WILL DETMOLD MIT

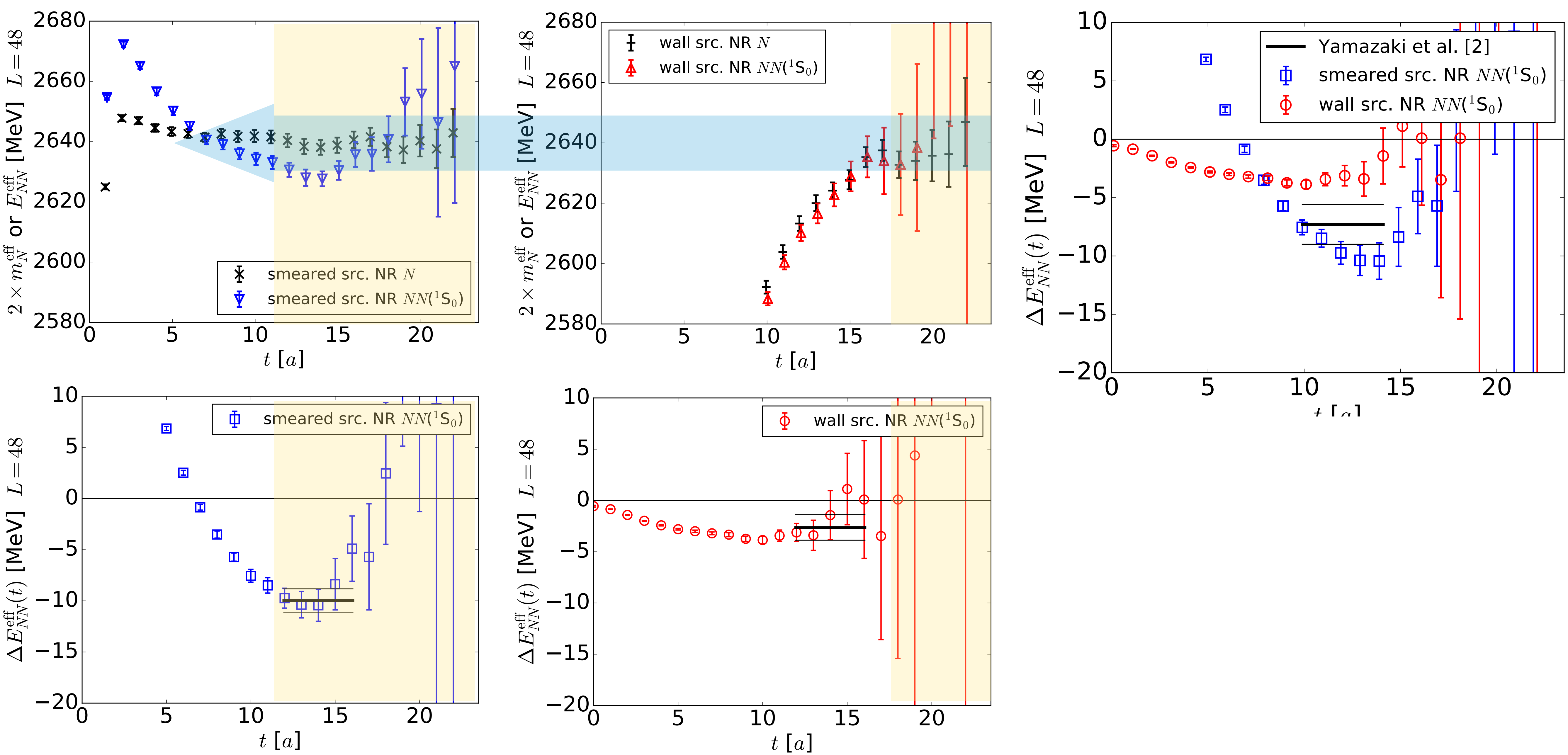
# PROPERTIES OF LIGHT NUCLEI FROM LATTICE QCD

Santa Fe Lattice Meeting 2019, Santa Fe, August 30th 2019

# HAL2016

$$R(t) = \frac{C_{NN}(t)}{(C_N(t))^2}$$

**from Iritani et al [HALQCD], JHEP1610(2016)101**



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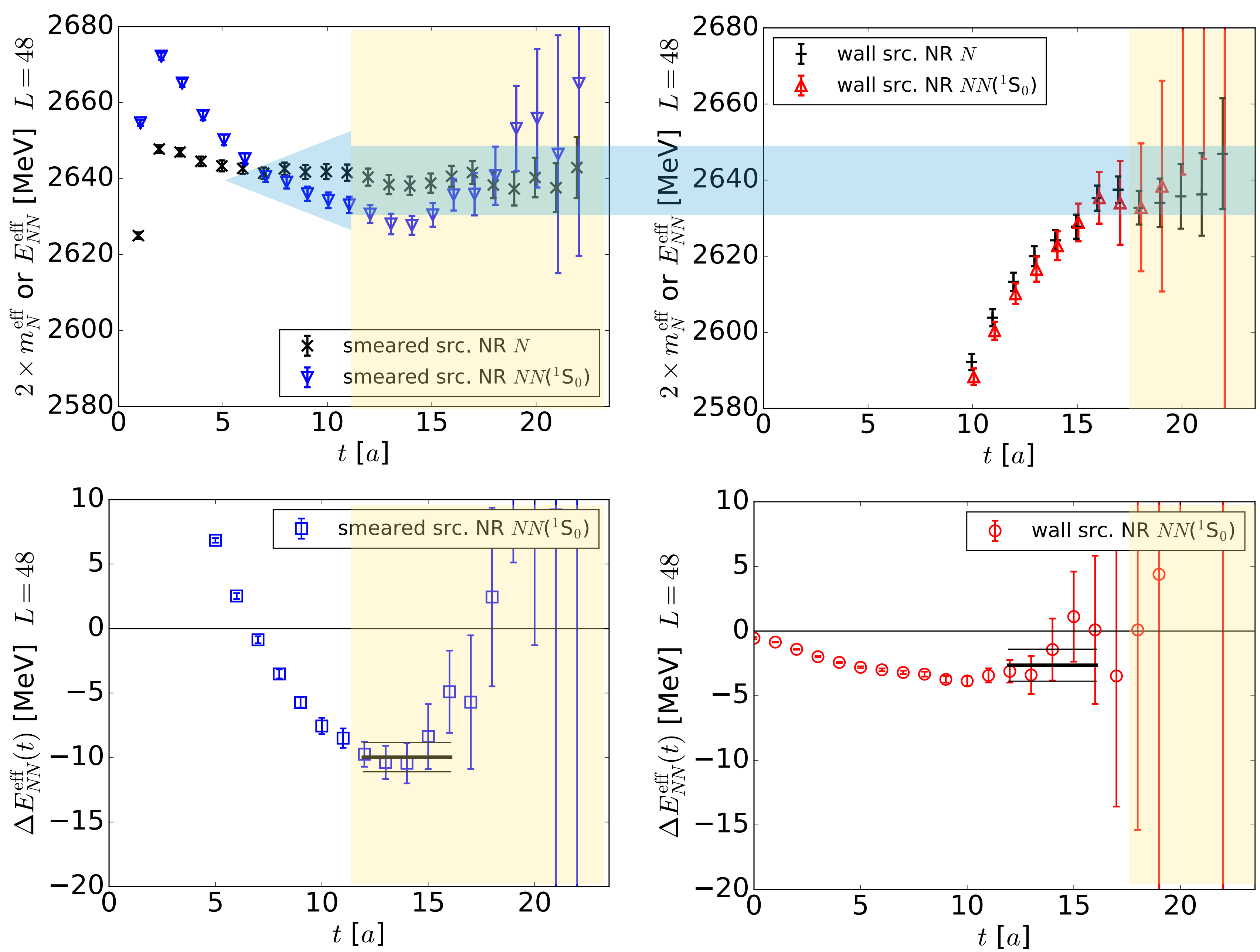
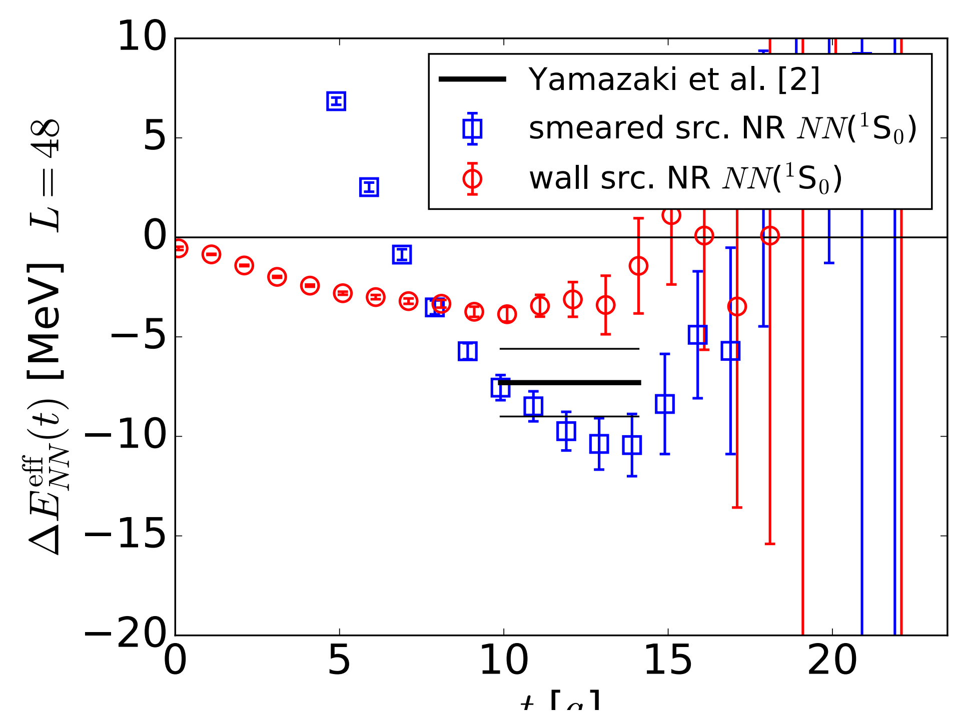
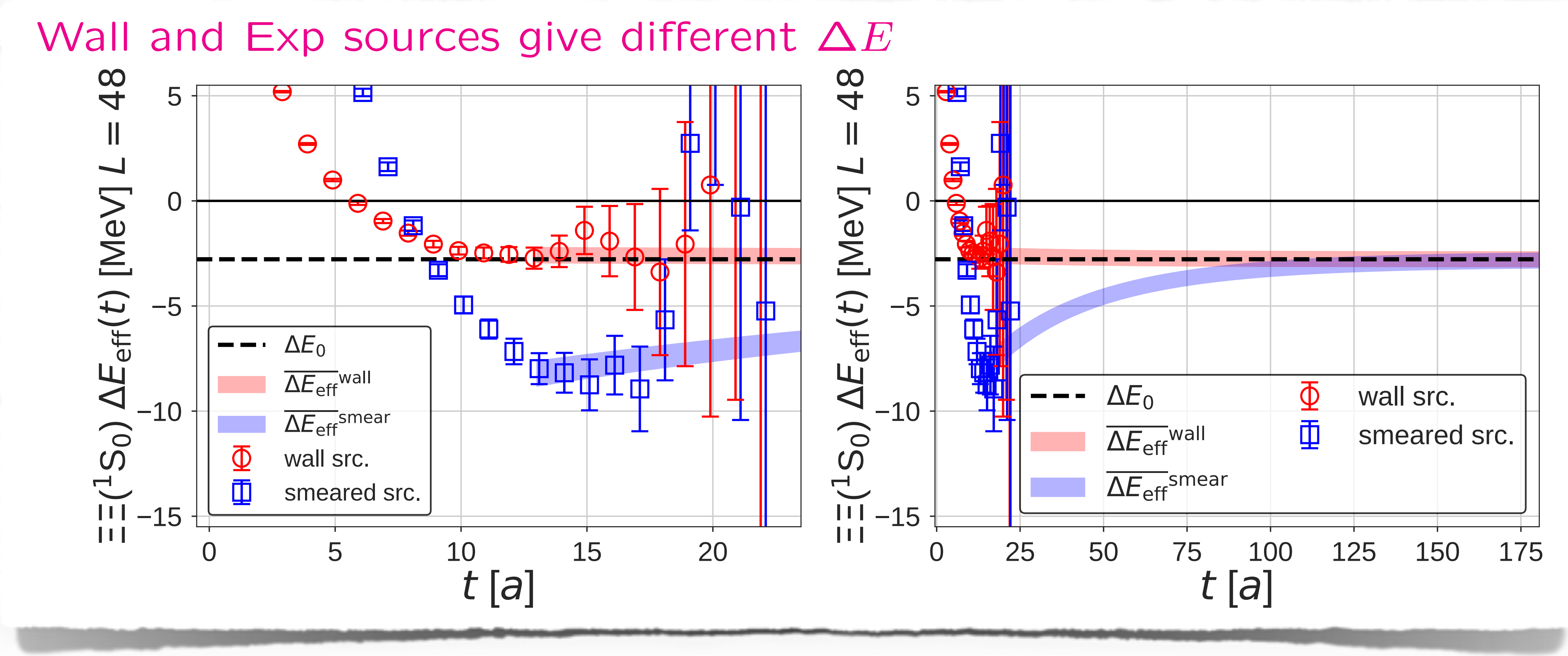



When single hadrons are in ground state there is consistency between extracted energy or energy shifts

# HAL2016

**from Iritani et al [HALQCD], JHEP1610(2016)101**




NB: this fig now for ΞΞ rather than NN, but same behaviour seen

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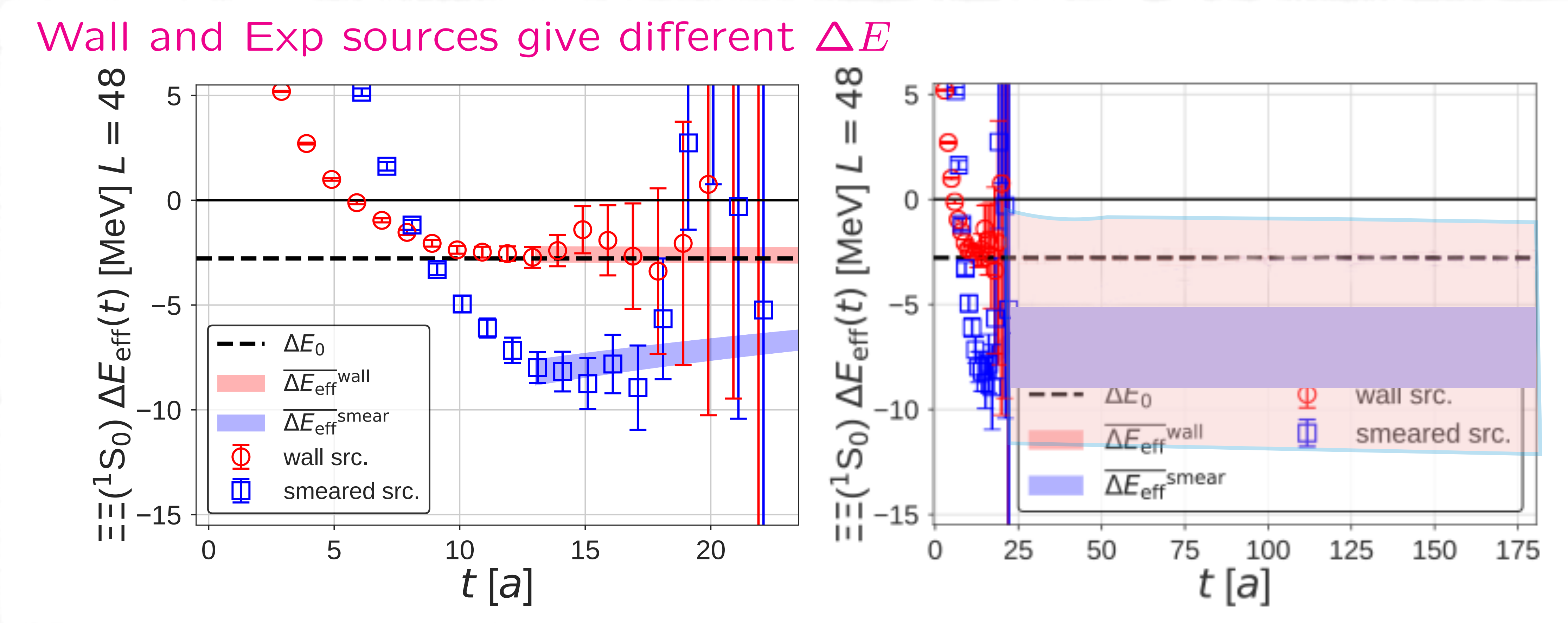
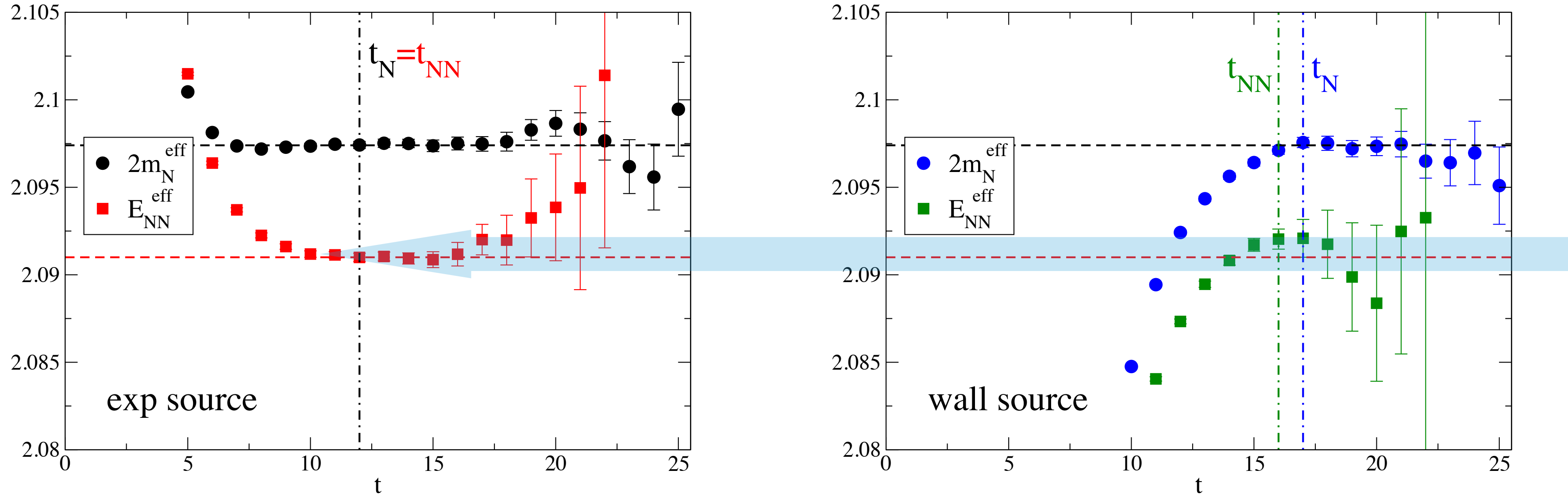



For more details, see extensive high statistics study by PACS-CS
T. Yamazaki et al [PACS collaboration], LATTICE 2017 arXiv:1710.08066
updates in YITP workshop in 2019
http://www2.yukawa.kyoto-u.ac.jp/~flqcd2019/slides/Yamazaki.pdf

NB: this fig now for ΞΞ rather than NN, but same behaviour seen

# PACS 2017 HIGH STATISTICS

Effective $2m_N$ and $E_{NN}$

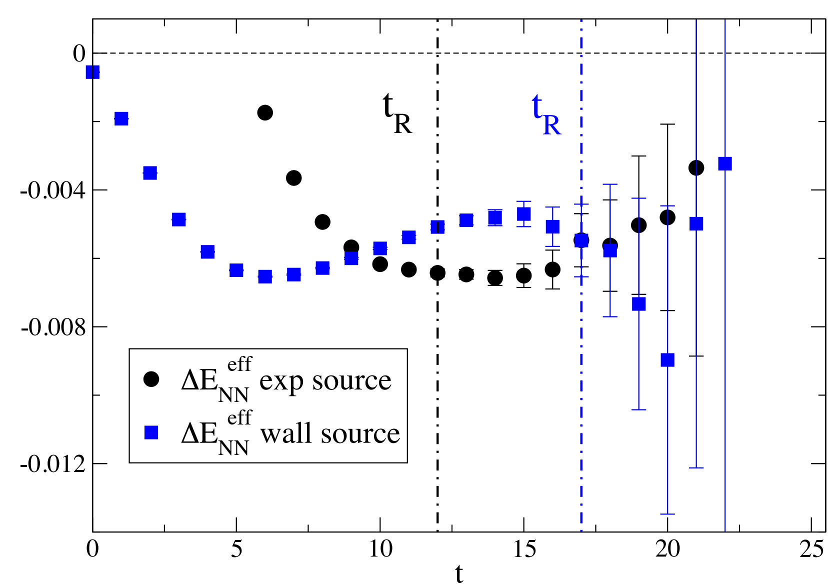



$t_N \sim t_{NN} \sim 12$ $\qquad$ $t_{NN} \sim 16, \;\; t_N \sim 17$

Completely consistent in plateau regions

| $L$ | $T$ | source | $N_{\text{meas}}$ |
|---|---|---|---|
| 16 | 64 | Exp | 15,544,000 |
| | | Wall | 8,307,200 |
| 20 | 64 | Exp | 5,504,000 |
| | | Wall | 4,480,000 |
| 32 | 64 | Exp | 10,496,000 |
| | | Wall | 8,307,200 |

Amazing statistics!




