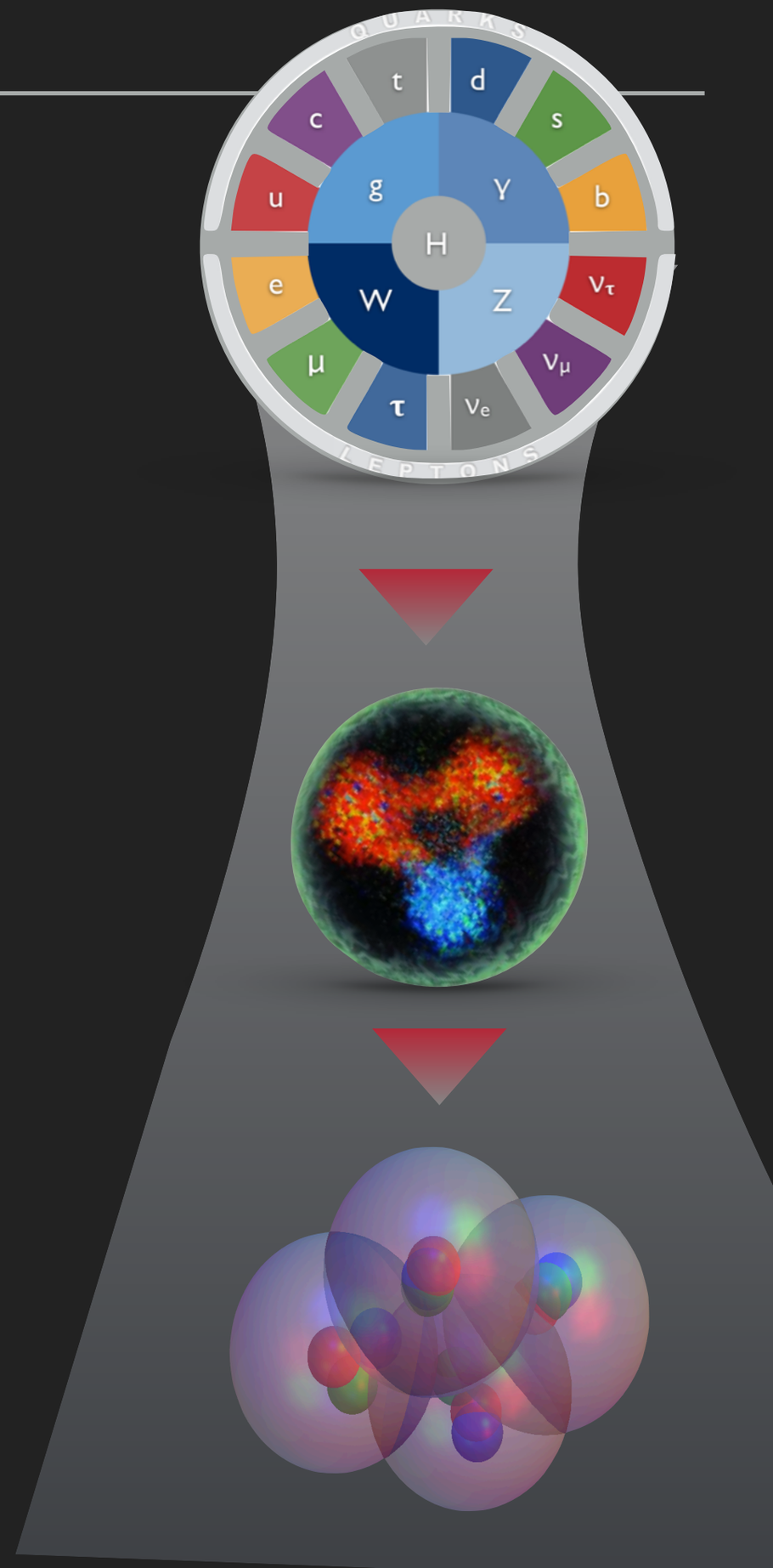
WILL DETMOLD MIT

COMPUTING THE PROPERTIES OF NUCLEI FROM QCD

CHEP 2019, Adelaide, Nov 5th, 2019

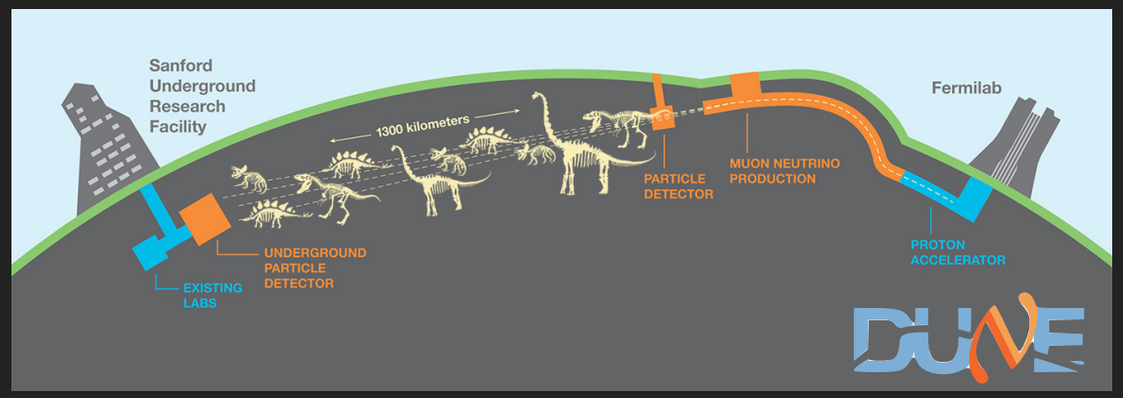
EMERGENCE OF NUCLEI

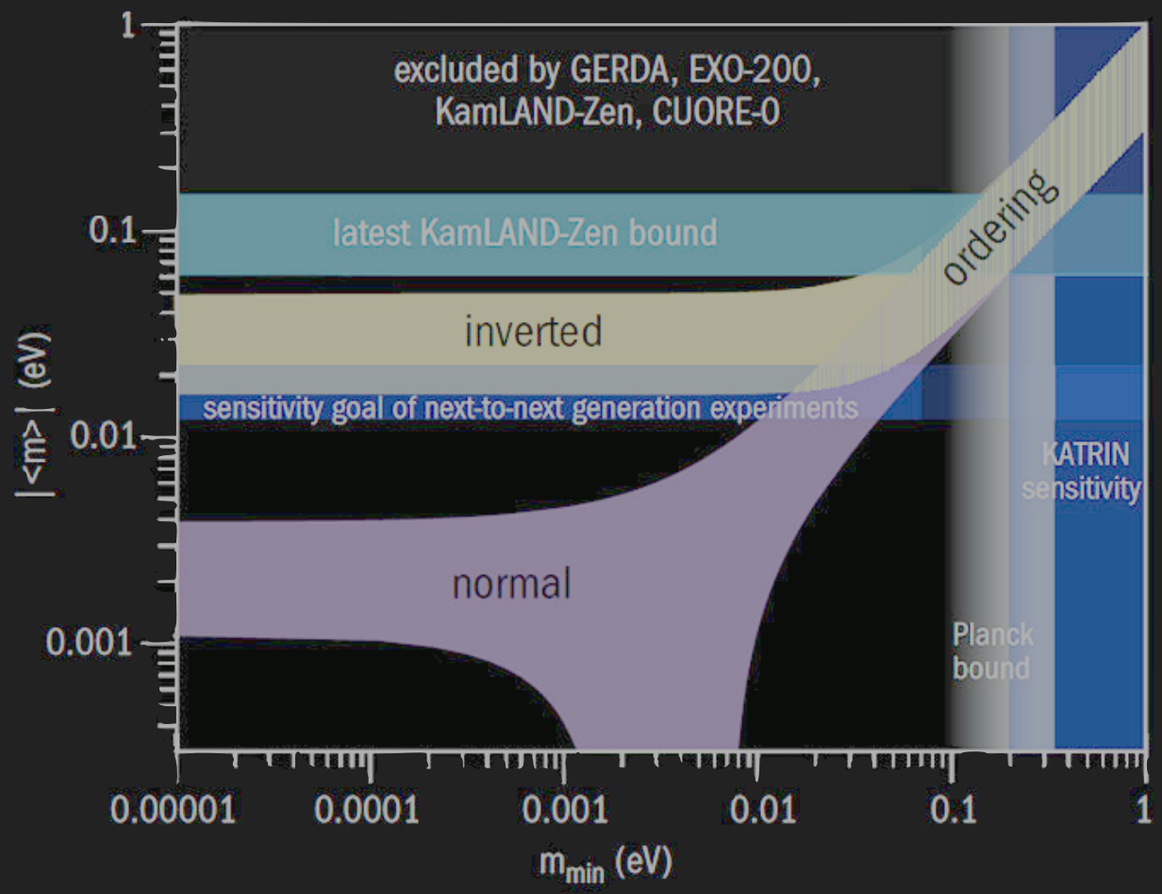
- QCD+EW encodes nuclear physics
- Computational challenge to see QCD produce nuclear physics
- Study emergence of layered complexity of nucleons and nuclei
- Input for intensity frontier experiments
  - Interactions of nuclei with external currents
  - Need lattice QCD calculations



