Nuclear Physics

Lattice QCD and Effective Field Theories

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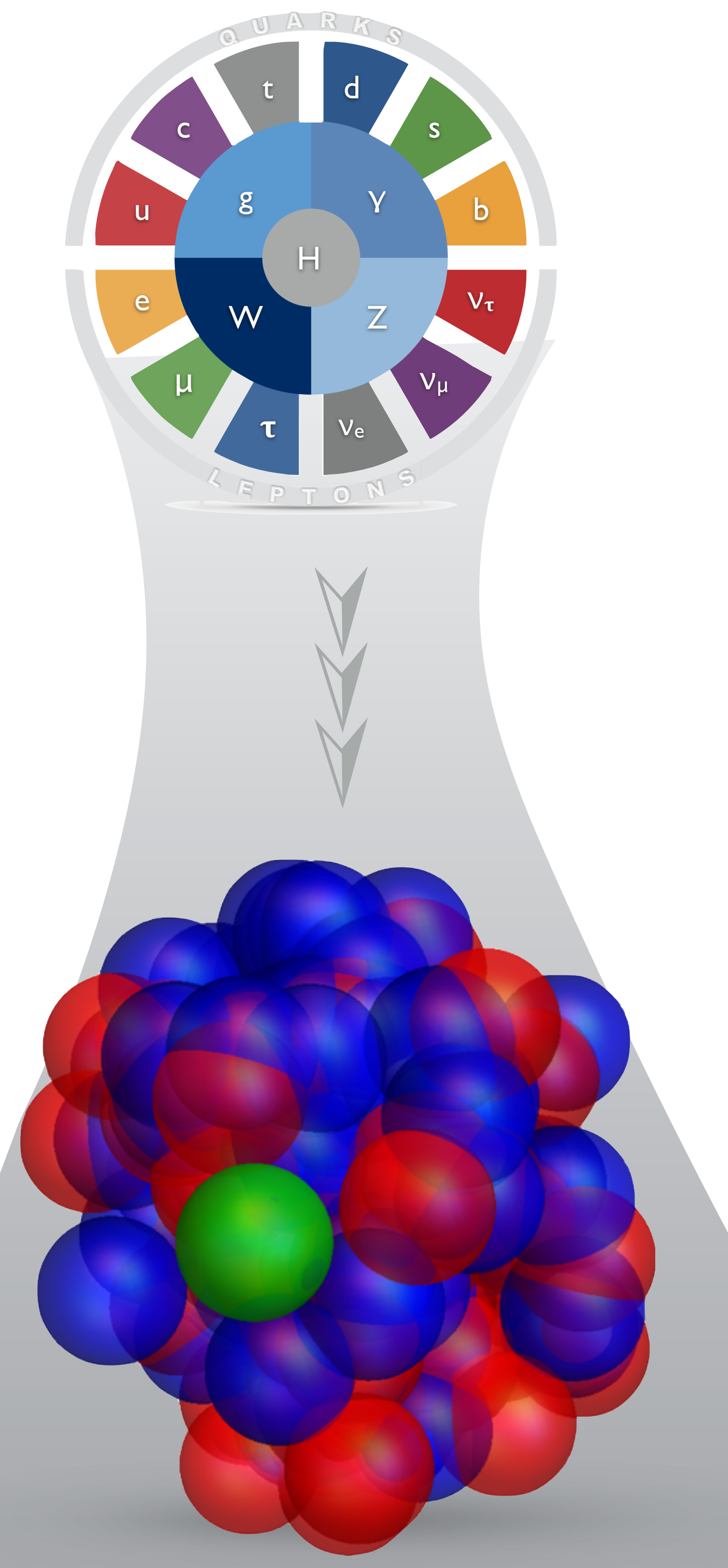
Nuclear physics:

- Nuclear physics is 105 years old!
  - Emergence of complexity in matter
- Physics at many scales
  - Hadron structure & interactions
  - Nuclei and nuclear structure
  - Neutron stars, supernovae, nucleosynthesis,…
- NP has been a data driven field
  - Many beautiful experimental results
  - Traditional understanding *very* phenomenological

Nuclear physics

- NP emerges from the Standard Model
- Present: LQCD calculations have begun to show how
  - Still quite limited in scope and fidelity
- Future
  - LQCD + EFT will enable precision nuclear physics
  - Explore nuclear physics more generally
    - Parameter dependence: fine tunings?
    - Complex structure in other gauge theories, …



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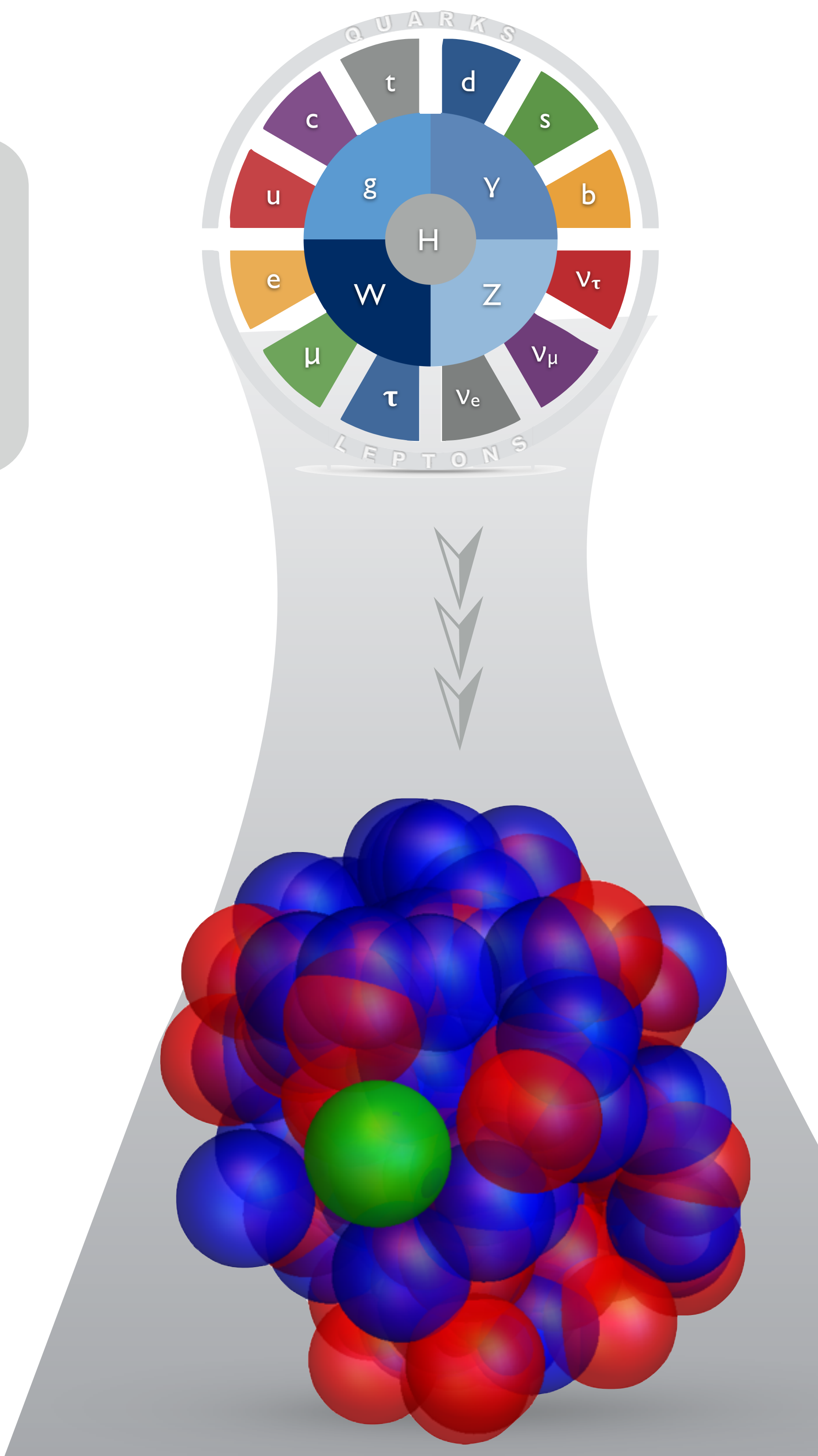

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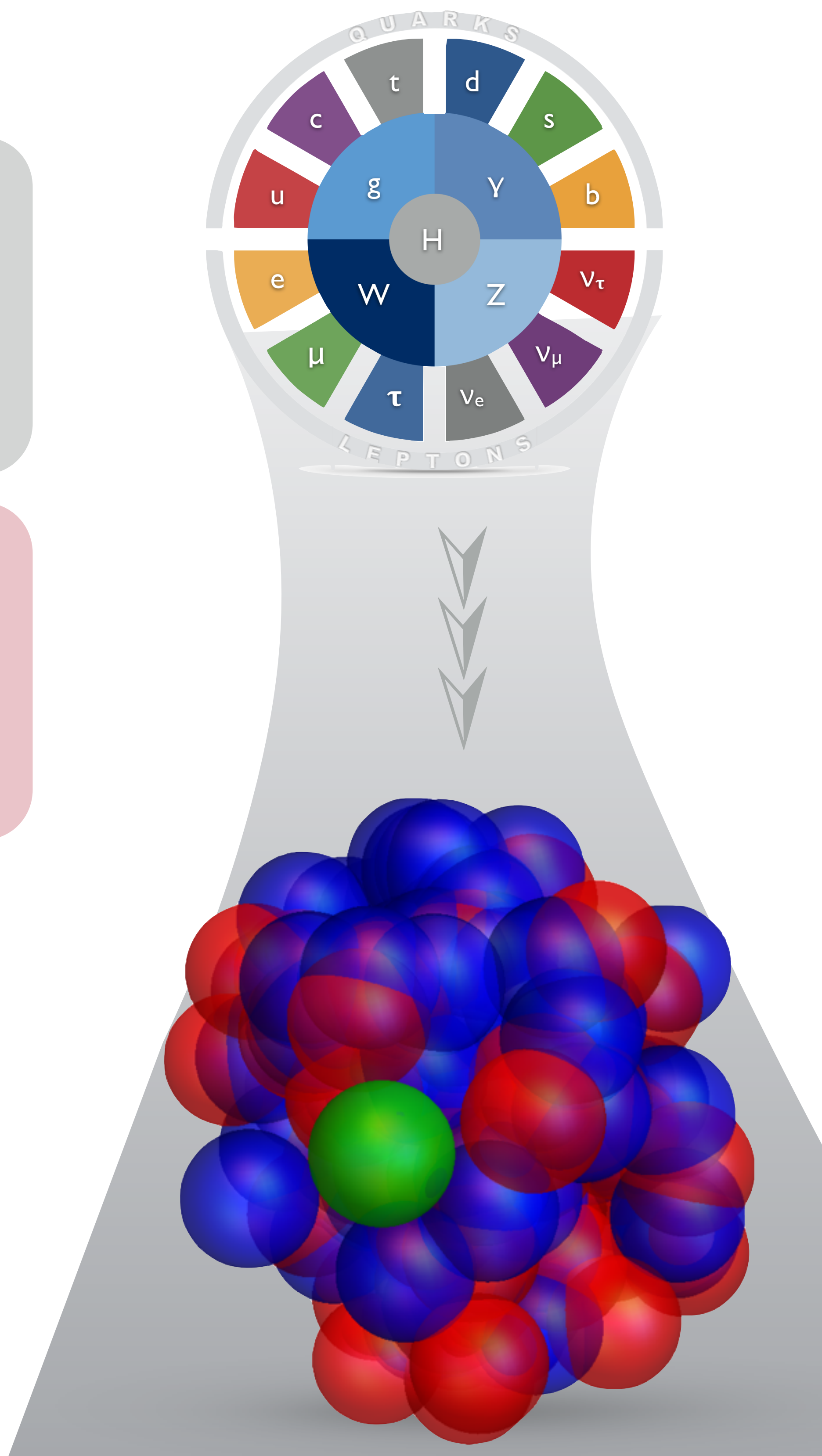

Nuclear Physics Tools

Lattice QCD and Effective Field THeory

Lattice QCD and EFT for nuclear physics

- LGT & EFT critical components
- New problems for LQCD for many-body systems
  - Contractions, excitation spectra, statistical noise
  - Develop new technologies for multi-nucleon systems
- New problems for EFT for many-body systems
  - Standard LQCD extrapolations: quark masses, volumes, continuum limit
  - Additional extrapolation: A>4…8: *Nuclear EFT*

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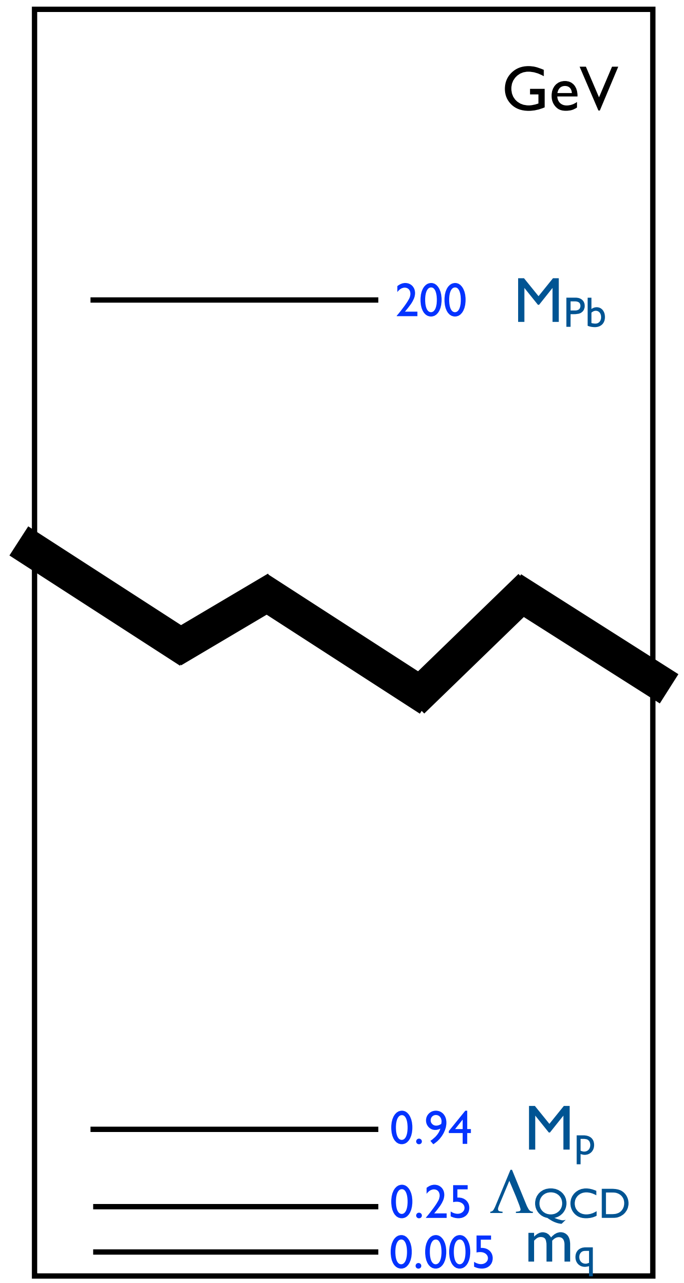
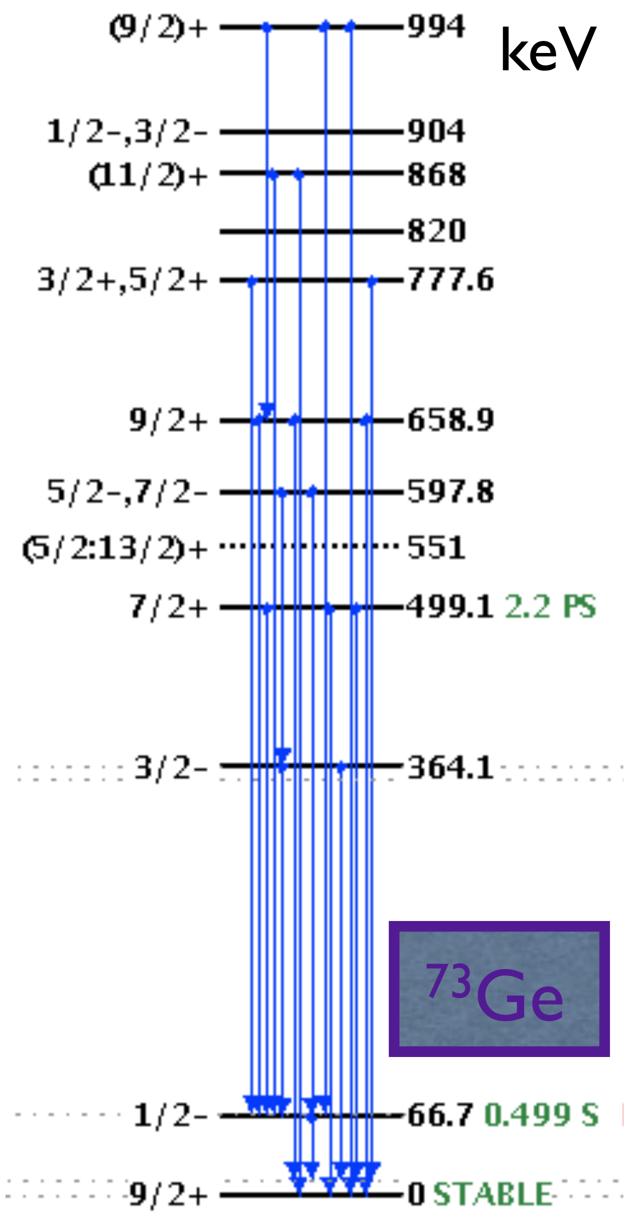
- Physics at multiple scales