Completely consistent in plateau regions once single hadron in ground state

NB: have exp & wall rather than smeared & wall, quenched cfgs

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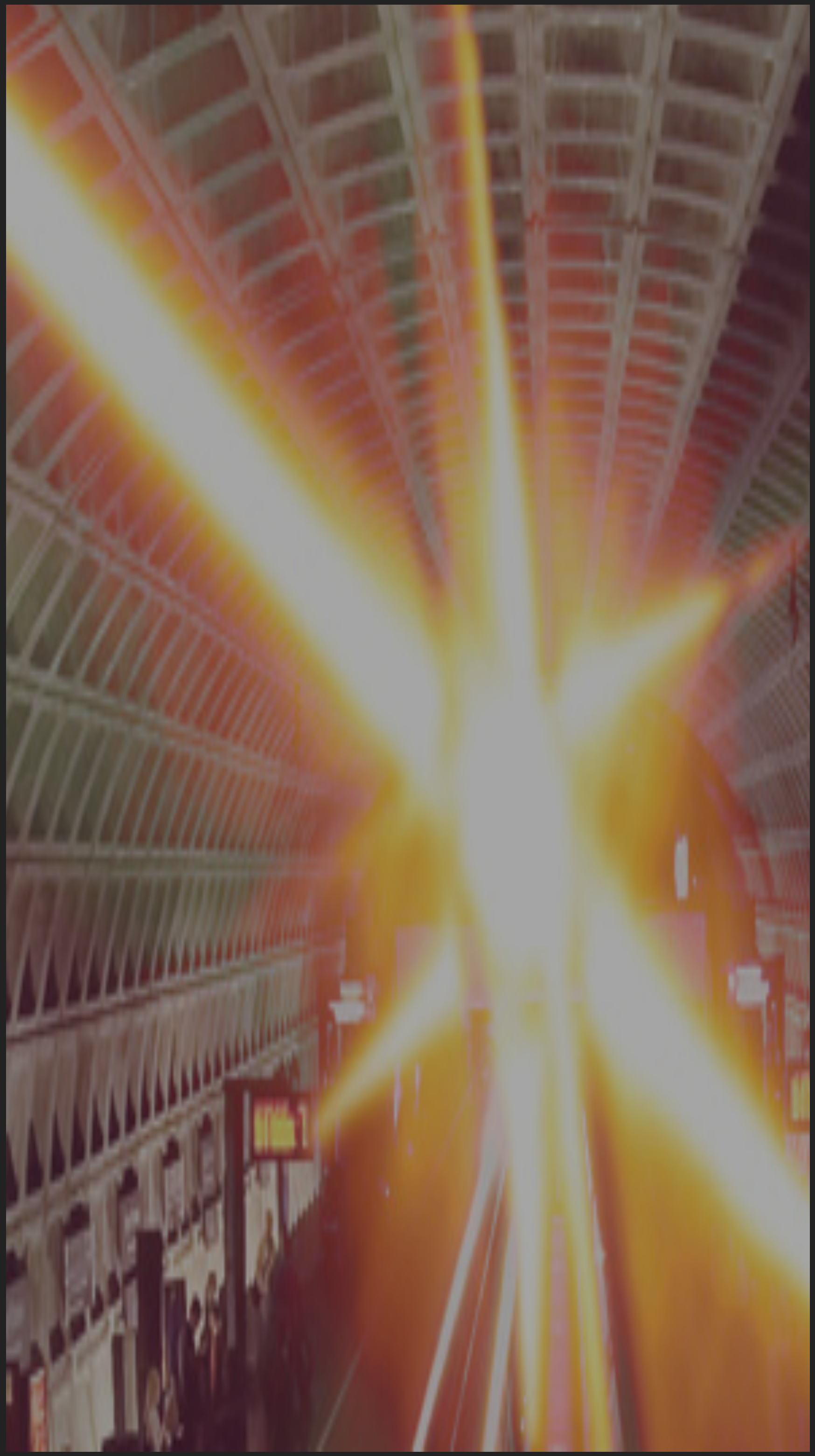
# PROPERTIES OF LIGHT NUCLEI FROM LATTICE QCD

Santa Fe Lattice Meeting 2019, Santa Fe, August 30th 2019

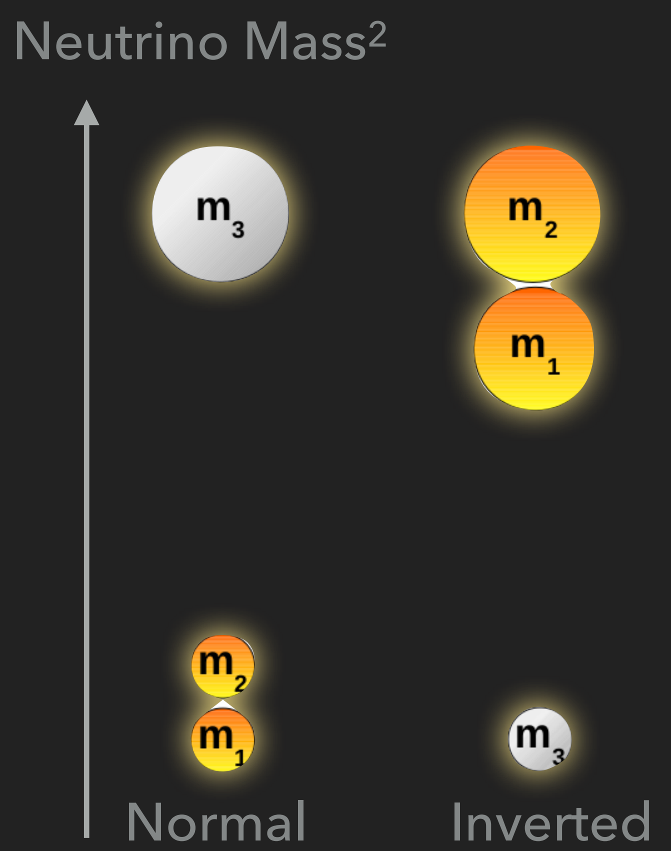
# THE INTENSITY FRONTIER

- Seek new physics through quantum effects
- Precise experiments
  - Sensitivity to probe the rarest interactions of the SM
  - Look for effects where there is no SM contribution
- Major component is nuclear targets
- Important focus of HEP/NP experimental program
  - Neutrino physics
  - Dark matter direct detection
  - Charged lepton flavour violation, EDMs, ββ-decay,

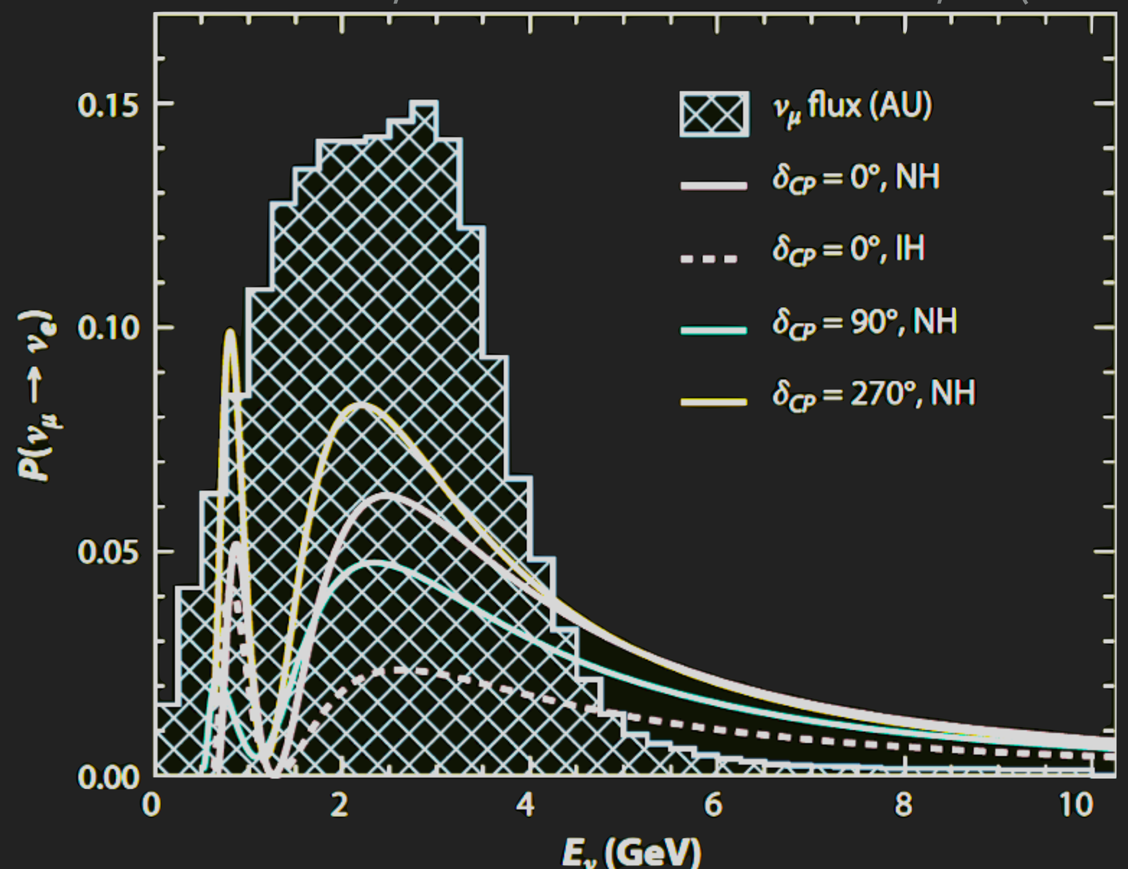


# LONG BASELINE NEUTRINO EXPERIMENTS

- Deep Underground Neutrino Experiment
  - Flagship facility for US HEP for next decades
  - Determine neutrino mass hierarchy and extract mixing parameters
- Neutrino scattering on argon target
  - Need fluxes/energies to high accuracy
  - Need to know interactions with argon over a wide range of energies

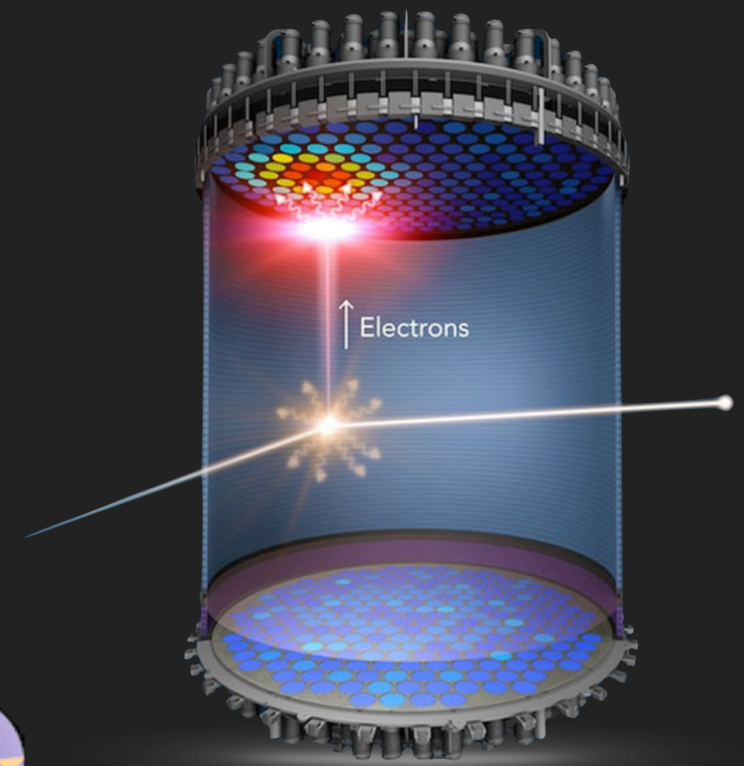


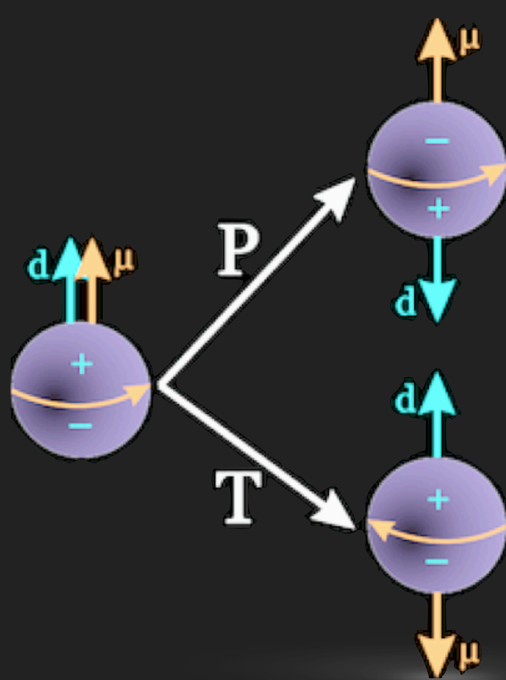

Diwan et al, Ann. Rev. Nucl. Part. Sci. 66, 47 (2016)

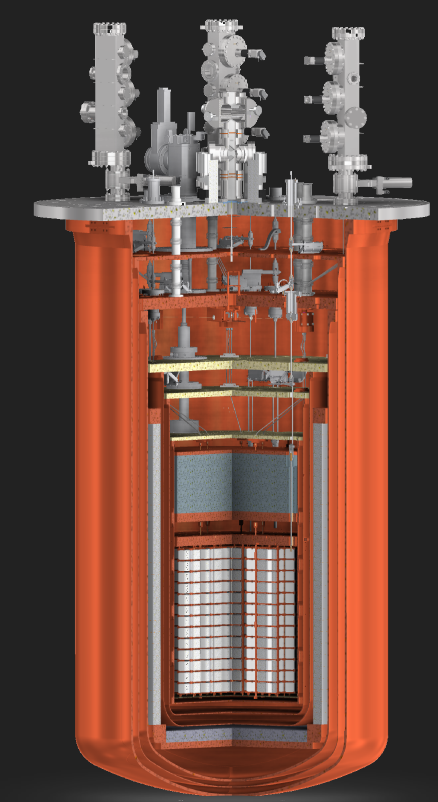


# NUCLEI IN NEW PHYSICS

- Scalar currents
  - Dark matter direct detection
  - Lepton flavour violation: μ2e
  - Precision spectroscopy
- Tensor currents
  - Electric dipole moments of neutrons and nuclei
- Neutrinoless double beta decay

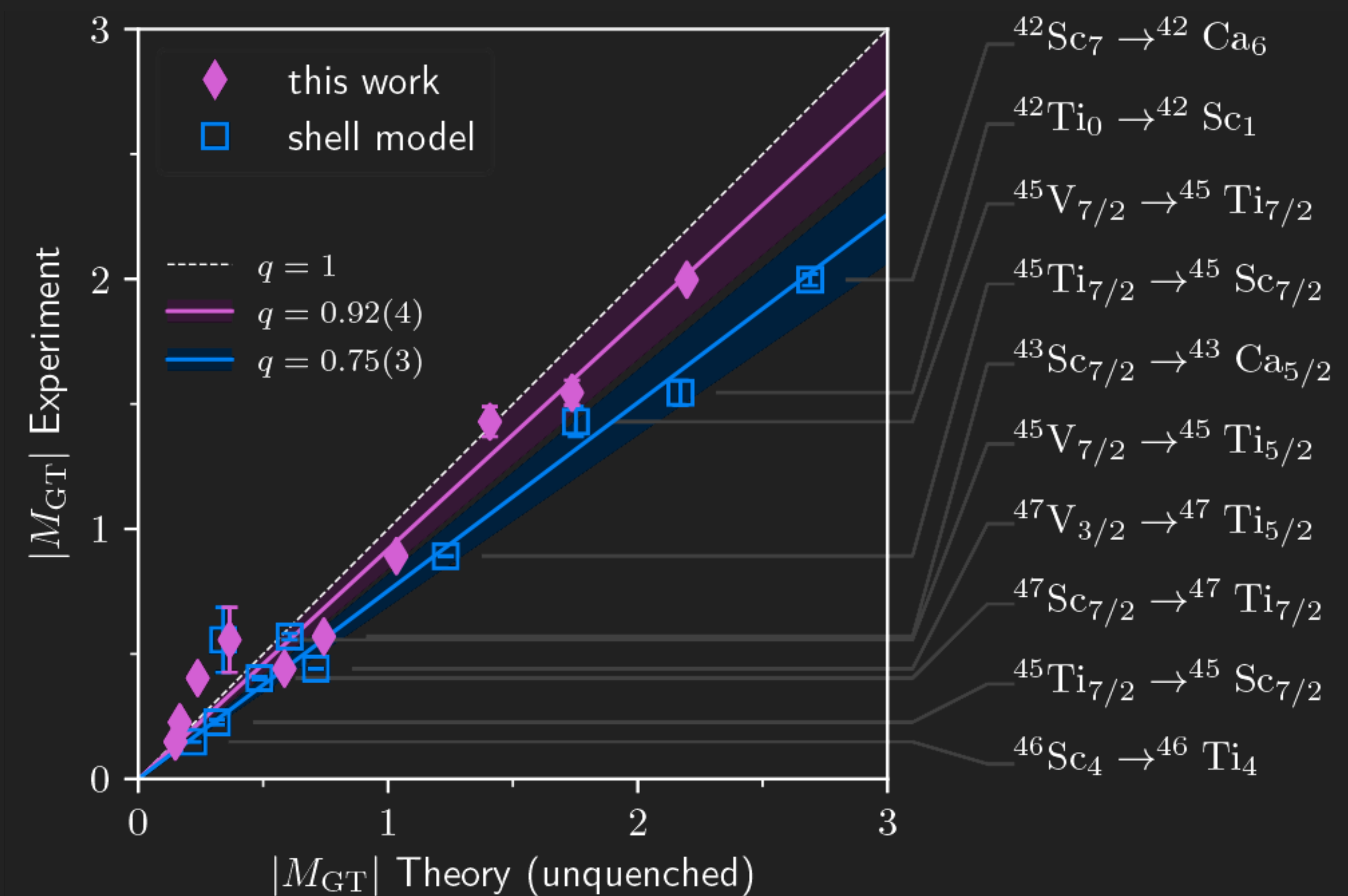


# NUCLEAR UNCERTAINTIES

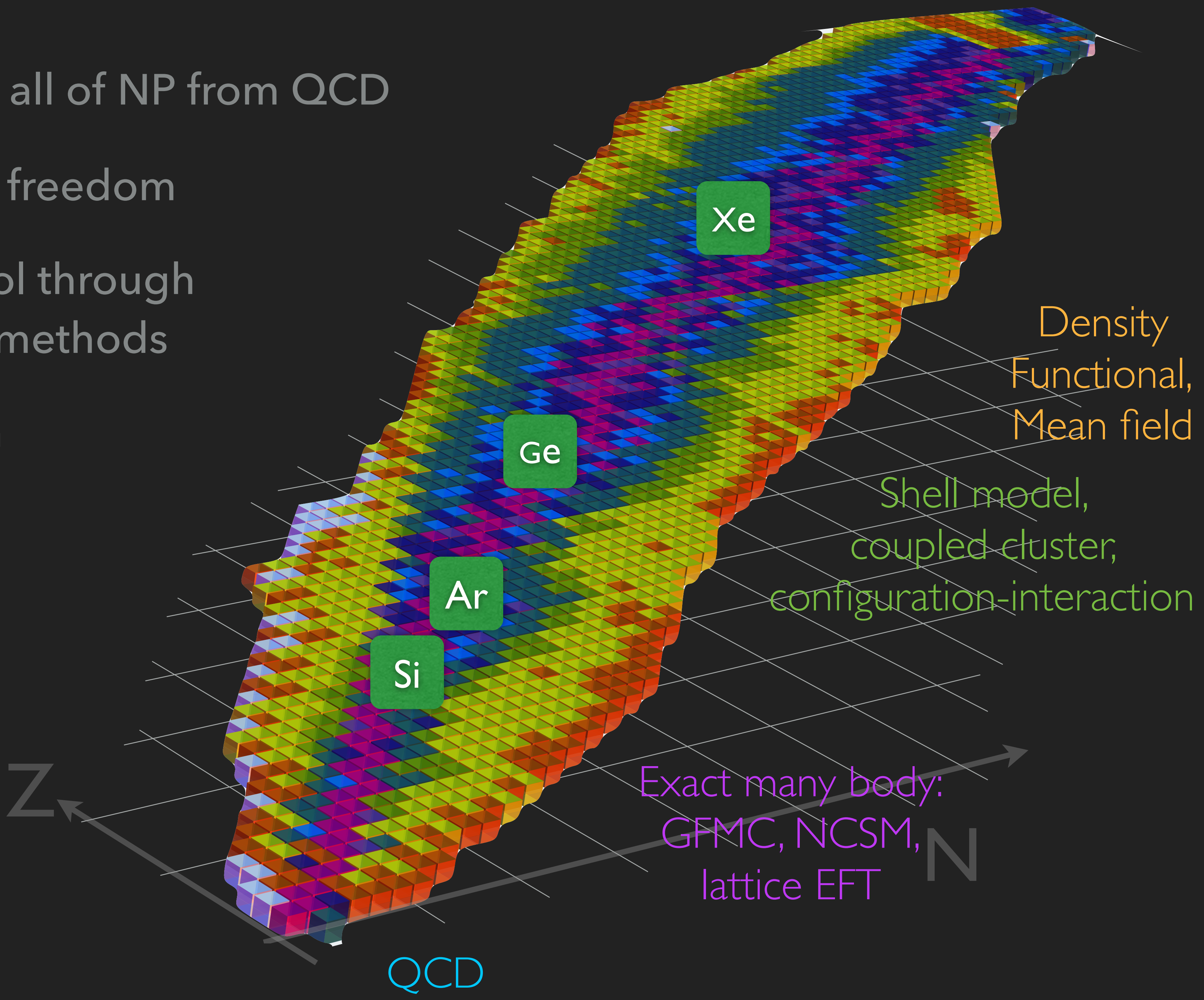
- How well do we know nuclear matrix elements?
- Gamow-Teller transitions in nuclei
  - Well measured for large range of nuclei (30<A<60)
  - Many nuclear structure calculations (shell-model,…) describe spectrum well
  - Matrix elements systematically off by 20-30%
  - Correct using 2 body currents
-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




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

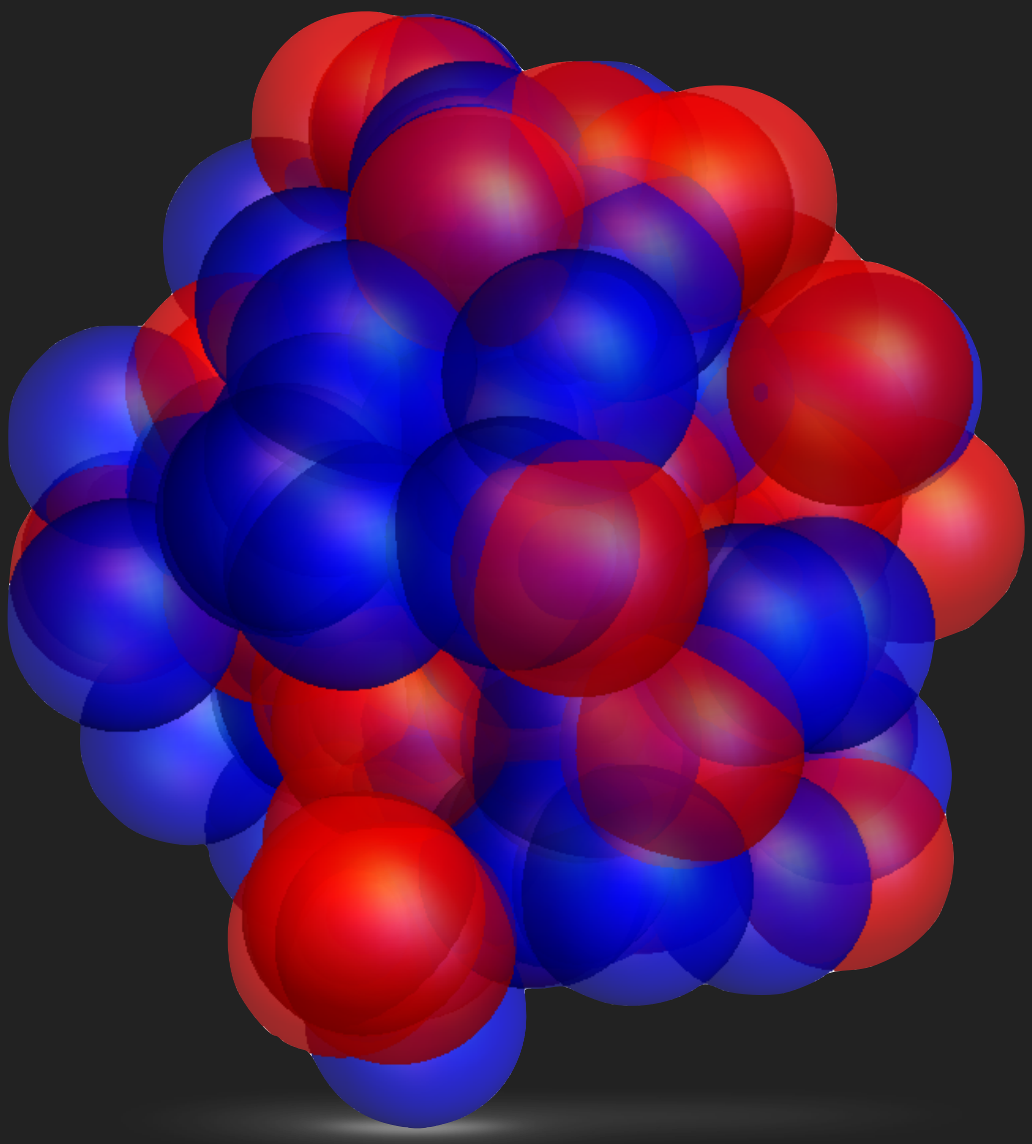
# PRECISION NUCLEAR PHYSICS

- Very challenging to explore all of NP from QCD
- Exploit effective degrees of freedom
- Establish quantitative control through linkages between different methods
  - QCD forms a foundation determines few body interactions & matrix elements
  - Match existing EFT and many body techniques onto QCD