ELECTROWEAK PROCESSES

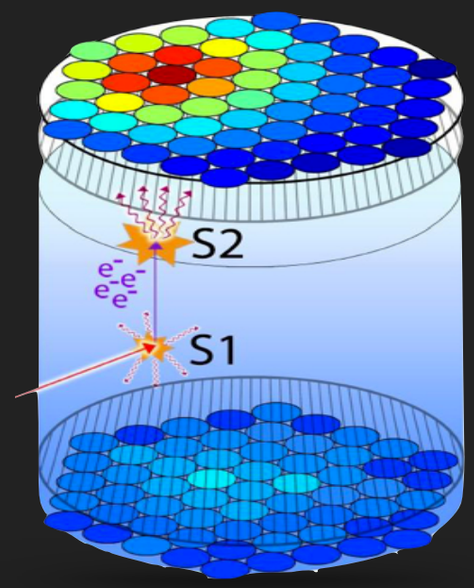
- Electroweak processes in nuclei
- Neutrino-nucleus interactions for long baseline neutrino program
  - Oscillation parameters require energy reconstruction from νA scattering
- Double-β decay: nn→pp
  - Nuclear matrix element uncertainties

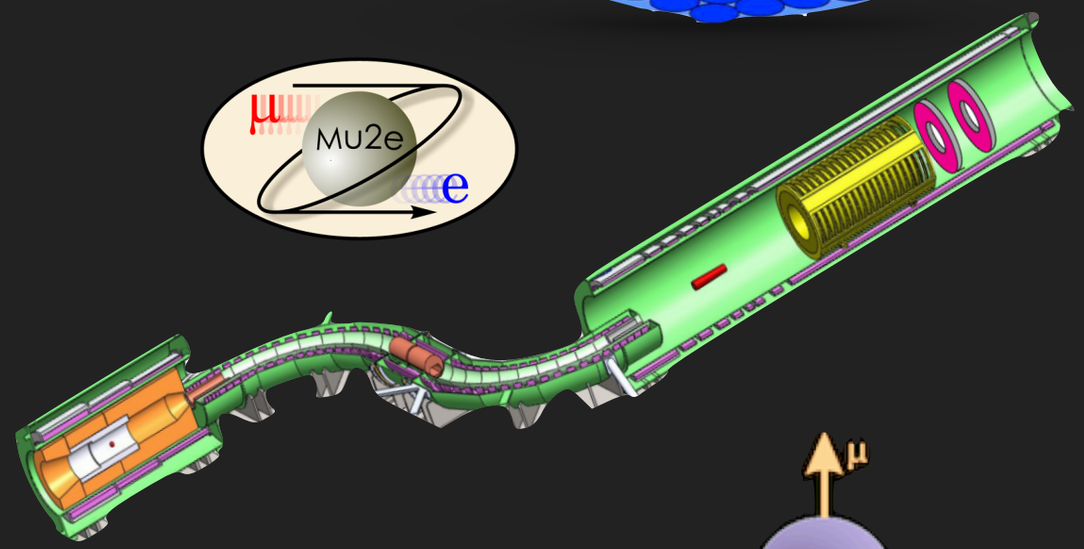


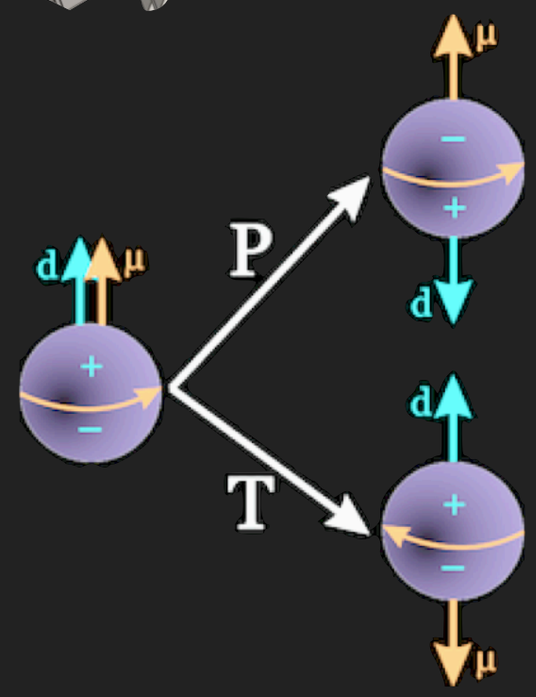


BSM SEARCHES

- Non standard model currents in light nuclei
- Scalar currents
  - Dark matter direct detection
  - Lepton flavour violation: μ2e
  - Precision spectroscopy
- Tensor currents
  - Quark contribution to EDMs of nuclei

