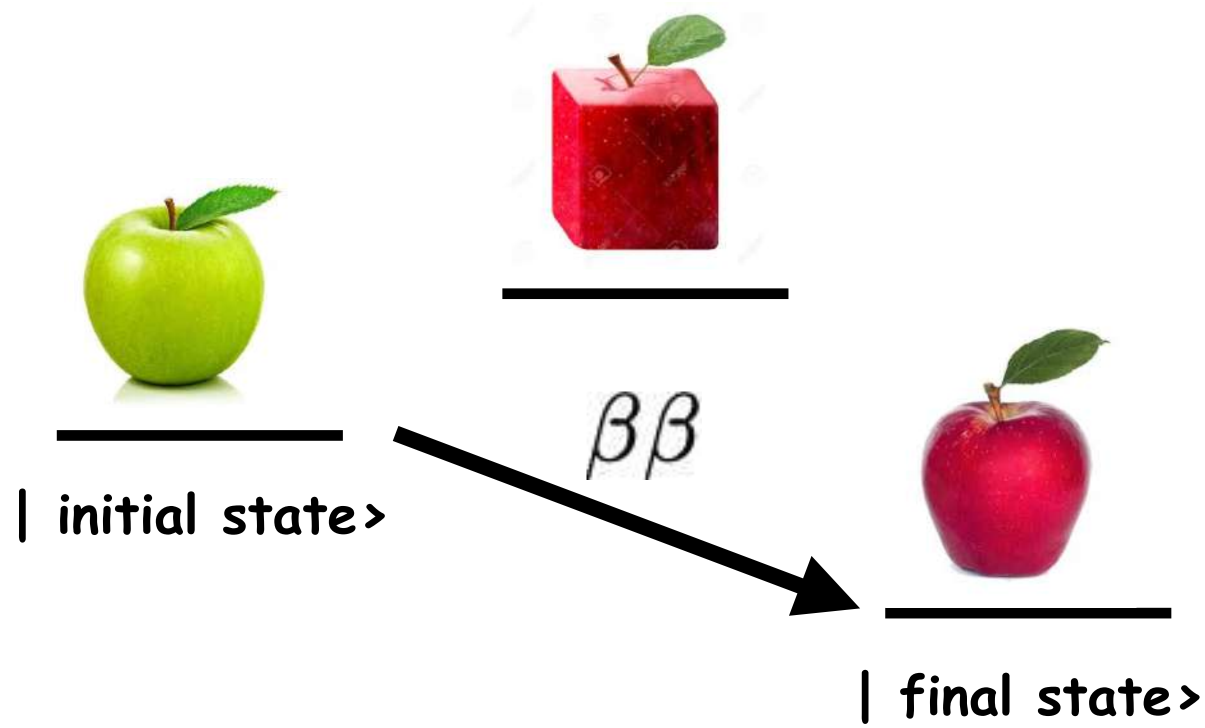
“无中微子双贝塔衰变”研讨会 2021年5月19-23日 珠海

$0\nu\beta\beta$衰变矩阵元的从头计算

尧江明
中山大学物理与天文学院
School of Physics and Astronomy
Sun Yat-sen University

2021年5月21日

Modeling of the NME for nuclear $0\nu\beta\beta$ decays

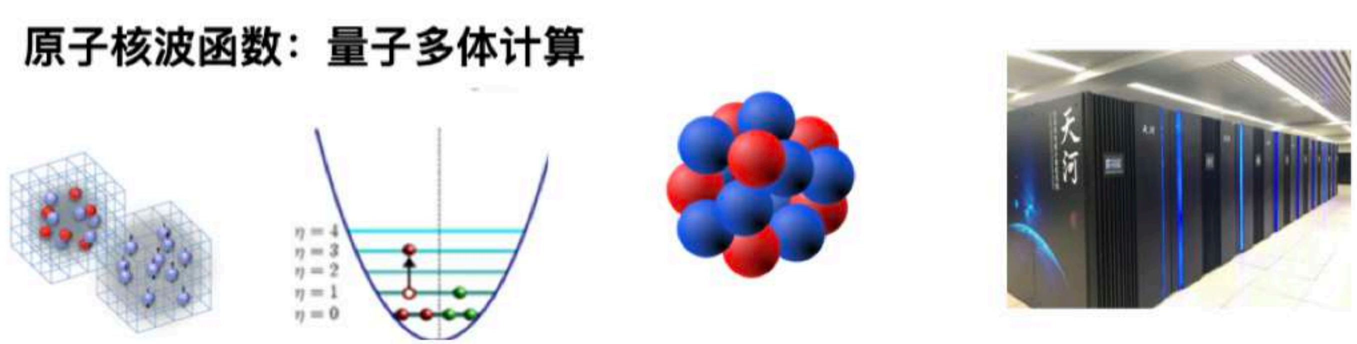


$$[T^{0\nu}_{1/2}]^{-1} = g_A^4 G_{0\nu} \left| \frac{\langle m_{\beta\beta}\rangle}{m_e} \right|^2 |M^{0\nu}|^2$$

Neutrino mass $m_{\beta\beta} = \sum_k U^2_{ek} m_k$

NME $M^{0\nu} = \langle \Psi_F | \hat{O}^{0\nu} | \Psi_I \rangle$

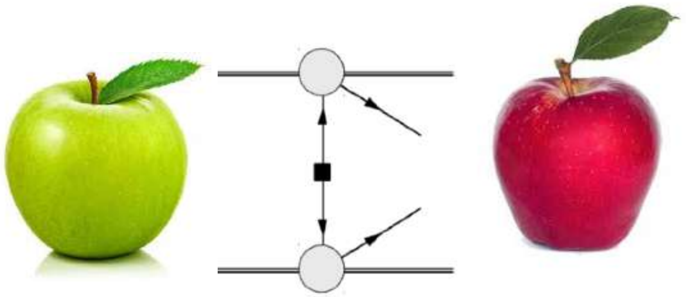
- **Nuclear many-body calculations (challenge)**



北京超级云计算中心
BEIJING SUPER CLOUD COMPUTING CENTER

- **Lepton-number-violating (LNV) mechanism**

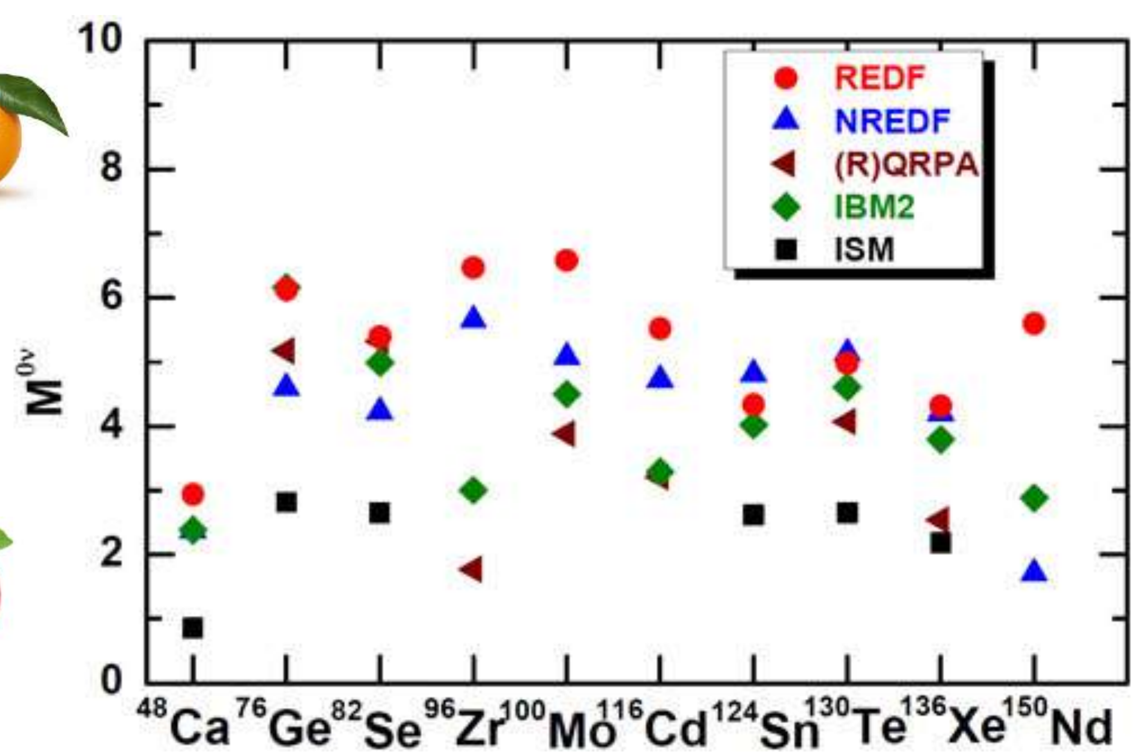
Low-energy effective operators in the "standard" mechanism

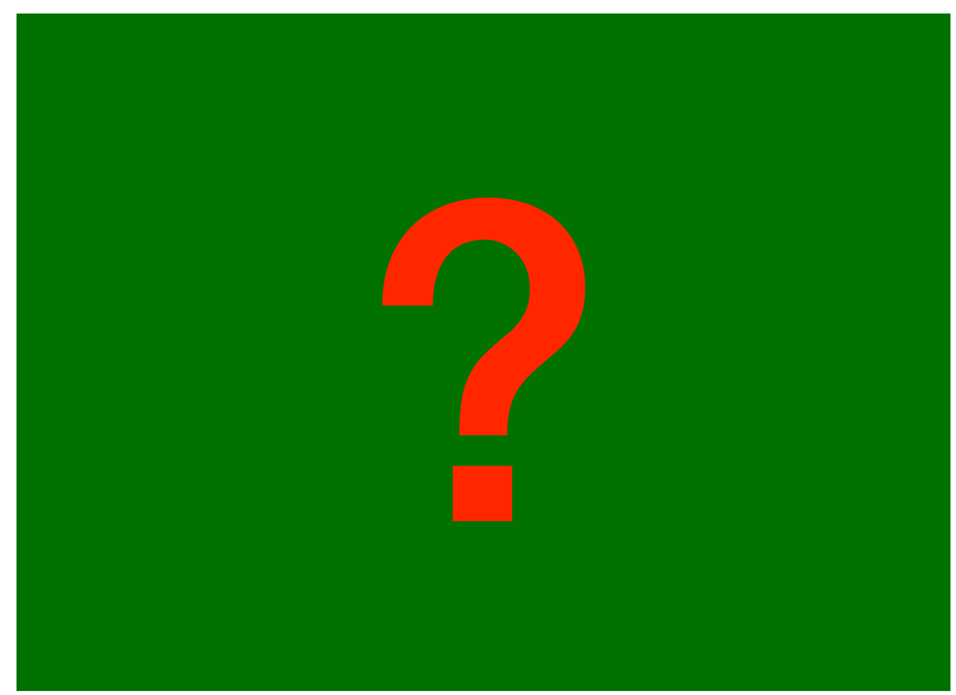


Nuclear Matrix Elements of $0\nu\beta\beta$ at the Crossroads

comparing apples to oranges?

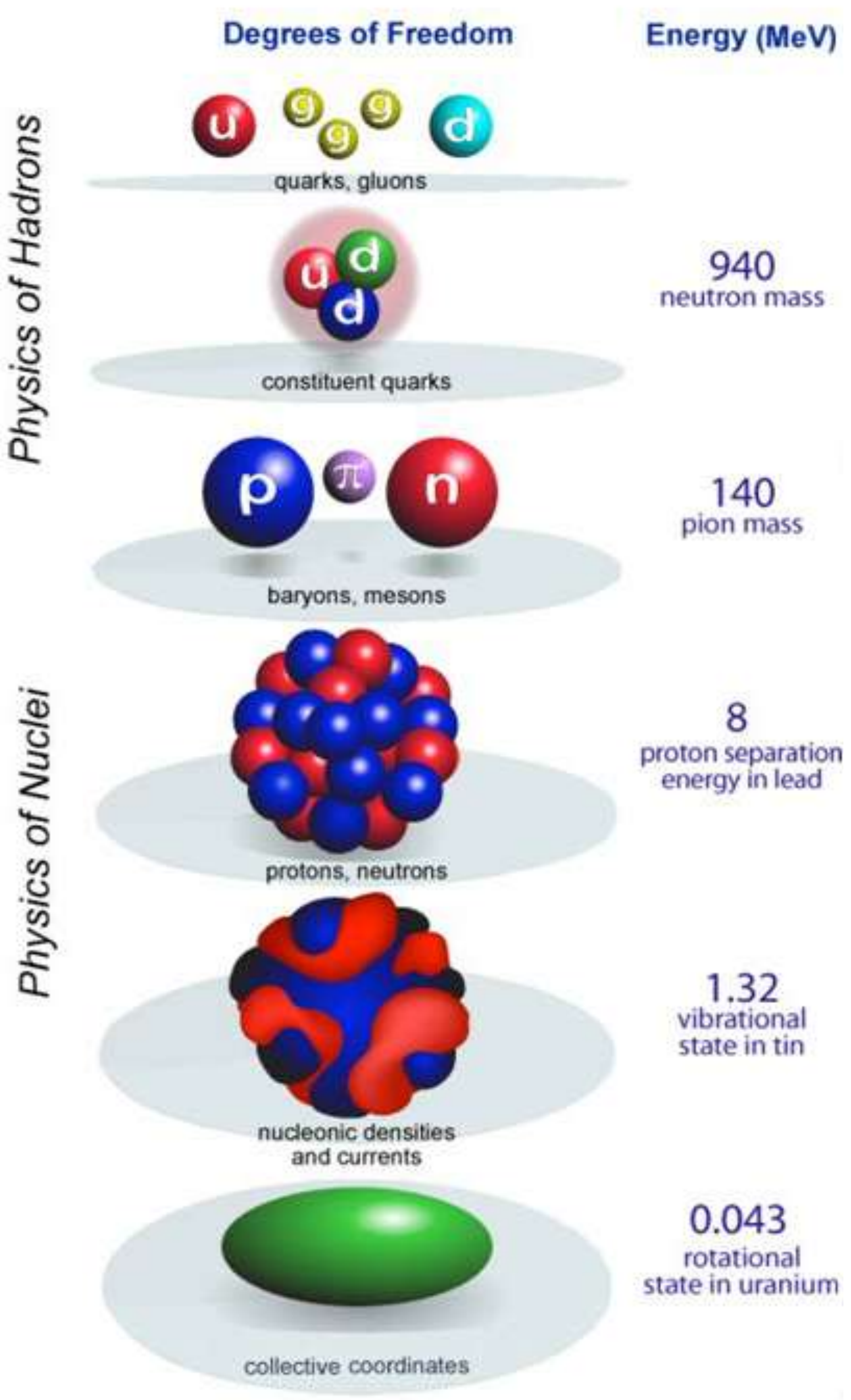
comparing apples to apples





参看房栋梁的报告

How to modeling atomic nuclei?



multi-faceted nuclei

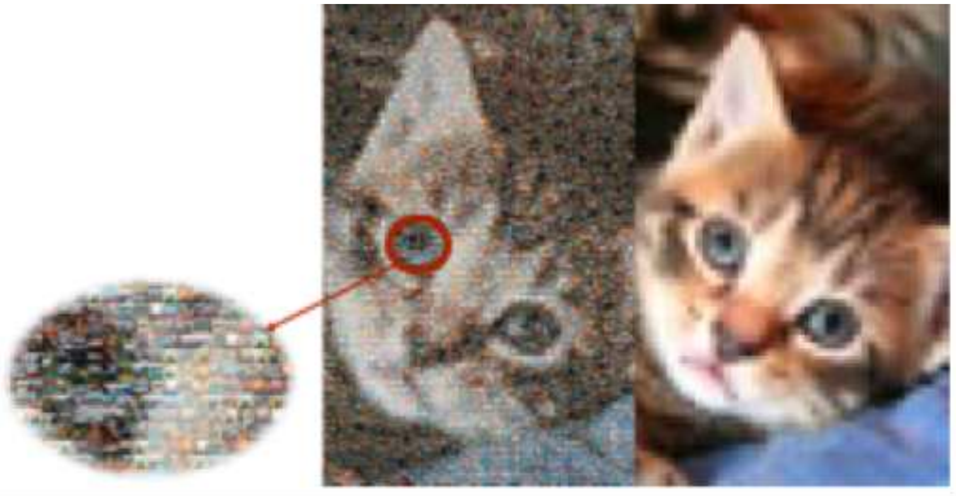
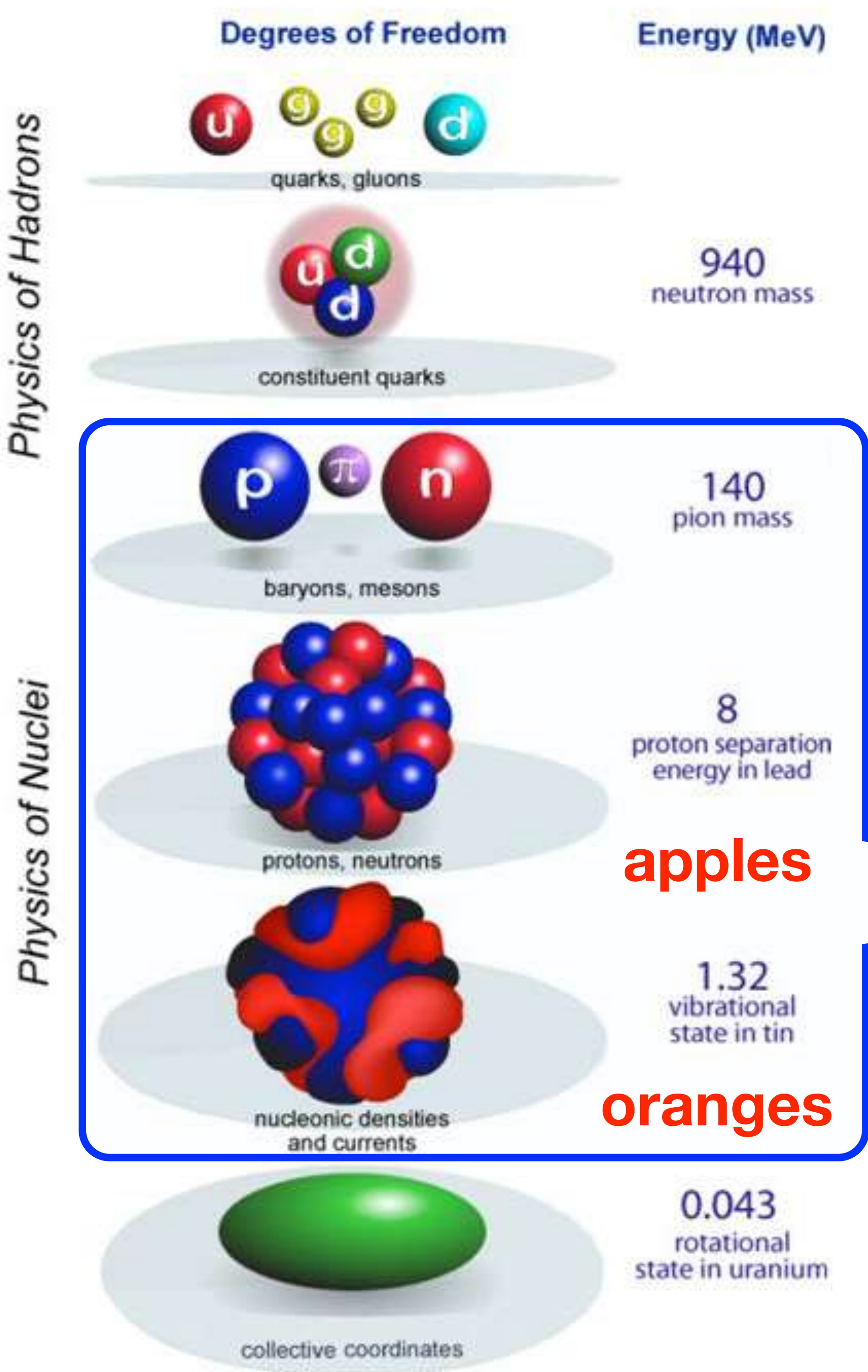


Image with different resolutions

RG equivalent (unitary transformation)

How to modeling atomic nuclei?



multi-faceted nuclei

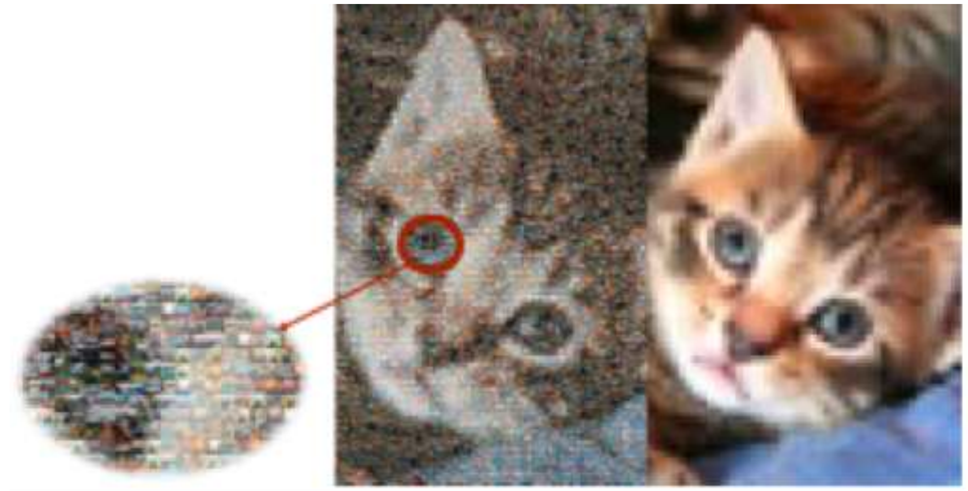
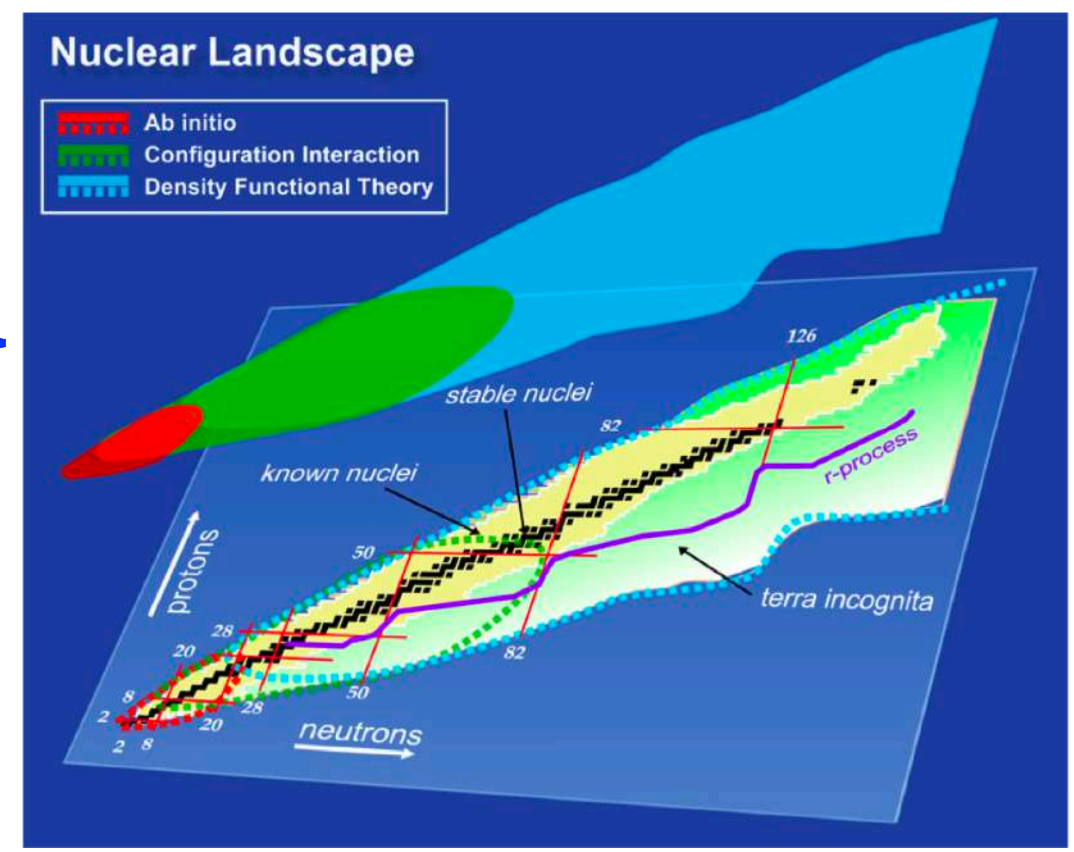


Image with different resolutions



NOT RG equivalent !

