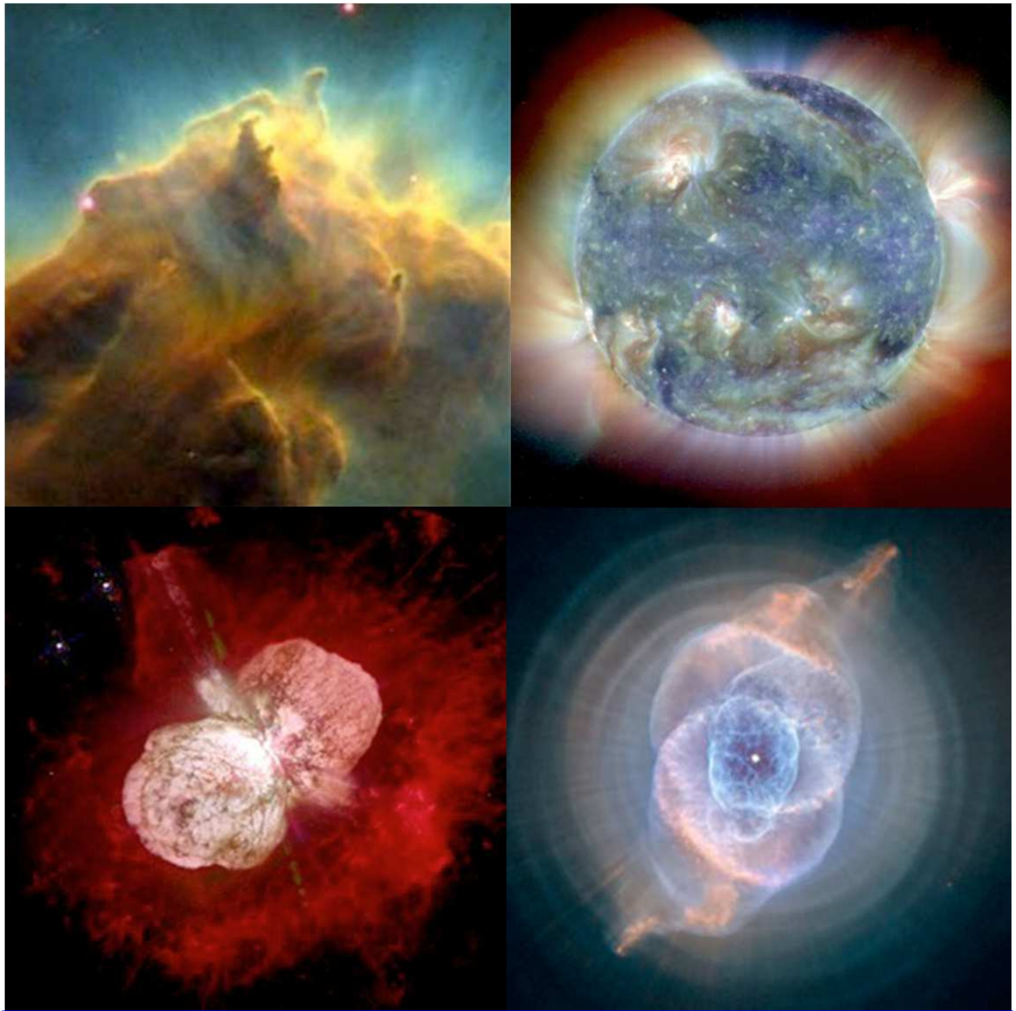
Pseudo-states in each channel

Phase shifts with λ= 1.5 fm^{-1}



N_{max}= 12 d(g.s.,$^3S_1$-$^3D_1$, $^3D_2$, $^3D_3$-$^3G_3$) + ^{4}He(g.s.) SRG-N^{3}LO NN potential with λ=1.5 fm^{-1}.

Conclusions and Outlook



Evolution of stars, birth, main sequence, death

- We are extending the *ab initio* NCSM/RGM approach to describe low-energy reactions with two- and three-nucleon interactions.

- We are able to describe:
  - Nucleon-nucleus collisions with NN+NNN interaction
  - Deuterium-nucleus collisions with NN+NNN interaction

- Work in progress
  - The present NNN force is "incomplete", need to go to N^3LO
  - Before definite conclusion
    - Study of λ dependence
    - Study of ħω dependence
  - Scattering of heavier target

Ab initio NCSM/RGM Formalism for binary clusters

a few details

$$\left|\Psi^{J^\pi T}\right\rangle = \sum_\nu \int \frac{g_\nu^{J^\pi T}(r)}{r} \hat{A}_\nu \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle \right)^{(sT)} Y_\ell(\hat{r}_{A-a,a}) \right]^{(J^\pi T)} \frac{\delta(r-r_{A-a,a})}{r r_{A-a,a}} r^2 dr$$

Relative wave functions subject to the boundary/scattering asymptotic solution within R-matrix theory

$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle$ (Jacobi) channel basis

We use the closure properties of HO radial wave function

$$\delta(r-r_{A-a,a}) = \sum_n R_{n\ell}(r) R_{n\ell}(r_{A-a,a})$$

We defined the RGM model space such that n<N_{max}, this expansion is good for localized parts of the integration kernels.

