Massachusetts Institute of Technology

Violating Parity in the In Medium Similarity Renormalization Group

PAINT 2026

Antoine Belley

25 February 2026

Acknowledgement

- Ronald Fernando Garcia Ruiz

- Ragnar Stroberg

- Takayuki Miyagi

- Jon Engel
- **Beatriz Romeo**

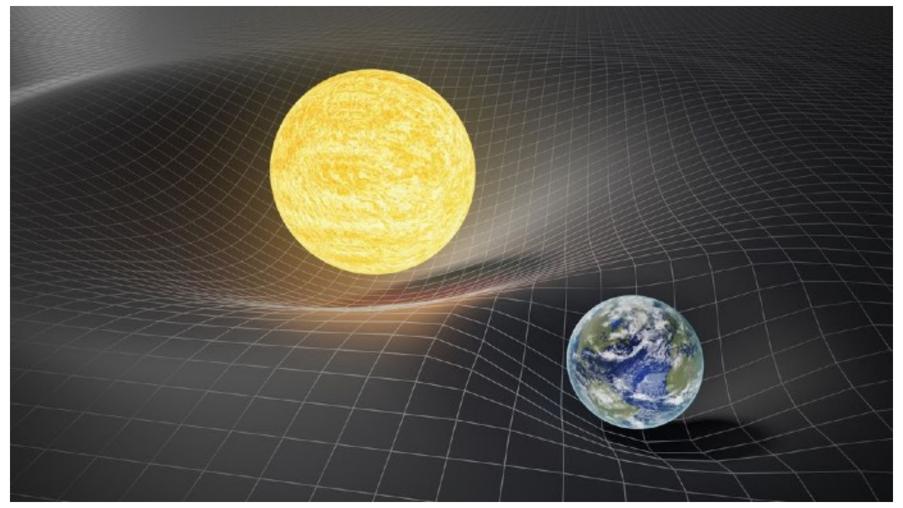
- Jason Holt
- Petr Navrátil

Shortcomings of the Standard Model

Shortcomings of the Standard Model

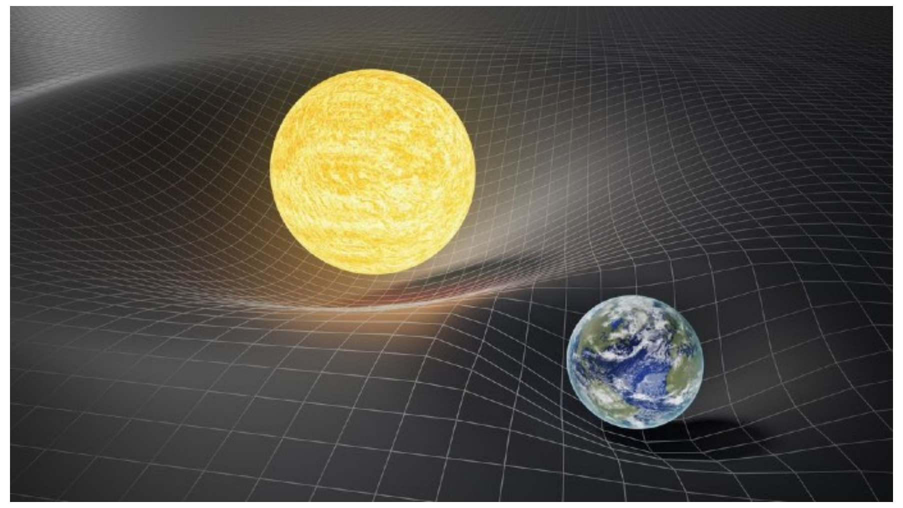
- Fails to explain gravity

Credit: vchal via Getty Images



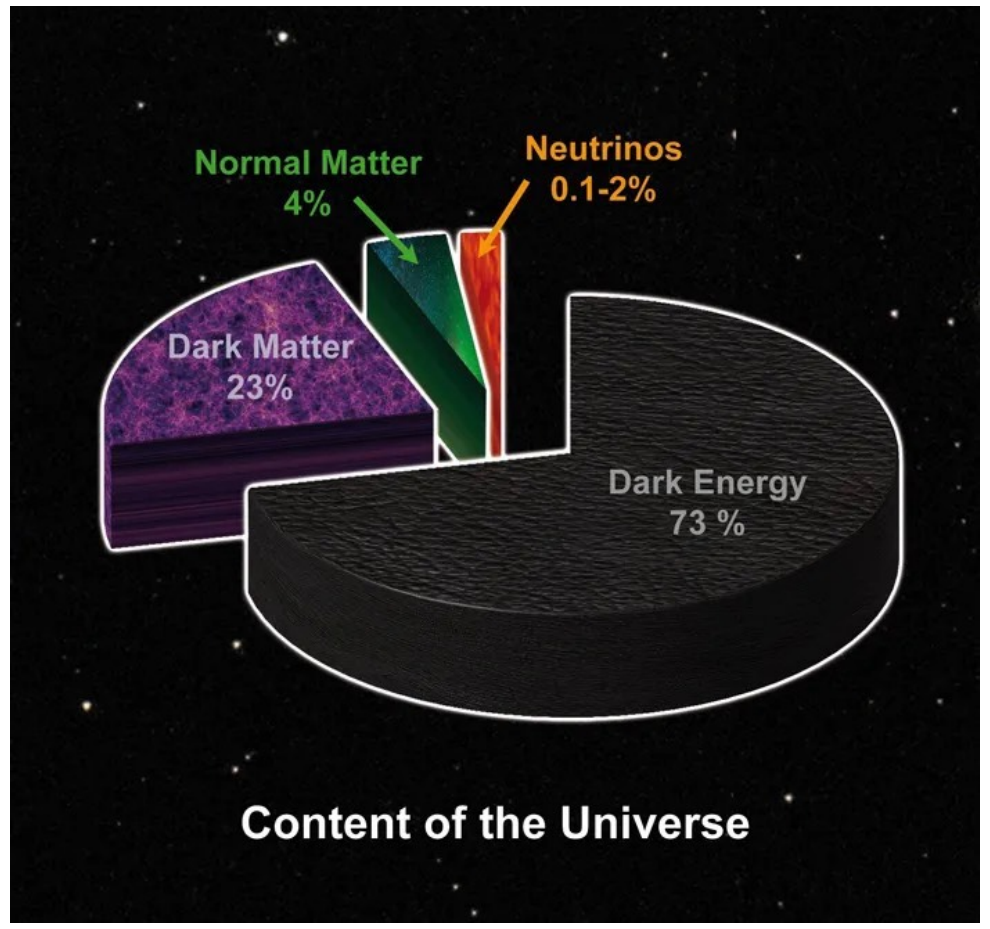
Shortcomings of the Standard Model

Credit: vchal via Getty Images



- Fails to explain gravity

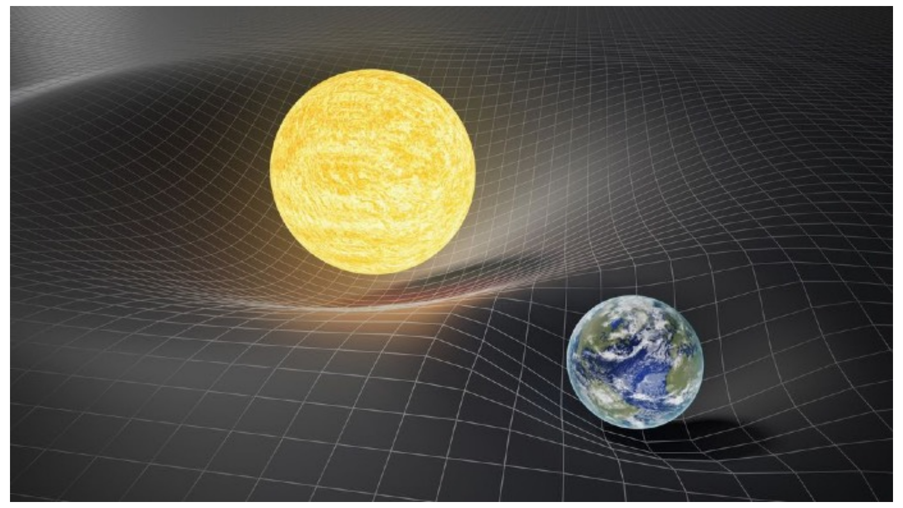
- Fails to explain most of the mass and energy of the universe



Credit: spacecentre.co.uk

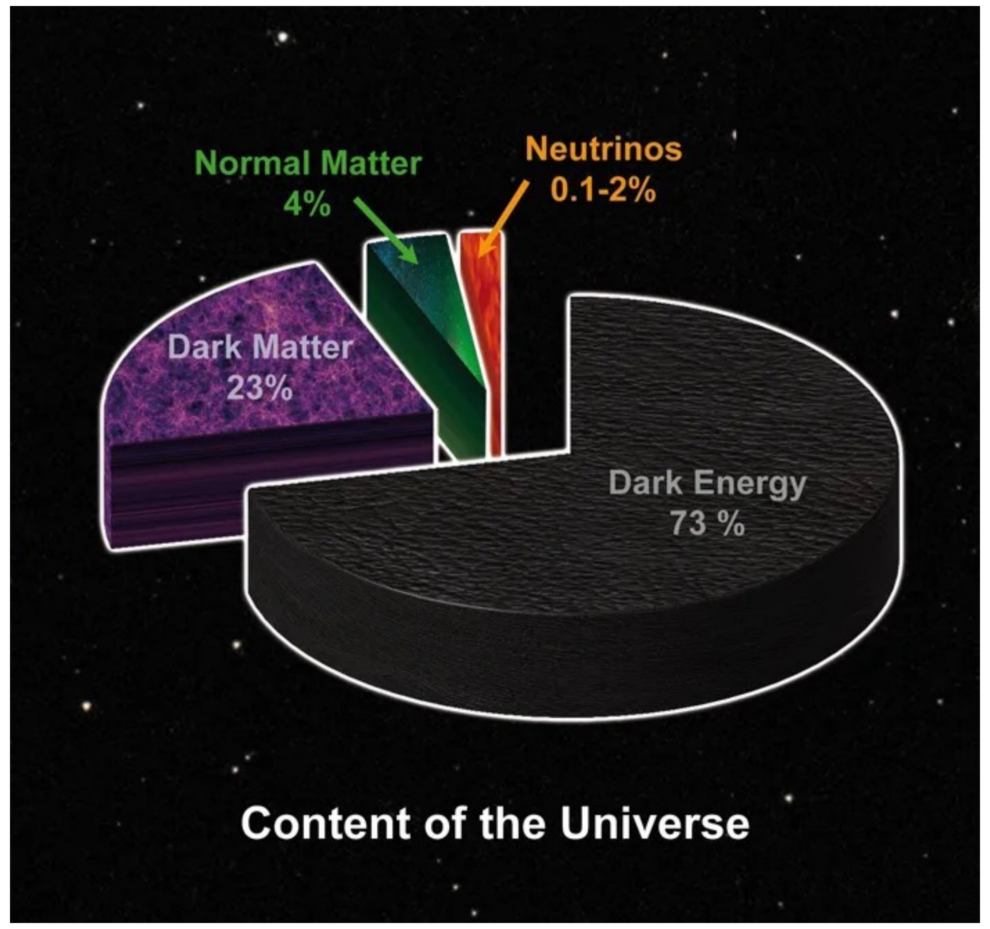
Shortcomings of the Standard Model

Credit: vchal via Getty Images



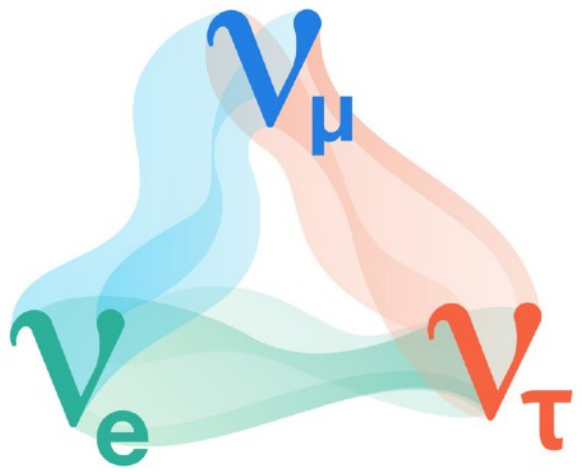
- Fails to explain gravity

- Fails to explain most of the mass and energy of the universe



Credit: spacecentre.co.uk

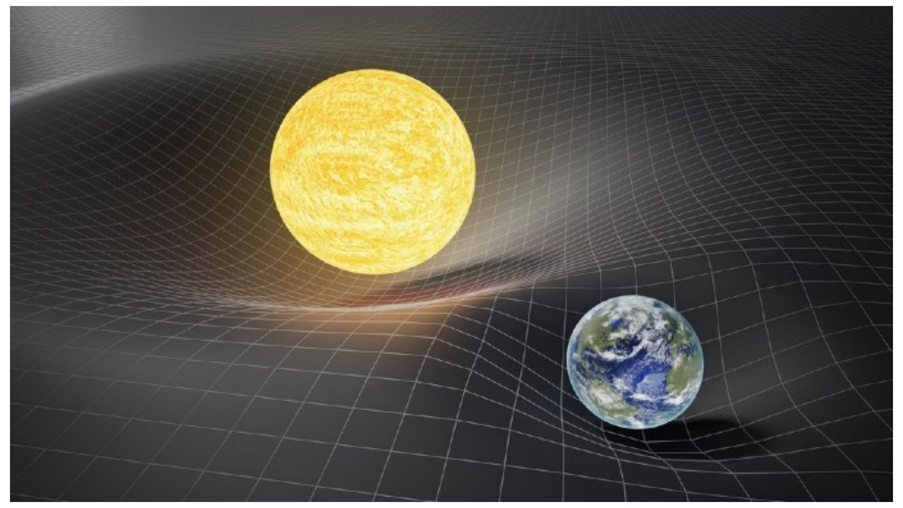
- Fails to explain neutrino mass and oscillation.



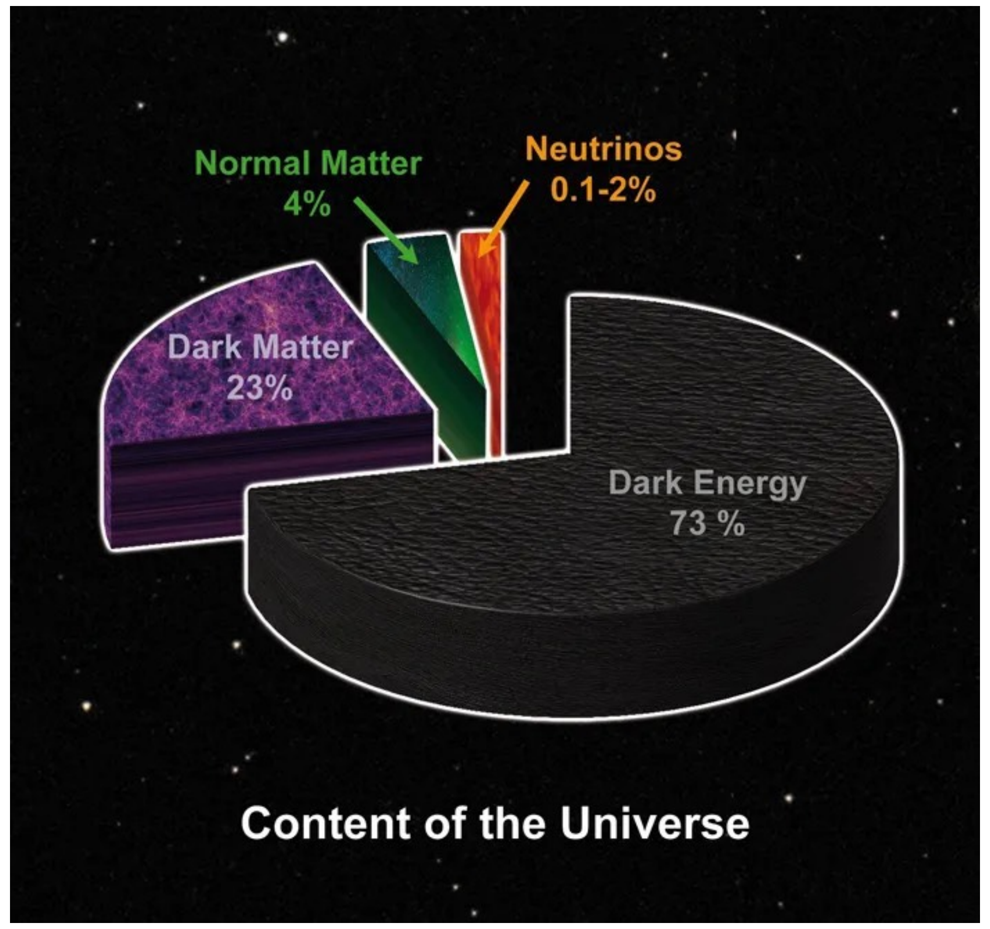
Credit: Sanford Lab/DUNE

Shortcomings of the Standard Model

Credit: vchal via Getty Images



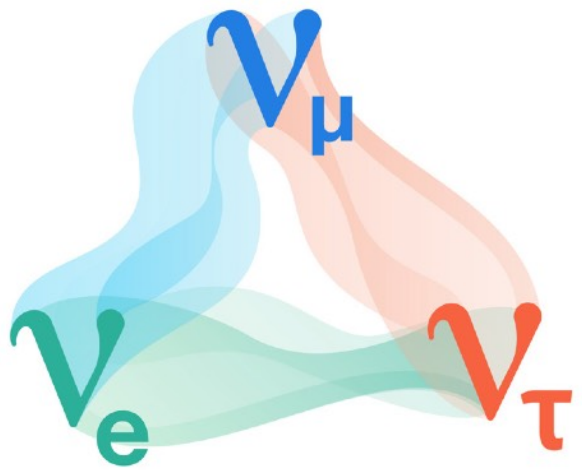
- Fails to explain gravity



Credit: spacecentre.co.uk

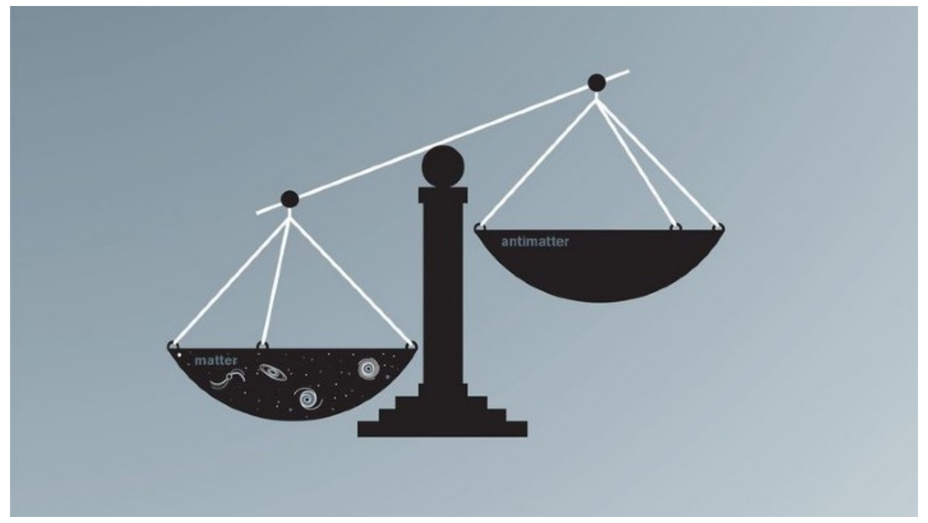
- Fails to explain most of the mass and energy of the universe

- Fails to explain neutrino mass and oscillation.



Credit: Sanford Lab/DUNE

- Fails to explain the matter-antimatter asymmetry.

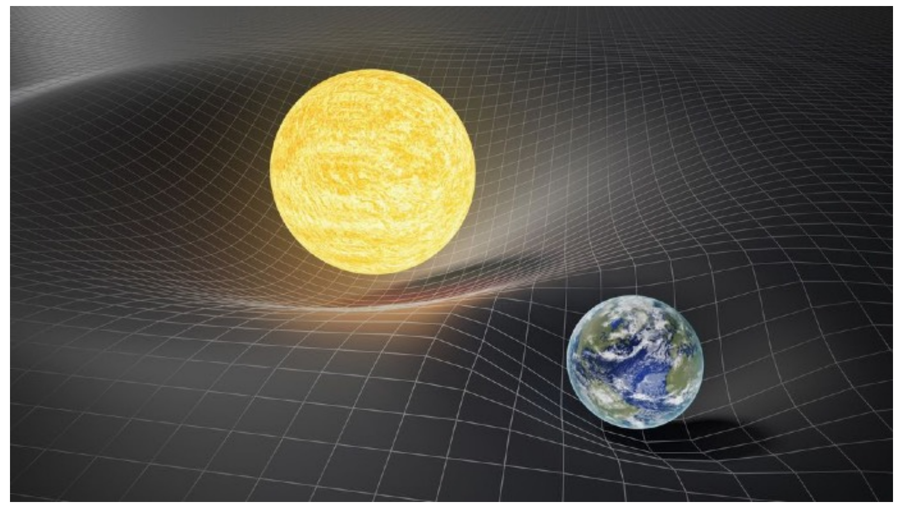


Credit: Symmetry Magazine / Sandbox Studio, Chicago

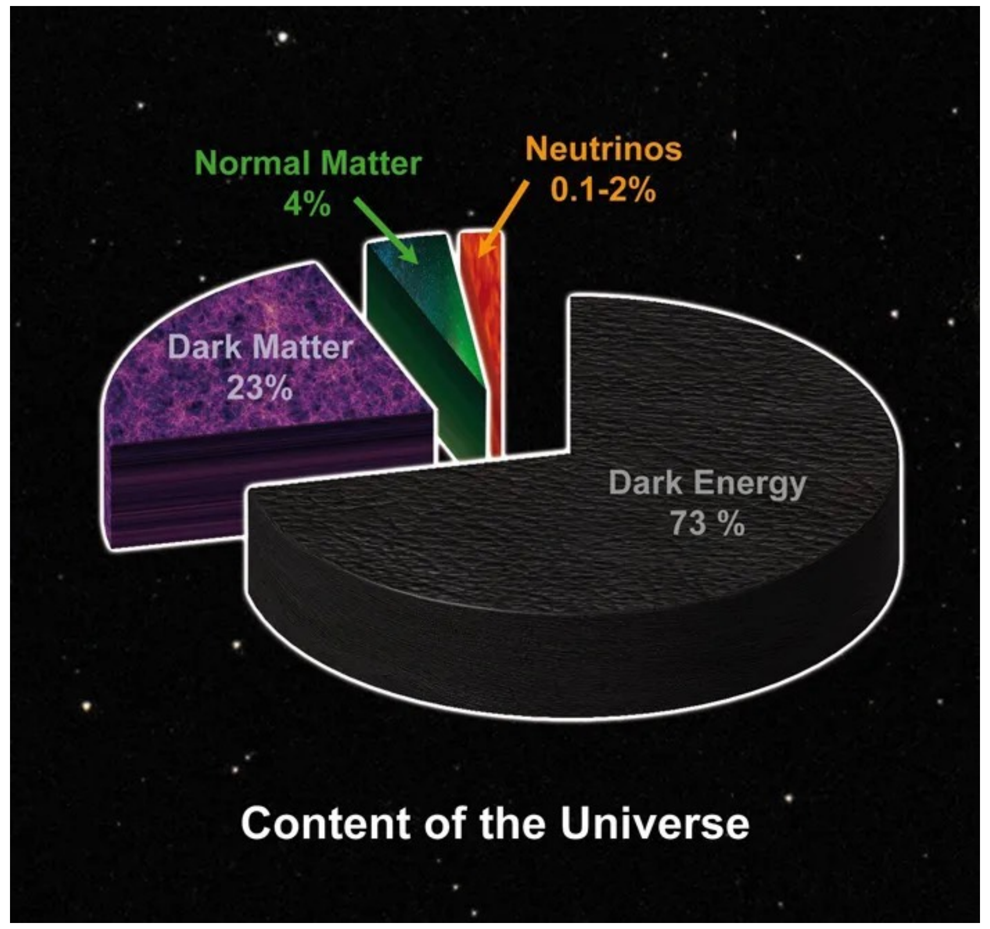
Shortcomings of the Standard Model

Credit: vchal via Getty Images

- Fails to explain gravity

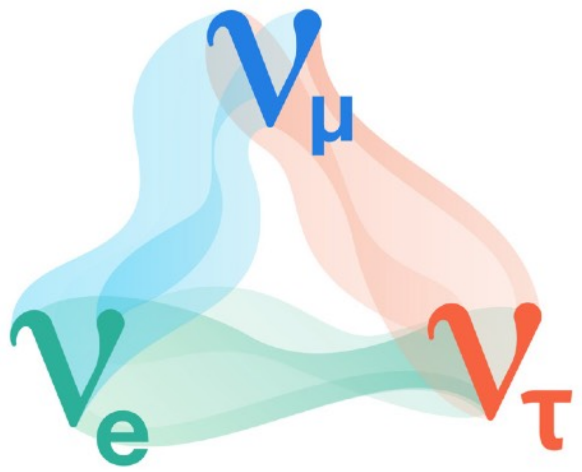


- Fails to explain most of the mass and energy of the universe



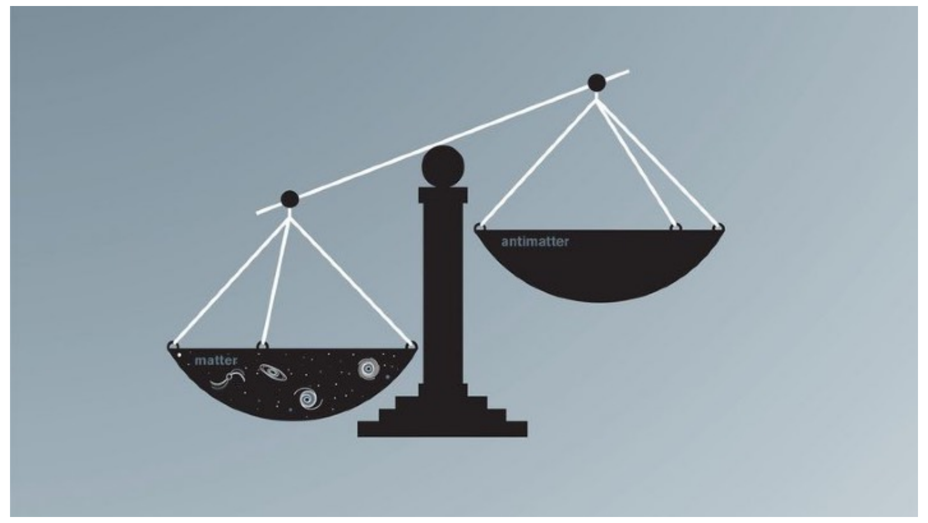
Credit: spacecentre.co.uk

- Fails to explain neutrino mass and oscillation.



Credit: Sanford Lab/DUNE

- Fails to explain the matter-antimatter asymmetry.



Credit: Symmetry Magazine / Sandbox Studio, Chicago

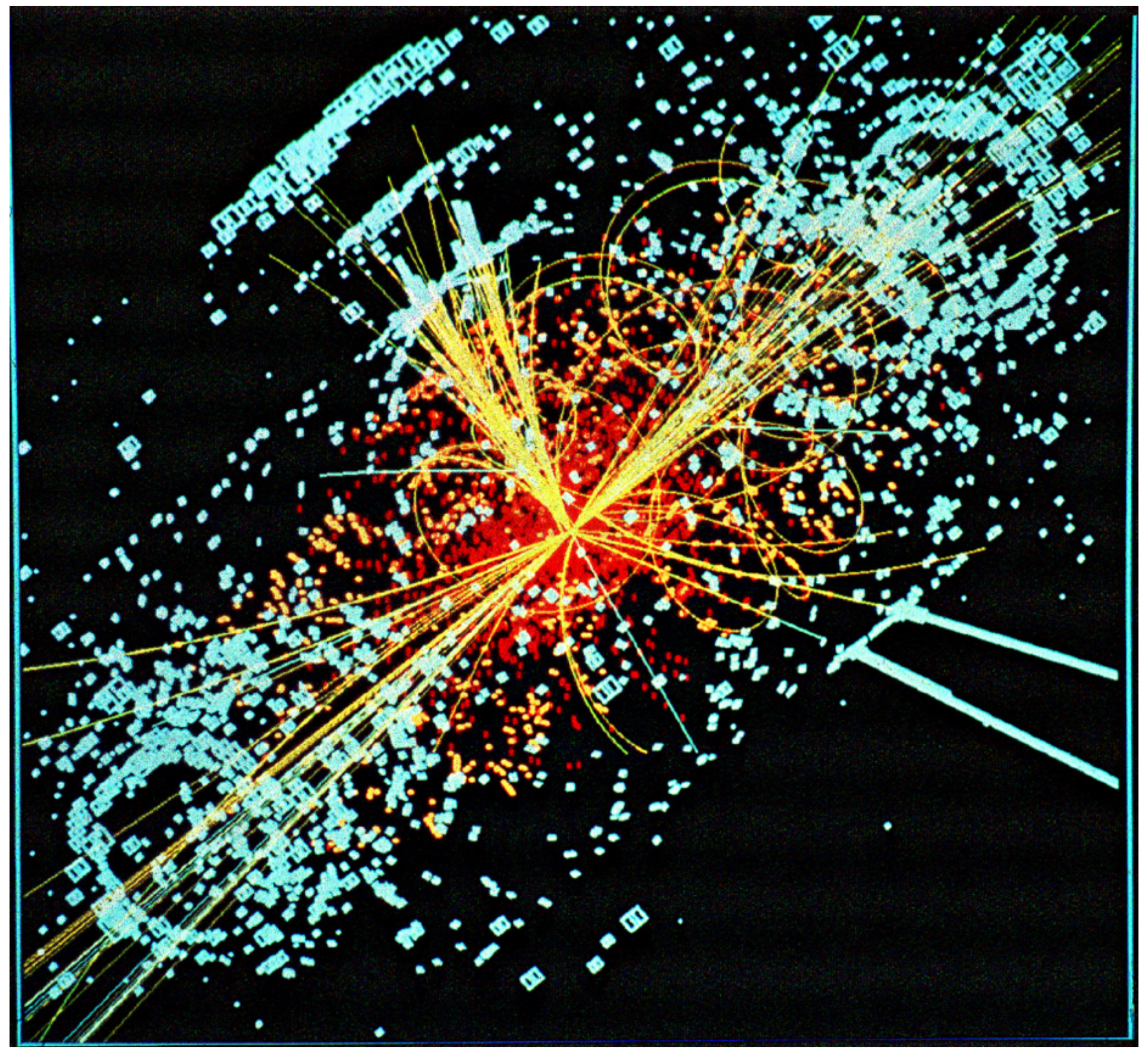
How should we search beyond the Standard Model to explain these shortcomings?