The Frontiers of Nuclear Science: A Long-Range Plan, 2007.

Ab initio modeling of nuclear $0\nu\beta\beta$ decays

Our goal is to provide ab initio calculations of the NMEs (personally):

- in nuclear many-body methods with **controllable approximations**
- using **nuclear interactions and weak transition operators derived consistently** from an (chiral) EFT
- with the feature of **order-by-order convergence**.

Clarifications (Three Not Necessaries):

- **Nuclear many-body methods** not necessary to be full configuration-interaction
- **Nuclear force** not necessary to be derived directly from QCD in terms of (q,g)
- **LNV transition operator** not necessary to be derived directly from a fundamental theory (if any)

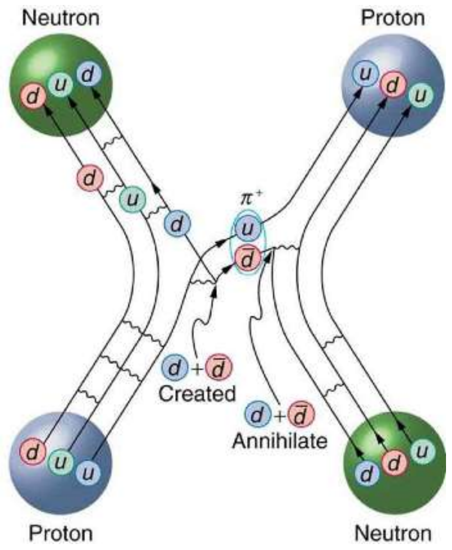
This talk will provide a brief overview of

☑ Advances in ab initio modeling of atomic nuclei (related to $0\nu\beta\beta$ decay)

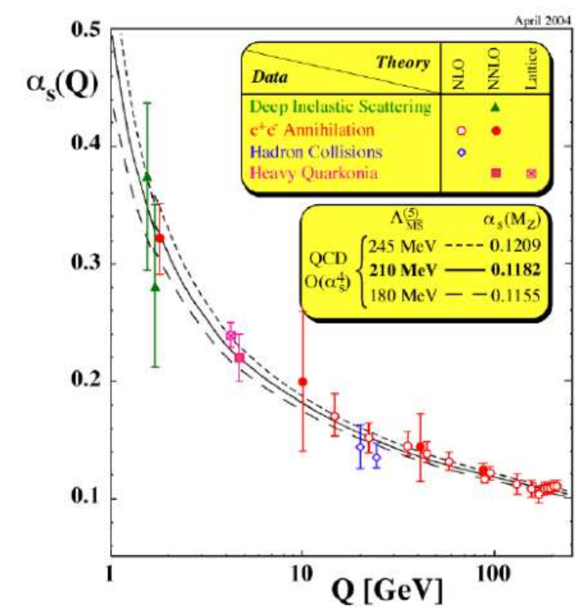
☑ Advances in the determination of leading-order contact transition operators in the "standard" mechanism

Modeling atomic nuclei from first principles?

- Construction of nuclear force directly from QCD (**difficult**)



Quark and gluons:
Non-perturbative nature of strong interaction in the low-energy regime relevant to nuclear physics

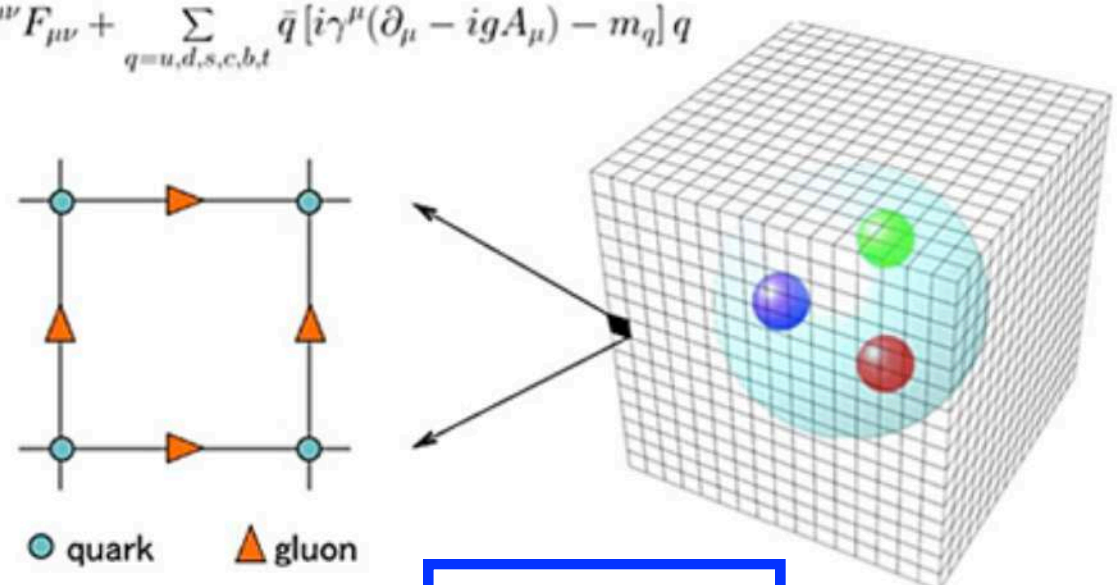


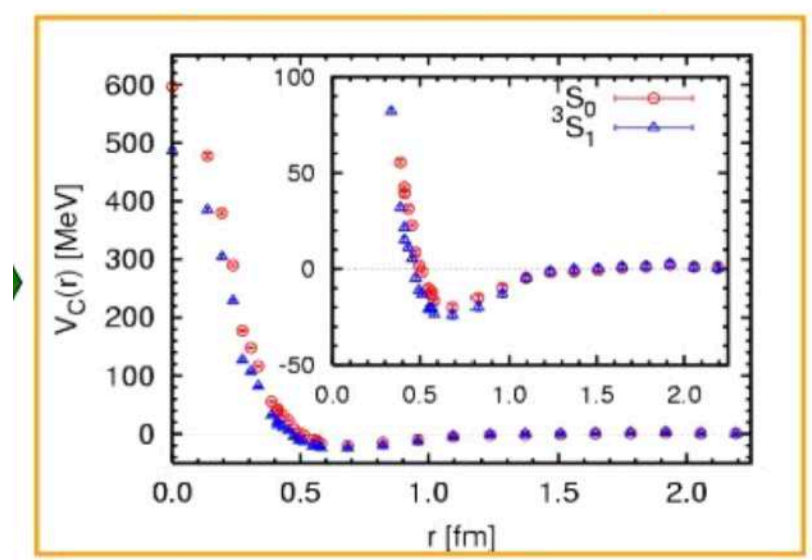
- Nuclear force from Lattice QCD (**infancy**)

Computation challenge at physical pion mass

QCD Lagrangian

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q}\left[i\gamma^\mu(\partial_\mu - igA_\mu) - m_q\right]q$$





参看冯旭的报告

Ishii-Aoki-Hatsuda, PRL99(2007)022001

Modeling atomic nuclei from first principles?

- Nuclear force from the chiral EFT

d.o.f.: nucleons and pions

140
pion mass

Weinberg's power counting:

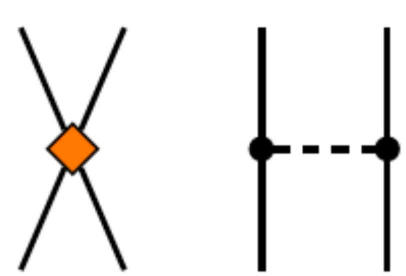
$$(Q/\Lambda_\chi)^\nu$$

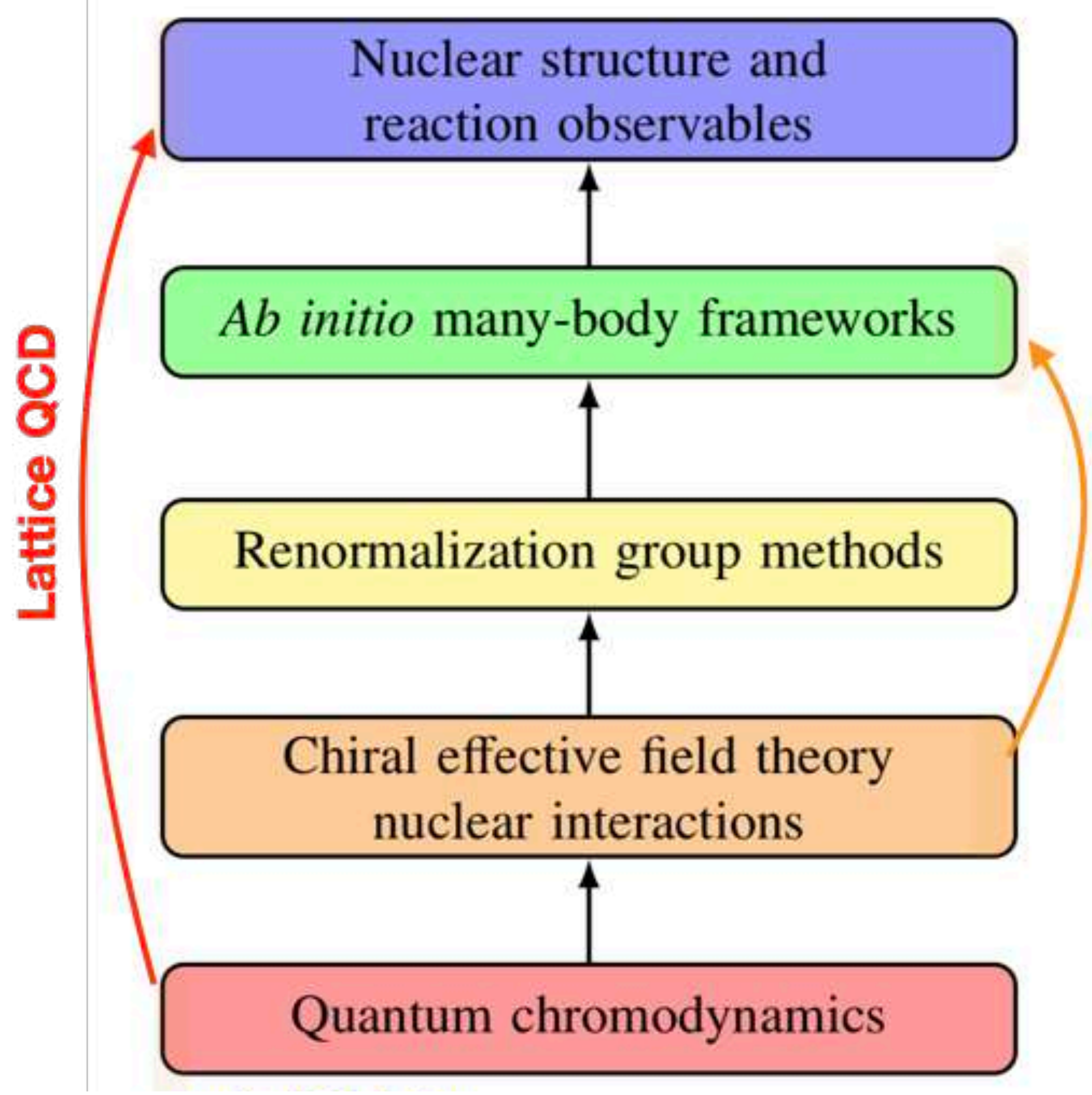
chiral-symmetry-breaking hard scale (~700 MeV)

soft scale associated with external momenta, pion mass (~140 MeV)

S.Weinberg, PLB251, 288 (1990)
S. Weinberg, NPB 363, 3 (1991)

LO

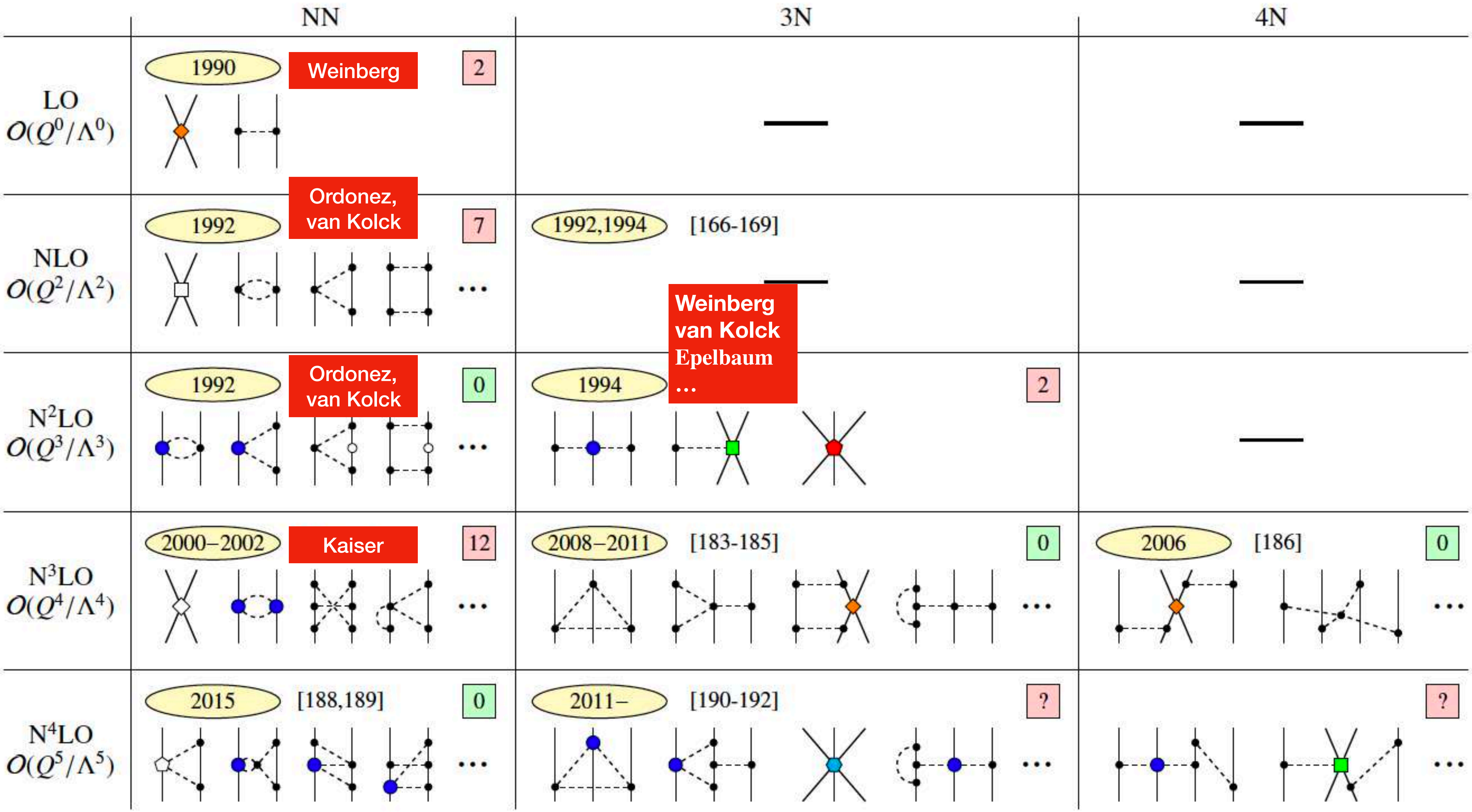




K. Hebeler, Phys. Rep. 890, 1 (2020)

参看耿立升、龙炳蔚报告

Nuclear force from chiral EFT



K. Hebeler, Phys. Rep. 890, 1 (2020)

ab initio many-body frameworks

- **Quantum Monte Carlo methods**

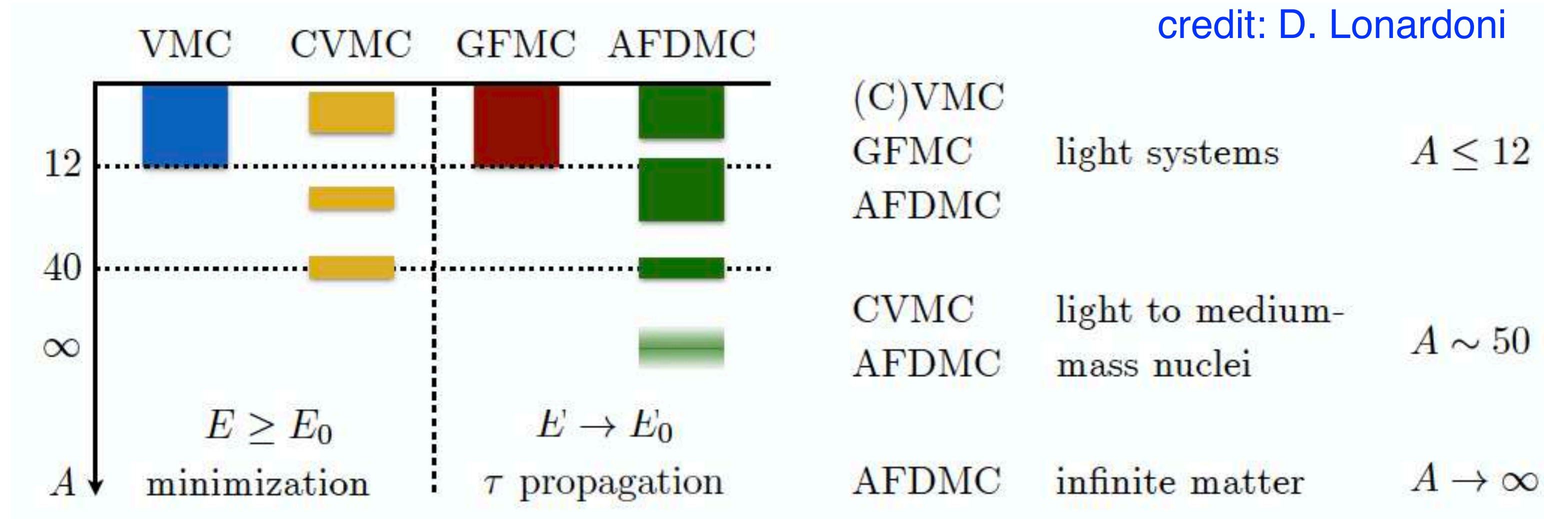
  Pieper, S.C.; Wiringa, R.B. (2001)
  J. Carlson et al., RMP 87, 1067 (2015)

  Variational Monte Carlo (VMC)

  Green's function Monte Carlo (GFMC)