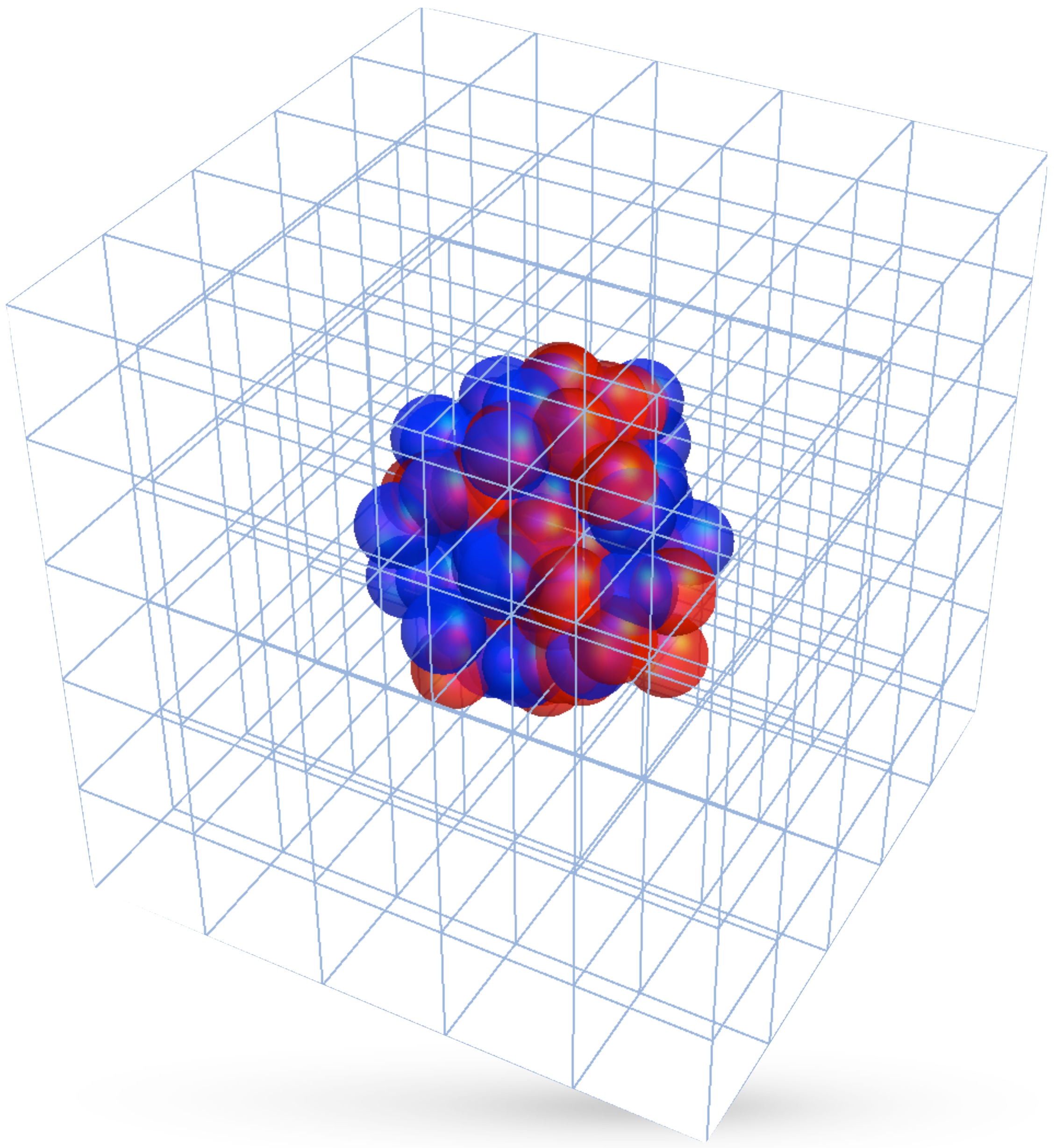


QCD for Nuclear Physics

- Nuclei in LQCD are a hard
- Physics at multiple scales

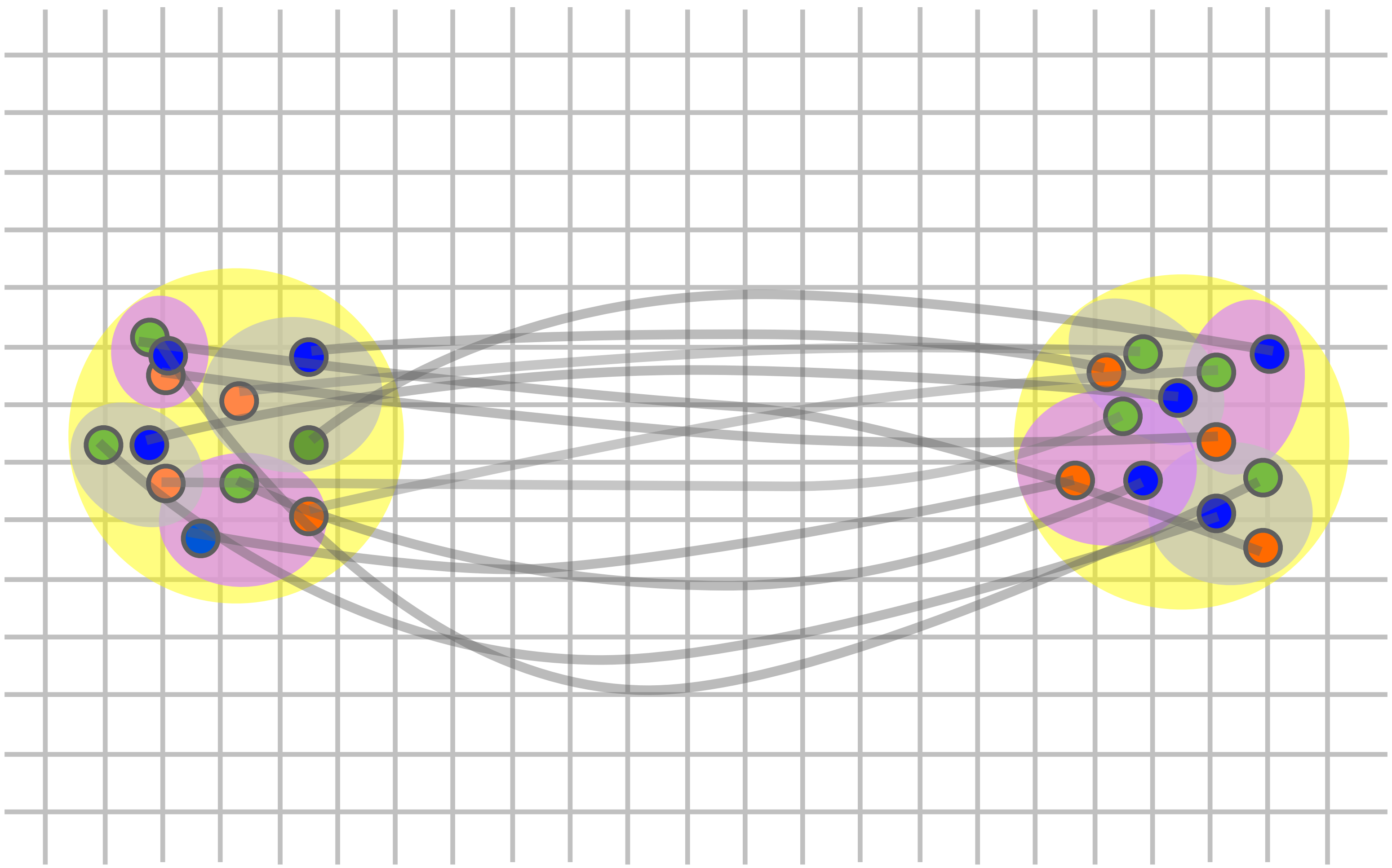


- Nuclei in LQCD are a hard
- Physics at multiple scales
- Three exponentially difficult challenges for LQCD
  - Spectral density
  - Contraction complexity grows factorially
  - Noise: probabilistic method so statistical uncertainty grows exponentially with A (naively)



QCD for Nuclear Physics

- Quarks need to be tied together in all possible ways
  - $N_{\text{contractions}} = N_u! N_d! N_s!$ (~10^{1500} for ^{208}Pb)



- Managed using algorithmic trickery [WD & Savage, WD & Orginos; Doi & Endres, Günther et al]
  - Study up to N=72 pion systems, A=5 (and 28) nuclei

Nuclear Effective Field Theory

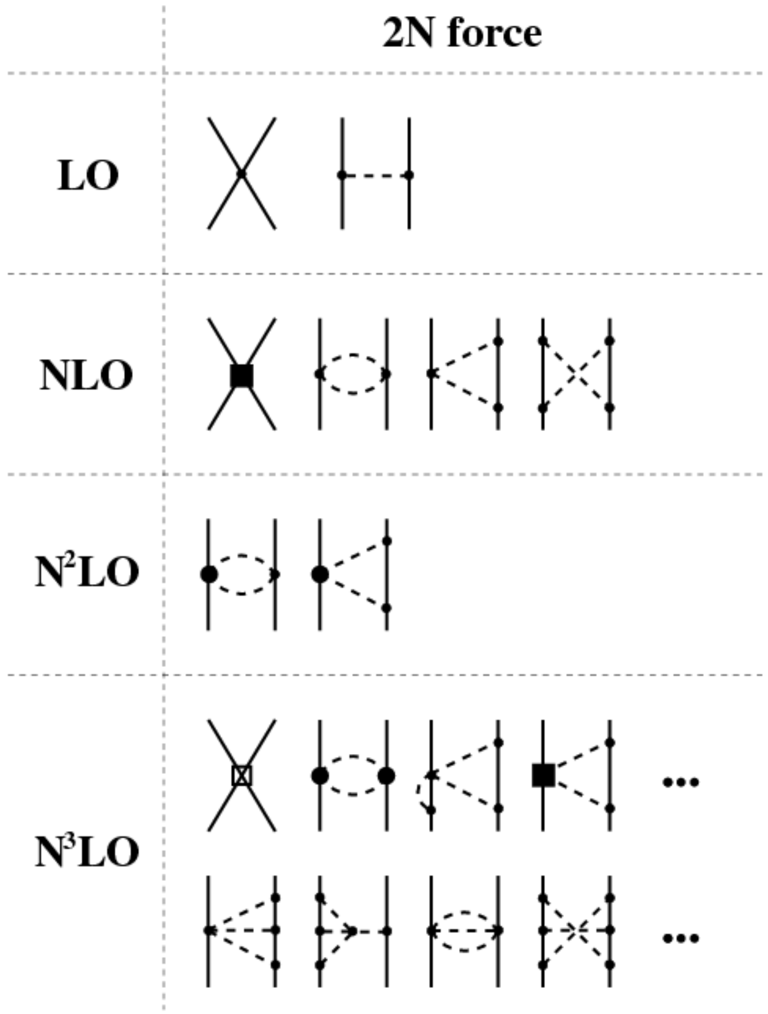
- Theory of nucleon-nucleon interactions based on underlying symmetries of QCD
  - Non-trivial EFT as there are very shallow bound states

$$a_{(^1S_0)} \sim -20 \text{ fm} \qquad a_{(^3S_1)} \sim 5.4 \text{ fm}$$

- Weinberg [1992] chiral NEFT
  - Degrees of freedom: nucleons + pions
  - All terms consistent with symmetries with new LECs at every order
  - Expansion in powers of momenta and quark masses

Nuclear EFT

- Pursued to high orders in expansion: contribution to NN potential @ N^3LO



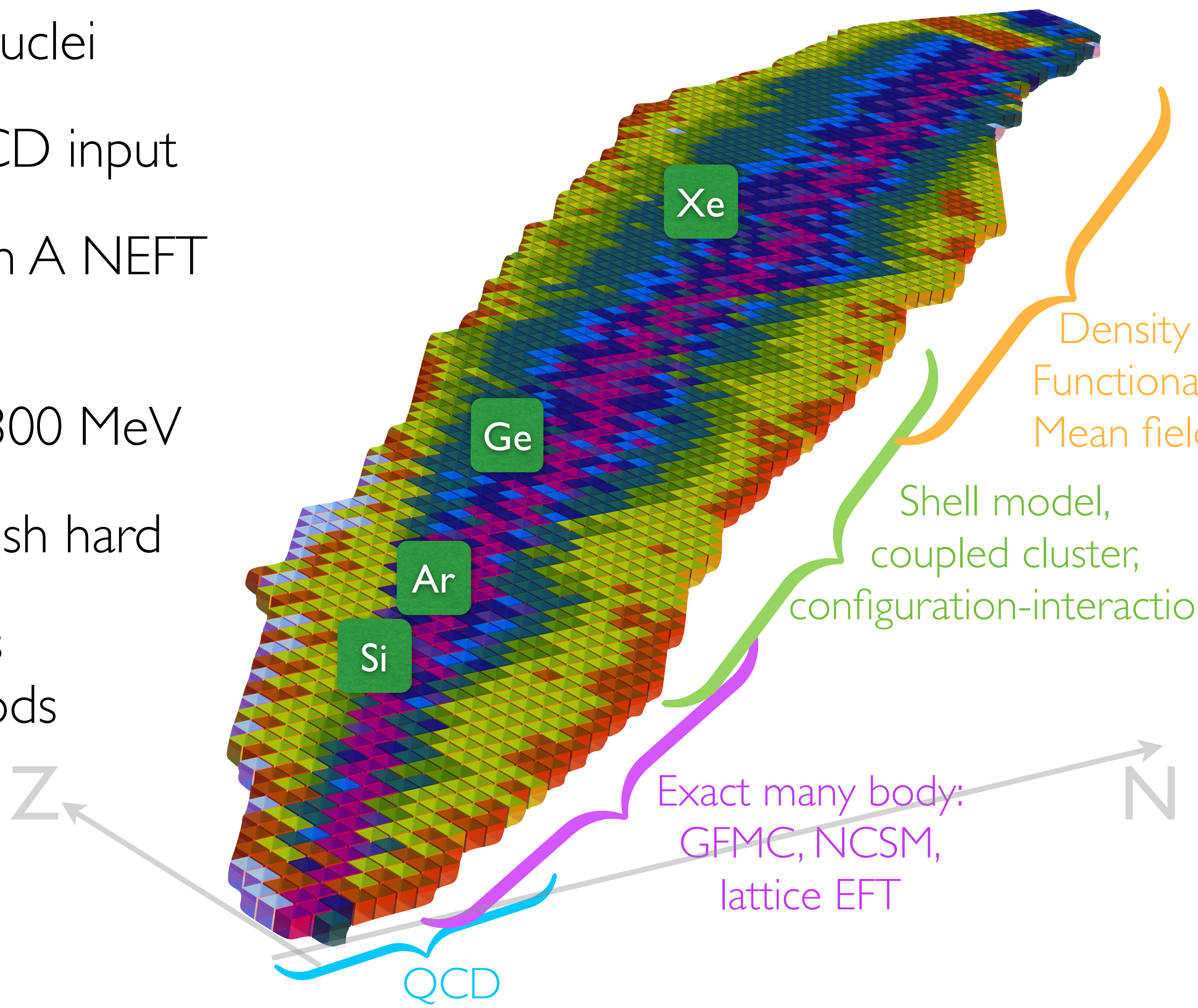
- Solve many body problem with NEFT Hamiltonian
  - Many methods used here (some exact, some approximate)

Nuclear EFT

- Alternate power-counting schemes [eg Kaplan, Savage, Wise 1996/7, …]: chiral expansion of amplitudes and resum certain types of contributions
  - Analytic control of mass dependence
  - Order-by-order renormalisable (Weinberg power-counting is not)
  - Convergence issues in some channels
- Many subsequent developments …

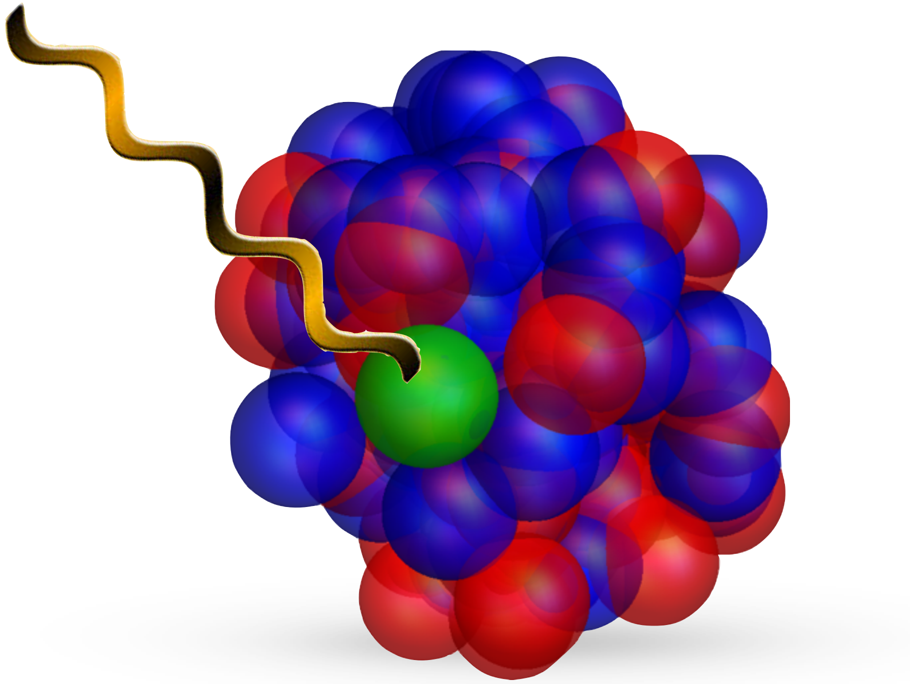
Nuclear EFT

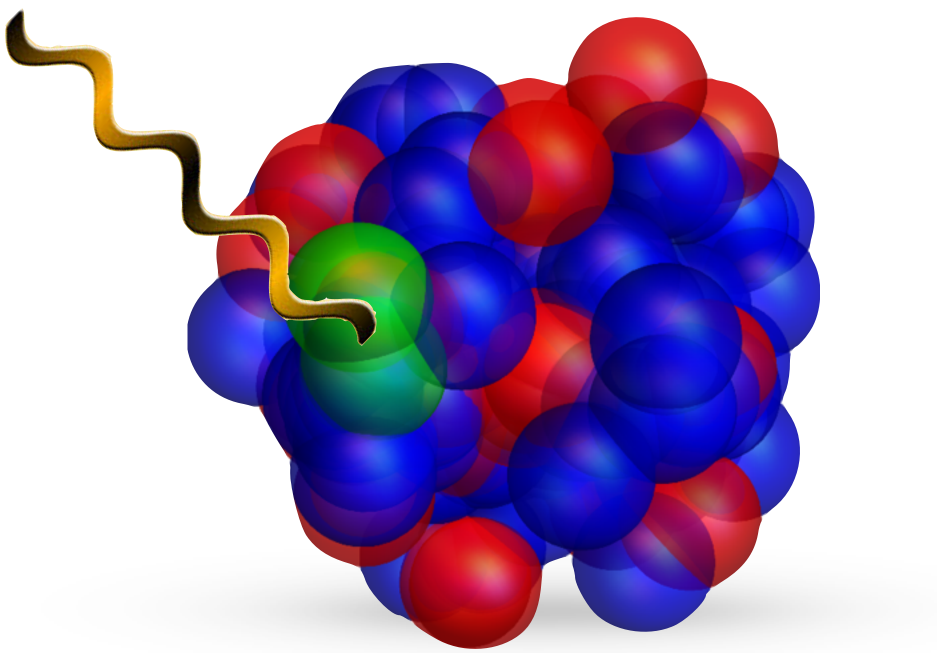
- Quantitative control throughout chart of nuclides
- Exact methods for light nuclei
  - Match NEFT onto QCD input
- Open question how far in A NEFT remains controlled
  - Fermi momentum ~ 300 MeV
  - Some practitioners push hard
- Use EFT to constrain less robust many-body methods



