International Conference on Meson-Nucleon Physics and the Structure of the Nucleon
Institute for Nuclear Physics of the Johannes Gutenberg University of Mainz
October 16-20, 2023

UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI WITH LATTICE QCD

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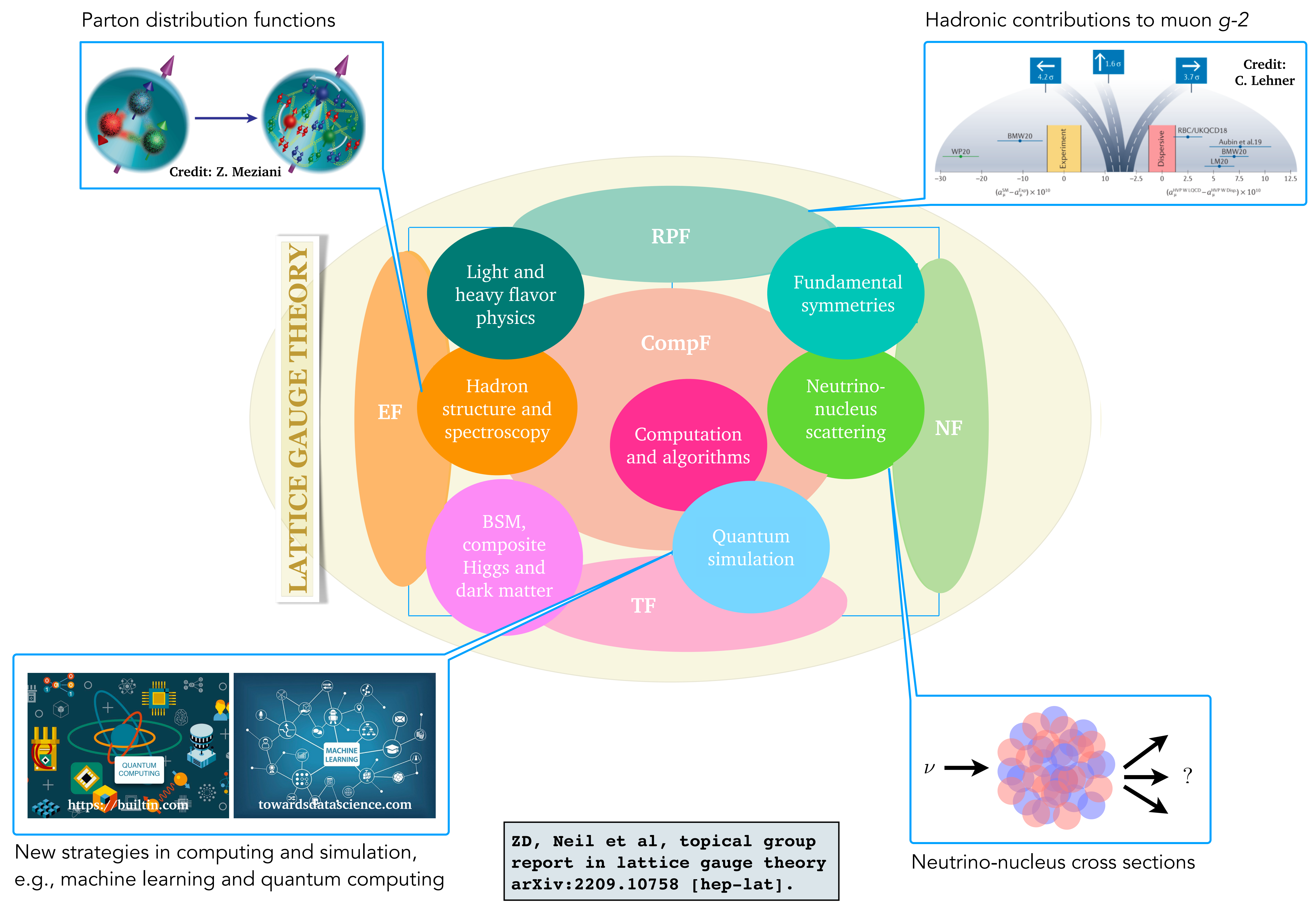
University of Maryland, College Park