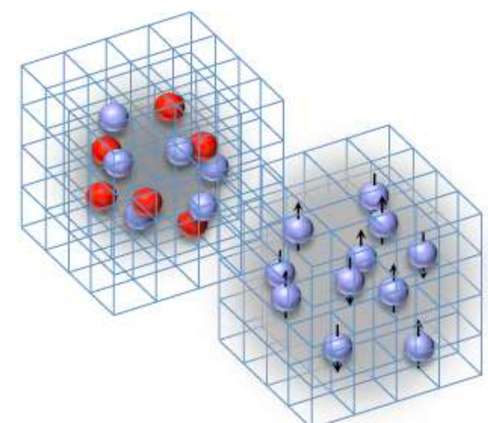
  Auxiliary-field diffusion Monte Carlo (AFDMC)

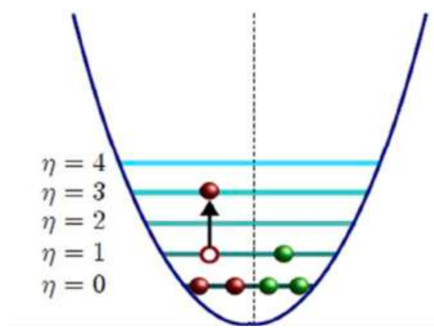
credit: D. Lonardoni



- **Lattice effective field theory (LEFT)**

  D. Lee, Prog. Part. Nucl. Phys. 63, 117 (2009)



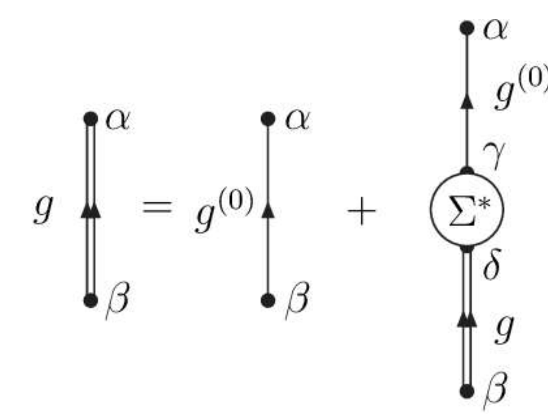


- **No-core shell model (NCSM)**

  Barrett, Navrátil, Vary, Prog. Part. Nucl. Phys. 69, 131 (2013)

- **Self-consistent Green's function (SCGF)**

  V. Somà, Frontiers in Physics 8, 340 (2020)



- **Coupled cluster (CC)**

  G. Hagen, T. Papenbrock, M. Hjorth-Jensen, and D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014)

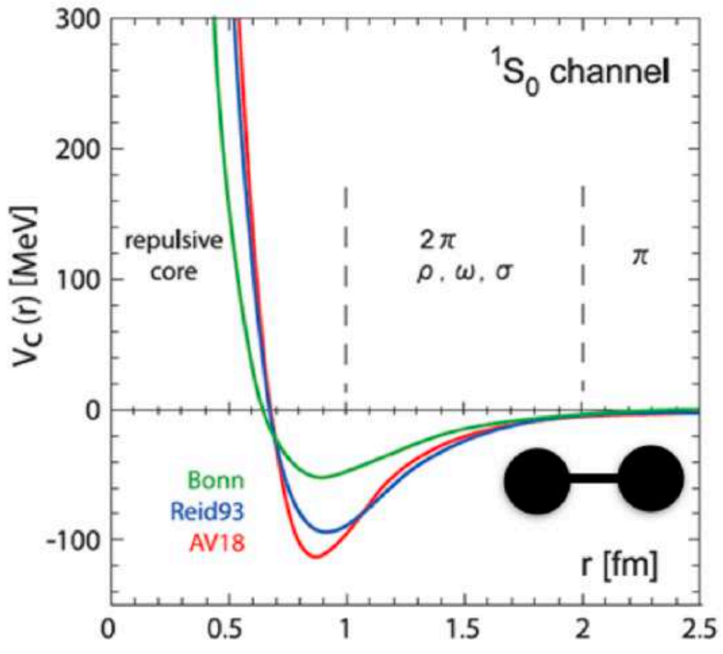
- **In-medium similarity renormalization group (IM-SRG)**

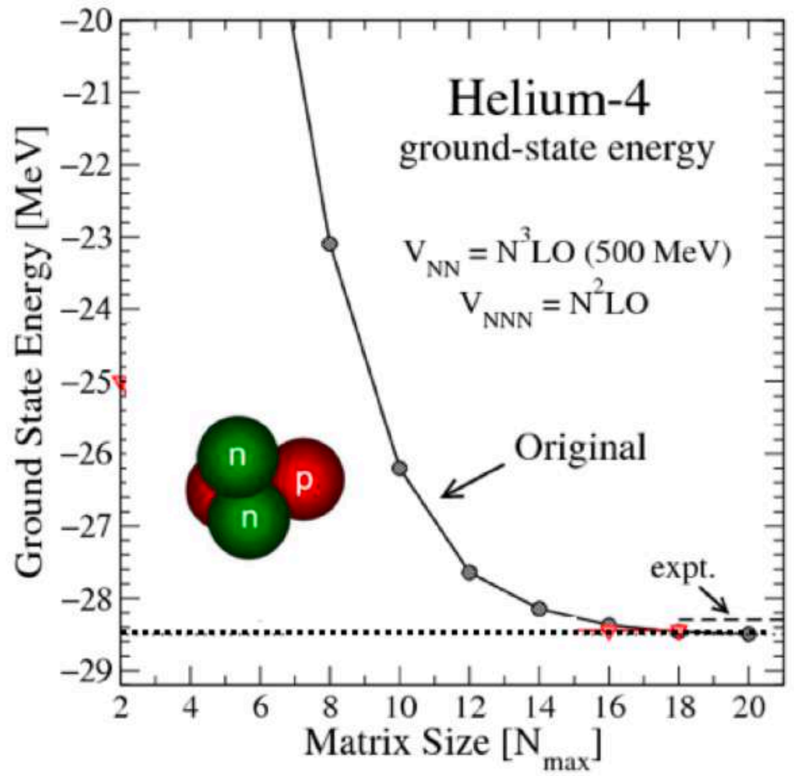
  H. Hergert, S. K. Bogner, T. D. Morris, A. Schwenk, and K. Tsukiyama, Phys. Rep. 621, 165 (2016)

参看吕炳楠的报告

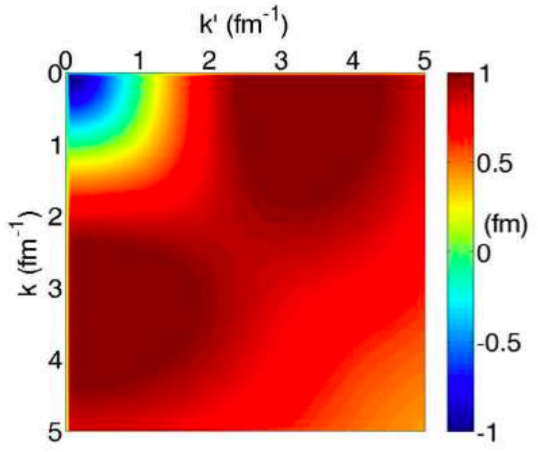
- MBPT, (R)BHF,… 北大孟杰教授课题组以及许甫荣教授课题组等

Realistic nuclear force: challenge





$$V_{\ell=0}(k,k') = \int d^3 r j_0(kr) V(r) j_0(k'r)$$



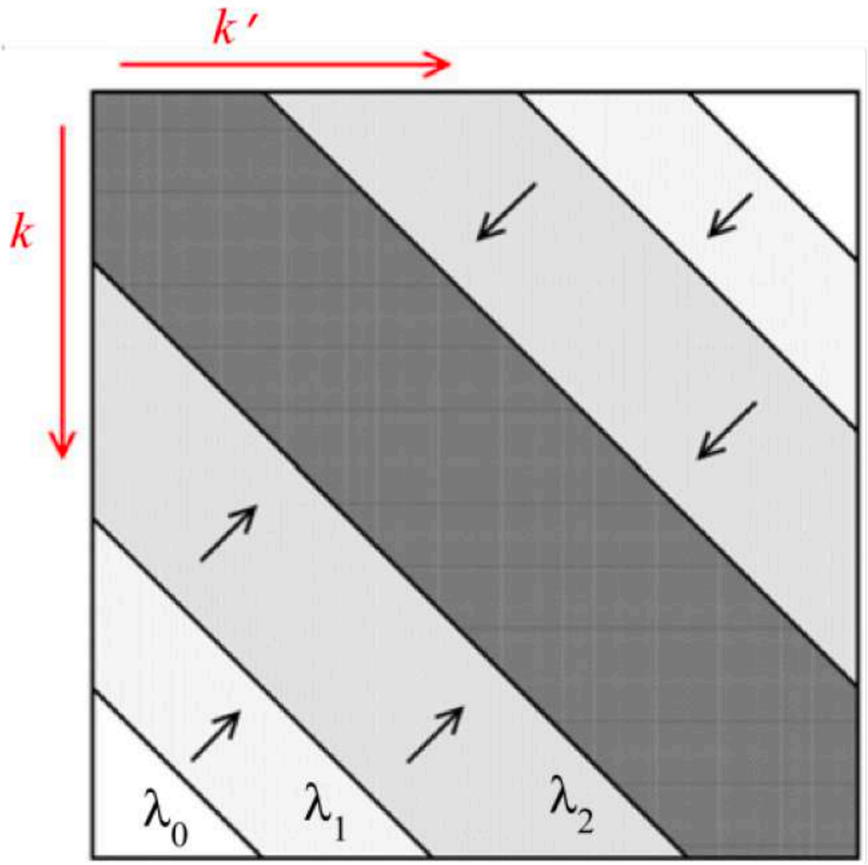
S. Bogner et al., PPNP (2010)

- Repulsive core & strong tensor force => low and high k modes strongly coupled by the interaction
- non-perturbative, poorly convergent basis expansions (cutoff Λ, No. of s.p. states D)

$$Dim(H) \sim \frac{D!}{(D-A)!A!}, \quad D \sim \Lambda^3 A \quad A\sim R^3$$

For $\Lambda = 4.0\ fm^{-1}$, $A = 16$, $Dim(H) \sim 10^{14}$.

Realistic nuclear force: SRG



The flow parameter s is usually replaced with $\lambda = s^{-1/4}$ with units of fm^{-1}.

S. K. Bogner, R. J. Furnstahl, and R. J. Perry (2007)

- Apply unitary transformations to Hamiltonian

$$H_s = U_s H U_s^\dagger \equiv T_{\mathrm{rel}} + V_s \tag{1}$$

- Flow equation

$$\frac{dH_s}{ds} = [\eta_s, H_s], \tag{2}$$

where the generator η_s is chosen to diagonalize $H(s)$ in the eigenbasis of T_{rel},

$$\eta_s = [T_{\mathrm{rel}}, H_s] \tag{3}$$

$$\frac{dV_s(k,k')}{ds} = -(k^2 - k'^2)V_s(k,k') + \frac{2}{\pi}\int_0^\infty q^2 dq (k^2 + k'^2 - 2q^2) V_s(k,q) V_s(q,k')$$

Realistic nuclear force: SRG

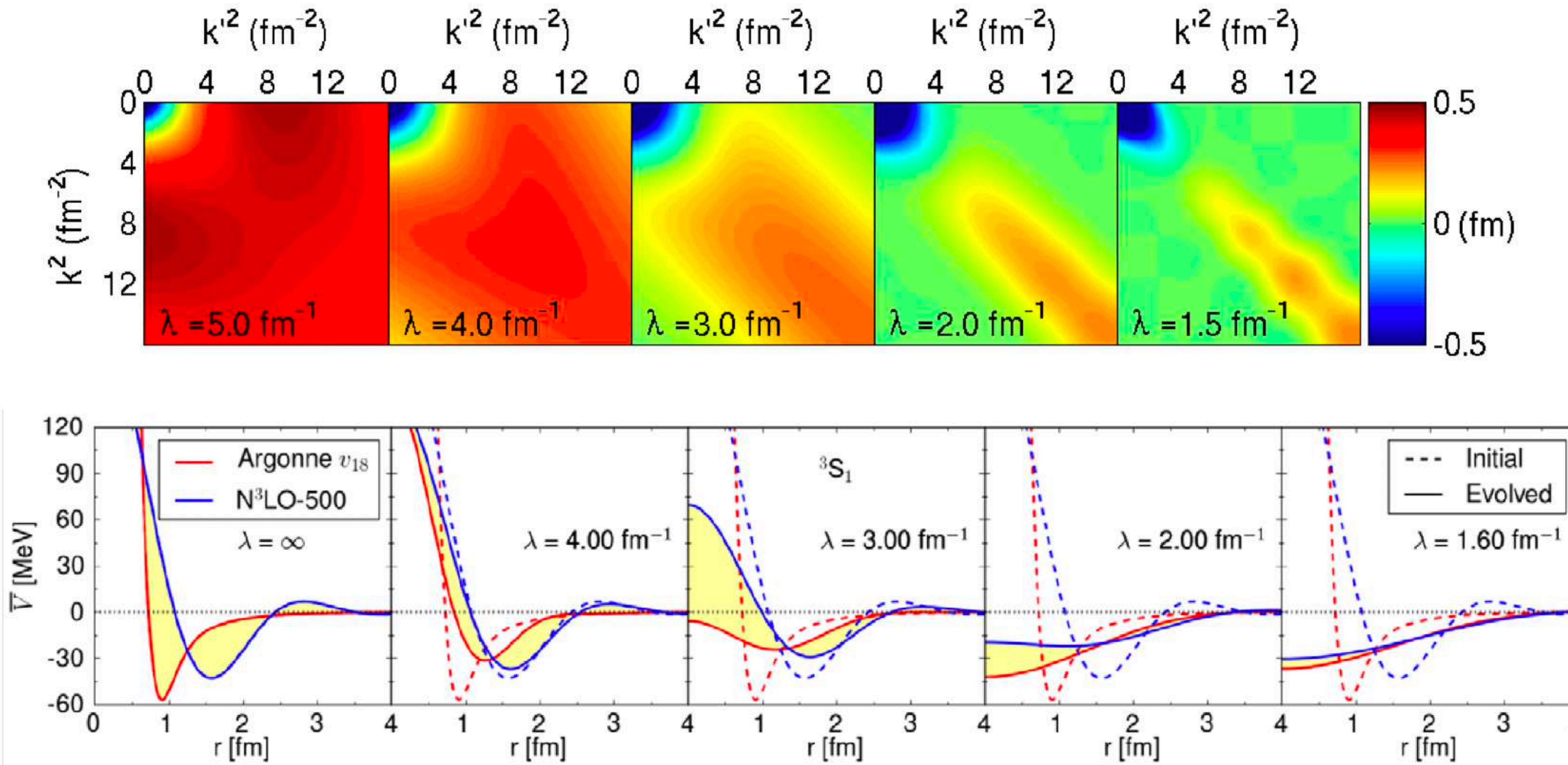


Figure: Local projection of AV18 and N^{3}LO(500 MeV) potentials $V(r)$ in $^3S_1$ channel.

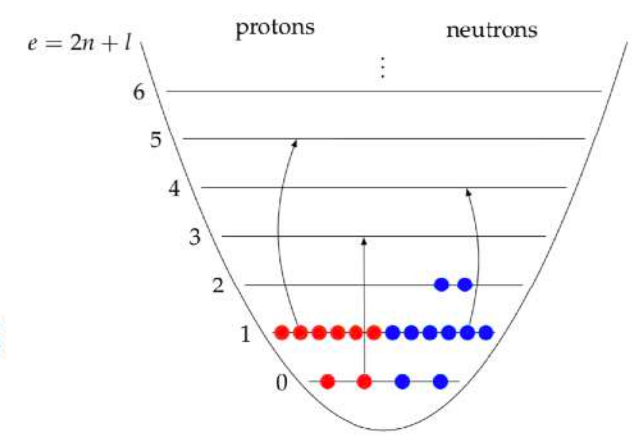
- "Hard core" disappears in the softened interactions

S. K. Bogner et al. (2010); Wendt et al. (2012)

NCSM: exponential growth of the model space

- The A-body Schroedinger equation

$$H|\Psi\rangle = E|\Psi\rangle,$$



- The wave function is expanded in terms of many-body basis states

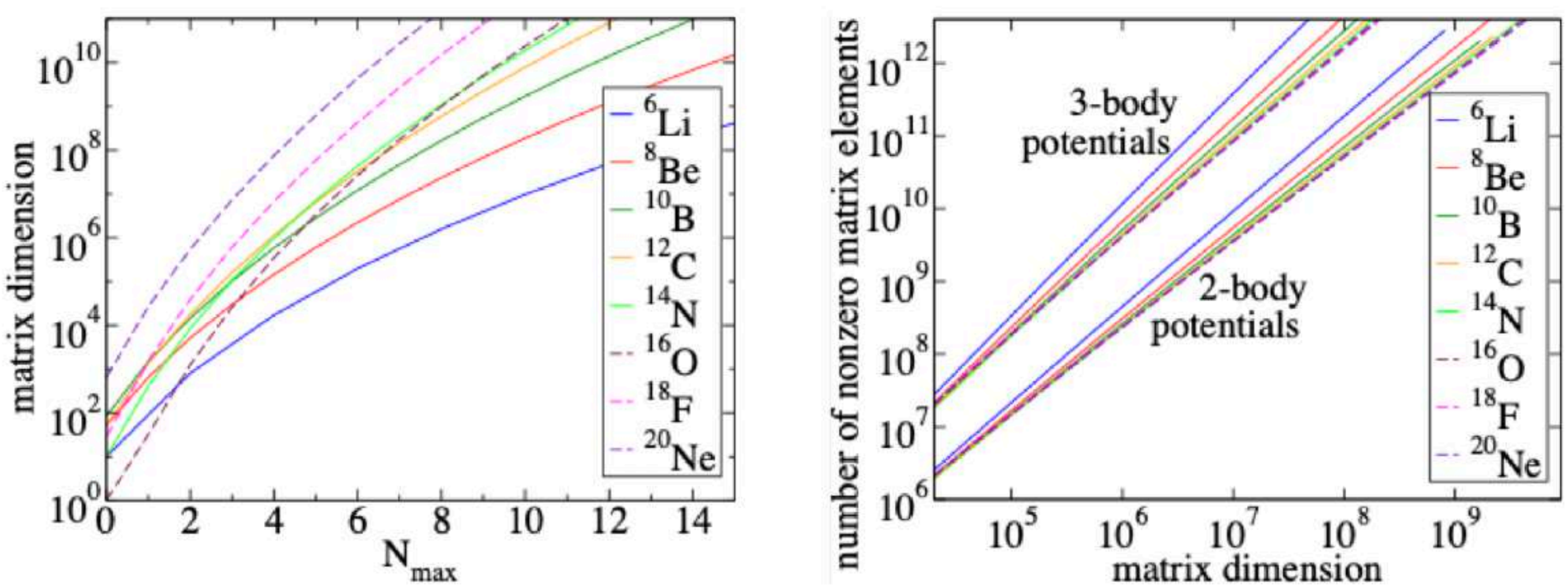
$$|\Psi\rangle = \sum_{\mu} c_\mu |\Phi_\mu\rangle,$$

where c_μ is to be determined from the diagonalization of the H. $|\Phi_\mu\rangle$ is a Slater Determinant of single-particle states occupied by the nucleons.

Dimension:

$$D \sim \binom{\Omega_\pi}{N_\pi} \binom{\Omega_\nu}{N_\nu}$$

Computation challenge



from: C. Yang, H. M. Aktulga, P. Maris, E. Ng, J. Vary, Proceedings of NTSE-2013

In-medium similarity renormalization group (IMSRG)

- A set of continuous unitary transformations onto the Hamiltonian

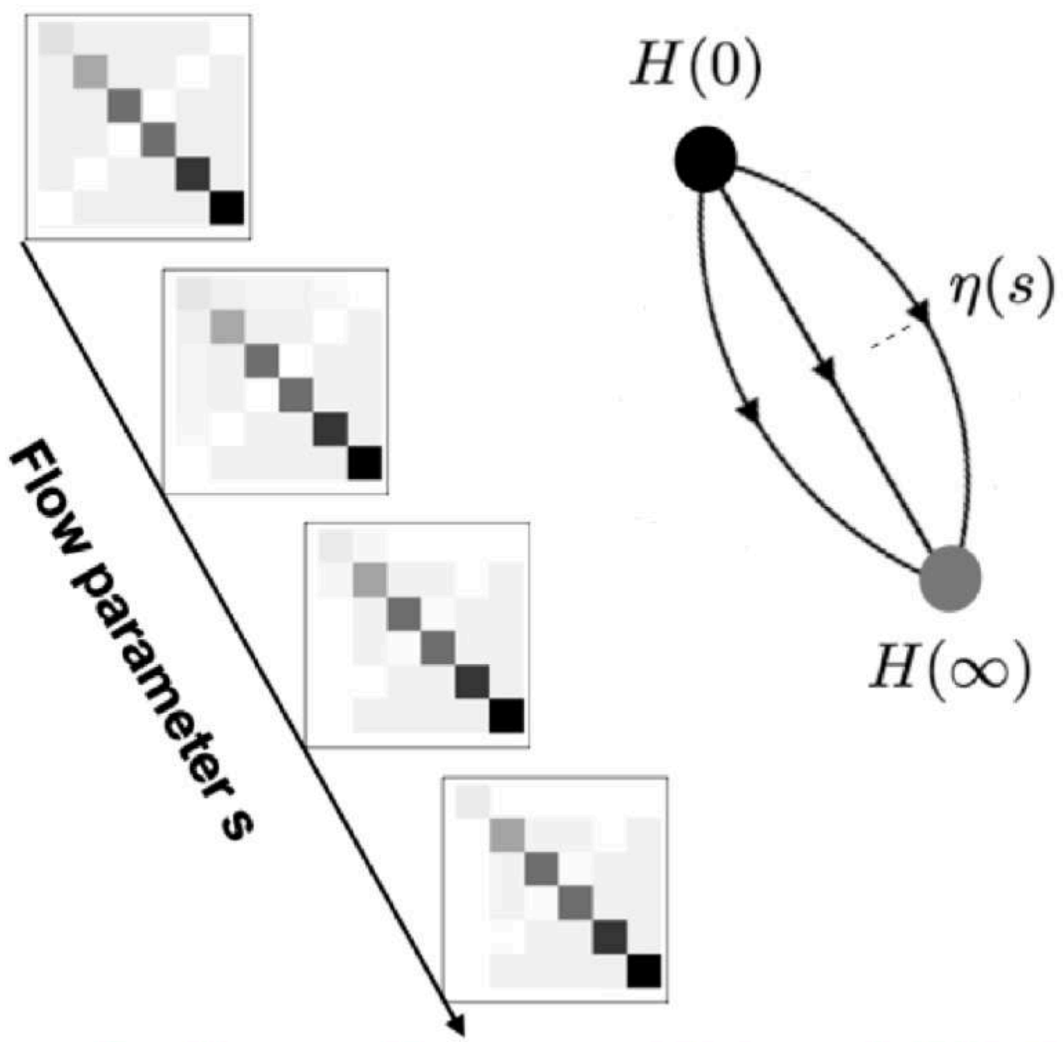
$$H(s) = U(s)H_0U^\dagger(s)$$

- Flow equation for the Hamiltonian

$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$

where the $\eta(s) = \frac{dU(s)}{ds}U^\dagger(s)$ is the so-called generator chosen to decouple a given reference state from its excitations.