Since we are using NCSM wave functions, it is convenient to introduce Jacobi channel states in the HO space

$$\left|\Phi_{\nu n}^{J^\pi T}\right\rangle = \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle \right)^{(sT)} Y_\ell(\hat{r}_{A-a,a}) \right]^{(J^\pi T)} R_{n\ell}(r_{A-a,a})$$

The coordinate space channel states are given by

$$\left|\Phi_{\nu r}^{J^\pi T}\right\rangle = \sum_n R_{n\ell}(r) \left|\Phi_{\nu n}^{J^\pi T}\right\rangle$$

Matrix elements of translationally invariant operators

Then the SD channel states are defined such that the eigenstates of the heaviest of the two clusters (target) are described by a SD wave function:

$$\left|\Phi^{J^\pi T}_{\nu n}\right\rangle_{SD} = \left[\left(\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle_{SD} \left|a\ \alpha_2 I_2^{\pi_2} T_2\right\rangle\right)^{(sT)} Y_\ell\left(\hat{R}^{(a)}_{c.m.}\right)\right]^{(J^\pi T)} R_{n\ell}\left(R^{(a)}_{c.m.}\right)$$

$$\left|A-a\ \alpha_1 I_1^{\pi_1} T_1\right\rangle \varphi_{00}\left(\vec{R}^{(A-a)}_{c.m.}\right)$$

Vector proportional to the c.m. coordinate of the A-a nucleons

Vector proportional to the c.m. coordinate of the a nucleons

In the case of the nucleon-nucleus system we can applied the following basis change

$$|\Phi^{J^\pi T}_{\nu n}\rangle_{\rm SD} = \sum_j \hat{s}\hat{j}\ (-1)^{I_1+J+j} \begin{Bmatrix} I_1 & \frac{1}{2} & s \\ \ell & J & j \end{Bmatrix}$$

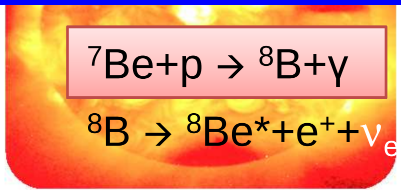
$$\times \left[|A-1\, \alpha_1 I_1^{\pi_1} T_1\rangle_{SD}\ \varphi_{n\ell j \frac{1}{2}}(\vec{r}_A \sigma_A \tau_A)\right]^{(J^\pi T)}$$

This basis is convenient to express the kernels with the help of second quantization.

Ab initio many-body calculation of the $^{7}Be(p,\gamma)^{8}B$ radiative capture

P. Navrátil, R. Roth, and S. Quaglioni, Phys. Lett. B704, 379 (2011)

Footprints of pp chain on earth

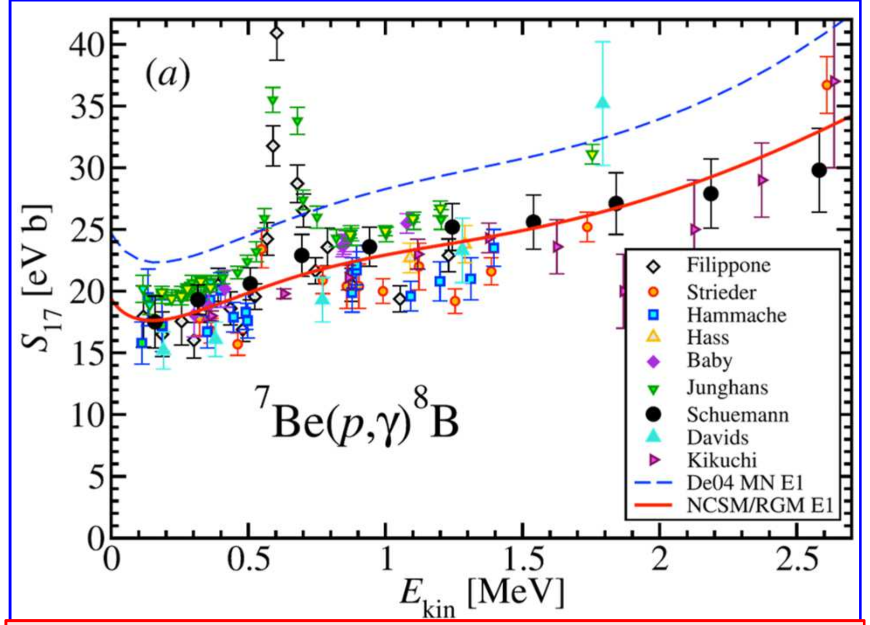


solar neutrinos
E_n < 15 MeV

The $^{7}Be(p,\gamma)^{8}B$ is the final step in the nucleosynthetic chain leading to ^{8}B and one of the main inputs of the standard model of solar neutrinos

- ~10% error in latest $S_{17}(0)$: dominated by uncertainty in theoretical models
- NCSM/RGM results with largest realistic model space (N_{max} = 10):
  - $p+{}^{7}Be$(g.s., $1/2^-$, $7/2^-$, $5/2_1^-$, $5/2_2^-$)
  - Siegert's E1 transition operator
- Parameter λ of SRG NN interaction chosen to reproduce separation energy: 136 keV (Expt. 137 keV)
- $S_{17}(0)$ = 19.4(7) eVb on the lower side of, but consistent with latest evaluation

$^{7}Be(p,\gamma)^{8}B$ astrophysical S-factor



Ab initio theory predicts simultaneously both normalization and shape of S_{17}

Astrophysical S-factor:

$$\sigma(E) = \frac{S(E)}{E} \exp\left(-\frac{2\pi Z_1 Z_2 e^2}{\hbar\sqrt{2mE}}\right)$$