Nuclear EFT currents

- NEFT: controlled way to include external currents (EW, scalar,…)
- Power counting
  - 1-body currents are dominant
  - 2-body currents are sub-leading *but non-negligible*
- Match NEFT to LQCD
  - Determine one body contributions from single nucleon
  - Determine few-body contributions from A=2,3,4...
  - Use NEFT to predict larger nuclei





Pionless EFT

- For very low energy processes, $q \ll m_\pi$, even pions can be integrated out: pionless EFT
  - Expansion in terms of contact nucleon operators and derivatives

$$\mathcal{L} = N^\dagger \left(i\partial_0 + \frac{\nabla^2}{2m} + \cdots \right) N - C_{0t}(N^\dagger P_t N)^2 - C_{0s}(N^\dagger P_s N)^2 + \cdots$$

  - (Works even better at heavy pion masses!)
  - Light quark mass dependence in counterterms
  - Equivalent to the effective range expansion of energies
    Consistently incorporates currents

Present

Unphysical nuclei

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- NPLQCD collaboration
- Case study QCD with
  $m_u = m_d = m_s^{\mathrm{phys}}$

$$\Rightarrow \quad \begin{aligned} m_\pi &\sim 800\ \mathrm{MeV} \\ m_p &\sim 1{,}600\ \mathrm{MeV} \end{aligned}$$

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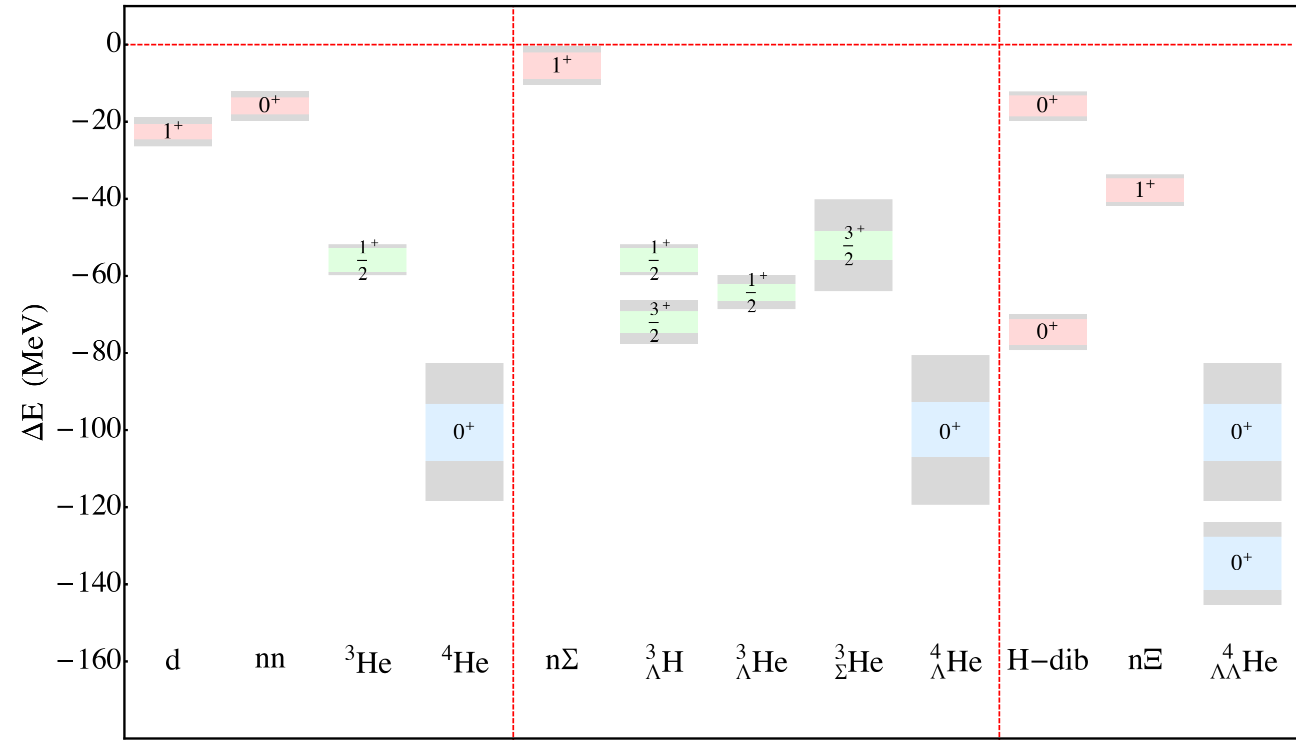
1. Spectrum of light nuclei (A<5)
   [PRD **87** (2013), 034506]



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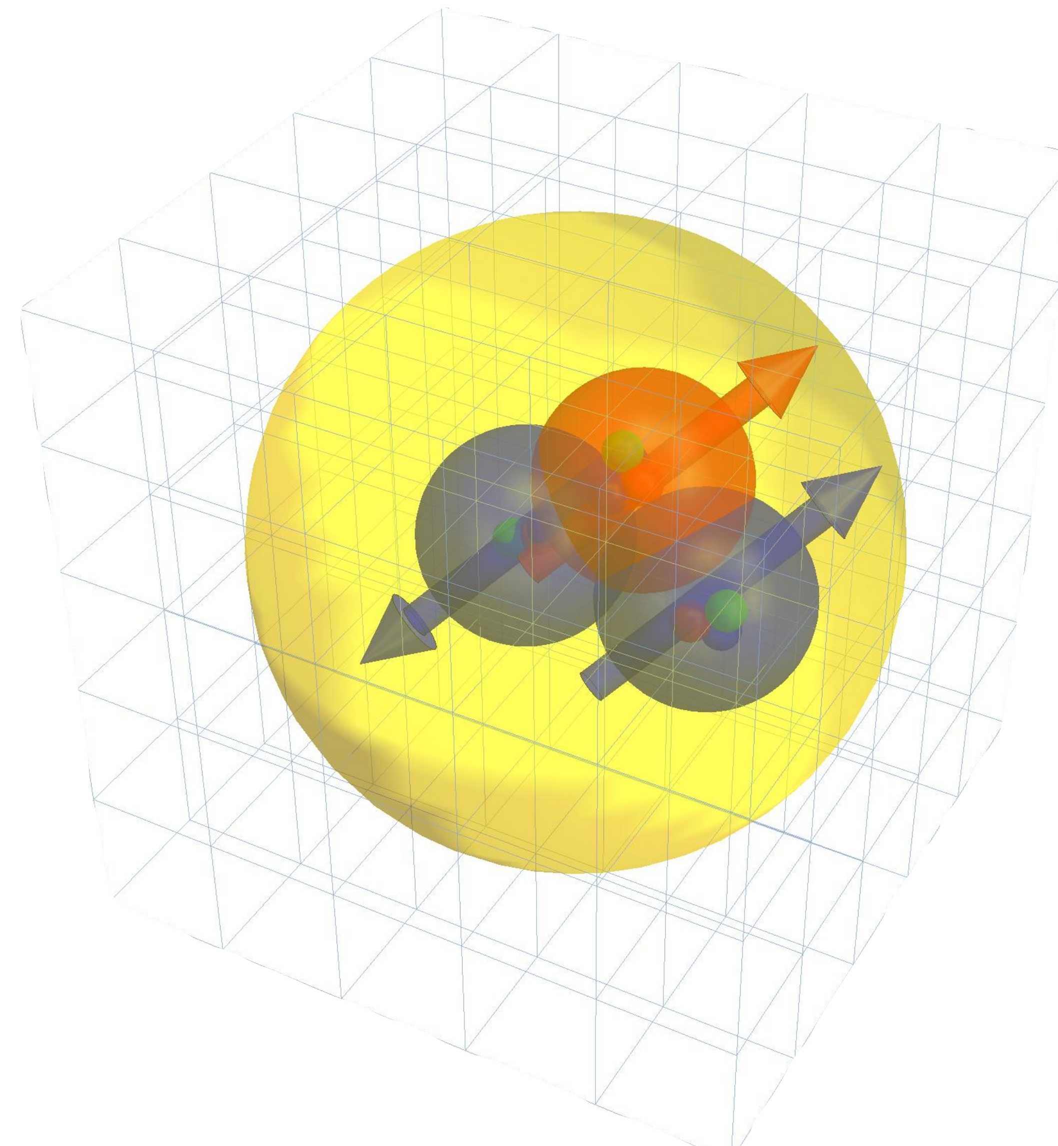
   [PRL **113**, 252001 (2014)]



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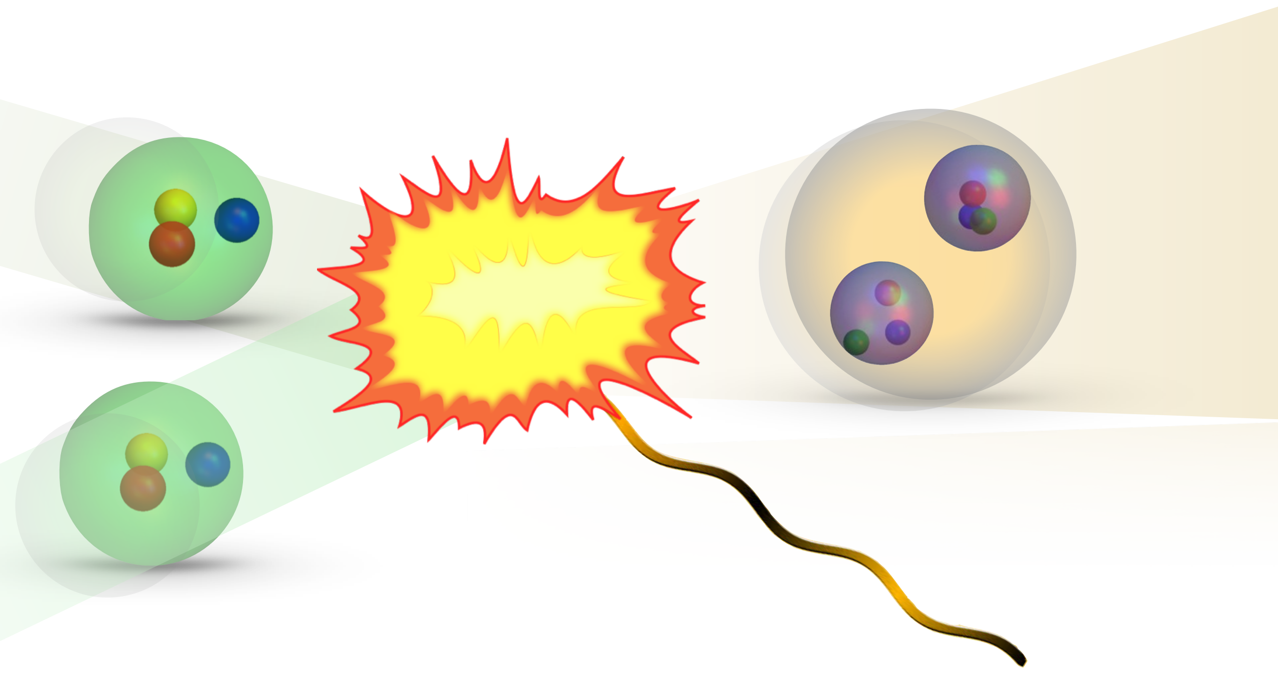
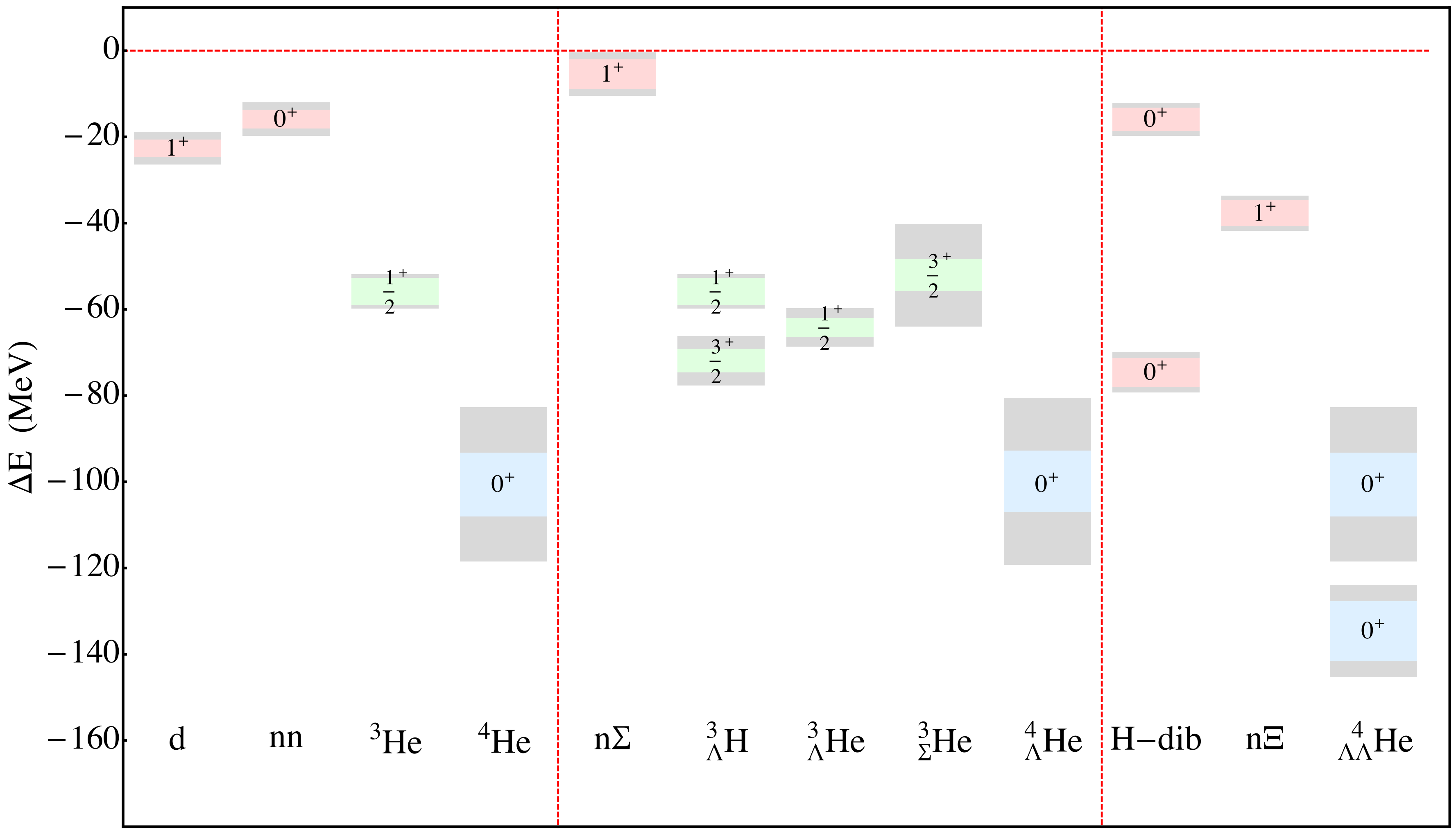
4. Nuclear reactions: np→dγ
   [PRL **115**, 132001 (2015)]



Light nuclei

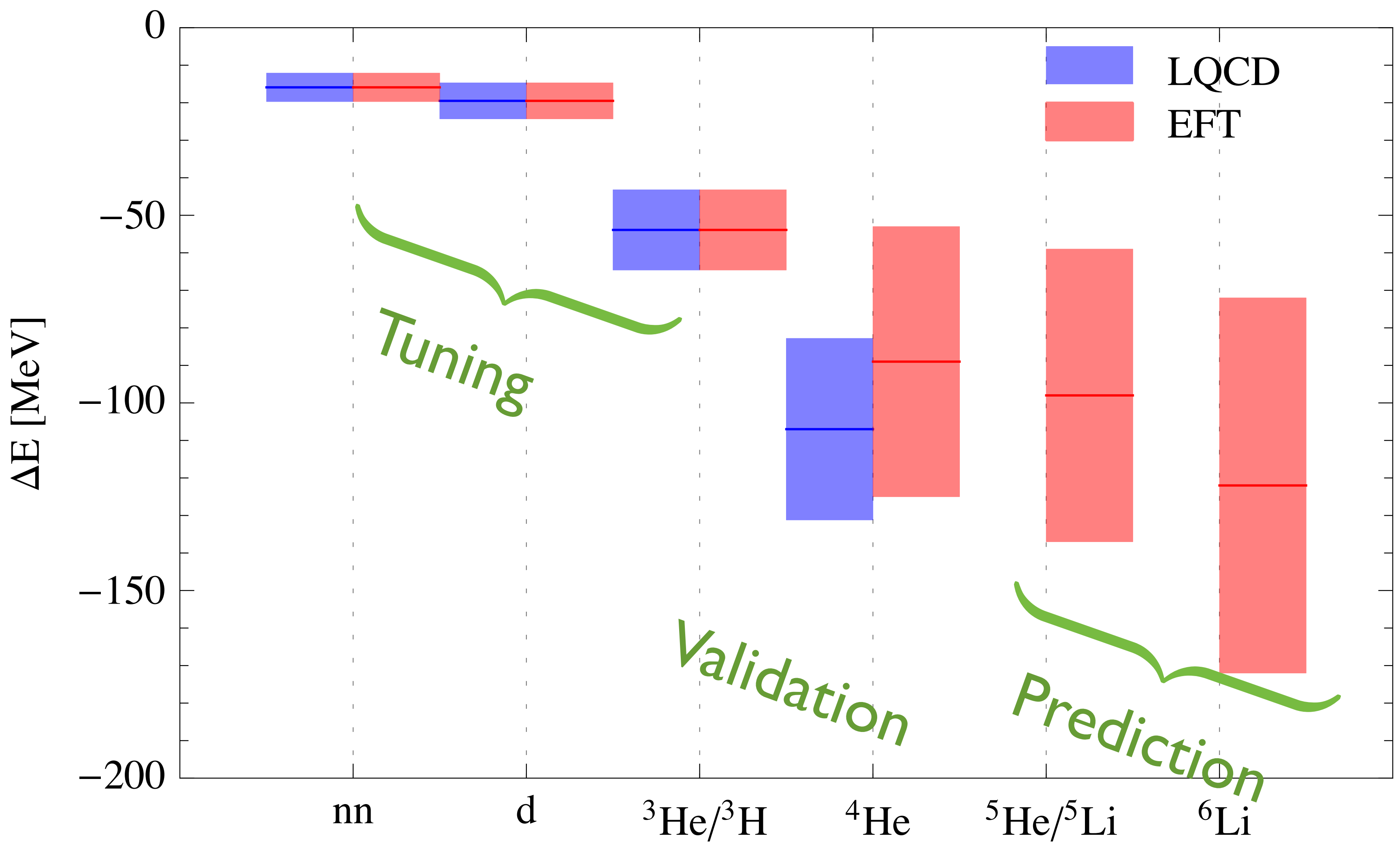
- Light hypernuclear binding energies @ m_π=800 MeV