Going Beyond

TeV Scale ⟷ < MeV Scale

Going Beyond

1. High energy Frontier

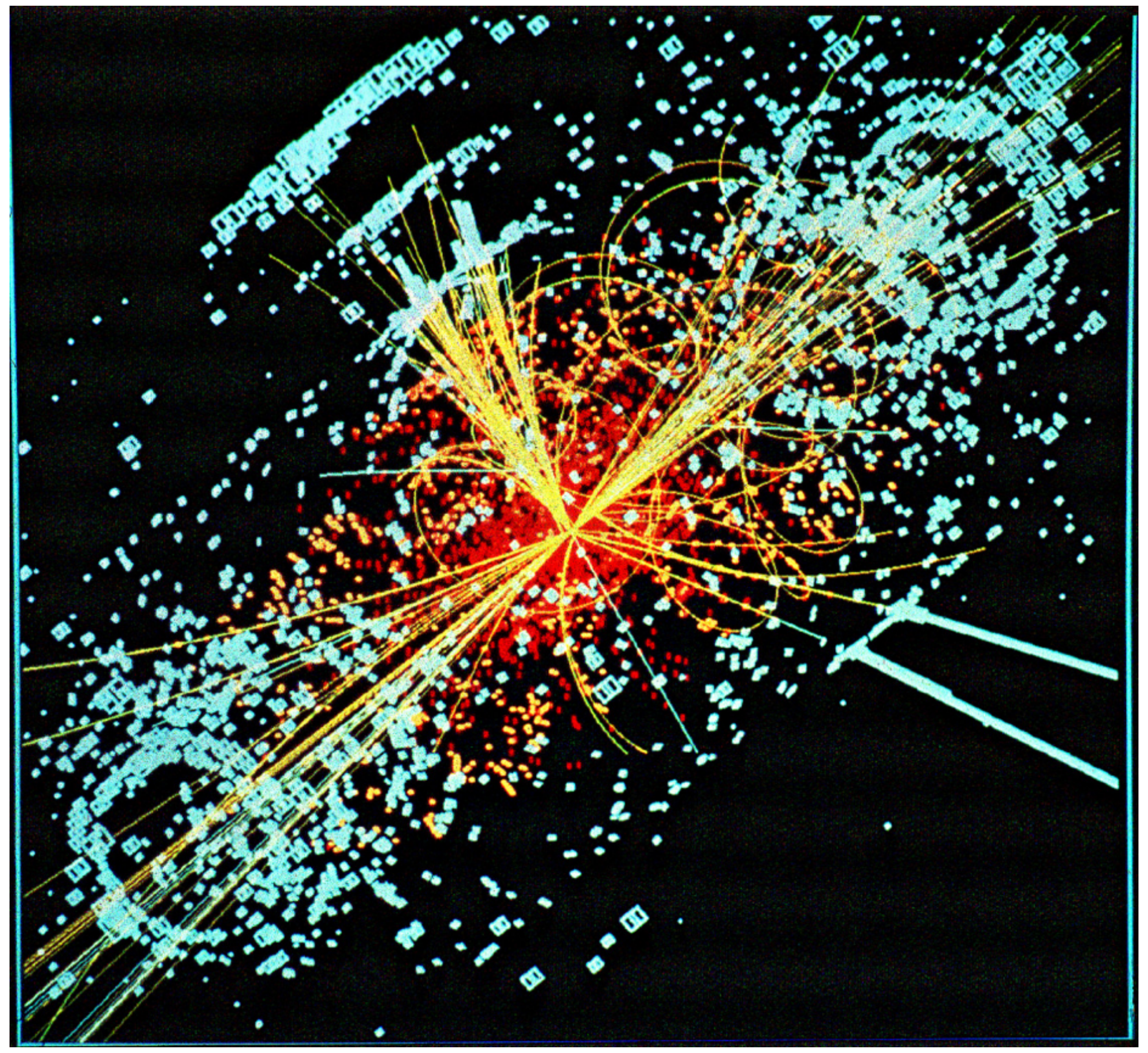


Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

TeV Scale ⟷ < MeV Scale

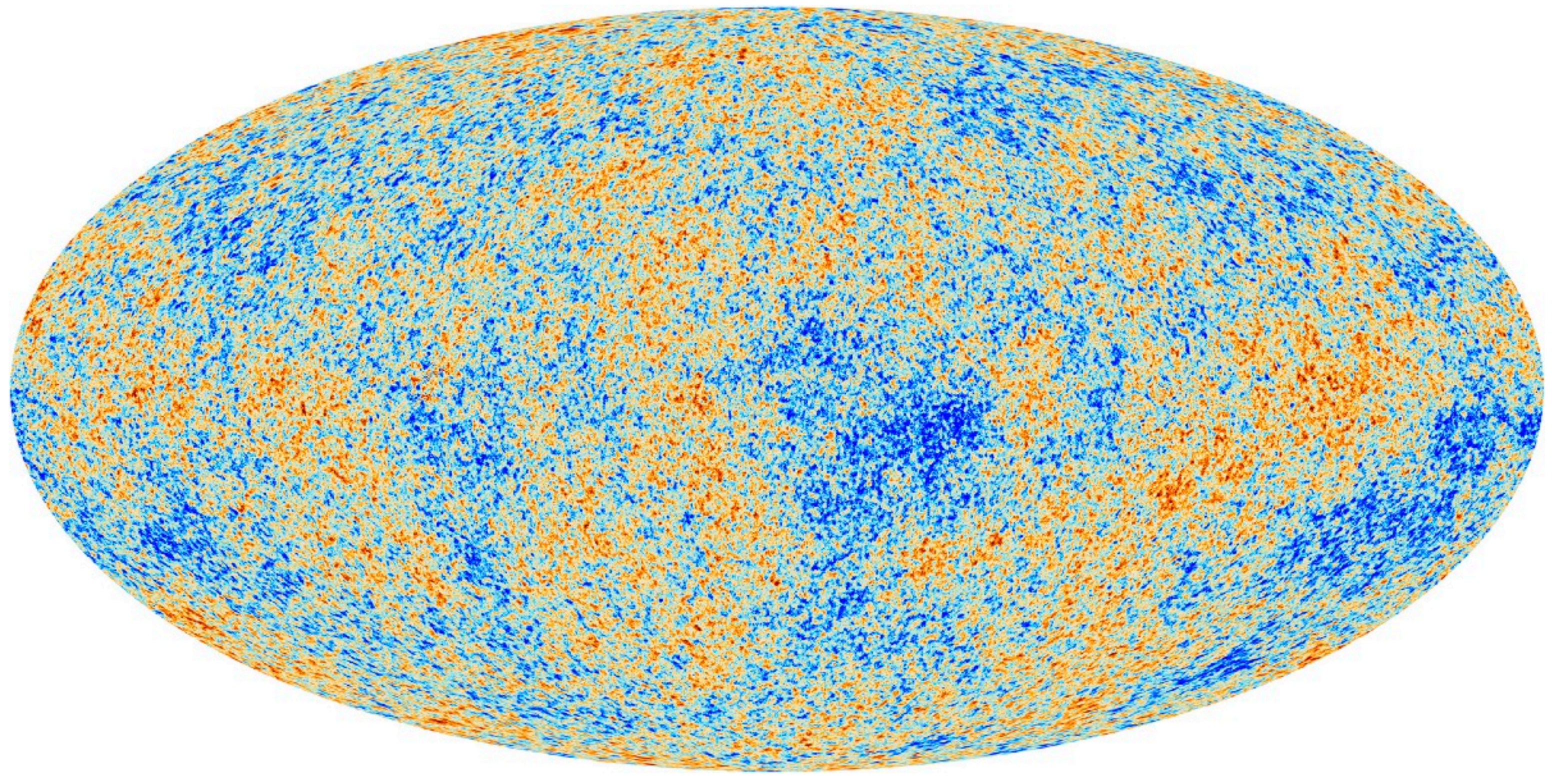
Going Beyond

1. High energy Frontier



Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

2. Cosmo+Astro Frontier

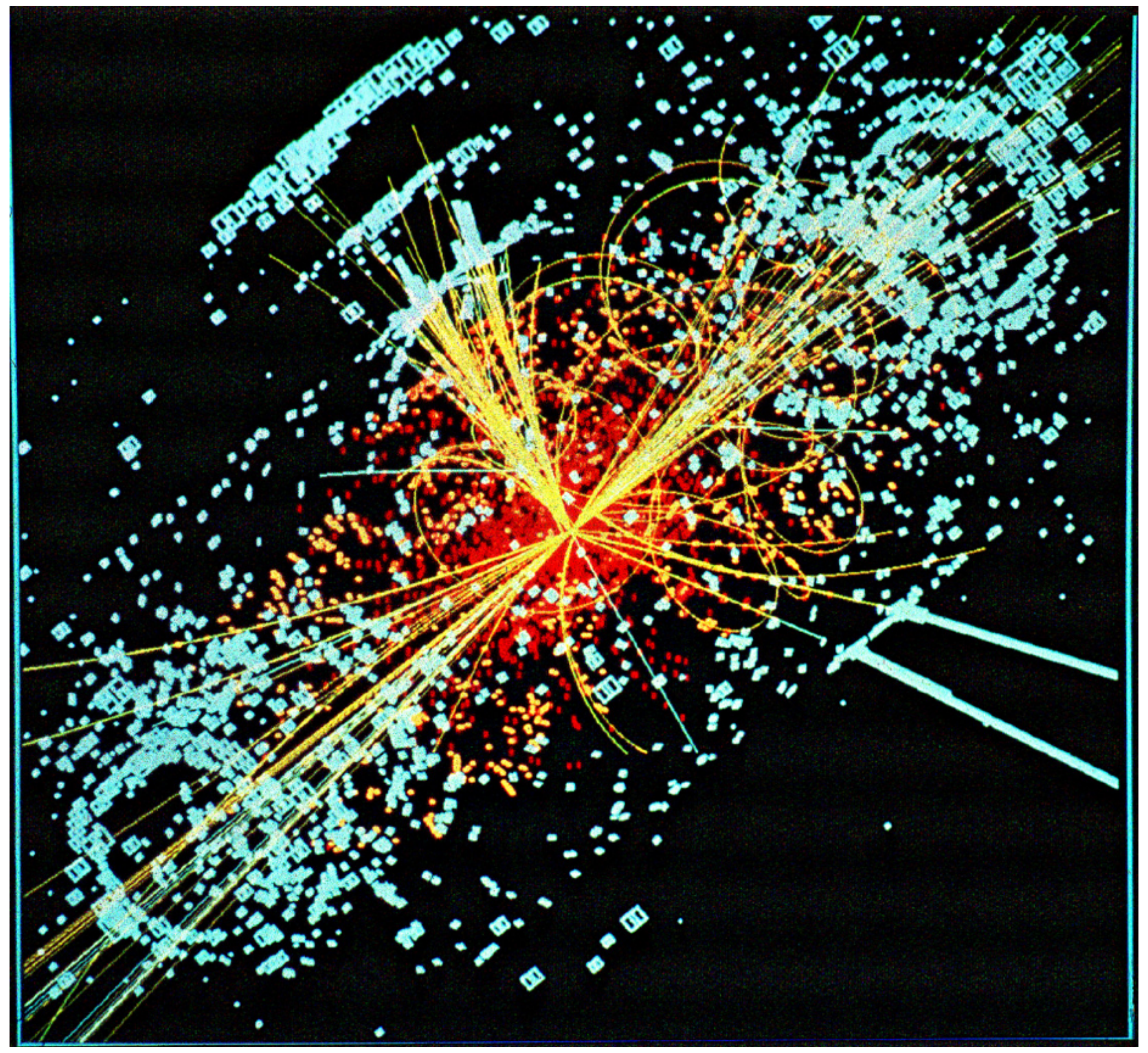


https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

TeV Scale ⟷ < MeV Scale

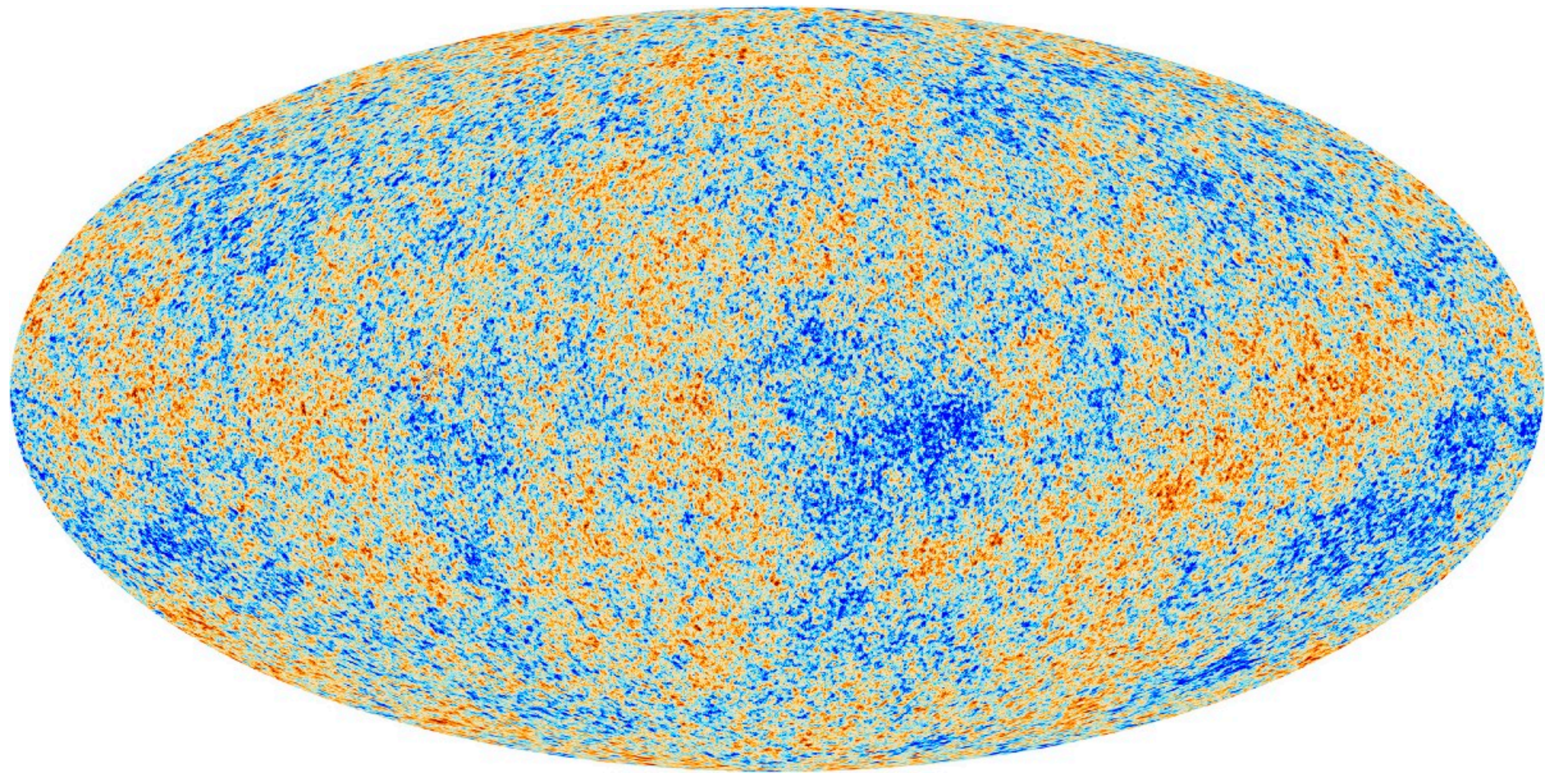
Going Beyond

1. High energy Frontier



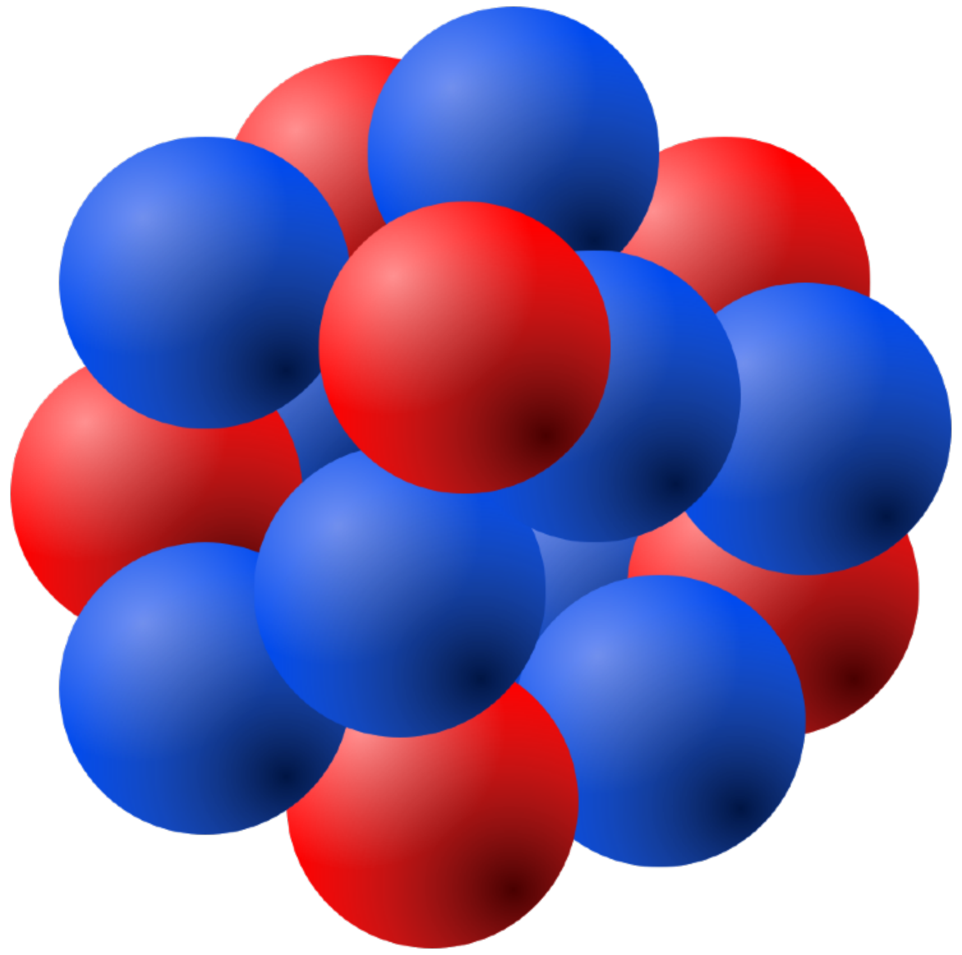
Lucas Taylor / CERN - http://cdsweb.cern.ch/record/628469

2. Cosmo+Astro Frontier



https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_CMB

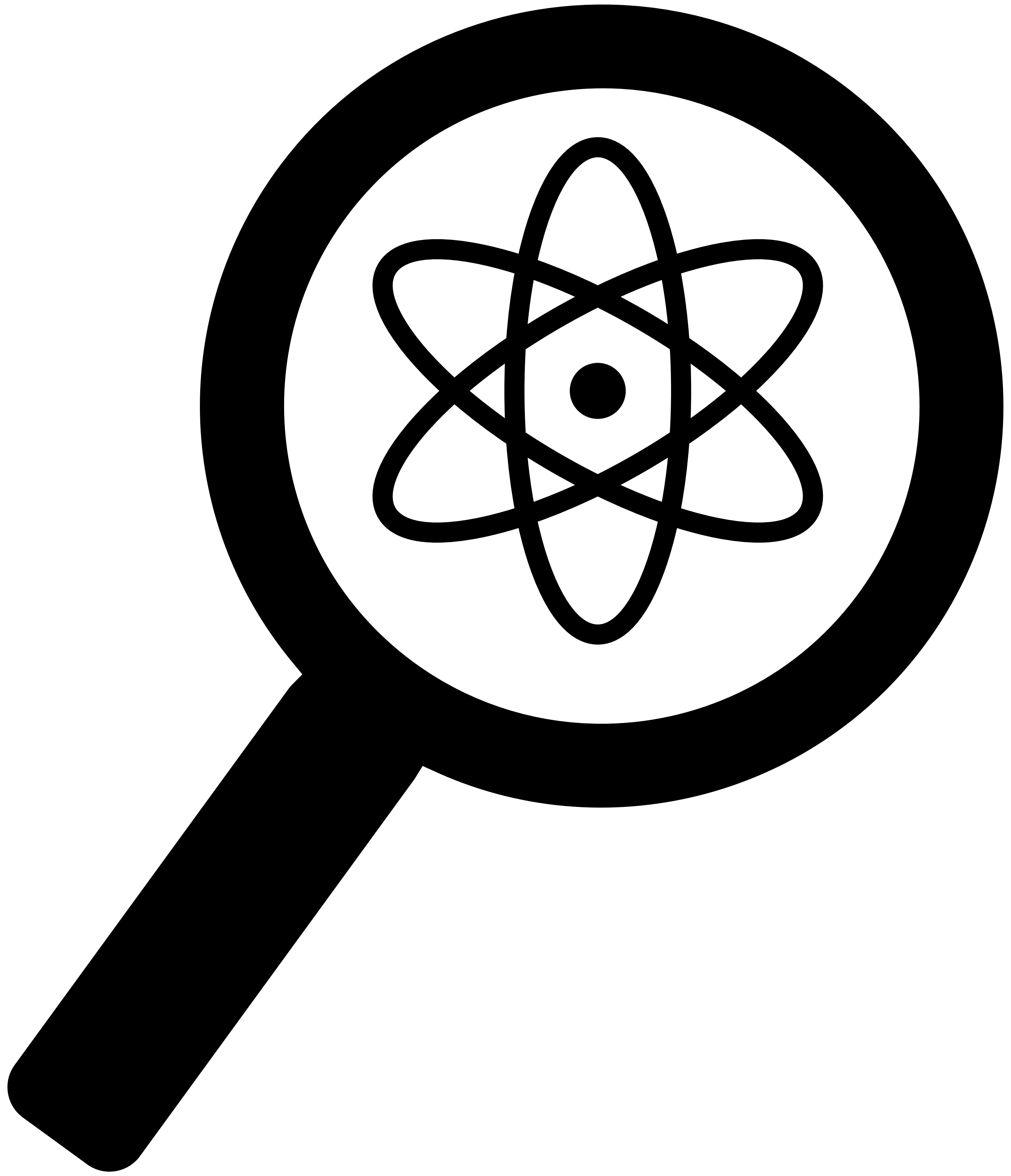
3. Precision frontier



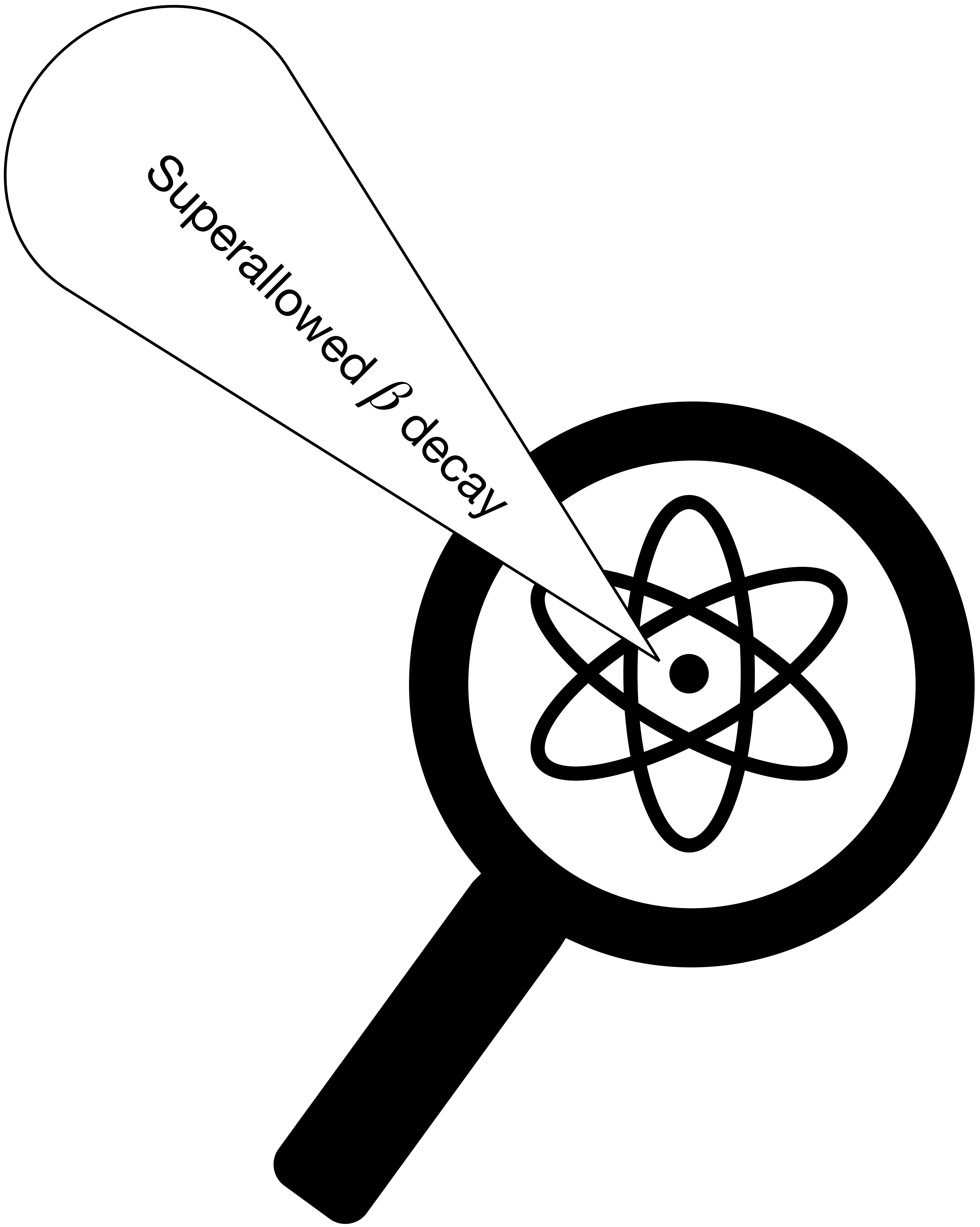
Marekich - https://commons.wikimedia.org/w/index.php?curid=21701588