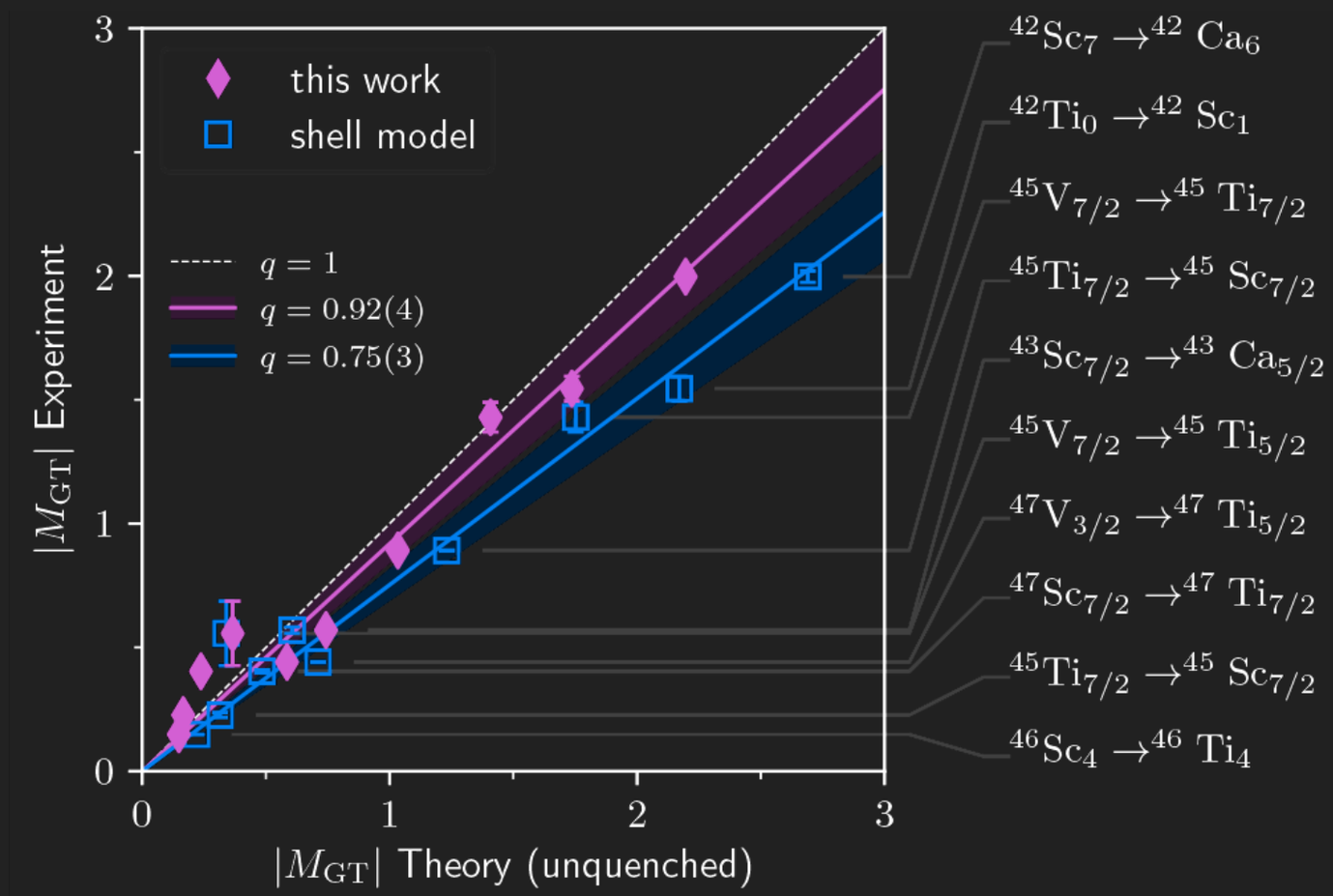






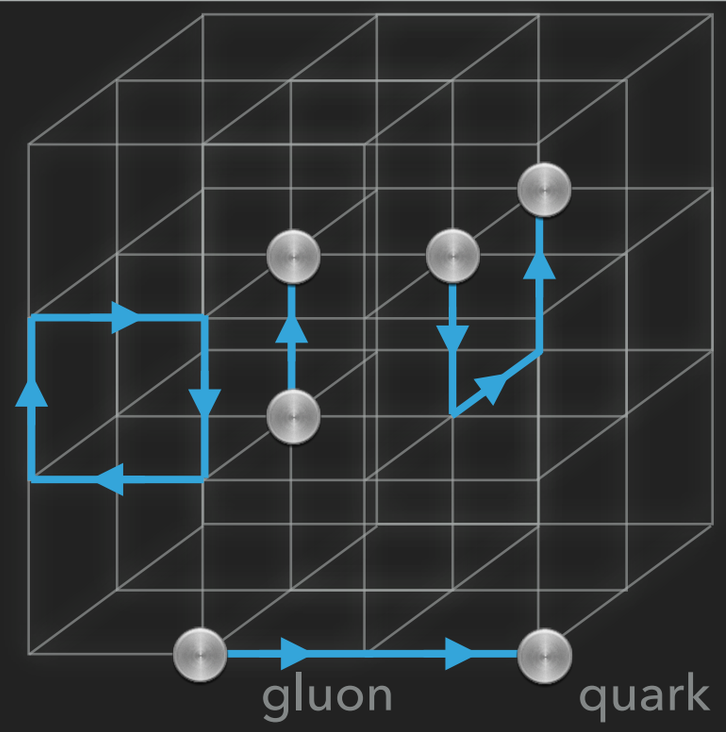
NUCLEAR UNCERTAINTIES

- How well do we know nuclear matrix elements?
- Gamow-Teller transitions in nuclei
  - Well measured for large range of nuclei (30<A<60)
  - Many nuclear structure calculations (shell-model,...) describe spectrum well
  - Matrix elements systematically off by 20-30%
  - Correct using 2 body currents
- Fundamental understanding from QCD

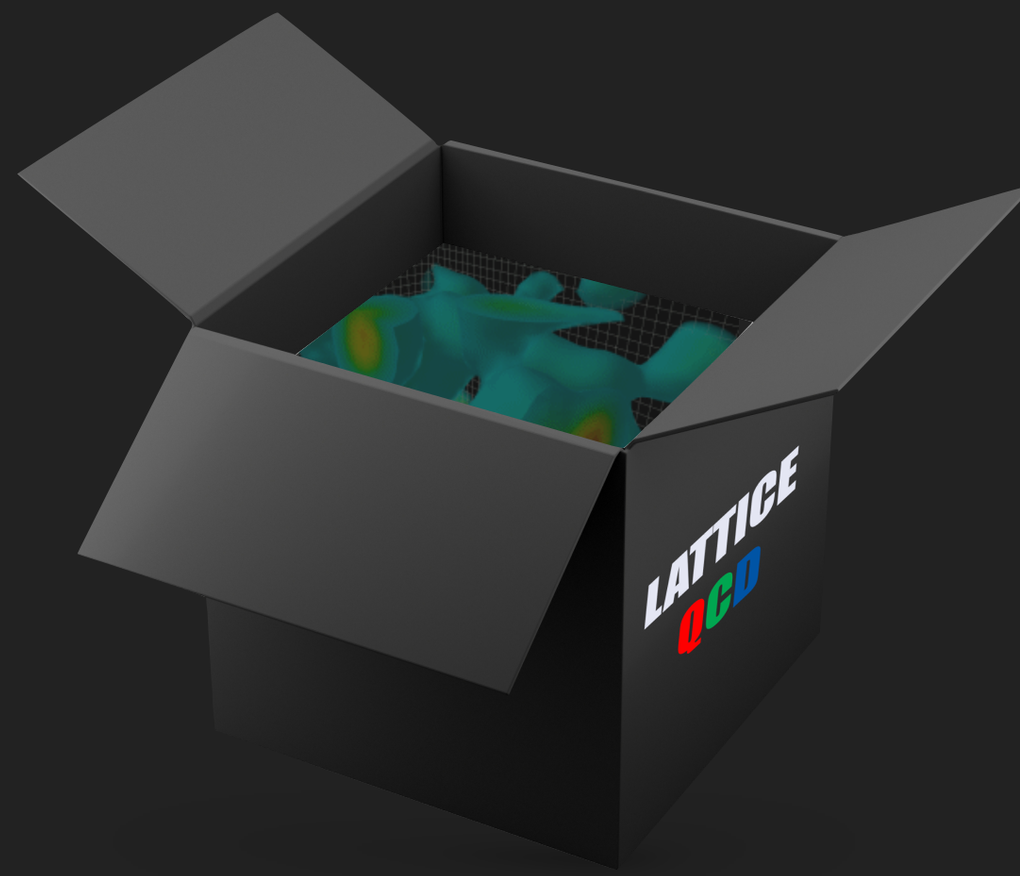


P Gysbers et al, Nature Phys. 15 (2019) no.5, 428-431

LATTICE QCD



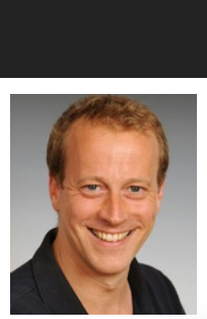
- Strong coupling definition of QCD
- Numerical tool for nonperturbative QCD calculations
  - Discretise and compactify spacetime
  - Requires integration over 10^{12} degrees of freedom in current calculations!
  - Major algorithmic and computational challenge
  - Solve using importance sampling Monte Carlo