# QCD FOR NUCLEAR PHYSICS

- Nuclear physics is Standard Model physics
  - Can compute the mass of lead nucleus ... in principle
- Complex physics
  - Wide range of scales
  - Closely spaced excitations
- Numerical challenges:
  - Statistical sampling
  - Contraction complexity



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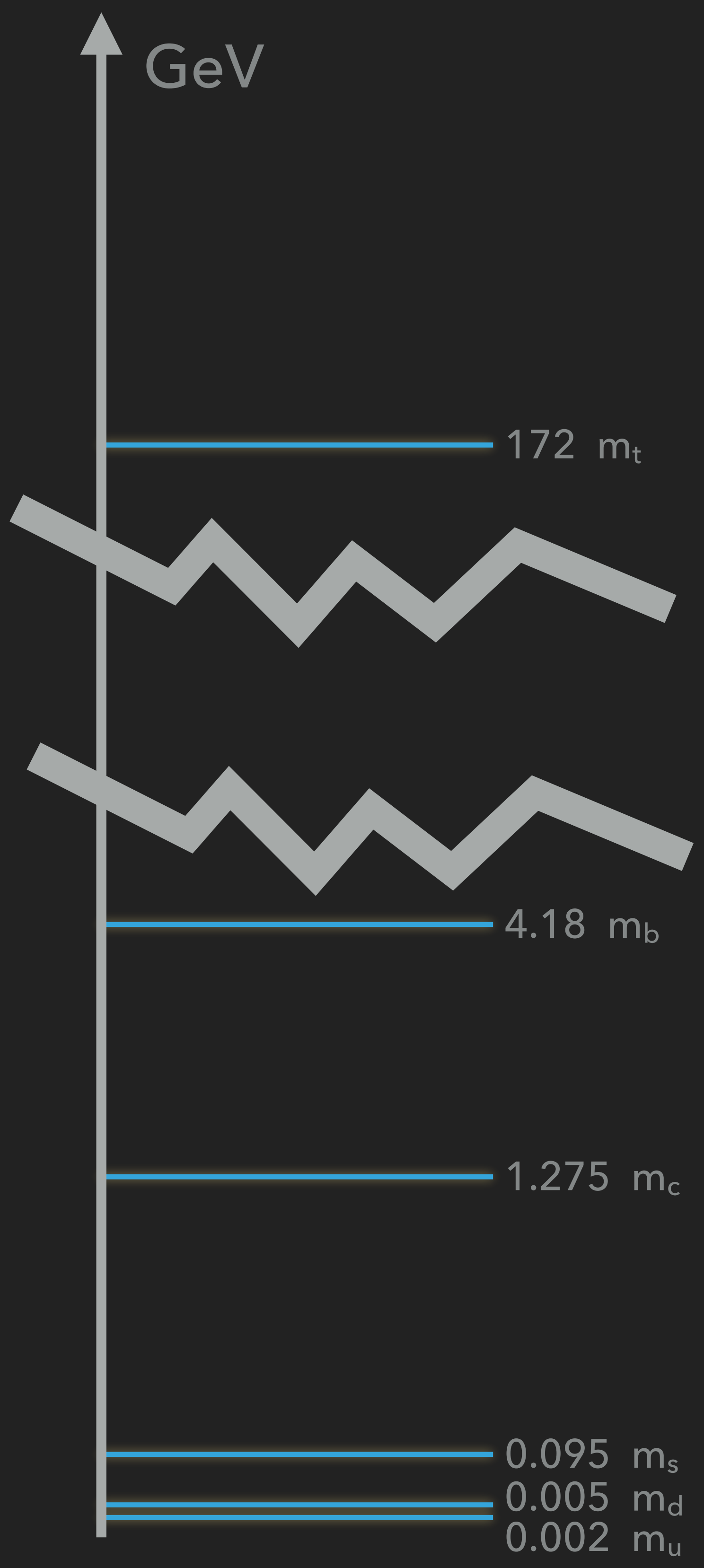

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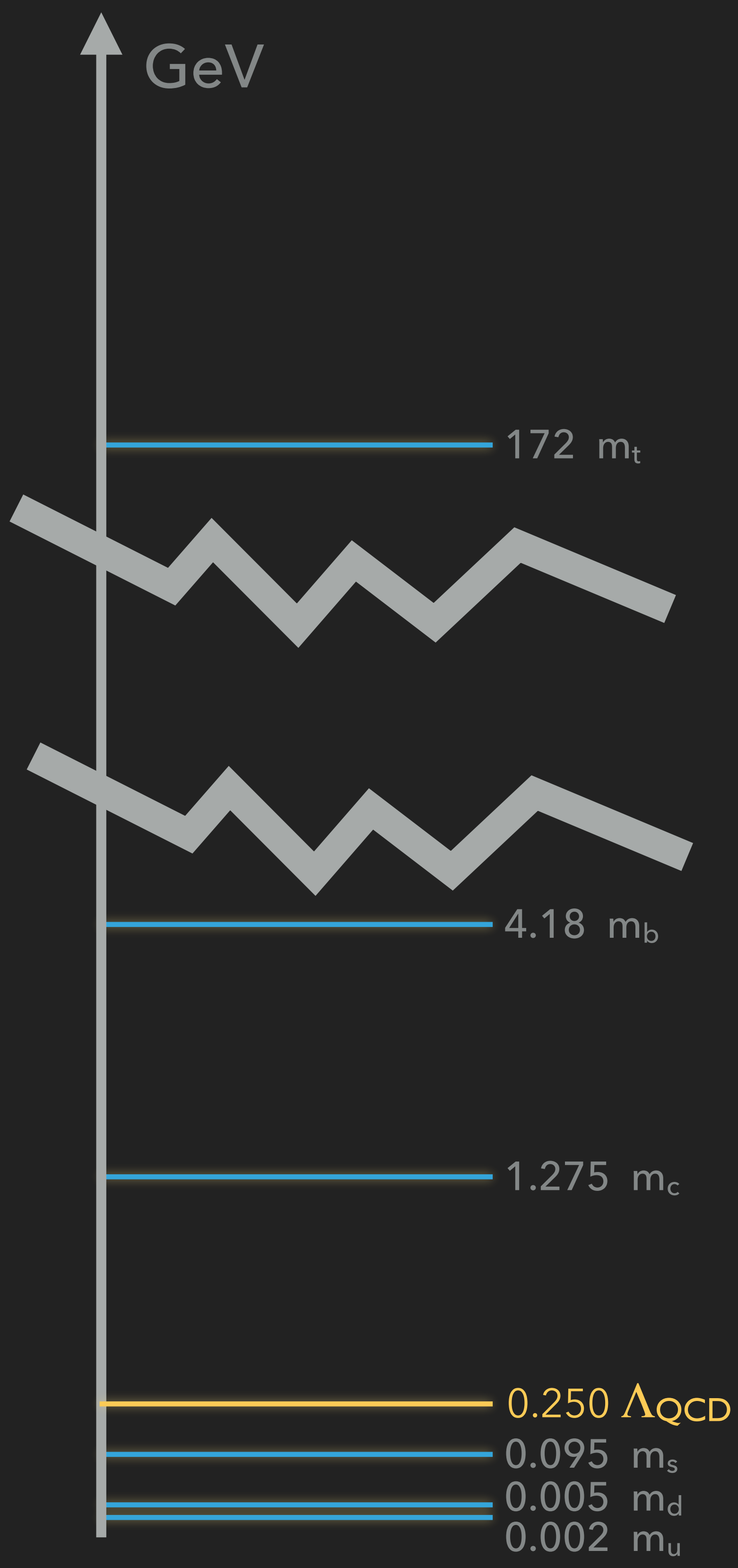

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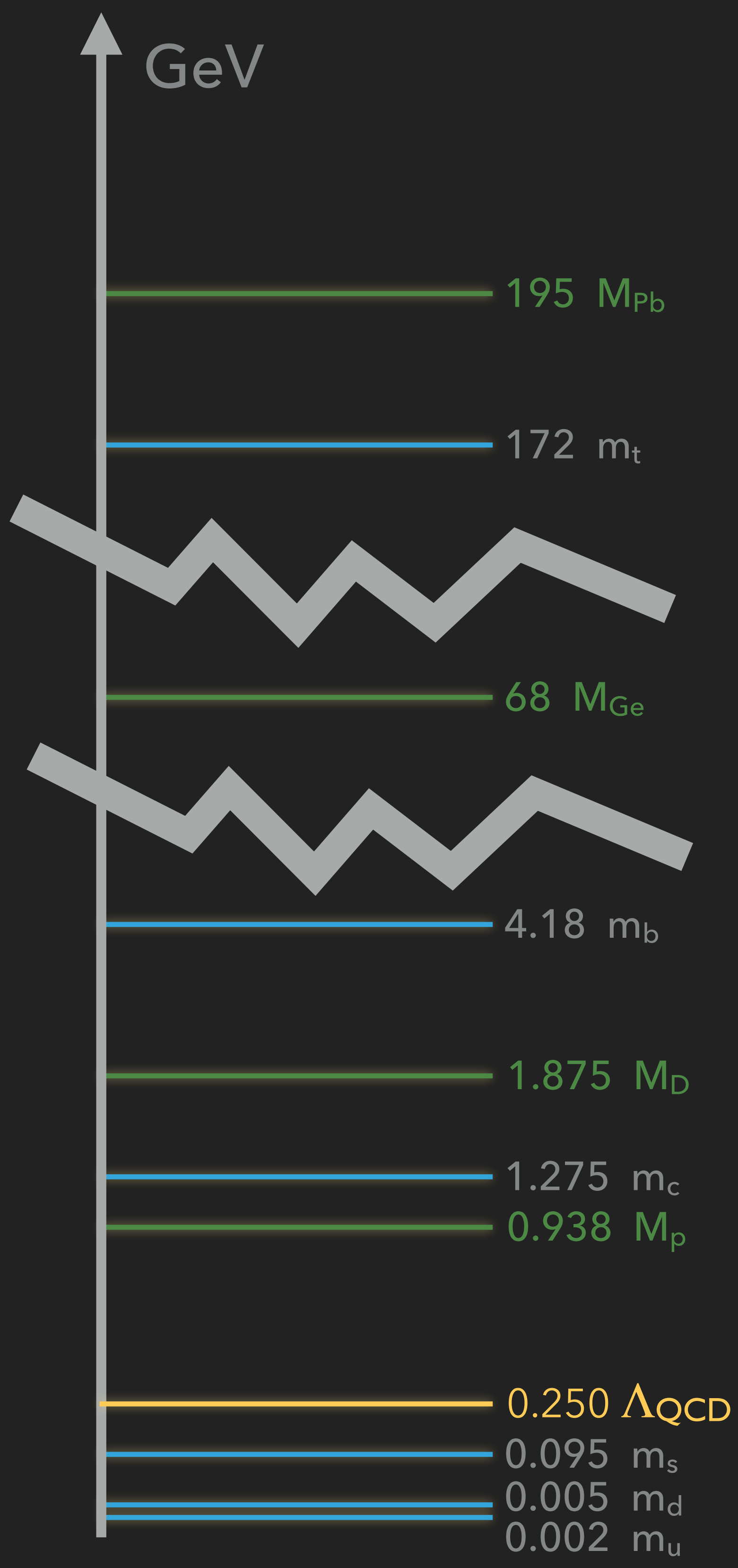

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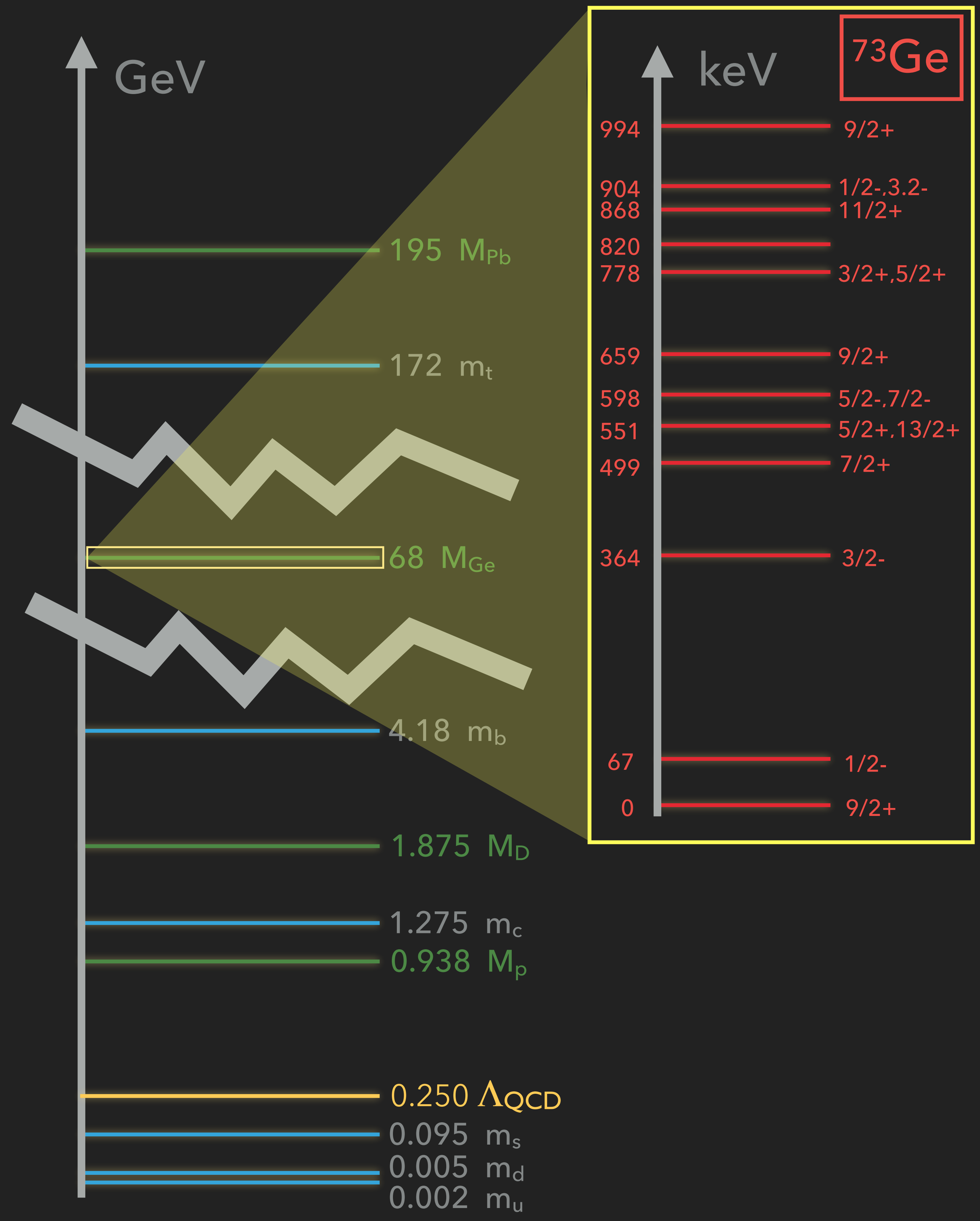
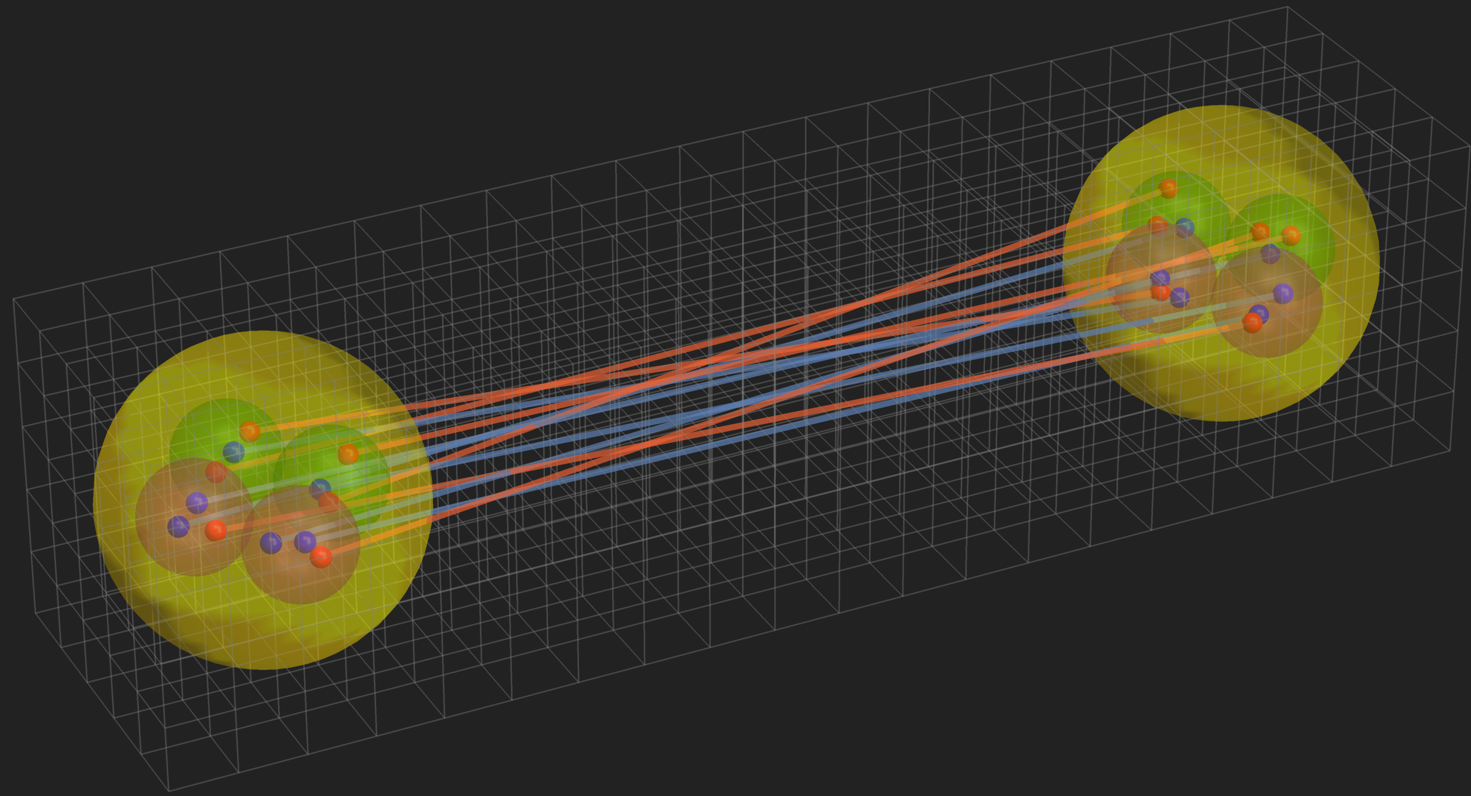


# NUCLEI



- New algorithms enabling study of nuclei
  - Efficient contractions
    - Graph theory & recursions [WD & Savage 2011; WD & Orginos 2012, Doi&Endres 2012; Gunther&Varnhorst 2013; WD & Vachaspati 2014]
  - Better statistical estimators [WD & Endres 2014, Wagman &Savage 2016; WD, Kanwar & Wagman 2018, Murphy et al. 2019]
- … and lots of computing!

$$\frac{\mathrm{cost}({}^N A_Z)}{\mathrm{cost}(\mathrm{proton})} \sim (2Z+N)!(2N+Z)!/2$$

Cost Ratio

| Nucleus | Naive | Optimised |
|---|---|---|
| $^{4}$He | 250,000 | ~100 |
| $^{8}$Be | $10^{31}$ | $10^{7}$ |
| $^{208}$Pb | $10^{1300}$ | ? |

# NPLQCD

- Case study QCD with unphysical quark masses ($m_\pi$~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→deν, $g_A(^3H)$ [PRL **119** 062002 (2017)]
5. Double β decay: pp→nn [PRL **119**, 062003 (2017)]
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+ Arjun Gambhir

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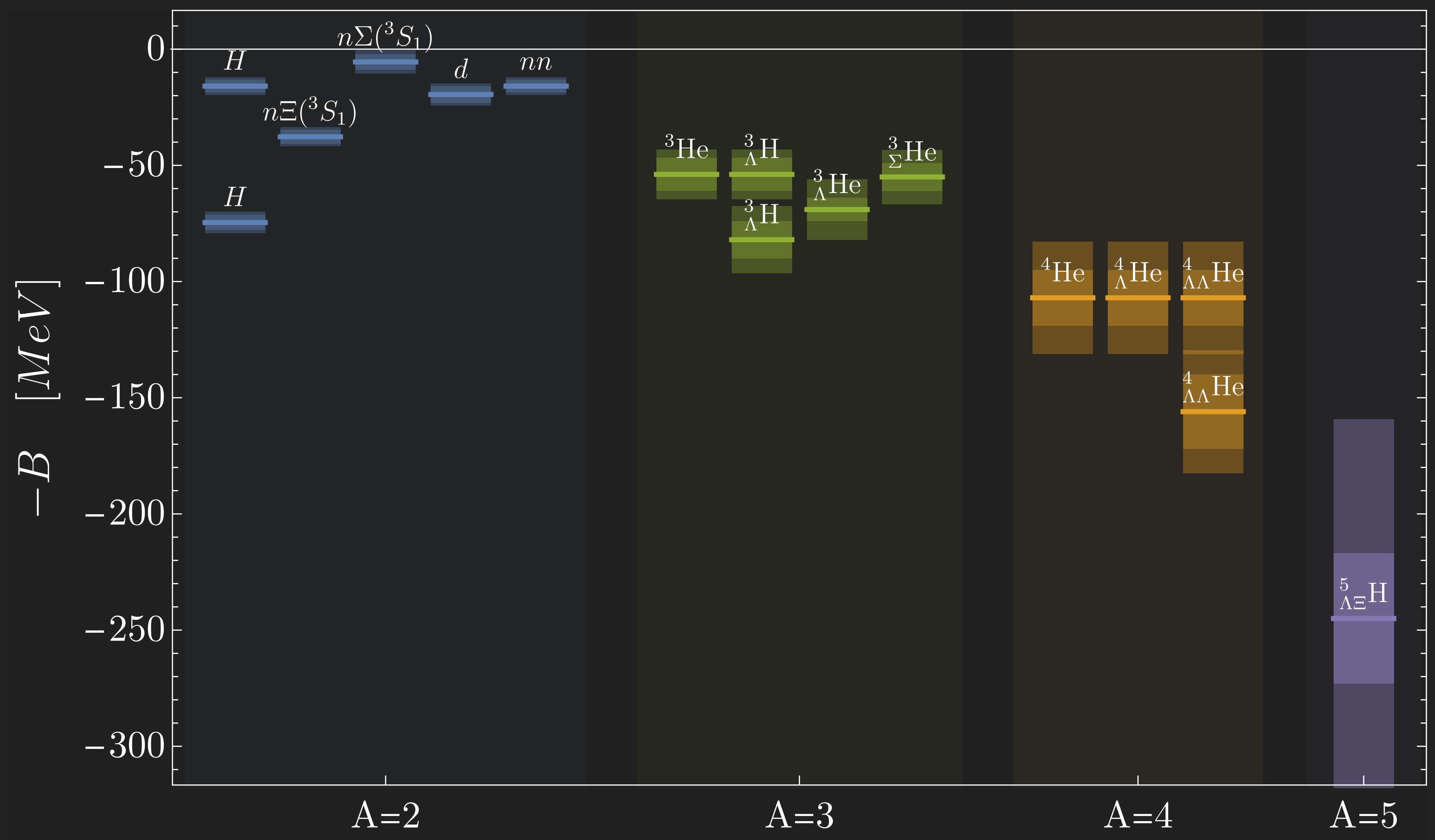
new since 2017


+ Arjun Gambhir

[NPLQCD collaboration, PRD 2013]