TeV Scale ⟷ < MeV Scale

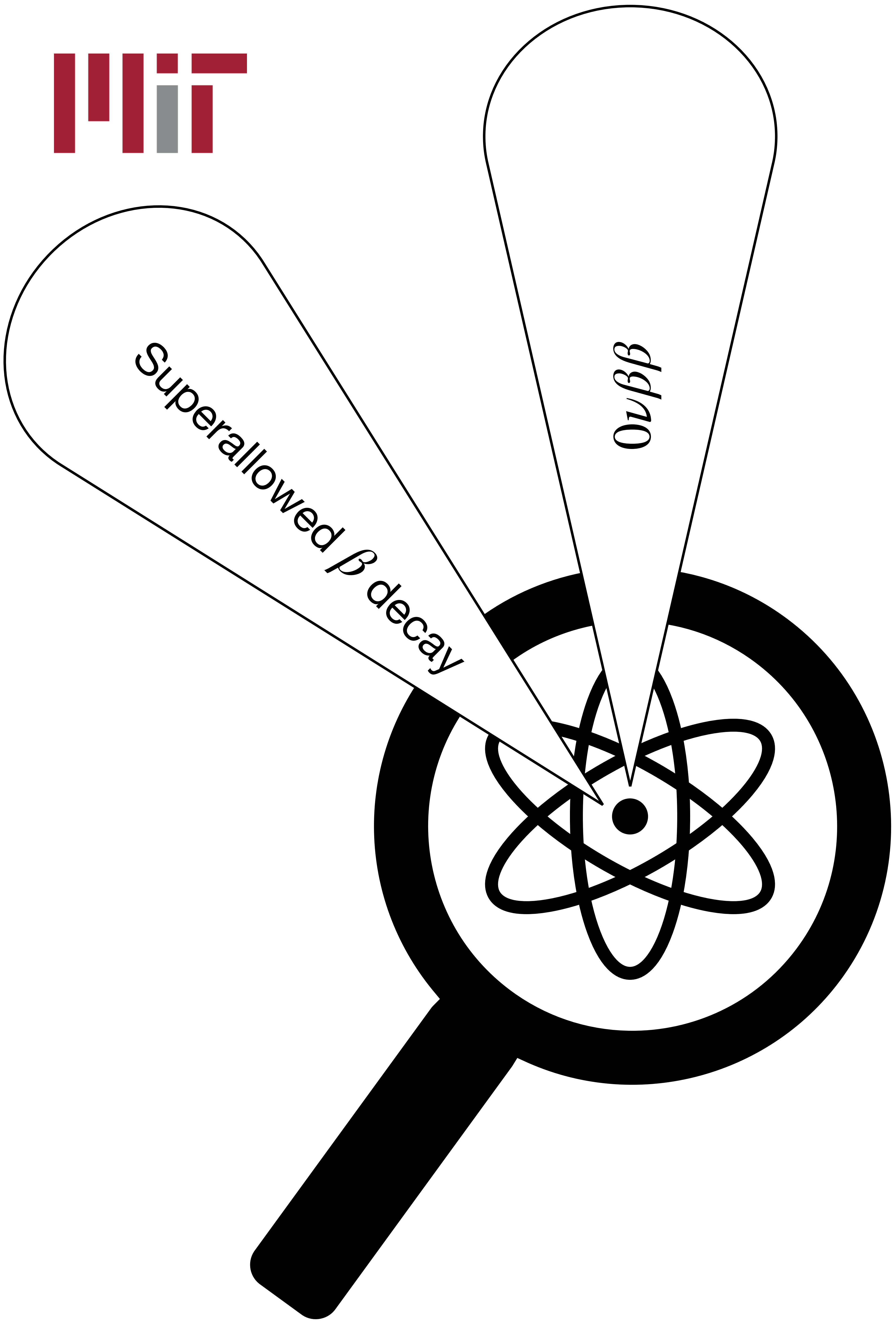
Atomic Nucleus as a Probe



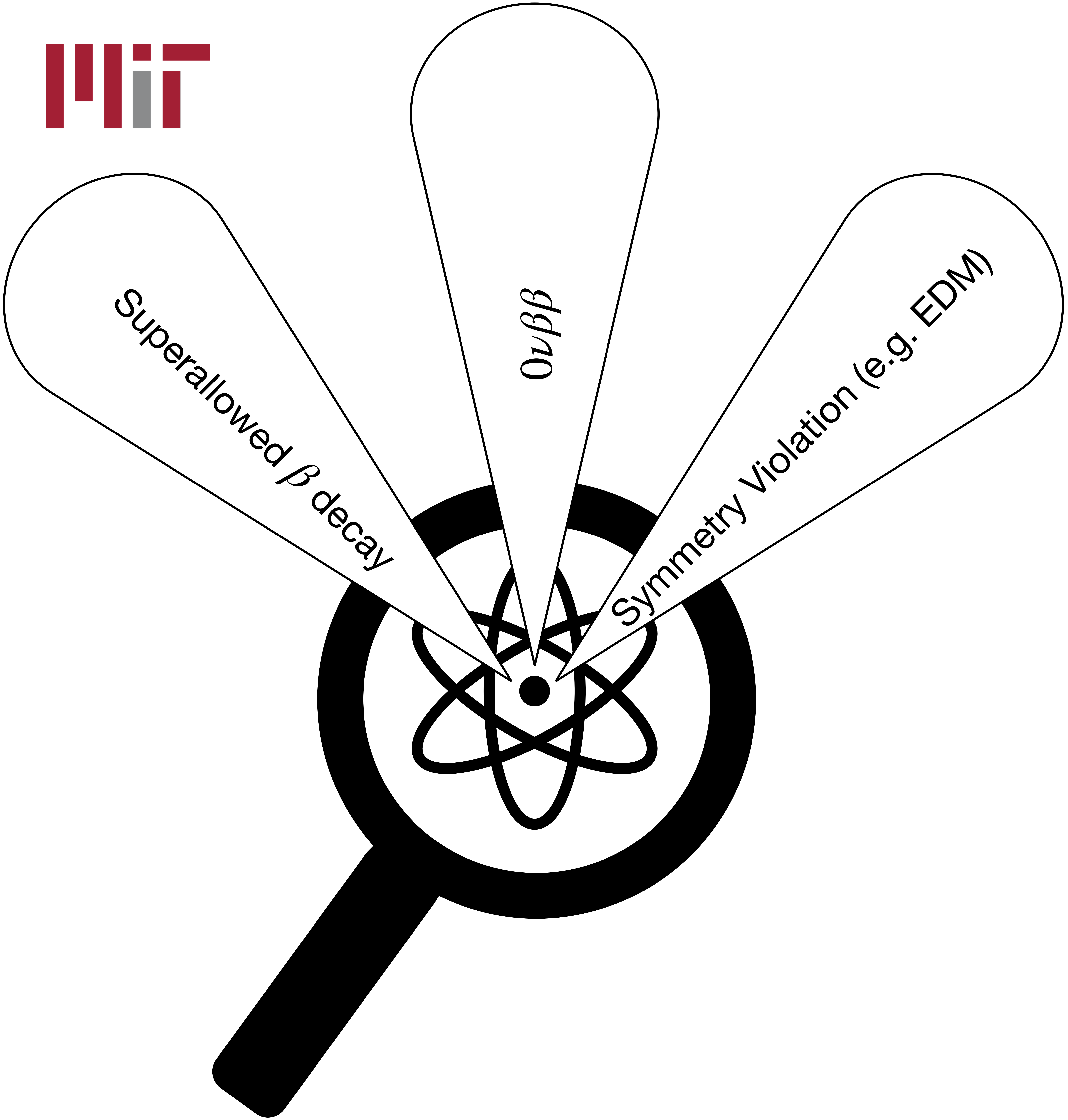
Atomic Nucleus as a Probe



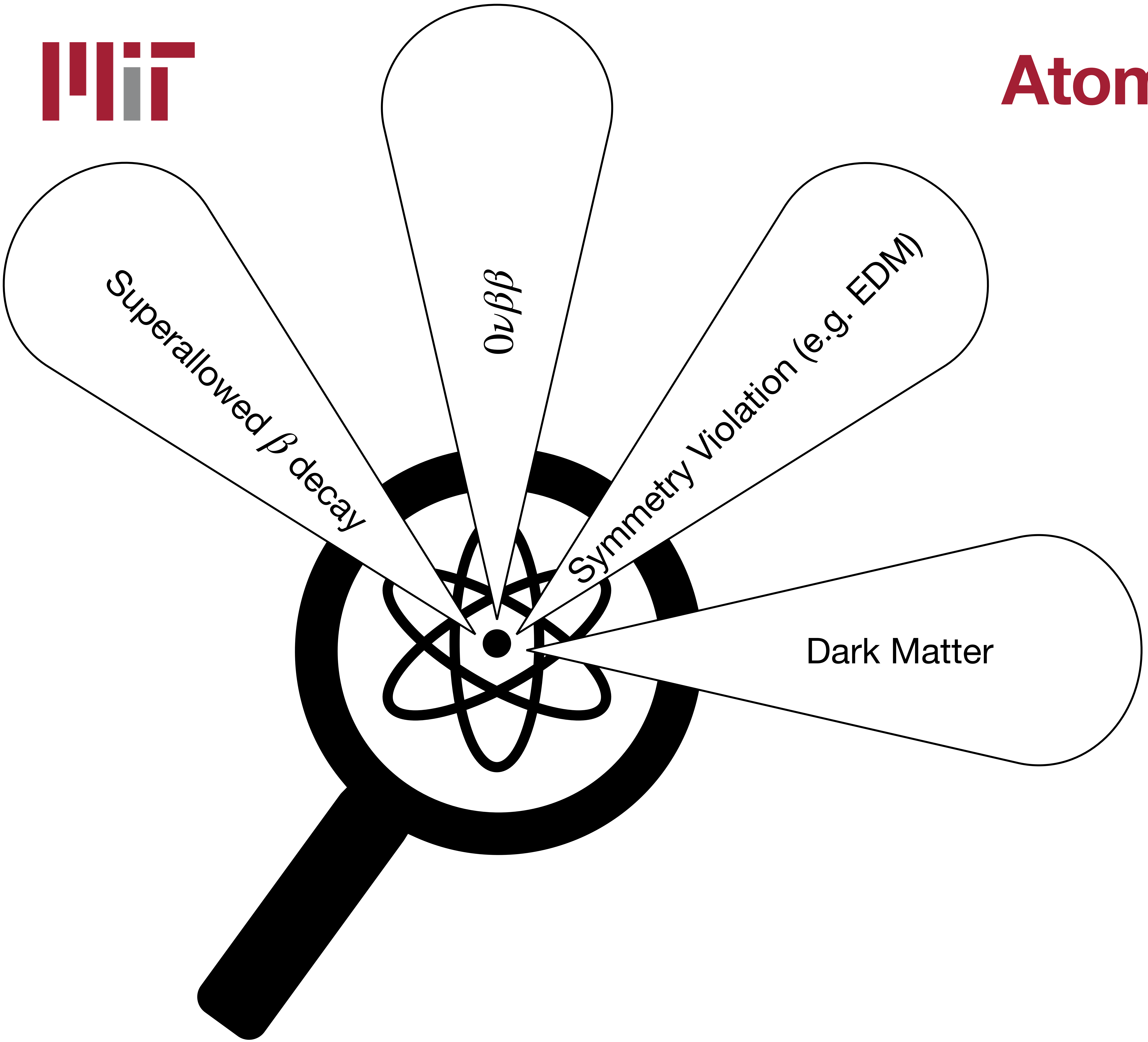
Atomic Nucleus as a Probe



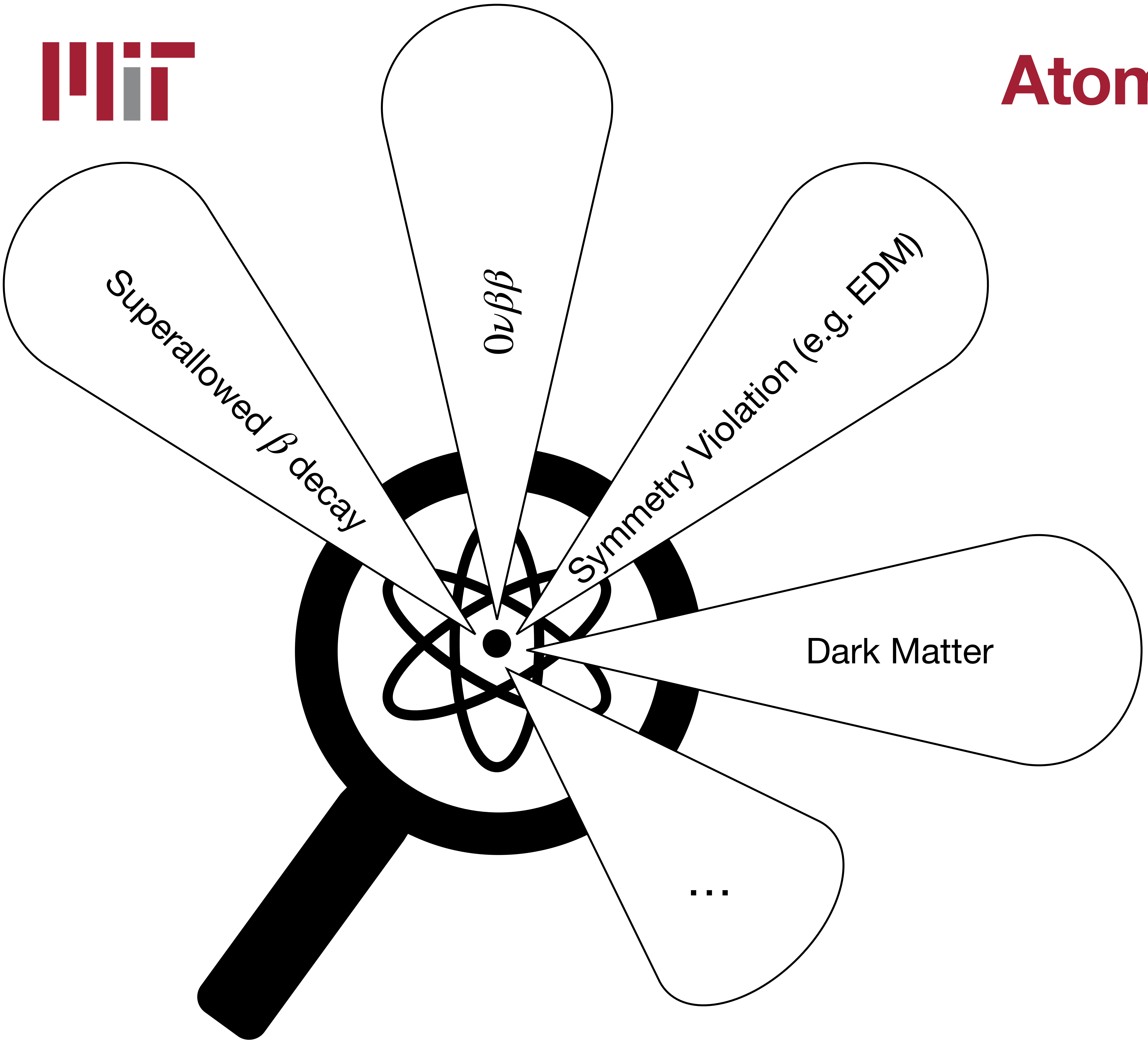
Atomic Nucleus as a Probe



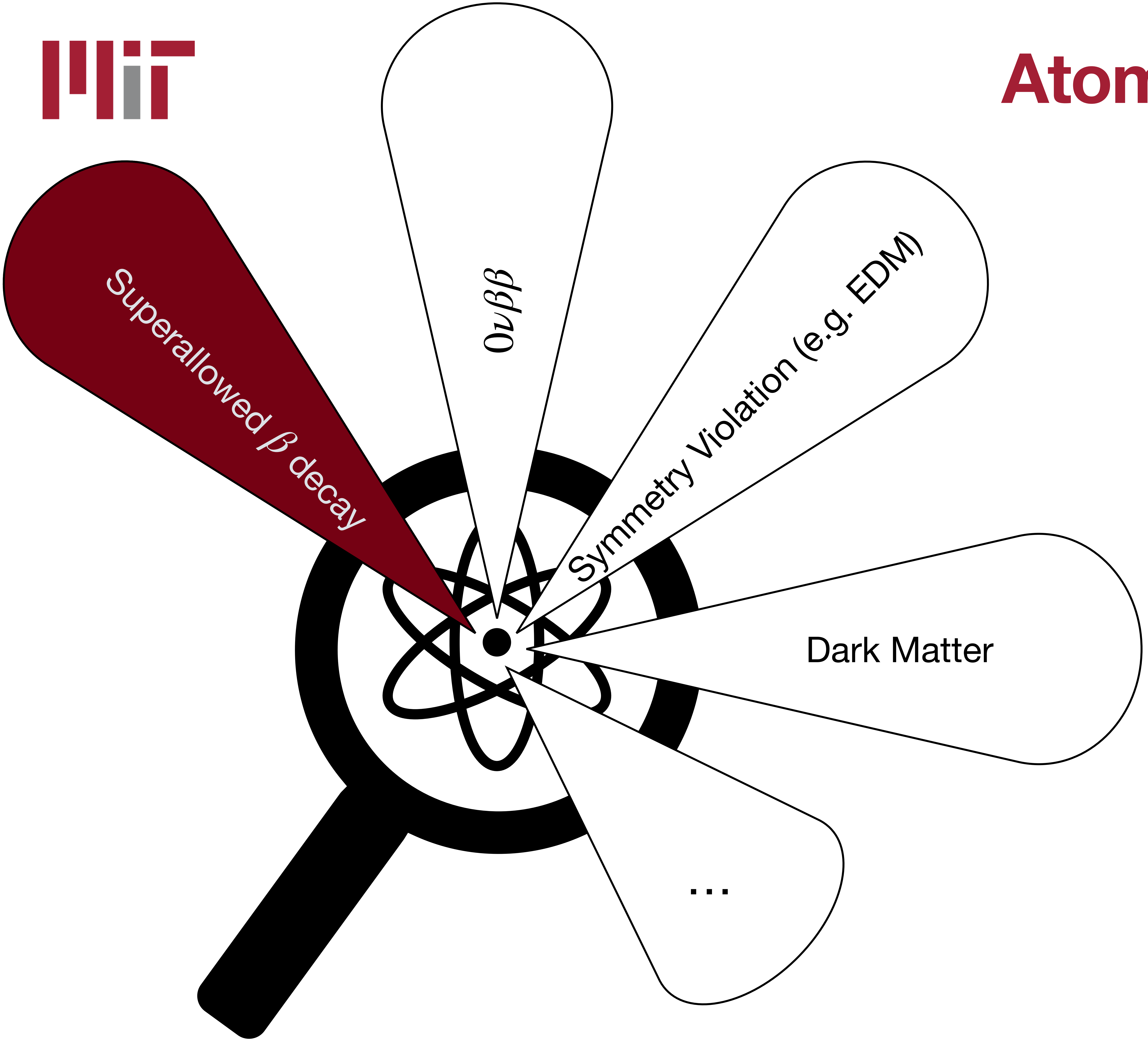
Atomic Nucleus as a Probe



Atomic Nucleus as a Probe

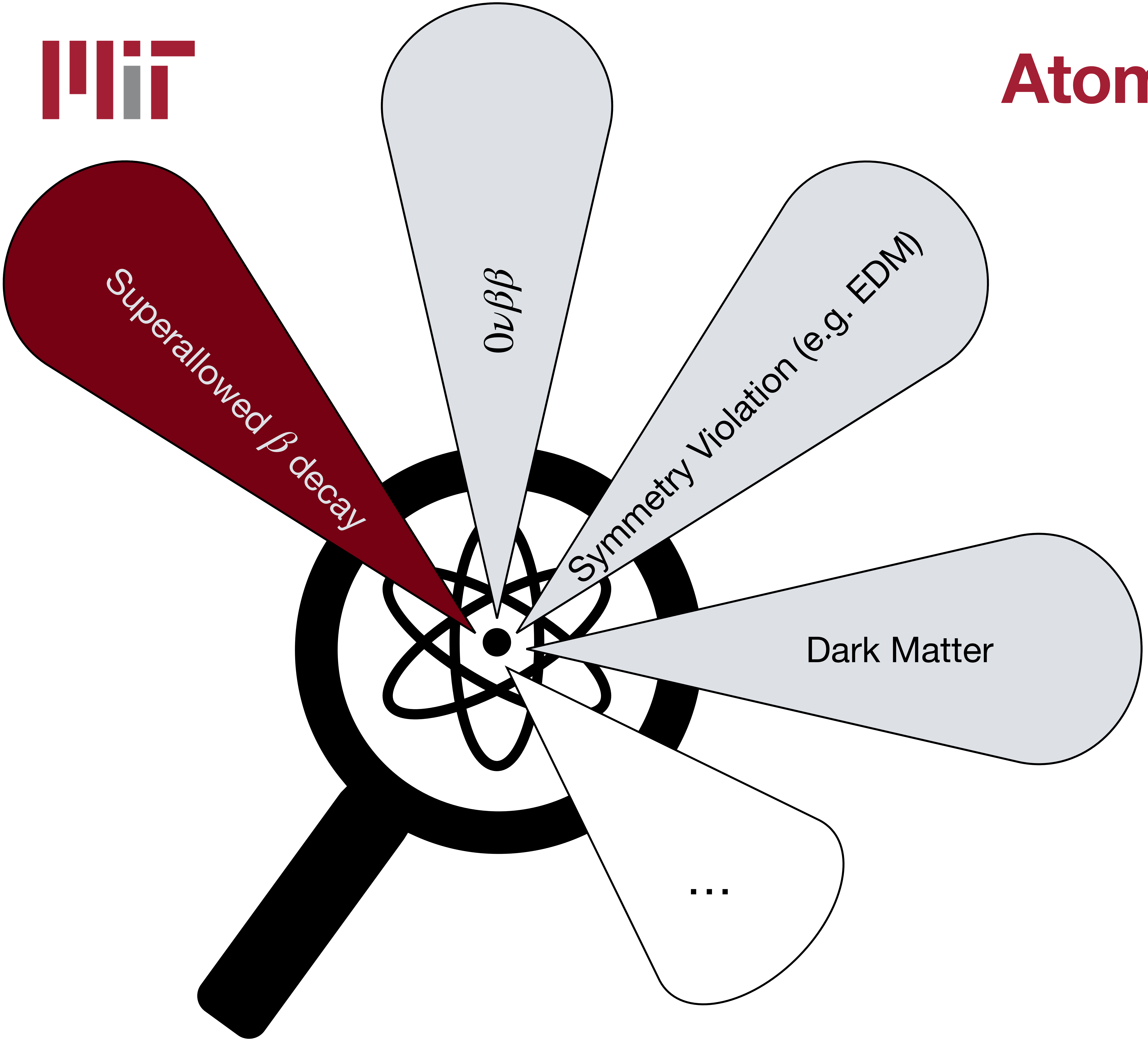


Atomic Nucleus as a Probe



1. Looking at deviation from Standard Model prediction.

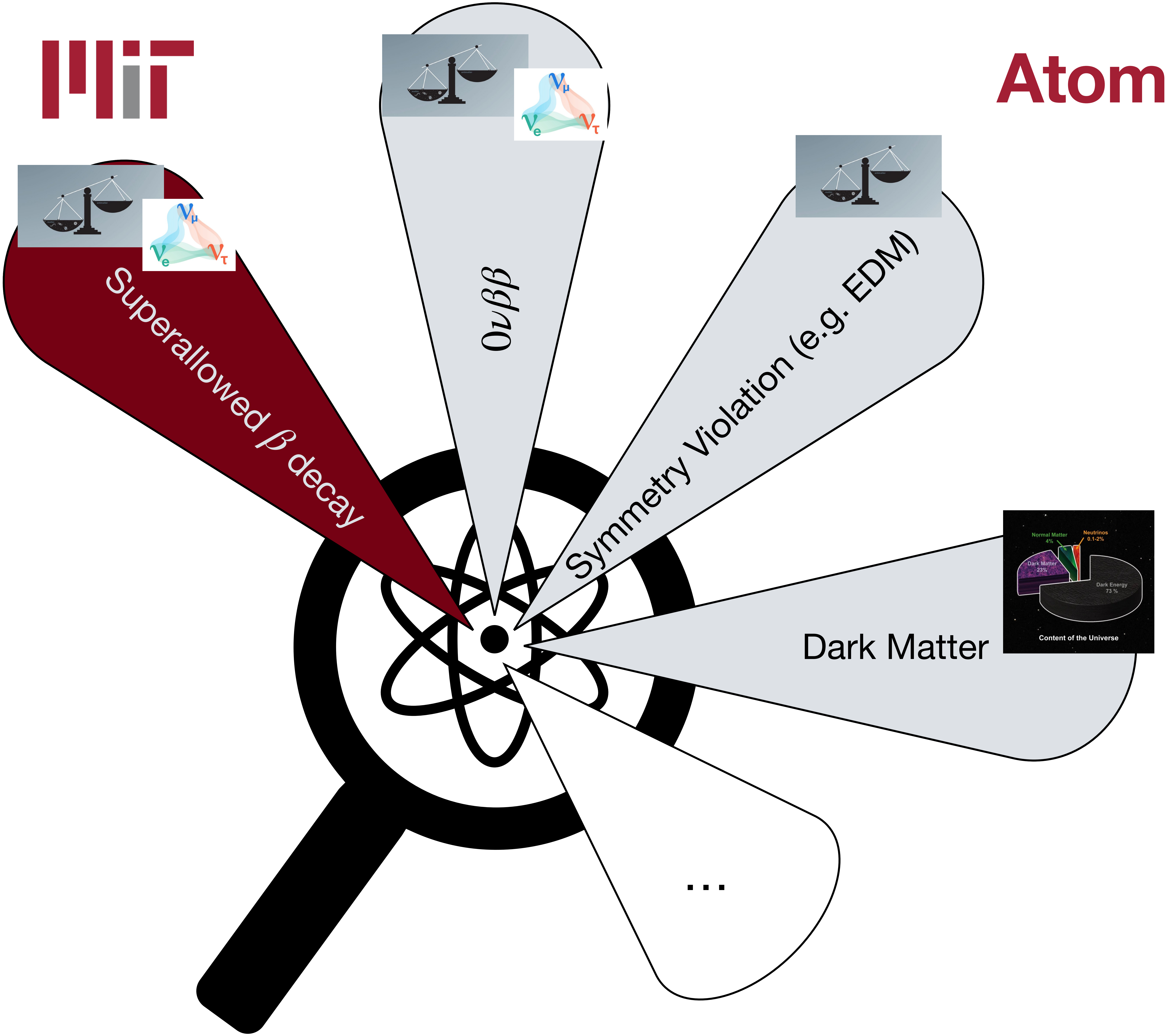
Atomic Nucleus as a Probe



1. Looking at deviation from Standard Model prediction.

2. Search for phenomena not predicted by the Standard Model.

Atomic Nucleus as a Probe



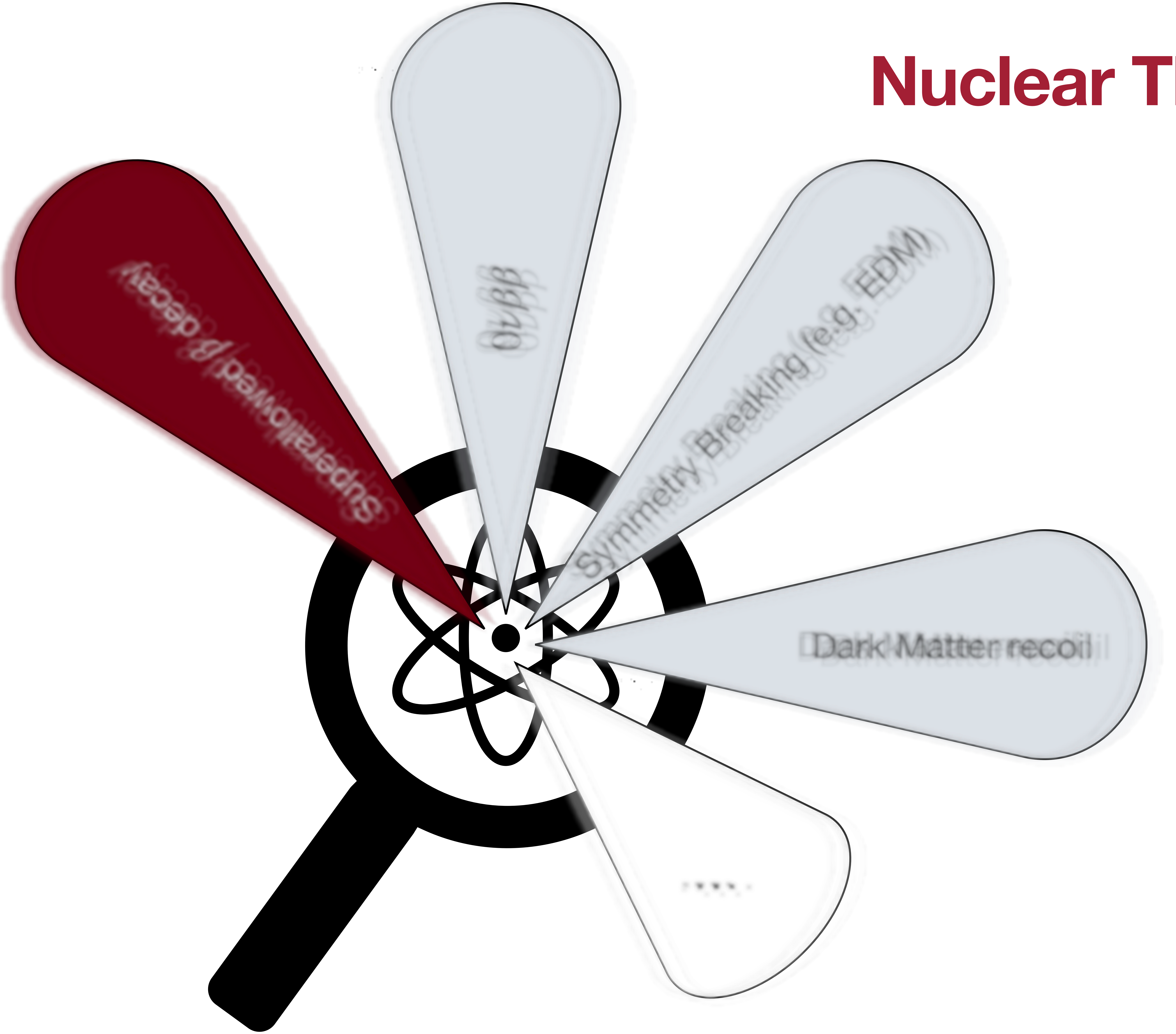
1. Looking at deviation from Standard Model prediction.
2. Search for phenomena not predicted by the Standard Model.

The Need for Nuclear Theory

In all cases, nuclear theory inputs are required in order to interpret experimental results:

- **Superallowed β decay:** Corrections from Standard Model δ_{NS} and δ_C.
- **$0\nu\beta\beta$:** Nuclear matrix elements $M^{0\nu}$.
- **Electric Dipole Moment:** The nuclear Schiff Moment.
- **Dark Matter Scattering:** WIMP Scattering structure factor S_A.
- …

Nuclear Theory Blur



Nuclear Theory Challenges

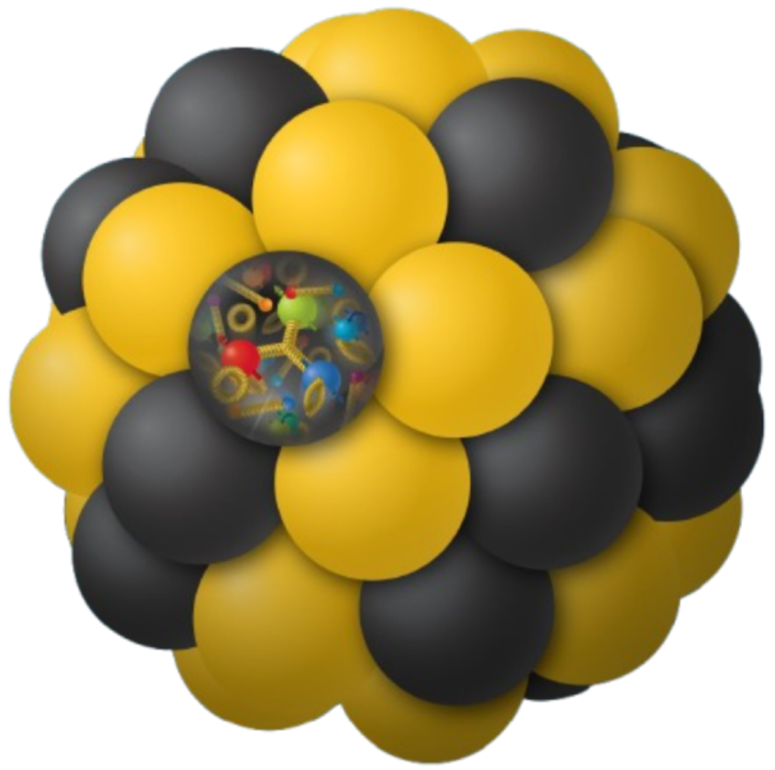
Understanding nuclear structure from microscopic physics

Figures courtesy of J. Muñoz

Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions



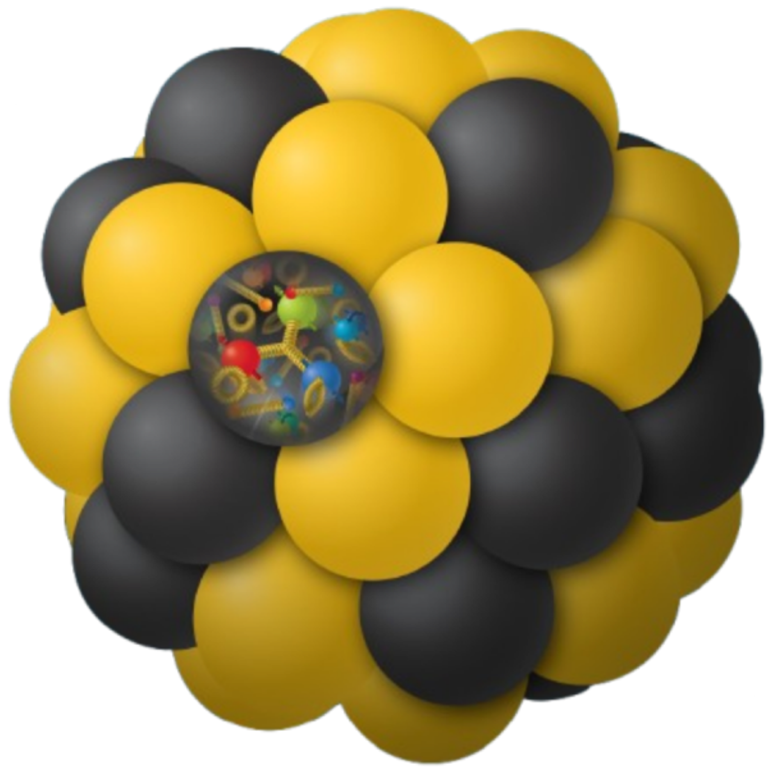
Figures courtesy of J. Muñoz

Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions

Wave functions



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

Figures courtesy of J. Muñoz

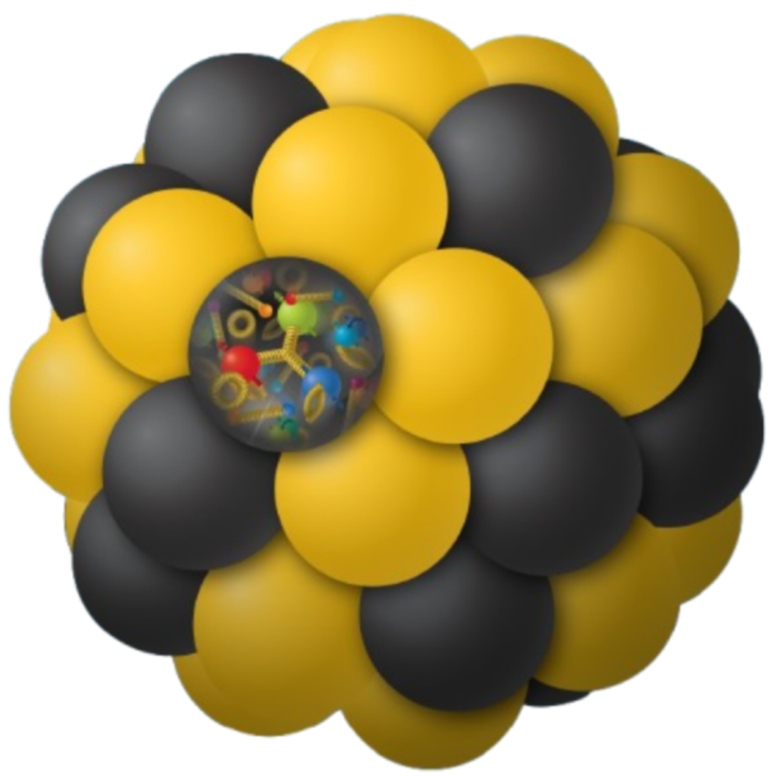
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

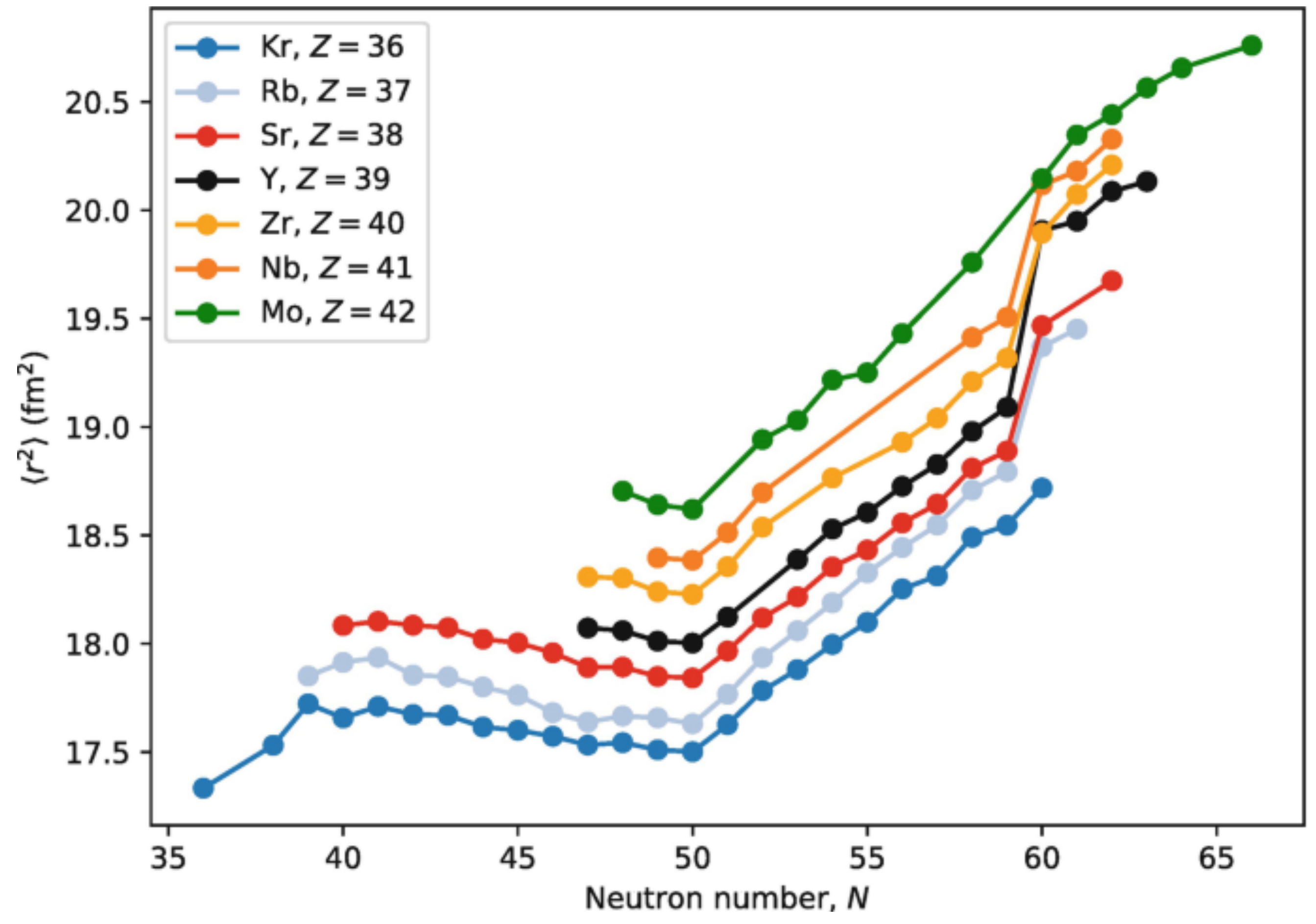
Nuclear Interactions

Wave functions

Observables



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

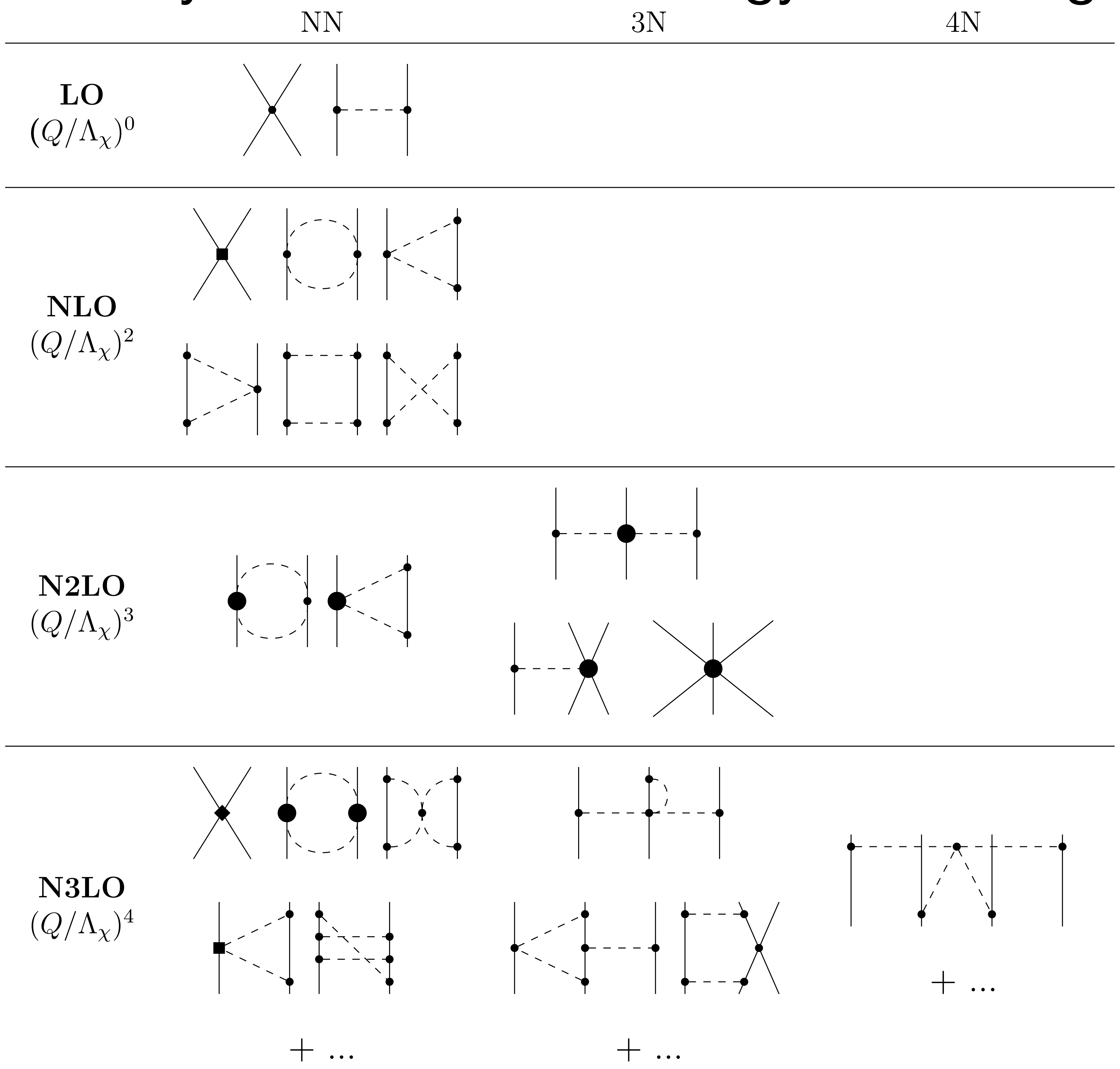


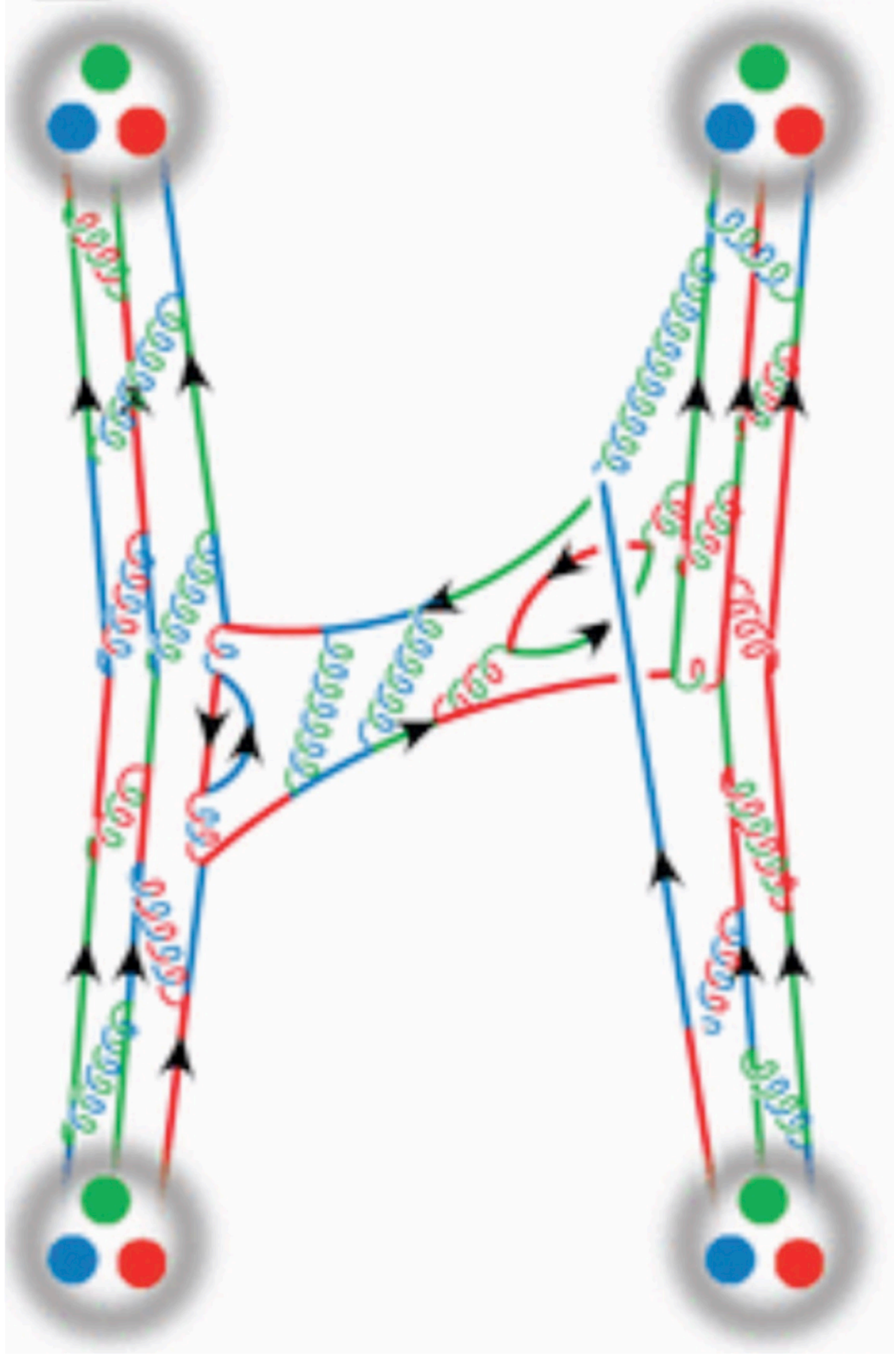
$$\langle\Psi|O|\Psi\rangle$$

Figures courtesy of J. Muñoz

Expansion order by order of the nuclear forces

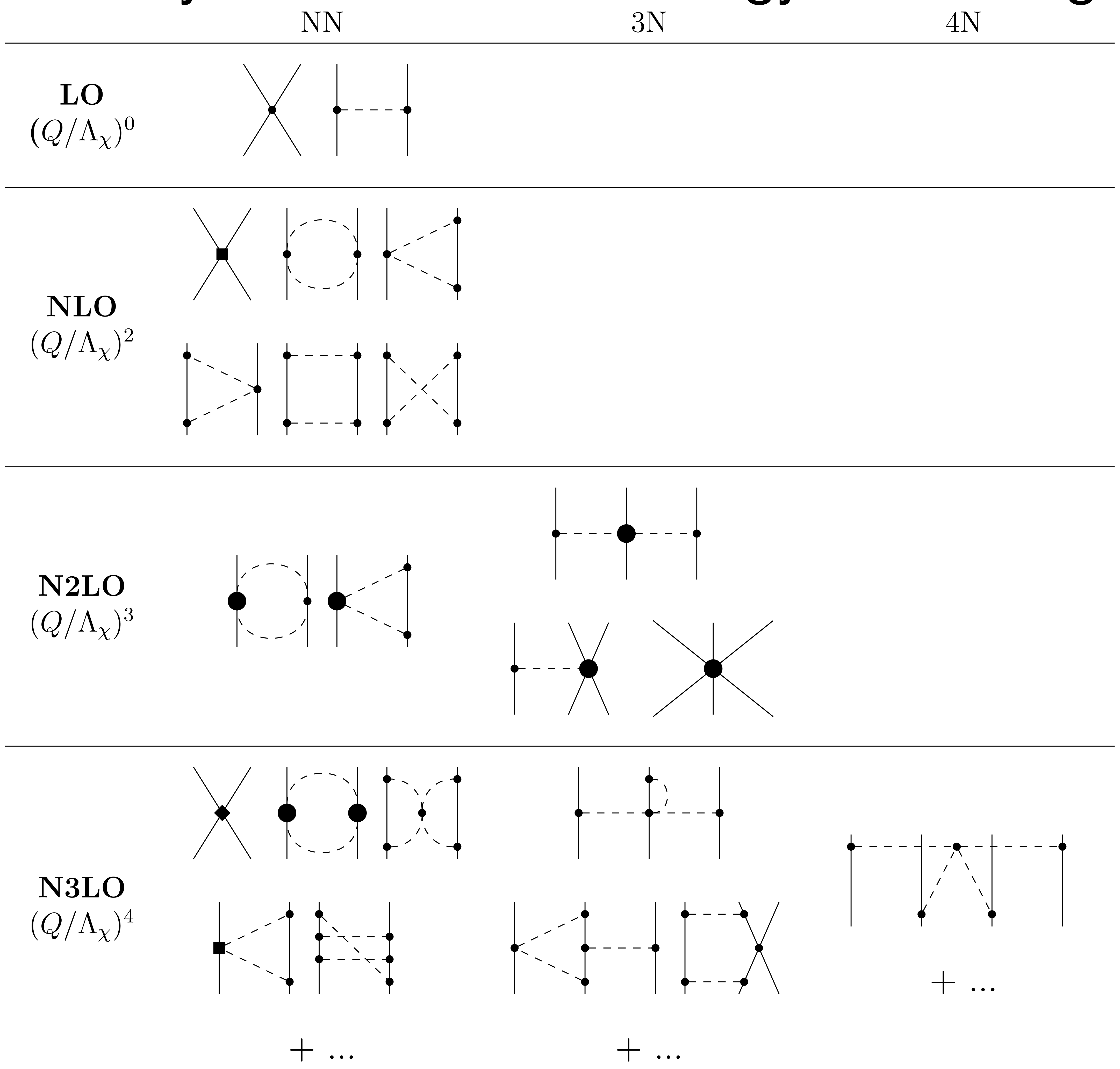
Reproduces symmetries of low-energy QCD using nucleons as fields and pions as force carriers.