LATTICE QCD TOUCHES ON ALMOST ALL AREAS OF HEP



GRAND PICTURE OF NEW PHYSICS DISCOVERY IN NUCLEON AND NUCLEI: EXAMPLE OF $0\nu\beta\beta$ decay

$\Lambda > \mathrm{TeV}$

Start with your favorite high-scale model, e.g.:

$\Lambda \sim 10^2\ \mathrm{GeV}$

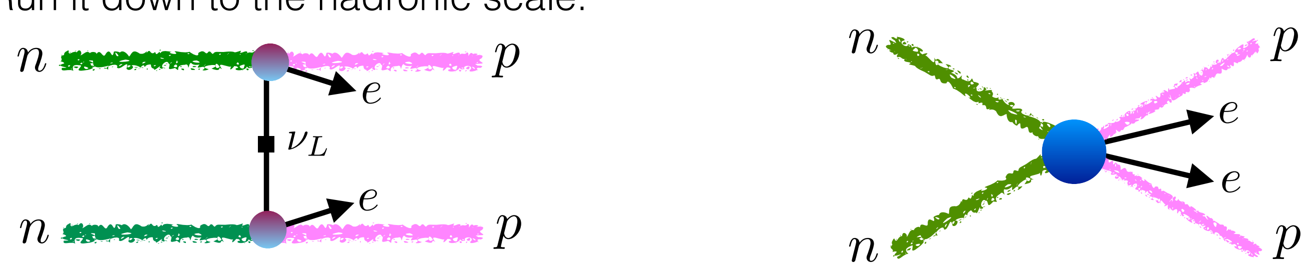
Run it down to the scale where the high-scale physics can be integrated out:

$\Lambda \sim 2\ \mathrm{GeV}$

Run it down to perturbative quark-level matrix elements:

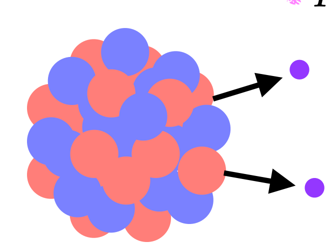
$\Lambda < \mathrm{GeV}$

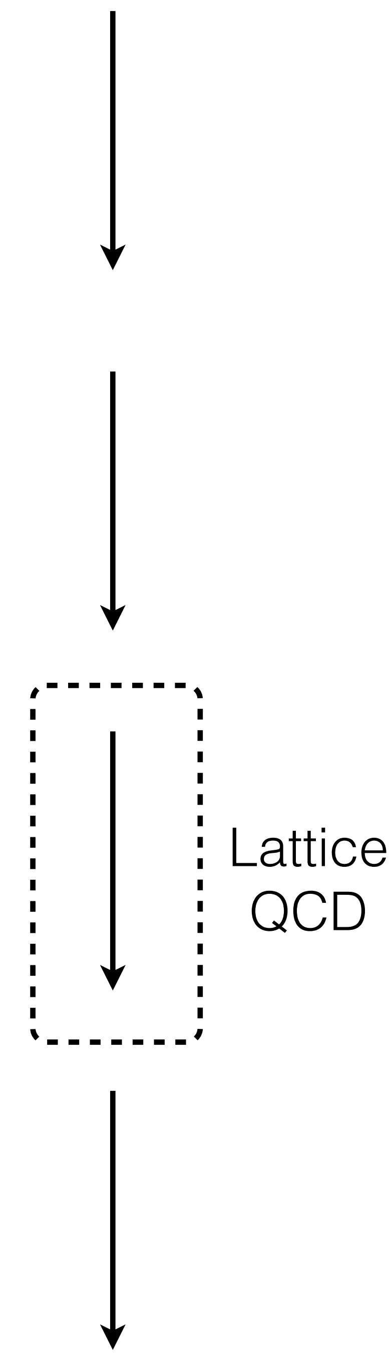
Run it down to the hadronic scale:



$\Lambda < \mathrm{MeV}$

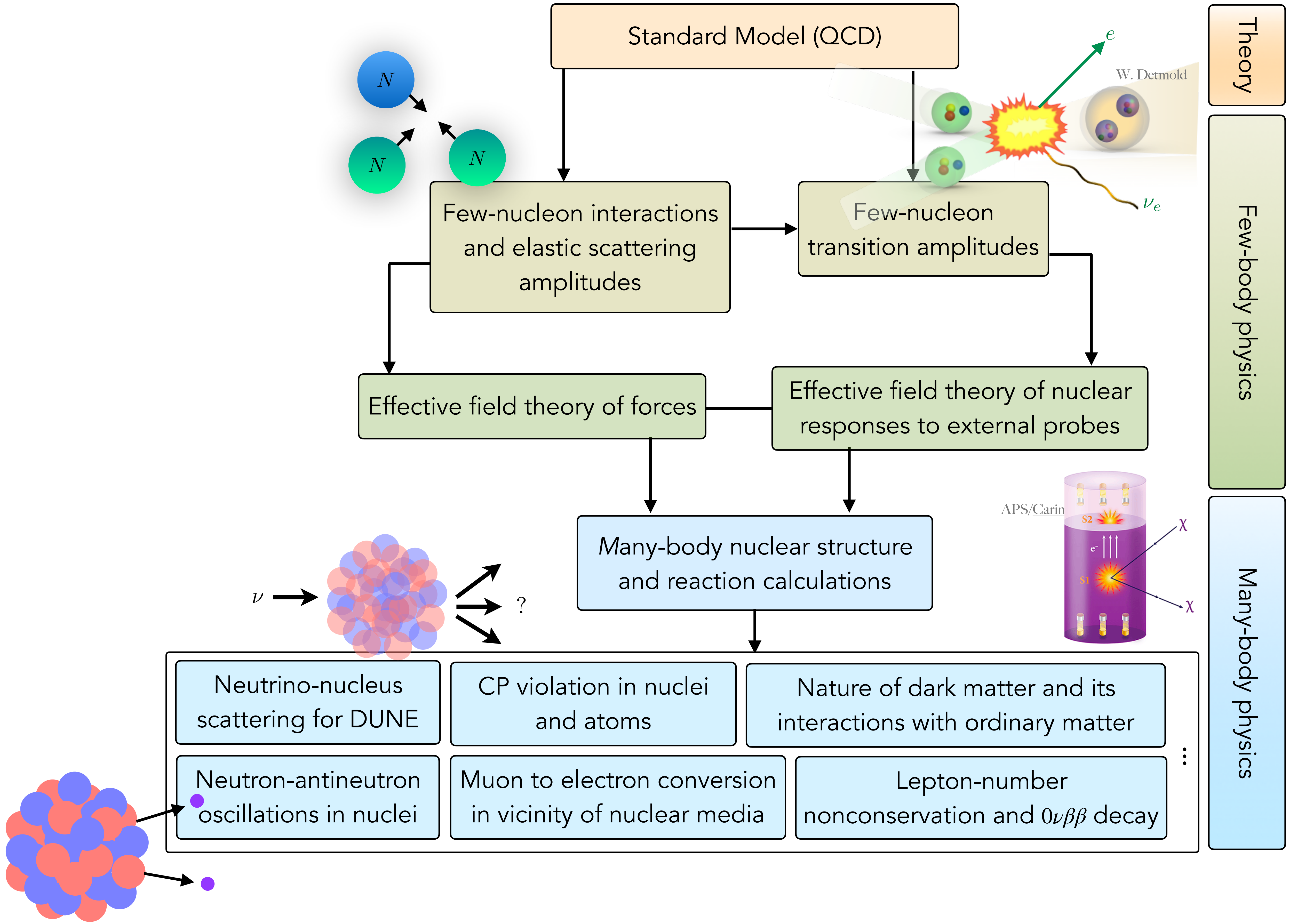
Use nuclear many-body calculation to match it to nuclear matrix elements:





Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197.