- More states bound; deeper bindings;

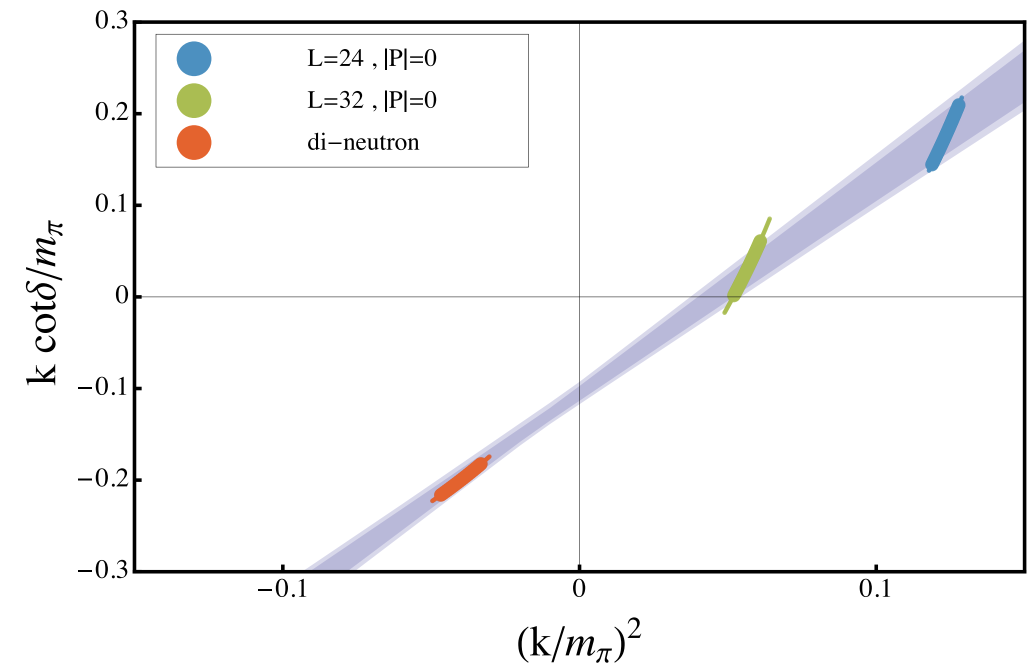
[NPLQCD PRD **87** (2013), 034506]

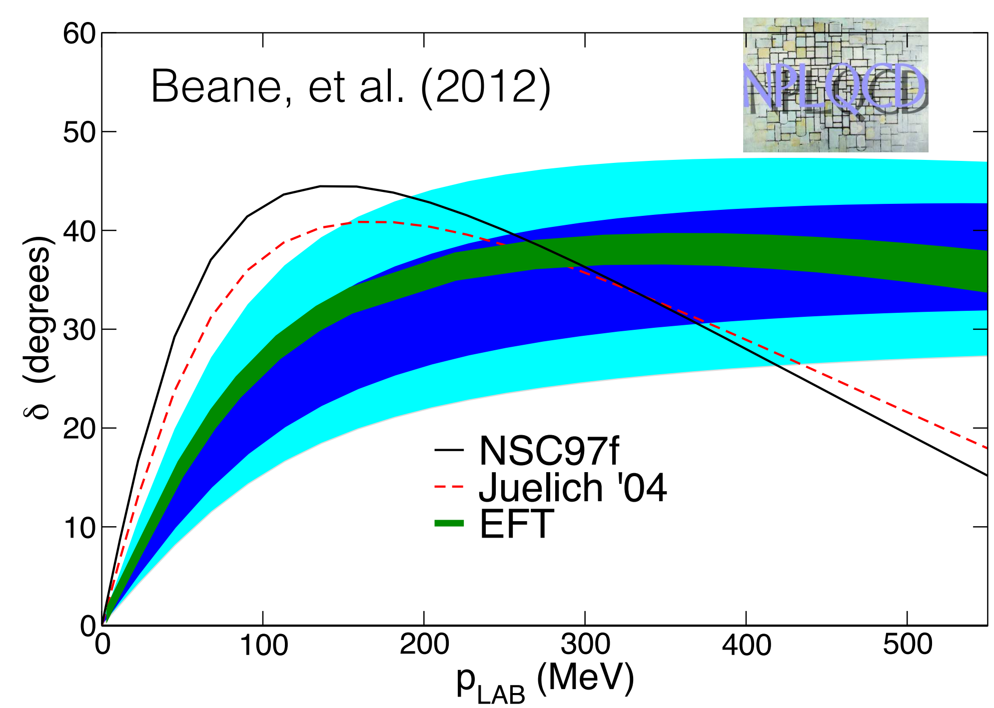
- Combining LQCD and pionless EFT [Barnea et al, PRL 2015]



- More detailed matchings possible (FV spectrum,…)

- Scattering phase shift extracted through Lüscher method
  - Two particle energies in finite volume depend on scattering information
- NEFT: extrapolate phase shifts to physical masses
  - Hyperon-nucleon interactions [Beane et al. PRL 2012]
- Determine NEFT LECs and use to predict ℓ=2 deuteron interaction from ℓ=0





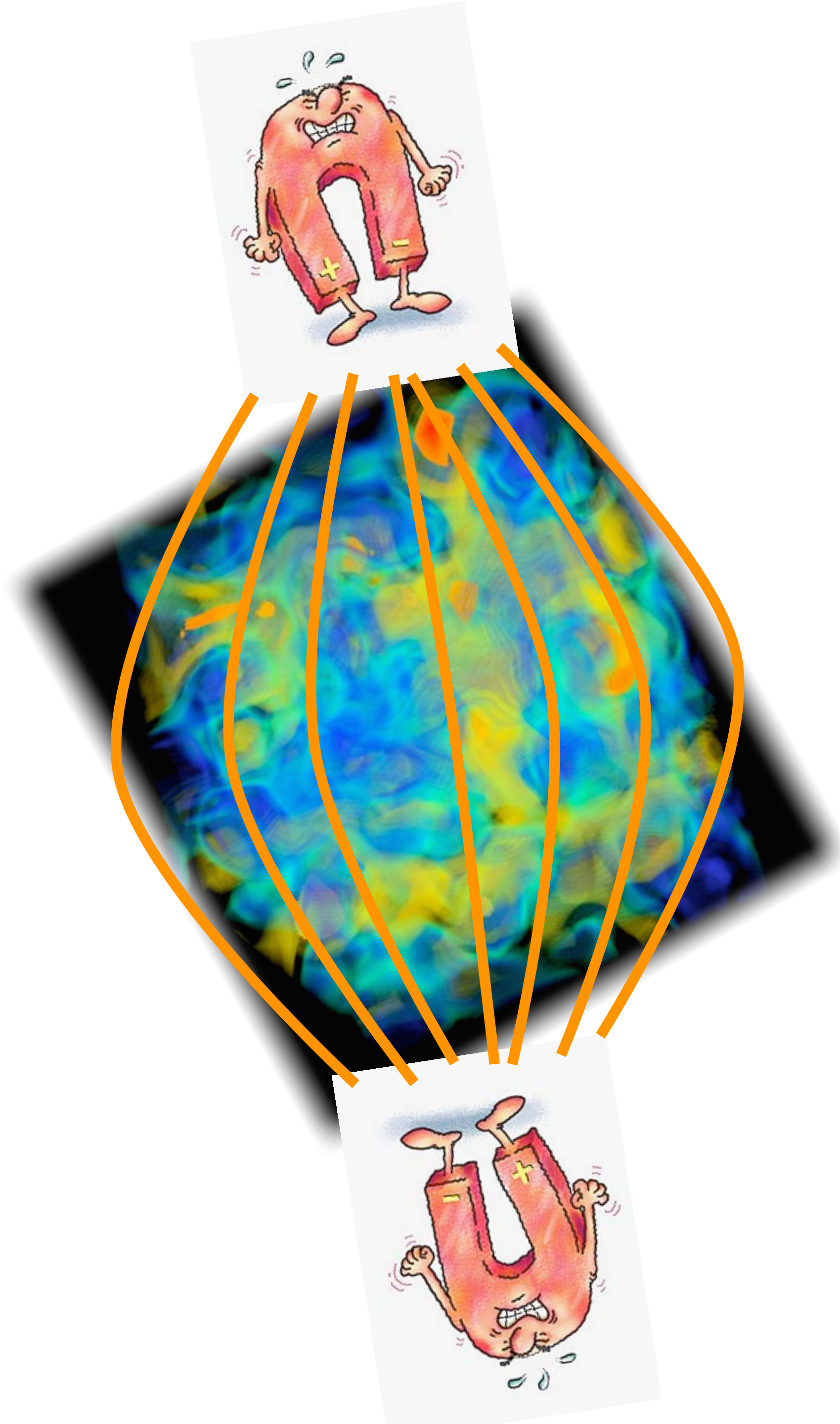
[NPLQCD 1508.07583]

Magnetic moments

- Hadron/nuclear energies are modified by presence of fixed external fields
- Eg: fixed B field

$$E_{h;j_z}(\mathbf{B}) \;=\; \sqrt{M_h^2 + (2n+1)|Q_h eB|} - \boldsymbol{\mu}_h \cdot \mathbf{B} \\ - 2\pi\beta_h^{(M0)}|\mathbf{B}|^2 - 2\pi\beta_h^{(M2)}\langle \hat{T}_{ij} B_i B_j \rangle + \ldots$$

- QCD calculations with multiple fields enable extraction of coefficients of response
  - Eg: magnetic moments, polarisabilities, …
  - Not restricted to simple EM fields (axial, twist-2,…)



[NPLQCD PRL **113**, 252001 (2014)]

Magnetic moments of nuclei

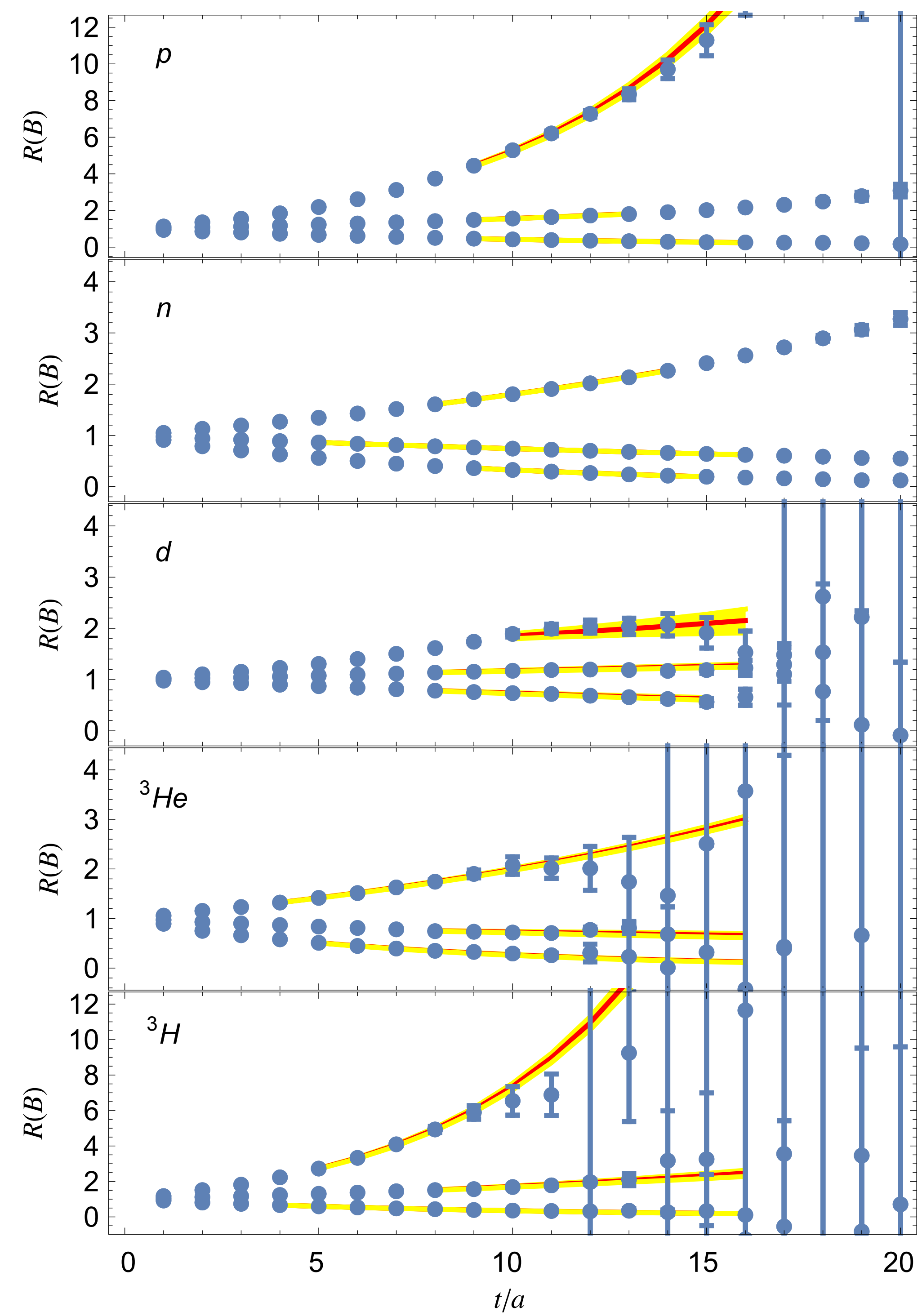
- Magnetic field in *z*-direction (strength quantised by lattice periodicity)
- Magnetic moments from spin splittings

$$\delta E^{(B)} \equiv E^{(B)}_{+j} - E^{(B)}_{-j} = -2\mu|\mathbf{B}| + \gamma|\mathbf{B}|^3 + \ldots$$

- Extract splittings from ratios of correlation functions

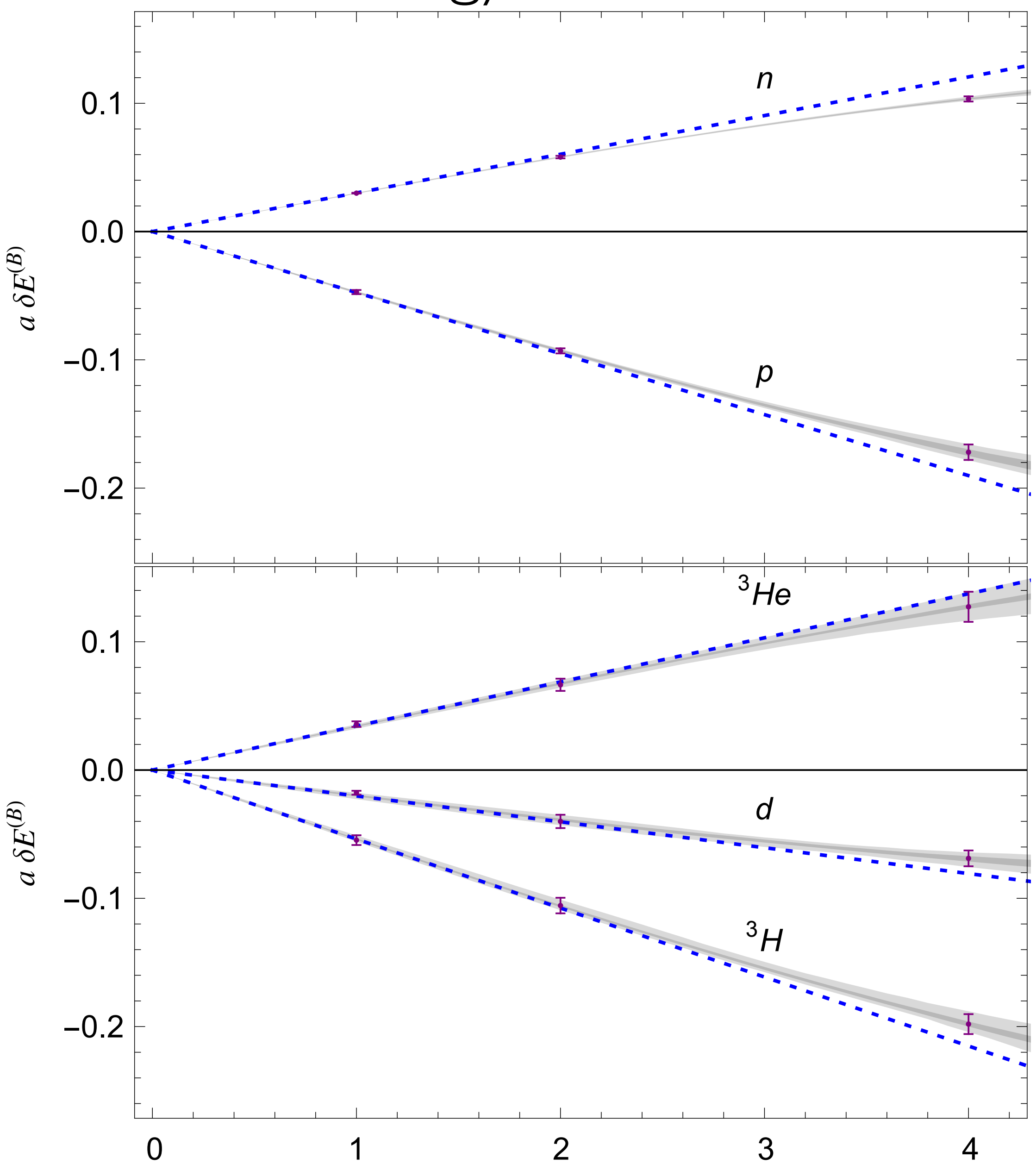
$$R(B) = \frac{C^{(B)}_{j}(t)\; C^{(0)}_{-j}(t)}{C^{(B)}_{-j}(t)\; C^{(0)}_{j}(t)} \overset{t\to\infty}{\longrightarrow} Z e^{-\delta E^{(B)} t}$$