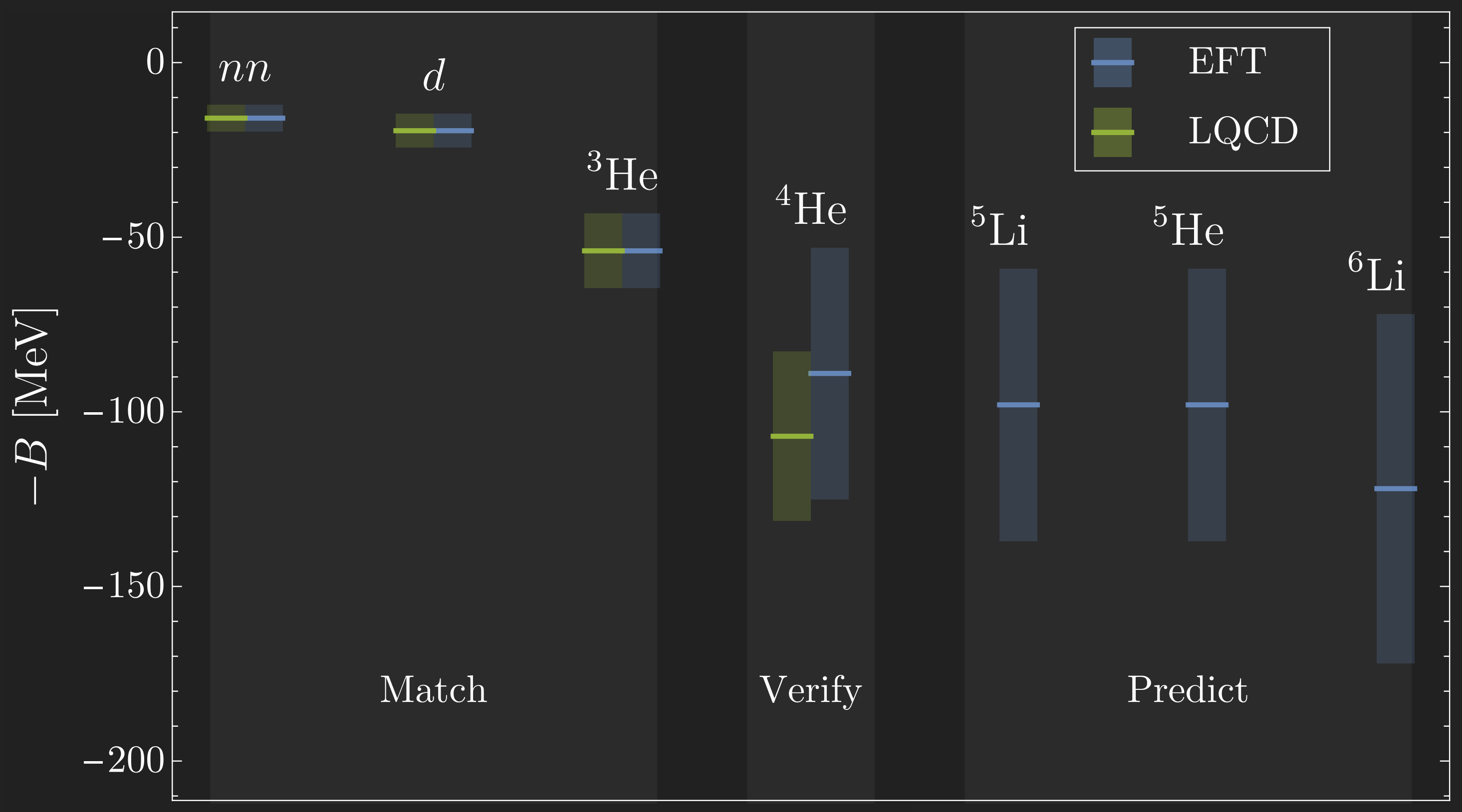
# NUCLEI (IN A HEAVY QUARK UNIVERSE, $M_{\pi}\sim$800 MEV)

- 2013: first QCD calculation of nuclei (heavy masses as numerically cheaper)



# NUCLEI (IN A HEAVY QUARK UNIVERSE, $M_\pi \sim 800$ MEV)

- Combine LQCD and nucleon based many-body effective field theory (EFT) methods
- Matching to LQCD determines NN, NNN interactions: allows predictions for larger nuclei




[Barnea et al, PRL 2015]

MORE EFFECTIVE: DIRECTLY MATCH FV ENERGIES IN LQCD AND EFT

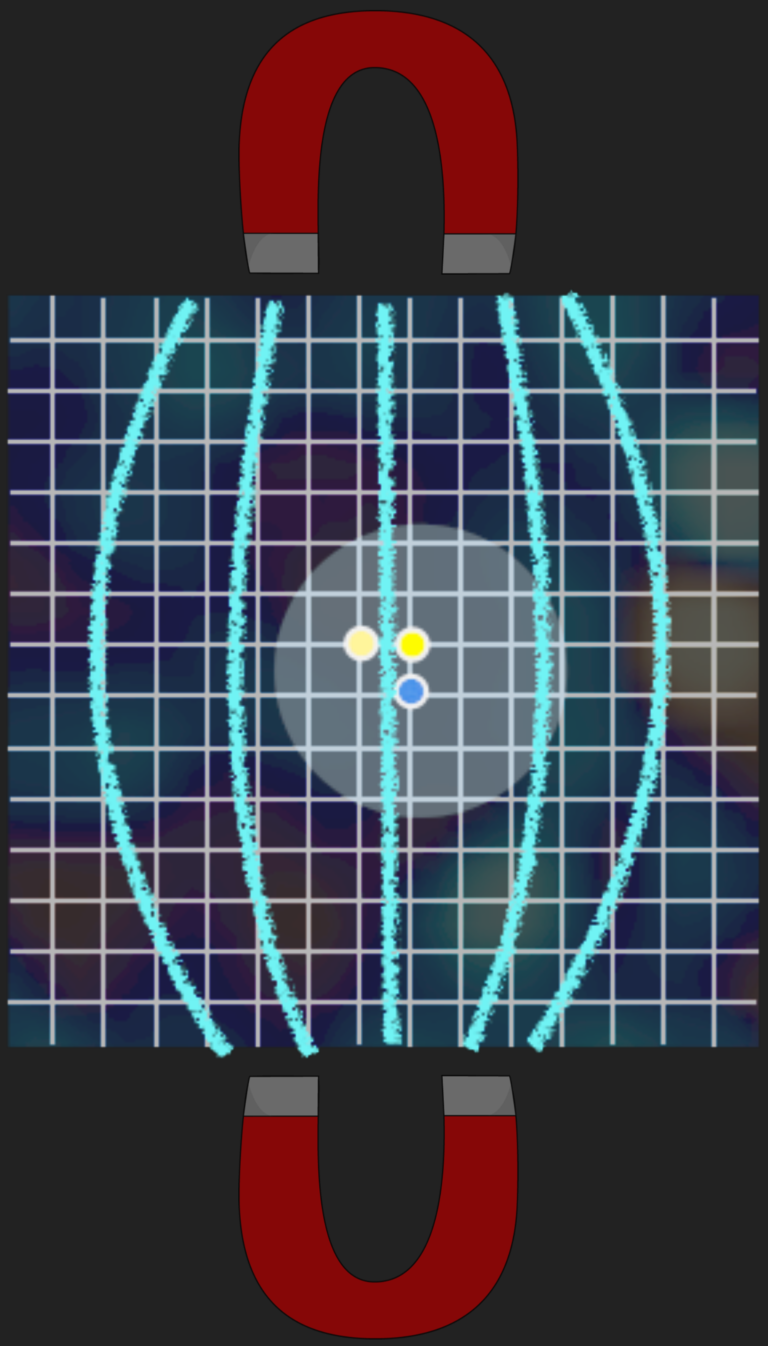
- Further studies extend to complex nuclei such as $^{16}$O [Contessi et al, Bansal et al.]

# MAGNETIC STRUCTURE

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

$$E_{h;j_z}(\mathbf{B}) = \sqrt{M_h^2 + (2n+1)|Q_h eB|} - \boldsymbol{\mu}_h \cdot \mathbf{B} - 2\pi\beta_h^{(M0)}|\mathbf{B}|^2 + \ldots$$

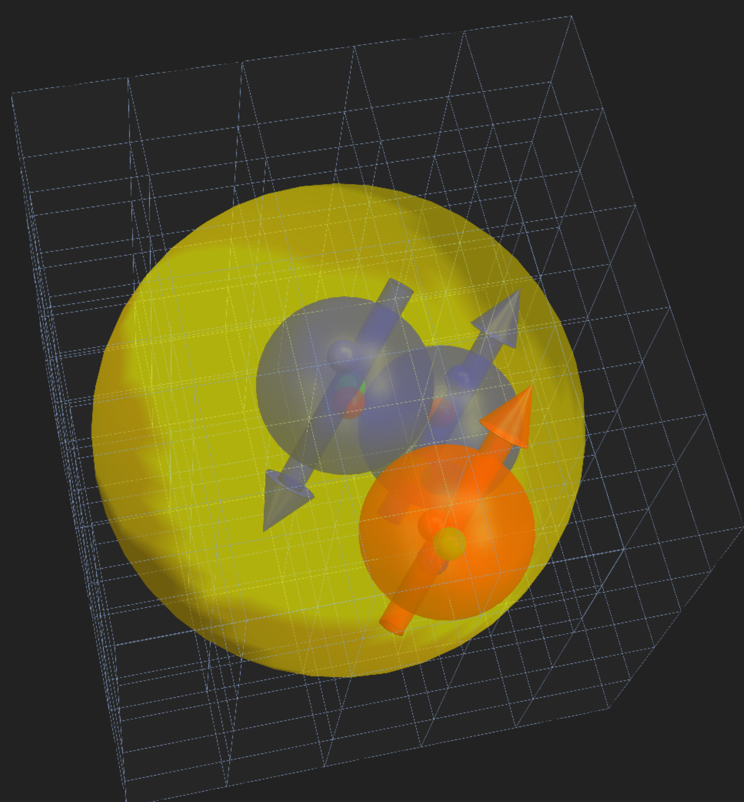
- QCD calculations with multiple fields enable extraction of coefficients of response
  - Magnetic moments, polarisabilities, …
- Similar techniques to study EW interactions, DM interactions, twist-2 matrix elements



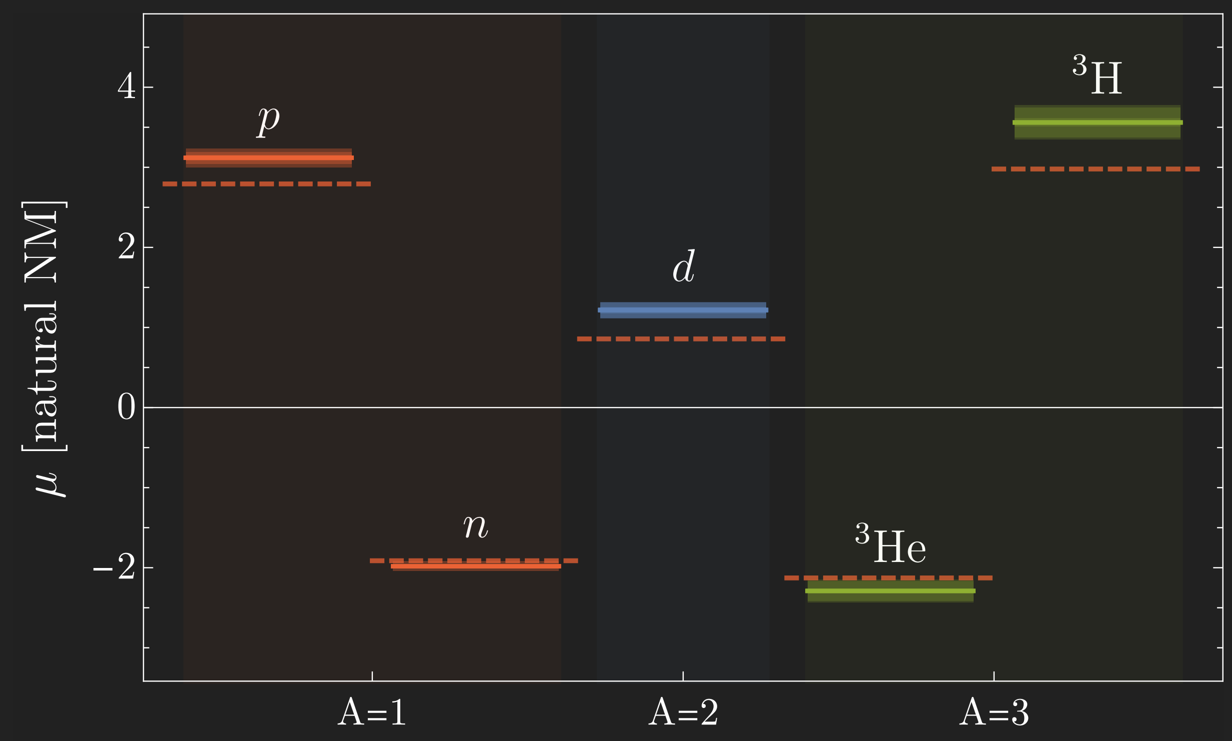
[NPLQCD PRL 2014,PRD 2014]

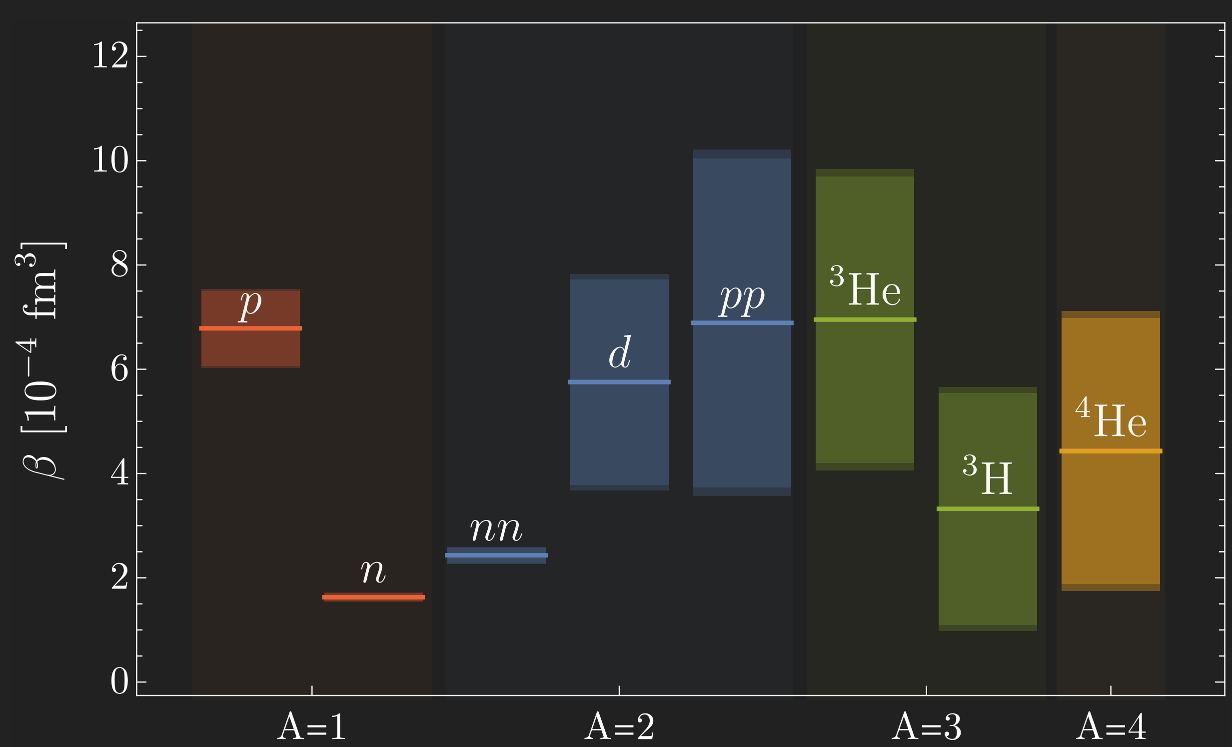
# MAGNETIC STRUCTURE

- LQCD calculation of nuclear magnetic moments (μ) and magnetic polarisabilities (β, deformation in B field)
- Simple shell model expectations



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

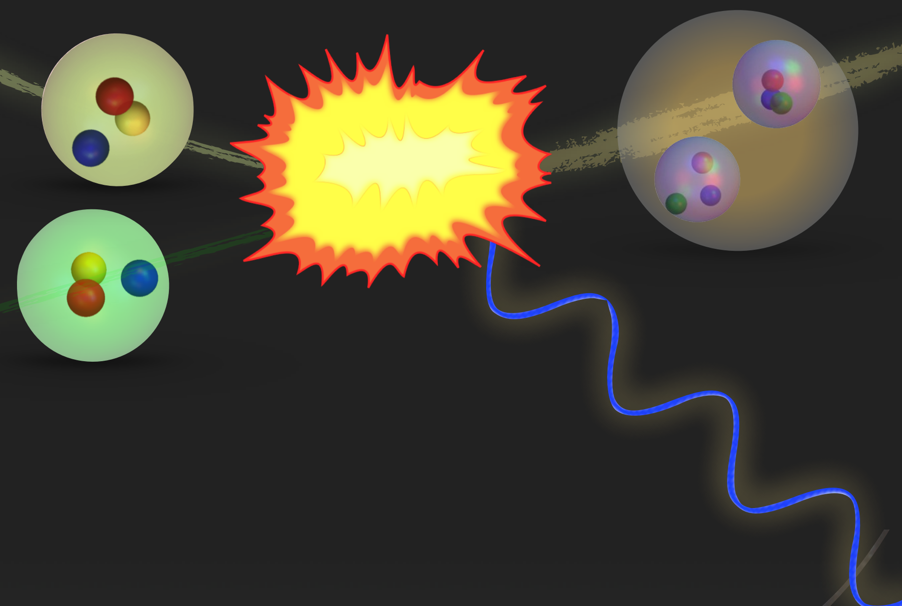


[NPLQCD, PRL 2015]

# BIG BANG NUCLEOSYNTHESIS

- Light nuclei are formed during the initial few minutes after the Big Bang
- First nuclear reaction: slow neutron capture np→dγ
  - 2015: First QCD calculation of a nuclear reaction
  - Reproduced measured rate
  - Ready to make predictions



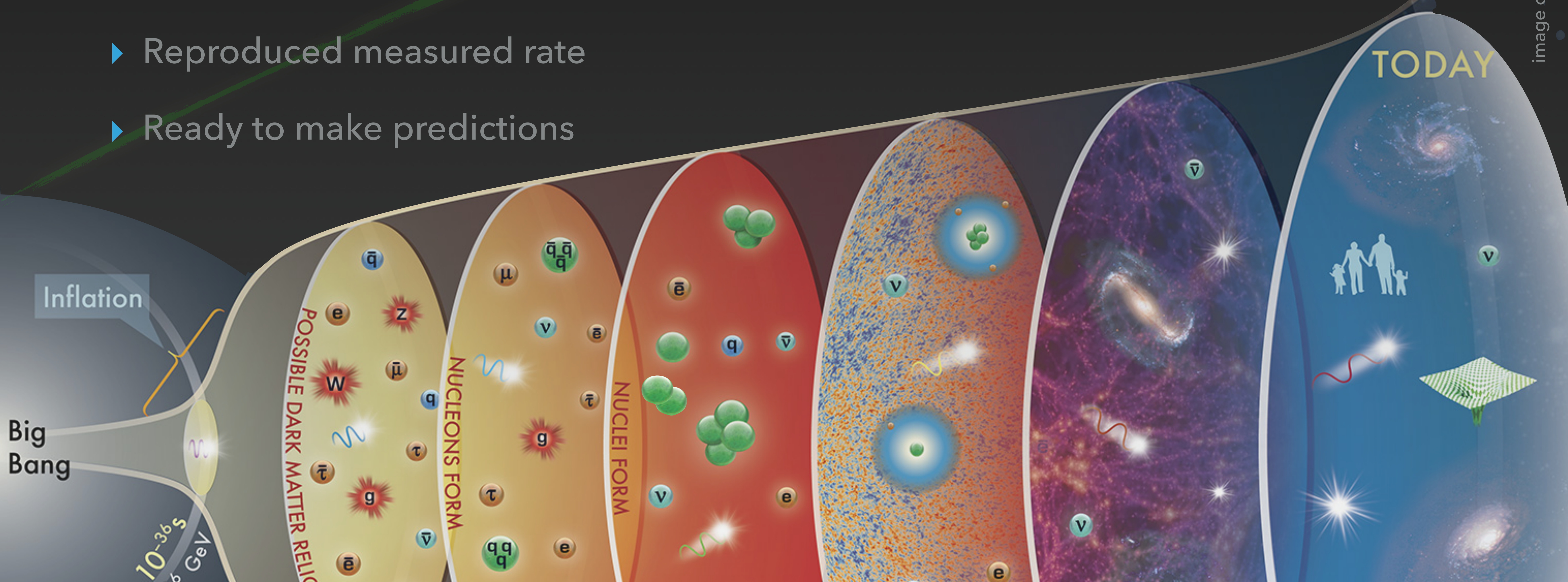
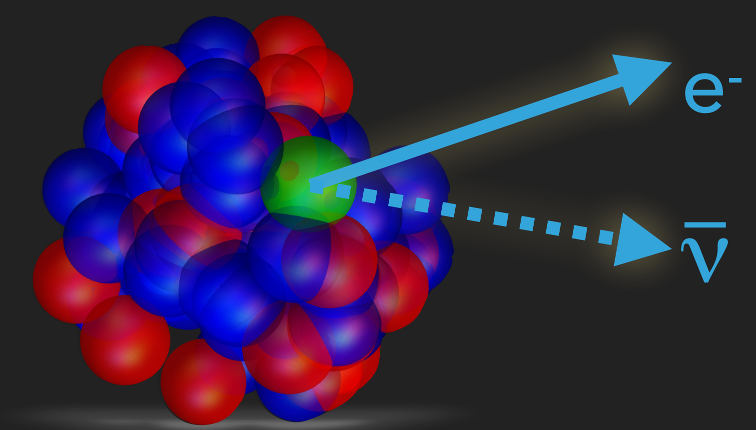



image credit: Particle Data Group

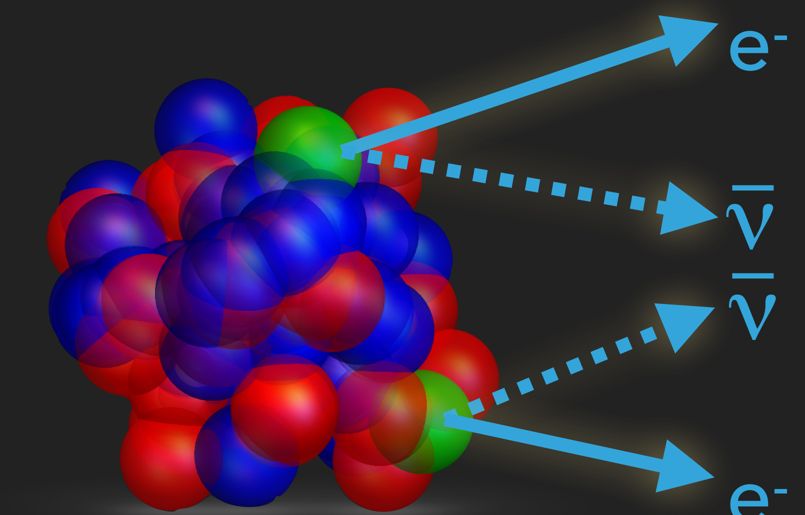
[NPLQCD, PRL 2017]