- Computation complexity scales polynomially with nuclear size

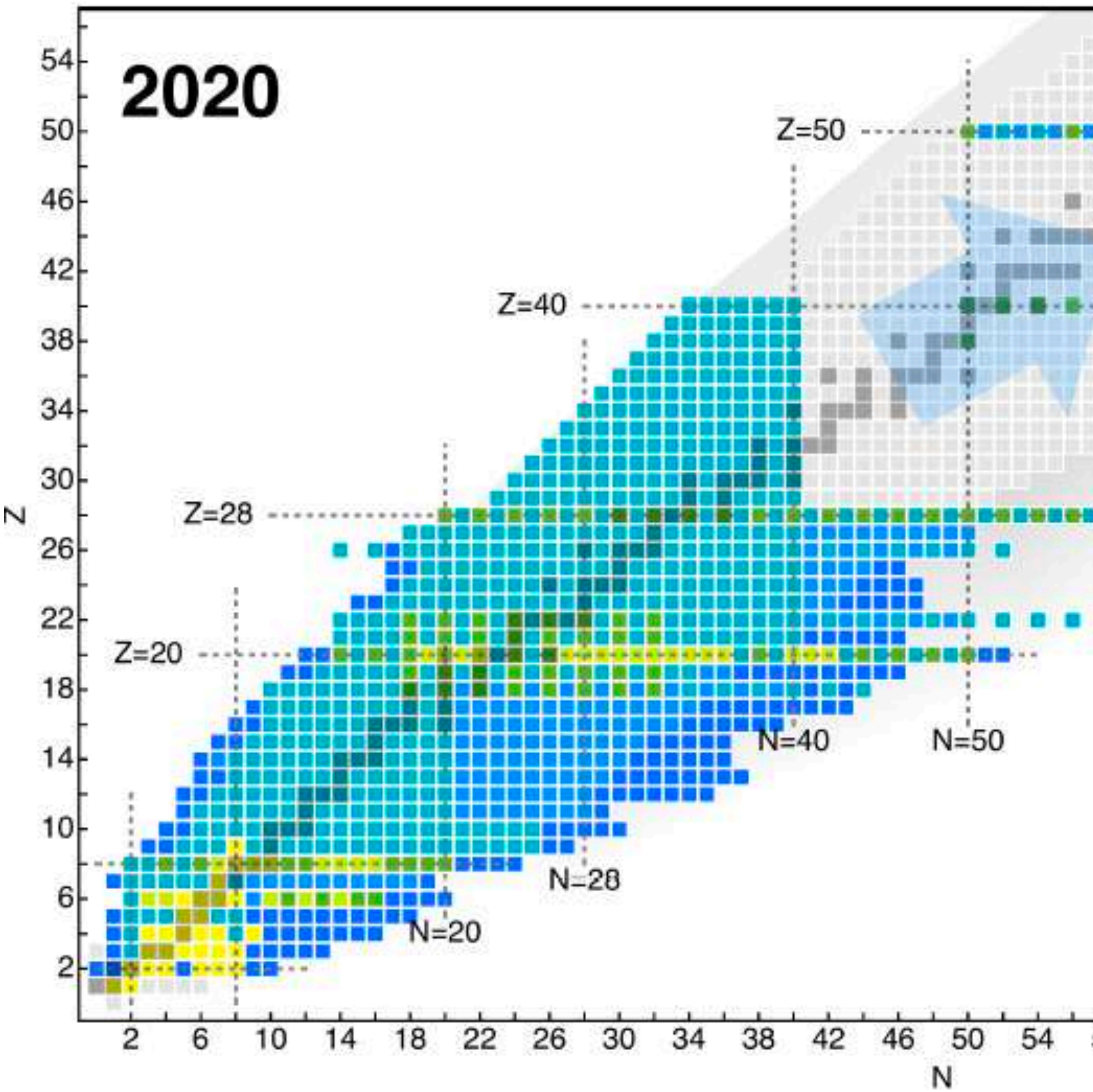


Tsukiyama, Bogner, and Schwenk (2011)
Hergert, Bogner, Morris, Schwenk, Tsukiyama (2016)

Not necessary to construct the H matrix elements in many-body basis !

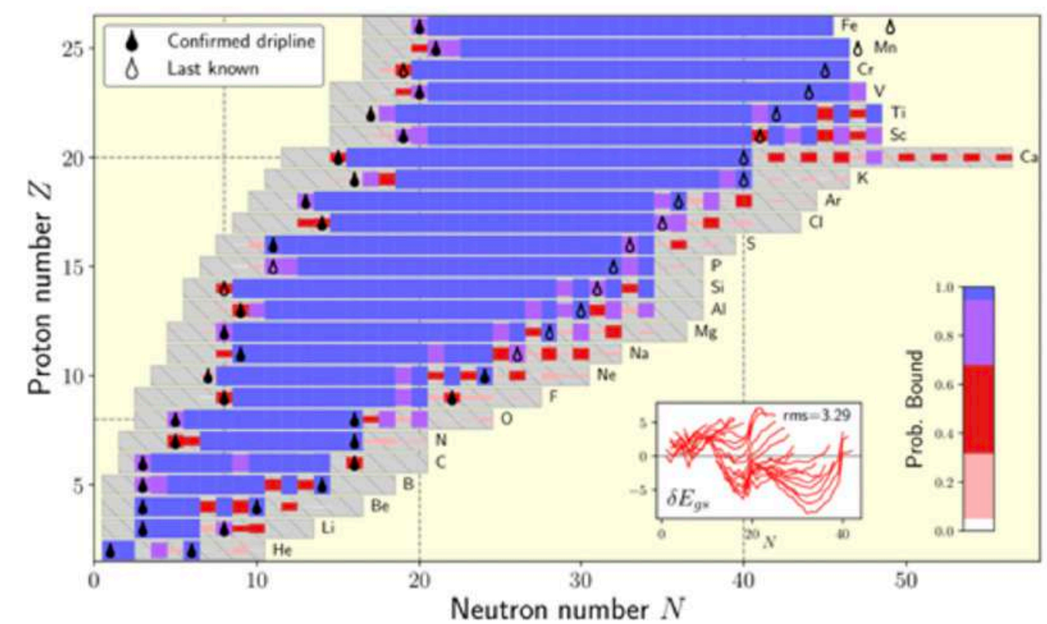
Achievements of ab initio calculations for nuclei

With the implementation of the SRG and IMSRG,



H. Hergert, Front. Phys. 8, 379 (2020)

First-principles calculations predict the properties of nearly 700 isotopes between helium and iron



S. R. Stroberg et al., PRL126, 022501 (2021)

g_A quenching in GT transition

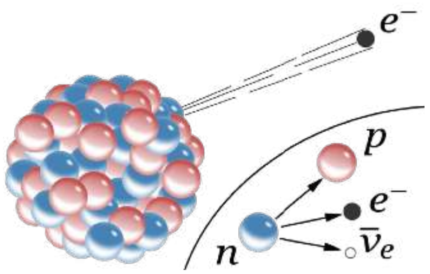
参看王龙军的报告

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers, G. Hagen, J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt

Nature Physics **15**, 428–431(2019) | Cite this article

Two-body currents+ many-body correlations

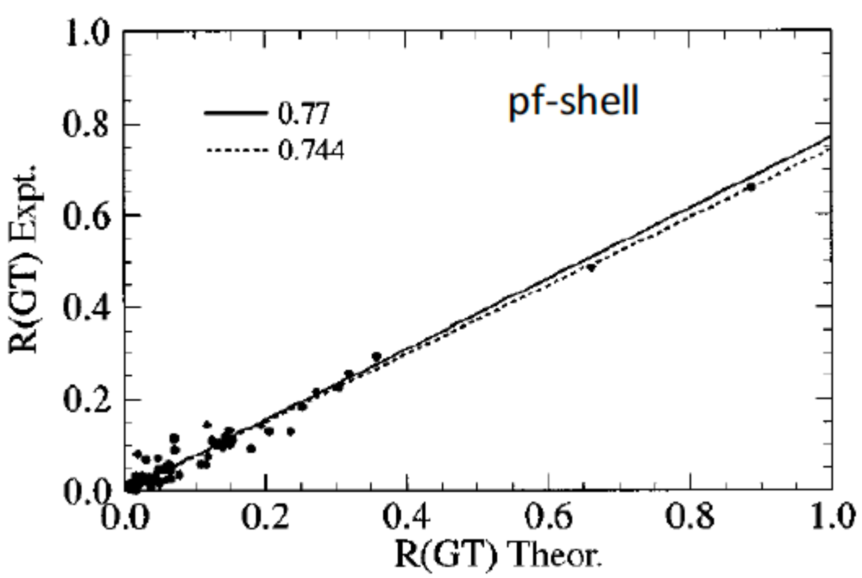


- The half-life of single-beta decay

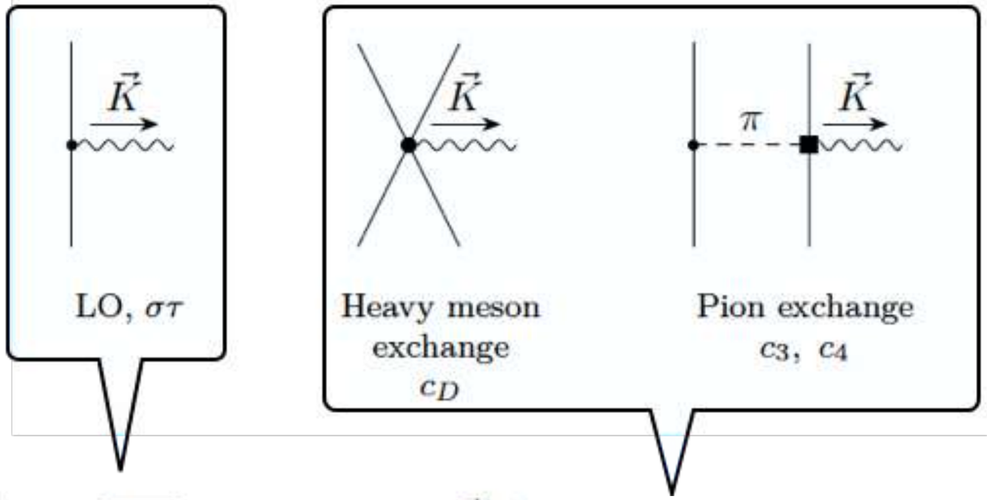
$$t_{1/2} = \frac{\kappa}{f_0(B_F + B_{\rm GT})},$$

$$B_F = \frac{g_V^2}{2J_i+1}|M_F|^2, \quad B_{\rm GT} = \frac{g_A^2}{2J_i+1}|M_{\rm GT}|^2$$

G. Martinez-Pinedo et al, PRC **53**, R2602 (1996)



- charge-changing axial-vector current



$$\vec{J}^A(\vec{K}) = \sum_j \imath g_A \boldsymbol{\sigma}_j \boldsymbol{\tau}_j^{\pm} e^{\imath \vec{K}\cdot\vec{r}_j}.$$

2B currents

Park, T.-S. et al. Phys. Rev. C 67, 055206 (2003)

- GT transition operator

$$O_{\rm GT} = O^{1b}_{\sigma\tau} + O^{2b}_{\rm 2BC}.$$

ab initio calculations of nuclear single-beta decay

g_A quenching in GT transition

参看王龙军的报告

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

P. Gysbers, G. Hagen, J. D. Holt, G. R. Jansen, T. D. Morris, P. Navrátil, T. Papenbrock, S. Quaglioni, A. Schwenk, S. R. Stroberg & K. A. Wendt

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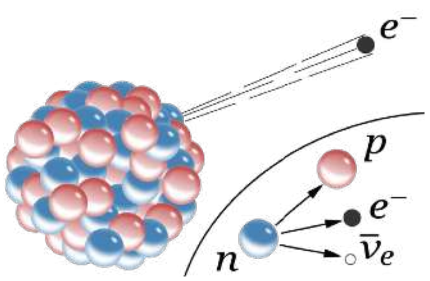
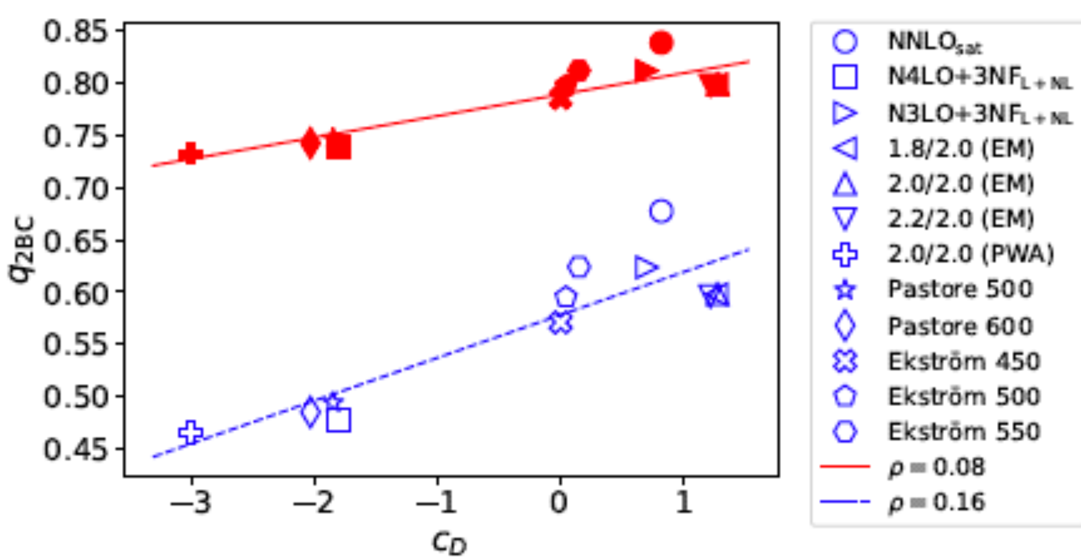
Two-body currents+ many-body correlations

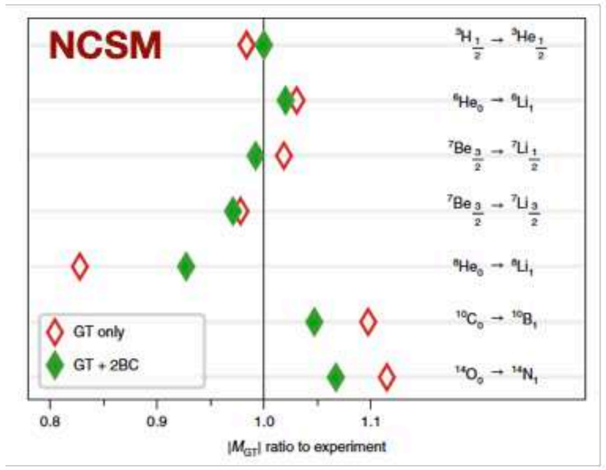


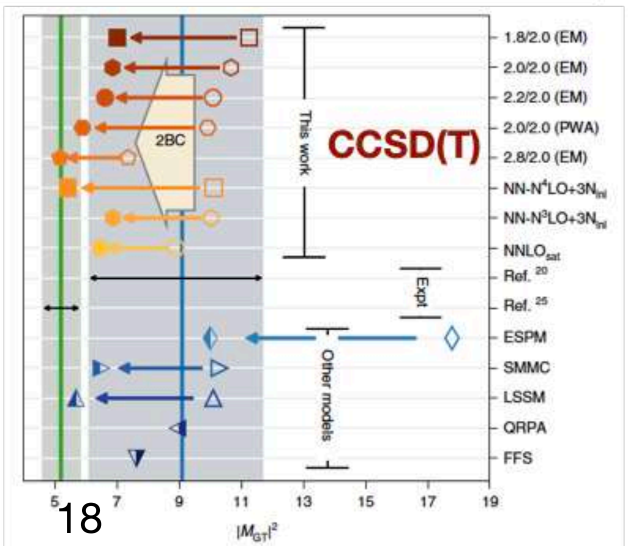
- **Intuitive picture**

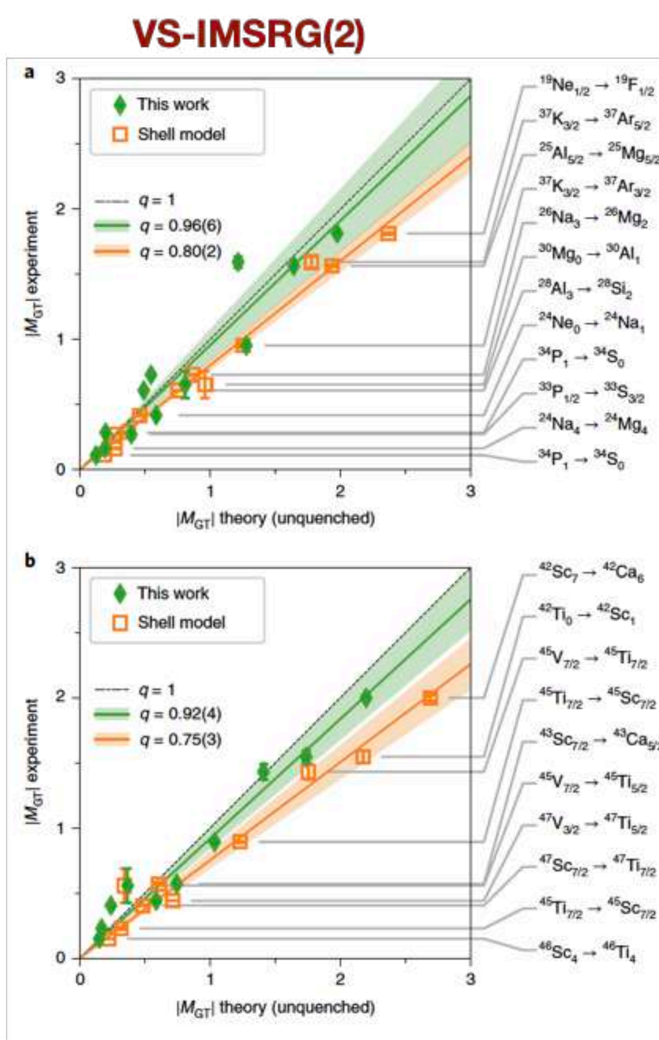
Normal-ordering the 2BC w.r.t nuclear matter of two diff. density rho.