NPLQCD COLLABORATION

- Case study LQCD with unphysical quark masses (m_π~800 MeV, 450 MeV)

1. Spectrum and scattering of light nuclei (A<5) [PRD 87 (2013), 034506]
2. Nuclear structure: magnetic moments, polarisabilities (A<5) [PRL **113**, 252001 (2014), PRL **116**, 112301 (2016)]
3. Nuclear reactions: np→dγ [PRL **115**, 132001 (2015)]
4. Gamow-Teller transitions: pp→dev, $g_A(^3H)$ [PRL **119** 062002 (2017)]
5. Double β decay: pp→nn [PRL **119**, 062003 (2017)]
6. Gluon structure (A<4) [PRD **96** 094512 (2017)]
7. Scalar/tensor currents (A<4) [PRL **120** 152002 (2018)]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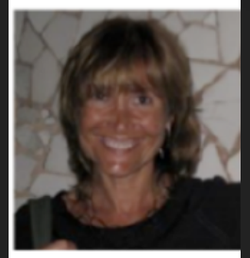
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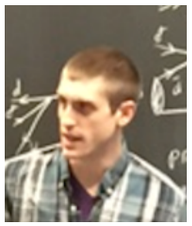
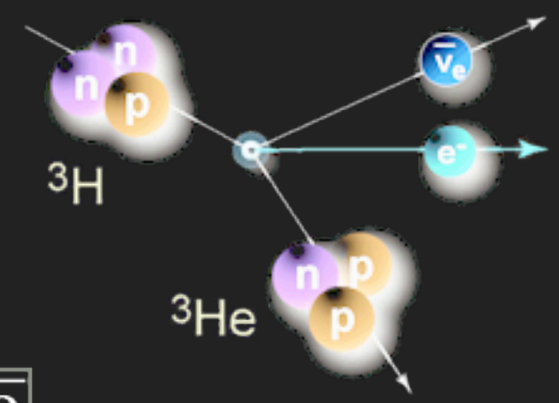

Mike Wagman
MIT


Phiala Shanahan
MIT

+ Arjun Gambhir + David Murphy

TRITIUM BETA DECAY



- Tritium decay half life

$$\frac{(1+\delta_R) f_V}{K/G_V^2} t_{1/2} = \frac{1}{\langle \mathbf{F} \rangle^2 + f_A/f_V \, g_A^2 \langle \mathbf{GT} \rangle^2}$$

half-life

vector ME

axial ME

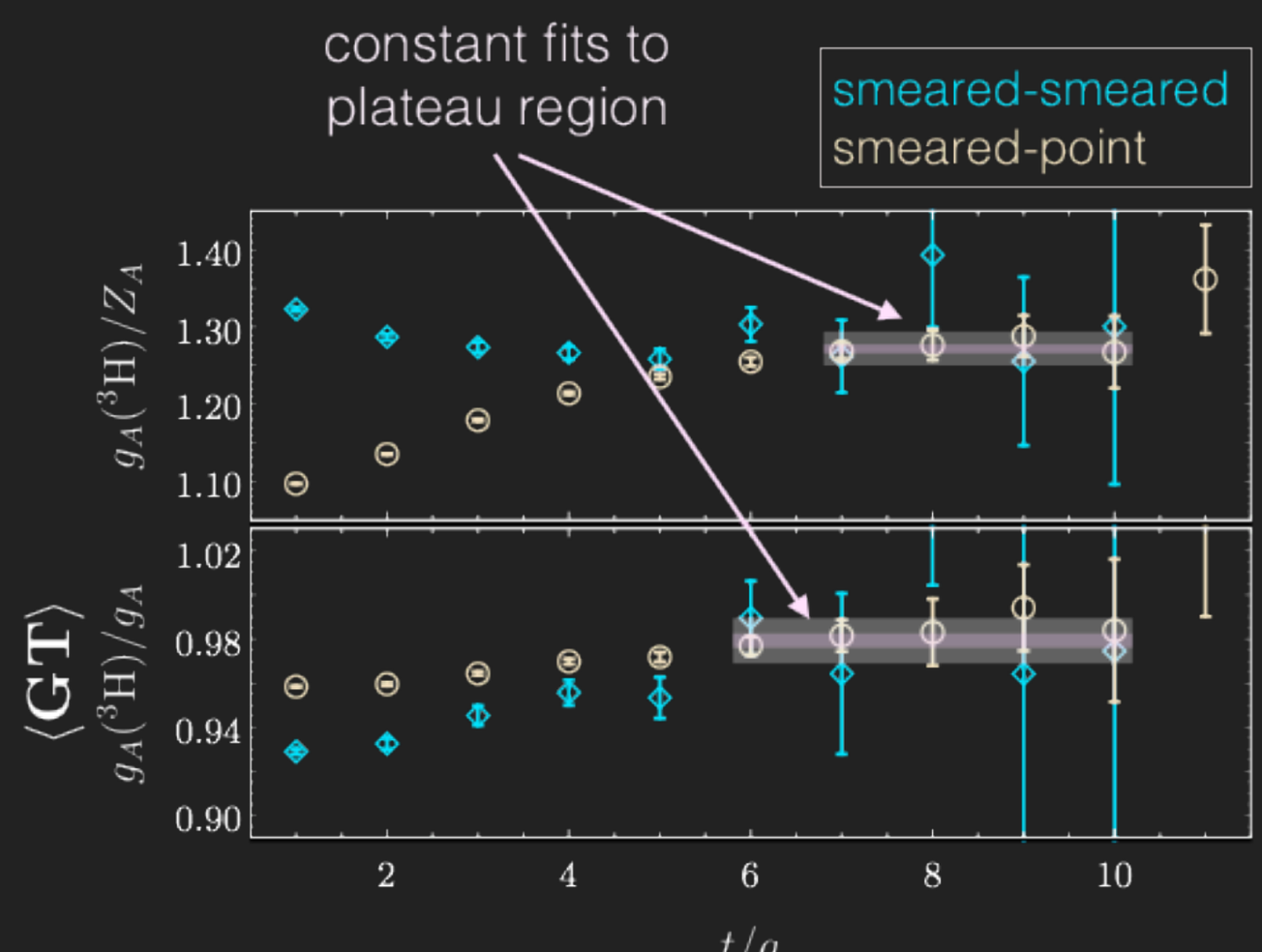
known from theory or expt.