# ELECTROWEAK PROCESSES

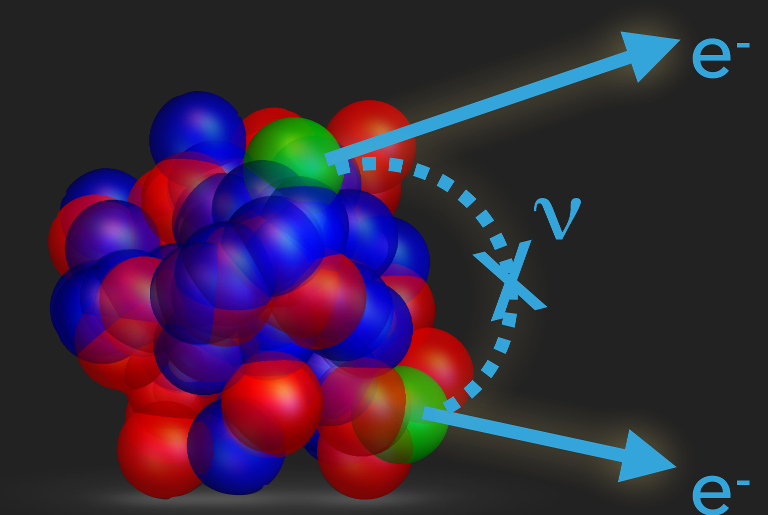
- Single β−decay
  LQCD calculation of decay of tritium
- Double β−decay
  - Neutrinoful case is rarest process observed
  - Neutrinoless case
    - Majorana particles? Lepton number violation? Baryon asymmetry?
  - Rates depend on nuclear matrix elements
    - Currently quite uncertain but important for design of future DBD search experiments
- Proton-Proton fusion powering the Sun



Beta decay

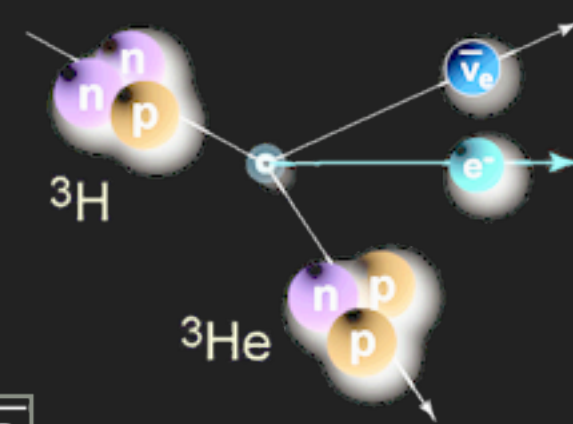


Two neutrino double β-decay



Neutrinoless double β-decay

# TRITIUM BETA DECAY




- Tritium decay half life

half-life

vector ME

axial ME

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

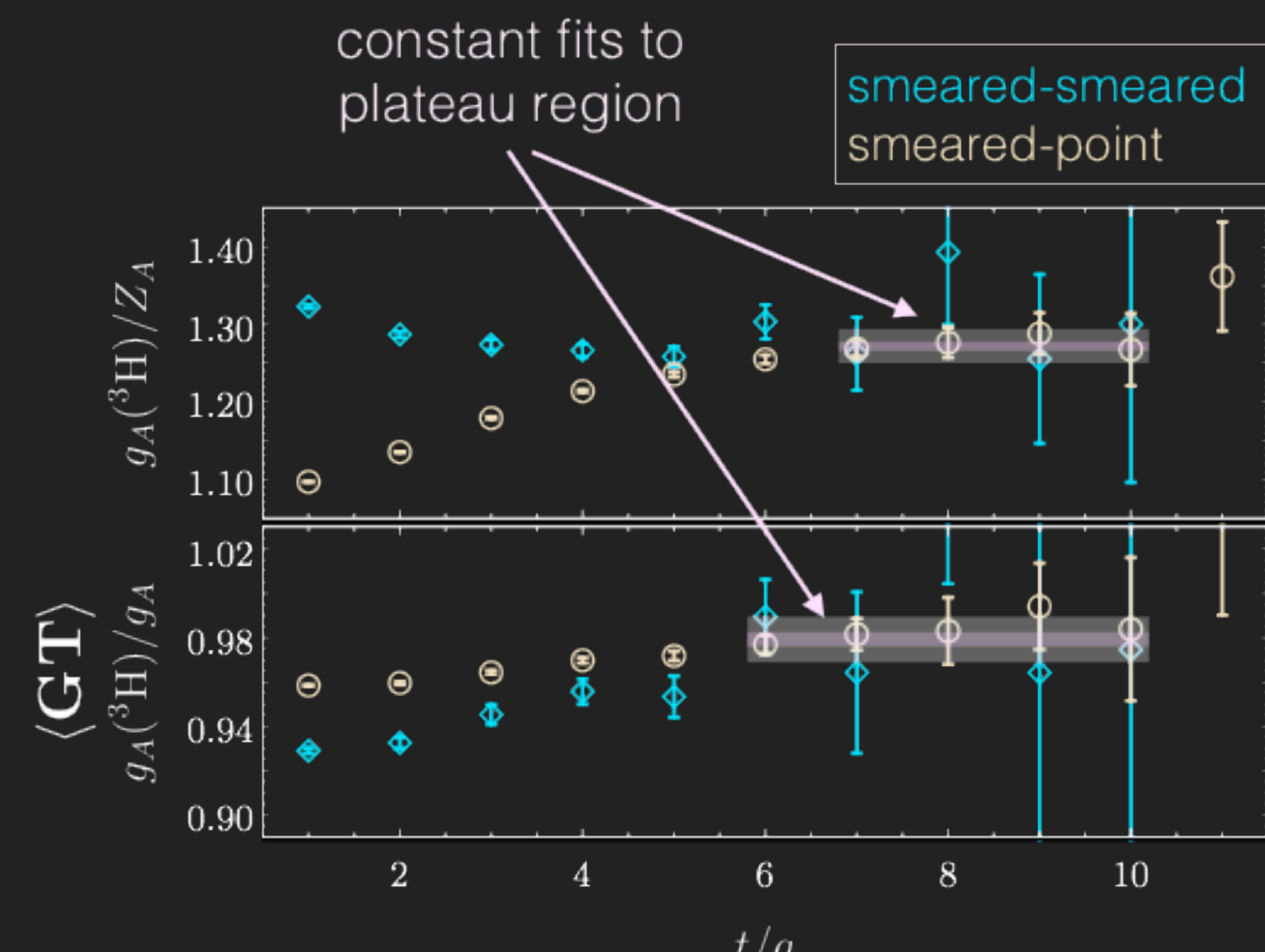
known from theory or expt.

- Biggest uncertainty in

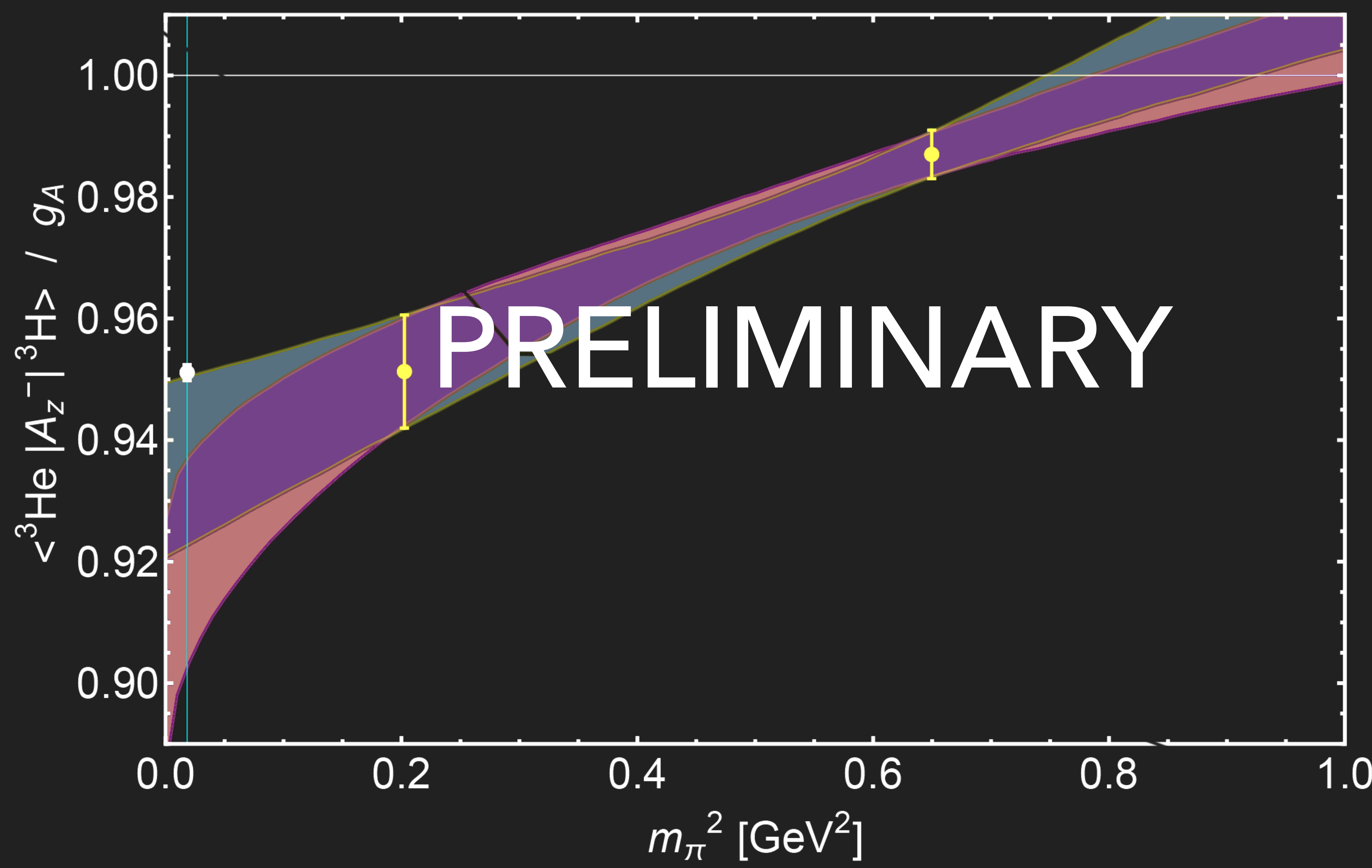
$$g_A \langle \mathbf{GT} \rangle = \langle {}^3\mathrm{He} | \bar{\mathbf{q}} \gamma_\mathbf{k} \gamma_\mathbf{5} \tau^- \mathbf{q} | {}^3\mathrm{H} \rangle$$

- Form ratios of correlators in axial background fields to extract QCD matrix element

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



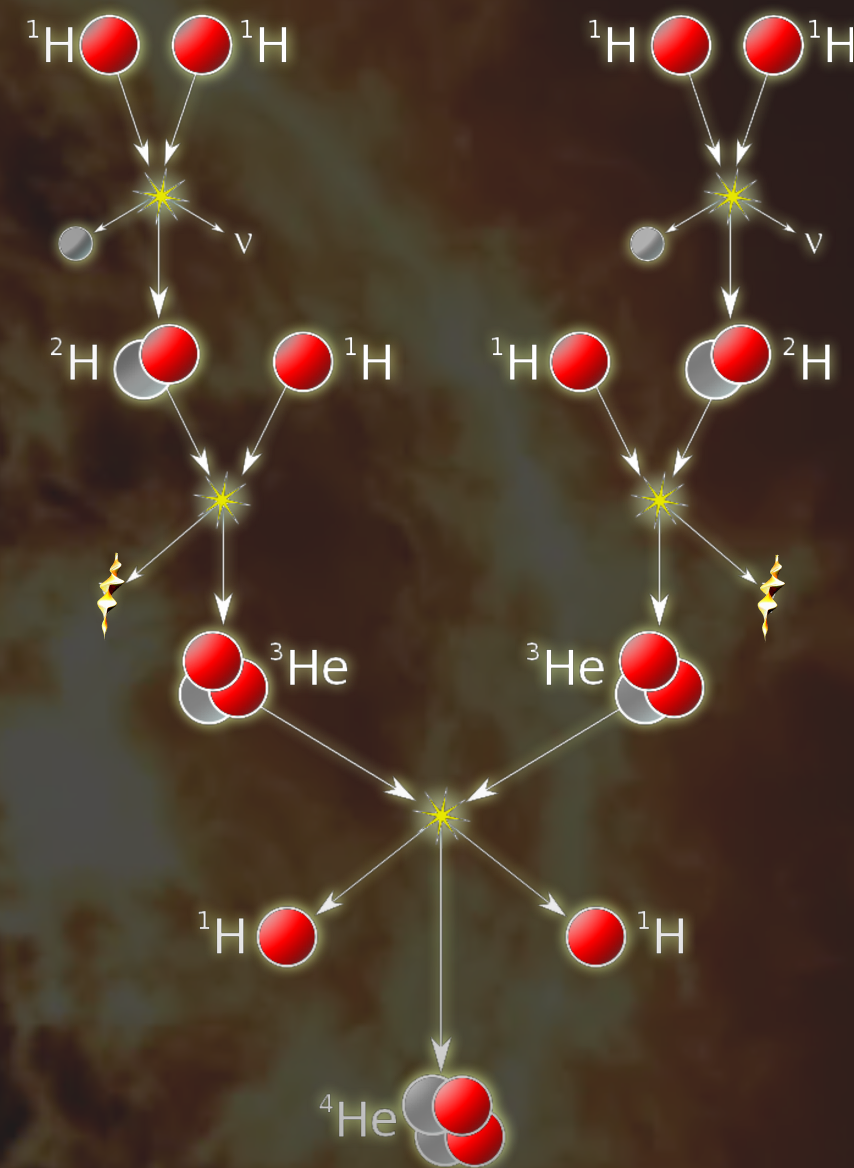
# MASS DEPENDENCE OF TRITON AXIAL CHARGE



[NPLQCD, PRL 2017]

# PROTON-PROTON FUSION

- First step in chain of reactions powering stars like the sun
- Intricate process involve all three SM forces
- Difficult to measure (Coulomb barrier)
- 2017: LQCD calculation of $pp$ fusion rate
  - Uncertainties competitive with phenomenological extractions
  - Next generation calculations will improve precision
    - Improve solar modelling



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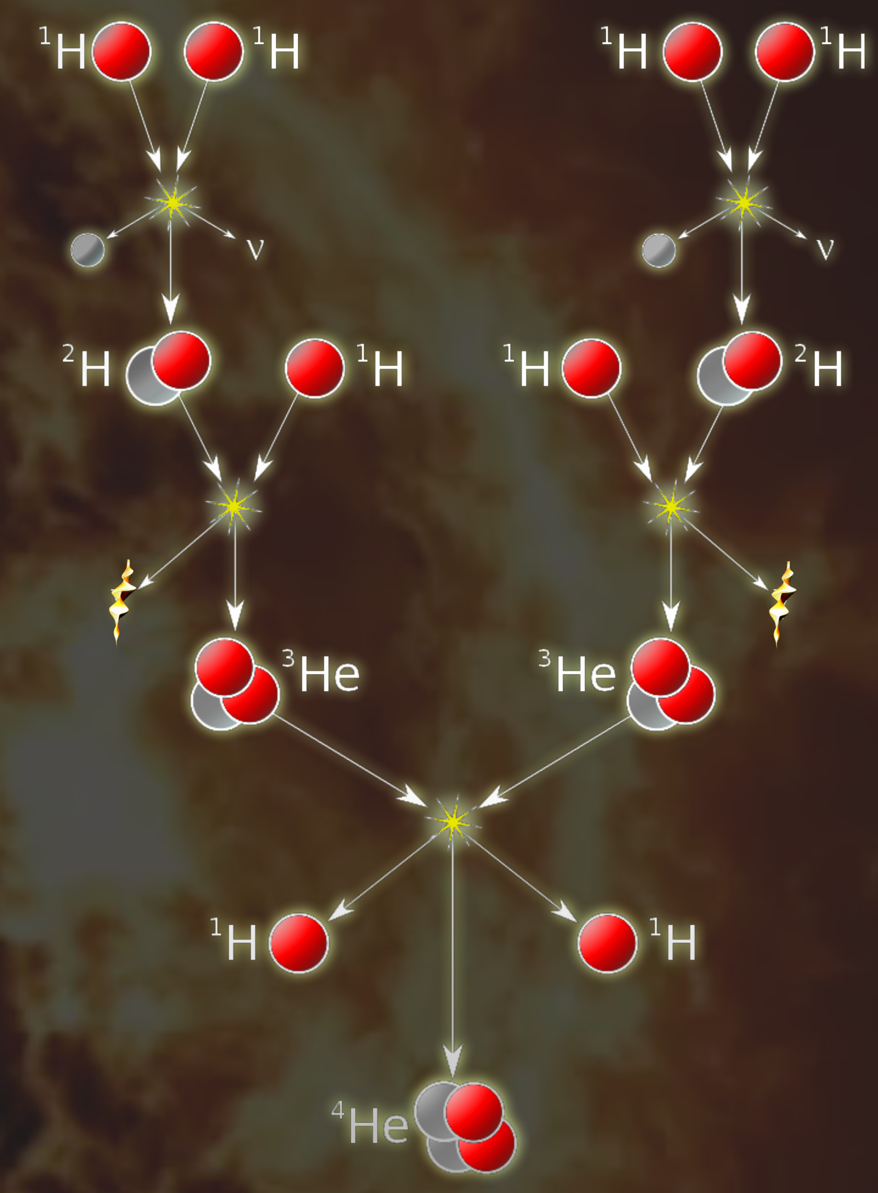

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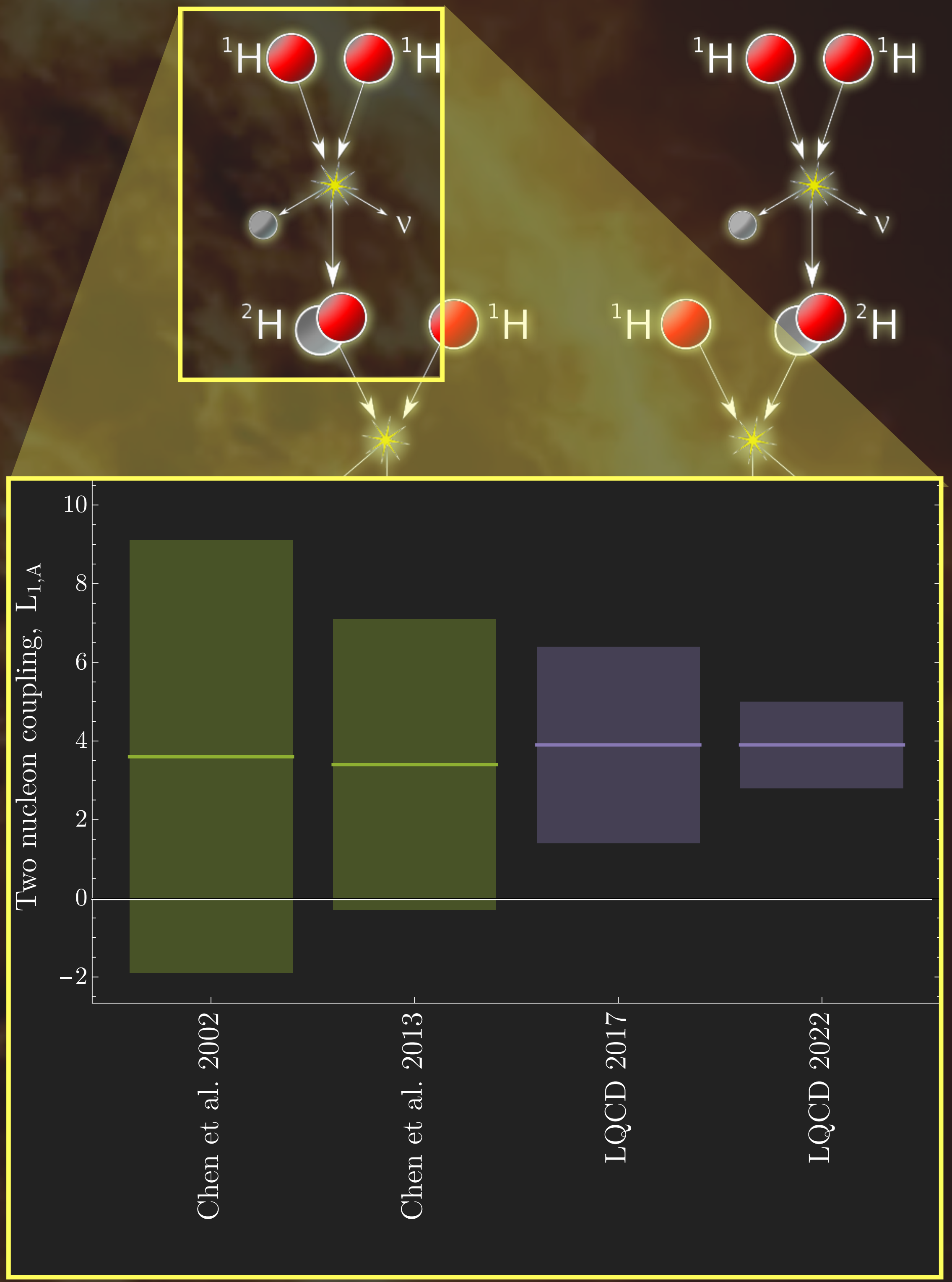
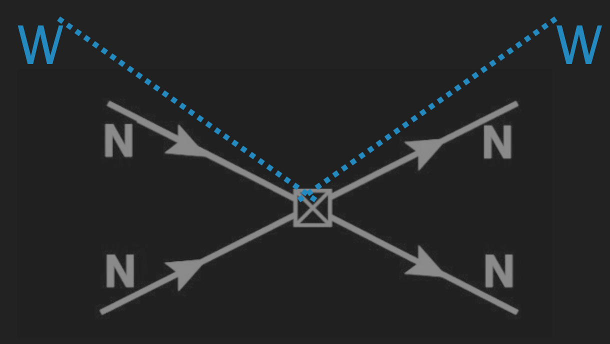


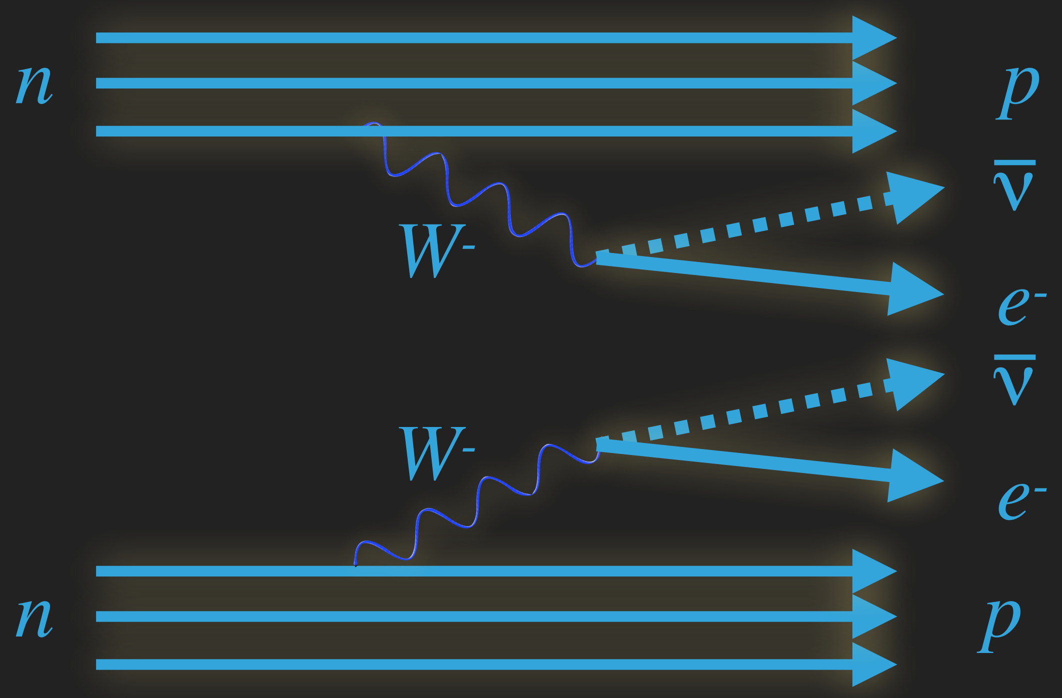
[NPLQCD, PRL 2017; WD, Murphy 1811.0554]