- **Ab initio calculations**







decay

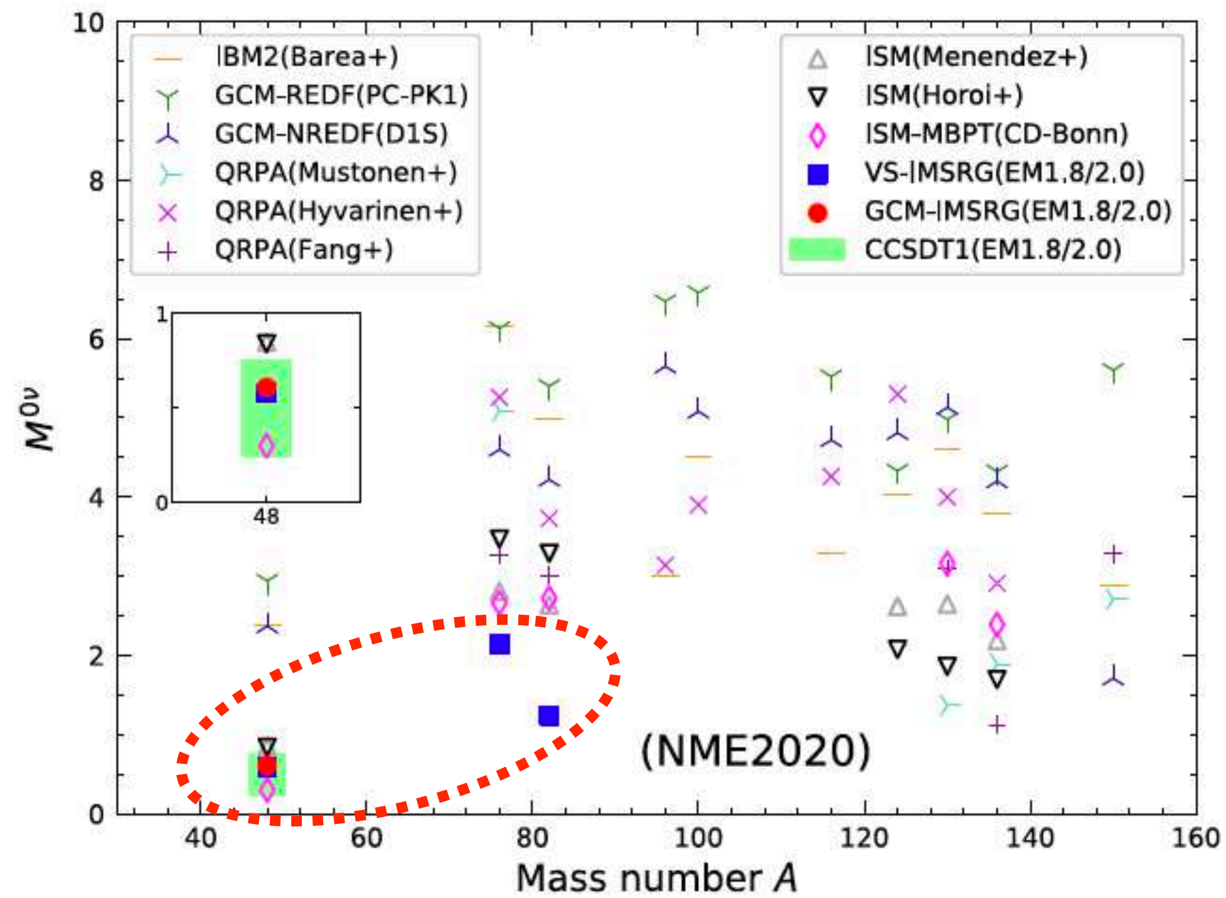
Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- Ab initio calculations of $0\nu\beta\beta$-decay candidate nuclei and corresponding NME of the decays
  - ✓ **In-medium similarity renormalization group (IMSRG)+Generator coordinate method (GCM)**

    JMY et al., PRL124, 232501 (2020)
  - ✓ **Valence-space IMSRG+ interacting-shell-model (ISM)**

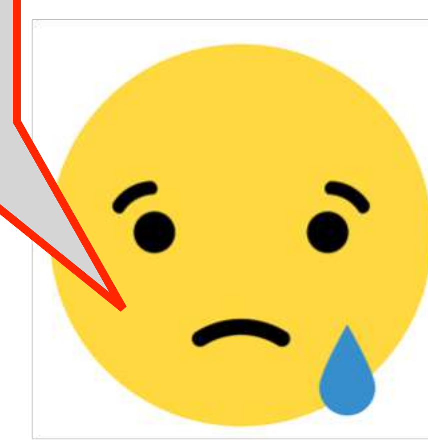
    A. Belley et al., PRL126, 042502 (2021)
  - ✓ **Coupled cluster (CC)**

    S. Novario et al., PRL126, 182502 (2021)



JMY, Science Bulletin (2021)

The NMEs by the three ab-initio methods consistently **smaller** than other phenomenological methods.



Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

☑ Benchmark calculations for light nuclei for which (quasi)-exact solution is possible

cross-checking among different models

✓ Quantum Monte Carlo vs **shell model**

X. Wang et al., PLB 798, 134974 (2019)

✓ NCSM vs IMSRG

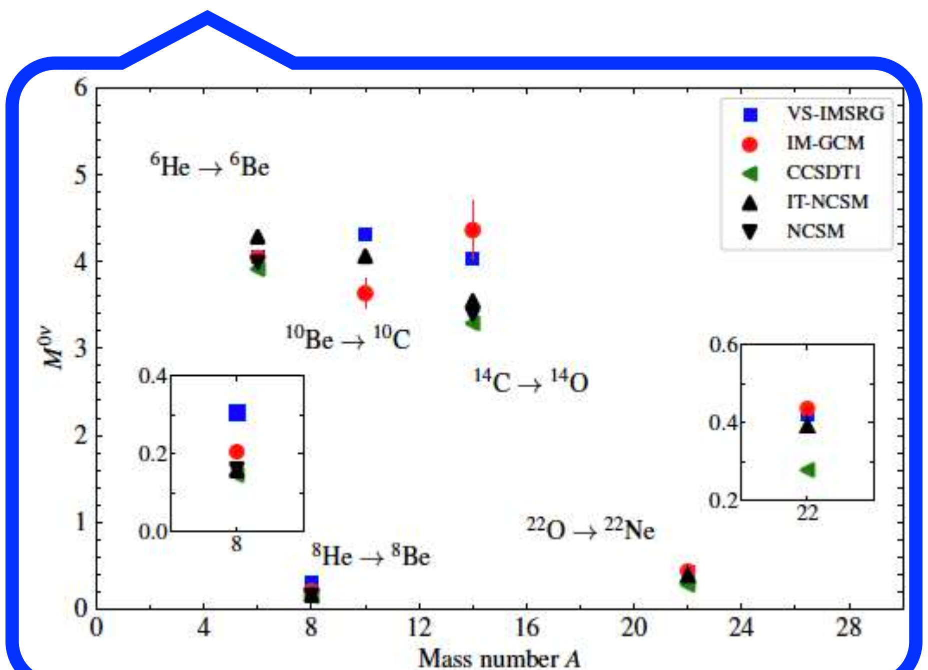
R. A. M. Basili et al., PRC102, 014302 (2020).

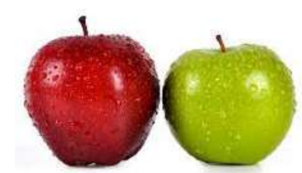
✓ NCSM vs CC

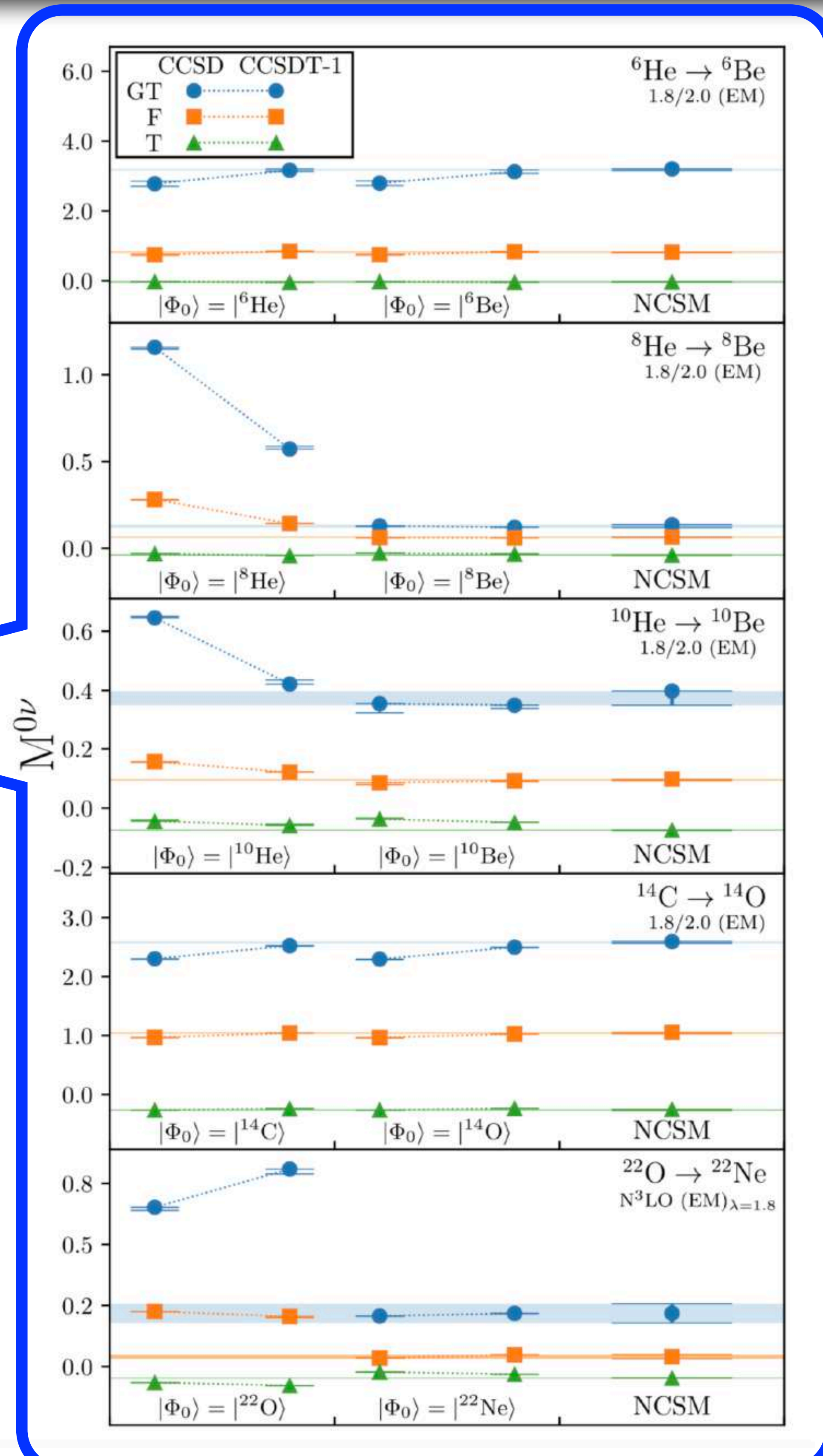
S. Novario et al., PRL126, 182502 (2021)

✓ NCSM vs IT-NCSM vs CC vs VS-IMSRG vs IM-GCM

JMY et al., PRC103, 014315 (2021)







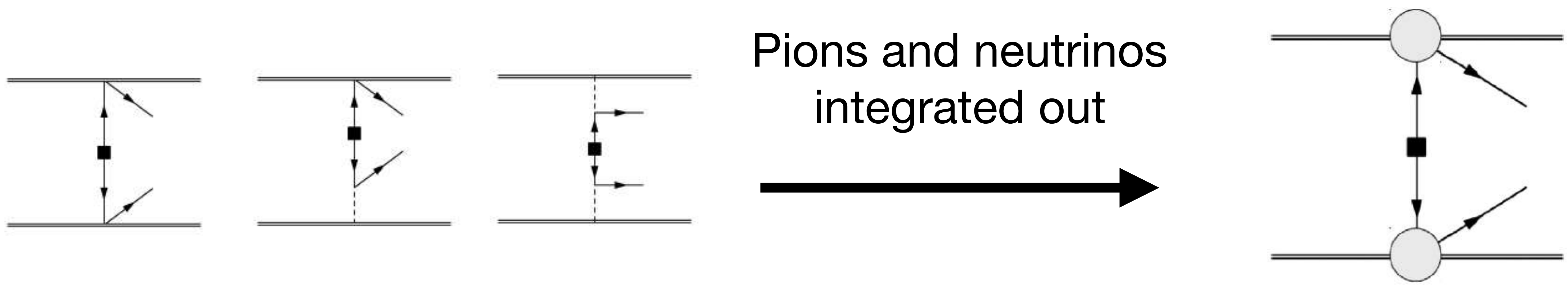
Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- The $0\nu\beta\beta$-decay in chiral EFT based on the "standard" mechanism of light Majorana neutrino exchange V. Cirigliano et al., PRC97, 065501 (2018)

✓ **Chiral expansion of neutrino potentials**

$$V_\nu = \sum_{a\neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \cdots \right).$$

LO



$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \frac{1}{\mathbf{q}^2} \left\{ 1 - g_A^2 \right.$$

$$\left. \times \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q}\, \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q}\, \frac{2m_\pi^2 + \mathbf{q}^2}{\left(\mathbf{q}^2 + m_\pi^2\right)^2} \right] \right\}$$

Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

✓ Chiral expansion of neutrino potentials

V. Cirigliano et al., PRC97, 065501 (2018)

$$V_\nu = \sum_{a\neq b} \left(V_{\nu,0}^{(a,b)} + V_{\nu,2}^{(a,b)} + \cdots\right).$$

N²LO

- **N²LO contributions to single-nucleon currents are usually taken into account by introducing dipole form factors,**

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \frac{1}{\mathbf{q}^2} g_A^2 \{h_F(\mathbf{q}^2)/g_A^2 - \boldsymbol{\sigma}^{(a)}\cdot\boldsymbol{\sigma}^{(b)} h_{GT}(\mathbf{q}^2) - S^{(ab)} h_T(\mathbf{q}^2)\},$$

dipole form factors

$$g_V(q) = g_V\left(1+\frac{q^2}{\Lambda_V^2}\right)^{-2}, \quad g_A(q) = g_A\left(1+\frac{q^2}{\Lambda_A^2}\right)^{-2},$$

$$g_M(q) = (1+\kappa_1)g_V(q), \quad g_P(q) = -\frac{2m_N g_A(q)}{q^2+m_\pi^2}.$$

- **Genuine N²LO contributions from loops corrections to the LO diagram (induce short-range neutrino potential) are NOT considered yet**

$$V_{\nu,2}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \times \left(\mathcal{V}_{VV}^{(a,b)} + \mathcal{V}_{AA}^{(a,b)} + \tilde{\mathcal{V}}_{AA}^{(a,b)} \ln\frac{m_\pi^2}{\mu_{us}^2} + \mathcal{V}_{CT}^{(a,b)}\right).$$

CT at N²LO

$$\mathcal{V}_{CT}^{(a,b)} = \frac{g_A^2}{(4\pi F_\pi)^2}\frac{\boldsymbol{\sigma}^{(a)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(b)}\cdot\mathbf{q}}{m_\pi^2}\left[\frac{5}{6}g_\nu^{\pi\pi}\frac{\hat{q}}{(1+\hat{q})^2} - g_\nu^{\pi N}\frac{1}{1+\hat{q}}\right] + \frac{2g_\nu^{NN}}{(4\pi F_\pi)^2}\mathbf{1}^{(a)}\times\mathbf{1}^{(b)}$$

- **Transition amplitude of the process (LO)** $nn \to pp + e^- e^-$

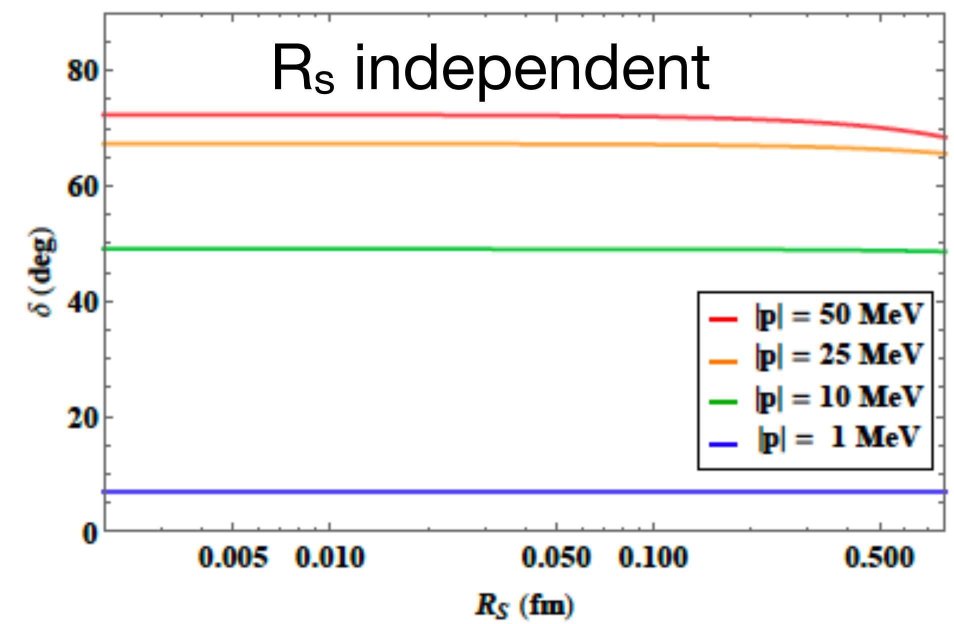
V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)

$$V_0(\mathbf{q}) = \tilde{C} + V_\pi(\mathbf{q}), \qquad V_\pi(\mathbf{q}) = -\frac{g_A^2}{4F_\pi^2}\frac{m_\pi^2}{\mathbf{q}^2 + m_\pi^2},$$

The contact nuclear potential is regularized as

$$\tilde{C}\delta^{(3)}(\mathbf{r}) \to \frac{\tilde{C}(R_S)}{(\sqrt{\pi}R_S)^3}\exp\left(-\frac{r^2}{R_S^2}\right) \equiv \tilde{C}(R_S)\delta_{R_S}^{(3)}(\mathbf{r}),$$

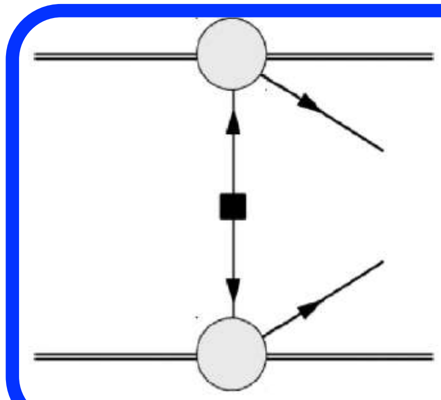
The LEC C(R) is adjusted to reproduce the np-scattering length for a given Rs.



Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

- **Transition amplitude of the process (LO)** $nn \to pp + e^- e^-$

V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)



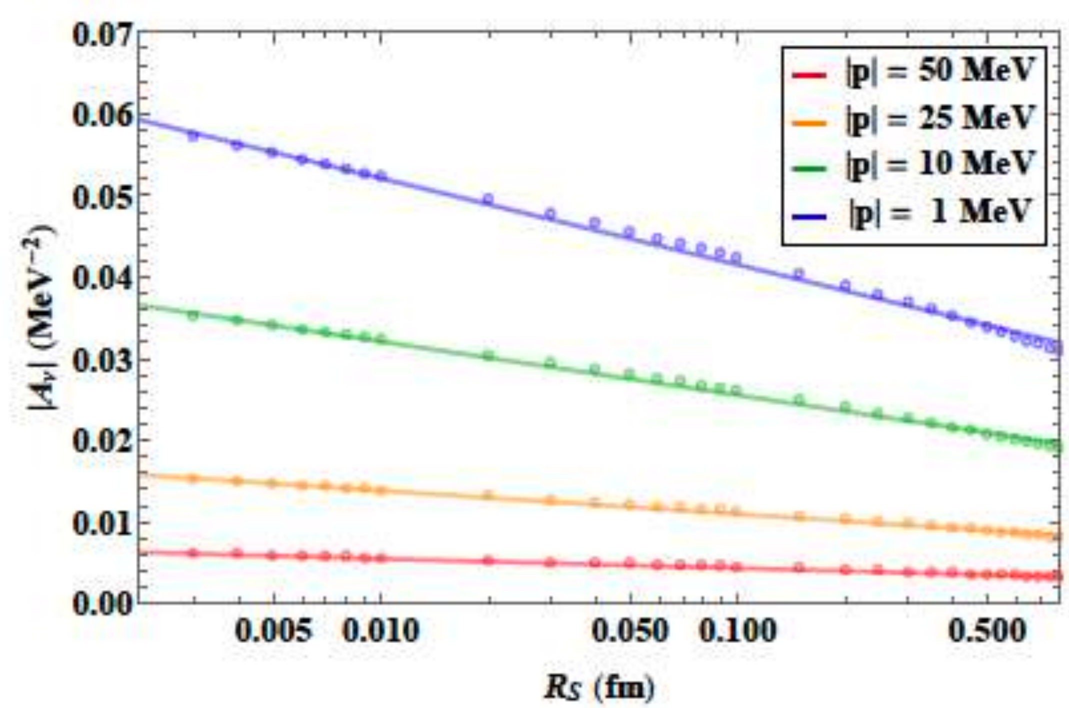
$$V_{\nu,0}(\mathbf{q}) = \tau^{(1)+}\tau^{(2)+}\frac{1}{\mathbf{q}^2}\left(1 - g_A^2\boldsymbol{\sigma}^{(1)}\cdot\boldsymbol{\sigma}^{(2)} + g_A^2\boldsymbol{\sigma}^{(1)}\cdot\mathbf{q}\,\boldsymbol{\sigma}^{(2)}\cdot\mathbf{q}\frac{2m_\pi^2+\mathbf{q}^2}{(\mathbf{q}^2+m_\pi^2)^2}\right),$$

$$\mathcal{A}_\nu(E,E') = -\langle\Psi_{pp}(E')|V_{\nu\,\mathrm{L}}^{^1S_0}|\Psi_{nn}(E)\rangle$$

$$E = \mathrm{p}^2/m_n \text{ and } E' = \mathrm{p}'^2/m_p$$

$$E' = E + 2(m_n - m_p - m_e)$$

$$|\mathrm{p}'| = \sqrt{\mathrm{p}^2 + 2m_N(m_n - m_p - m_e)},$$



The transition amplitude is regulator dependent! Needs a counter term (contact operator) at LO in order to ensure renormalizability.