- Careful to be in single exponential region of each correlator



[NPLQCD PRL **113**, 252001 (2014)]

Energy shift vs B



e |**B**|

[NPLQCD PRL **113**, 252001 (2014)]

Magnetic moments of nuclei

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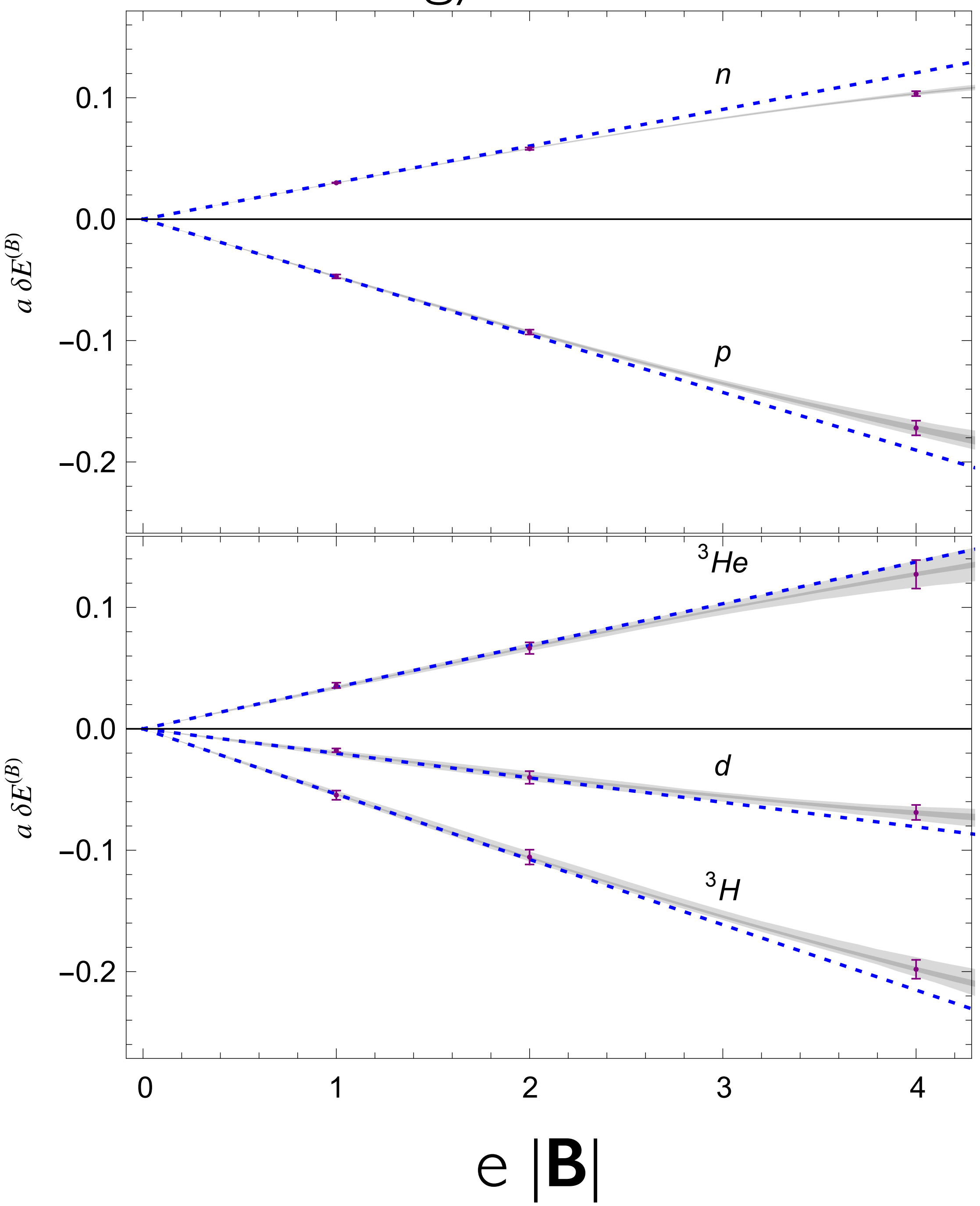
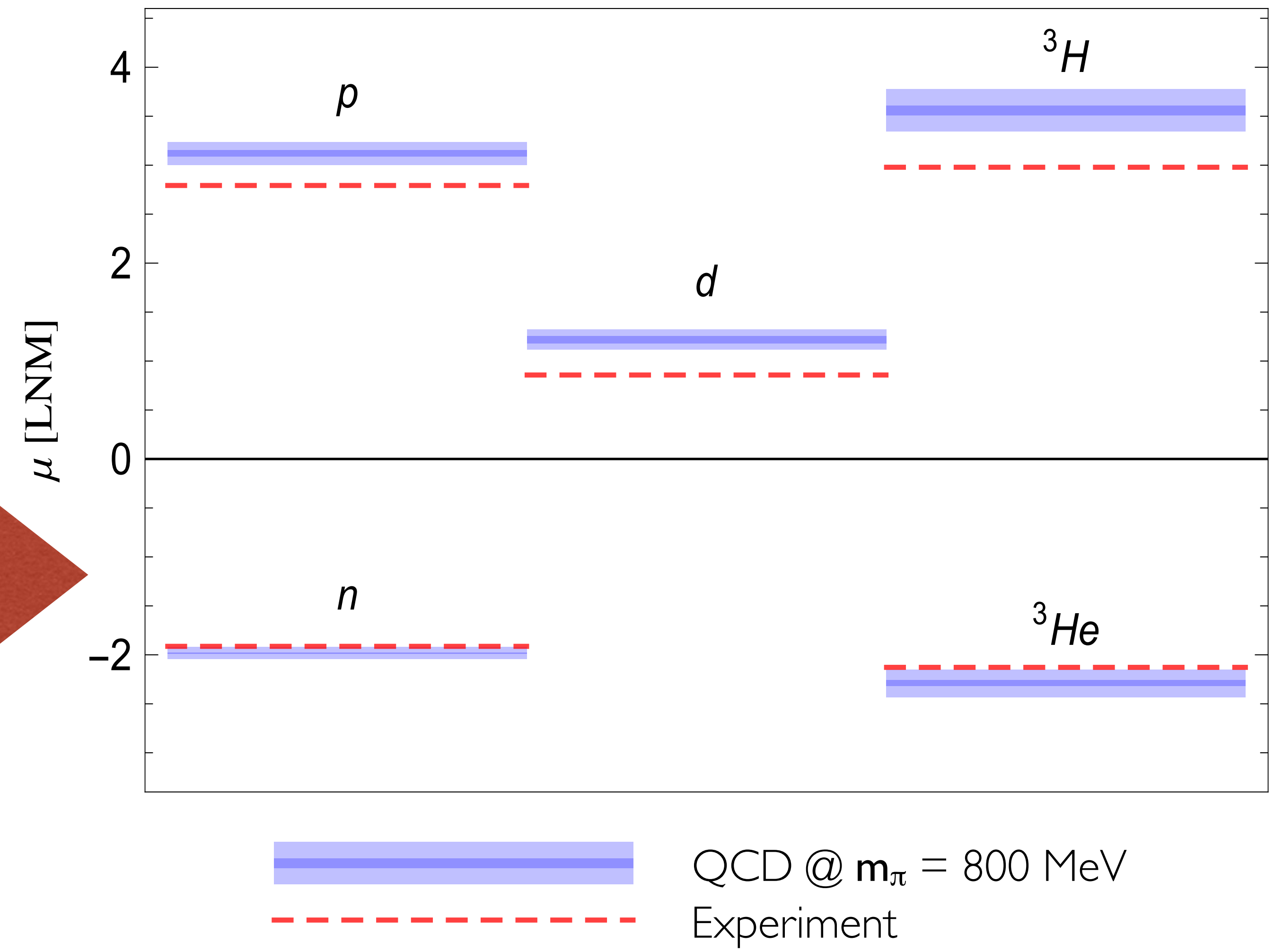




	n	p	d	3	3
μ	-1.98(1)(2)	3.21(3)(6)	1.22(4)(9)	-2.29(3)(12)	3.56(5)(18)

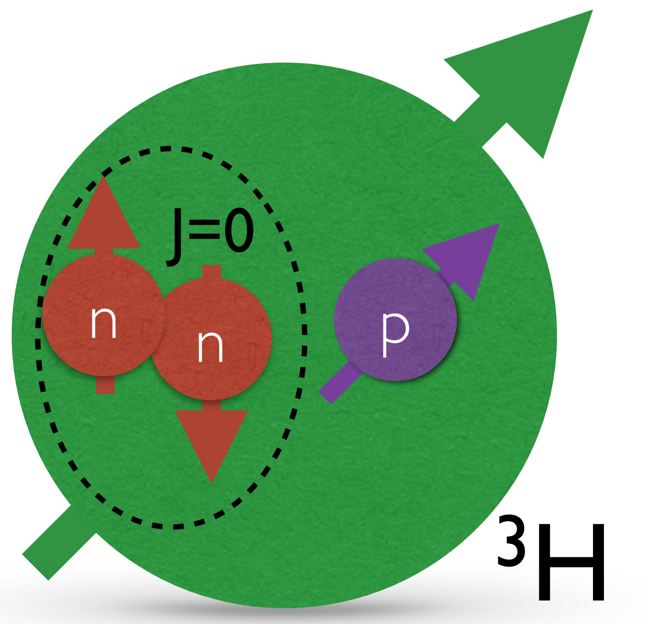
In units of appropriate nuclear magnetons (heavy M_N)

[NPLQCD PRL **113**, 252001 (2014)]

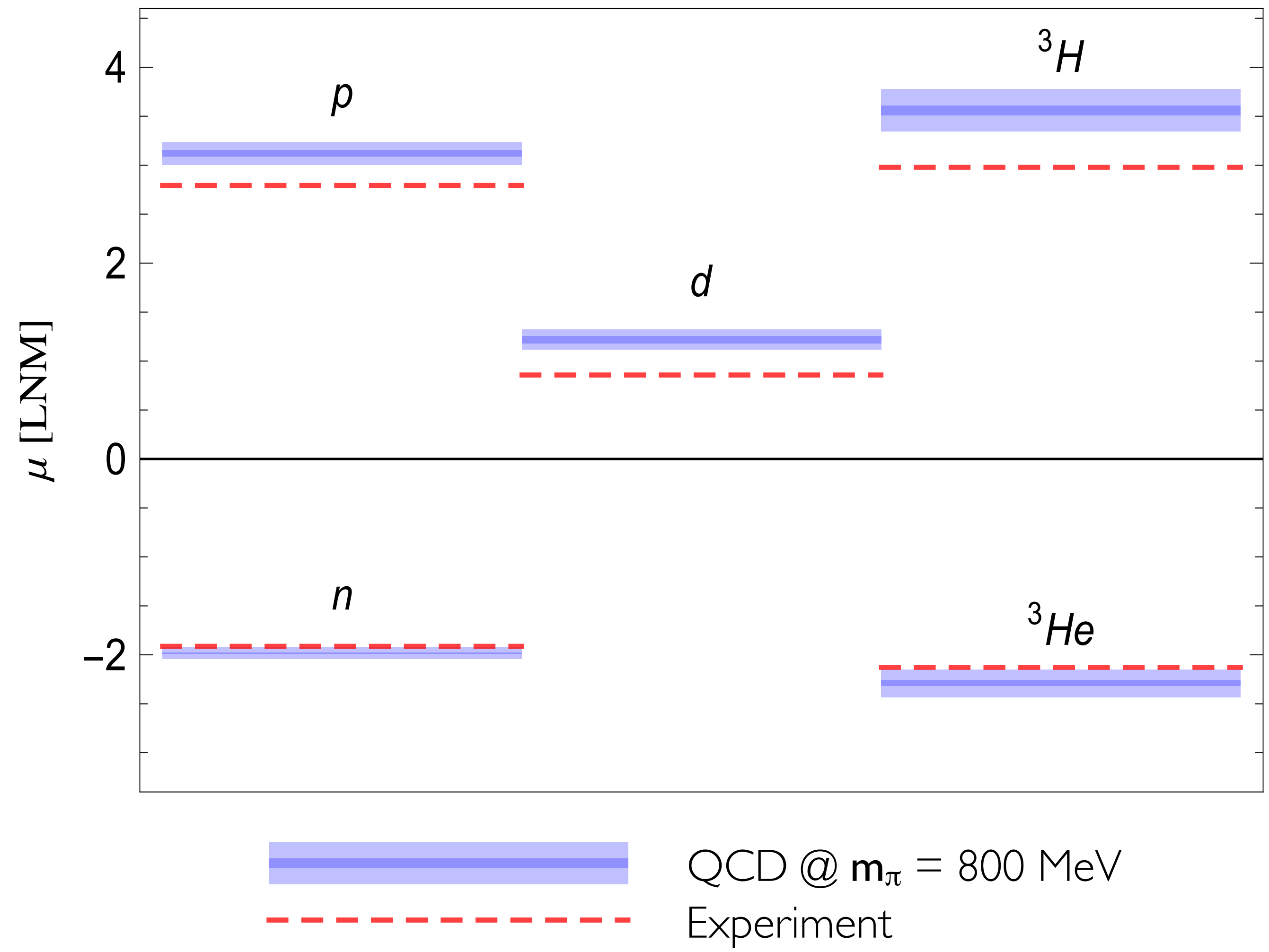
Magnetic moments of nuclei

- Numerical values are surprisingly interesting
- Shell model expectations

$$\mu_d = \mu_p + \mu_n$$
$$\mu_{^3\mathrm{H}} = \mu_p$$
$$\mu_{^3\mathrm{He}} = \mu_n$$



- Lattice results appear to suggest heavy quark nuclei are shell-model like!



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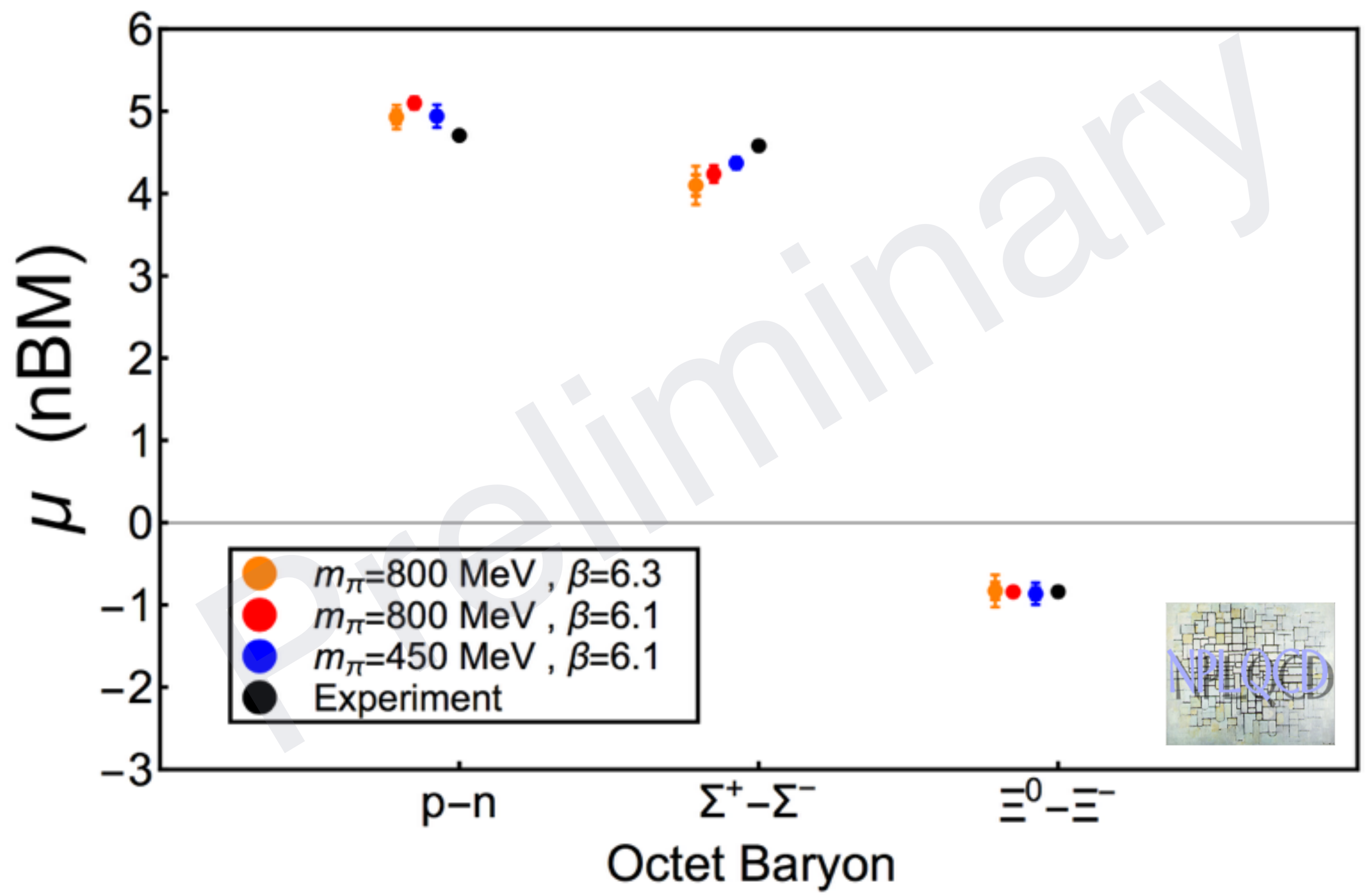
An puzzle for EFT?