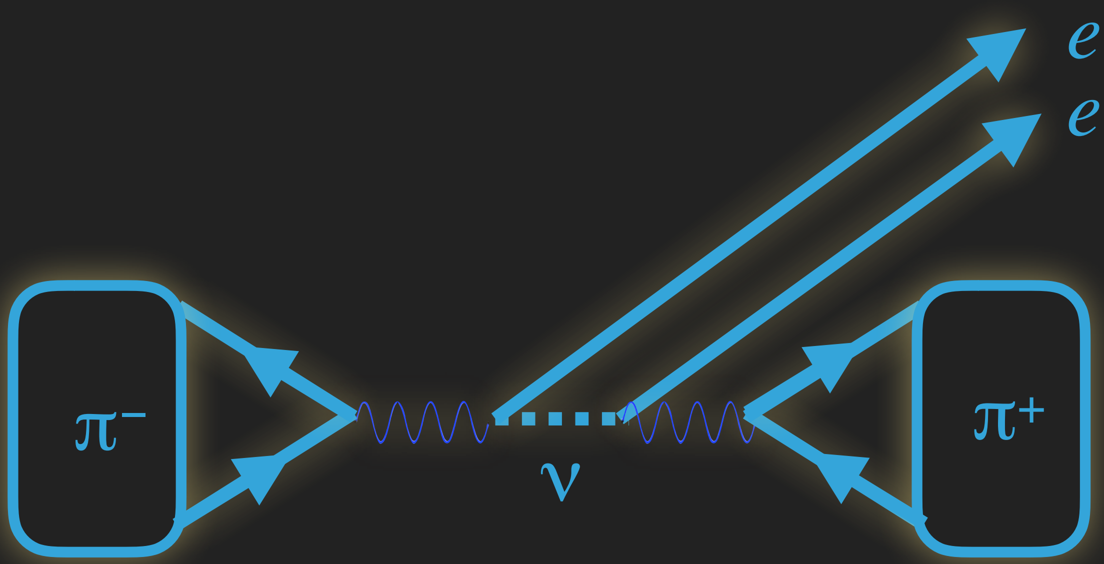
# DOUBLE BETA DECAY

- QCD calculation of subprocess
  $nn \rightarrow pp e^- e^- \bar{\nu}\bar{\nu}$
  [NPLQCD, PRL 2017b]
  - Revealed significant nuclear effects (even beyond $g_A$ quenching)

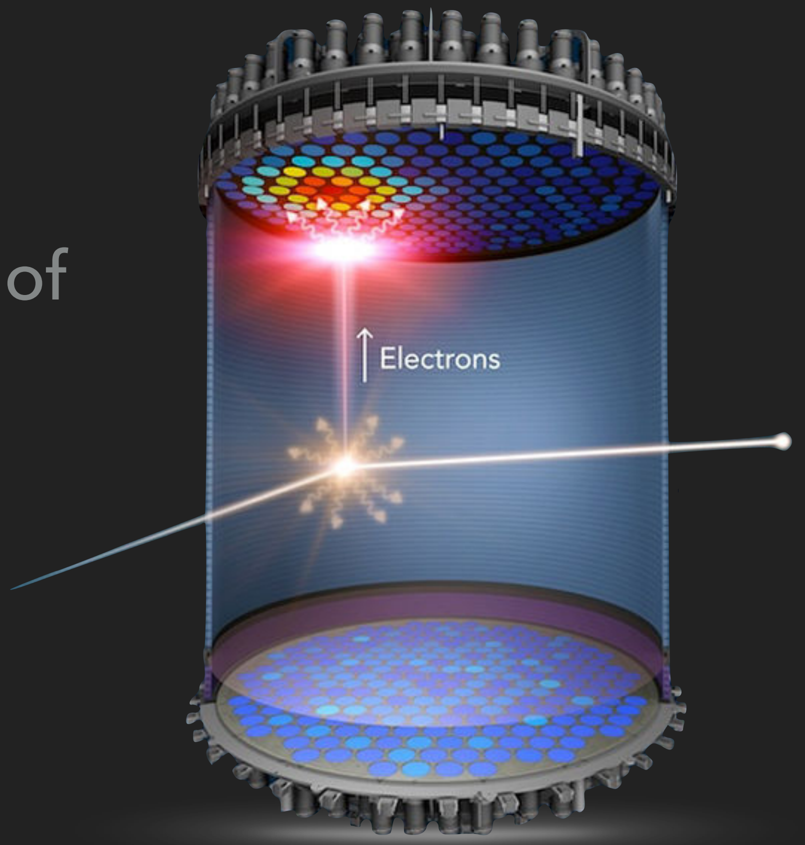



- Beginning calculations of neutrinoless processes
  [WD, Murphy 1811.0554]
  - Disallowed pion transition as a test
    $$\pi^- \rightarrow \pi^+ e^- e^-$$
  - Light nuclei are next



# DARK MATTER INTERACTIONS



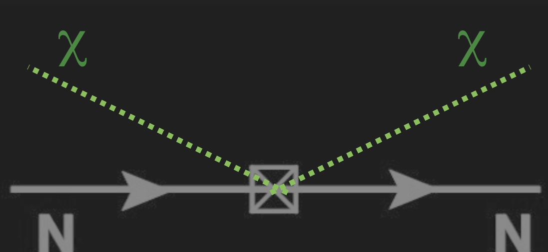

- DM direct detection experiments search for recoil of nucleus from DM scattering
- One popular class of DM interactions is through scalar exchange

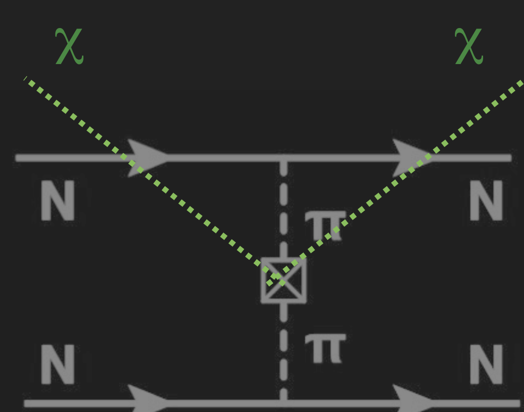
$$\mathcal{L} = \frac{G_F}{2} \sum_q \kappa_q (\overline{\chi}\chi)(\overline{q}q)$$

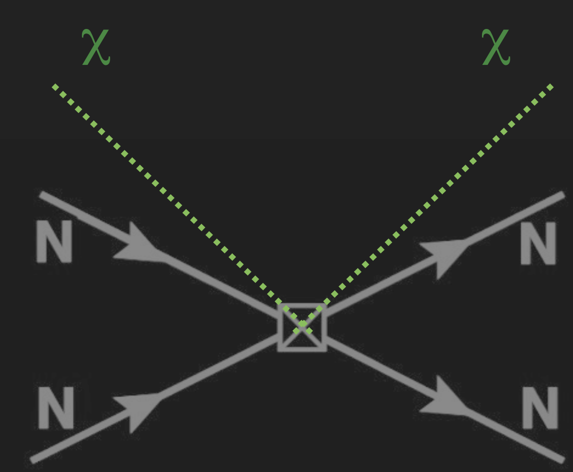
- Direct detection depends on nuclear matrix element

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

- At hadronic/nuclear level

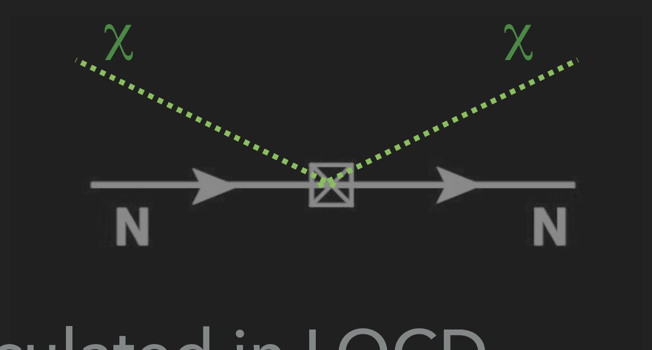


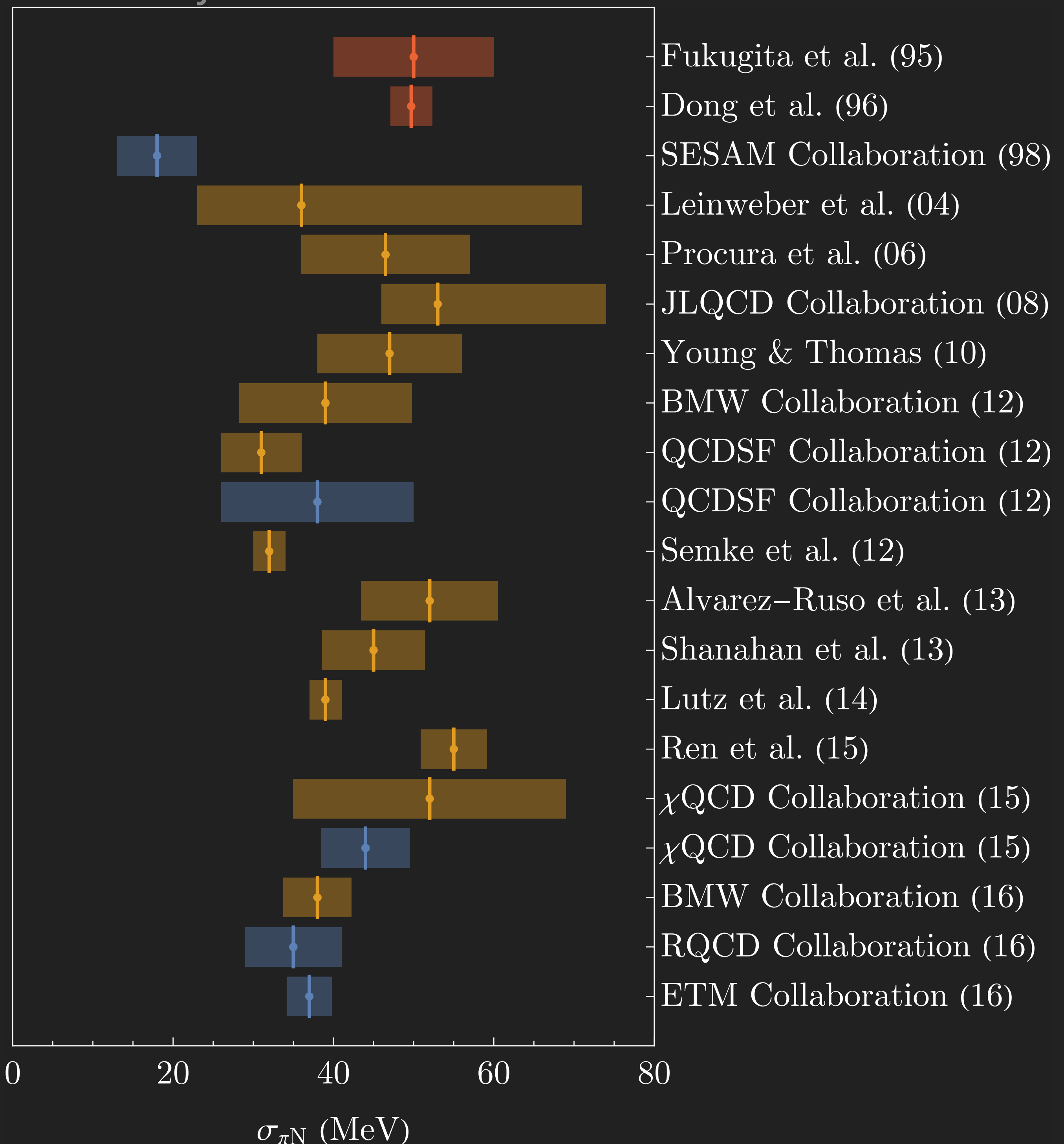
# NUCLEON SCALAR COUPLING

- Single nucleon contribution




- Calculated in LQCD
- Results from many groups

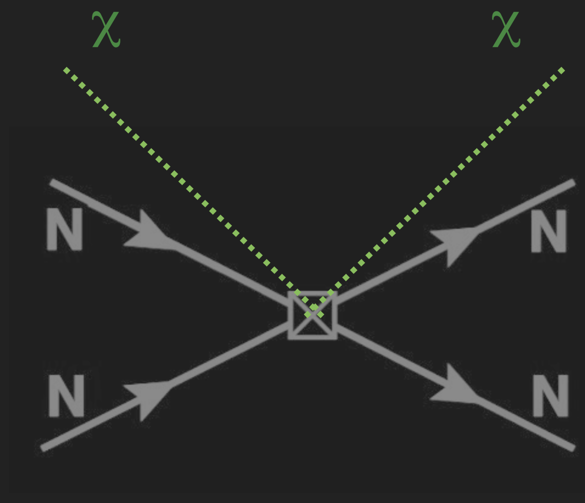
Summary from Shanahan 2016

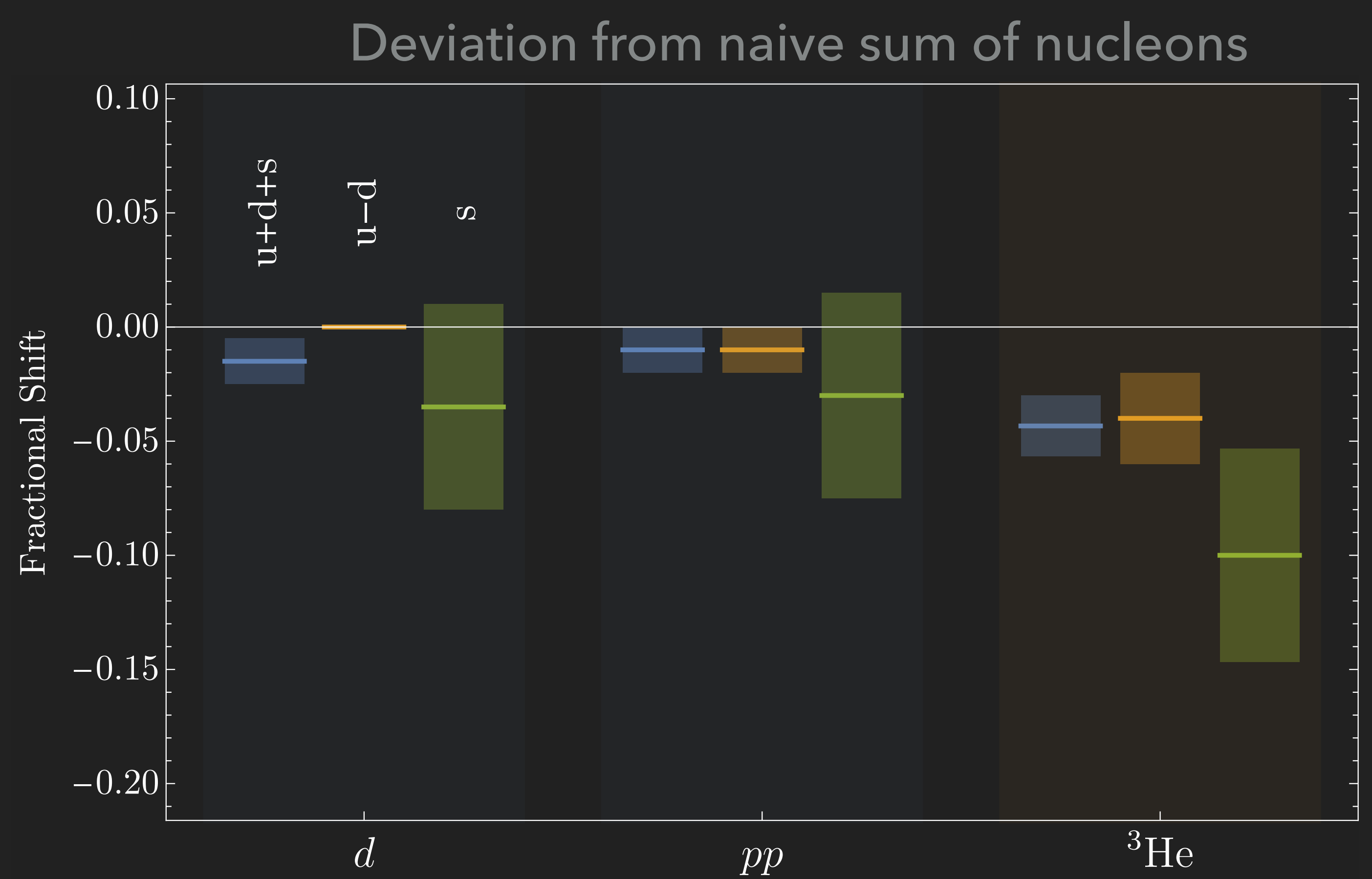


[NPLQCD, PRL 2018]

# 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

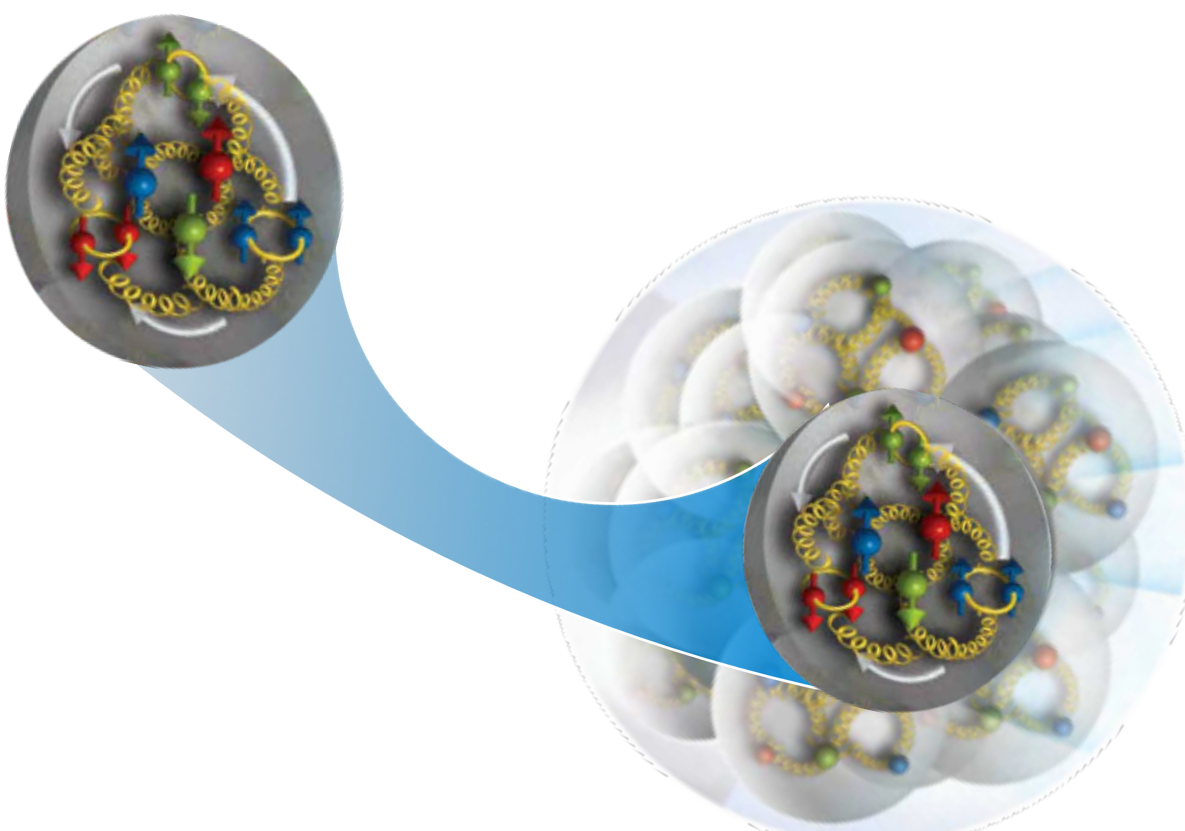


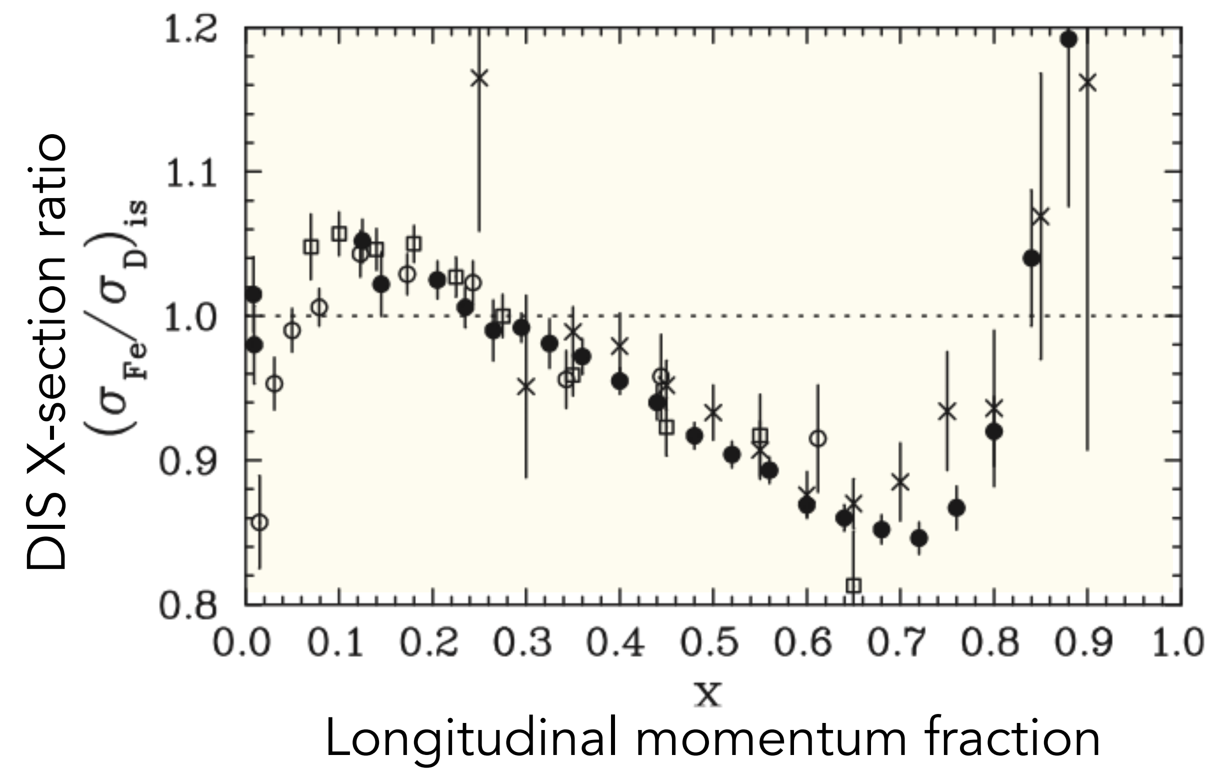
# EMC-type effects from Lattice QCD

Understanding the quark and gluon
structure of matter

How is the partonic structure of nucleons modified in nuclei?