Lines fitted to $\mathcal{A}_\nu = a + b\ln R_S$

logarithmic dependence on R_S

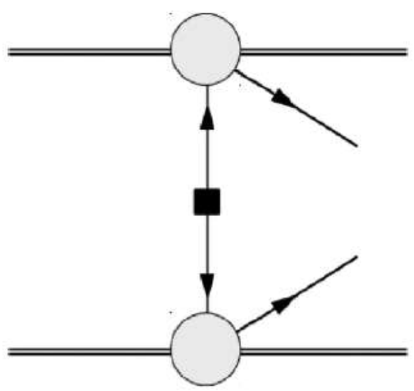
Violation of power counting? (龙炳蔚的报告)

Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

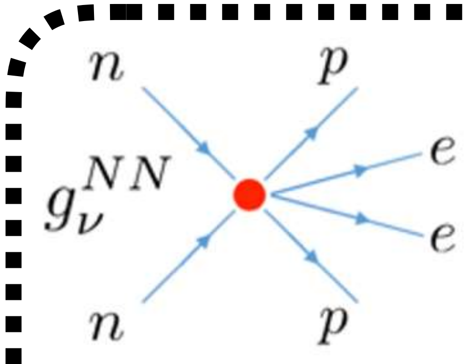
- **Necessary of introducing a contact term at LO** $nn \to pp + e^- e^-$

V. Cirigliano et al., PRL120, 202001 (2018); PRC97,065501 (2019)

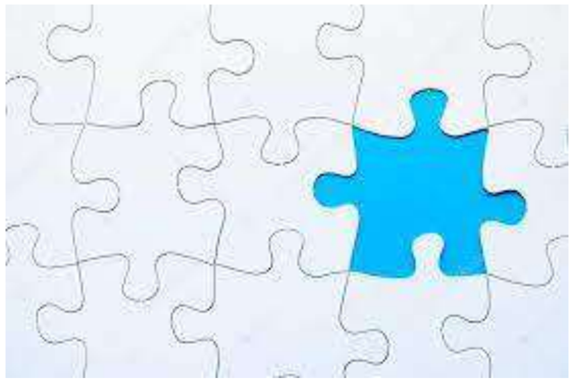
An missing piece



+



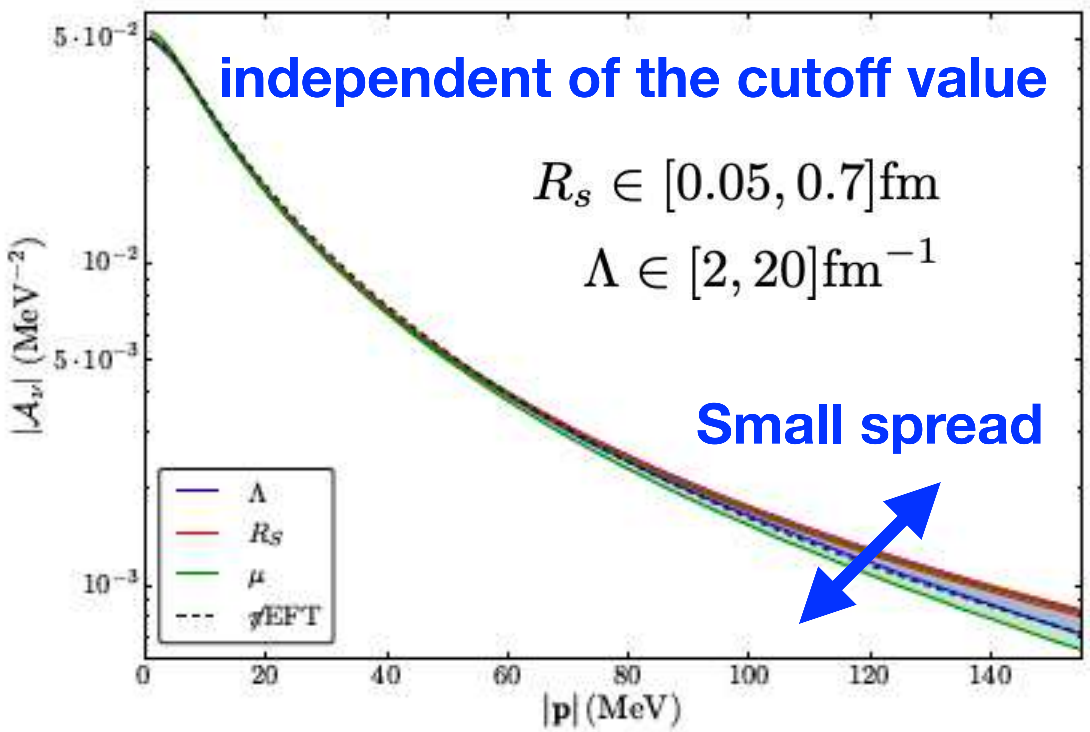
$$V_{\nu,CT} = -2g_\nu^{\rm NN}\tau^{(1)+}\tau^{(2)+},$$



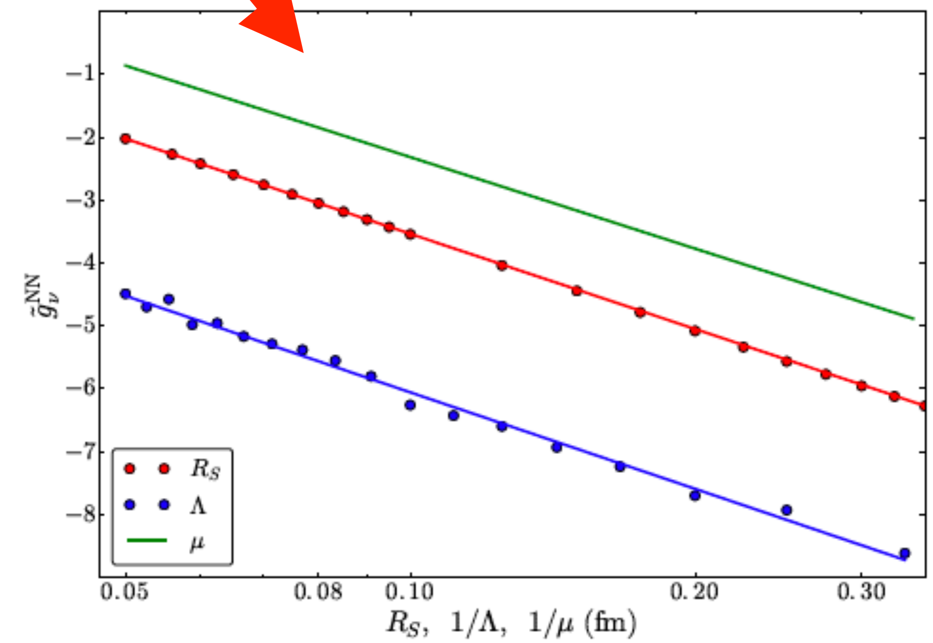
Total transition amplitude $\mathcal{A}(p,p') = \mathcal{A}_L(p,p') - 2g\mathcal{A}_S(p,p').$

Fitted to an arbitrary value

$$\mathcal{A}_\nu(|\mathbf{p}| = 1\,\mathrm{MeV},\ |\mathbf{p}'| = 38\,\mathrm{MeV})e^{-i(\delta_{^1S_0}(E)+\delta_{^1S_0}(E'))} \doteq -0.05\,\mathrm{MeV}^{-2}$$



LEC



Determination of the leading-order contact operator

- The LEC should be fitted to **data** or the LD+SD **amplitude by Lattice QCD**

Light-Neutrino Exchange and Long-Distance Contributions to $0\nu 2\beta$ Decays: An Exploratory Study on $\pi\pi \to ee$

Xu Feng, Lu-Chang Jin, Xin-Yu Tuo, and Shi-Cheng Xia
Phys. Rev. Lett. **122**, 022001 – Published 15 January 2019

参看冯旭的报告

LQCD: $$\left.\frac{\mathcal{A}(\pi\pi \to ee)}{F_\pi^2 T_{\rm lept}}\right|_{m_\pi=140\ \rm MeV} = 1.820(6)$$

$$T_{\rm lept} = 4G_F^2 V_{ud}^2 m_{\beta\beta} \bar{u}_L(p_1) u_L^c(p_2).$$

Chiral EFT(LO): $$\mathcal{A}^{\rm LO}(\pi\pi \to ee) = 2F_\pi^2 T_{\rm lept}$$

discrepancy might be from

- lattice artifacts and finite-volume effects
- LO chiral expansion error

Path from Lattice QCD to the Short-Distance Contribution to $0\nu\beta\beta$ Decay with a Light Majorana Neutrino

Zohreh Davoudi and Saurabh V. Kadam
Phys. Rev. Lett. **126**, 152003 (2021) – Published 16 April 2021

Providing a framework to match the total transition amplitude of the nn→ppe-e- process from the calculations of both **lattice QCD** and **chiral effective field theory**.

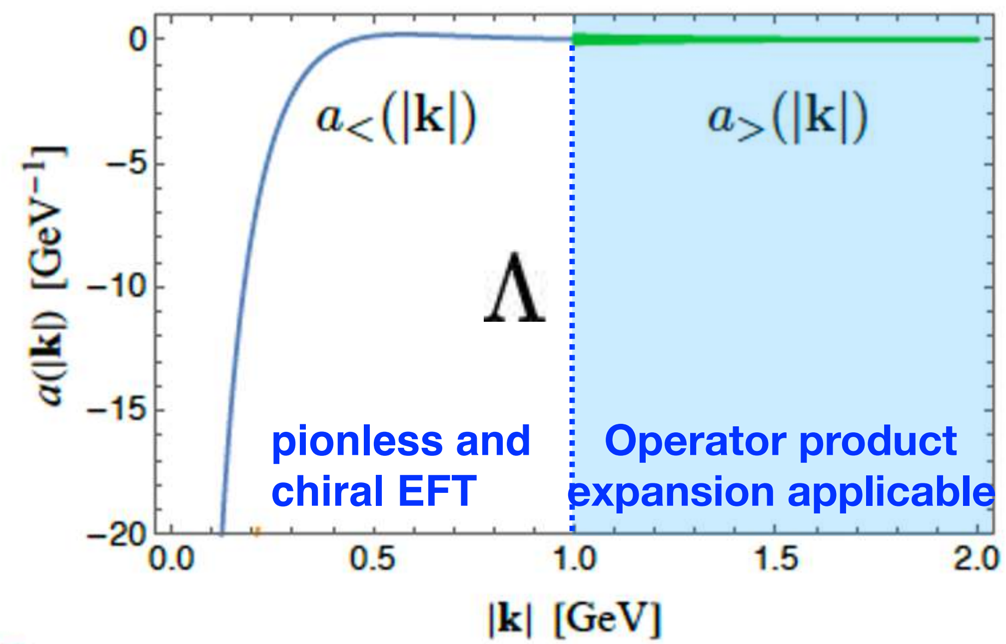
Advances in ab initio modeling of $0\nu\beta\beta$-decay NME

▸ **Determination of the LEC for the contact term**

Toward Complete Leading-Order Predictions for Neutrinoless Double β Decay

Vincenzo Cirigliano, Wouter Dekens, Jordy de Vries, Martin Hoferichter, and Emanuele Mereghetti

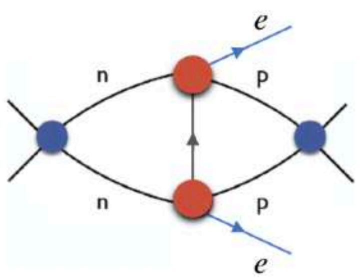
Phys. Rev. Lett. **126**, 172002 (2021) – Published 30 April 2021



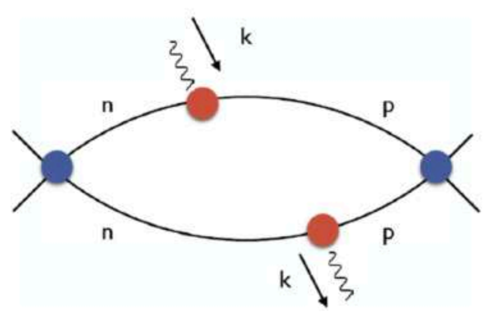
- **Cottingham formula** W.N. Cottingham, Ann. Phys. 25, 424 (1963)

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4}\frac{g_{\mu\nu}}{k^2+i\epsilon}\int d^4x\, e^{ik\cdot x}\langle pp|T\{j^\mu_{\rm w}(x)j^\nu_{\rm w}(0)\}|nn\rangle$$

$$\mathcal{A}_\nu =$$



$$\propto \int \frac{d^4k}{(2\pi)^4}\frac{1}{k^2+i\epsilon}$$



forward Compton amplitude

$$\mathcal{A}_\nu^{\rm full} = \int_0^\infty d|\mathbf{k}|\; a^{\rm full}(|\mathbf{k}|) = \mathcal{A}^< + \mathcal{A}^>\,,$$

$$\mathcal{A}^< = \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|)\,,$$

$$\mathcal{A}^> = \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)\,,$$

- **Synthetic datum**

$$\mathcal{A}_\nu(|\mathbf{p}|,|\mathbf{p}'|)\times e^{-i(\delta_{^1S_0}(|\mathbf{p}|)+\delta_{^1S_0}(|\mathbf{p}'|))} = -\left(2.271 - 0.075\,\tilde{C}_1(4\,M_\pi)\right)\times 10^{-2}\,\mathrm{MeV}^{-2}$$

$$|\mathbf{p}| = 25\,\mathrm{MeV}\ \ (|\mathbf{p}'| = 30\,\mathrm{MeV}) \qquad = -1.95(5)_{\tilde{C}_1}\times 10^{-2}\,\mathrm{MeV}^{-2}\,,$$

Uncertainty from the estimate of the **inelastic** contributions

The amplitude is observable and thus scheme independent.

Determination of the leading-order contact operator

- **Contribution of the contact term to the NME of finite nuclei**

R. Wirth, JMY, H. Hergert, arXiv:2105.05415 [nucl-th]

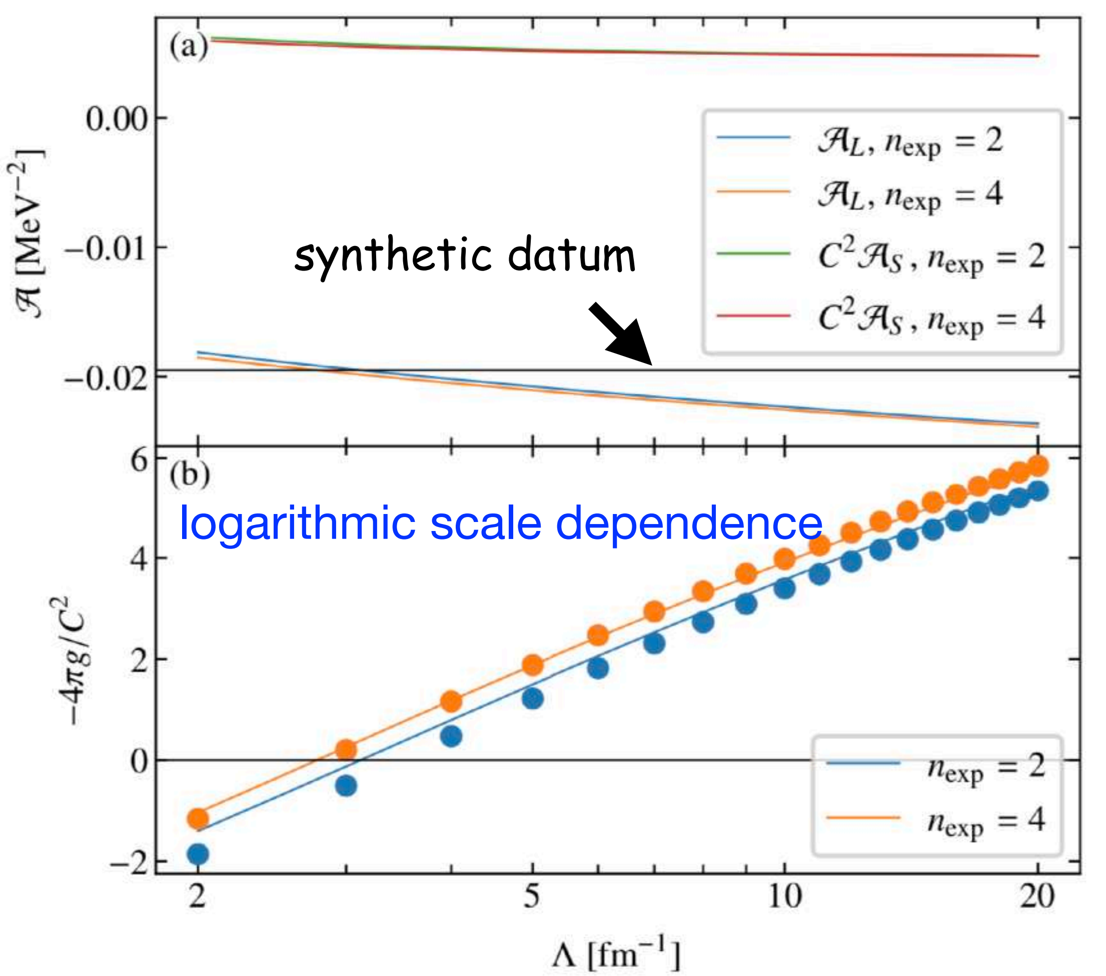
$$\mathcal{A}(p, p') = \mathcal{A}_L(p, p') - 2g\mathcal{A}_S(p, p').$$

SRG scale

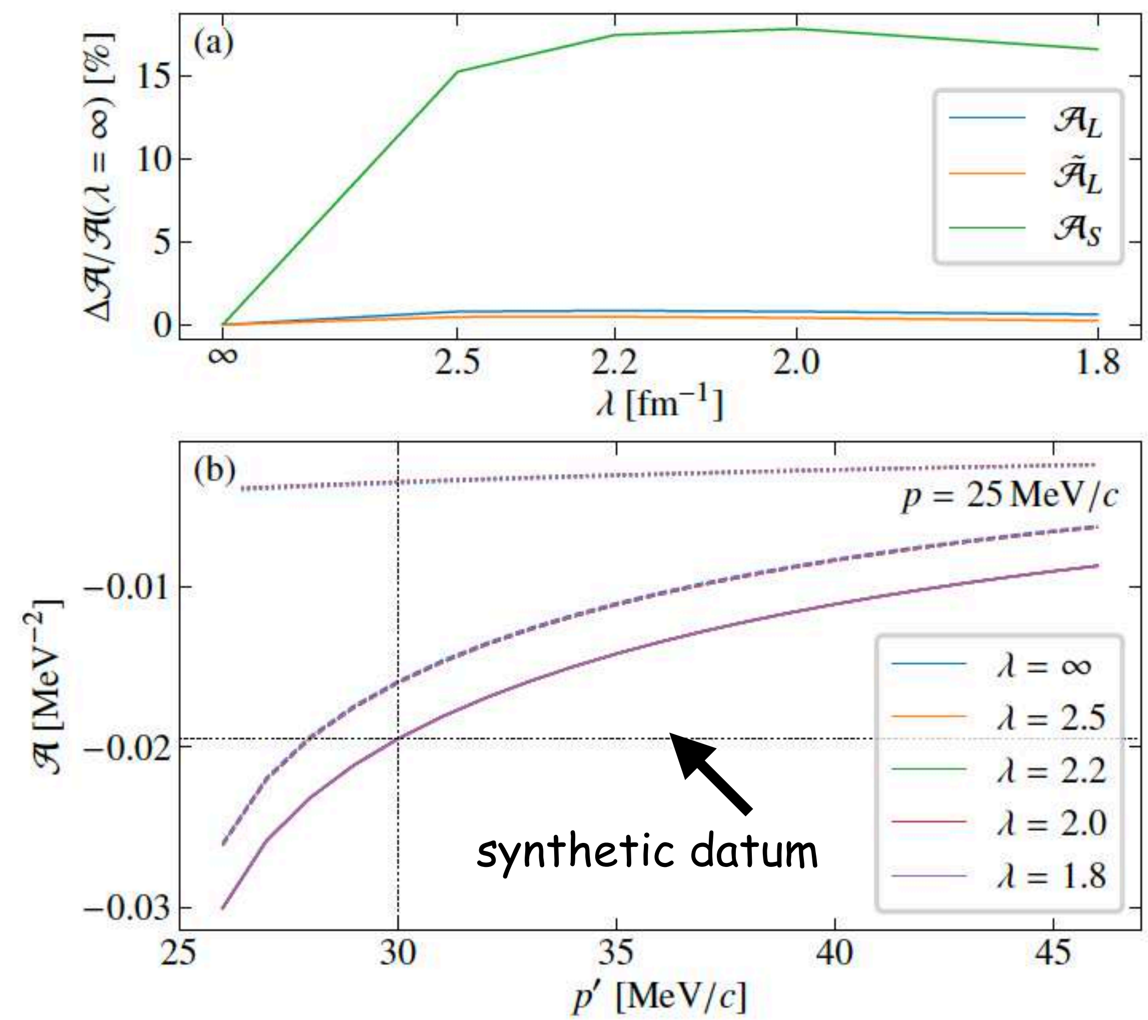
$$H_s = U(s) H U^\dagger(s)$$

$$\frac{dH_s}{ds} = [\eta(s), H_s],$$

$$\lambda \equiv s^{-1/4}$$



The dimensionless LEC C is adjusted to reproduce the neutron–proton scattering length $a_{np} = -23.74$ fm.