- Quark mass dependence on magnetic moments becomes very flat in natural nuclear magnetons $\frac{e}{2M_B(m_\pi)}$



- NOT the expectation of ChPT:

$$\mu_N \sim \mu_0 + c\, m_\pi \quad \text{vs} \quad M_N \sim M_0 + d\, m_\pi^2$$

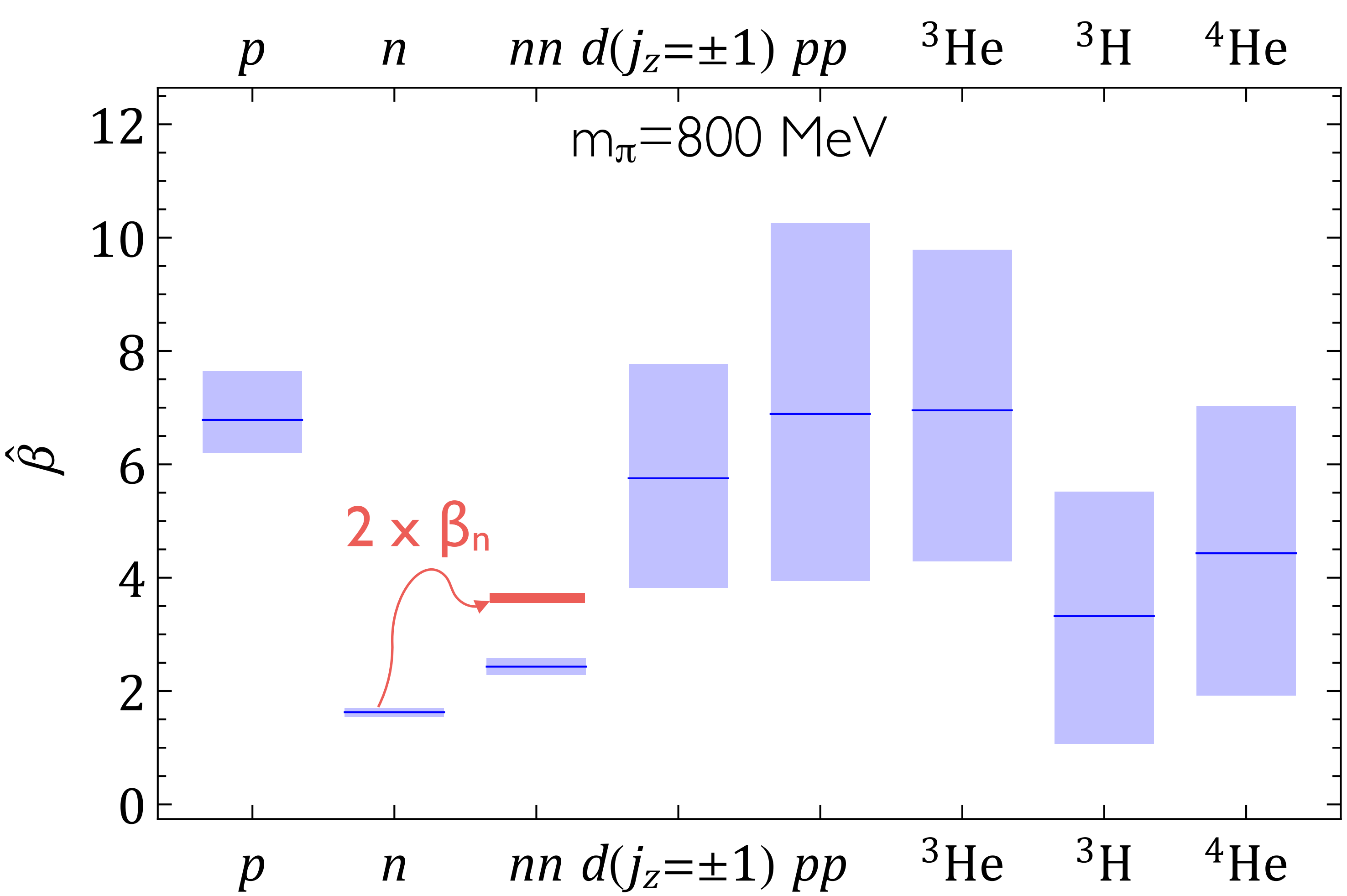
Magnetic Polarisabilities

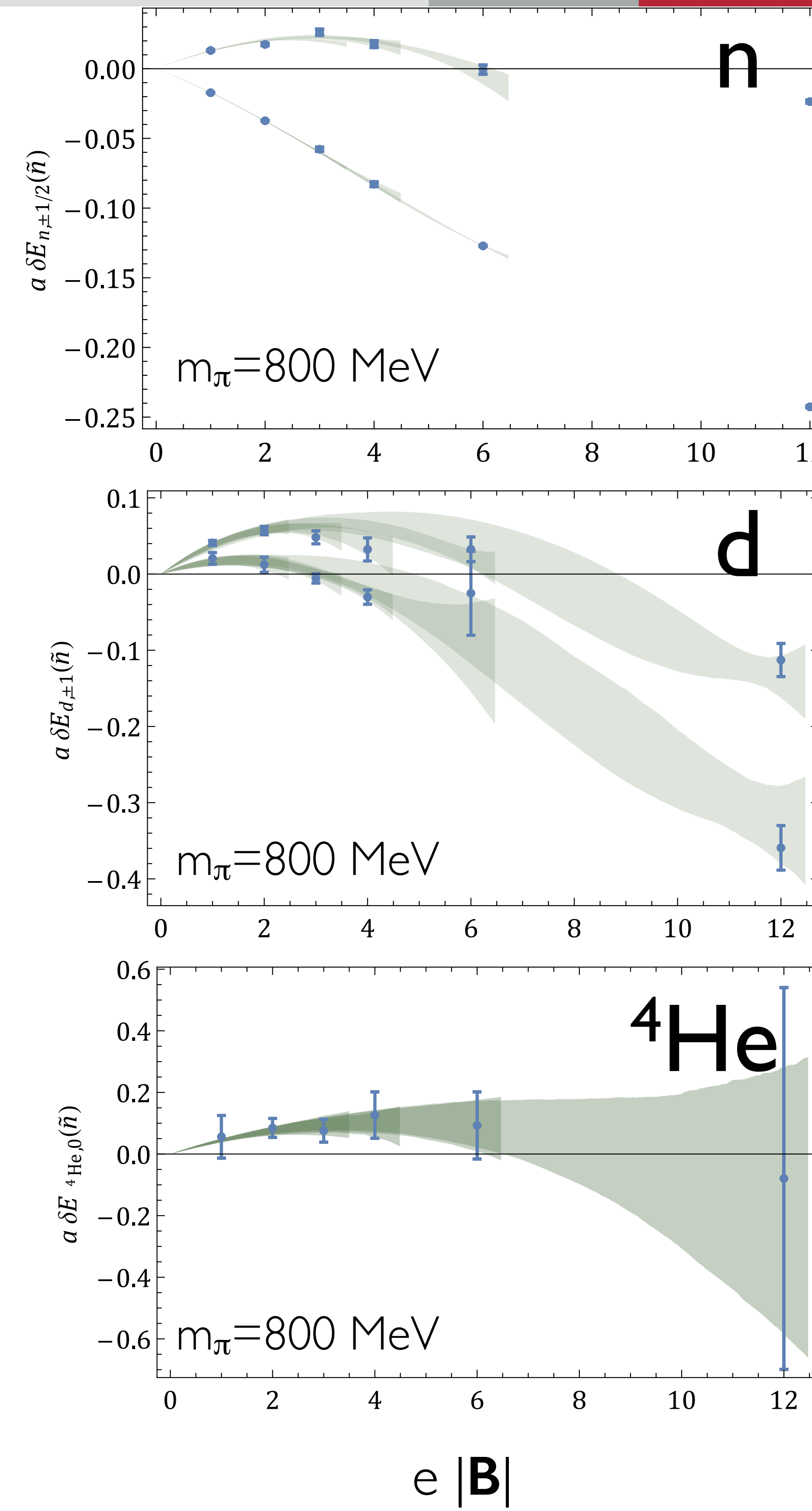
[NPLQCD 1506.05518]

- Second order shifts

$$E_{h;j_z}(\mathbf{B}) \;=\; \sqrt{M_h^2 + (2n+1)|Q_h e B|} - \boldsymbol{\mu}_h \cdot \mathbf{B} - 2\pi\beta_h^{(M0)}|\mathbf{B}|^2 - 2\pi\beta_h^{(M2)}\langle \hat{T}_{ij} B_i B_j \rangle + \ldots$$

- Care required with Landau levels
- Polarisabilities (dimensionless units)

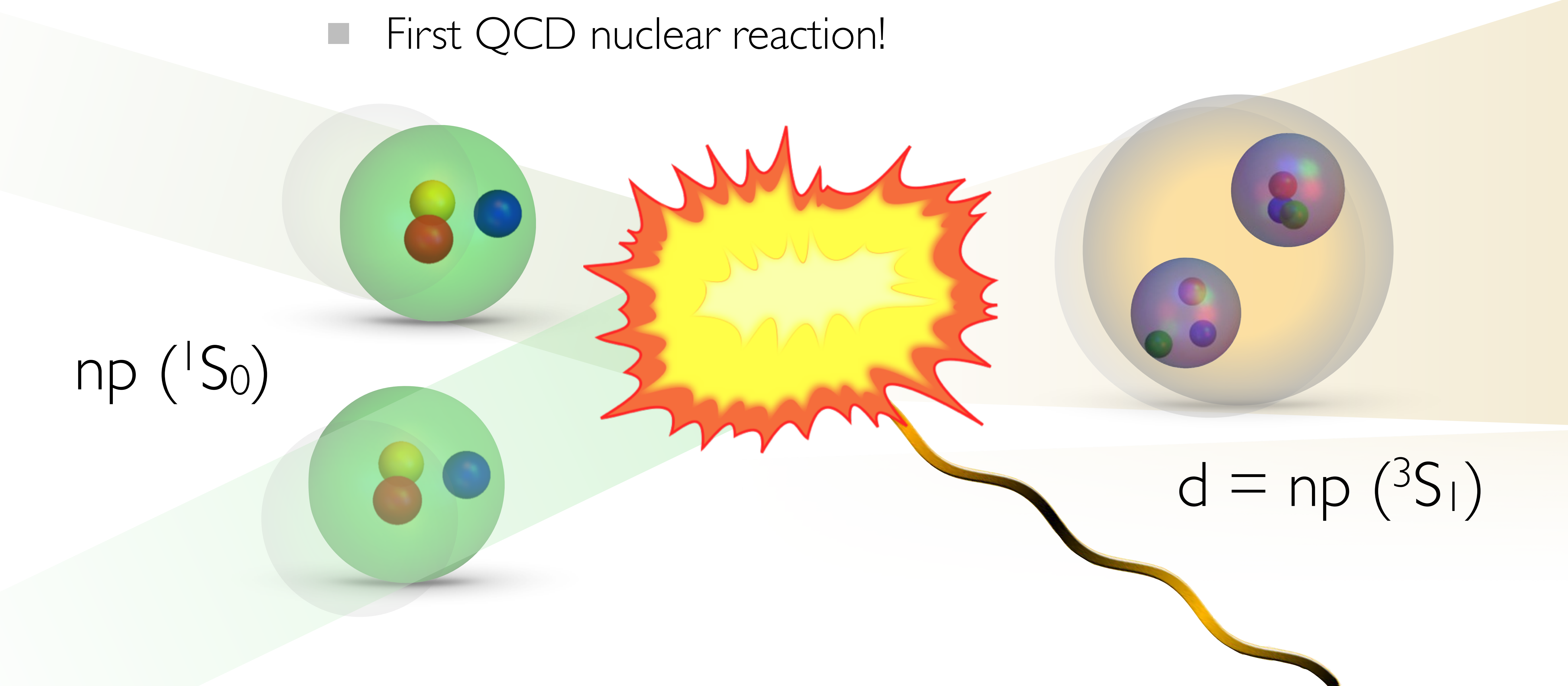




Thermal Neutron Capture Cross-Section

[NPLQCD PRL 115, 132001 (2015)]

- Thermal neutron capture cross-section: np→dγ
  - Critical process in Big Bang Nucleosynthesis
  - Historically important: nucleus is not just nucleons
  - First QCD nuclear reaction!



np→dγ in pionless EFT

$$Z_d = 1/\sqrt{1-\gamma_0 r_3}$$

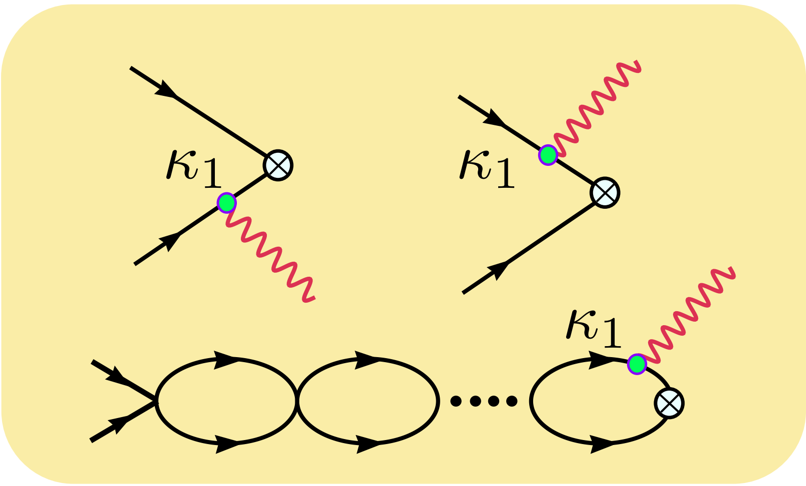
- Cross-section at threshold calculated in pionless EFT

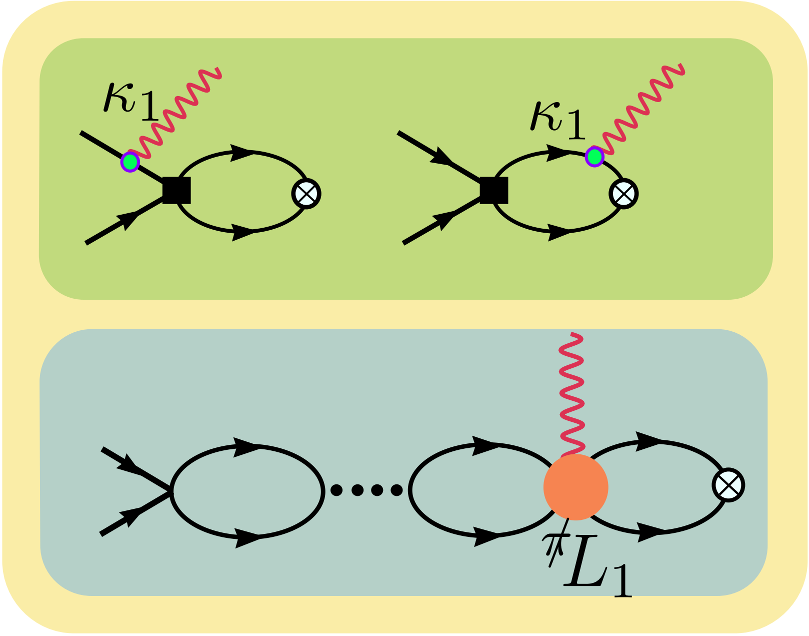
$$\sigma(np\to d\gamma) = \frac{e^2(\gamma_0^2+|\mathbf{p}|^2)^3}{M^4\gamma_0^3|\mathbf{p}|}|\tilde{X}_{M1}|^2+\ldots$$

- EFT expansion at LO given by mag. moments NLO contributions from short-distance two nucleon operators

$$\tilde{X}_{M1} = \frac{Z_d}{-\frac{1}{a_1}+\frac{1}{2}r_1|\mathbf{p}|^2 - i|\mathbf{p}|} \times\left[\frac{\kappa_1\gamma_0^2}{\gamma_0^2+|\mathbf{p}|^2}\left(\gamma_0-\frac{1}{a_1}+\frac{1}{2}r_1|\mathbf{p}|^2\right)+\frac{\gamma_0^2}{2}l_1\right]$$

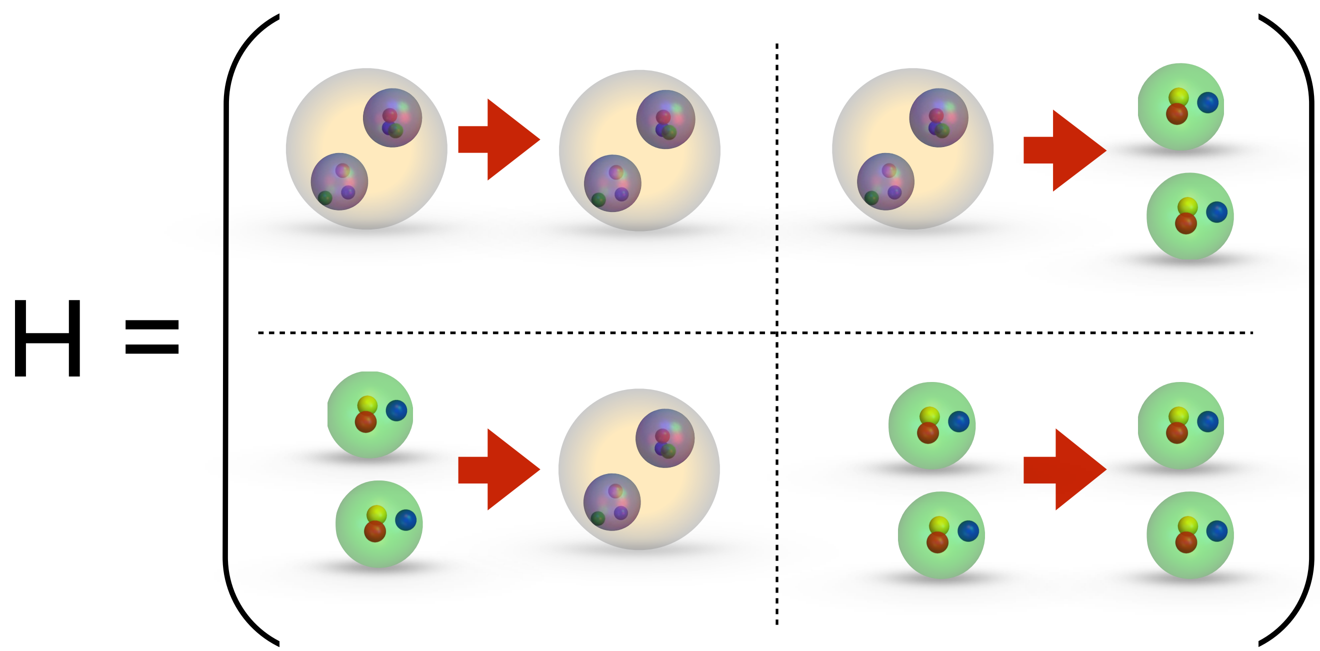
- Phenomenological description with 1% accuracy for E < 1 MeV
  - Short distance (MEC) contributes ~10%





MECs: Riska, Phys.Lett. B38 (1972) 193
Hokert et al, Nucl.Phys. A217 (1973) 14
EFT: Chen et al.,Nucl.Phys. A653 (1999) 386
Chen et al, Phys.Lett. B464 (1999) 1
Rupak Nucl.Phys. A678 (2000) 405