Encoded in EMC-type effects



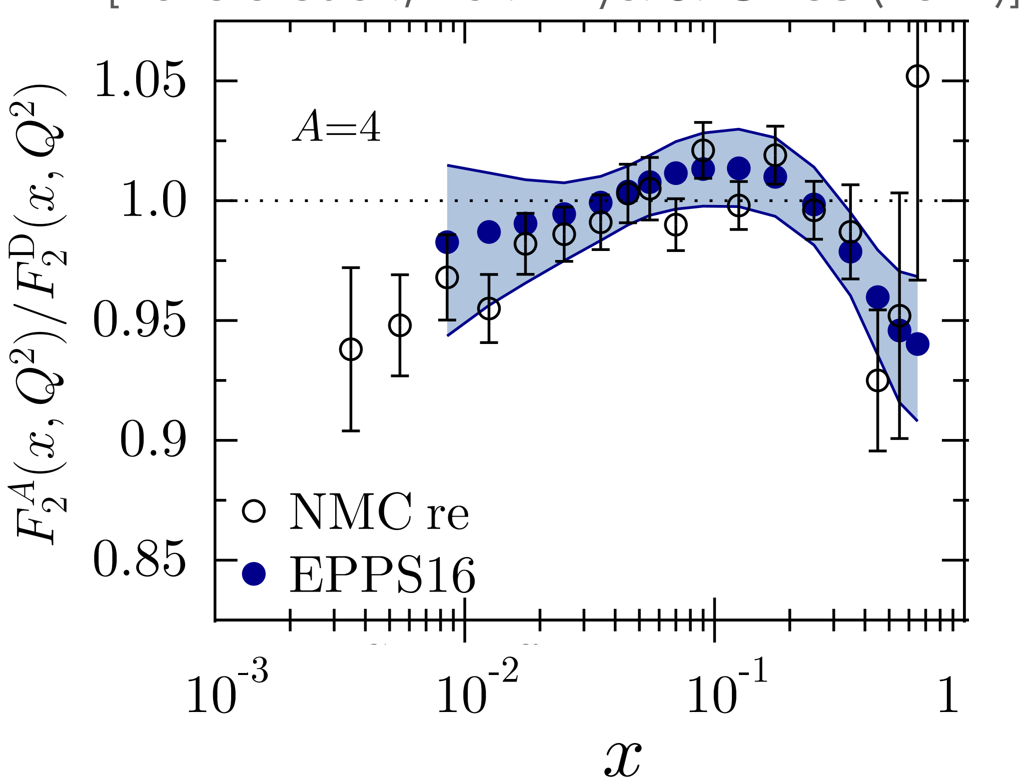

(EMC: Aubert et al., 1983)

# EMC effects in Mellin moments

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Calculable from local operators
- BUT EMC effects in moments are very small

[Eskola et al., Eur. Phys. J. C 163 (2017)]




Classic EMC effect is defined in $F_2$:

$$F_2(x,Q^2) = \sum_{q=u,d,s\ldots} x\, e_q^2 \left[q(x,Q^2) + \overline{q}(x,Q^2)\right]$$

Number density of partons of flavour q

→ x-integrals of numerator and denominator $\int_0^1 dx\, x^n q(x,Q^2)$

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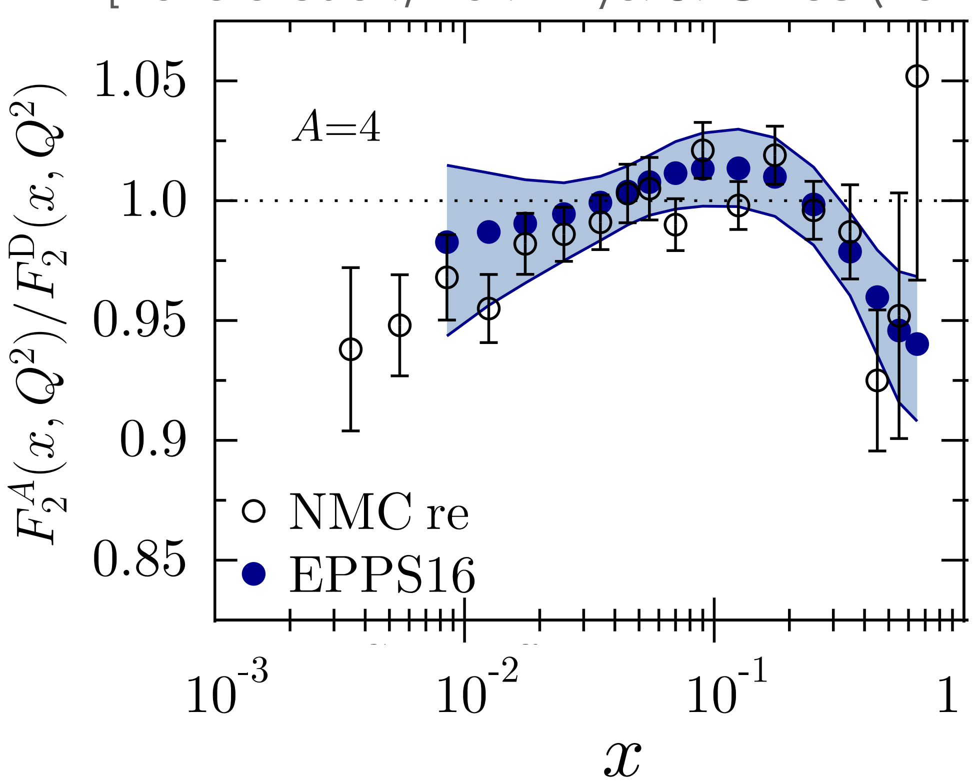
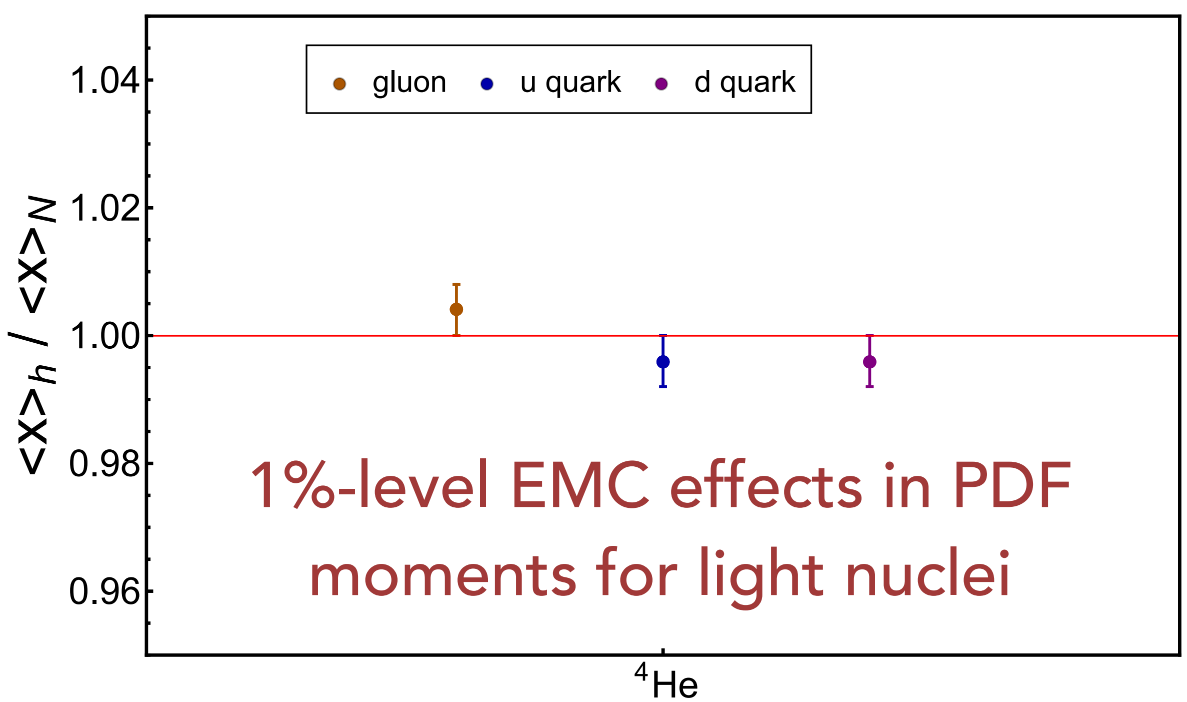


# Momentum fraction of nuclei

First investigation of EMC-type effects from LQCD:
Nuclear effects in Mellin moments of PDFs

- Lowest Mellin moment of spin-independent PDF defines fraction of momentum of nucleus A carried by parton of type f

$$\langle x \rangle_A^f = \int_0^1 dx\, x f^A(x) \qquad \sum_{f=q,g} \langle x \rangle_h^f = 1$$

- Momentum sum rule implies **nucleus-independent ratio of quark and gluon EMC effects** in the first moment

$$\left( \frac{\langle x \rangle_A^f}{\langle x \rangle_p^f} - 1 \right) = E_A^f \qquad \frac{E_A^g}{E_A^q} = -\frac{\langle x \rangle_p^q}{\langle x \rangle_p^g} \approx -1.4$$

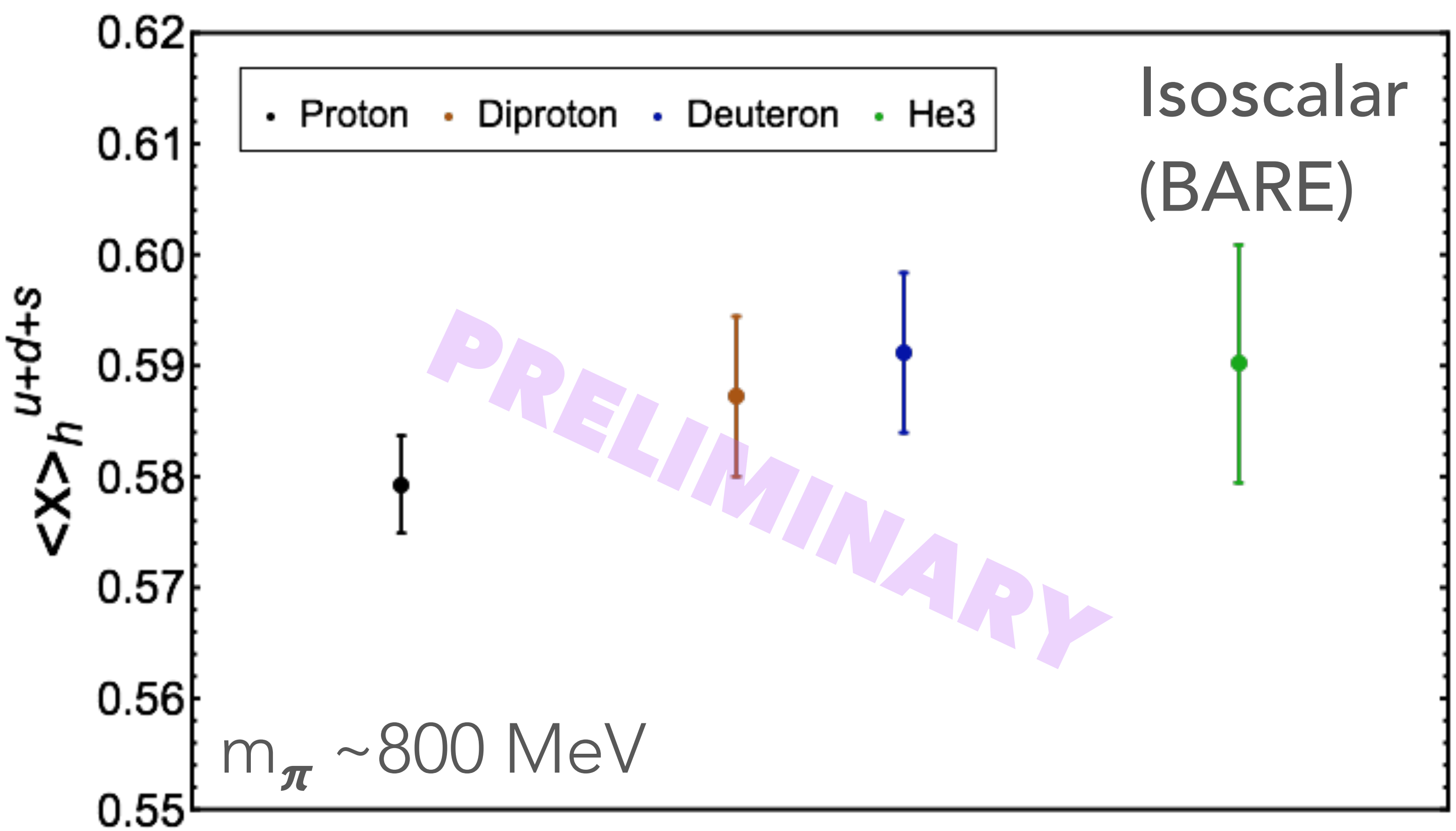
$\overline{\mathrm{MS}}\ (\mu = 2\mathrm{GeV})$

# Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

→ **first QCD determination of momentum fraction of nuclei**

- Few-percent determination of quark momentum fraction
  ~10% determination of strange quark contributions

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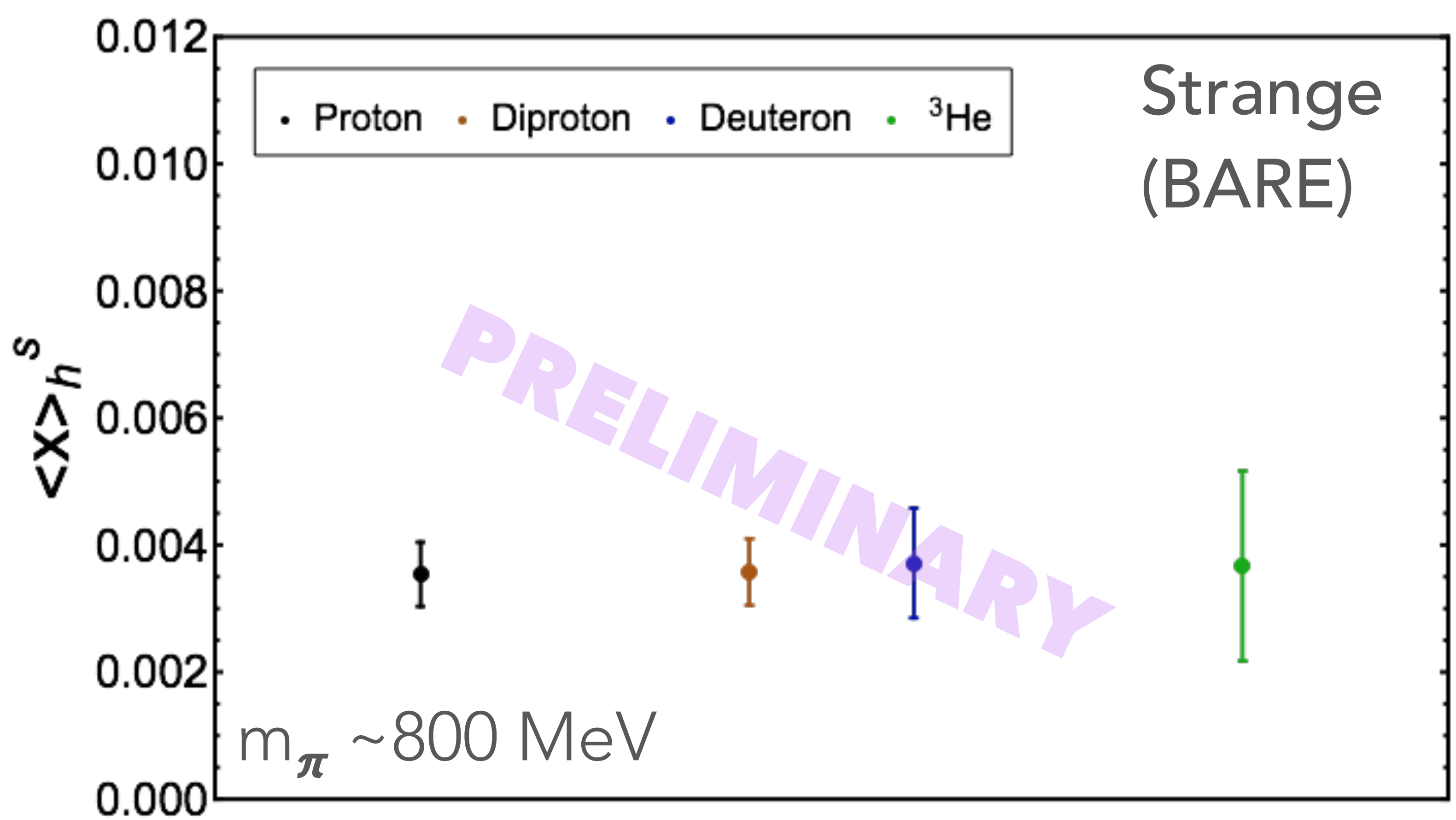


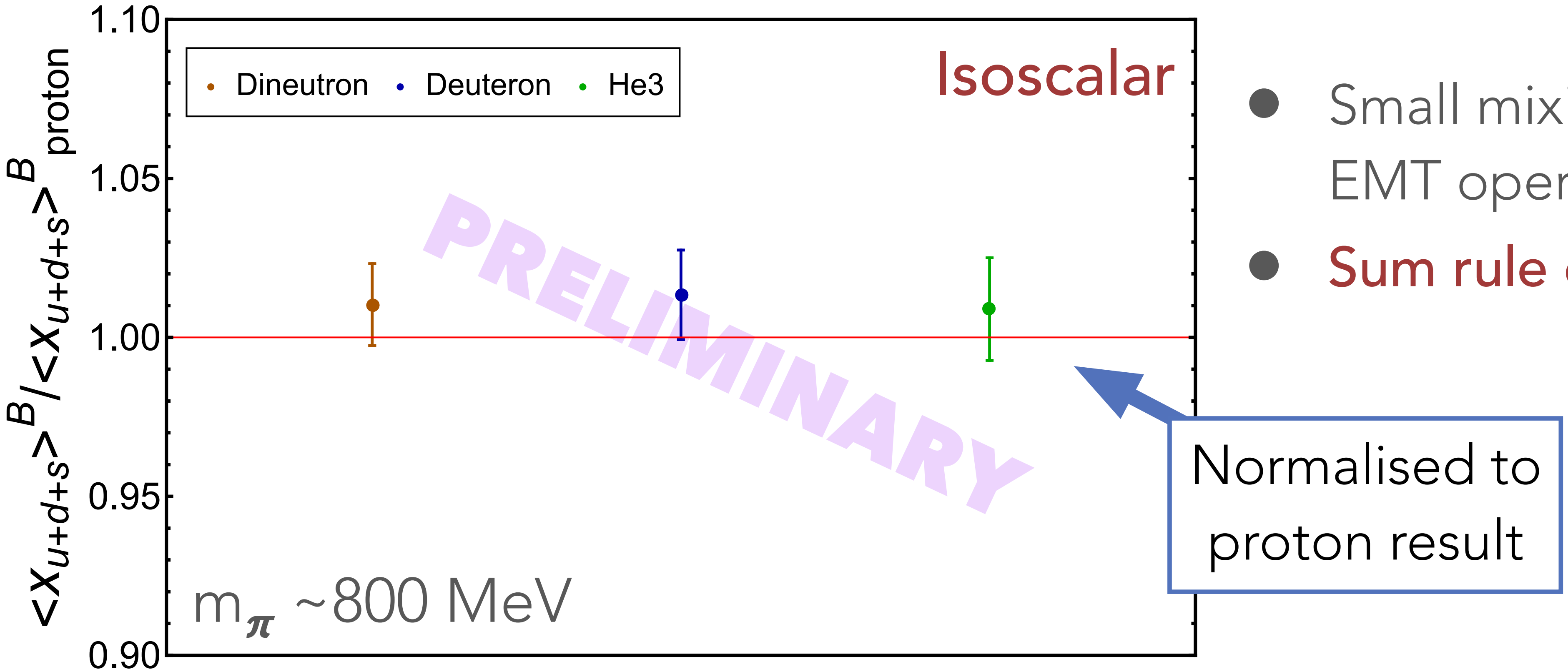

# Momentum fraction of nuclei

Matrix elements of the Energy-Momentum Tensor in light nuclei

→ **first QCD determination of momentum fraction of nuclei**

- Bounds on EMC effect in moments at ~few percent level, consistent with phenomenology

Ratio of quark momentum fraction in nucleus to nucleon




- Small mixing with gluon EMT operators (neglected)
- Sum rule constraint

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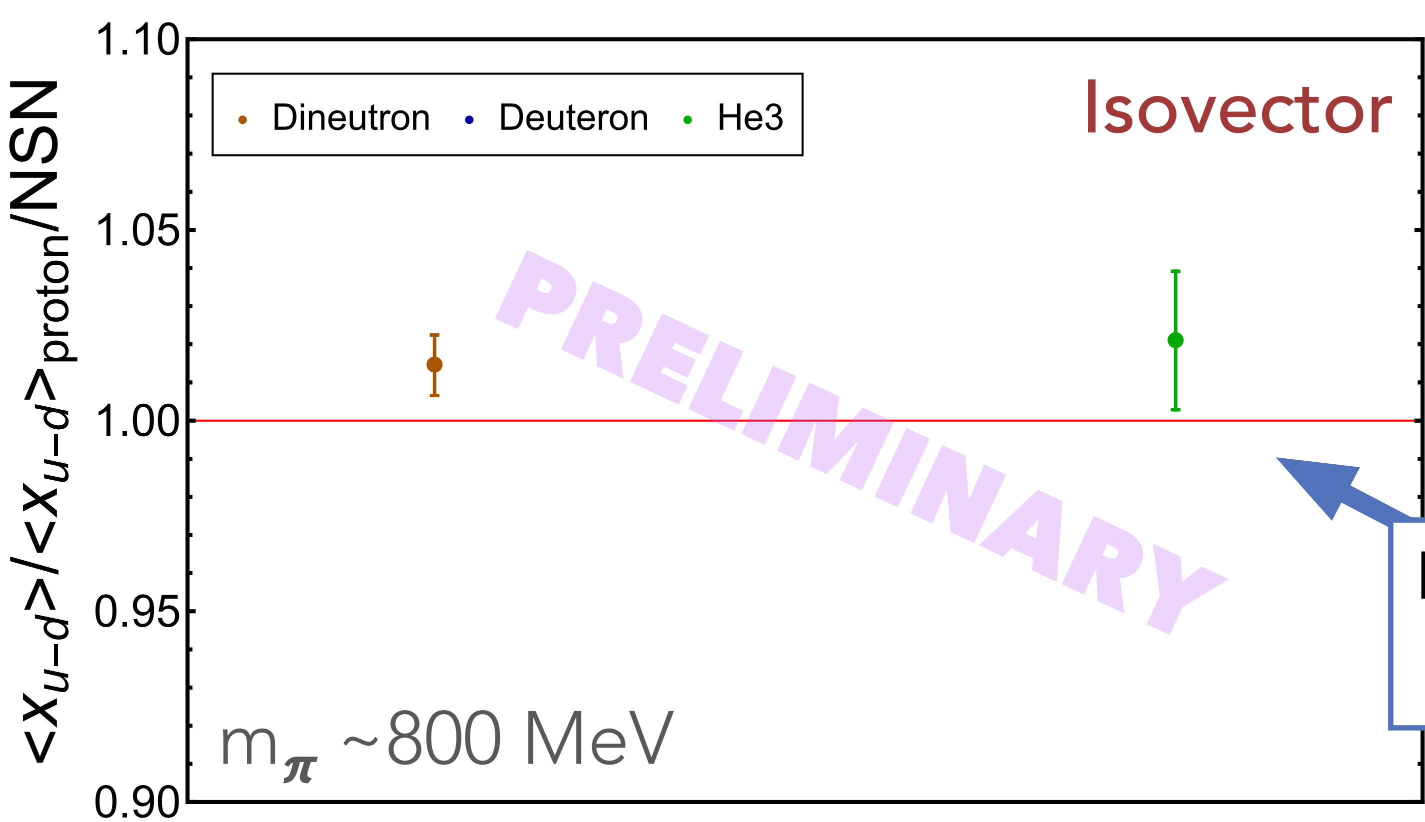