Determination of the leading-order contact operator

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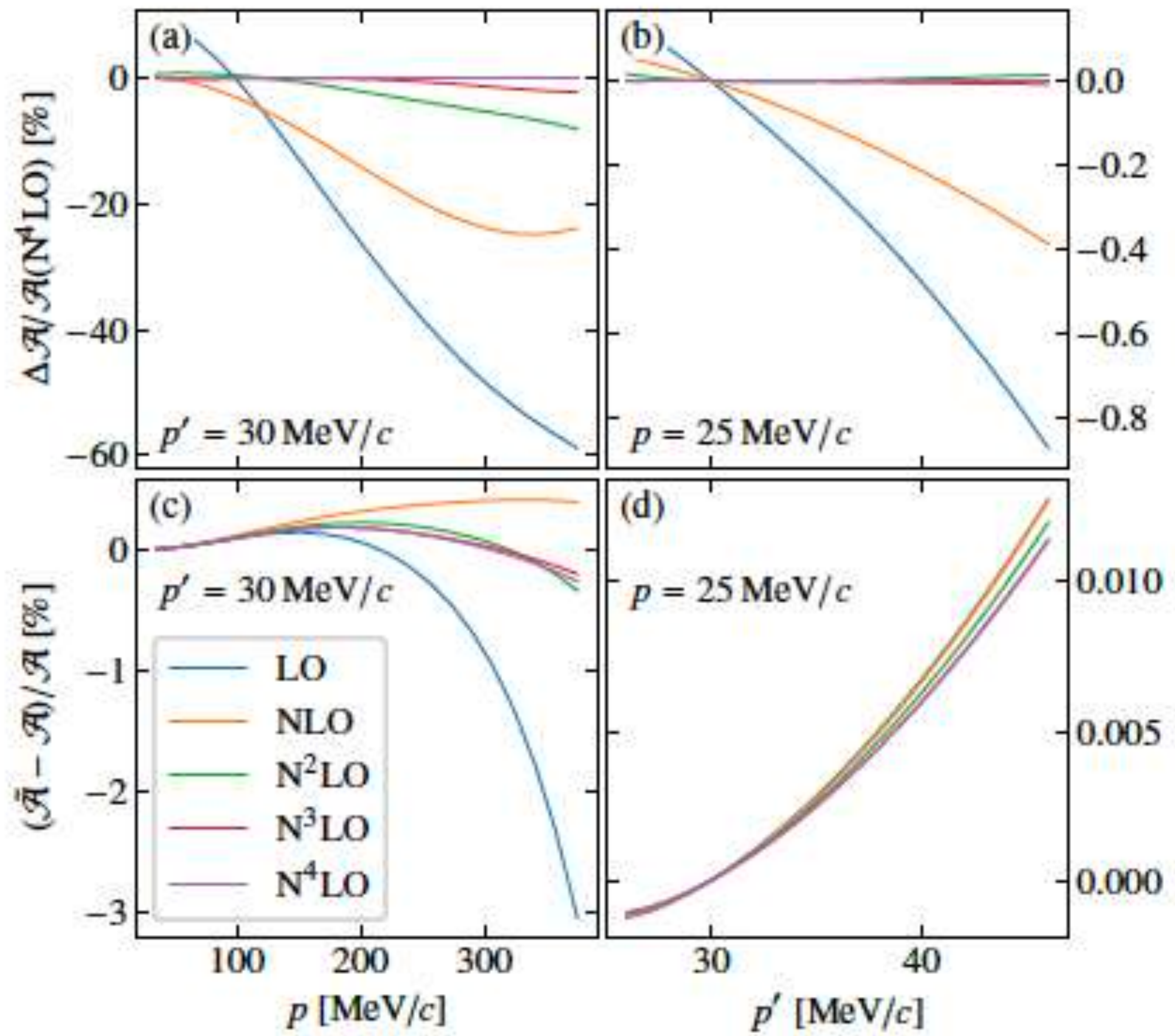
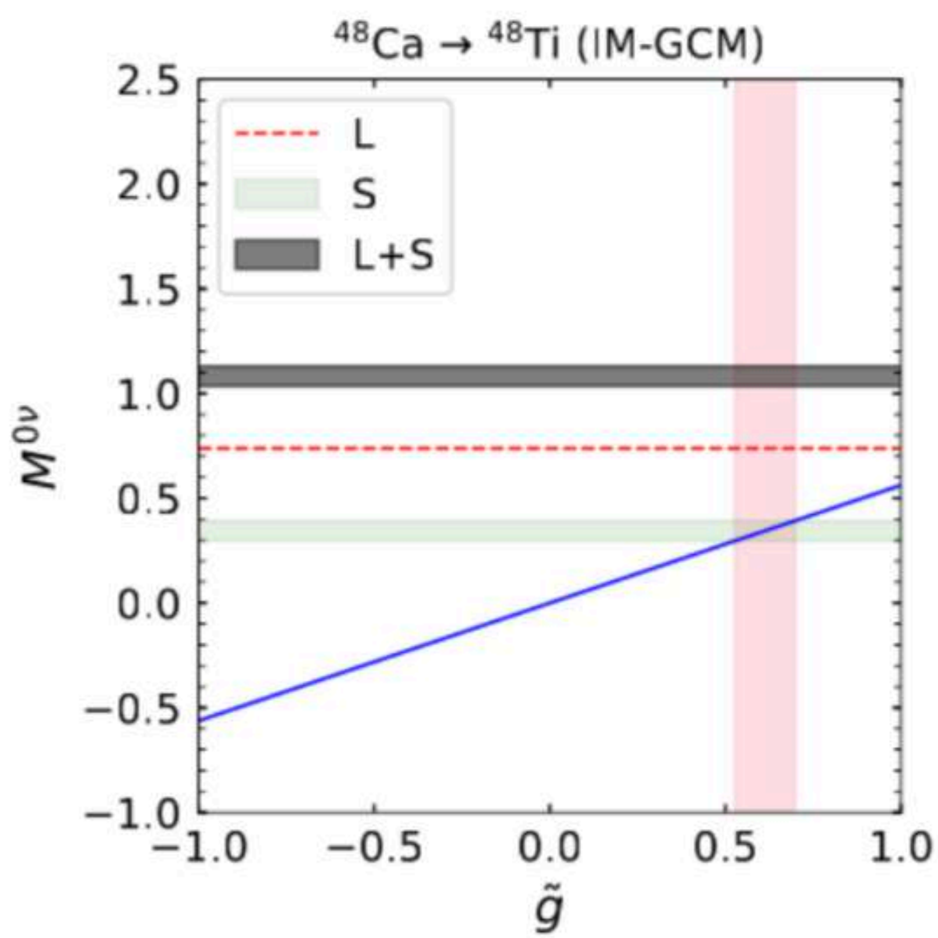
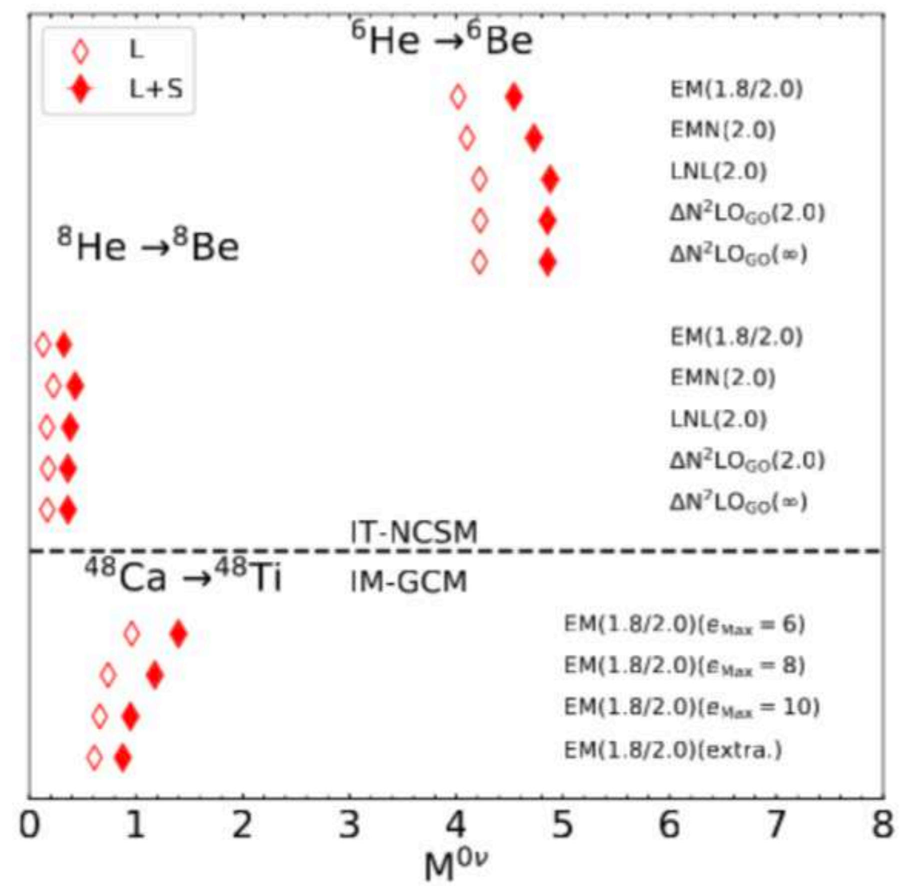


- Chiral expansion order of the nuclear interaction (not transition operator)
- LO and N^2LO (partial) neutrino potential

- **The contribution of the contact term to the NME**

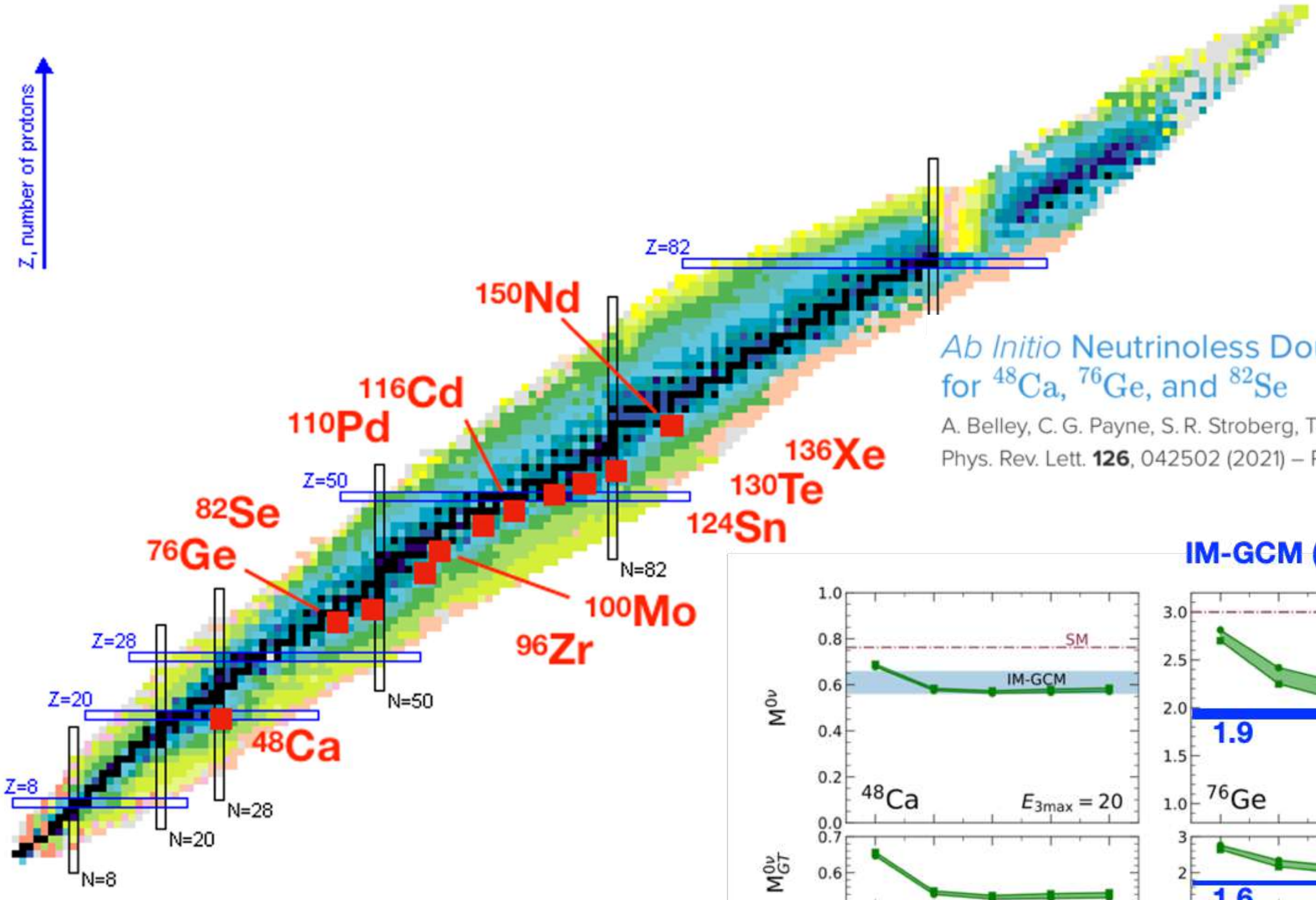
R. Wirth, JMY, H. Hergert, arXiv:2105.05415 [nucl-th]





- The contact term **enhances the NME for ^{48}Ca by 43(7)%**, the uncertainty is propagated only from the synthetic datum.
- An important positive message for planning and interpreting future experiments.

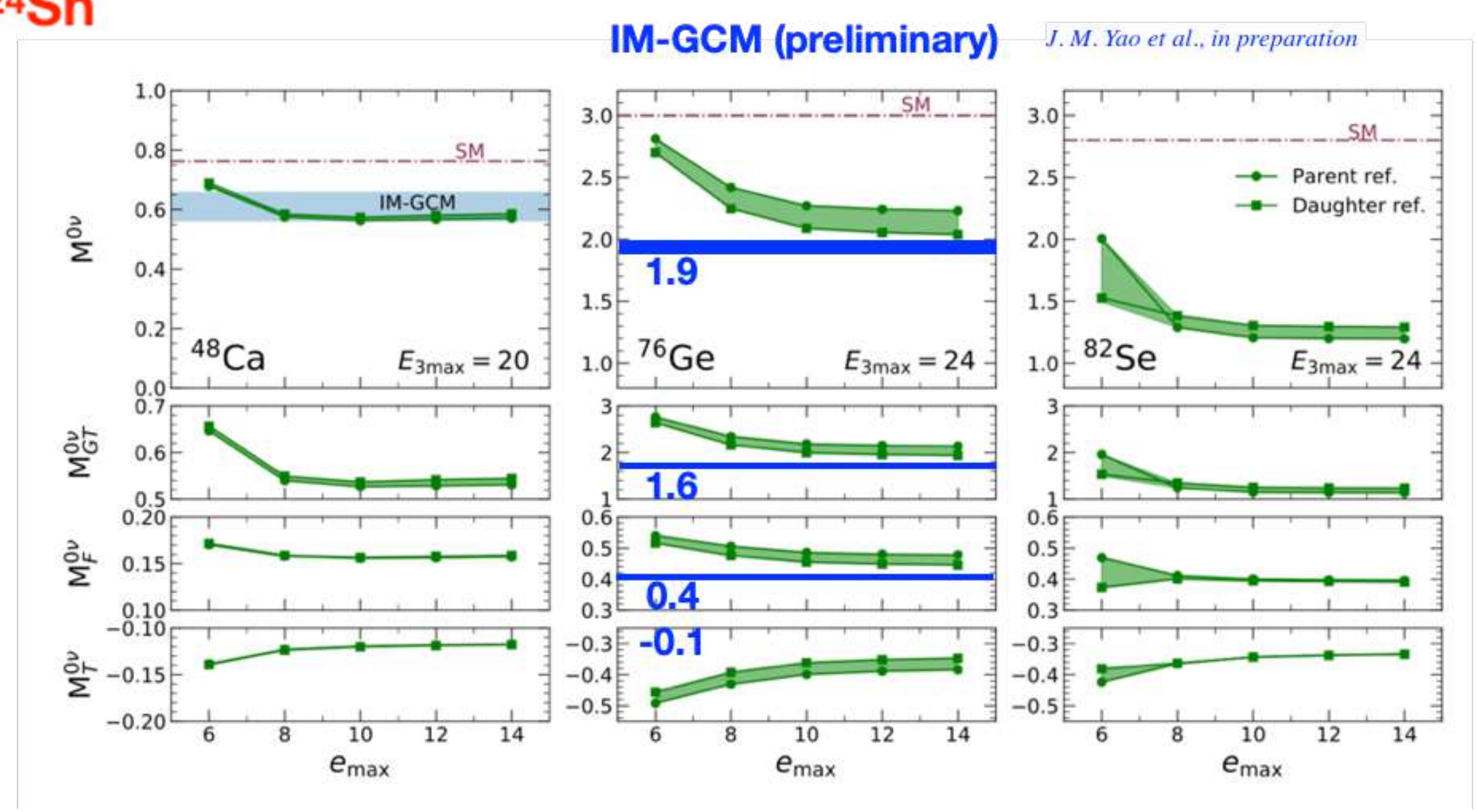
Extension to heavier $0\nu\beta\beta$ candidates



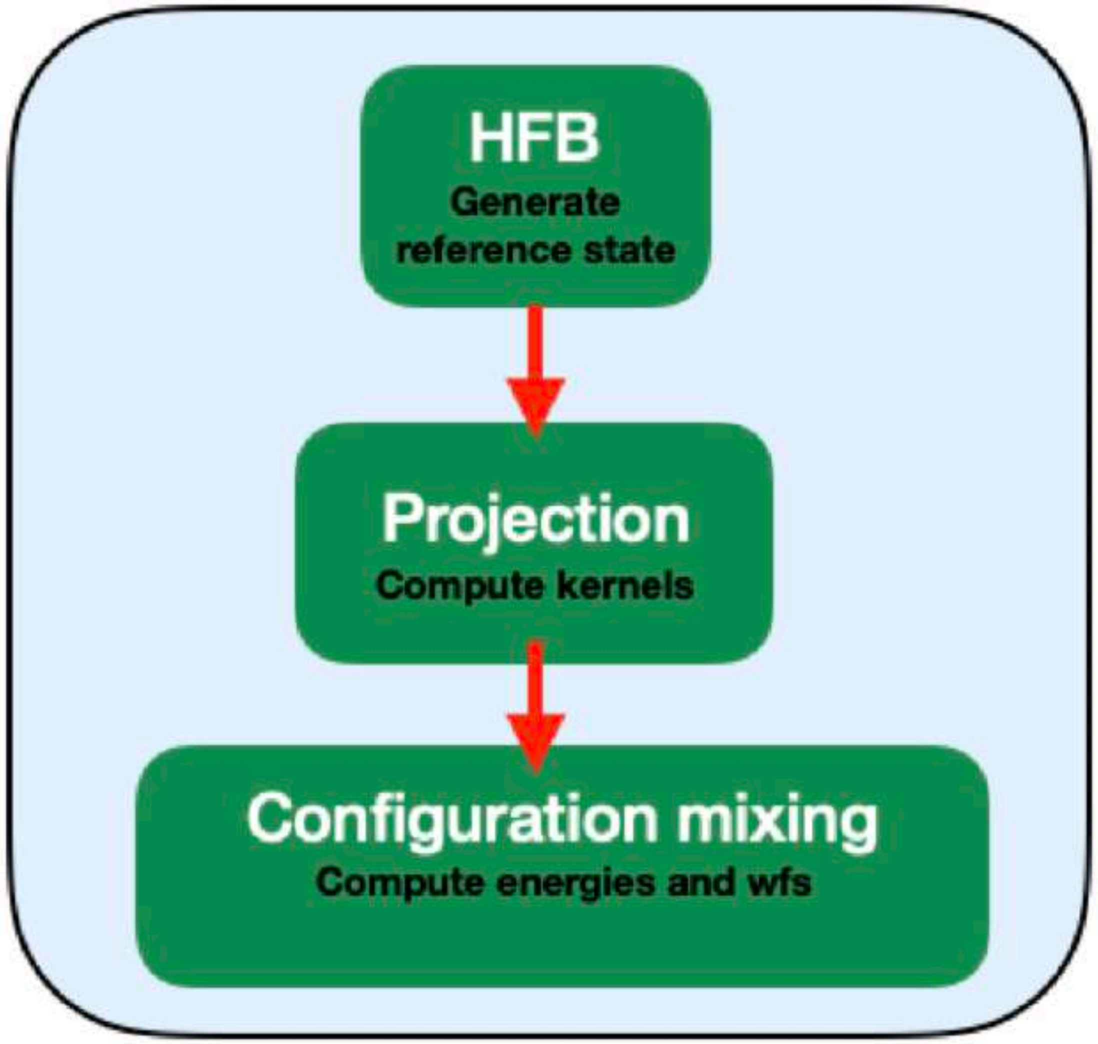
Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt

Phys. Rev. Lett. **126**, 042502 (2021) – Published 29 January 2021



Generator coordinate method (GCM) in a nutshell



- The trial wave function of a GCM state

$$|\Phi^{JNZ\cdots}\rangle = \sum_{Q} F_{Q}^{JNZ} \hat{P}^{J} \hat{P}^{N} \hat{P}^{Z} \cdots |\Phi_{Q}\rangle$$

$|\Phi_Q\rangle$ are a set of HFB wave functions from constraint calculations, Q is the so-called generator coordinate.

- The mixing weight F_Q^{JNZ} is determined from the Hill-Wheeler-Griffin equation:

$$\sum_{Q'} \left[H^{JNZ}(Q,Q') - E^{J} N^{JNZ}(Q,Q') \right] F_{Q'}^{JNZ} = 0$$

Features (pros) of GCM

– The Hilbert space in which the H will be diagonalized is defined by the Q. Many-body correlations are controlled by the Q

– The Q is chosen as (collective) degrees of freedom relevant to the physics.