Expansion order by order of the nuclear forces

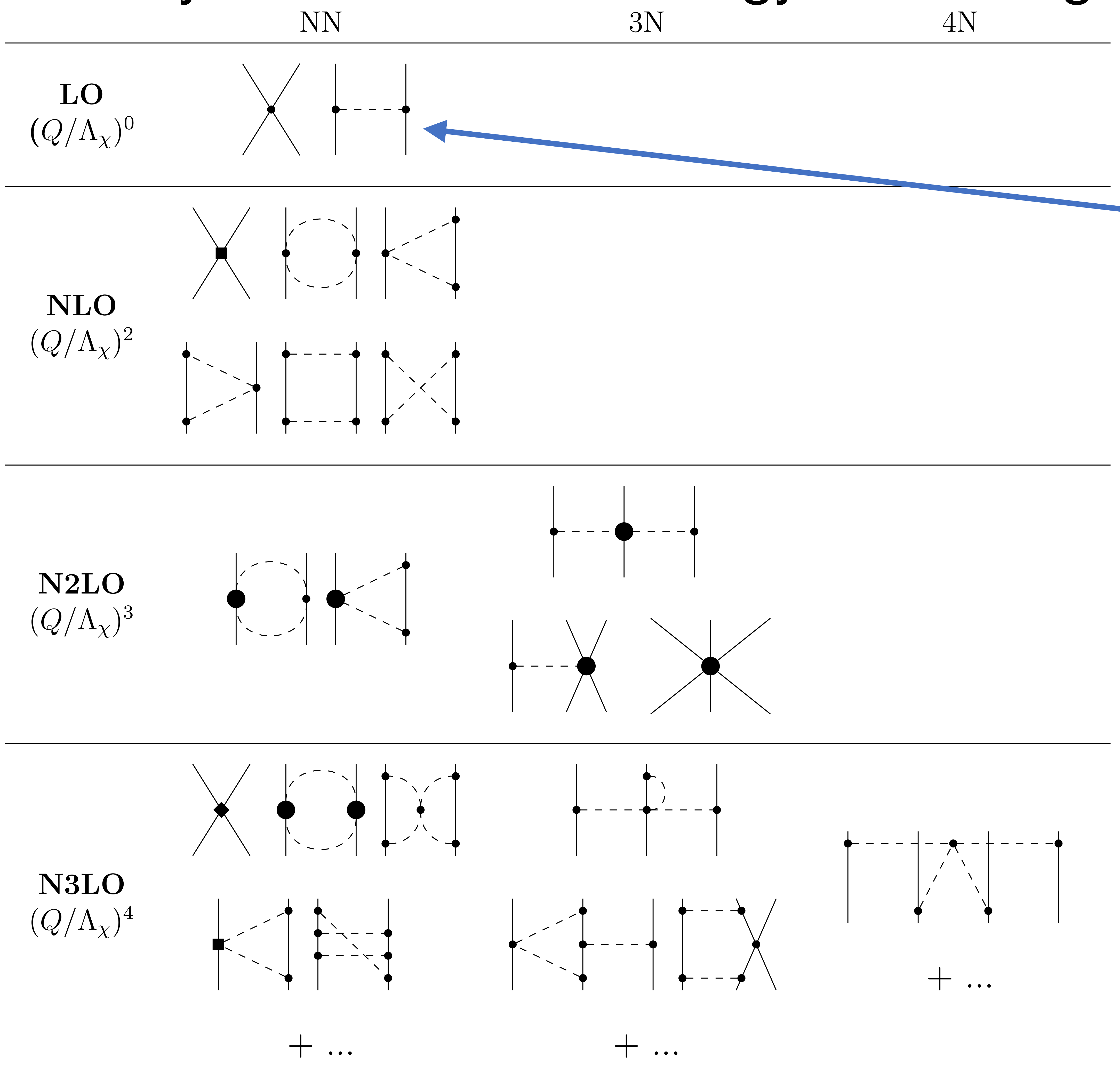
Reproduces symmetries of low-energy QCD using nucleons as fields and pions as force carriers.



χ-EFT

Expansion order by order of the nuclear forces

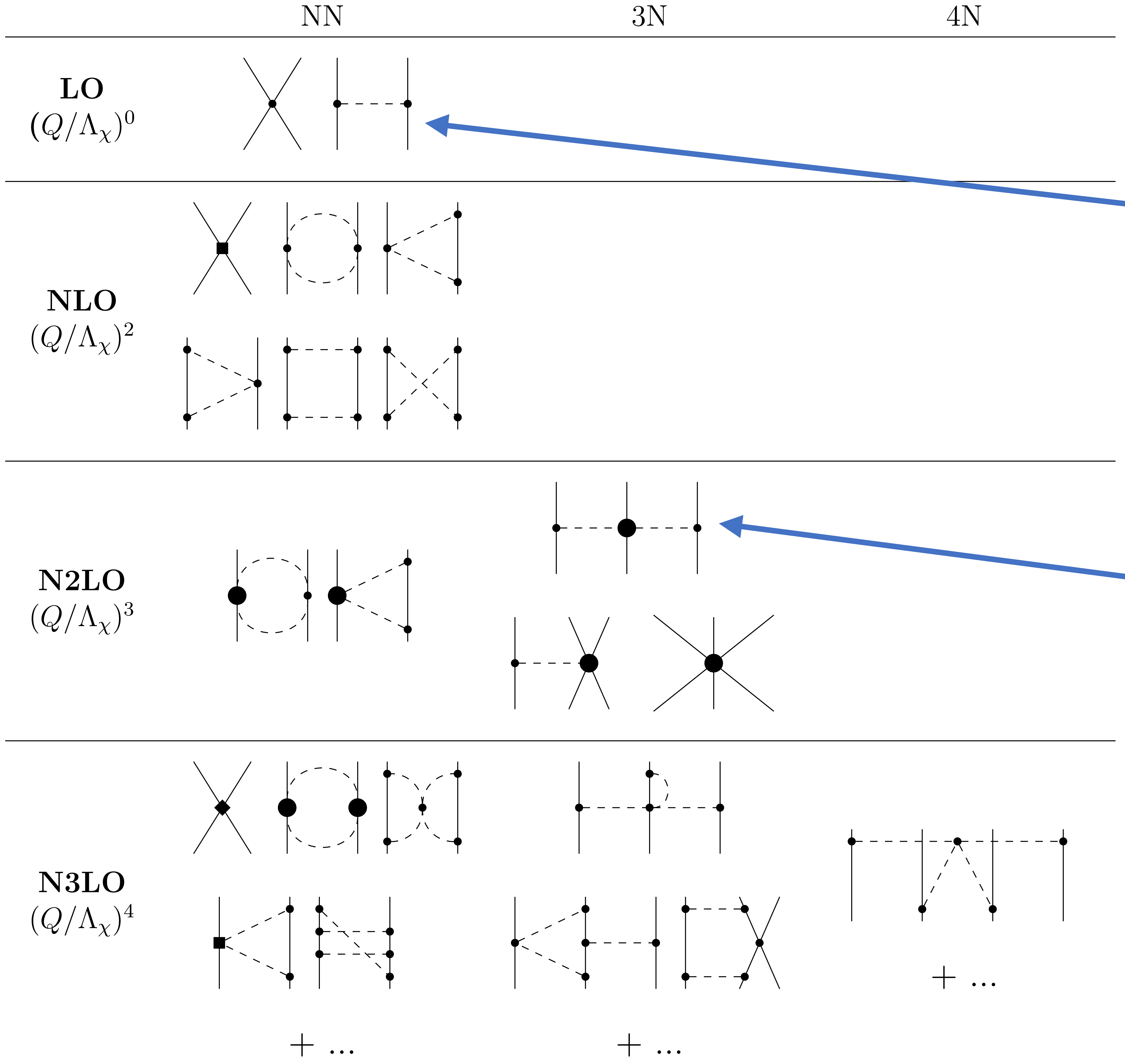
Reproduces symmetries of low-energy QCD using nucleons as fields and pions as force carriers.



The different low energy coupling constants (LECs) are fitted to few-nucleon data to absorb the effect of higher order terms

Expansion order by order of the nuclear forces

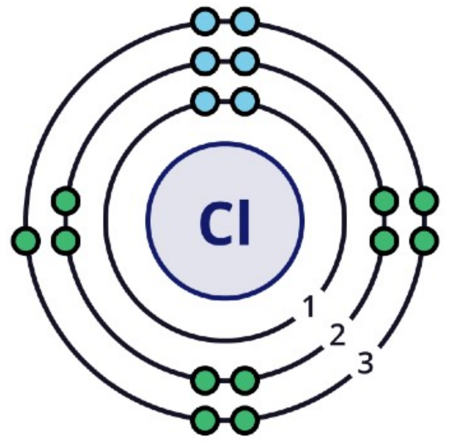
Reproduces symmetries of low-energy QCD using nucleons as fields and pions as force carriers.



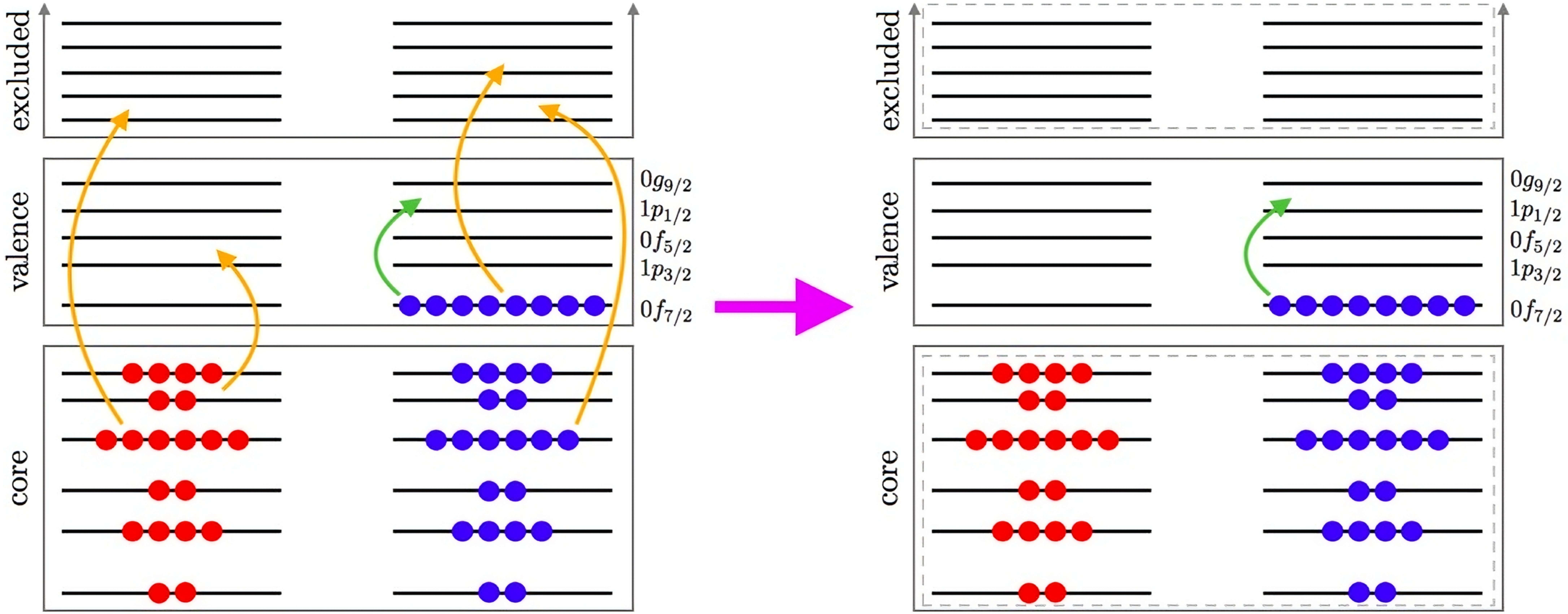
The different low energy coupling constants (LECs) are fitted to few-nucleon data to absorb the effect of higher order terms

Three- (and higher-)body forces needed

The VS-IMSRG



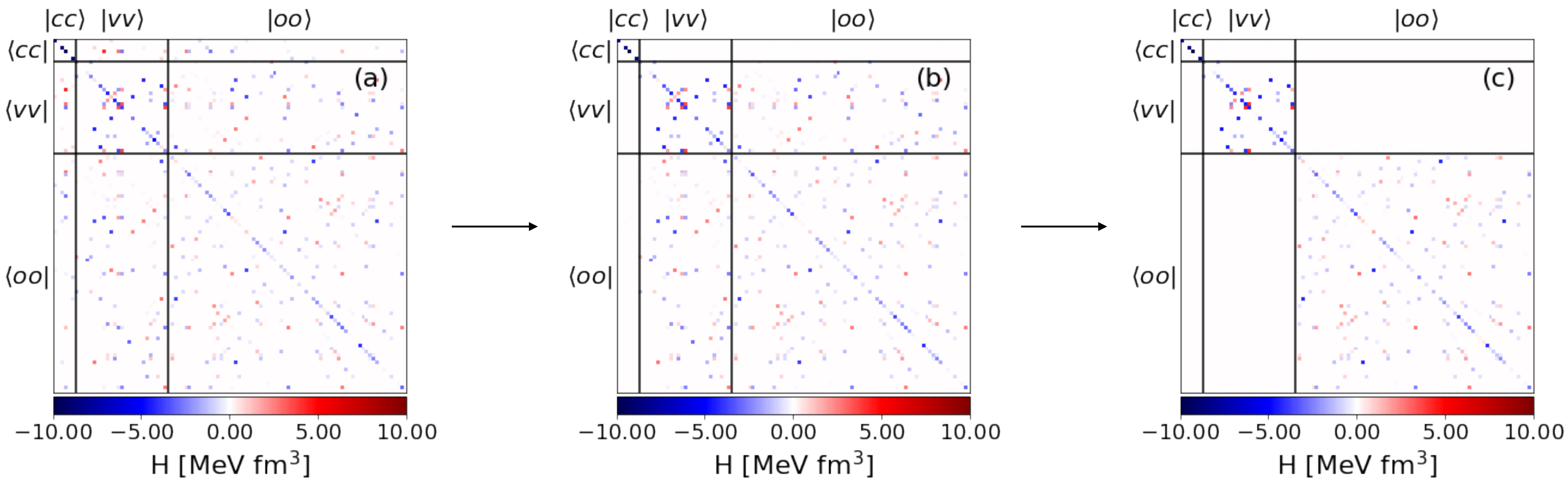
Valence Space In Medium Similarity Renormalization Group



Charlie Payne, Master'sThesis, UBC (2018)

The VS-IMSRG

Valence Space In Medium Similarity Renormalization Group



Bare Hamiltonian

$$\hat{H}(0)$$

Core is decoupled

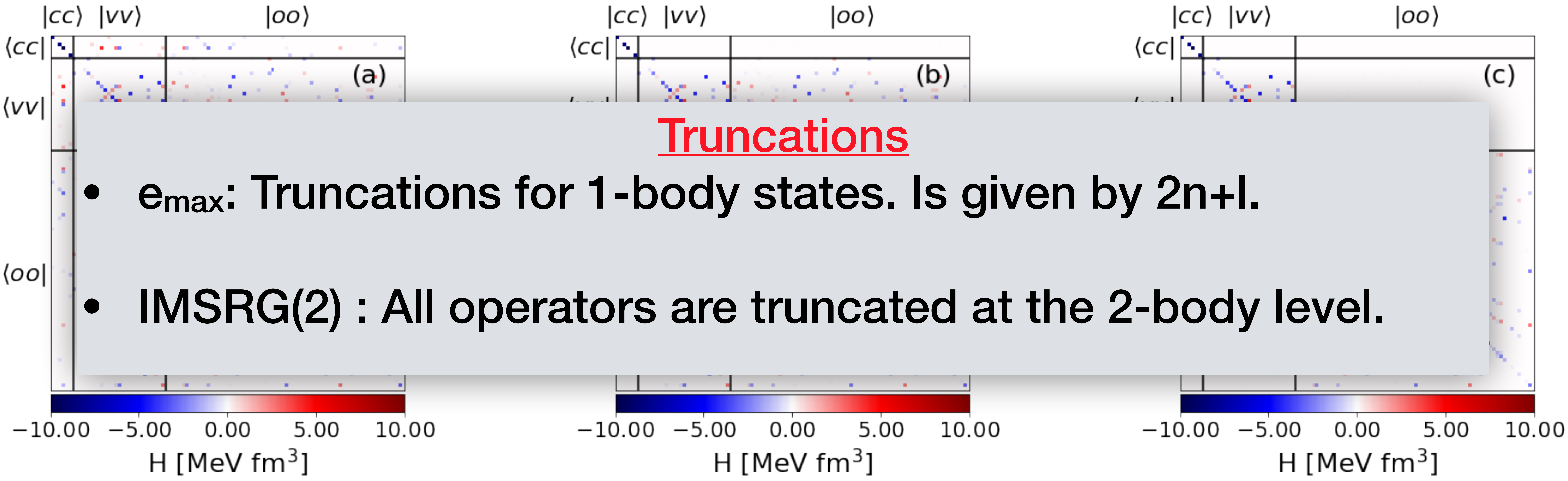
$$\hat{H}(s) = e^{\Omega_c(s)}\hat{H}(0)e^{-\Omega_c(s)}$$

$$\hat{H}_c = e^{\Omega_c(\infty)}\hat{H}(0)e^{-\Omega_c(\infty)}$$

Valence-space is decoupled

$$\hat{H}(s) = e^{\Omega_v(s)}\hat{H}_c e^{-\Omega_v(s)}$$

Valence Space In Medium Similarity Renormalization Group



Truncations

- e_{max}: Truncations for 1-body states. Is given by 2n+l.
- IMSRG(2) : All operators are truncated at the 2-body level.

Bare Hamiltonian

$$\hat{H}(0)$$

Core is decoupled

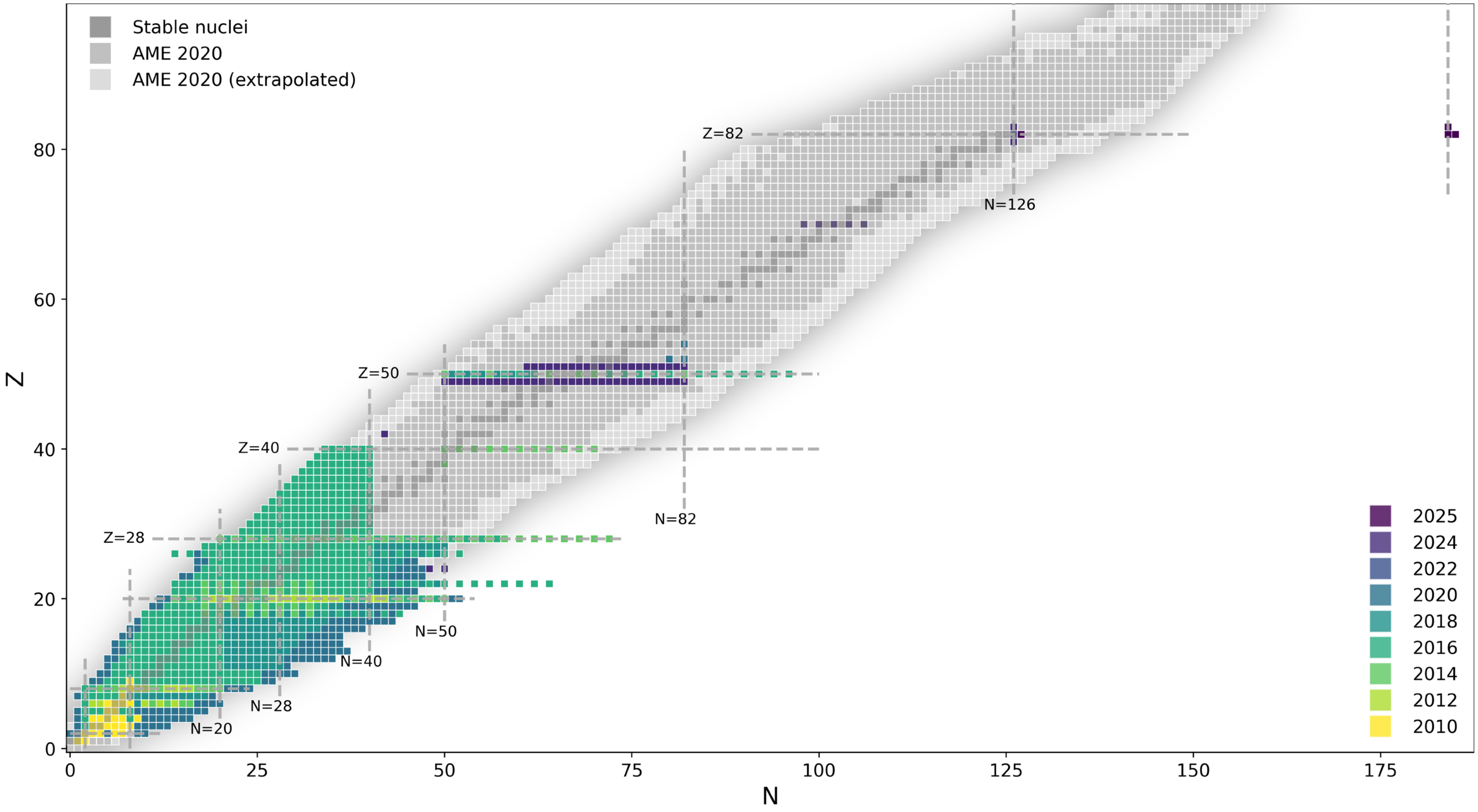
$$\hat{H}(s) = e^{\Omega_c(s)}\hat{H}(0)e^{-\Omega_c(s)}$$

$$\hat{H}_c = e^{\Omega_c(\infty)}\hat{H}(0)e^{-\Omega_c(\infty)}$$

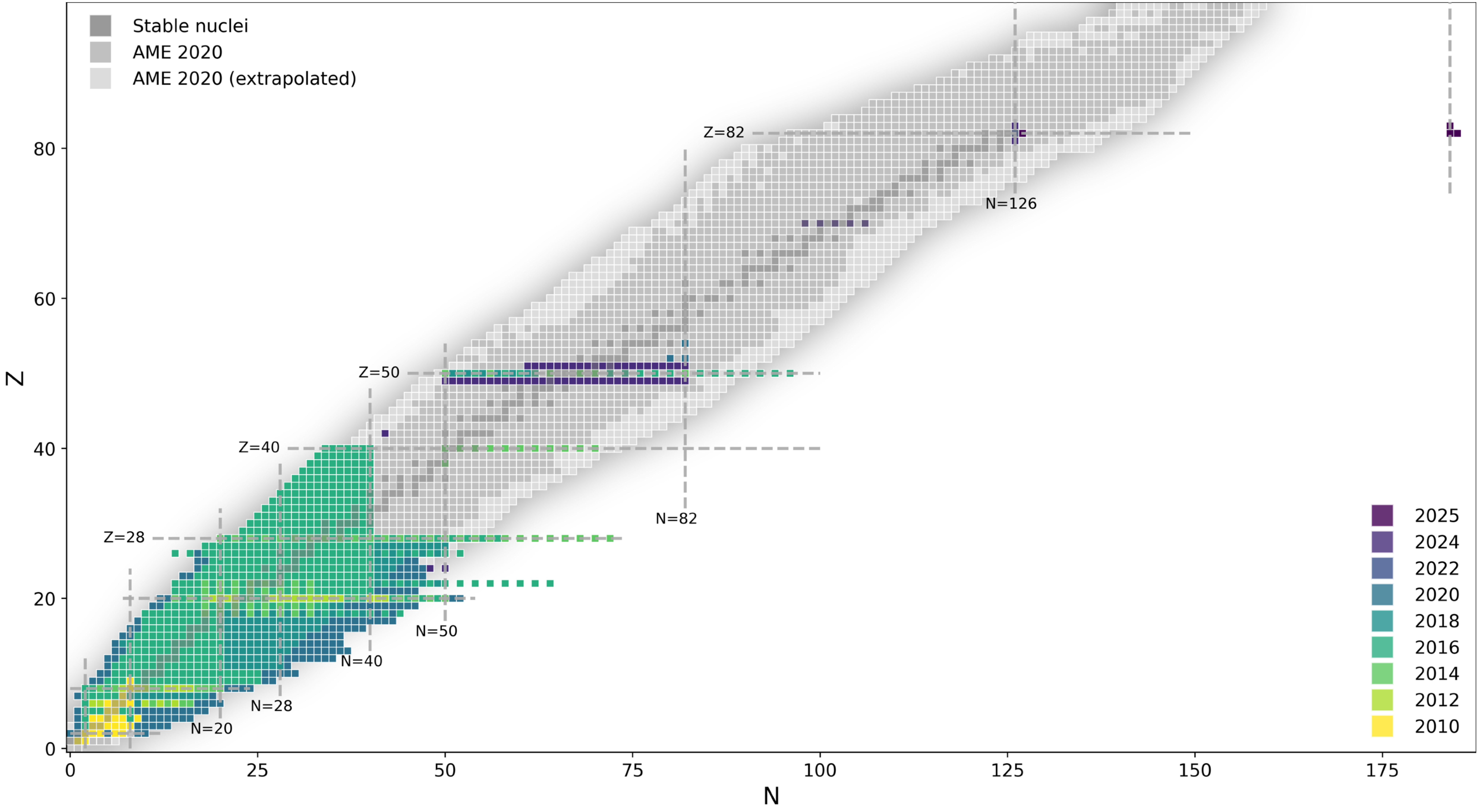
Valence-space is decoupled

$$\hat{H}(s) = e^{\Omega_v(s)}\hat{H}_c e^{-\Omega_v(s)}$$

Ab initio Revolution



Ab initio Revolution



Python version on github!

Challenges with Parity Violation

Parity Violation

Parity Violation

Charge-Parity-Time (CPT) symmetry is simultaneously conserved in the Standard Model

Charge-Parity-Time (CPT) symmetry is simultaneously conserved in the Standard Model

C: $e \rightarrow -e$

P: $x \rightarrow -x$ (in spherical coordinates, even(odd) l is even(odd) under parity transformation)

T: $t \rightarrow -t$

Charge-Parity-Time (CPT) symmetry is simultaneously conserved in the Standard Model

C: $e \to -e$

P: $x \to -x$ (in spherical coordinates, even(odd) l is even(odd) under parity transformation)

T: $t \to -t$

Both P and CP(=T) are violated very slightly in the Standard Model.

Charge-Parity-Time (CPT) symmetry is simultaneously conserved in the Standard Model

C: $e \rightarrow -e$

P: $x \rightarrow -x$ (in spherical coordinates, even(odd) l is even(odd) under parity transformation)

T: $t \rightarrow -t$

Both P and CP(=T) are violated very slightly in the Standard Model.

Effects are so small that parity is considered to be conserved in standard nuclear calculations.

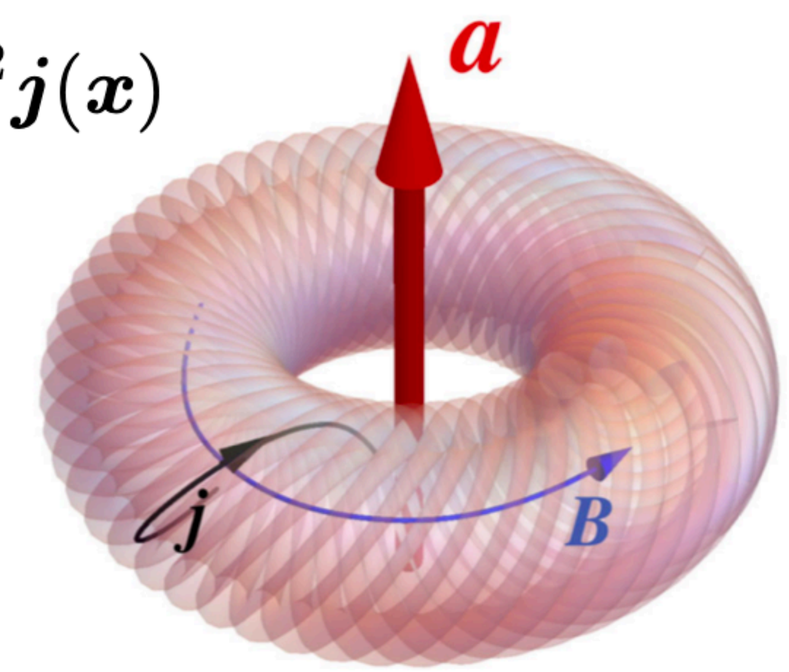
Why add PV?

Why add PV?

PV forces: The anapole moment

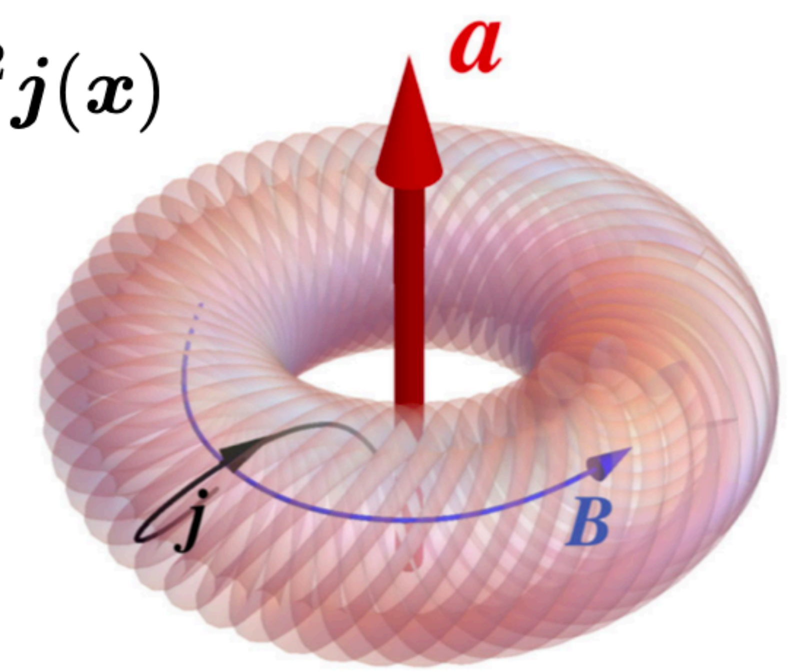
PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$



PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$

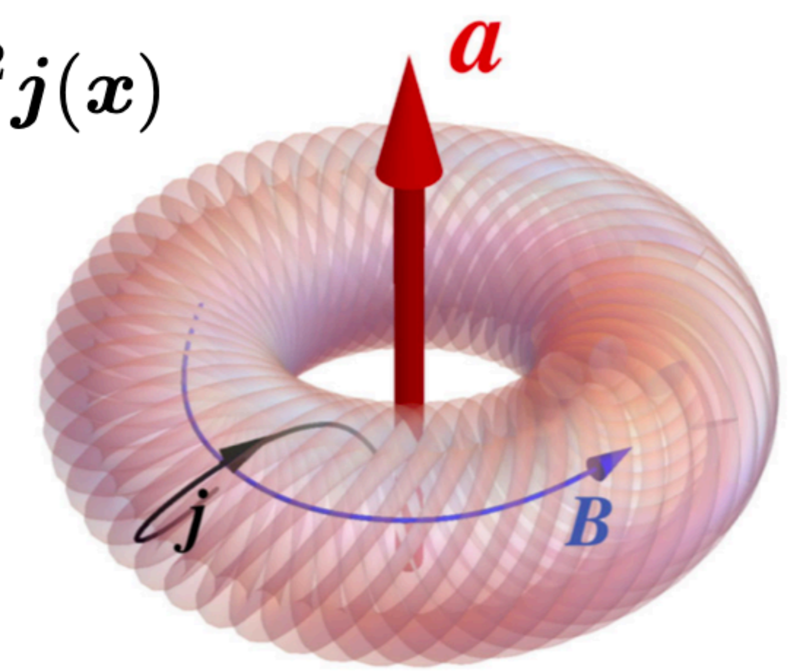


- Arises from weak corrections to EM currents (probes hadronic weak sector)

Why add PV?

PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$

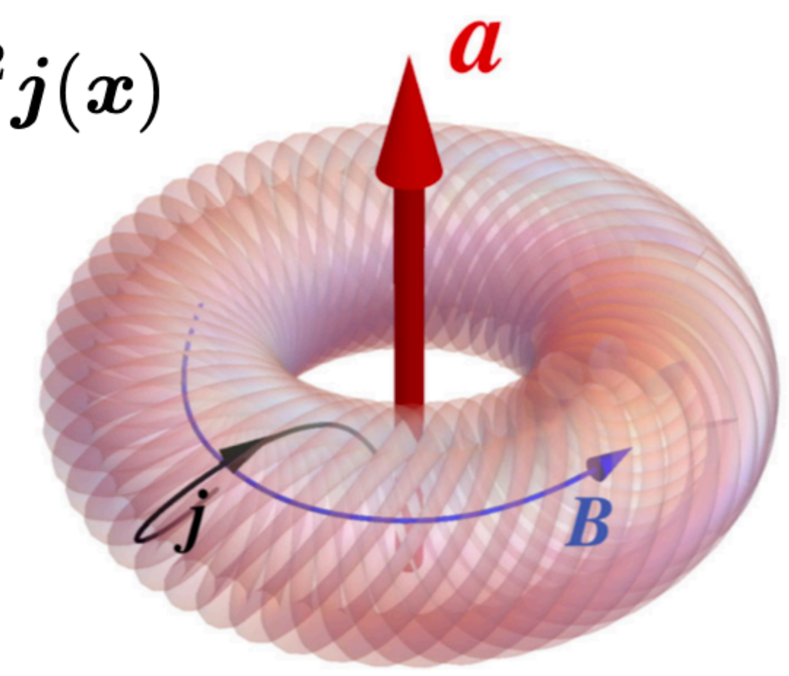


- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)

Why add PV?

PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$

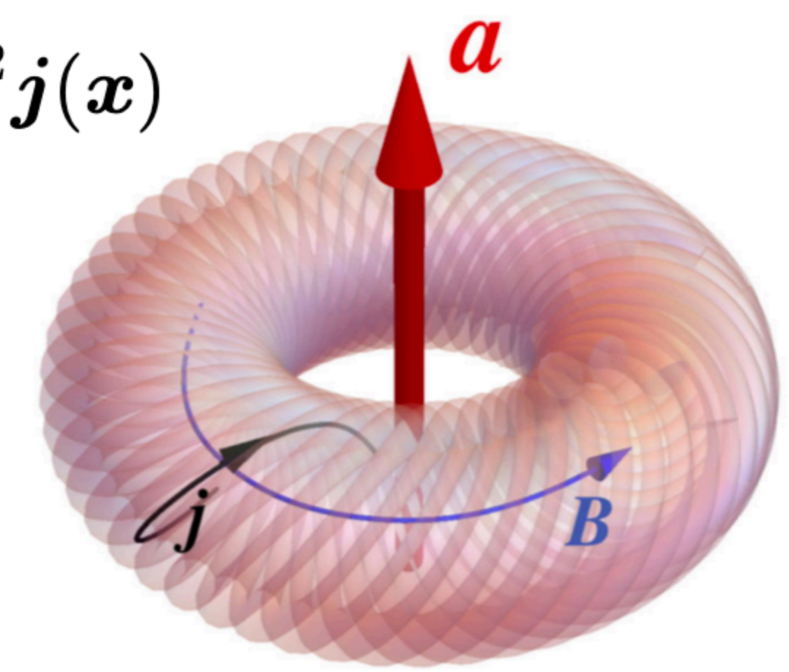


- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model

Why add PV?

PV forces: The anapole moment

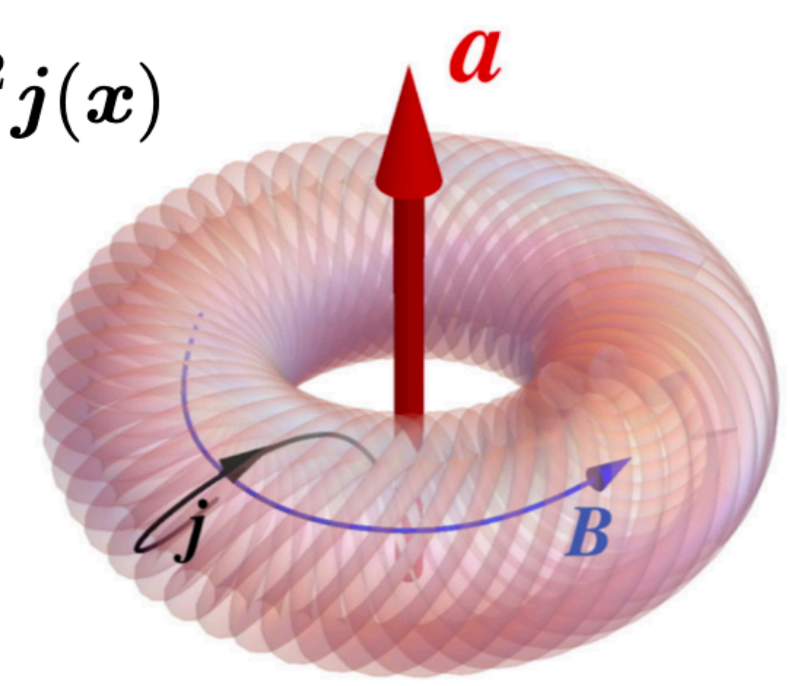
$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$



- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z' low mass boson

PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$

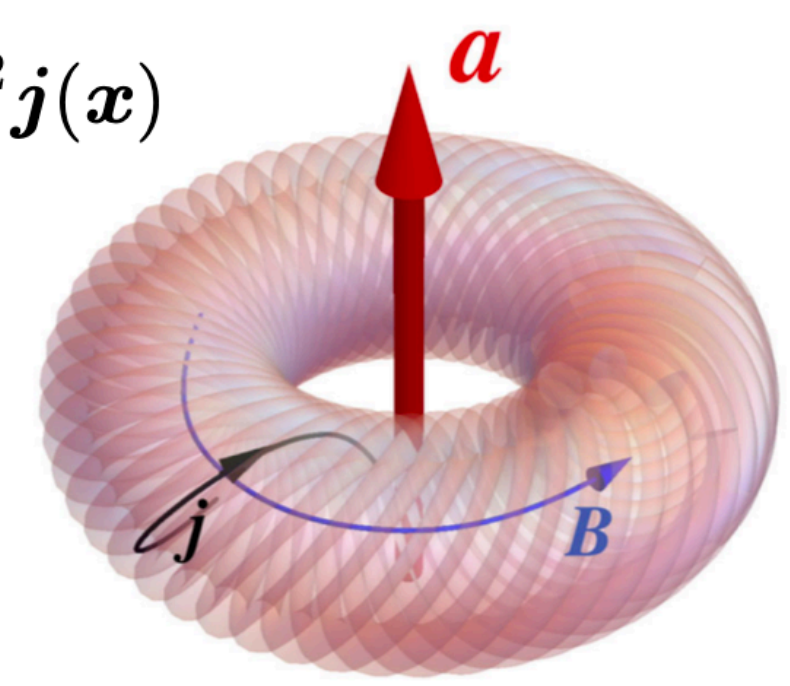


- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z’ low mass boson
- Nuclear contribution arise from term κ_A

Why add PV?

PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$

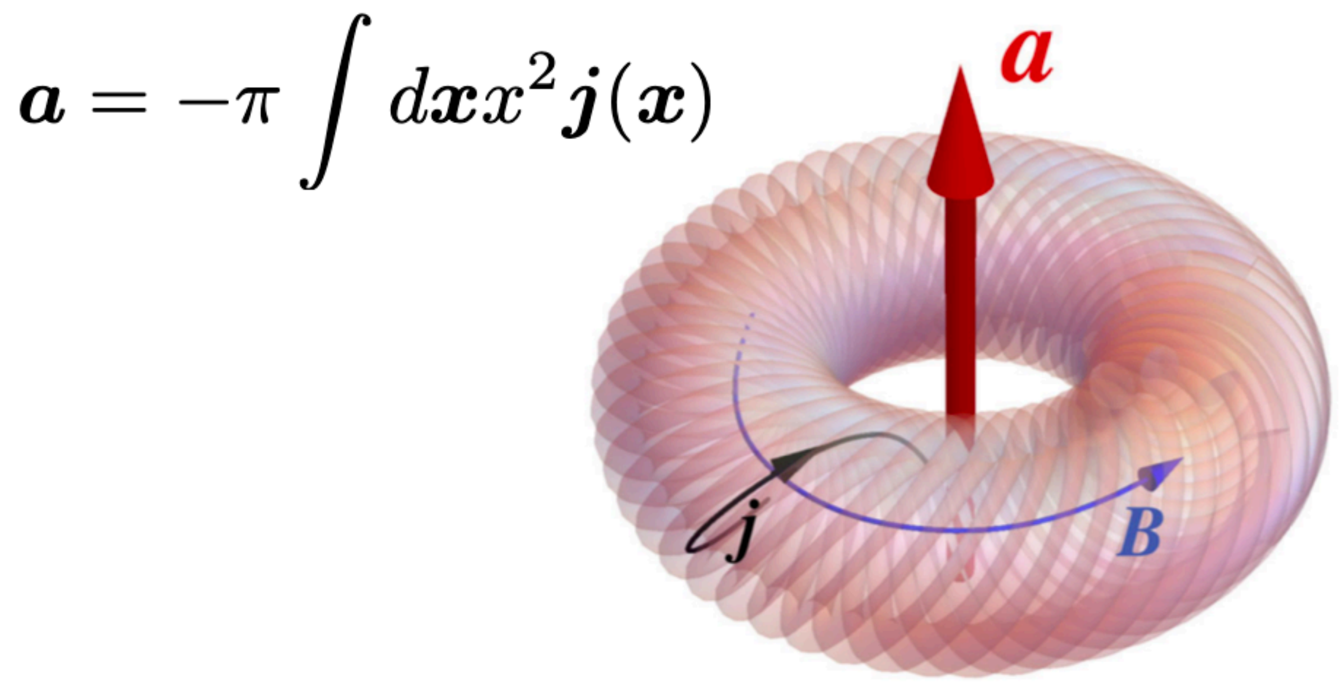


- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z’ low mass boson
- Nuclear contribution arise from term κ_A

PVTV forces: The nuclear EDM

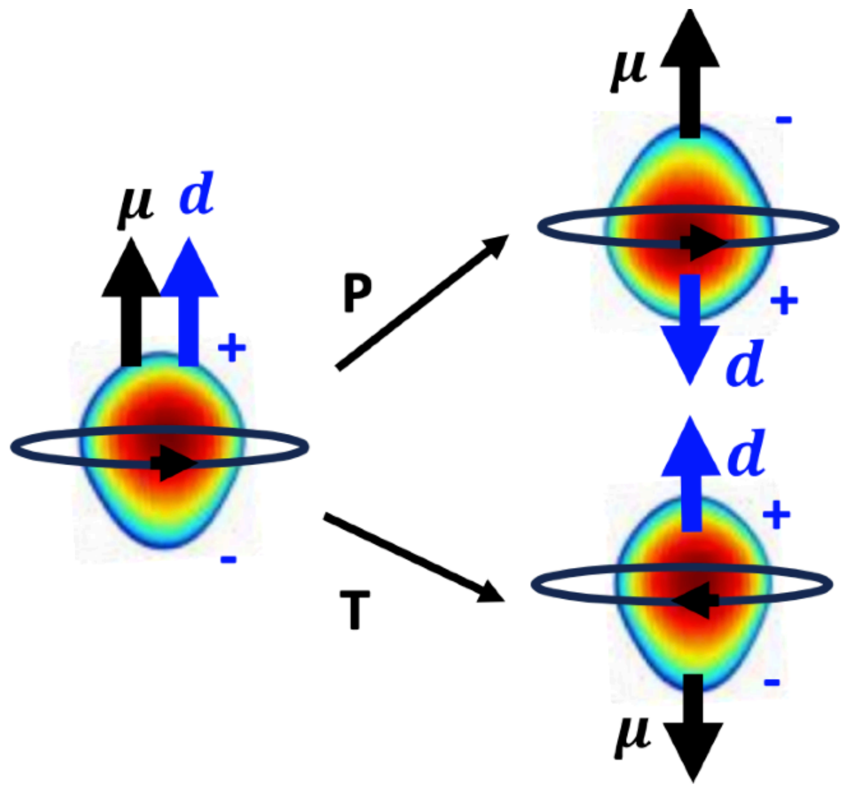
Why add PV?

PV forces: The anapole moment



- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z' low mass boson
- Nuclear contribution arise from term κ_A

PVTV forces: The nuclear EDM

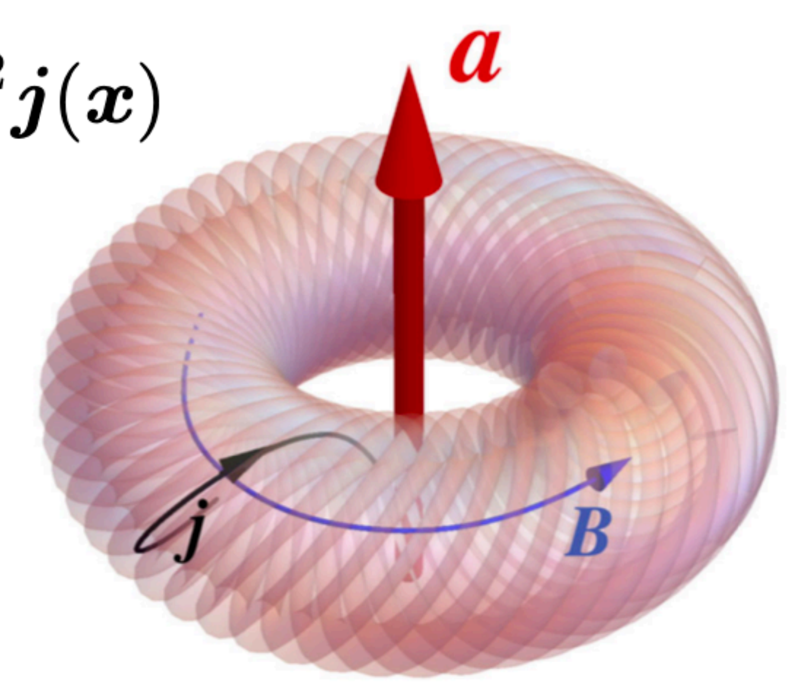


- EDM violates both P and T symmetry separately

Why add PV?

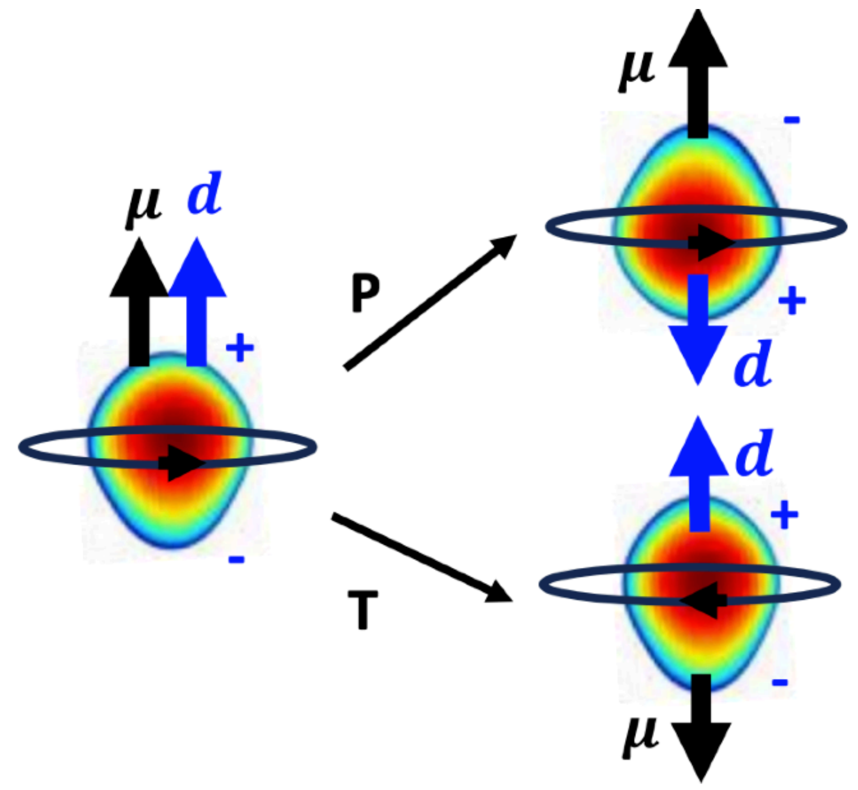
PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$



- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z' low mass boson
- Nuclear contribution arise from term κ_A

PVTV forces: The nuclear EDM

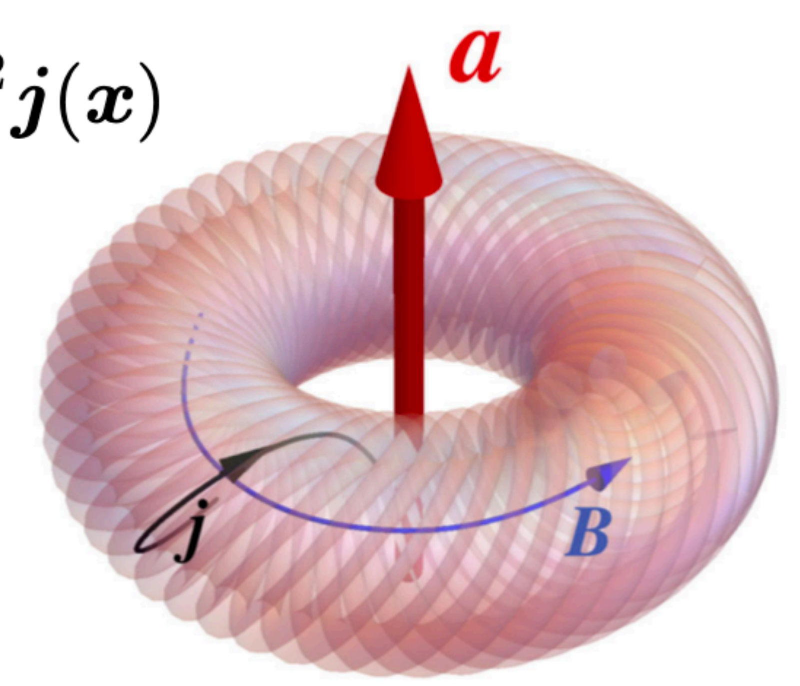


- EDM violates both P and T symmetry separately
- Assuming point like nucleon, effects would be completely shielded by electron cloud

Why add PV?

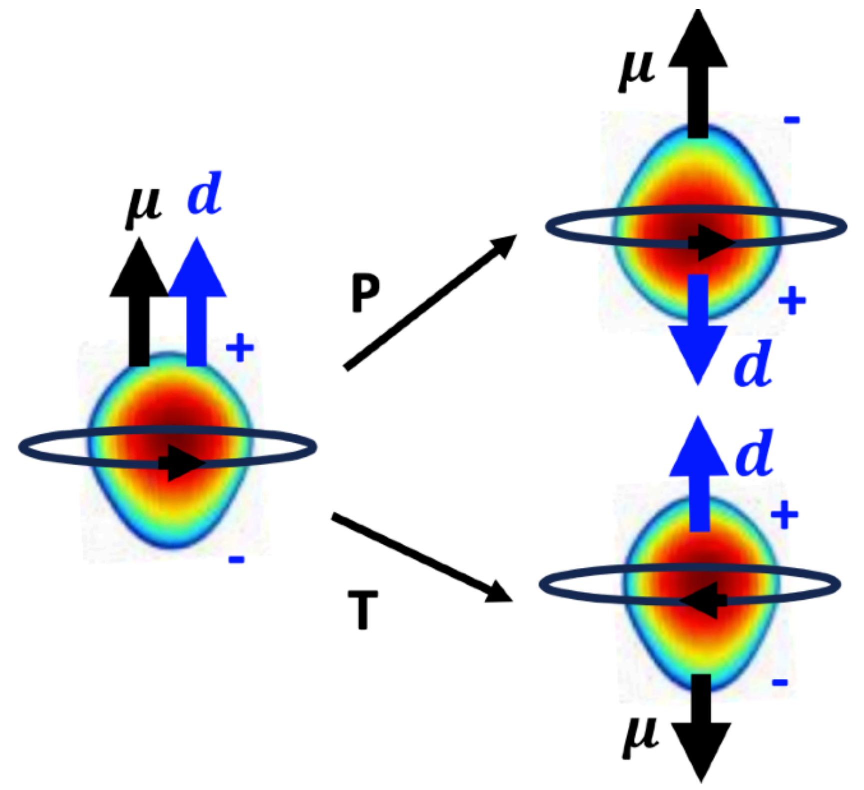
PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$



- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z' low mass boson
- Nuclear contribution arise from term κ_A

PVTV forces: The nuclear EDM

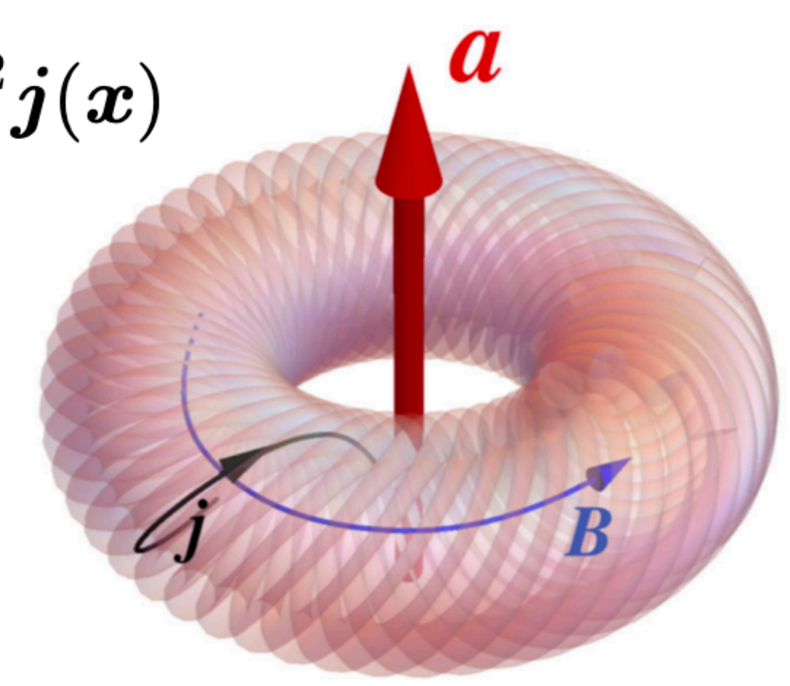


- EDM violates both P and T symmetry separately
- Assuming point like nucleon, effects would be completely shielded by electron cloud
- Observable due to higher order effect given by the nuclear Schiff moment

Why add PV?

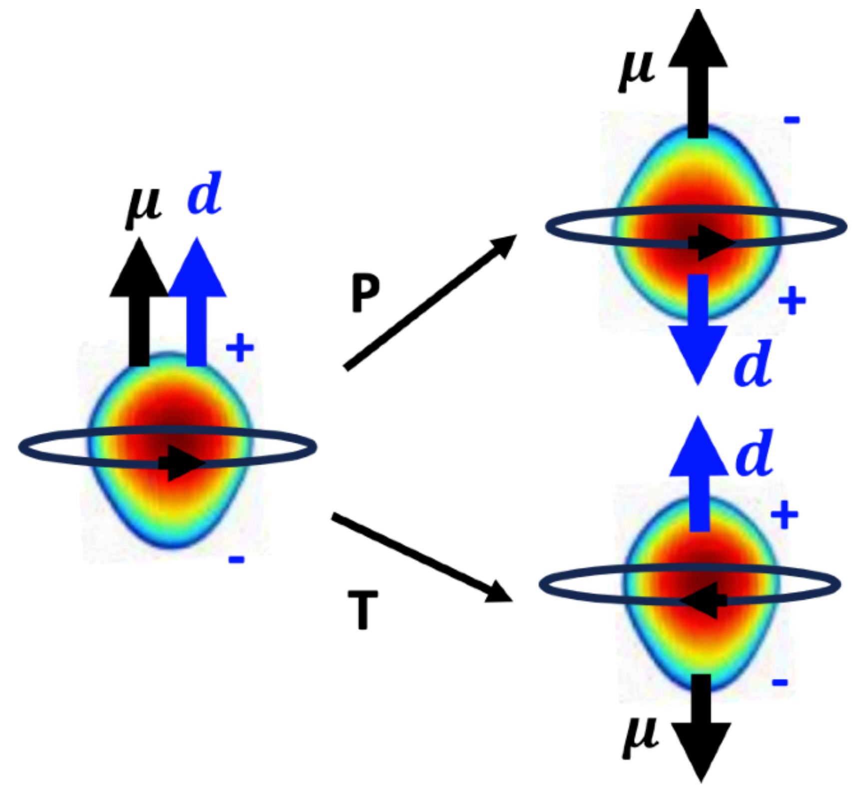
PV forces: The anapole moment

$$\boldsymbol{a} = -\pi \int d\boldsymbol{x} x^2 \boldsymbol{j}(\boldsymbol{x})$$



- Arises from weak corrections to EM currents (probes hadronic weak sector)
- Observed in one isotope (^{133}Cs)
- Offer precision test of the Standard Model
- Possible extensions with Z' low mass boson
- Nuclear contribution arise from term κ_A

PVTV forces: The nuclear EDM



- EDM violates both P and T symmetry separately
- Assuming point like nucleon, effects would be completely shielded by electron cloud
- Observable due to higher order effect given by the nuclear Schiff moment
- Contribution normally given in terms of a_0, a_1 and a_2 which are isoscalar, isovector and isotensor contributions

Nuclear Theory Challenges

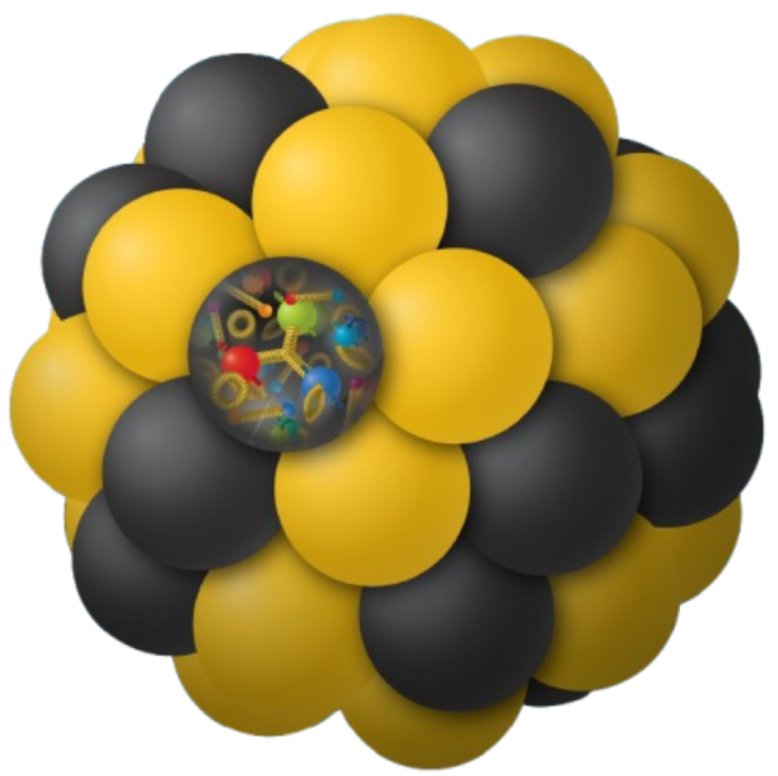
Understanding nuclear structure from microscopic physics

Figures courtesy of J. Muñoz

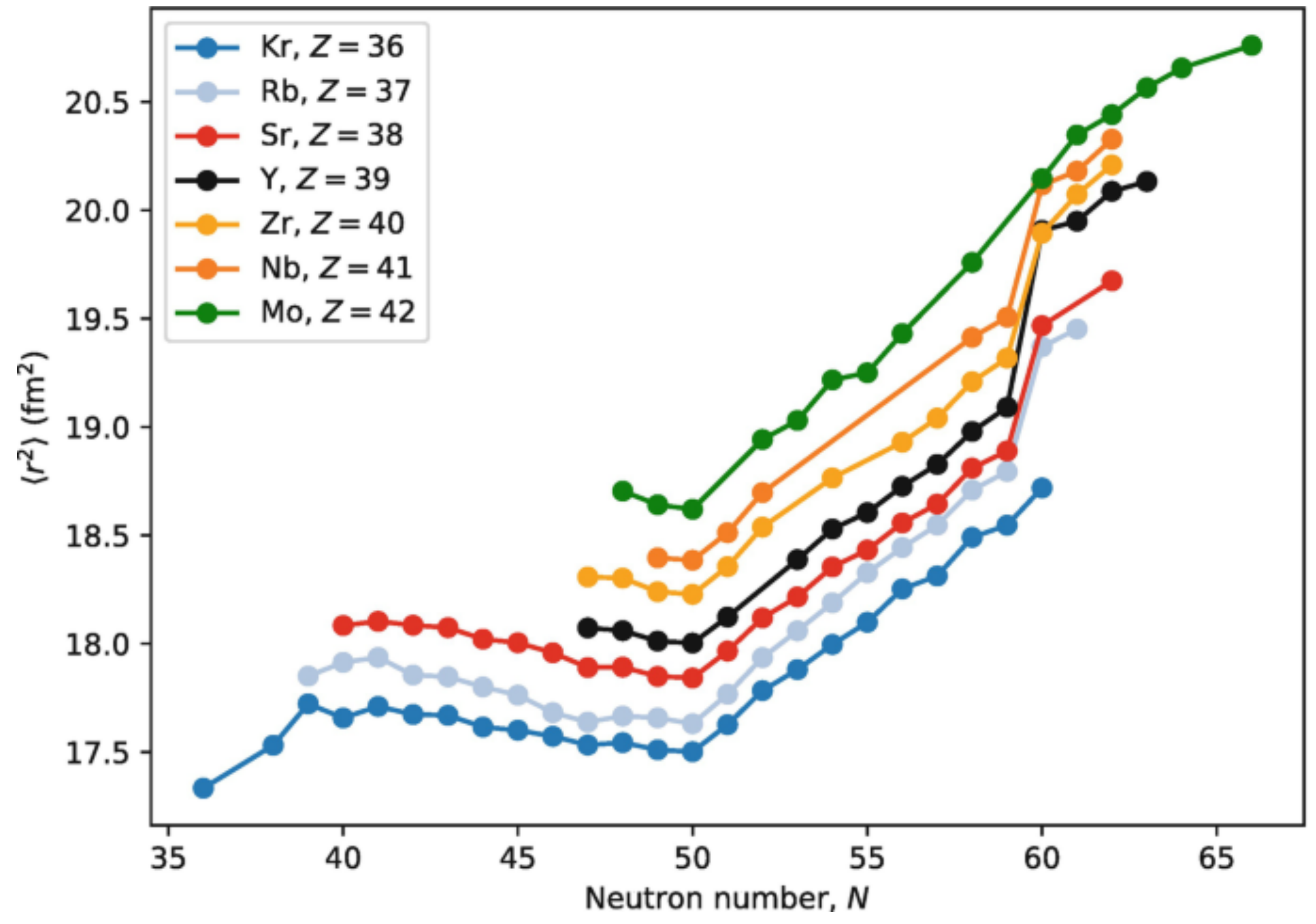
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions | Wave functions | Observables



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



Figures courtesy of J. Muñoz

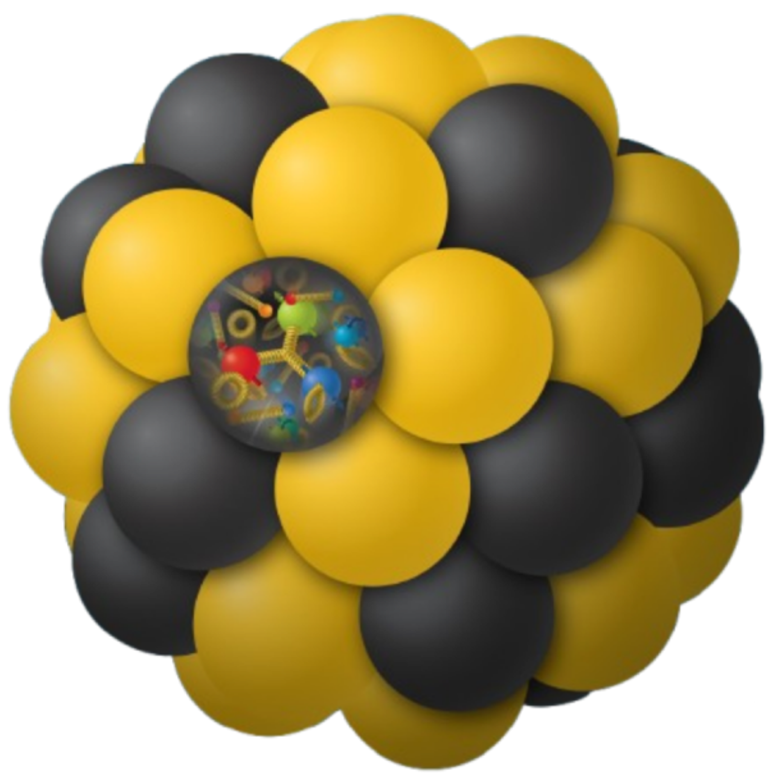
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