- Biggest uncertainty in

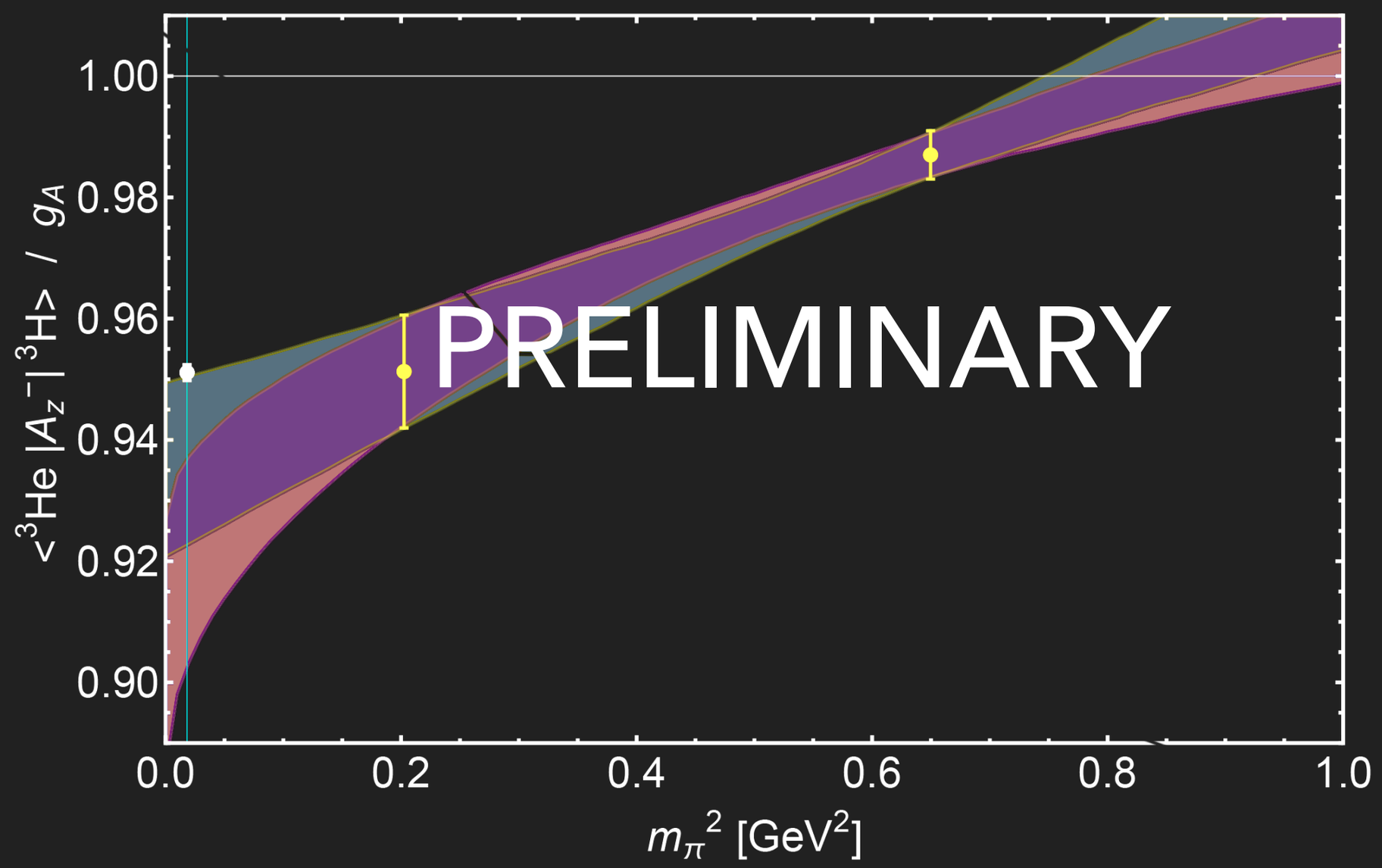
$$g_A \langle \mathbf{GT} \rangle = \langle {}^3\mathrm{He} | \overline{\mathbf{q}} \gamma_\mathbf{k} \gamma_5 \tau^- \mathbf{q} | {}^3\mathrm{H} \rangle$$

- Form ratios of correlators to cancel leading time-dependence:

$$\frac{\overline{R}_{^3\mathrm{H}}(t)}{\overline{R}_p(t)} \xrightarrow{t\to\infty} \frac{g_A(^3\mathrm{H})}{g_A} = \langle \mathbf{GT} \rangle$$

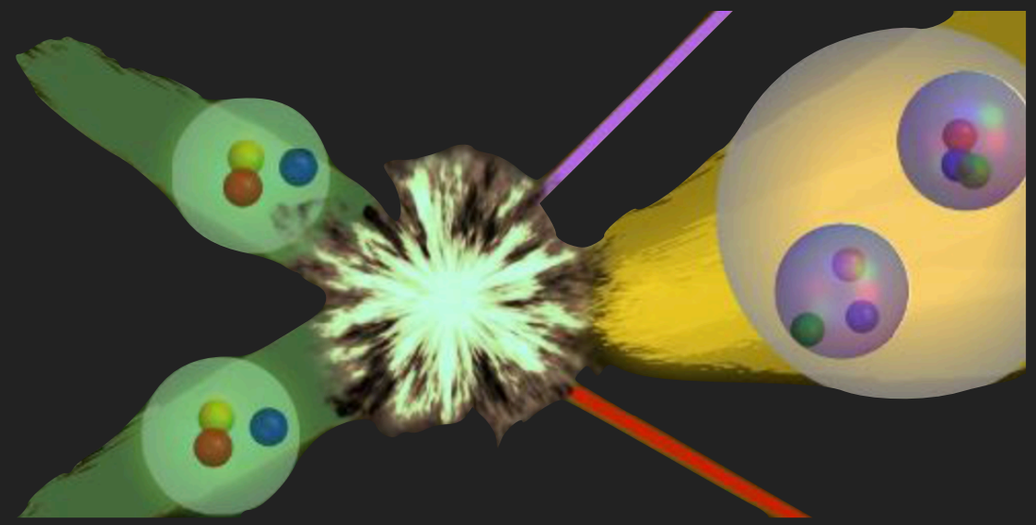


MASS DEPENDENCE OF TRITON AXIAL CHARGE

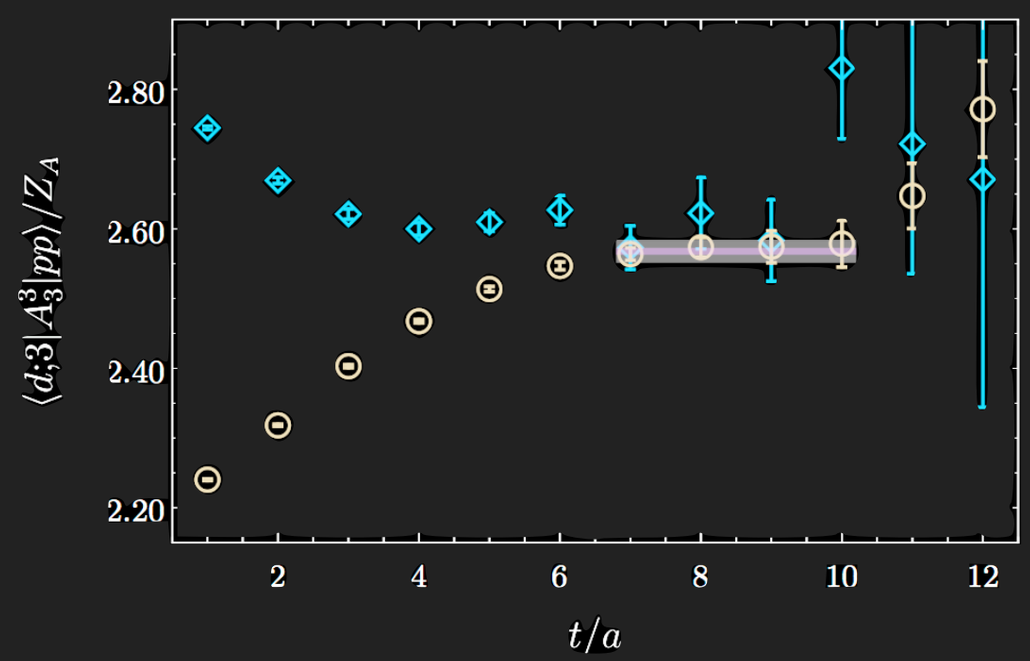


[NPLQCD PRL **119**, 062002 (2017), PRL **119**, 062003 (2017)]