- Presence of magnetic field mixes $I_z = J_z = 0$ $^3S_1$ and $^1S_0$ *np* systems



- Calculate energies in presence of B fields

- Shift of eigenvalues determined by transition amplitude
  [WD, & M Savage 2004]

$$\Delta E_{^3S_1,^1S_0} = \mp\left(\kappa_1 + \overline{L}_1\right)\frac{eB}{M} + \ldots$$

[NPLQCD PRL **115**, 132001 (2015)]

np→dγ

Lattice correlator
with $^3S_1$ source and $^1S_0$ sink

- Iz=Jz=0 correlation matrix

$$\mathbf{C}(t;\mathbf{B}) \;=\; \begin{pmatrix} C_{^3S_1,^3S_1}(t;\mathbf{B}) & C_{^3S_1,^1S_0}(t;\mathbf{B}) \\ C_{^1S_0,^3S_1}(t;\mathbf{B}) & C_{^1S_0,^1S_0}(t;\mathbf{B}) \end{pmatrix}$$

- Generalised eigenvalue problem

$$[\mathbf{C}(t_0;\mathbf{B})]^{-1/2}\mathbf{C}(t;\mathbf{B})[\mathbf{C}(t_0;\mathbf{B})]^{-1/2}v = \lambda(t;\mathbf{B})v$$

- Ratio of correlator ratios to extract 2-body

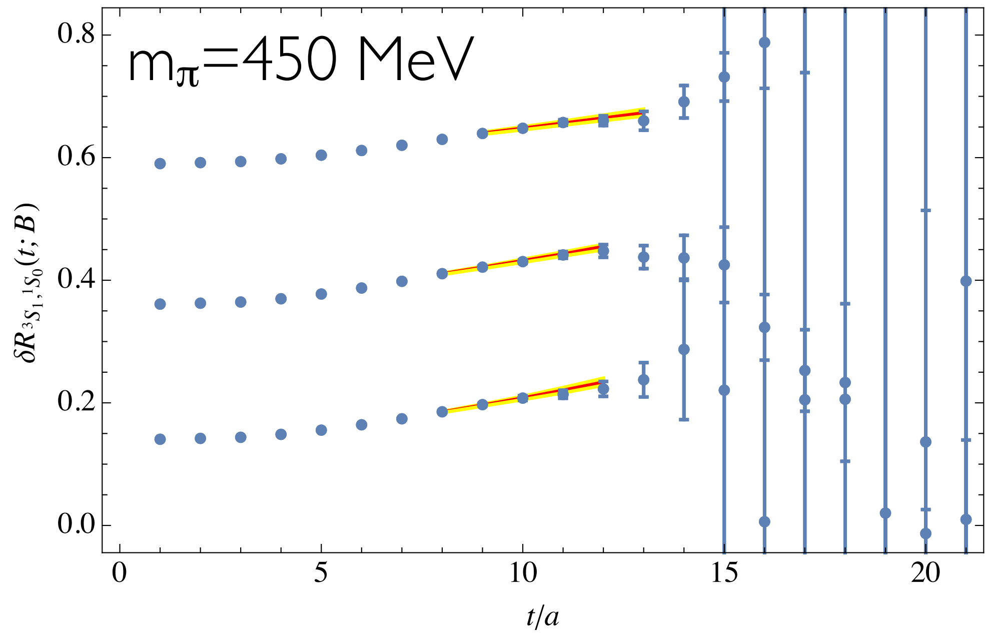
$$R_{^3S_1,^1S_0}(t;\mathbf{B}) = \frac{\lambda_+(t;\mathbf{B})}{\lambda_-(t;\mathbf{B})} \overset{t\to\infty}{\longrightarrow} \hat{Z}\exp\left[2\ \Delta E_{^3S_1,^1S_0}t\right]$$

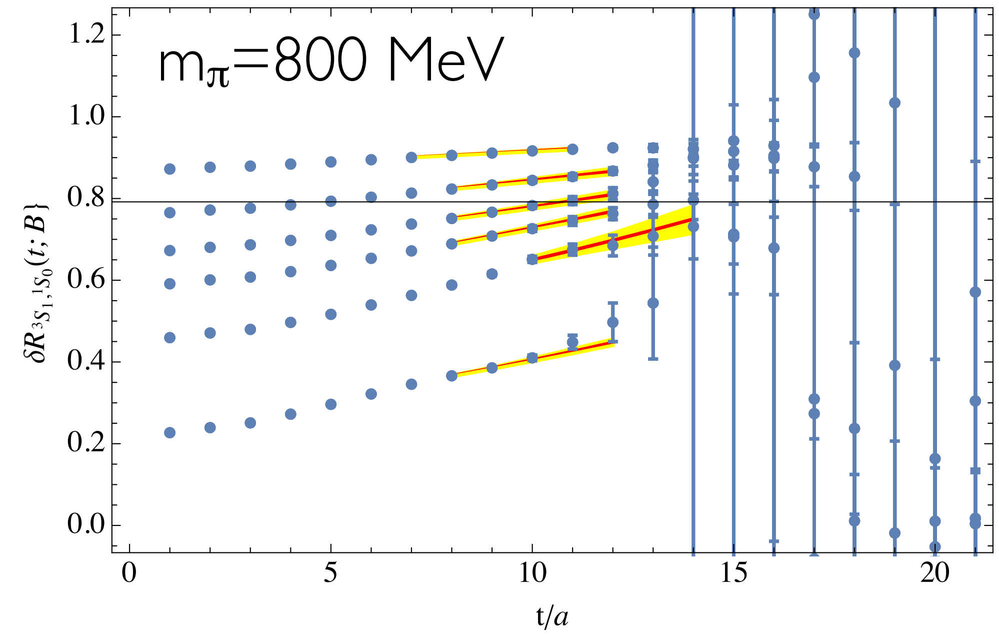
$$\delta R_{^3S_1,^1S_0}(t;\mathbf{B}) = \frac{R_{^3S_1,^1S_0}(t;\mathbf{B})}{\Delta R_p(t;\mathbf{B})/\Delta R_n(t;\mathbf{B})} \;\to A\ e^{-\delta E_{^3S_1,^1S_0}(\mathbf{B})t}$$

$$\begin{aligned}\delta E_{^3S_1,^1S_0} \;&\equiv\; \Delta E_{^3S_1,^1S_0} - [E_{p,\uparrow} - E_{p,\downarrow}] + [E_{n,\uparrow} - E_{n,\downarrow}] \\ &\to\; 2\overline{L}_1|e\mathbf{B}|/M + \mathcal{O}(\mathbf{B}^2)\end{aligned}$$

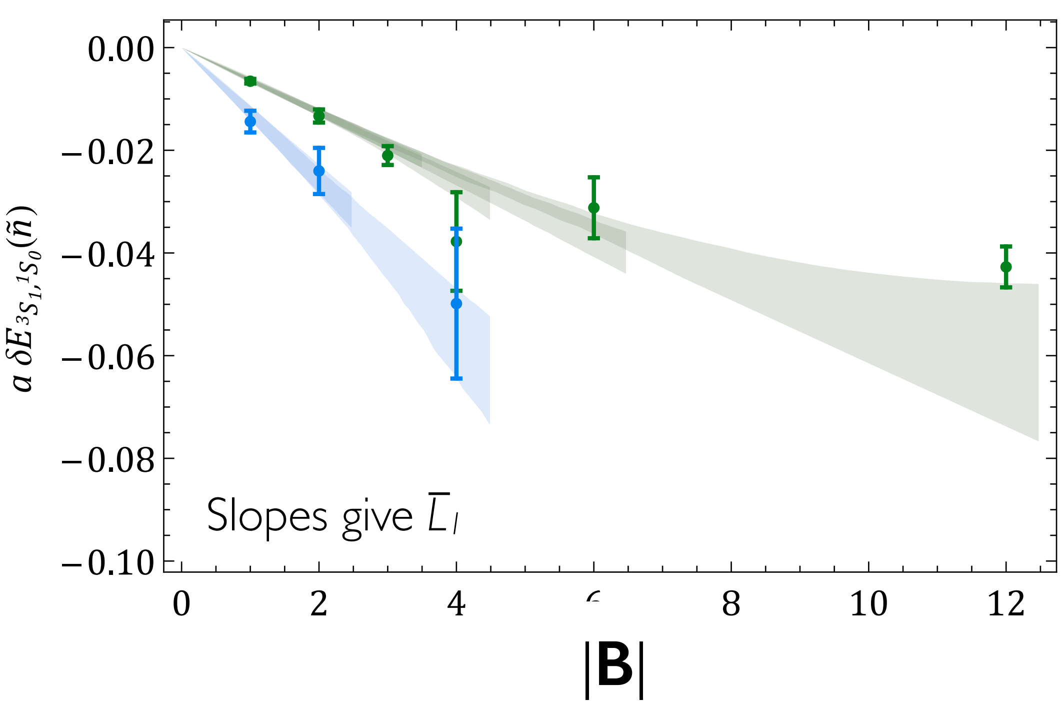
[NPLQCD PRL **115**, 132001 (2015)]

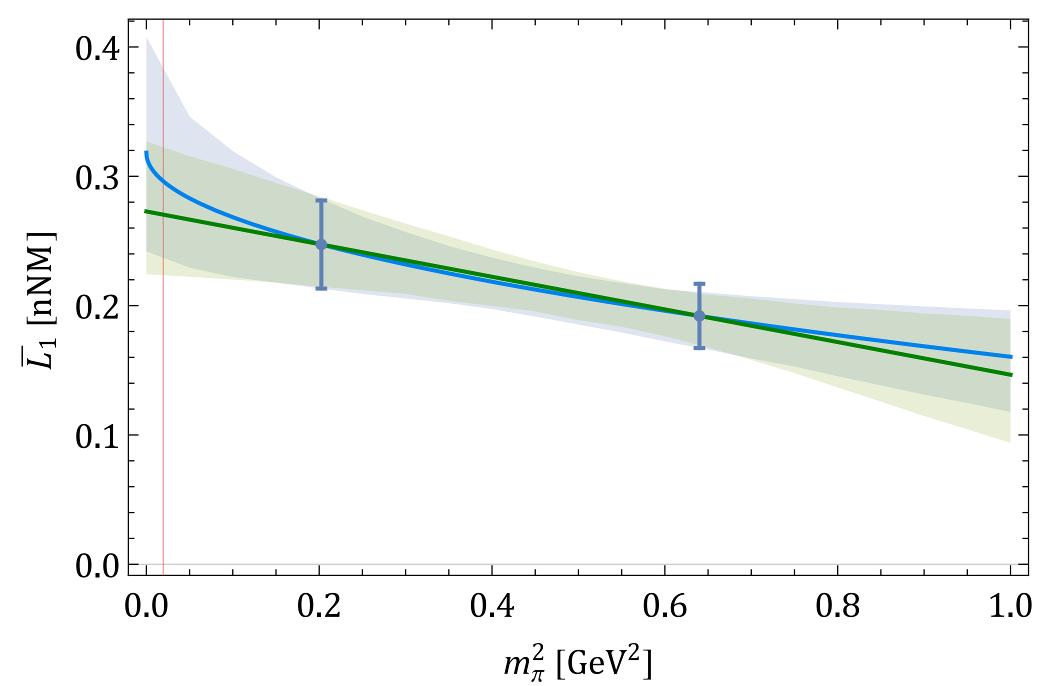
- Correlator ratios





- Field strength & mass dependence





[NPLQCD PRL **115**, 132001 (2015)]

np→dγ

- Key point: extract short-distance contribution at physical mass

$$\overline{L}_1^{\mathrm{lqcd}} = 0.285({}^{+63}_{-60}) \quad \mathrm{NM}$$

- Use EFT to combine with phenomenological nucleon magnetic moment, scattering parameters

$$\sigma^{\mathrm{lqcd}}(np \to d\gamma) = 307.8(1 + 0.273\ \overline{L}_1^{\mathrm{lqcd}})\ \mathrm{mb}$$

$$\sigma^{\mathrm{lqcd}}(np \to d\gamma) = 332.4({}^{+5.4}_{-4.7})\ \mathrm{mb}$$

c.f. phenomenological value

$$\sigma^{\mathrm{expt}}(np \to d\gamma) = 334.2(0.5)\ \mathrm{mb}$$

- NB: at m_π=800 MeV, use LQCD for all inputs (ab initio)

$$\sigma^{800\ \mathrm{MeV}}(np \to d\gamma) \sim 10\ \mathrm{mb}$$

[NPLQCD PRL **115**, 132001 (2015)]

Future: Precision Nuclear Physics

Nuclear matrix elements

Nuclear matrix elements

- *Major component is many current and upcoming experiments is nuclear targets*
- Intensity frontier: precise experiments
  - Sensitivity to probe the rarest interactions of the SM
  - Look for effects where there is no SM contribution
- Neutrino beams
- Dark matter direct detection
- $\beta\beta$ decay, charged lepton flavour violation, EDMs, proton decay, neutron-antineutron oscillations…
- Important focus of HEP/NP experimental programs

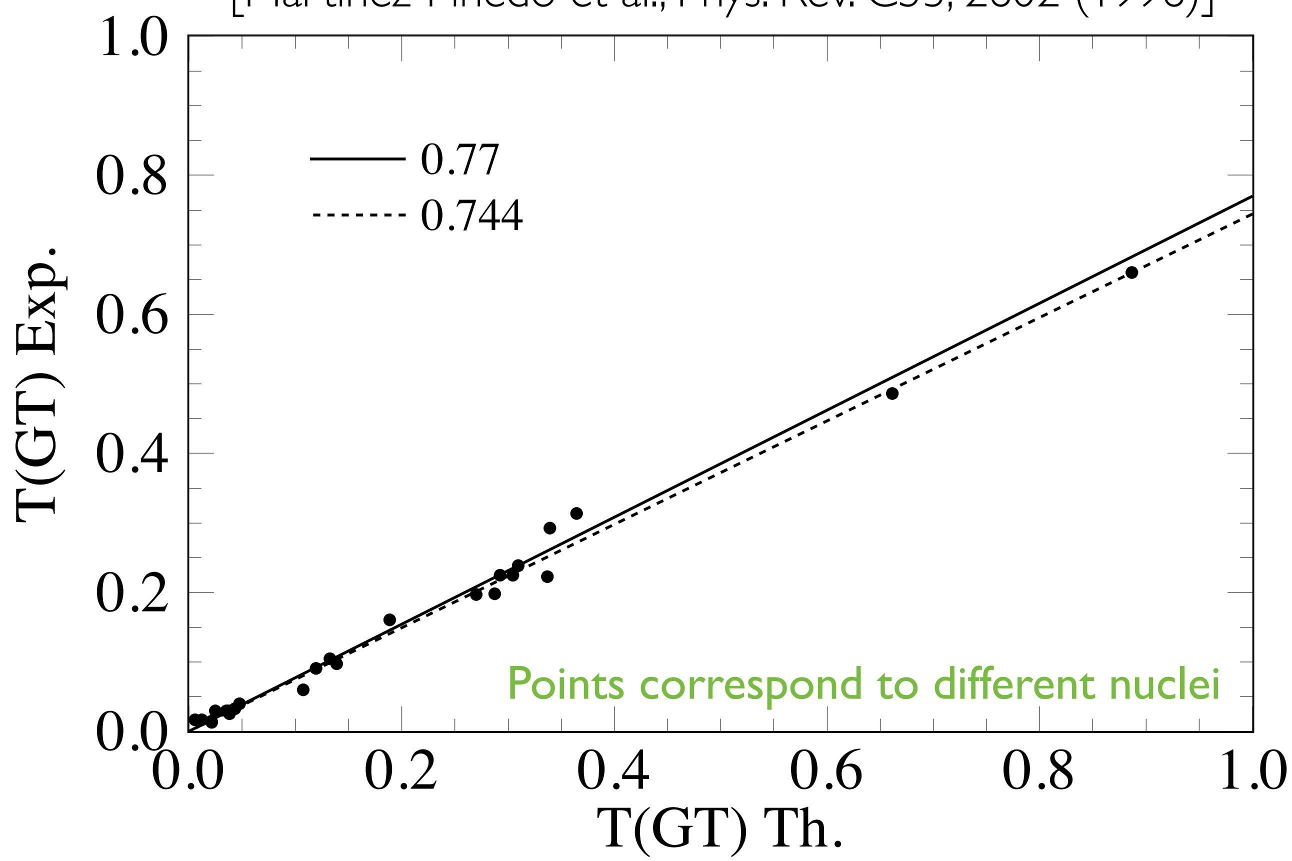
Nuclear uncertainties

- How well do we know nuclear matrix elements?

😢 Stark example of problems: Gamow-Teller transitions in nuclei

- Well measured for large range of nuclei (30<A<60)
- Many nuclear structure calcs (QRPA, shell-model,…) – spectrum well described
- GT matrix elements systematically off by 20–30%
- "Correct" by "quenching" axial charge in nuclei ...