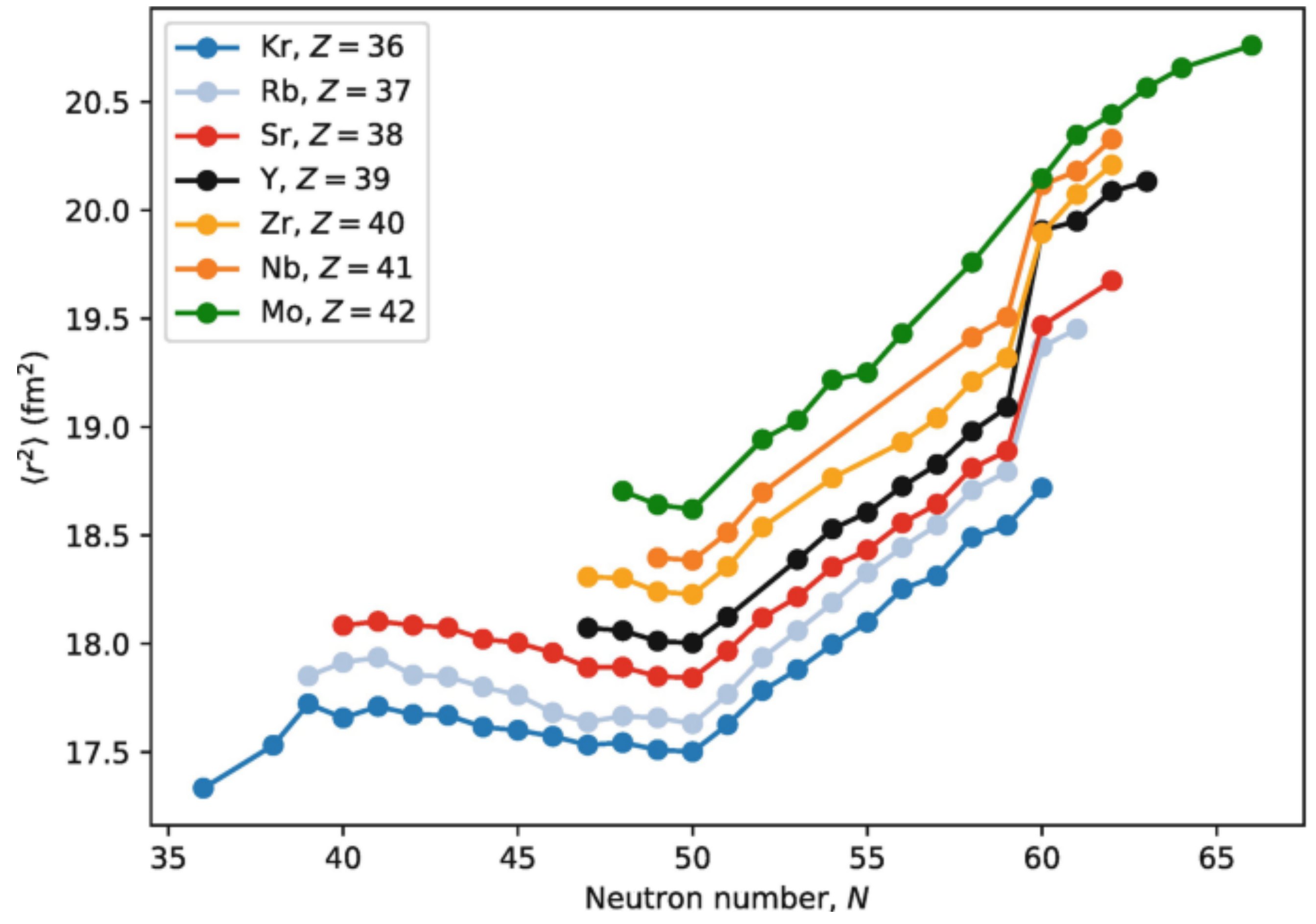
Nuclear Interactions

Wave functions

Observables



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

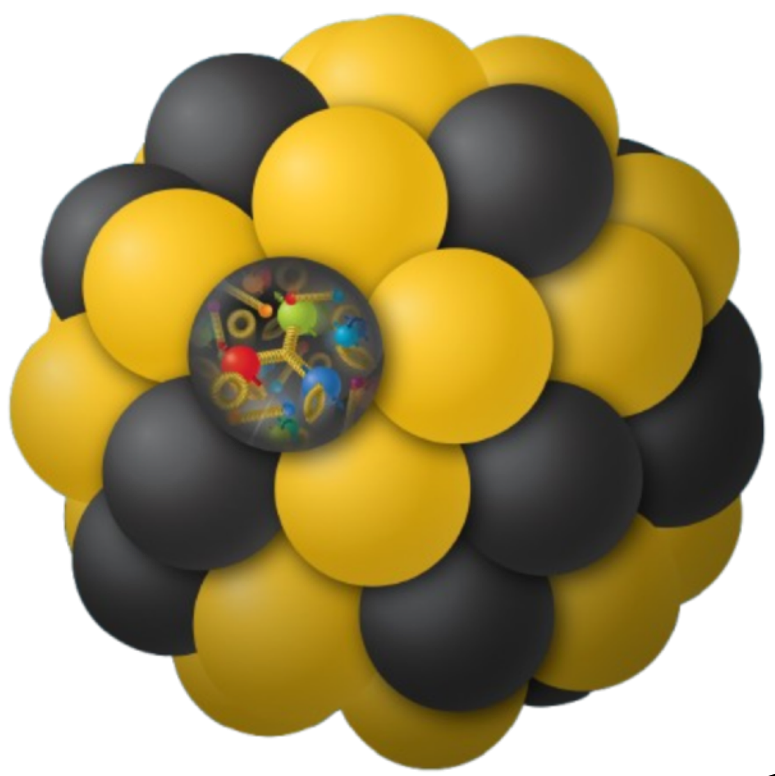


Figures courtesy of J. Muñoz

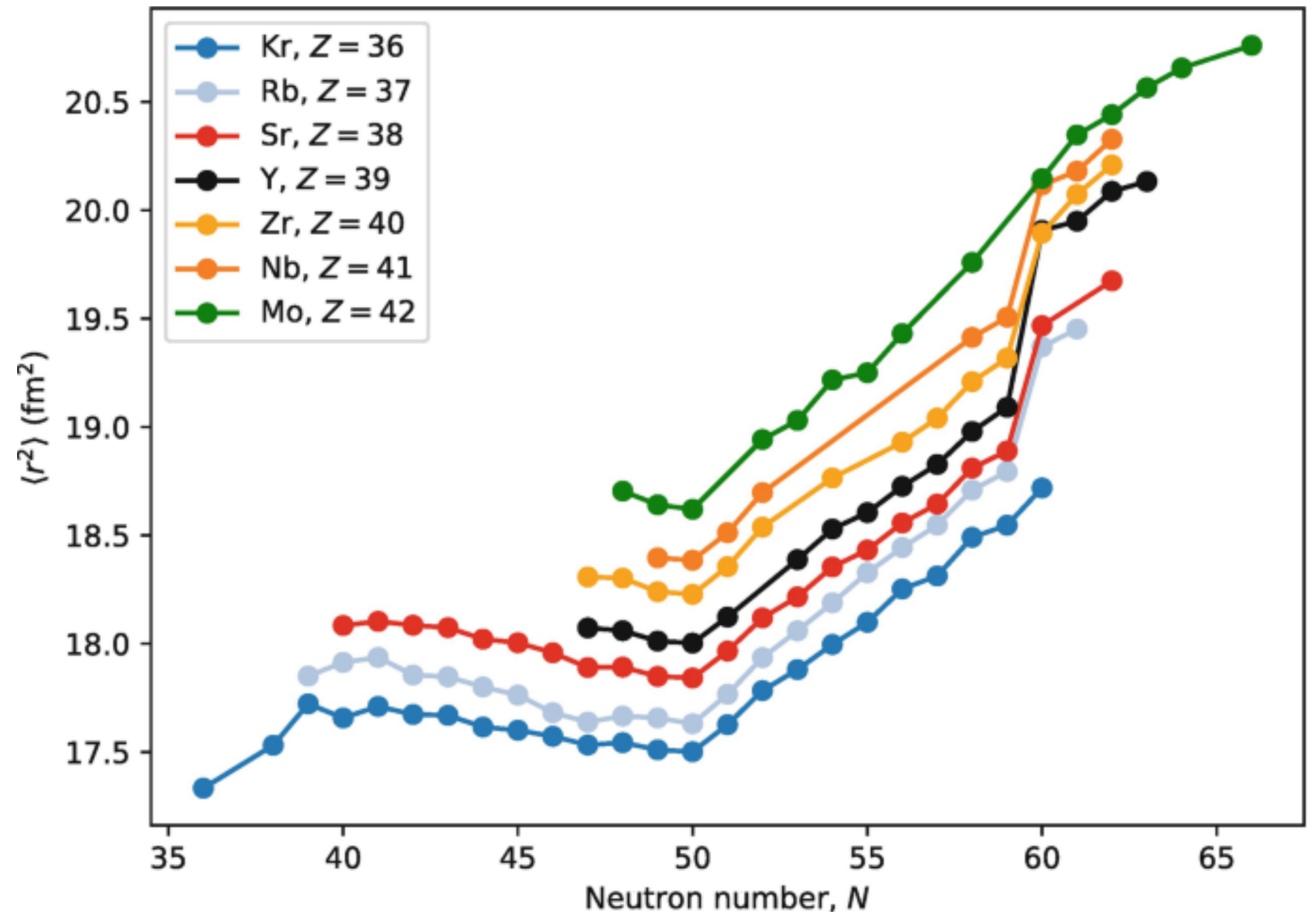
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions | Wave functions | Observables



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



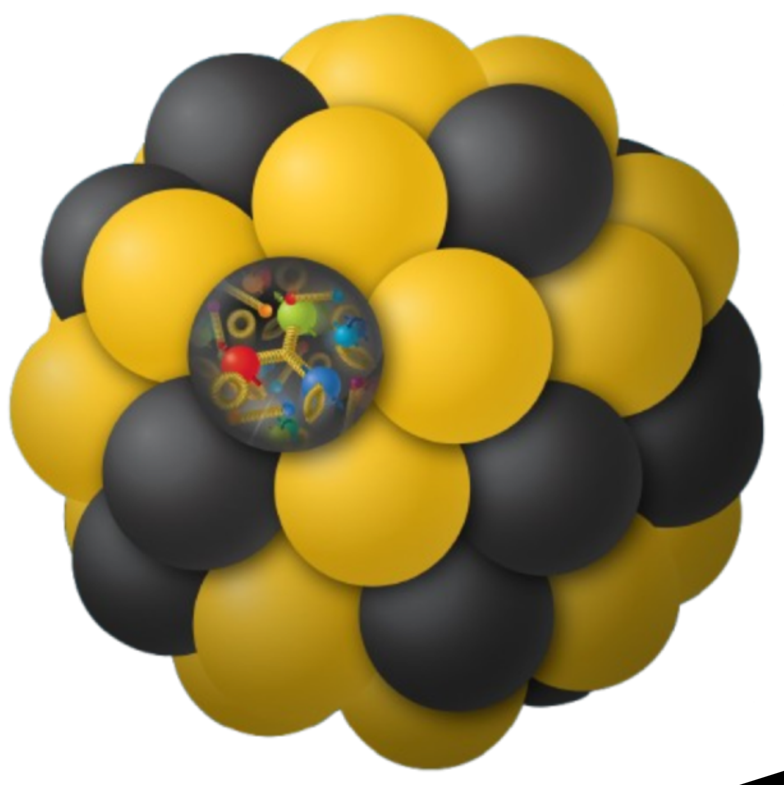
$$H = H_0 + V_{PV}$$

Figures courtesy of J. Muñoz

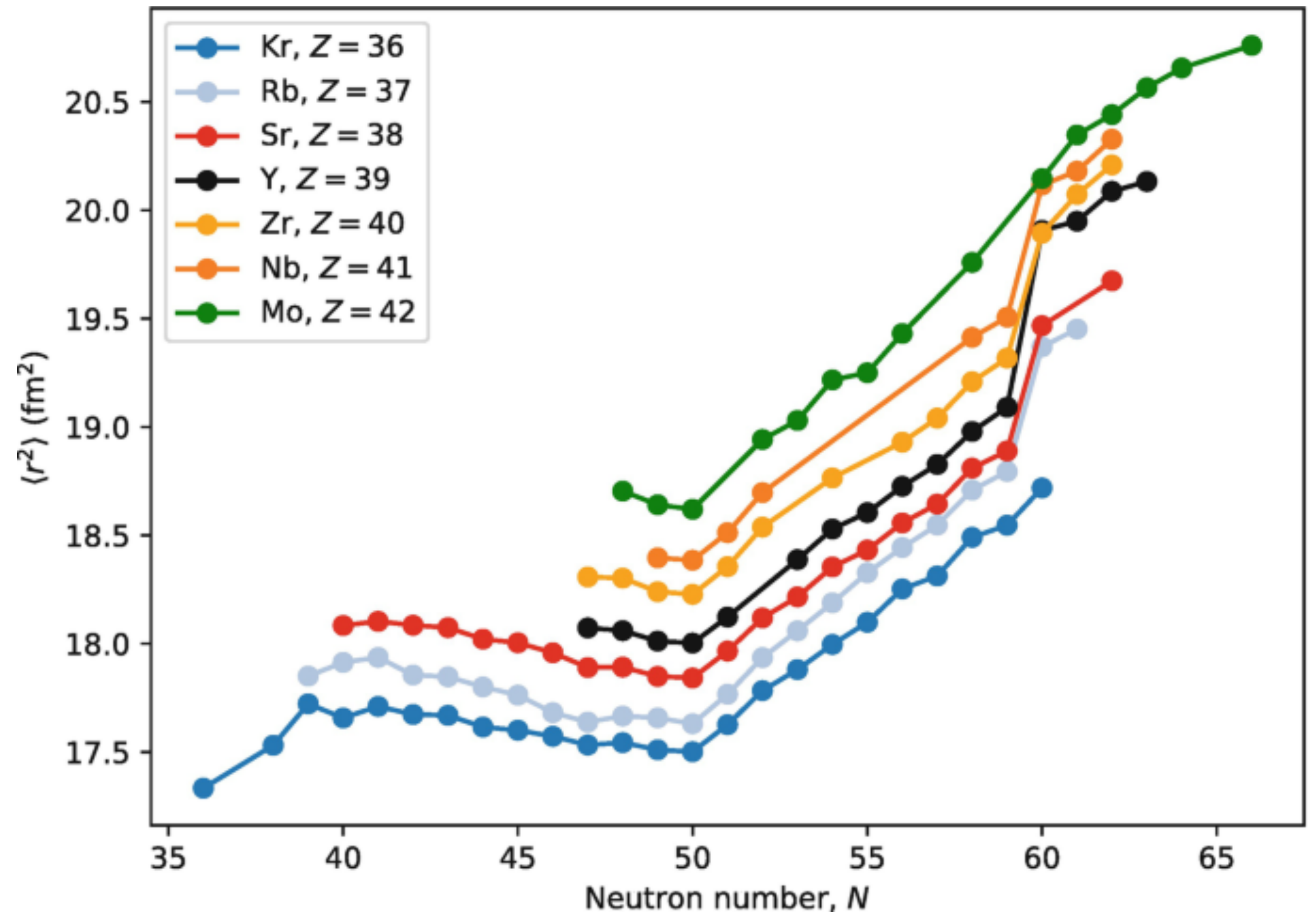
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions | Wave functions | Observables



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



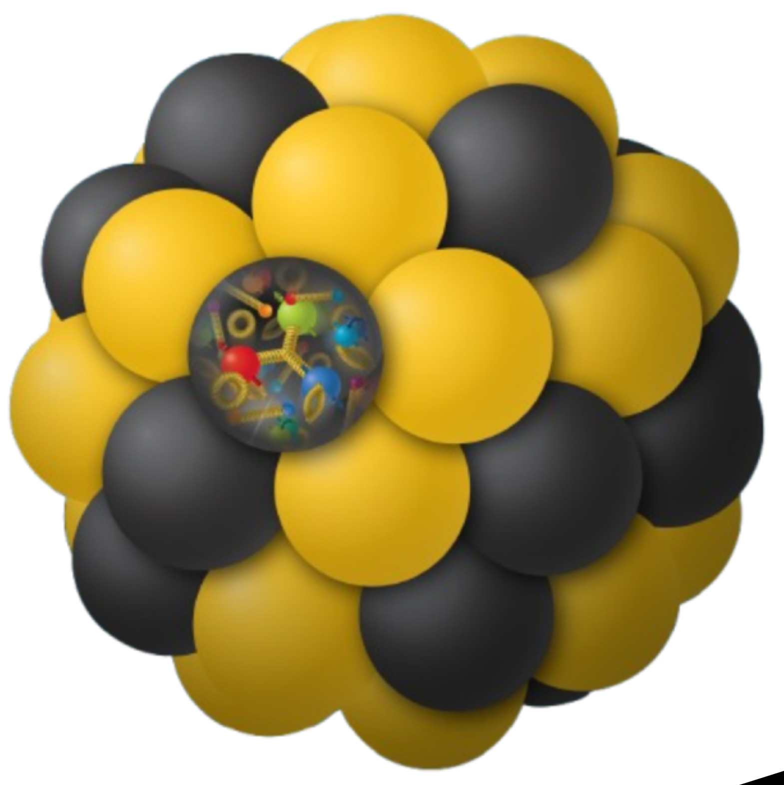
$$H = H_0 + V_{PV}$$

Figures courtesy of J. Muñoz

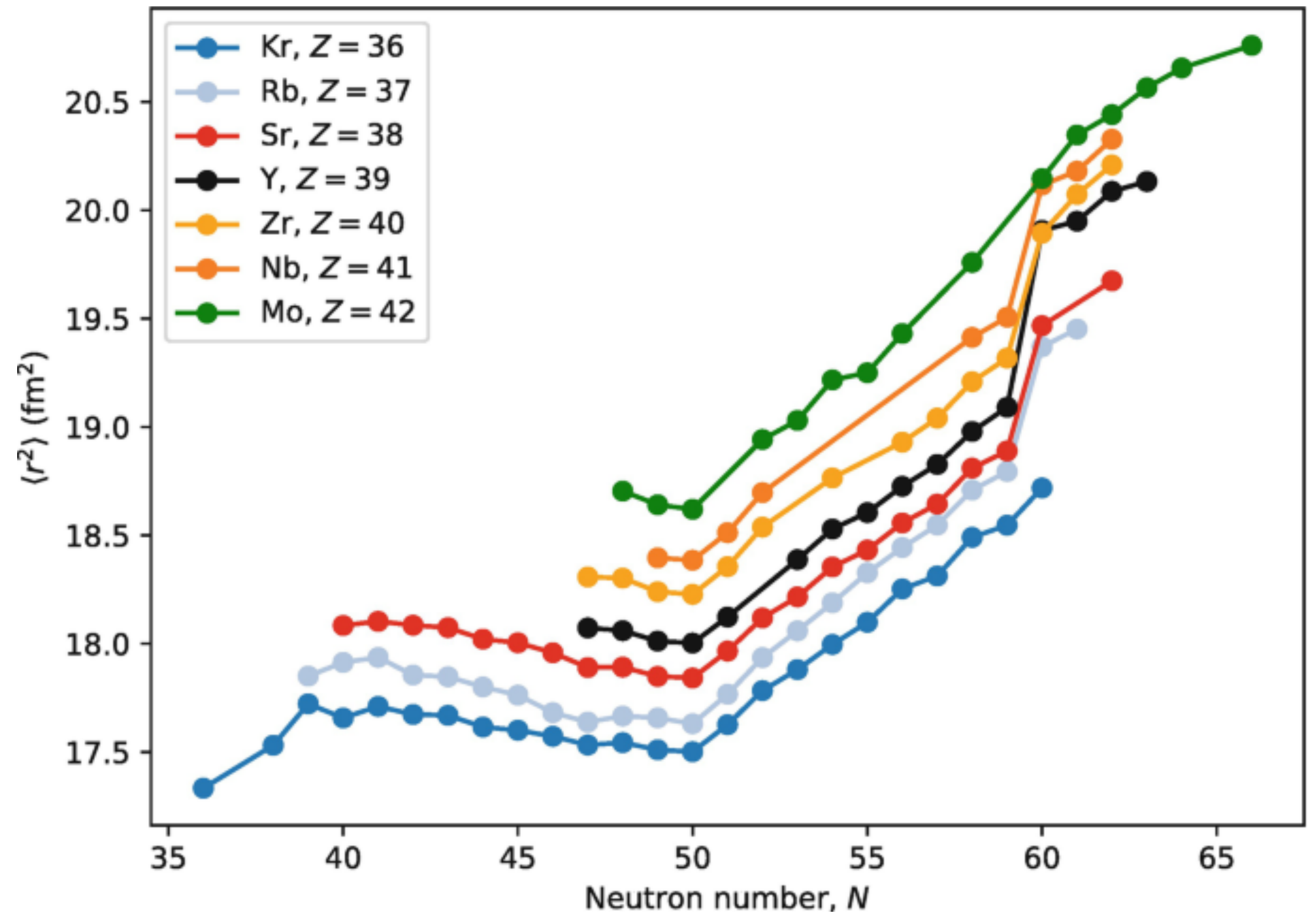
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions | Wave functions | Observables



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



$$H = H_0 + V_{PV}$$

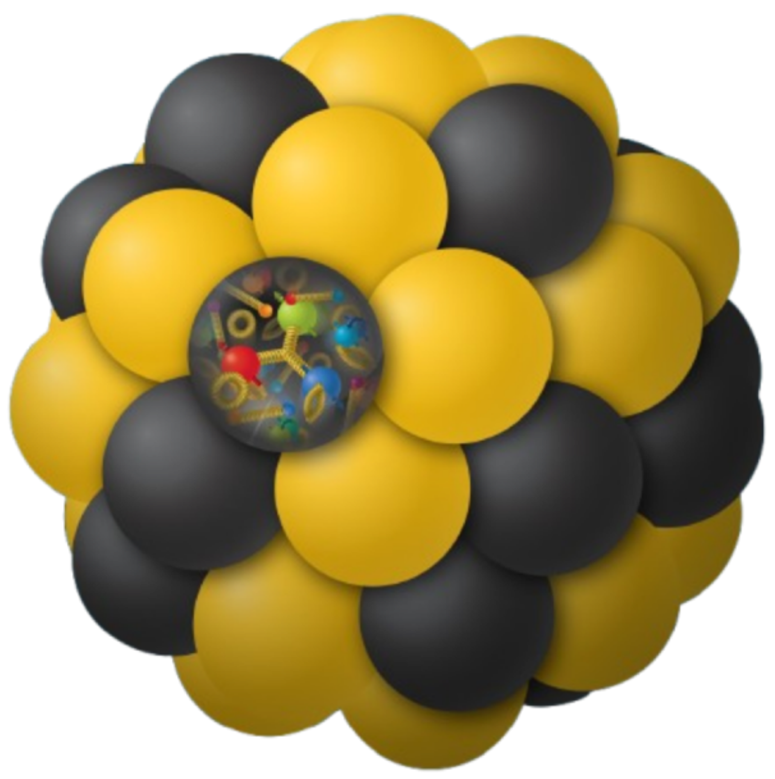
$$|\Psi_{gs}J\rangle = |\Psi_{gs}J^{\pi}\rangle + \sum_k |\Psi_k J^{-\pi}\rangle \frac{1}{E_{gs} - E_k} \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle$$

Figures courtesy of J. Muñoz

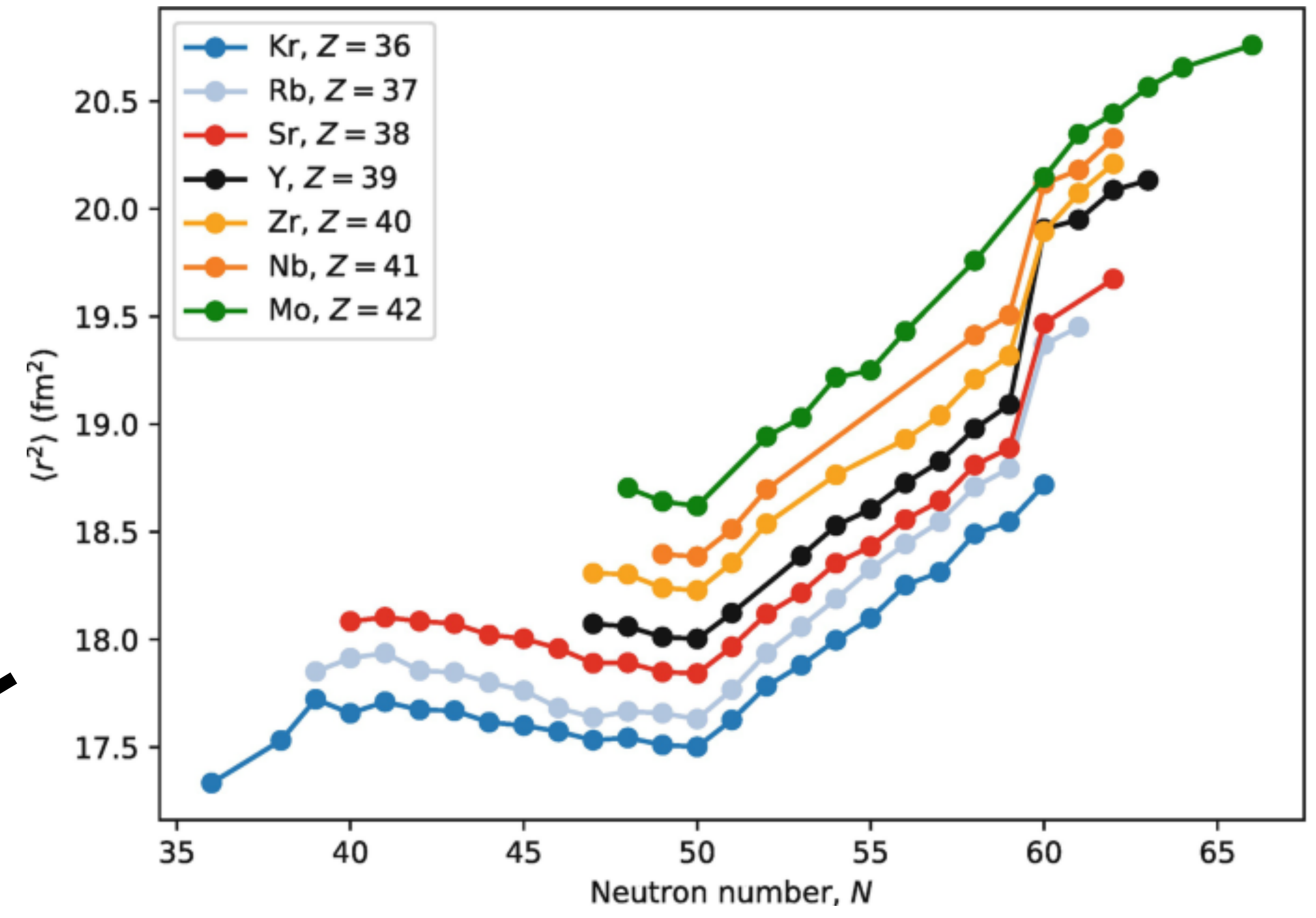
Nuclear Theory Challenges

Understanding nuclear structure from microscopic physics

Nuclear Interactions | Wave functions | Observables



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



$$< O_{PV} > \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

Figures courtesy of J. Muñoz

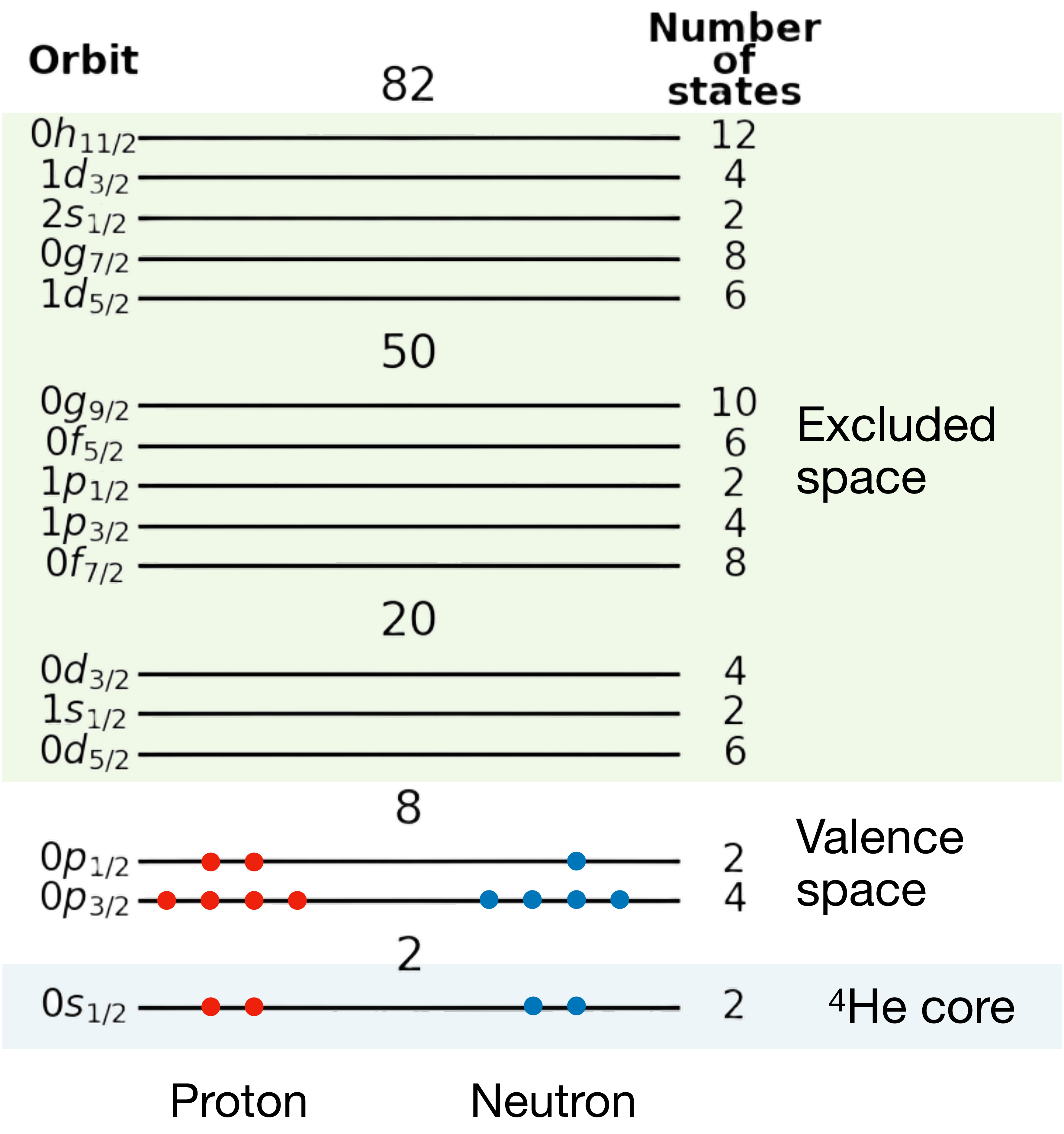
Valence Space Issue

$$< O_{PV} > \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

Valence Space Issue

$$< O_{PV} > \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

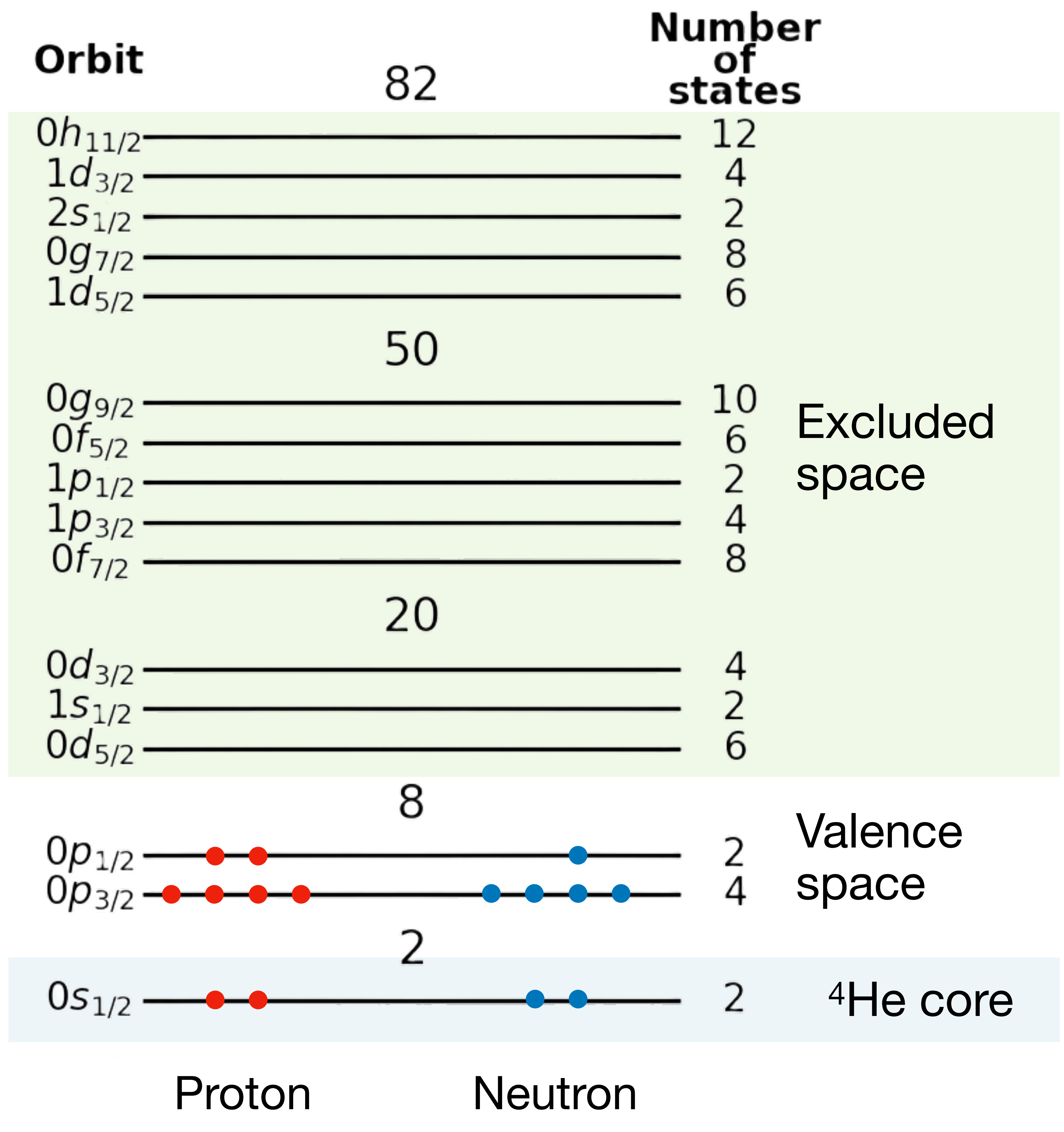
^{15}N



Valence Space Issue

$$< O_{PV} > \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

^{15}N

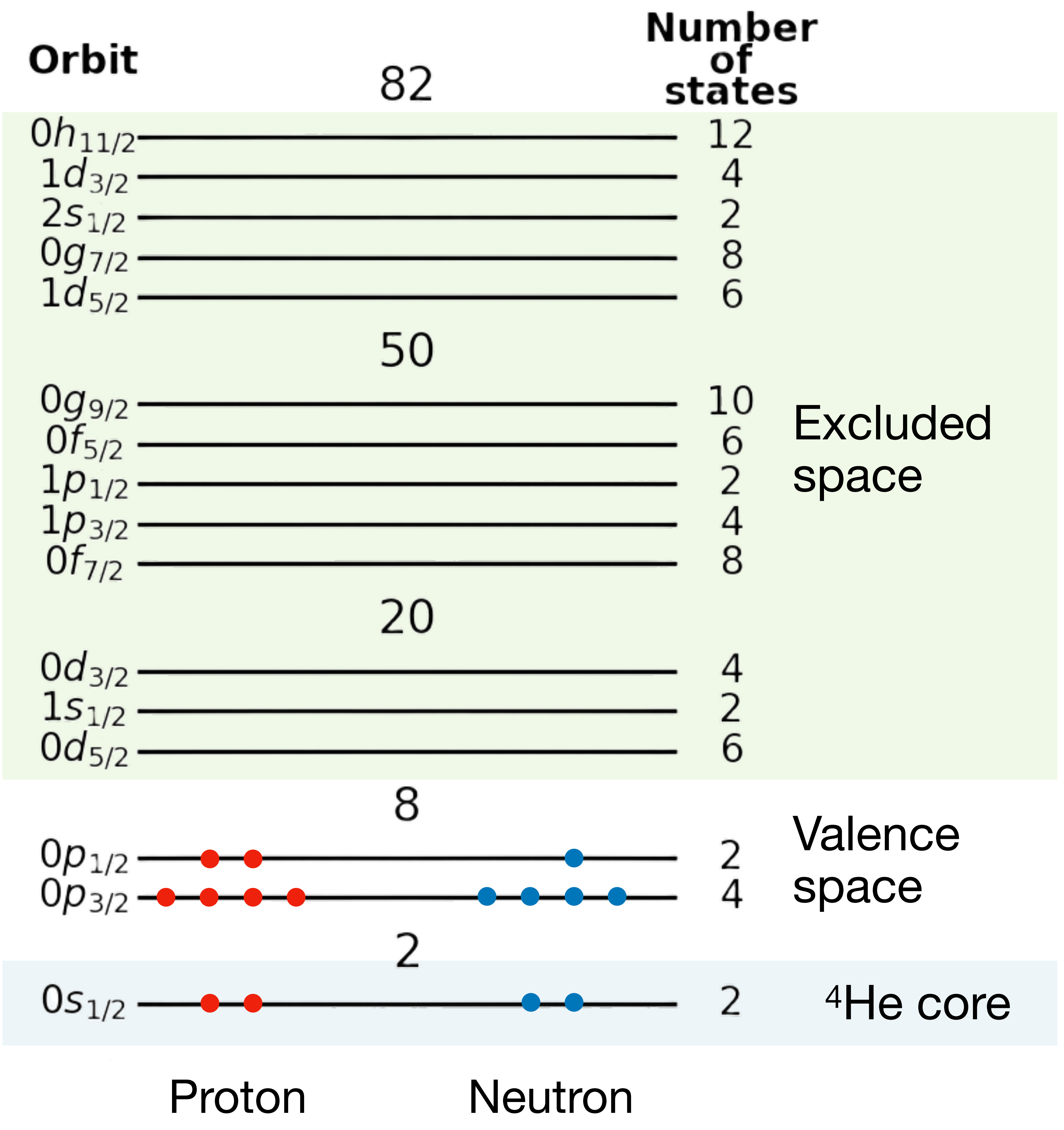


Ground state wave function can be computed in the valence space.