PP FUSION



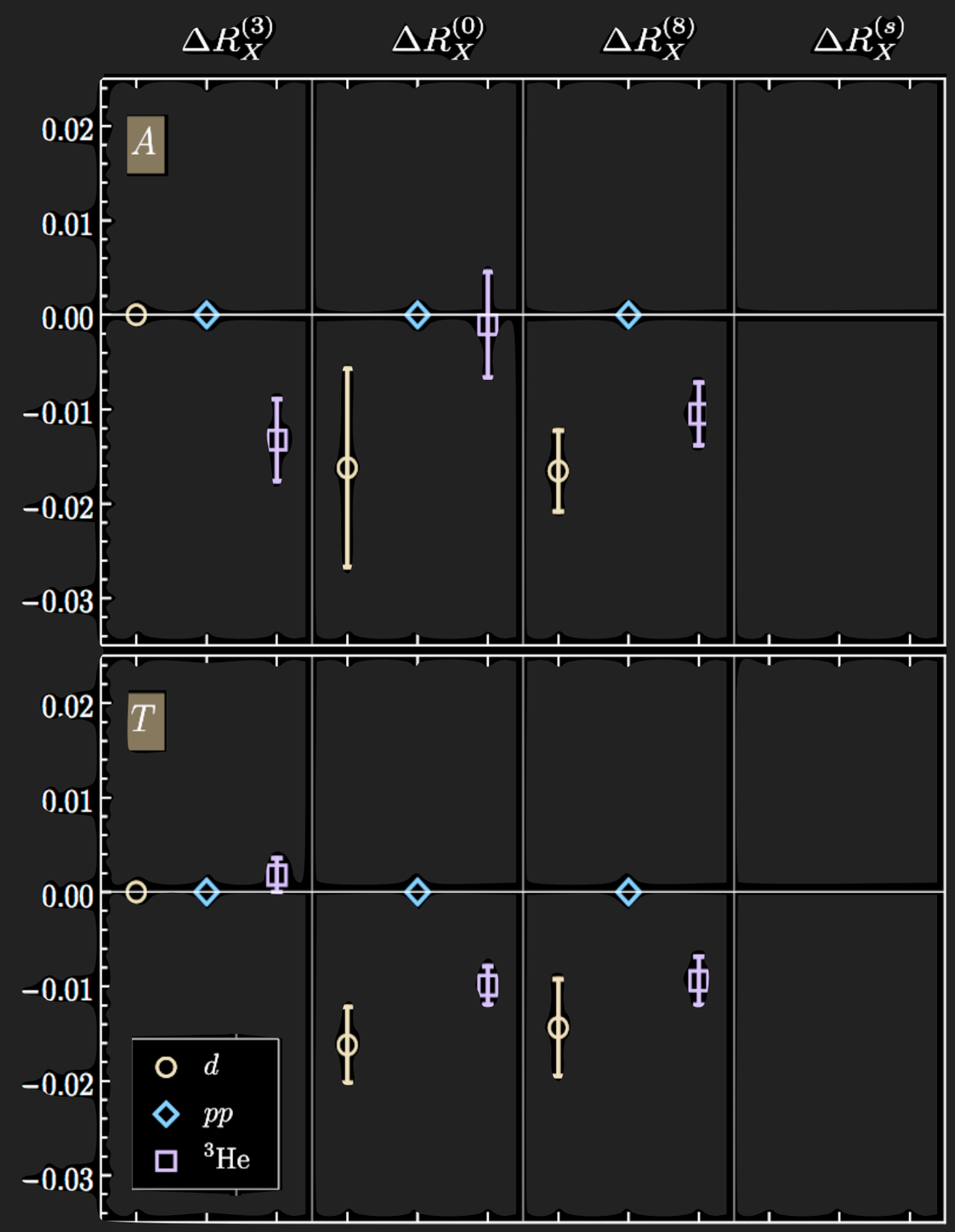
- Axial transition in two nucleon system: $pp \to de^+\nu$, $\mu d \to nn\nu$, $\nu d \to ppe^-$
- Important EFT contribution form two-body currents
- First LQCD calculation of $pp \to de\nu$ [NPLQCD PRL **119**, 062002 (2017)]
- Determines counter-term at similar precision to knowledge from pheno
- Goal: precise prediction for current MuSun experiment



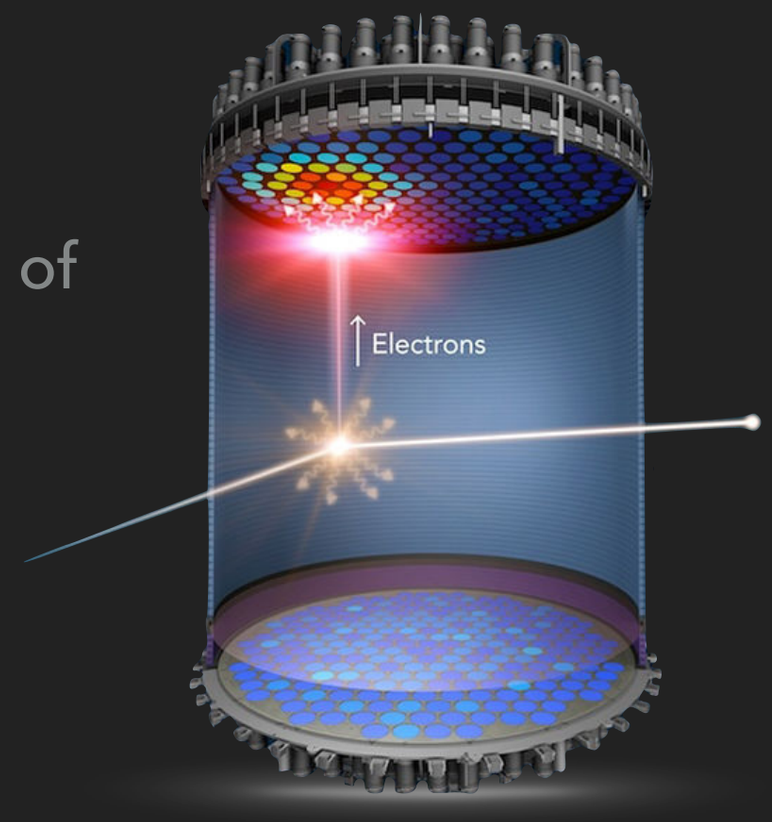
[NPLQCD, PRL **120**, 152002 (2018)]

AXIAL AND TENSOR CURRENTS

- Complete flavour breakdown of nuclear effects on axial and tensor matrix elements
  - Calculated forward limit MEs for A=1,2,3
  - Disconnected contributions using hierarchical probing [Gambhir et al.]
- Axial and tensor MEs show small nuclear effects
  - Axial consistent with experiment



DARK MATTER INTERACTIONS



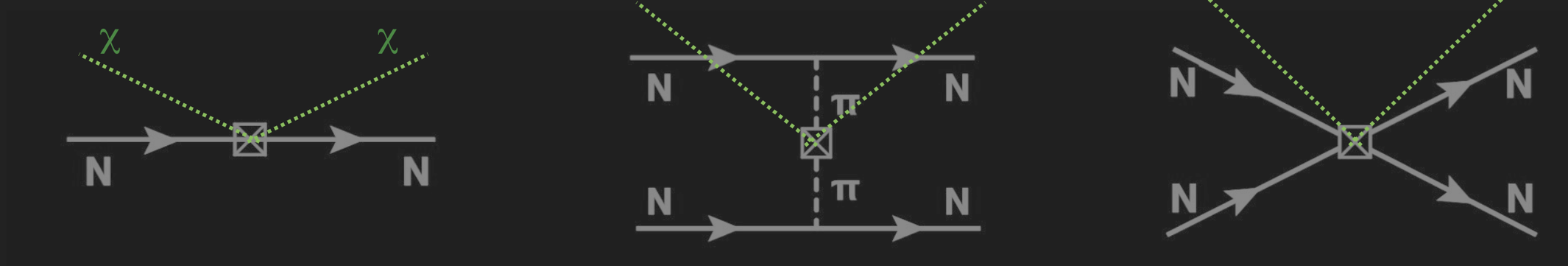
- DM direct detection experiments search for recoil of nucleus from DM scattering
- One popular class of DM interactions is through scalar exchange

$$\mathcal{L} = \frac{G_F}{2} \sum_q \kappa_q (\overline{\chi}\chi)(\overline{q}q)$$