[Martinez-Pinedo et al., Phys. Rev. C53, 2602 (1996)]

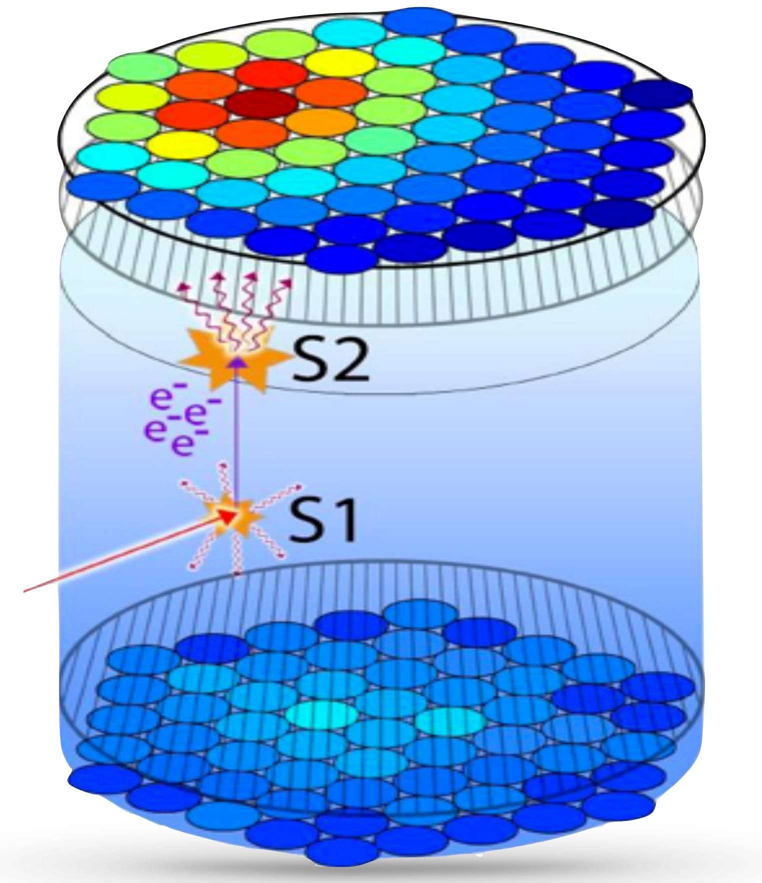


$$T(GT) \sim \sqrt{\sum_f \langle \boldsymbol{\sigma} \cdot \boldsymbol{\tau} \rangle_{i \to f}}$$

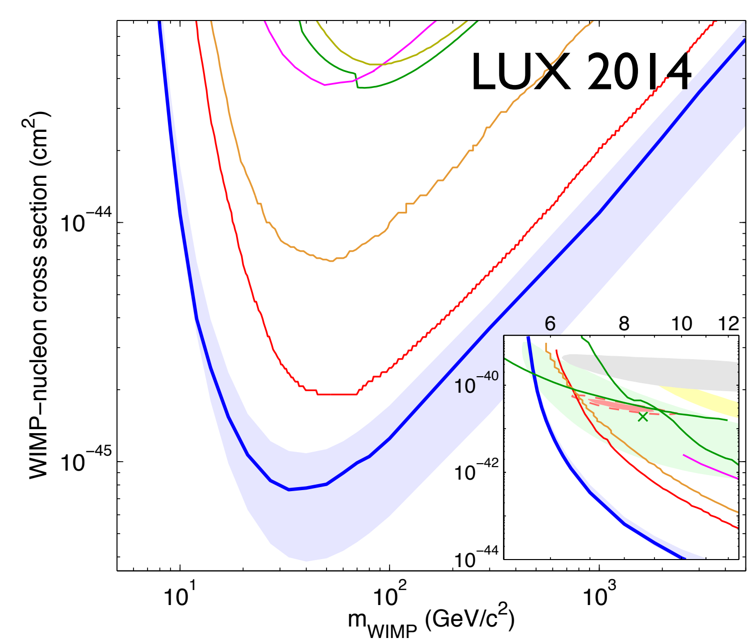
$$\langle \boldsymbol{\sigma\tau} \rangle = \frac{\langle f || \sum_k \boldsymbol{\sigma}^k \boldsymbol{t}^k_{\pm} || i \rangle}{\sqrt{2J_i + 1}}$$

The intensity frontier

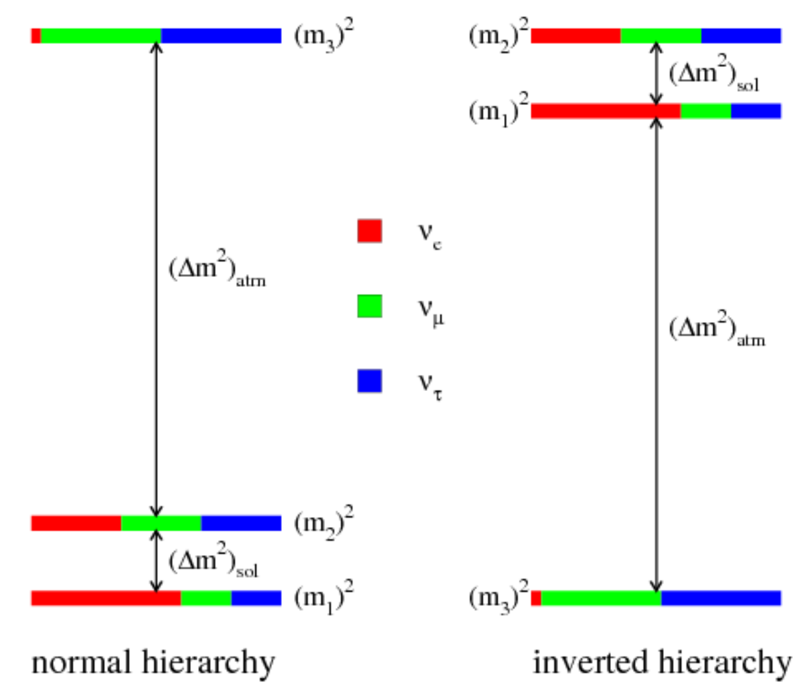
- Dark matter direct detection: nuclear recoils in large bucket of nuclei as signal
  - Detection rate/bounds depends on dark matter properties/dynamics and x-sec on nucleus
- 😍 Positive signals would be unambiguous
- 😟 Post-detection: precise nuclear x-sec (with quantified uncertainties) to discern underlying dynamics
- Potentially understand seemingly conflicting positive and negative signals
- Inform experimental design and backgrounds

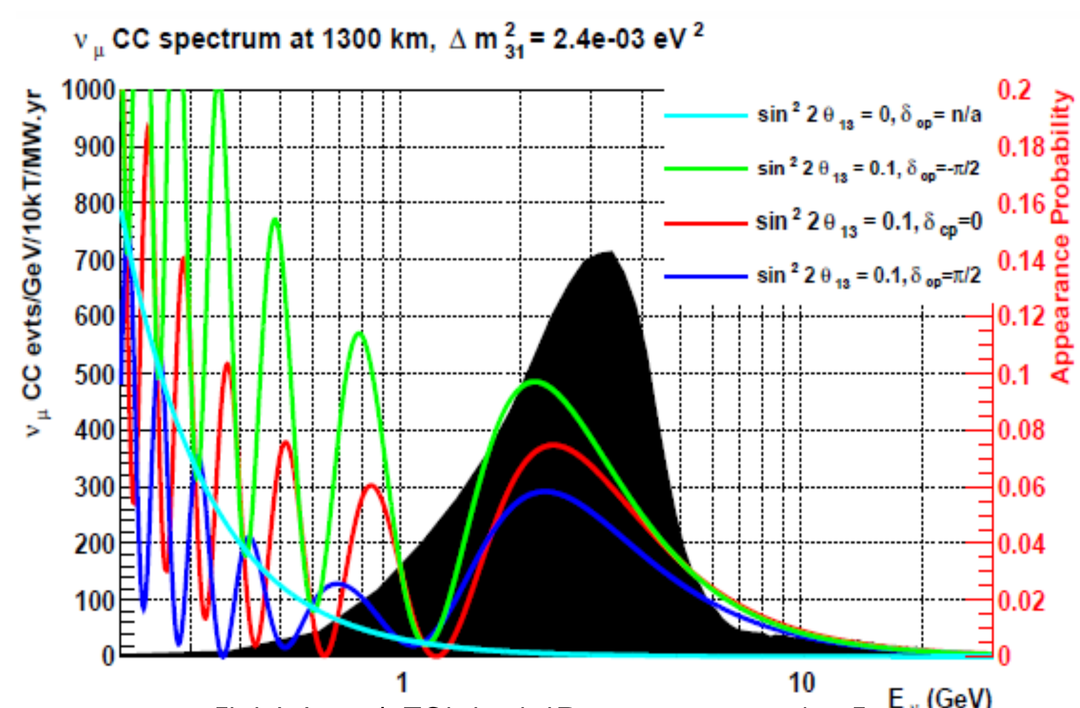


http://www.hep.ucl.ac.uk/darkMatter/



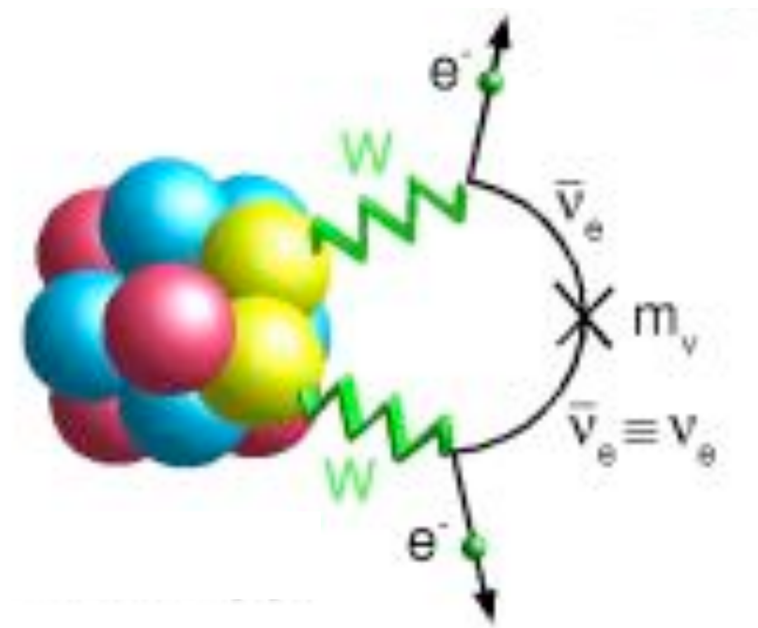
- LBNF/DUNE: extraction of neutrino mass hierarchy and precise mixing parameters
- Neutrino scattering on argon target
- Requires knowing energies/fluxes to high accuracy
  - Nuclear axial & transition form factors
  - Resonances
  - Neutrino-nucleus DIS
- ~10% uncertainty on oscillation parameters [C Mariani, INT workshop 2013]



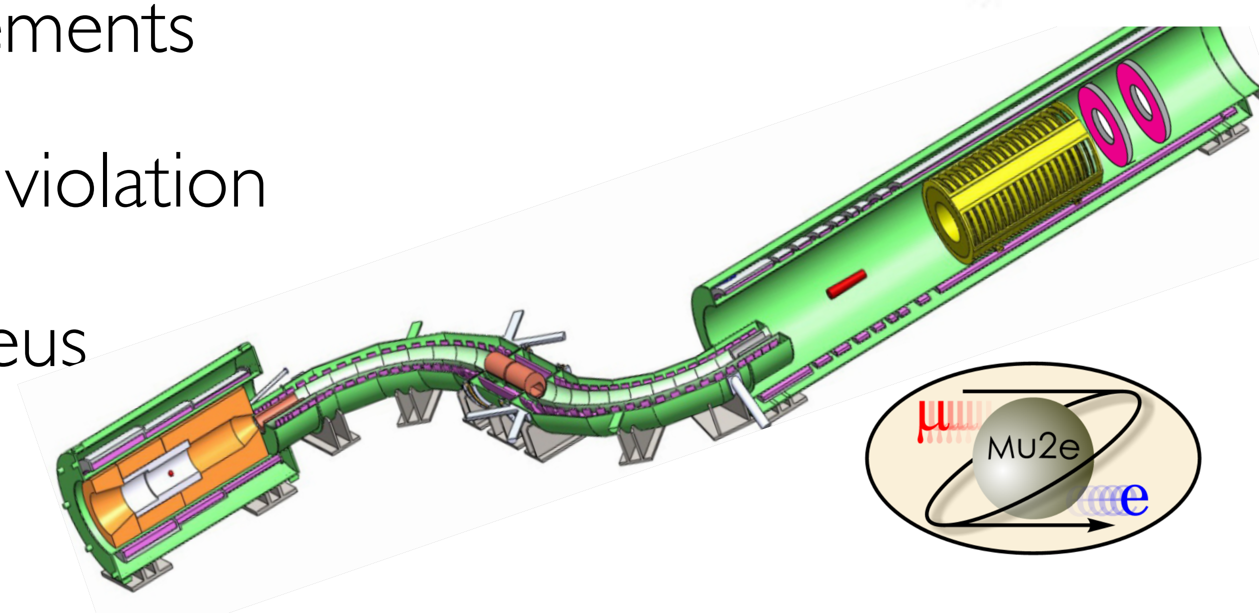


[U Mosel FSNu NP town meeting]

The intensity frontier



- EDMs: potential light nuclear EDM experiments offer complementary handles on CPV
- $0\nu\beta\beta$ decay: fundamental nature of neutrinos
    - Rates depend on nuclear matrix elements
- μ2e: search for charged lepton flavour violation
    - μ→e conversion in field of Al nucleus



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The intensity frontier

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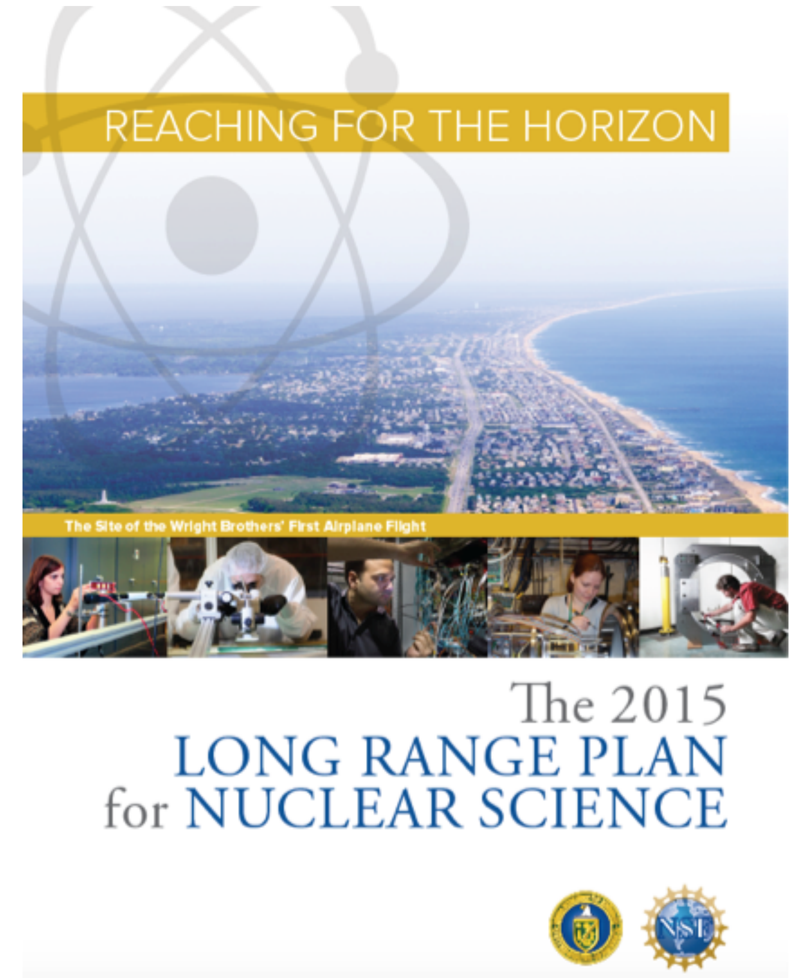
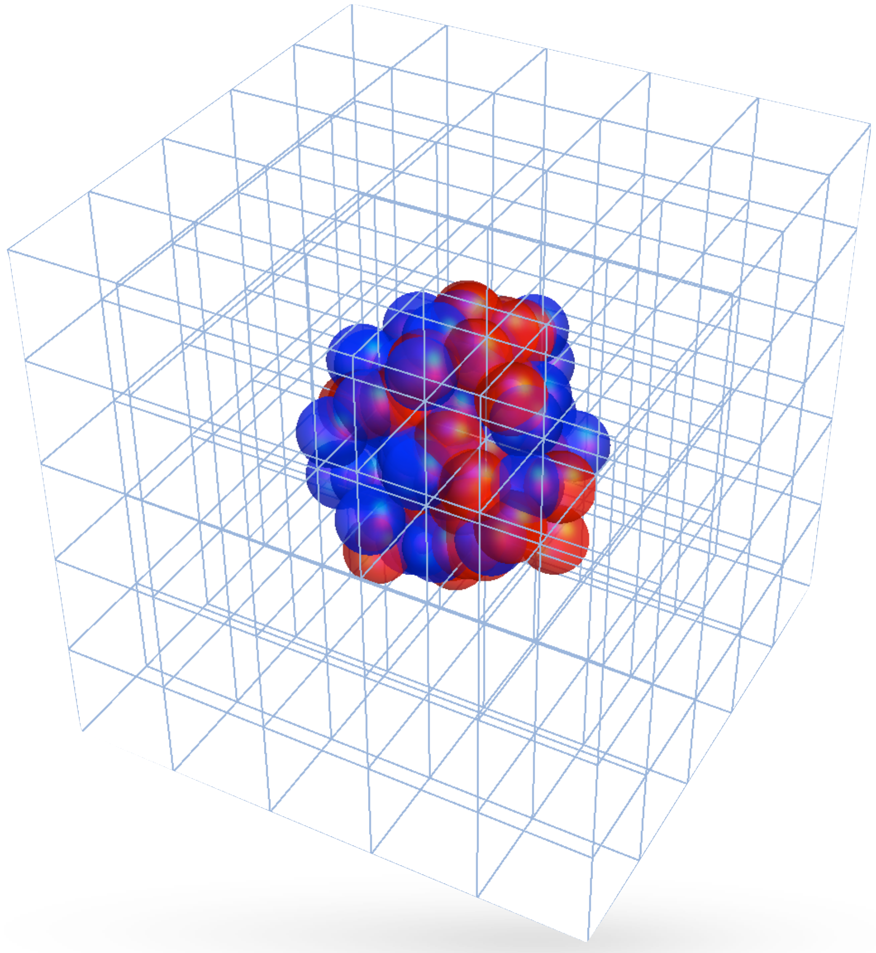


Nuclear theory at the intensity frontier

- Definitive need for precision determinations of nuclear matrix elements
  - Must be based on the Standard Model
  - Must have fully quantified uncertainties
  - Timeframe and precision goals set by experiment
- Current state is far from this but magnetic moment calculations show it is feasible
- Achieve with a combination of LQCD and NEFT?



Challenges

- Realistic to expect LQCD calculations of A~7 spectroscopy and simple matrix elements
  - Challenge: many experiments focus on much larger nuclei: how much information is necessary to constrain NEFT
- Long baseline neutrino scattering probes nuclear form factors (and transition form factors) for $0 \leq Q^2 \leq 10\ \mathrm{GeV}^2$
  - Challenge: χPT/NEFT surely breaks down at such momenta
- $0\nu\beta\beta$ decay (light Majorana)
  - Challenge: non-local matrix elements

QCD for nuclei

- Nuclei are under study directly from QCD
  - Spectroscopy of light nuclei and exotic nuclei
  - Structure: magnetic moments and polarisabilities
  - Electroweak interactions: thermal capture cross-section
- EFT important in many ways
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics
  - Critical role in current and upcoming intensity frontier experimental program
  - Learn many interesting things about the nature of nuclear physics along the way