Valence Space Issue

$$< O_{PV} > \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

^{15}N



Ground state wave function can be computed in the valence space.

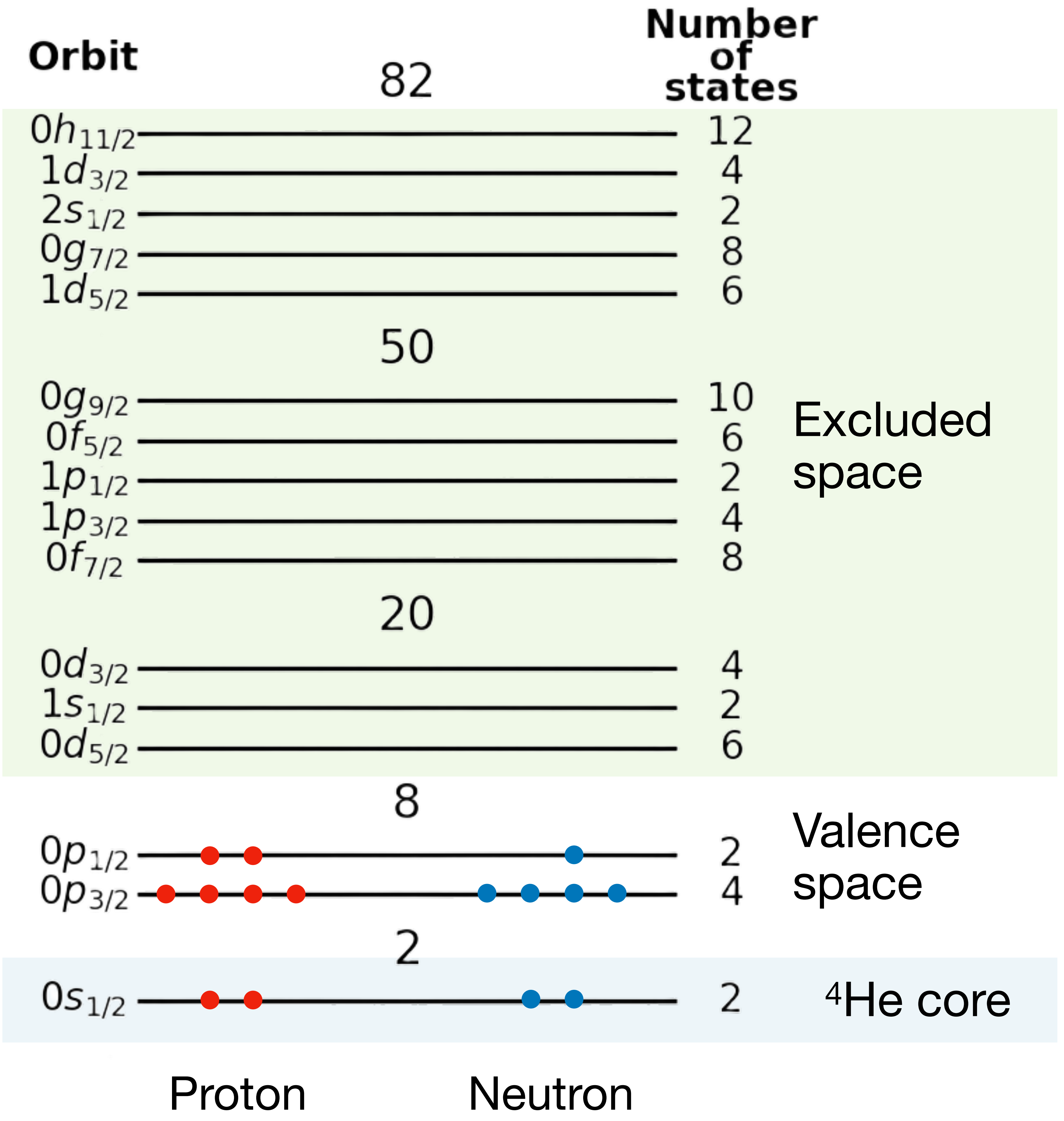
Opposite parity states are absent from the valence space!

Solutions to Valence Space

Solutions to Valence Space

1. Multi-shell valence space

^{15}N

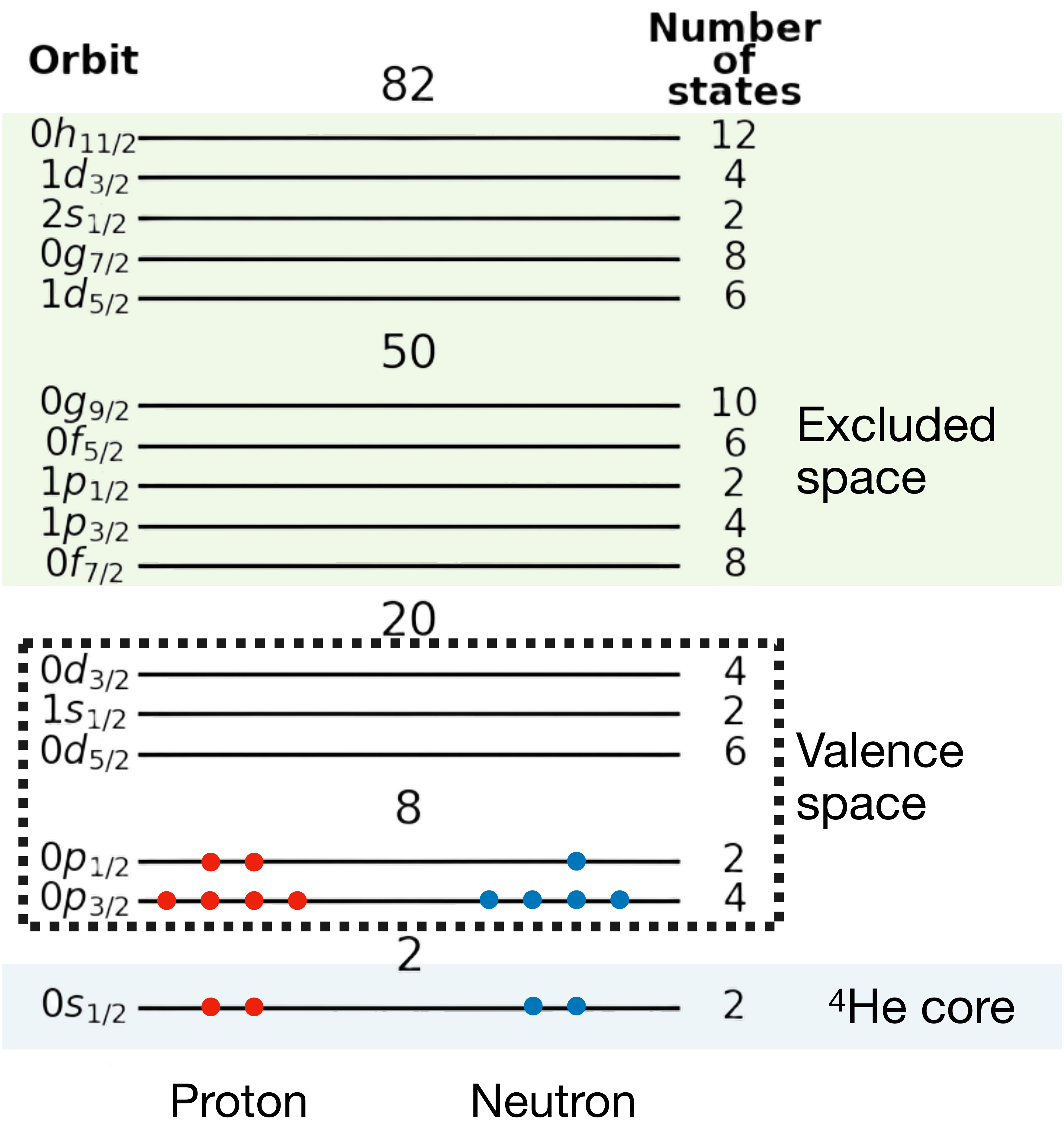


Miyagi et al., Phys. Rev. C 102, 034320 (2020).

Solutions to Valence Space

1. Multi-shell valence space

^{15}N

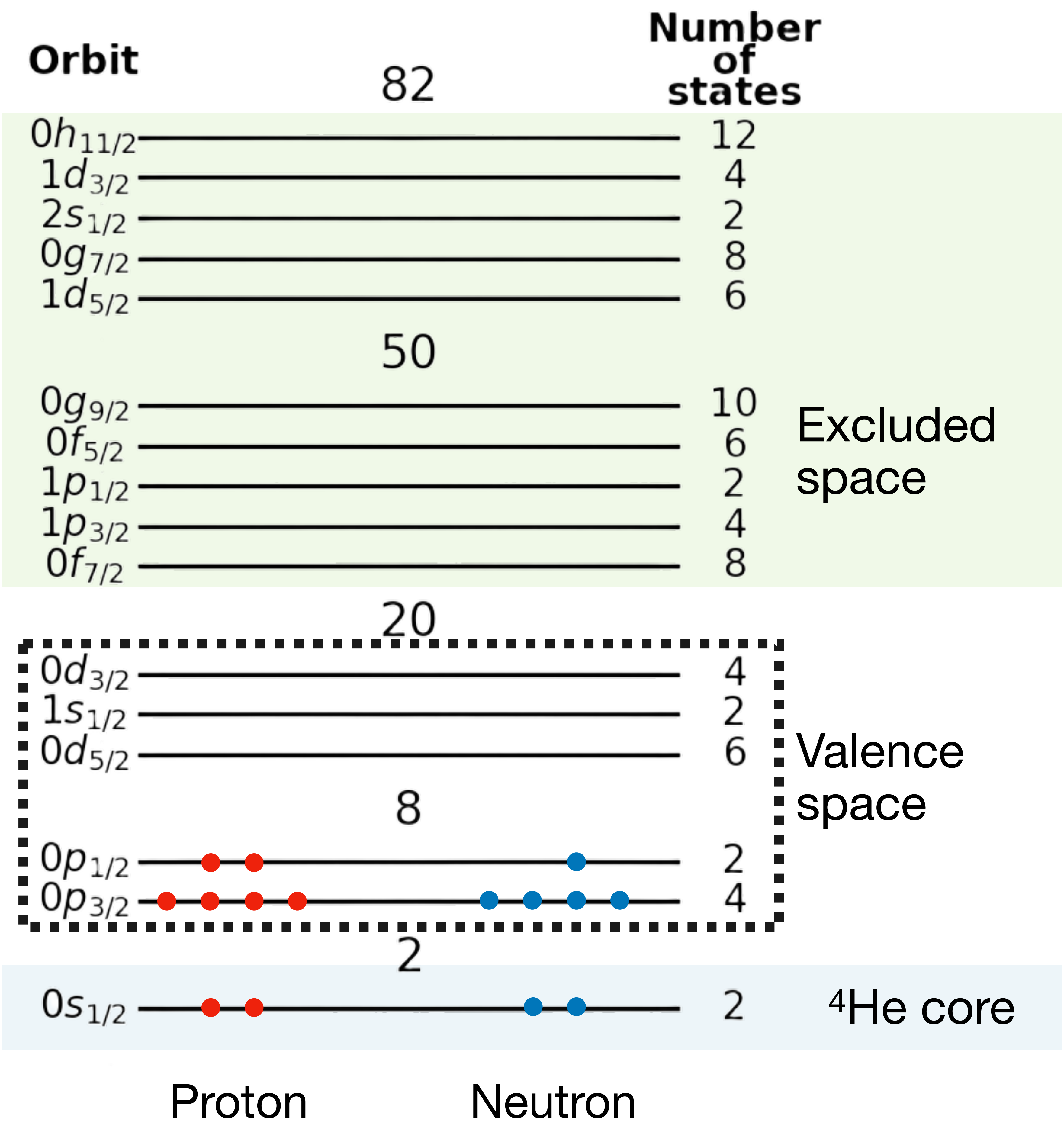


Miyagi et al., Phys. Rev. C 102, 034320 (2020).

Solutions to Valence Space

1.Multi-shell valence space

^{15}N



Miyagi et al., Phys. Rev. C 102, 034320 (2020).

Cons

- Valence space is harder to diagonalize (problematic for heavier nuclei).
- Need to compute many intermediate states to converge.
- Intermediate states are harder to compute correctly in the IMSRG(2).

Solutions to Valence Space

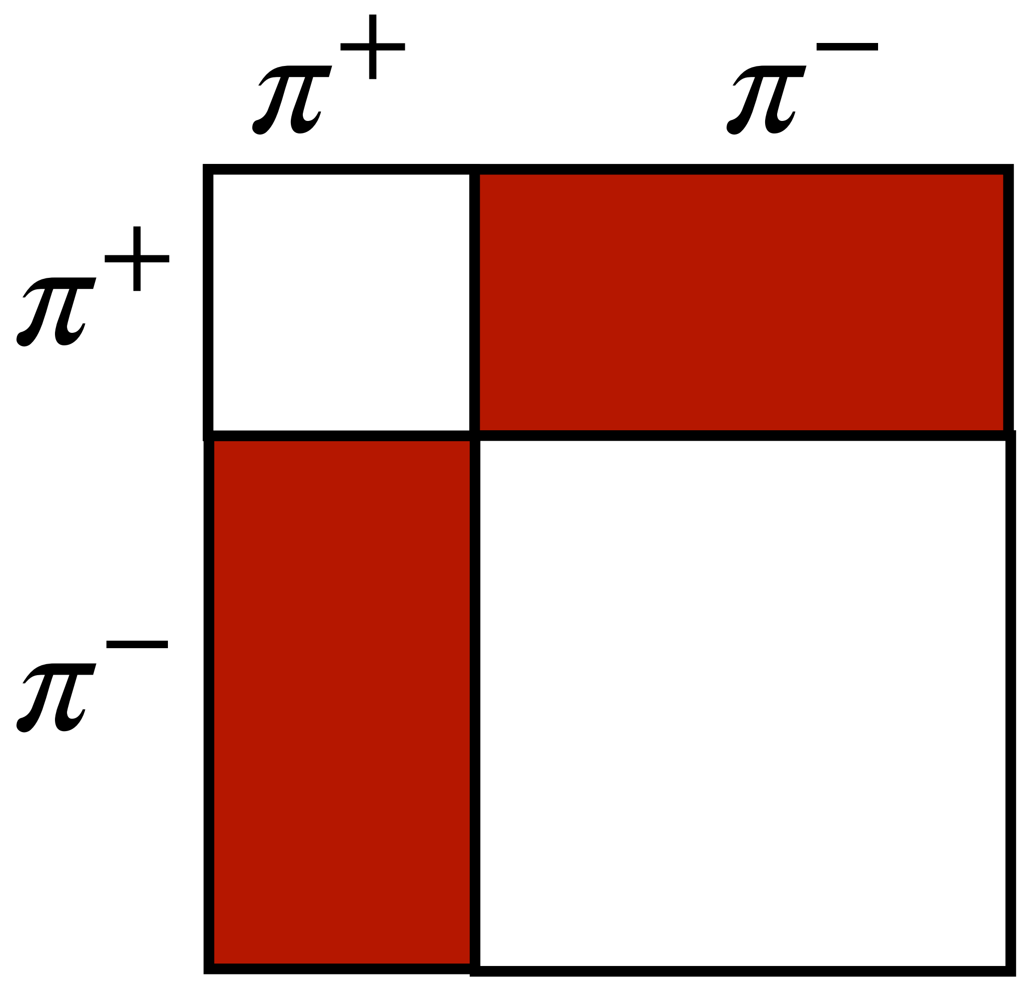
2. <u>Parity violating IMSRG</u>

2.Parity violating IMSRG

Use IMSRG to decouple PV part of interaction, inducing a PC operator.

2.Parity violating IMSRG

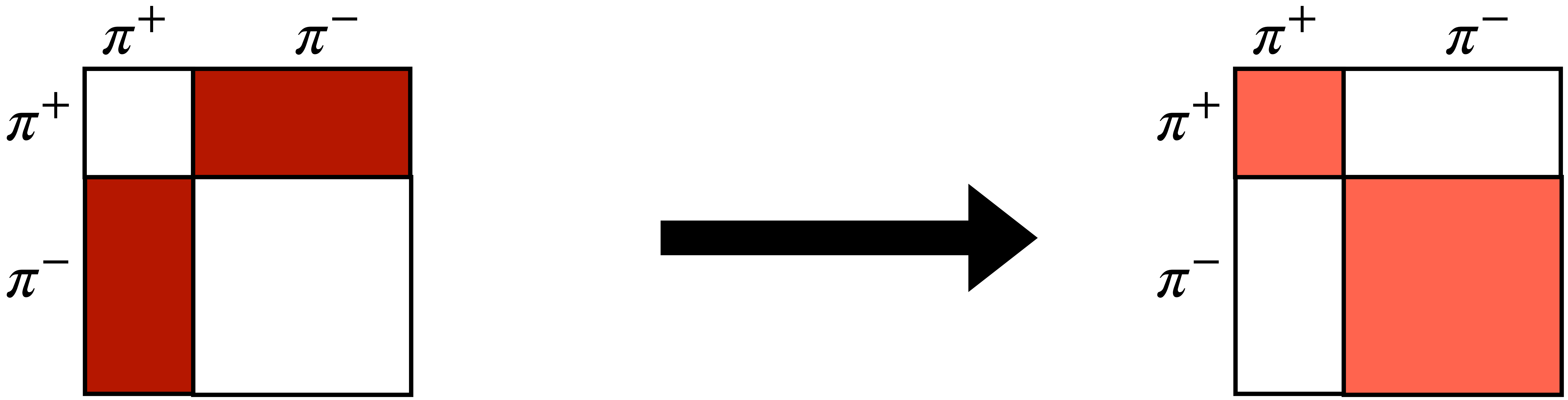
Use IMSRG to decouple PV part of interaction, inducing a PC operator.



$$\langle O \rangle = \langle O_{PV} \rangle \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

2. Parity violating IMSRG

Use IMSRG to decouple PV part of interaction, inducing a PC operator.



$$\langle O \rangle = \langle O_{PV} \rangle \propto \sum_k \frac{\langle \Psi_{gs} J^{\pi} | O_{PV} | \Psi_k J^{-\pi} \rangle \langle \Psi_k J^{-\pi} | V_{PV} | \Psi_{gs} J^{\pi} \rangle}{E_{gs} - E_k}$$

$$\langle O \rangle = \langle O_{PC} \rangle = \langle \Psi_{gs} J^{\pi} | O_{PC} | \Psi_{gs} J^{\pi} \rangle$$

IMSRG flow

IMSRG flow

Normal Ordered Two-Body approximation

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body 2-body

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij} \eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl} \eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl} \Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij} \eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl} \eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij} \eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl} \eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ldots$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij}\eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

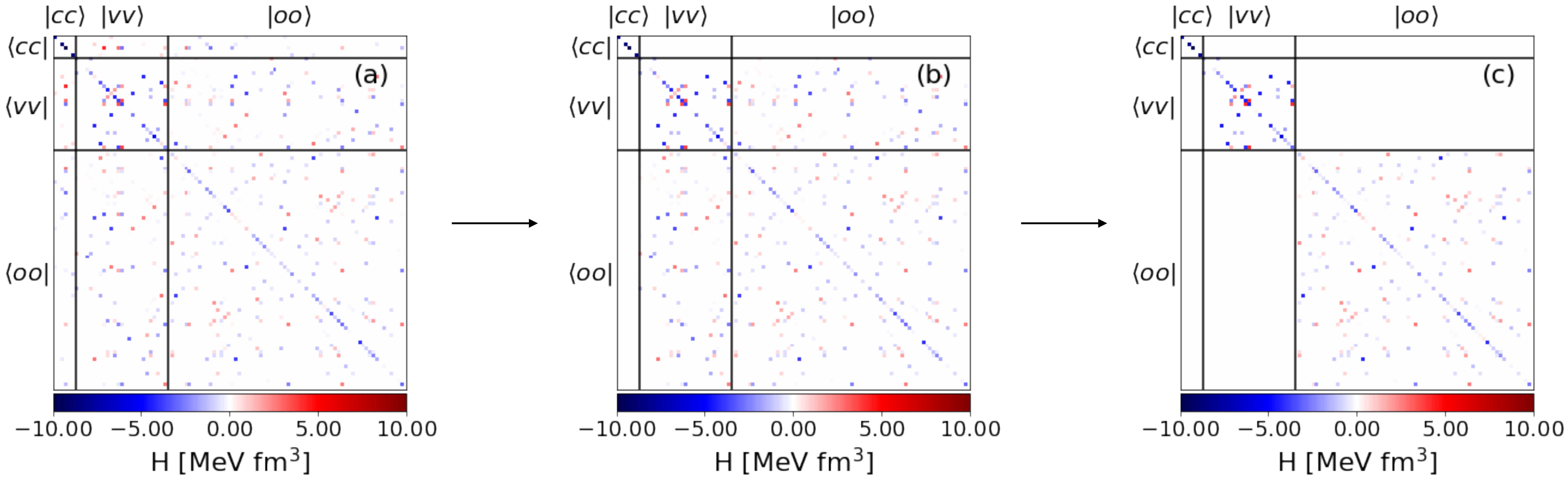
e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ldots$$

The VS-IMSRG

Valence Space In Medium Similarity Renormalization Group



Bare Hamiltonian

Core is decoupled

Valence-space is decoupled

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij}\eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ldots$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij}\eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ \ldots$$

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

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij}\eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ldots$$

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

$$= [\eta(s), H(s)]_{0B} + [\eta(s), H(s)]_{1B} + [\eta(s), H(s)]_{2B} + [\eta(s), H(s)]_{3B} + \ldots$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j^\dagger a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij} \eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \dots$$

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

$$= [\eta(s), H(s)]_{0B} + [\eta(s), H(s)]_{1B} + [\eta(s), H(s)]_{2B} + [\eta(s), H(s)]_{3B} + \dots$$

IMSRG flow

Normal Ordered Two-Body approximation

$$H(s) = E(s) + \sum_{ij} f_{ij}(s)\{a_i^\dagger a_j\} + \frac{1}{4}\sum_{ijkl}\Gamma_{ijkl}\{a_i^\dagger a_j a_l a_k\}$$

0-body 1-body 2-body

$$\eta(s) = \sum_{ij}\eta_{ij}(s)\{a_i^\dagger a_j\} + \sum_{ijkl}\eta_{ijkl}(s)\{a_i^\dagger a_j^\dagger a_l a_k\}$$

e.g.

matrix elements we want to suppress

$$\eta_{ij} = \frac{f_{ij}}{f_{ii} - f_{jj}}, \ldots$$

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

$$= [\eta(s), H(s)]_{0B} + [\eta(s), H(s)]_{1B} + [\eta(s), H(s)]_{2B} + [\eta(s), H(\ldots_{B} + \ldots$$

For operators: $\dfrac{dO(s)}{ds} = [\eta(s), O(s)]$

IMSRG

IMSRG

Operators

$$\begin{cases} H(s) \\ \eta(s) \\ O(s) \end{cases}$$

IMSRG

Operators

$$H(s)$$

$$\eta(s)$$

$$O(s)$$

Flow Equations

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

$$\frac{dO}{ds} = [\eta, O]$$

PV-IMSRG flow

IMSRG → **PV-IMSRG**

Operators

$$H(s)$$

$$\eta(s)$$

$$O(s)$$

Flow Equations

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

$$\frac{dO}{ds} = [\eta, O]$$

PV-IMSRG flow

IMSRG

Operators

$$\begin{cases} H(s) \\ \eta(s) \\ O(s) \end{cases}$$

Flow Equations

$$\begin{cases} \dfrac{dH}{ds} = [\eta, H] \\ \dfrac{dO}{ds} = [\eta, O] \end{cases}$$

→

PV-IMSRG

$$H(s) = H_0(s) + \lambda V_{PV}(s)$$

$$\eta(s) = \eta_{pc}(s) + \lambda \eta_{pv}(s)$$

$$O(s) = O_{PC}(s) + O_{PV}(s)$$

PV-IMSRG flow

	IMSRG		**PV-IMSRG**
Operators	$H(s)$ $\eta(s)$ $O(s)$	→	$H(s) = H_0(s) + \lambda V_{PV}(s)$ $\eta(s) = \eta_{pc}(s) + \lambda \eta_{pv}(s)$ $O(s) = O_{PC}(s) + O_{PV}(s)$
Flow Equations	$\frac{dH}{ds} = [\eta, H]$ $\frac{dO}{ds} = [\eta, O]$		$\frac{dH_0}{ds} = [\eta_{PC}, H_0] + \lambda^2 [\eta_{PV}, V_{PV}]$ $\frac{dV_{PV}}{ds} = \lambda [\eta_{PC}, V_{PV}] + \lambda [\eta_{PV}, H_0]$ $\frac{dO_{PC}}{ds} = [\eta_{PC}, O_{PC}] + \lambda [\eta_{PV}, O_{PV}]$ $\frac{dO_{PV}}{ds} = [\eta_{PC}, O_{PV}] + \lambda [\eta_{PV}, O_{PC}]$

PV-IMSRG flow

Remarks:

- With no truncation, at any point in the flow: $\langle O \rangle = \langle O_{PC} \rangle + \langle O_{PV} \rangle$
- For a unitary flow $\langle O \rangle(s) = \langle O \rangle$ constant in the full model space
- At s=0 : $\langle O_{PC} \rangle = 0$ and $\langle O \rangle = \langle O_{PV} \rangle(0)$
- At s=∞: $\langle O_{PV} \rangle = 0$ and $\langle O \rangle = \langle O_{PC} \rangle(\infty)$

PV-IMSRG flow

Remarks:

- With no truncation, at any point in the flow: $\langle O \rangle = \langle O_{PC} \rangle + \langle O_{PV} \rangle$
- For a unitary flow $\langle O \rangle (s) = \langle O \rangle$ constant in the full model space
- At s=0 : $\langle O_{PC} \rangle = 0$ and $\langle O \rangle = \langle O_{PV} \rangle (0)$
- At s=∞: $\langle O_{PV} \rangle = 0$ and $\langle O \rangle = \langle O_{PC} \rangle (\infty)$

Pros:

- Only requires grounds state expectation value.
- No dependency on intermediate states.

PV-IMSRG flow

Remarks:

- With no truncation, at any point in the flow: $\langle O \rangle = \langle O_{PC} \rangle + \langle O_{PV} \rangle$
- For a unitary flow $\langle O \rangle(s) = \langle O \rangle$ constant in the full model space
- At s=0 : $\langle O_{PC} \rangle = 0$ and $\langle O \rangle = \langle O_{PV} \rangle(0)$
- At s=∞: $\langle O_{PV} \rangle = 0$ and $\langle O \rangle = \langle O_{PC} \rangle(\infty)$

Pros:

- Only requires grounds state expectation value.
- No dependency on intermediate states.

Cons:

- Requires 4x the amount of commutator evaluation.
- Extra flow is also truncated, possible truncation errors.

Results

Preservation of Unitarity

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

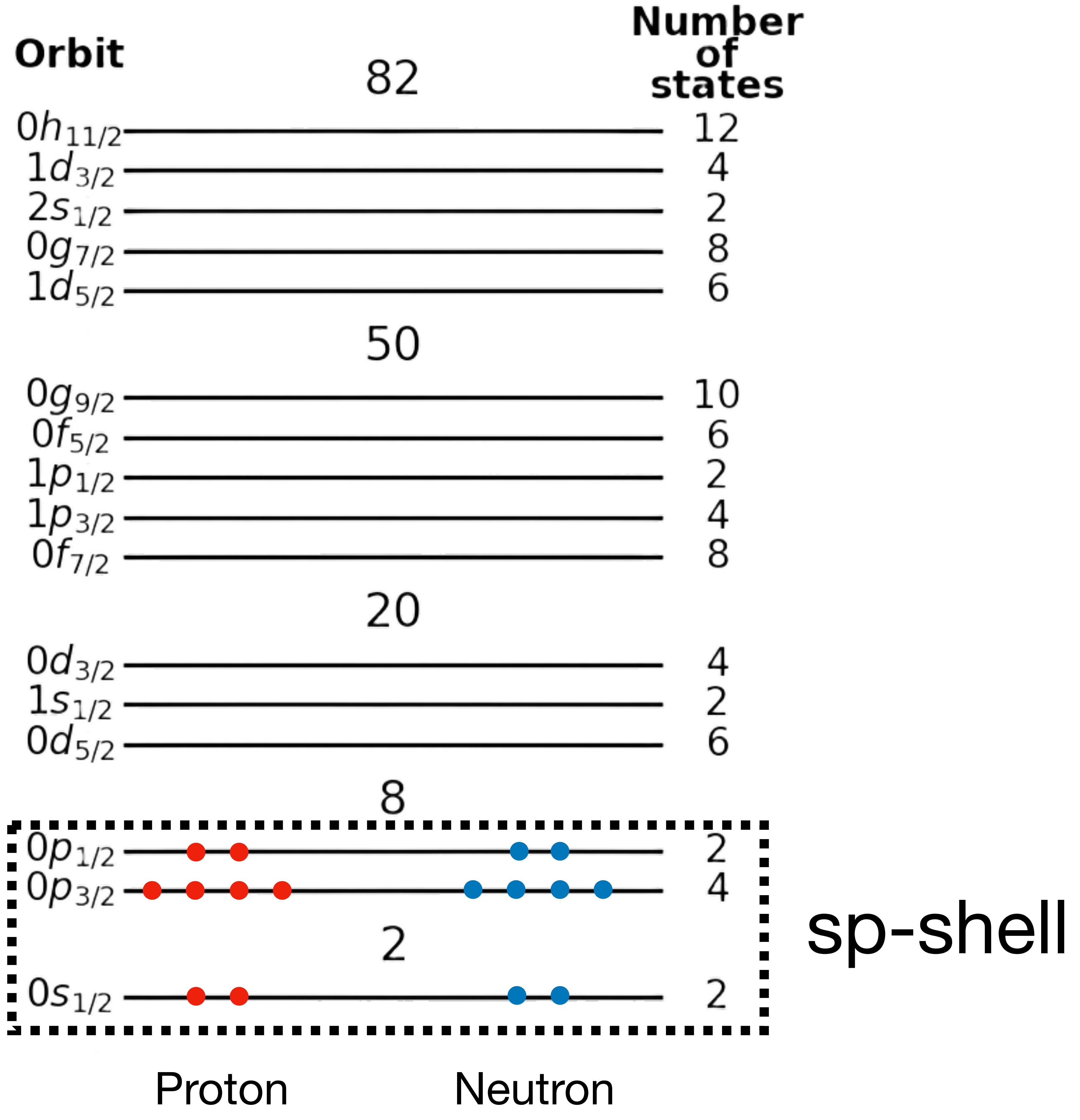
Preservation of Unitarity

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

Exact sum in full sp-shell, PV-IMSRG computed in s-shell valence space.