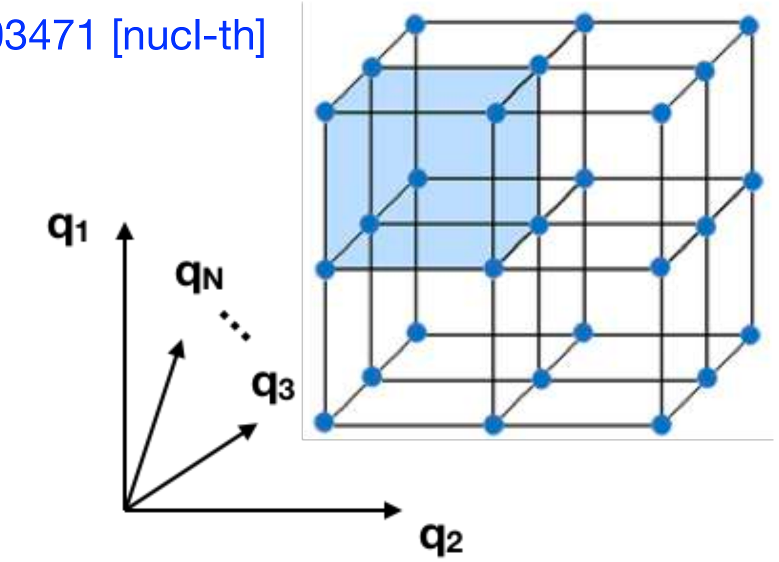
– Dimension of the space in GCM is generally much smaller than full CI calculations.

Optimization of GCM

"dimensionality curse" in GCM

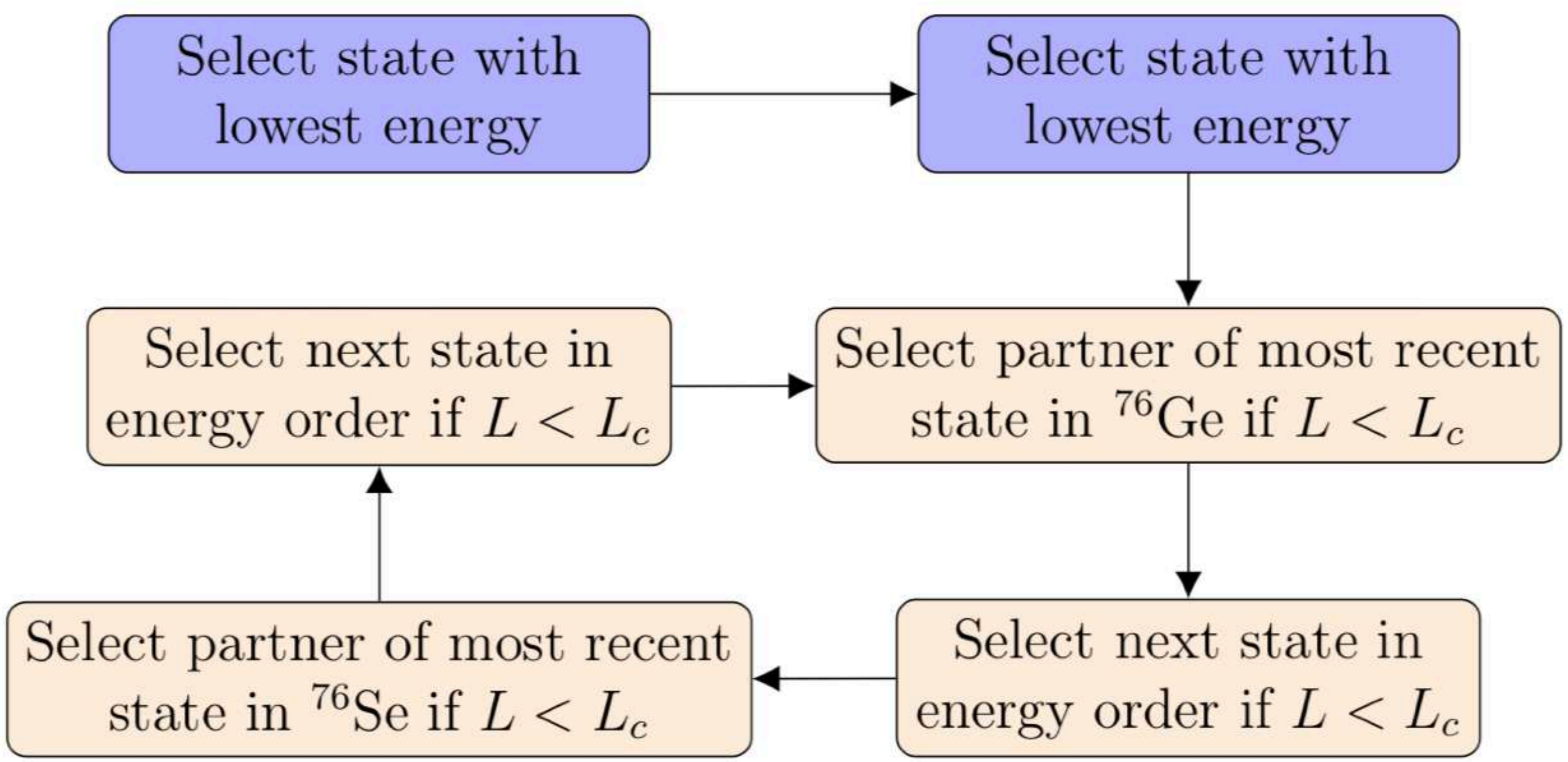
A.M. Romero, J. Engel, JMY, arXiv:2105.03471 [nucl-th]

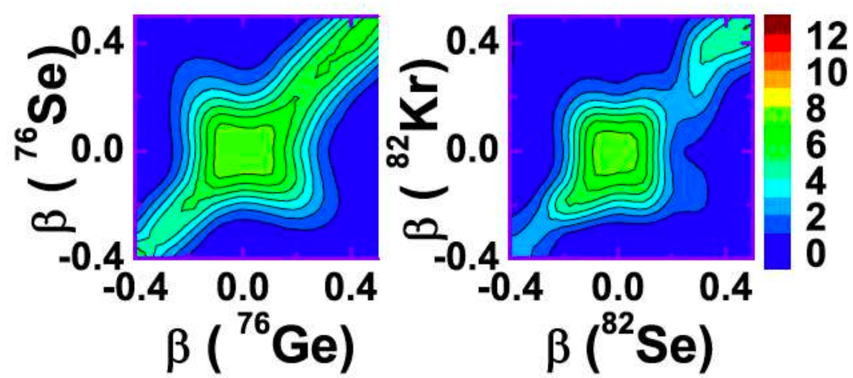
N dimensional collective space $Q=(q_1,q_2,\dots,q_N)$



- energy-transition-orthogonality procedure (ENTROP)

^{76}Ge ^{76}Se



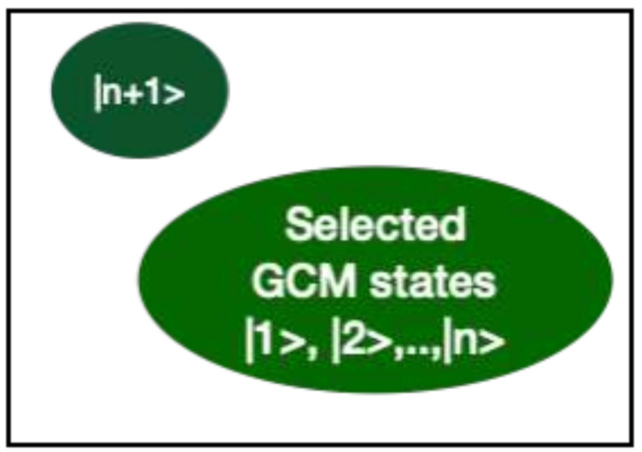


JMY, L. S. Song, K. Hagino, P. Ring, and J. Meng PRC91, 024316 (2015)

$$L = \frac{\langle n+1|P^{(n)}|n+1\rangle}{\langle n+1|n+1\rangle}$$

$$P^{(n)}|n+1\rangle = \sum_{i=1}^{n} \alpha_i^{(n)}|i\rangle,$$

L: a measure if the model space is complete or not.

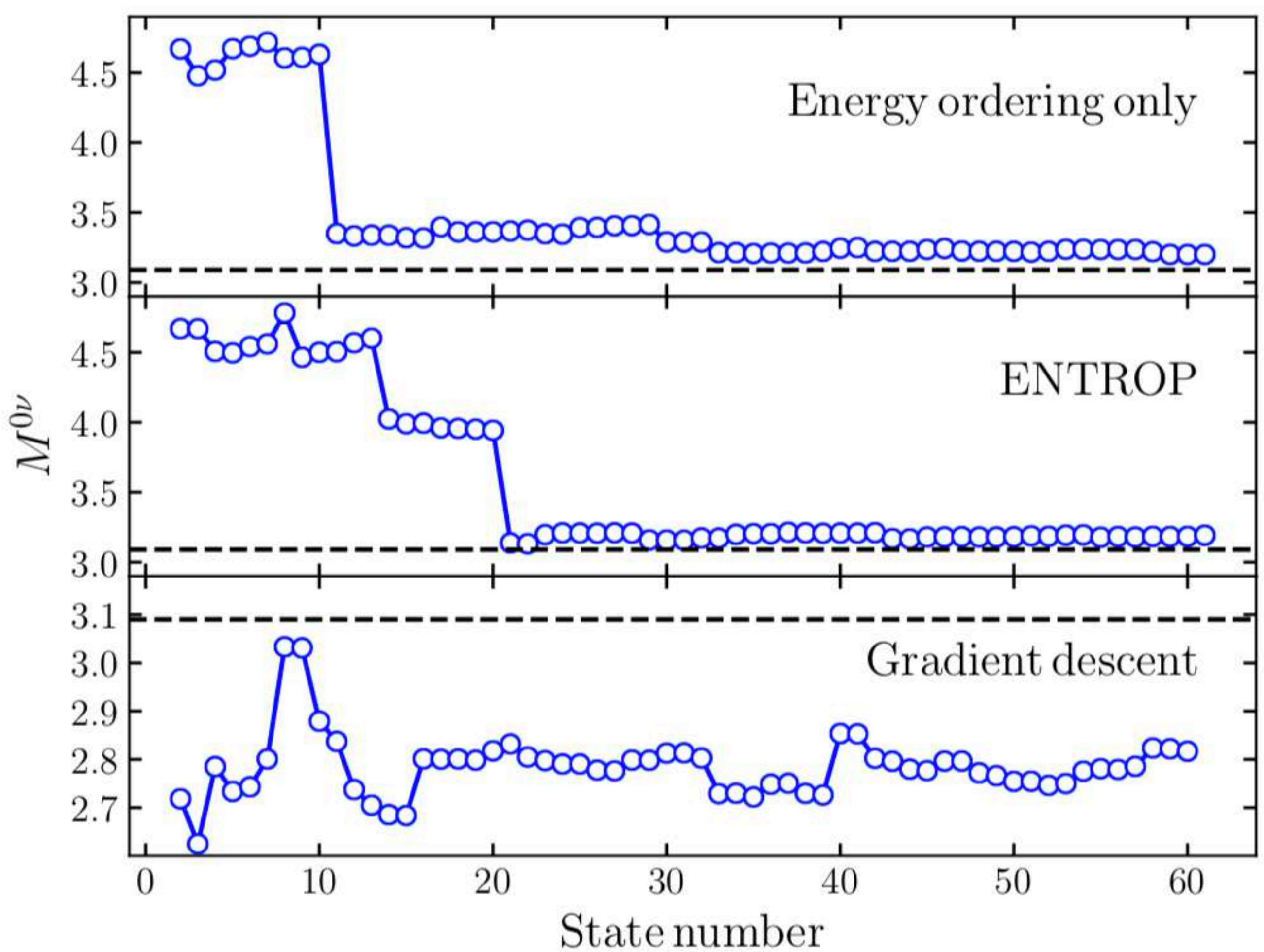


Optimization of GCM

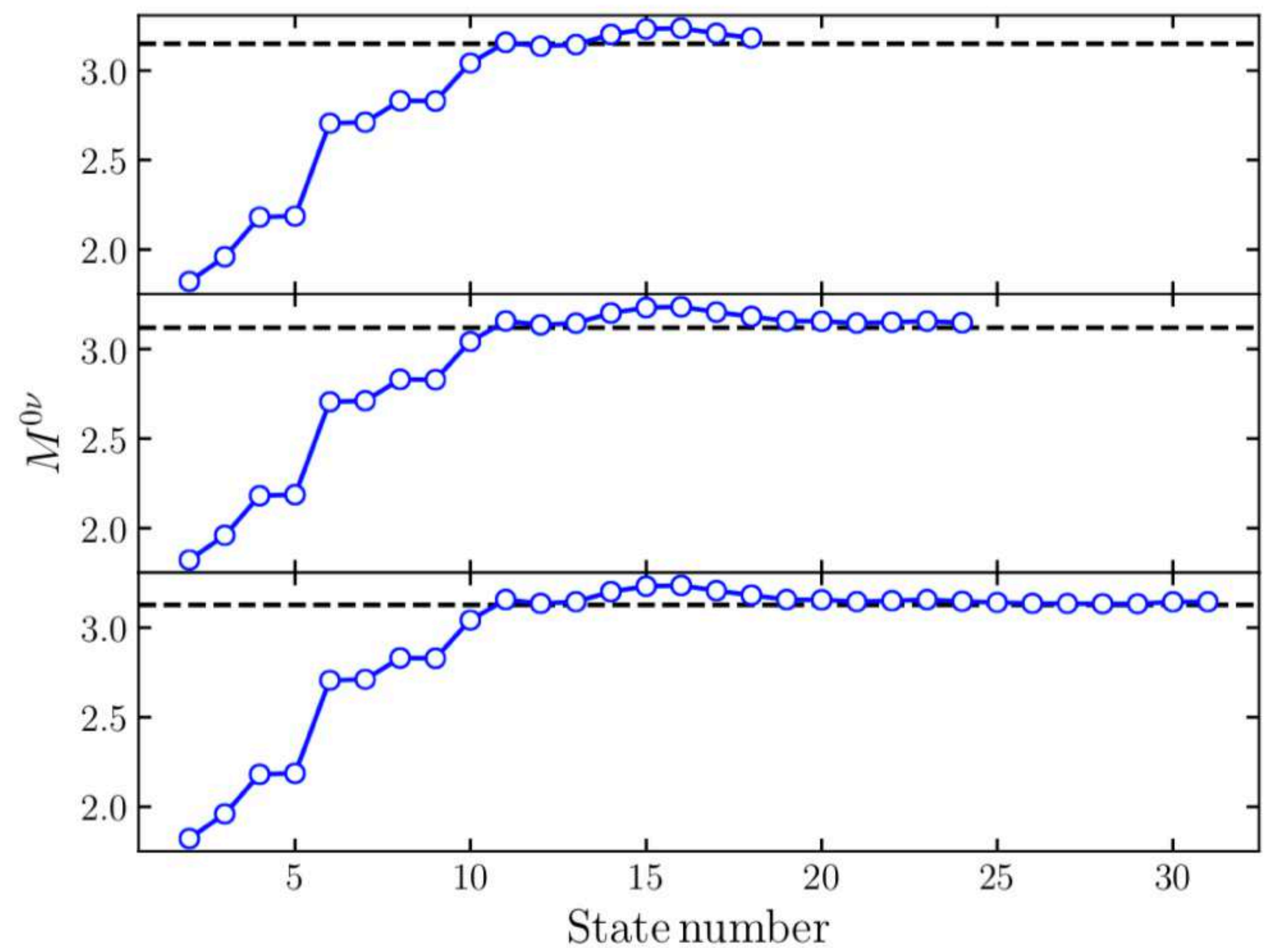
"dimensionality curse" in GCM A.M. Romero, J. Engel, JMY, arXiv:2105.03471 [nucl-th]

N dimensional collective space $Q=(q_1,q_2,\ldots,q_N)$

- energy-transition-orthogonality procedure (ENTROP)



GCM with shell-model interaction GCN2850



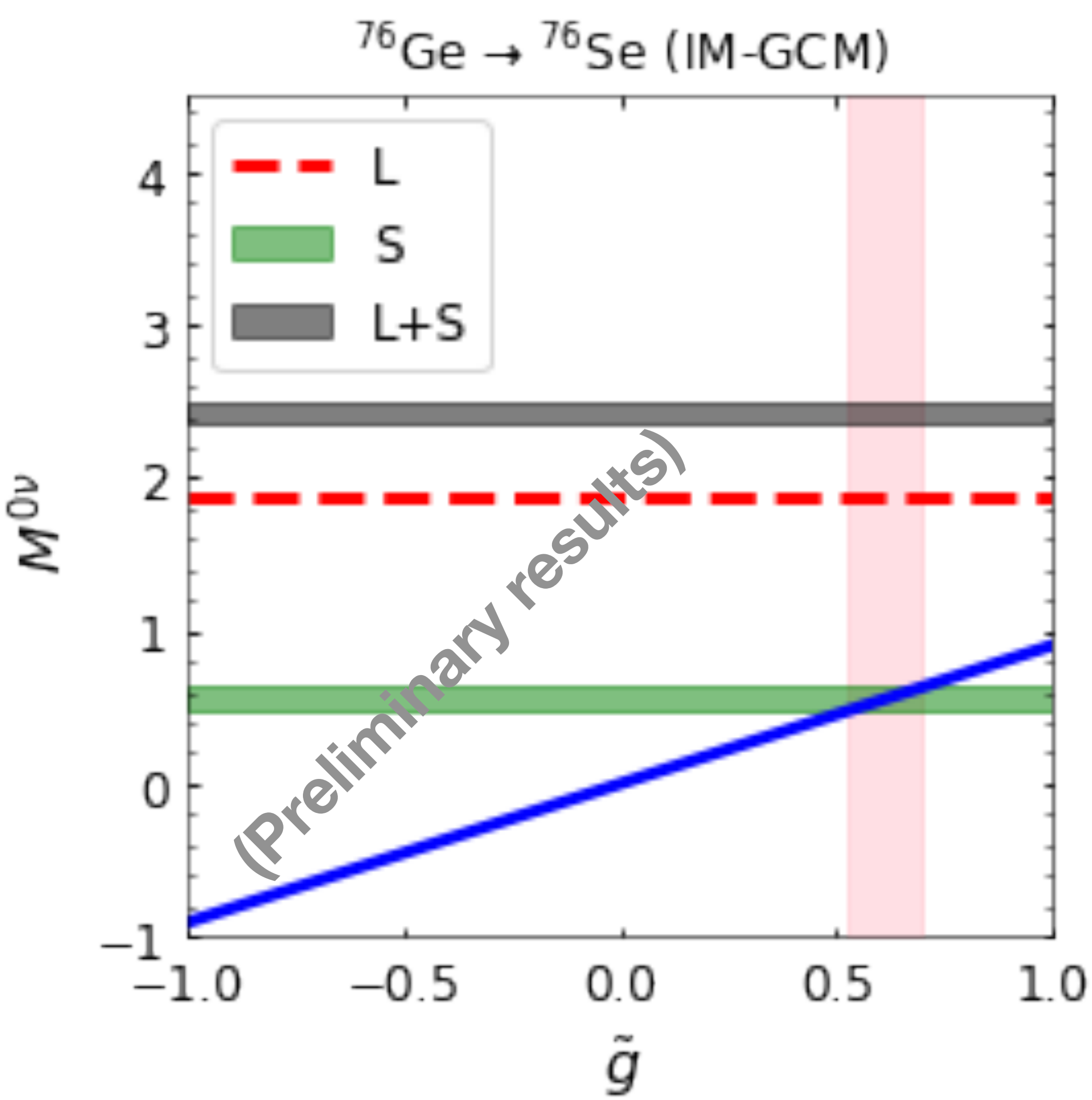
IM-GCM with a chiral nuclear force (eMax=6)

Determination of the leading-order contact operator

- **The contribution of the contact term to the NME**

JMY et al., in preparation

$$e_{\mathrm{Max}} = 8, \hbar\omega = 12 \ \mathrm{MeV}$$



The contact term **enhances the NME for ^{76}Ge by 29(5)% !**

Summary and outlook

✦ Summary

- Experimental searches of $0\nu\beta\beta$ decay are pushing up to tonne-scale detectors with the half-life sensitivity up to 10^{28} years.
- Significant advances in ab initio modeling of atomic nuclei.

  From light to medium-mass nuclei,
  close-shell to open-shell nuclei,
  spherical to deformed nuclei.

- Ab initio calculation of the NMEs of candidate nuclei with both long- and short-range operators are possible.

  ✓ The leading-order short-range operator generally enhances the NME in the ab initio calculations using a chiral nuclear force with low-energy scale regulator.
  ✓ Ready to compute the NME of heavier candidate nuclei.

Summary and outlook

✦ Outlook (TODO LIST)

- **Standard mechanism:** trans. operators derived consist. from EFT)
- **Other mechanisms:** Left-Right mixing, etc.
- **Uncertainty Quantification:** Truncation error in both nuclear interactions and many-body methods, IMSRG(3)
- **Building an emulator for the NME**: Machine learning?

Missing many pieces?

Collaborators and acknowledgement

Collaborators

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- P. Ring, Technical University of Munich, Germany
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- **J. Engel, A. Marquez Romero**, UNC-CH, USA
- **A. Belley, T. Miyagi, C. G. Payne, J. D. Holt**, TRIUMF, Canada
- **B. Bally, Tomás R. Rodríguez**, Universidad Autónoma de Madrid, Spain
- and more …

Thank you for your attention
And enjoy sunshine in Zhuhai!