- Direct detection depends on nuclear matrix element

$$\overline{m}\langle Z, N | \overline{u}u + \overline{d}d | Z, N \rangle$$

- At hadronic/nuclear level

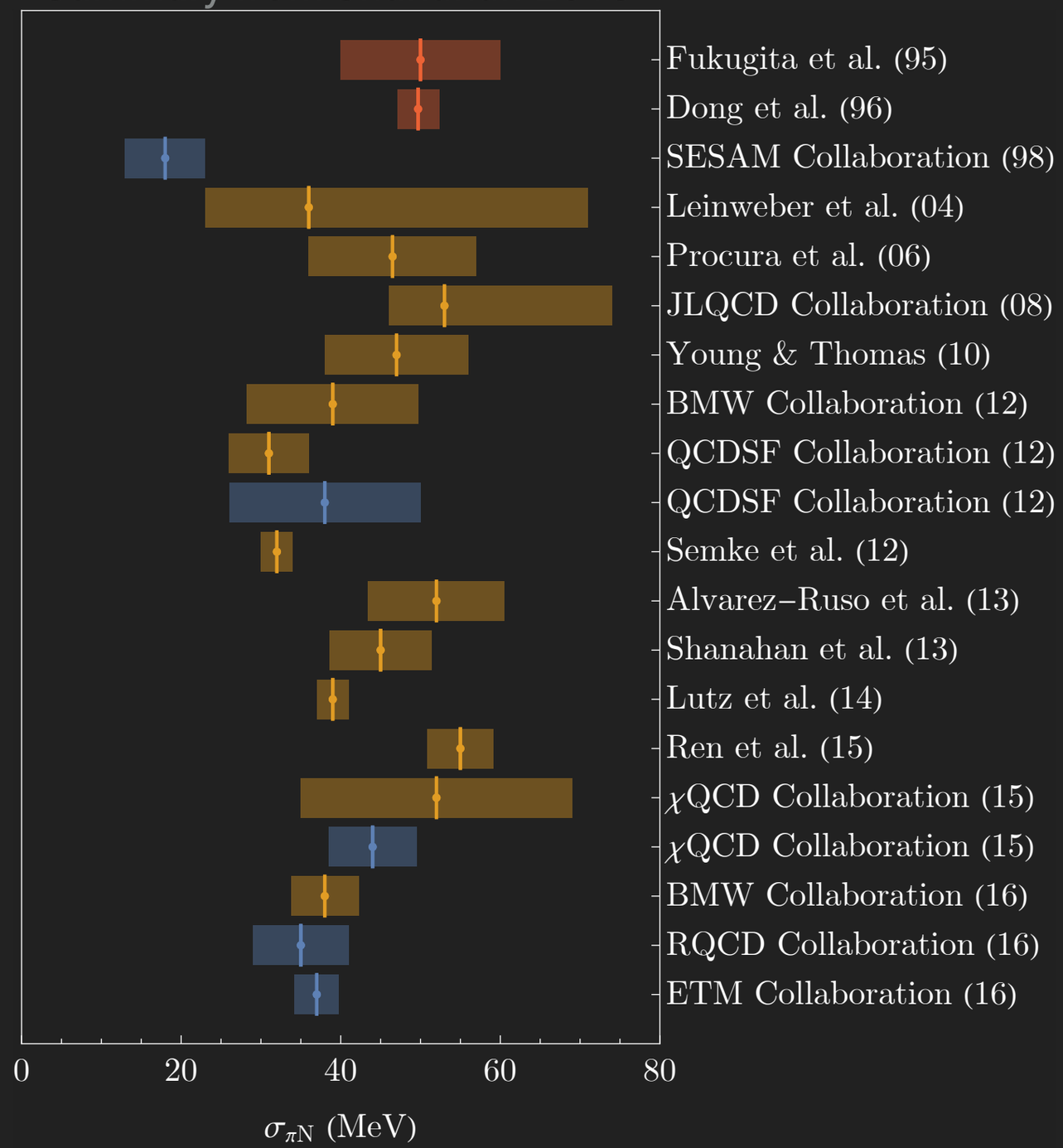


NUCLEON SCALAR COUPLING

- Single nucleon contribution

- Calculated in LQCD
- Results from many groups

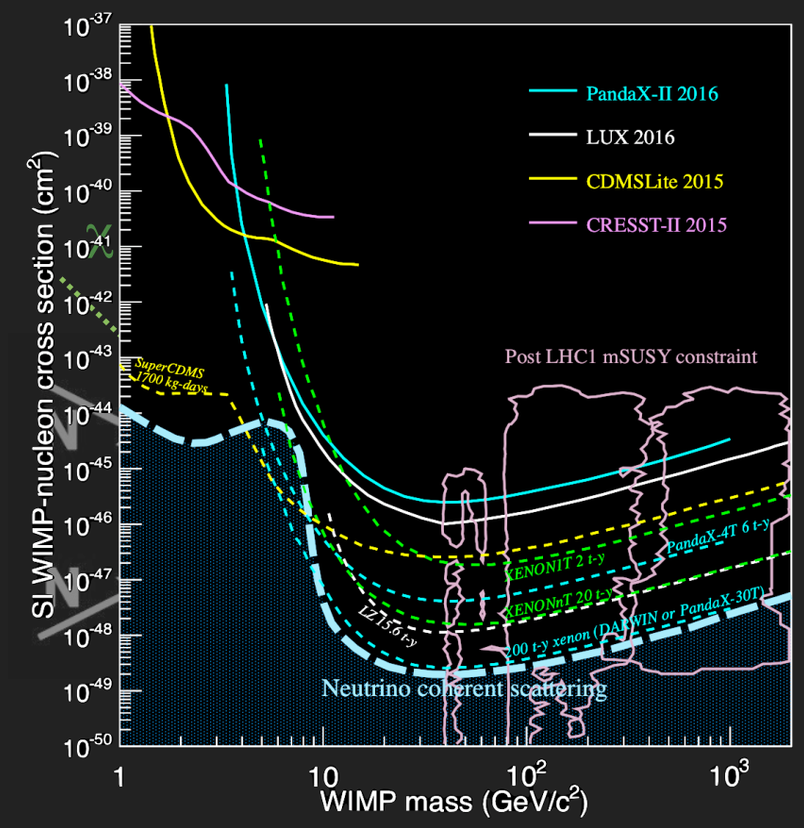
Summary from Shanahan 2016



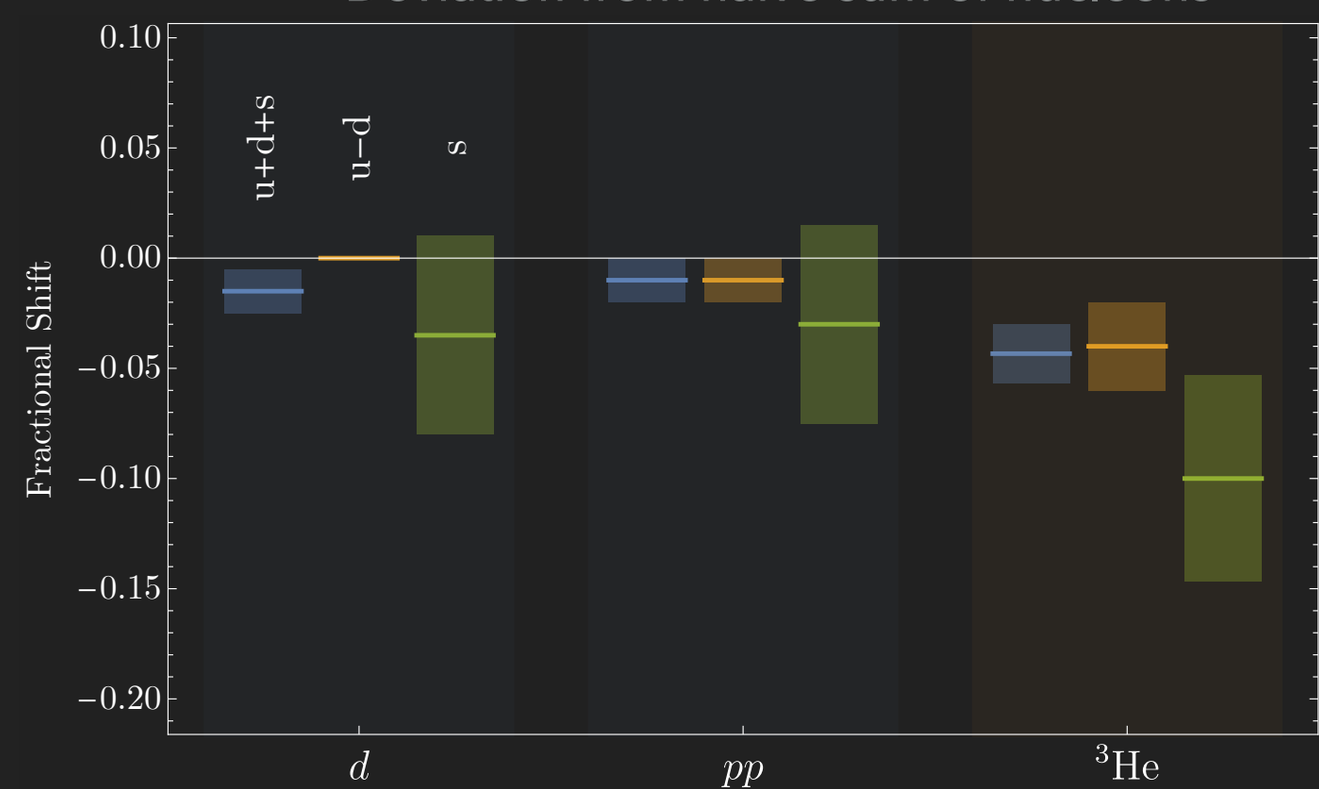
[NPLQCD, PRL 2018]

NUCLEAR EFFECTS CAN BE LARGE!

- LQCD study of scalar couplings for A=1,2,3
- Unexpectedly large (~10%) deviation from sum of nucleon matrix elements for A=3