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

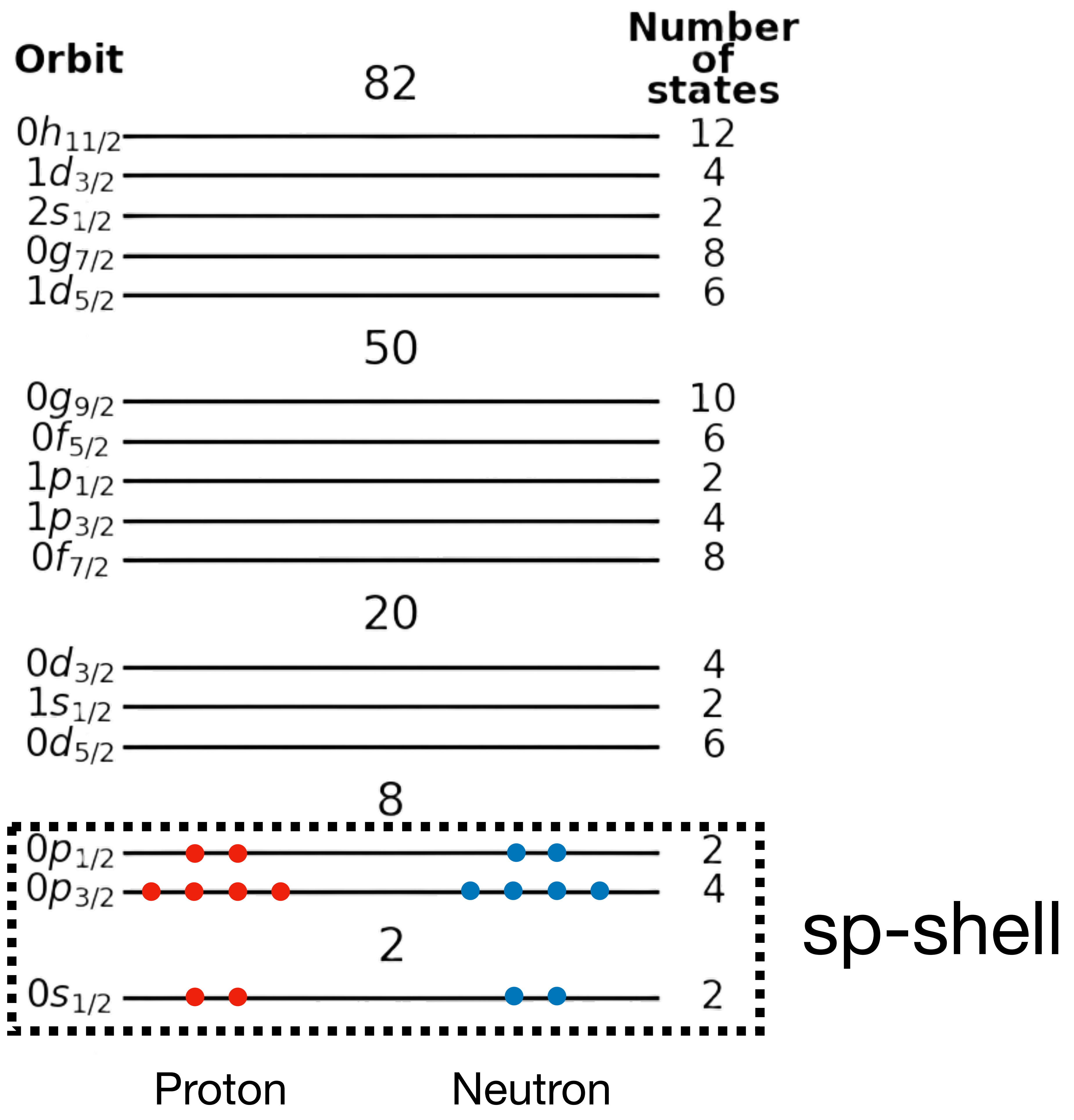
Exact sum in full sp-shell, PV-IMSRG computed in s-shell valence space.

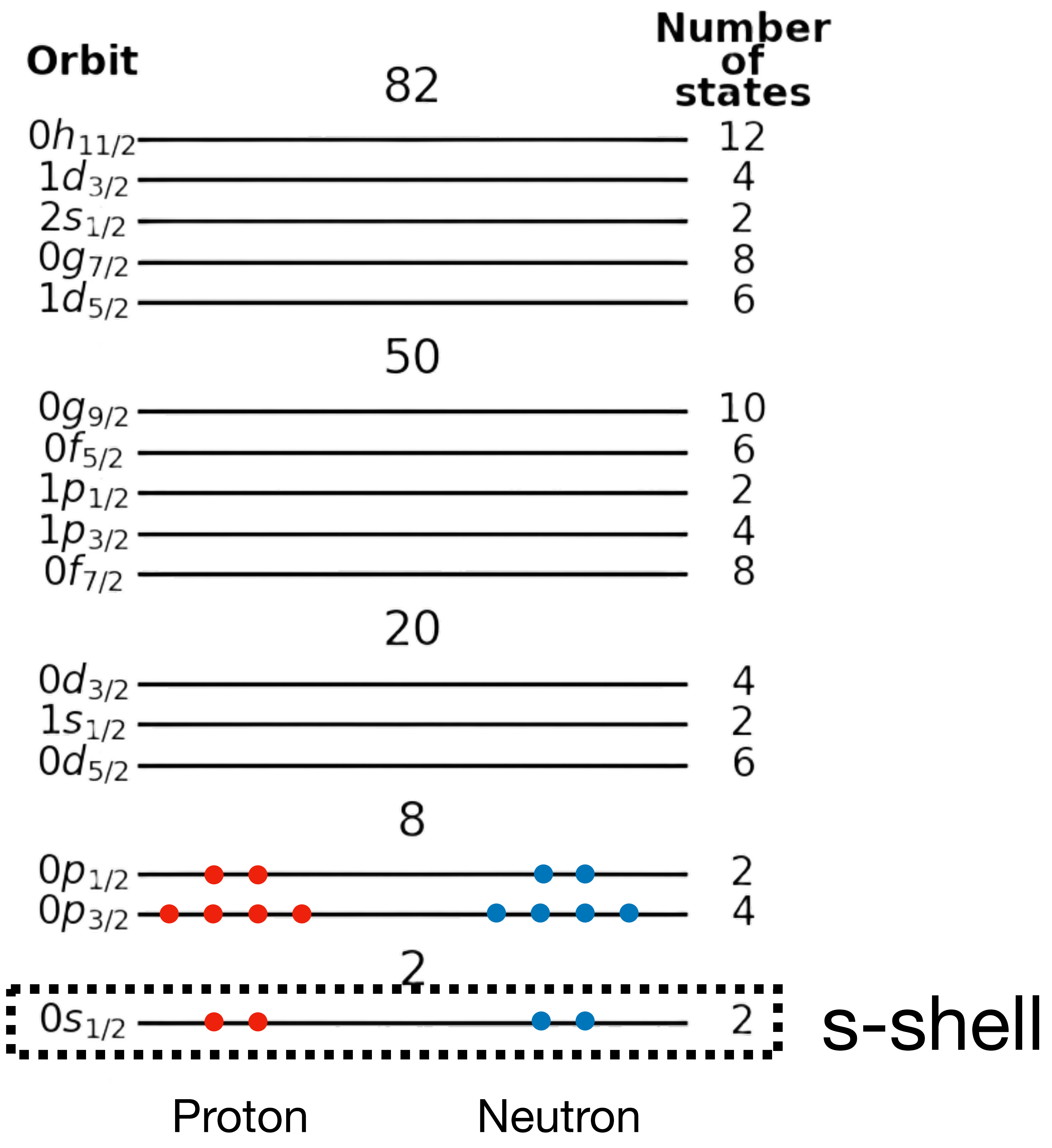


Preservation of Unitarity

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

Exact sum in full sp-shell, PV-IMSRG computed in s-shell valence space.

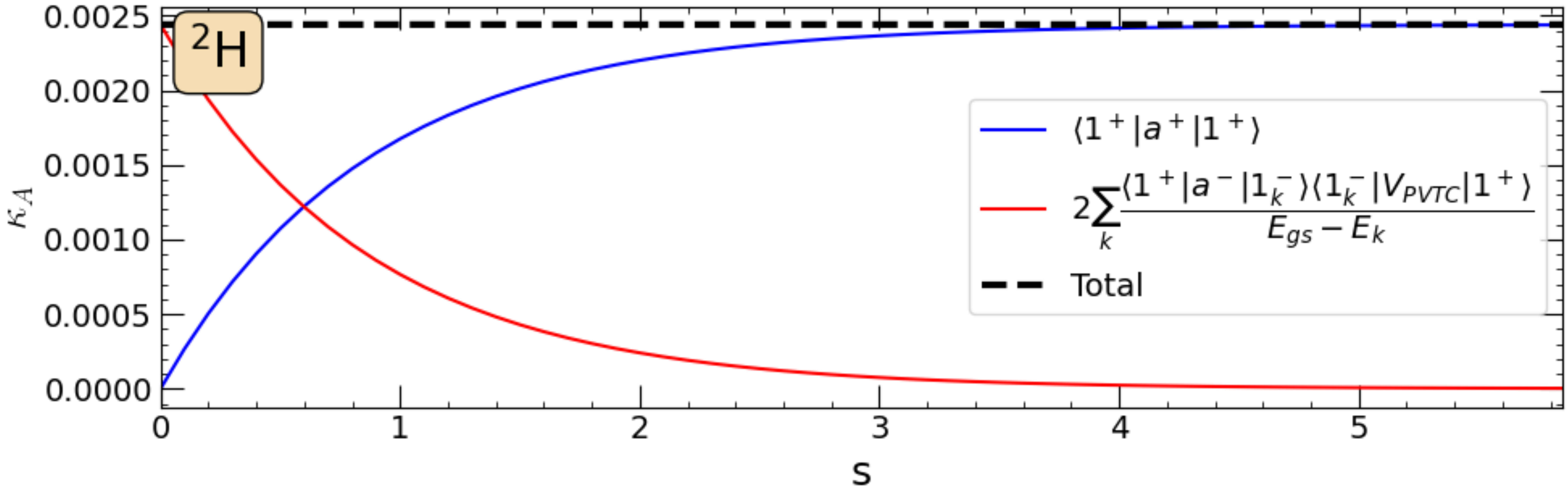




Preservation of Unitarity

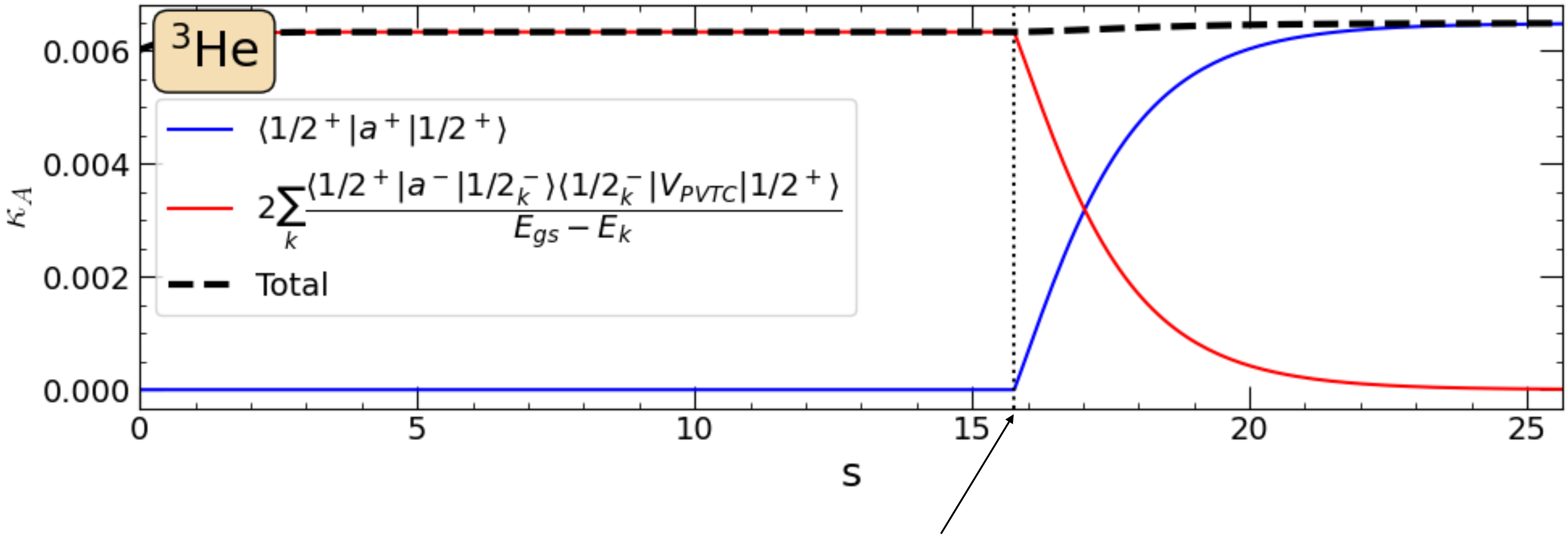
Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

Exact sum in full sp-shell, PV-IMSRG computed in s-shell valence space.



Preservation of Unitarity

To avoid cost of the PV-IMSRG, we can first decouple the PC Hamiltonian before doing the PV-IMSRG.



Beginning of PV-IMSRG

Going to the p-shell

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

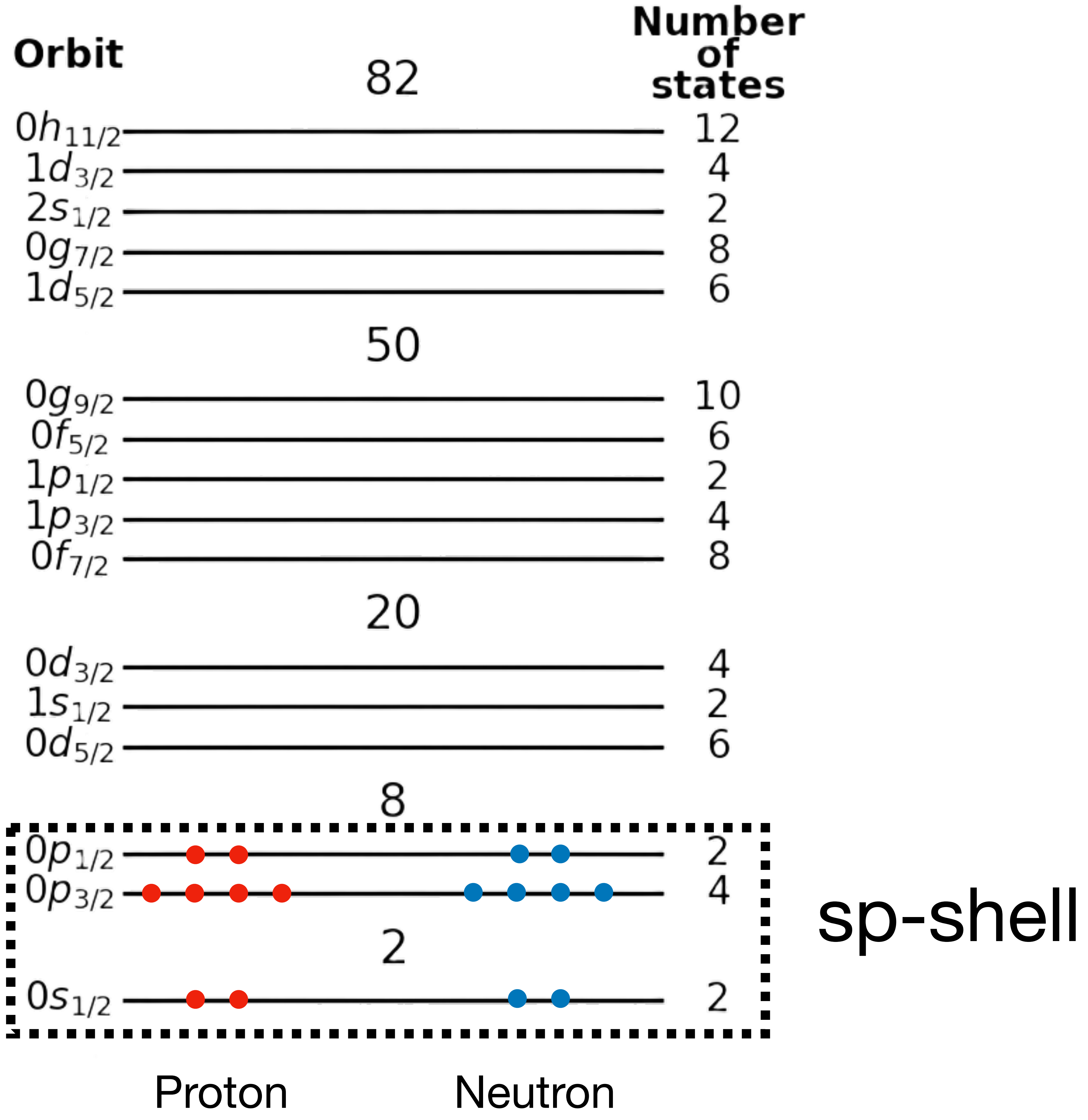
Going to the p-shell

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

Exact sum in full sp-shell, PV-IMSRG computed in p-shell valence space.

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

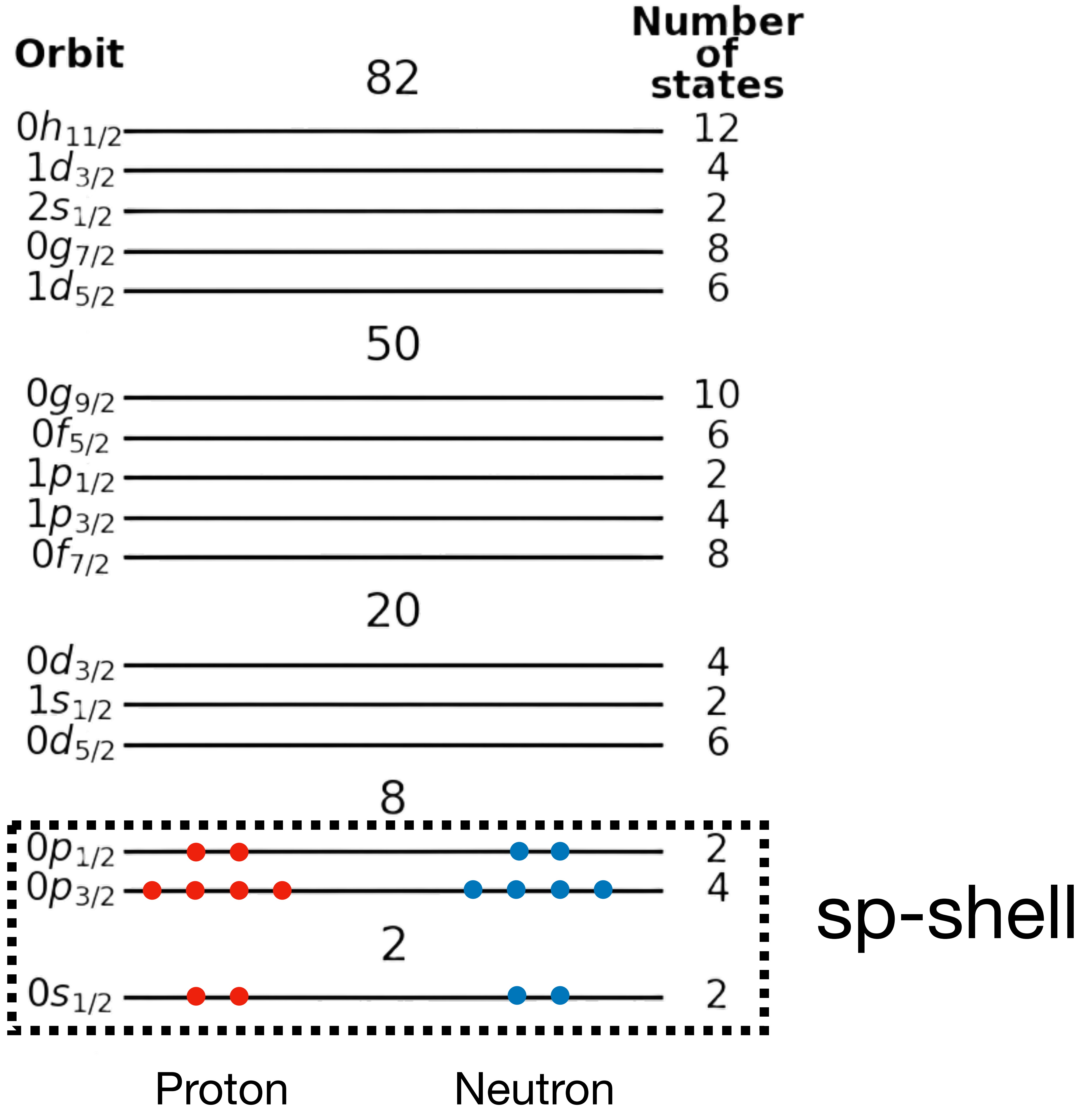
Exact sum in full sp-shell, PV-IMSRG computed in p-shell valence space.

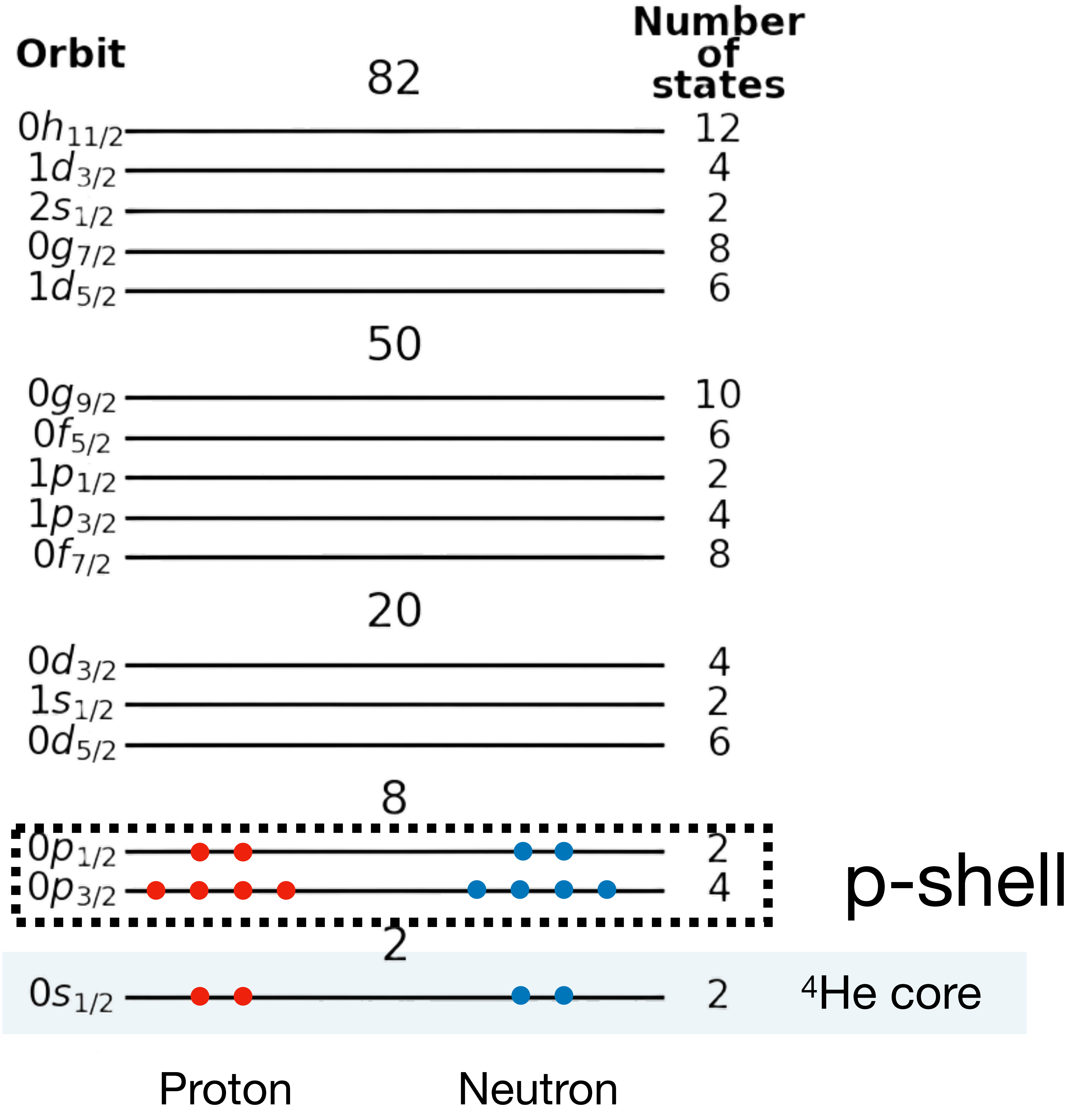


Going to the p-shell

Exact sum and PV-IMSRG results in small model space (e_{max} = 1, all orbit in sp-shell).

Exact sum in full sp-shell, PV-IMSRG computed in p-shell valence space.

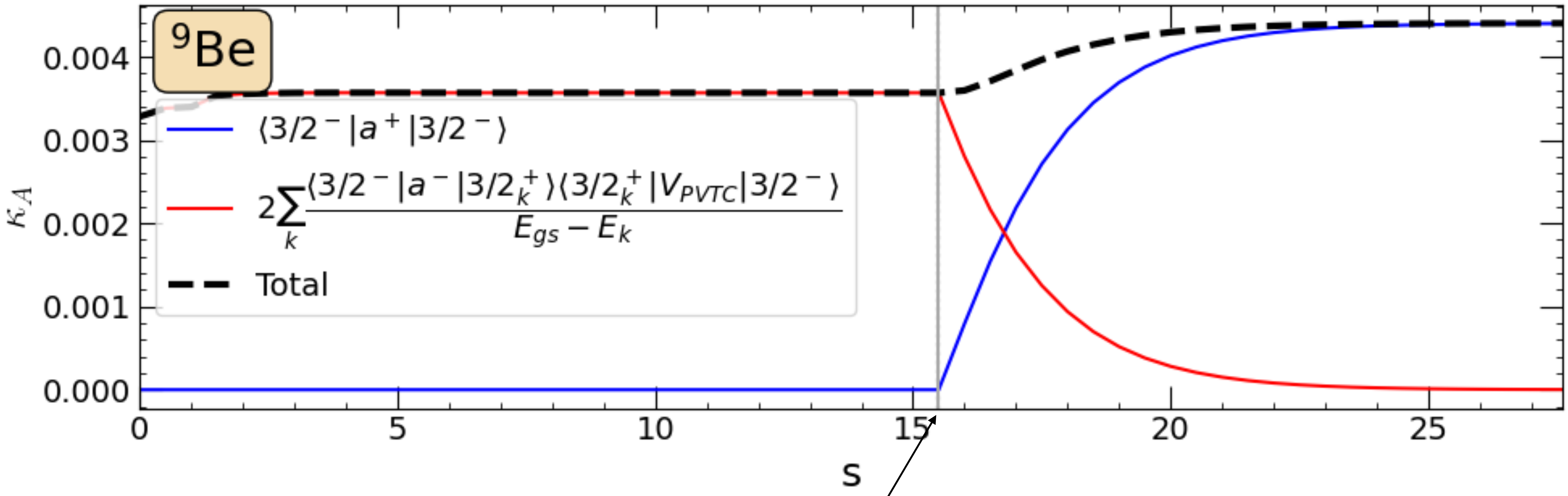




Preservation of Unitarity

First decouple the core and then the valence-space.

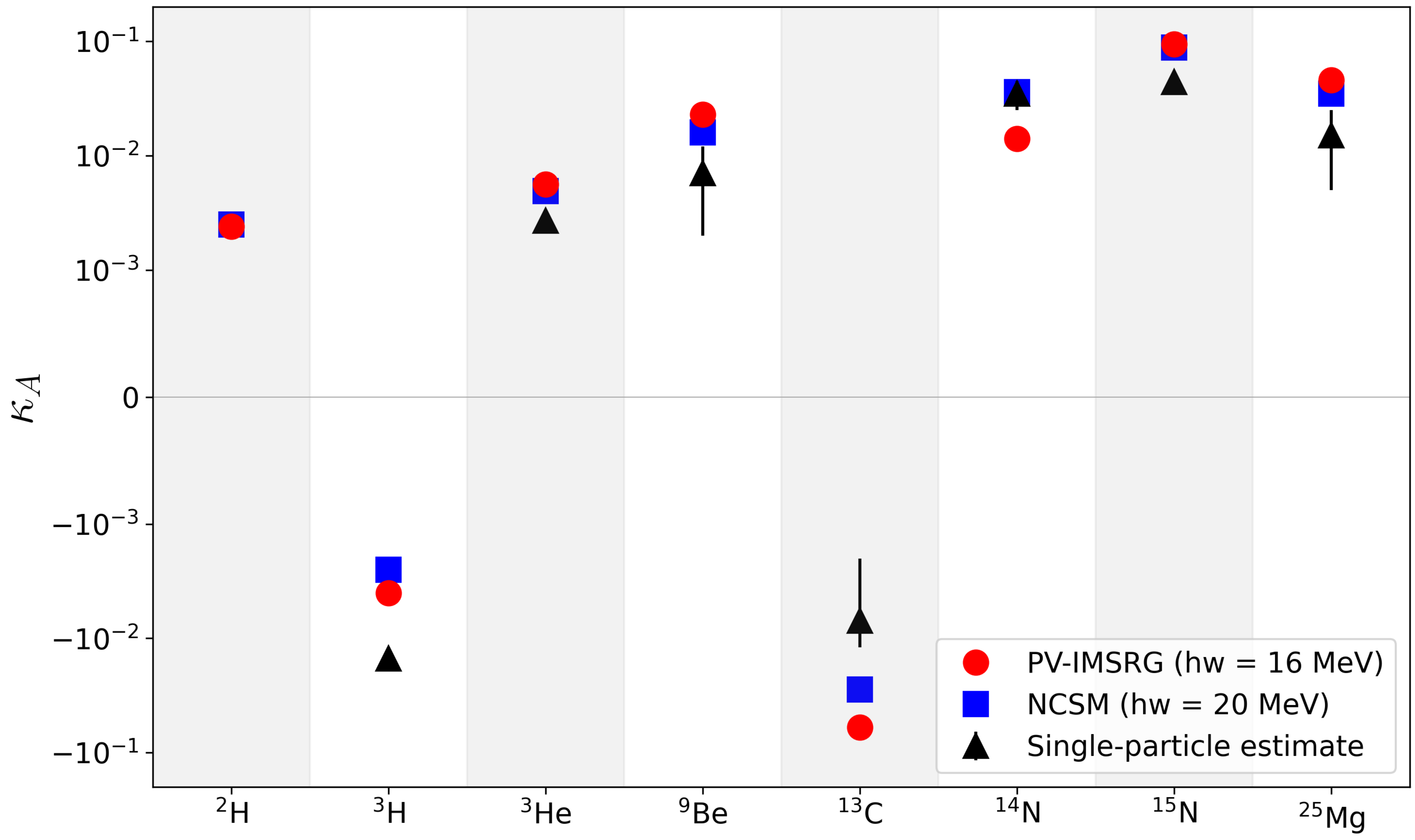
Get error of about 25% due to truncation errors.



Start of valence-space decoupling

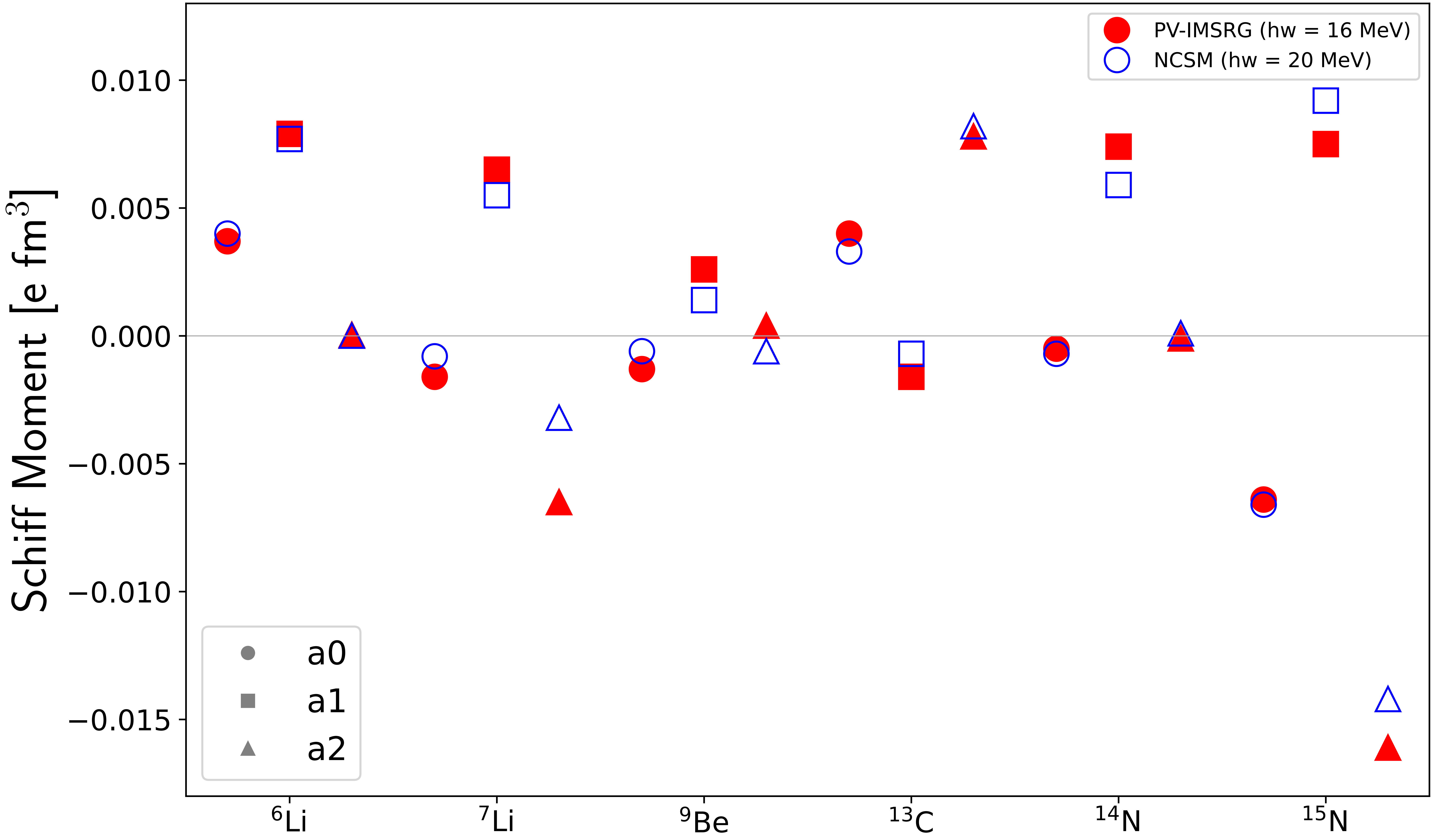
Benchmark with NCSM

Anapole Moments



Schiff Moments

Work from Beatriz Romeo



Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

… and Outlook

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

… and Outlook

- Apply PV-IMSRG for isotopes of experimental interests.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

… and Outlook

- Apply PV-IMSRG for isotopes of experimental interests.
- Do a more systematic study of uncertainty in the calculation (e.g. different nuclear interactions, variation of PV-forces, etc.).

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

… and Outlook

- Apply PV-IMSRG for isotopes of experimental interests.
- Do a more systematic study of uncertainty in the calculation (e.g. different nuclear interactions, variation of PV-forces, etc.).
- Get better understanding on truncation errors and their possible importance in heavier nuclei.

Thank you!

Summary …

- PV IMSRG is a new many-body method for parity-violating observables.
- Parity conserving operator is induced.
- Allows to bypass computation of parity-violating excited states.
- Initial test in small model-spaces show that unitarity is roughly conserved.
- Initial benchmark with NCSM show encouraging agreement in light nuclei.

… and Outlook

- Apply PV-IMSRG for isotopes of experimental interests.
- Do a more systematic study of uncertainty in the calculation (e.g. different nuclear interactions, variation of PV-forces, etc.).
- Get better understanding on truncation errors and their possible importance in heavier nuclei.

Thank you!