Normalised to proton result

- No mixing
- No sum rule constraint

# Gluon momentum fraction of nuclei

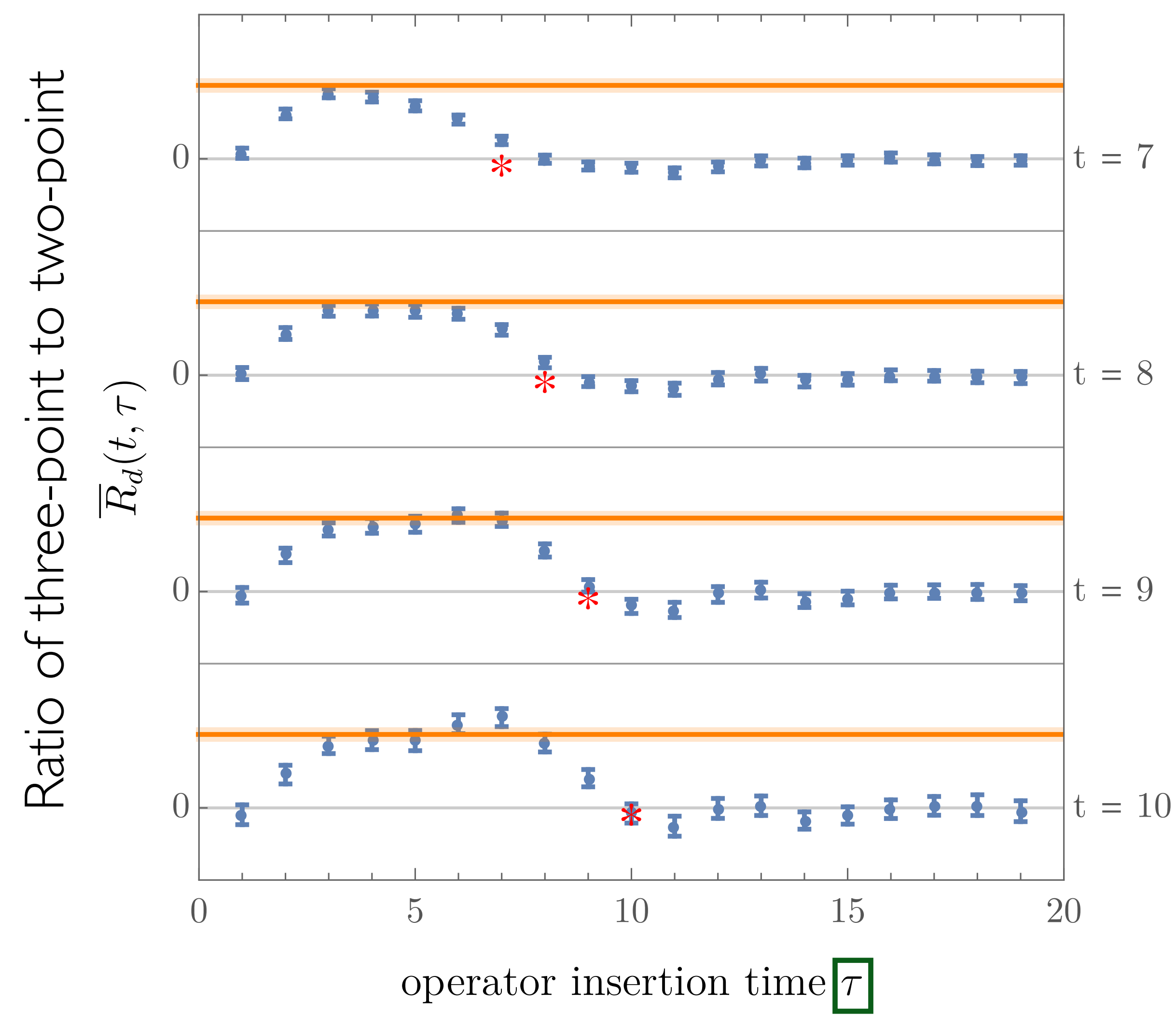
Matrix elements of the spin-independent gluon operator in nucleon + light nuclei

→ **first determination of gluon momentum fraction of nuclei**

**Doubly challenging:**

- Nuclear matrix element
- Gluon observable (suffer from poor signal-to-noise)
- BUT: clean signals at ~5% precision

Deuteron gluon momentum fraction




[NPLQCD PRD96 094512 (2017)]

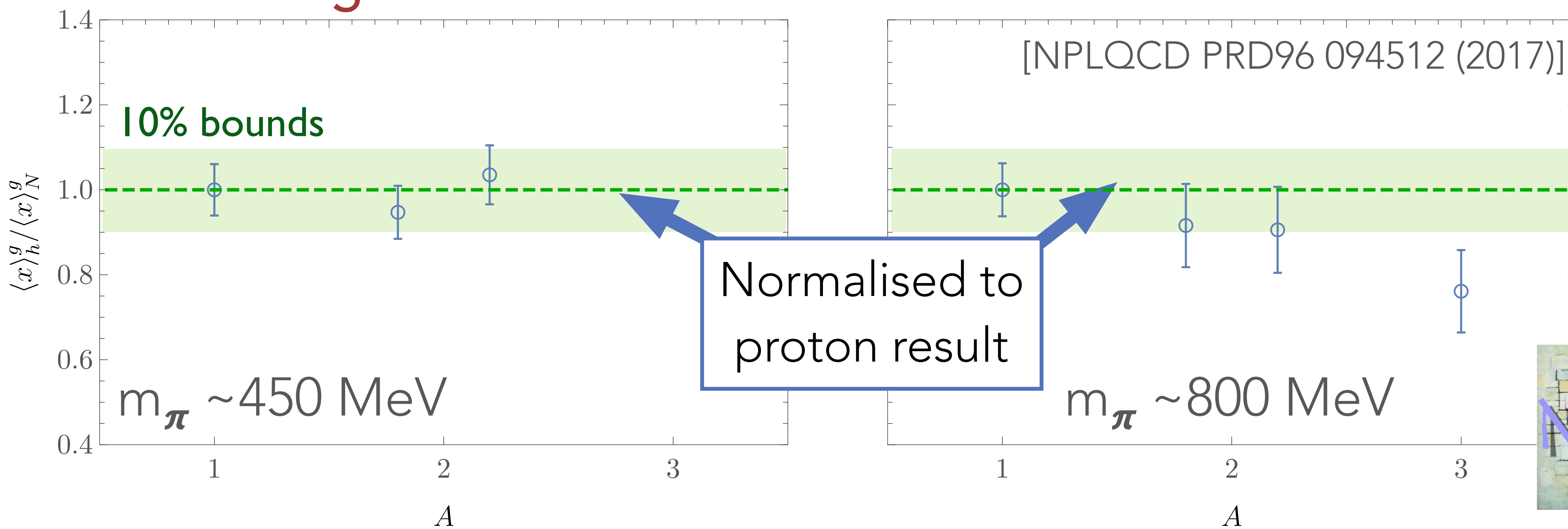
# Gluon momentum fraction of nuclei

Matrix elements of the spin-independent gluon operator in nucleon + light nuclei [NPLQCD PRD96 094512 (2017)]

→ **first determination of gluon momentum fraction of nuclei**

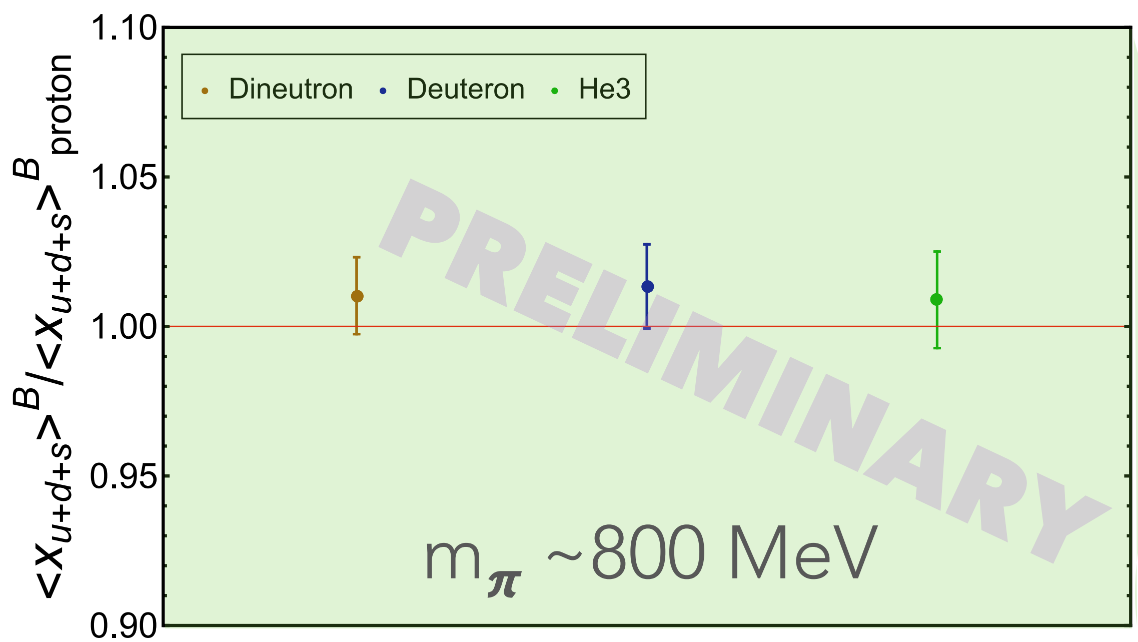
- Constraints at ~10% level on EMC-effect in gluon momentum fraction
- Small mixing with quark EMT operators (neglected)
- Sum rule constraint

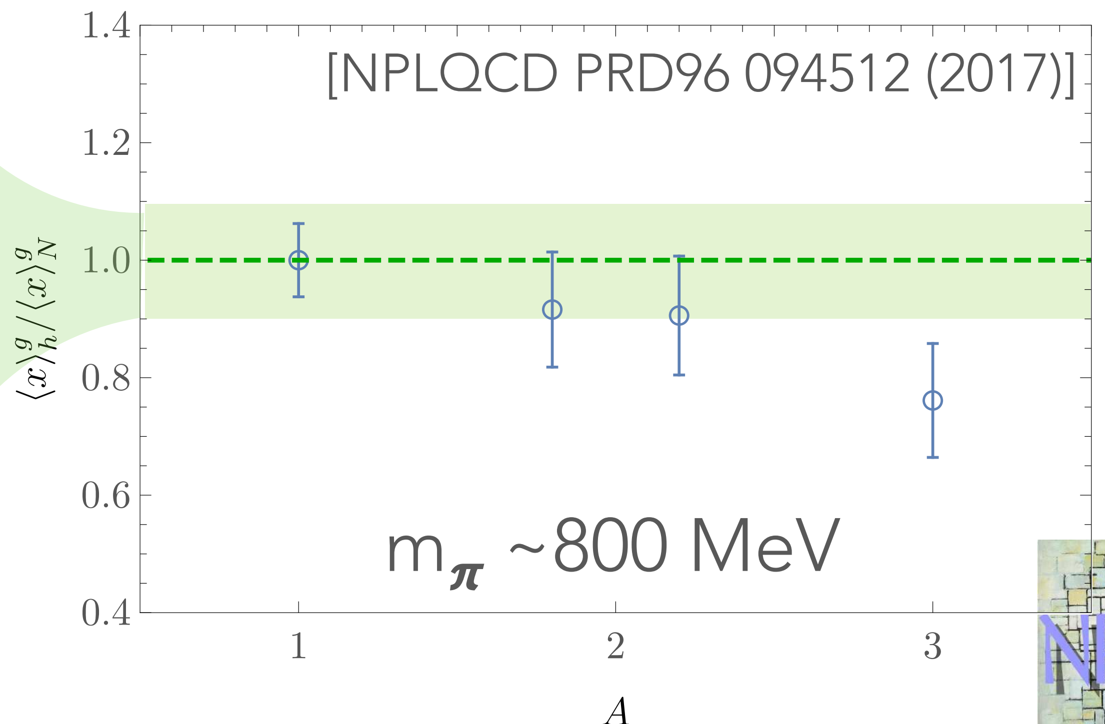
## Ratio of gluon momentum fraction in nucleus to nucleon



# Momentum fractions of nuclei

- First determination of all components of momentum decomposition of light nuclei
- Small mixing between quark and gluon EMT operators neglected
- Constraint on either quark or gluon EMC in this quantity implies constraint on the other from sum rules:



# Exotic glue in the deuteron

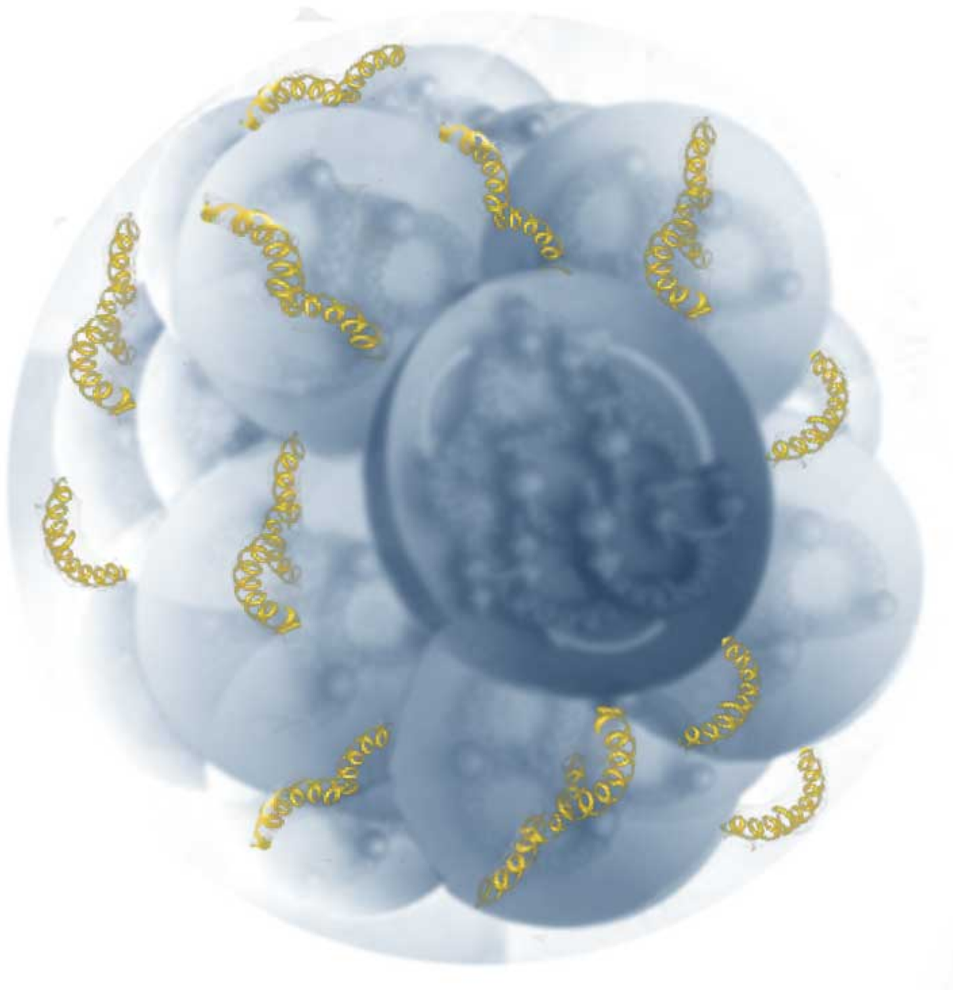
## a "pure" EMC-type effect

Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

Exotic glue operator:

nucleon $\langle p|\mathcal{O}|p\rangle = 0$

nucleus $\langle N, Z|\mathcal{O}|N, Z\rangle \neq 0$

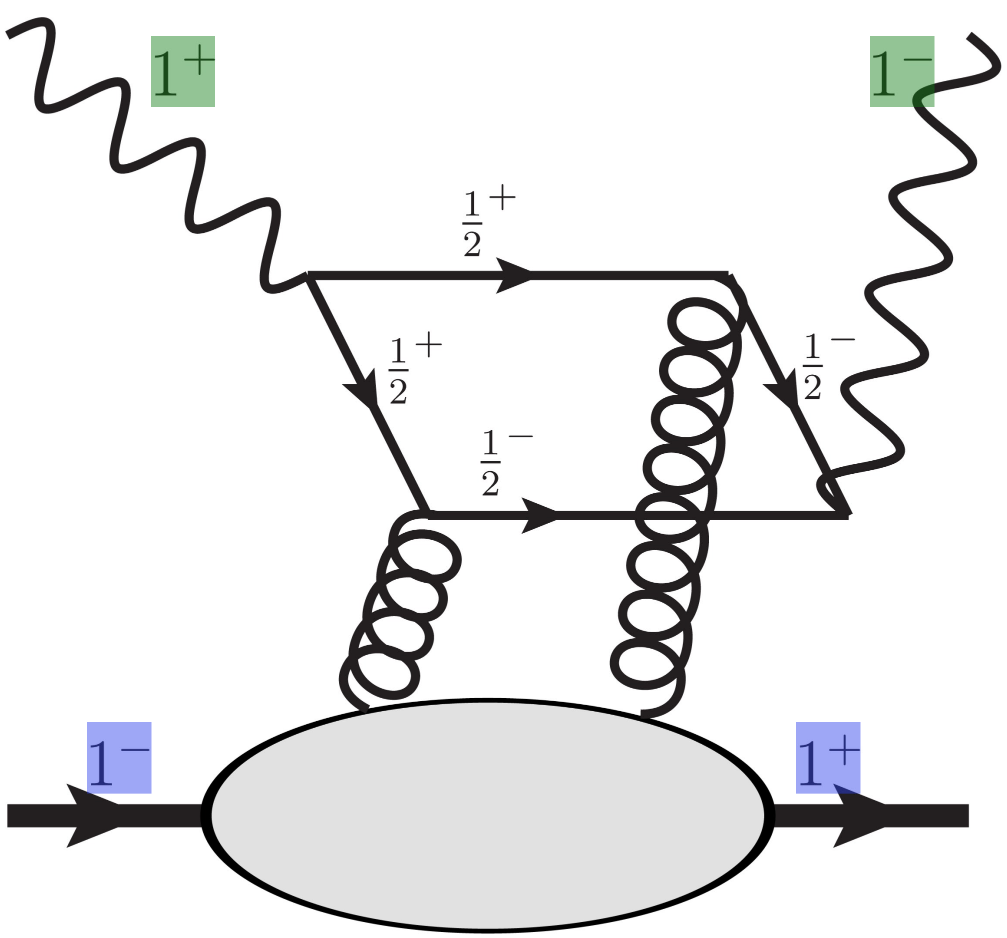


Jaffe and Manohar, "Nuclear Gluonometry"
Phys. Lett. B223 (1989) 218

# Exotic glue in the deuteron

## a "pure" EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$:
changes both photon and target helicity by 2 units




- **Unambiguously gluonic:** no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin≥1
- **Experimentally measurable** in unpolarised electron DIS on polarised target
  - Nitrogen target: JLab LoI 2015
  - Polarised nuclei at EIC
- **Moments calculable in LQCD**

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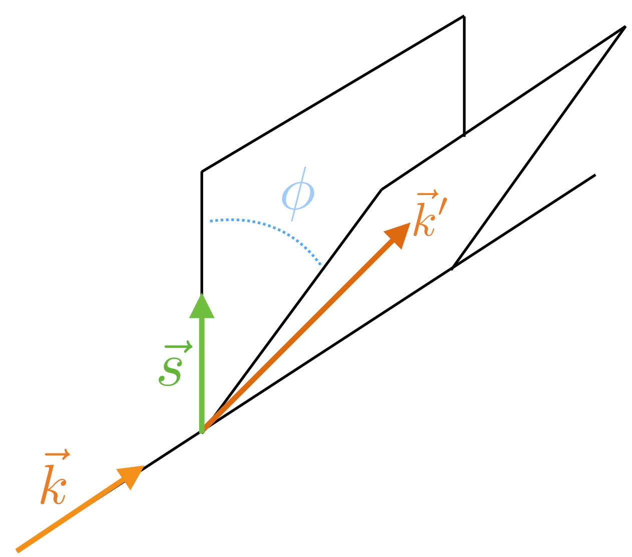


Measure azimuthal variation

$$\lim_{Q^2\to\infty}\frac{d\sigma}{dx\,dy\,d\phi}=\frac{e^4ME}{4\pi^2Q^4}\left[xy^2F_1(x,Q^2)+(1-y)F_2(x,Q^2)\right.$$
$$\left.-\frac{x(1-y)}{2}\Delta(x,Q^2)\cos 2\phi\right]$$

- **Unambiguously gluonic:** no analogous quark PDF at twist-2
- Non-vanishing in forward limit for targets with spin$\geq$1
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  - Nitrogen target: JLab LoI 2015
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# Exotic glue in the deuteron

## a "pure" EMC-type effect

Double helicity flip structure function $\Delta(x,Q^2)$:
changes both photon and target helicity by 2 units

Parton model interpretation: gluonic transversity

$$\Delta(x,Q^2) = -\frac{\alpha_s(Q^2)}{2\pi}\mathrm{Tr}\mathcal{Q}^2\, x^2 \int_x^1 \frac{dy}{y^3}\left[g_{\hat{x}}(y,Q^2) - g_{\hat{y}}(x,Q^2)\right]$$

$g_{\hat{x},\hat{y}}(y,Q^2)$: probability of finding a gluon with momentum fraction y linearly polarised in $\hat{x}$, $\hat{y}$ direction

# Non-nucleonic glue in deuteron

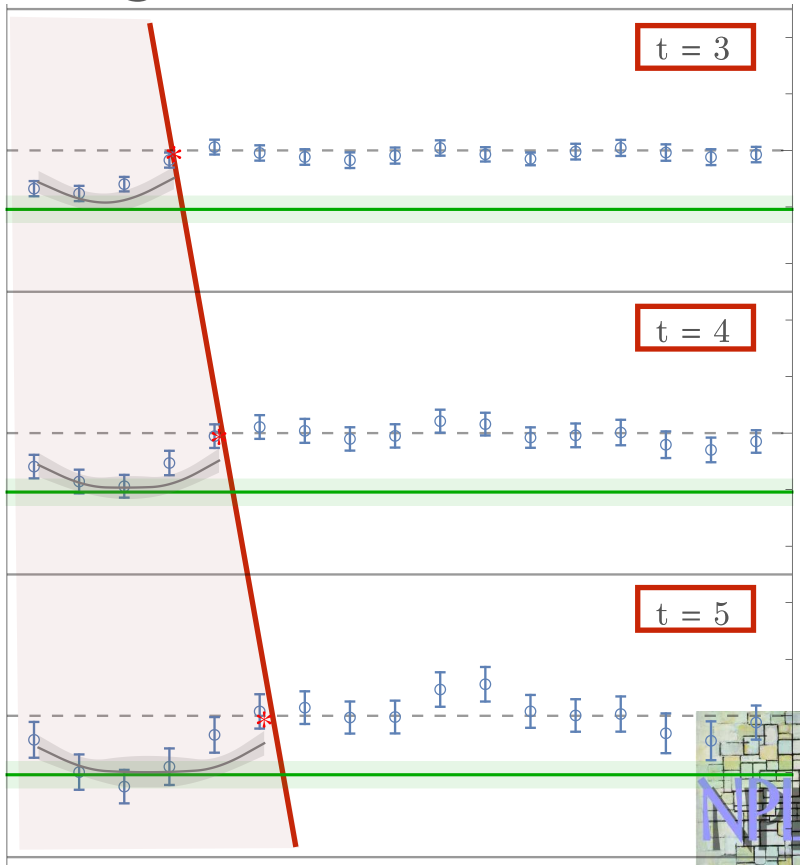
Contributions to nuclear structure from gluons not associated with individual nucleons in nucleus

nucleon: $\langle p|\mathcal{O}|p\rangle = 0$

nucleus: $\langle N, Z|\mathcal{O}|N, Z\rangle \neq 0$

- First moment of gluon transversity distribution in the deuteron [Jaffe, Manohar PLB223 (1989) 218]
- First evidence for non-nucleonic gluon contributions to nuclear structure: LQCD with $m_\pi$ ~800 MeV [NPLQCD PRD96 (2017)]
- Magnitude relative to momentum fraction as expected from large-$N_c$

Signal in LQCD data



# OUTLOOK

- Nuclei are under study directly from QCD
  - Spectroscopy of light nuclei and exotic nuclei
  - Structure: magnetic moments, parton structure
  - Interactions: $np \rightarrow d\gamma$, $pp \rightarrow de^{+}\nu$, $nn \rightarrow pp$, DM
- 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
- Exponential improvements needed for larger nuclei: machine learning & quantum computing