- Naive extrapolation to ^{136}Xe implies significant consequences for dark matter detection sensitivity

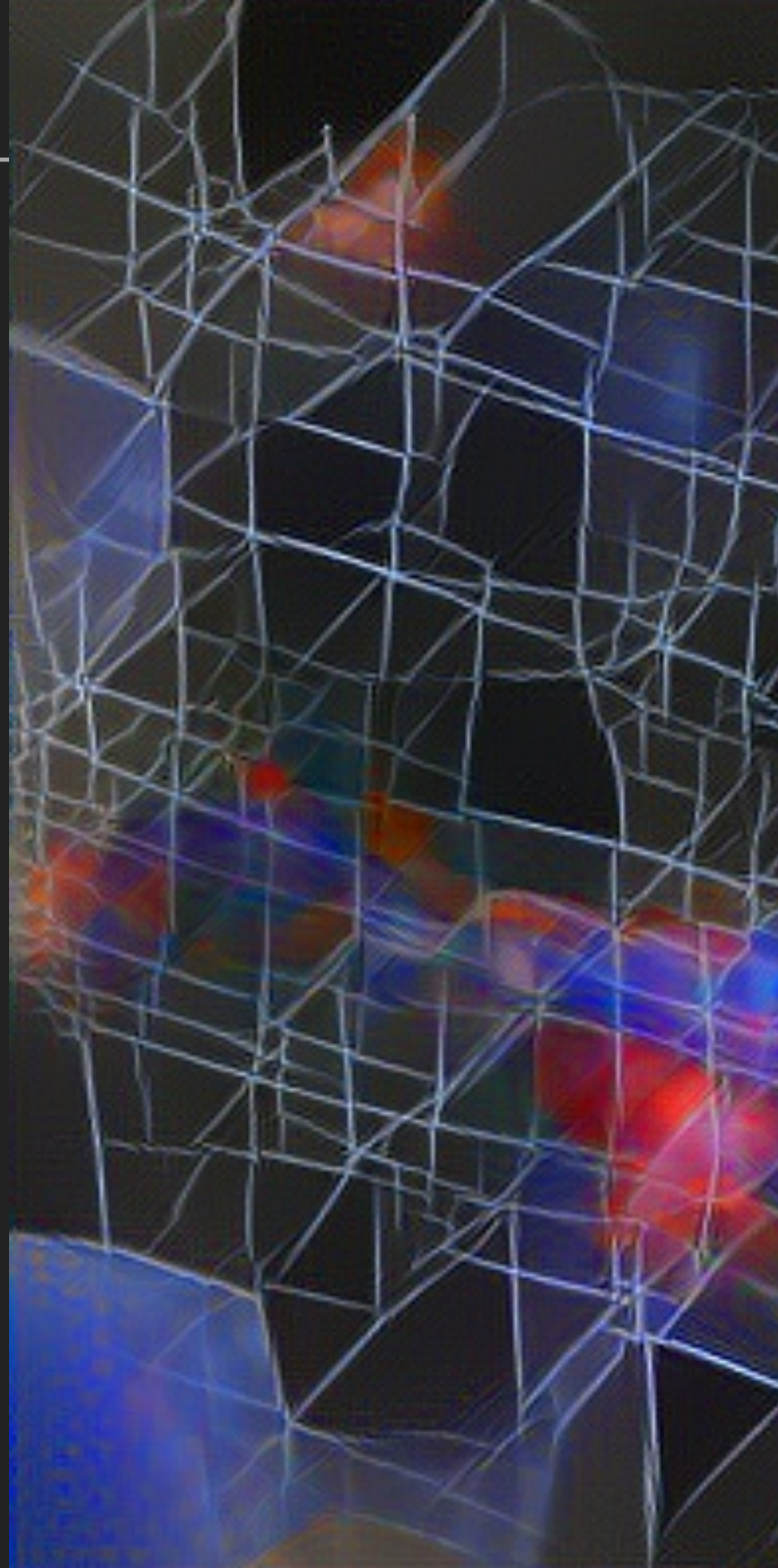


Deviation from naive sum of nucleons



OUTLOOK

- Nuclei are under study directly from QCD
  - Comprehensive study of matrix elements at heavy quark masses
- Prospect of a quantitative connection to QCD makes this an exciting time for nuclear physics
  - Important role in current and upcoming intensity frontier experimental program
  - Learn many interesting things about the nature of hadrons and nuclei along the way
- Next steps: nuclear form factors



-FIN-