MORE DETAILS ON THE ROADMAP FROM QCD TO NUCLEAR OBSERVABLES FOR HEP



UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI

Physics	Target Quantity	Experiments
CP Violation and Neutrino Phenomenology	Neutrino-nucleus Scattering Cross Sections	DUNE, other Long-baseline Neutrino Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
CP Violation and Baryon Asymmetry in Universe	Electric Dipole Moment	Hg, Ra, *n* EDM at SNS and LANL
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197, Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

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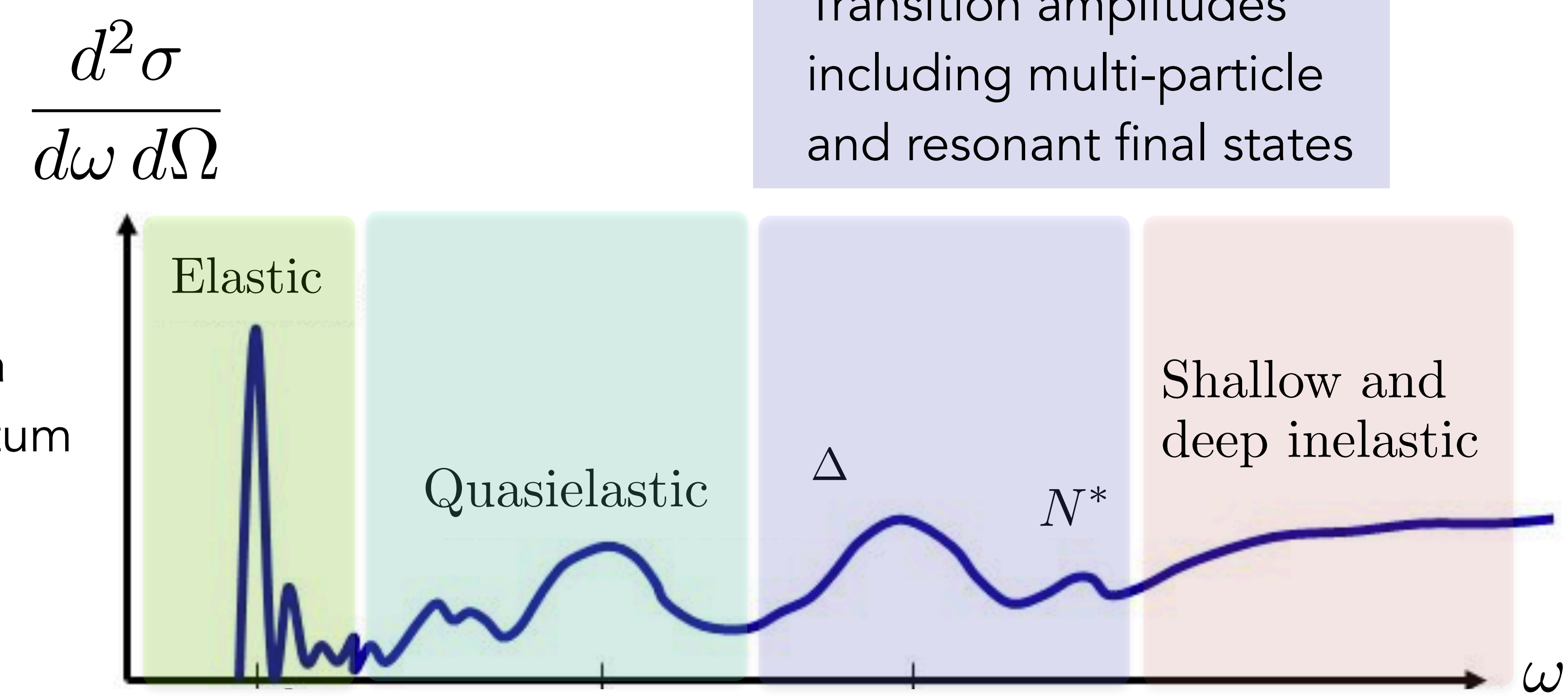
At DUNE, one needs to constrain nuclear response to incoming neutrino of various energy. How can lattice QCD help?

Transition amplitudes including multi-particle and resonant final states



ν-nucleus scattering at a fixed momentum transfer

$\nu_\ell A \to \ell^- X$

Forward form factors, radii

Off-forward form factors

Parton distribution functions, hadron tensor

Need to compute various matrix elements in nucleon, multi-hadron states, and (light) nuclei:

$$\langle f|J_\nu|i\rangle, \qquad \langle f|J_\mu^\dagger J_\nu|i\rangle, \qquad \langle f|\mathcal{O}|i\rangle$$

and resort to EFTs to connect to large isotopes in experiments.

Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

Ruso et al, Snowmass whitepaper, arXiv:2203.09030 [hep-ph].

Example: Axial charge and form factors of the nucleon from lattice QCD

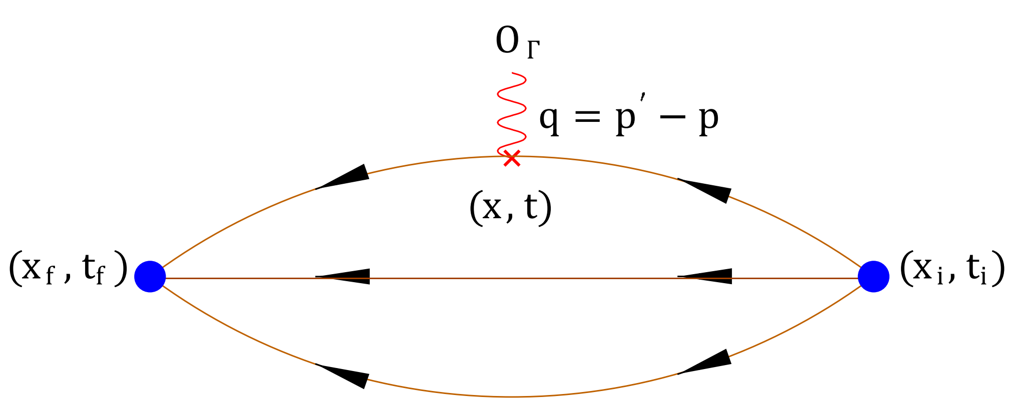
$$\langle N(p',s')|\bar{\psi}(x)\,\gamma_\mu\,\gamma_5\,\psi(x)|N(p,s)\rangle = i\left(\frac{m_N^2}{E_N(\mathbf{p}')E_N(\mathbf{p})}\right)^{1/2}\bar{u}_N(p',s')\left[G_A(q^2)\gamma_\mu\gamma_5 + \frac{q_\mu\gamma_5}{2m_N}G_p(q^2)\right]u_N(p,s)$$

Axial-vector current

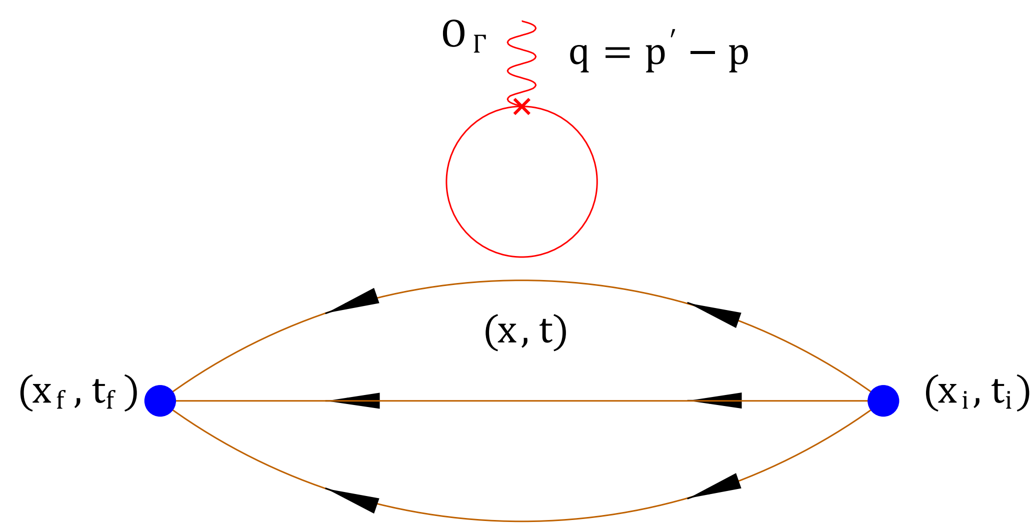
Nucleon spinor

Axial and pseudo scalar form factors

$G_A(0) = g_A$



Connected contribution



Disconnected contribution (vanishes at isospin limit for isovector quantities)

Constantinou, arXiv:1411.0078 [hep-lat].

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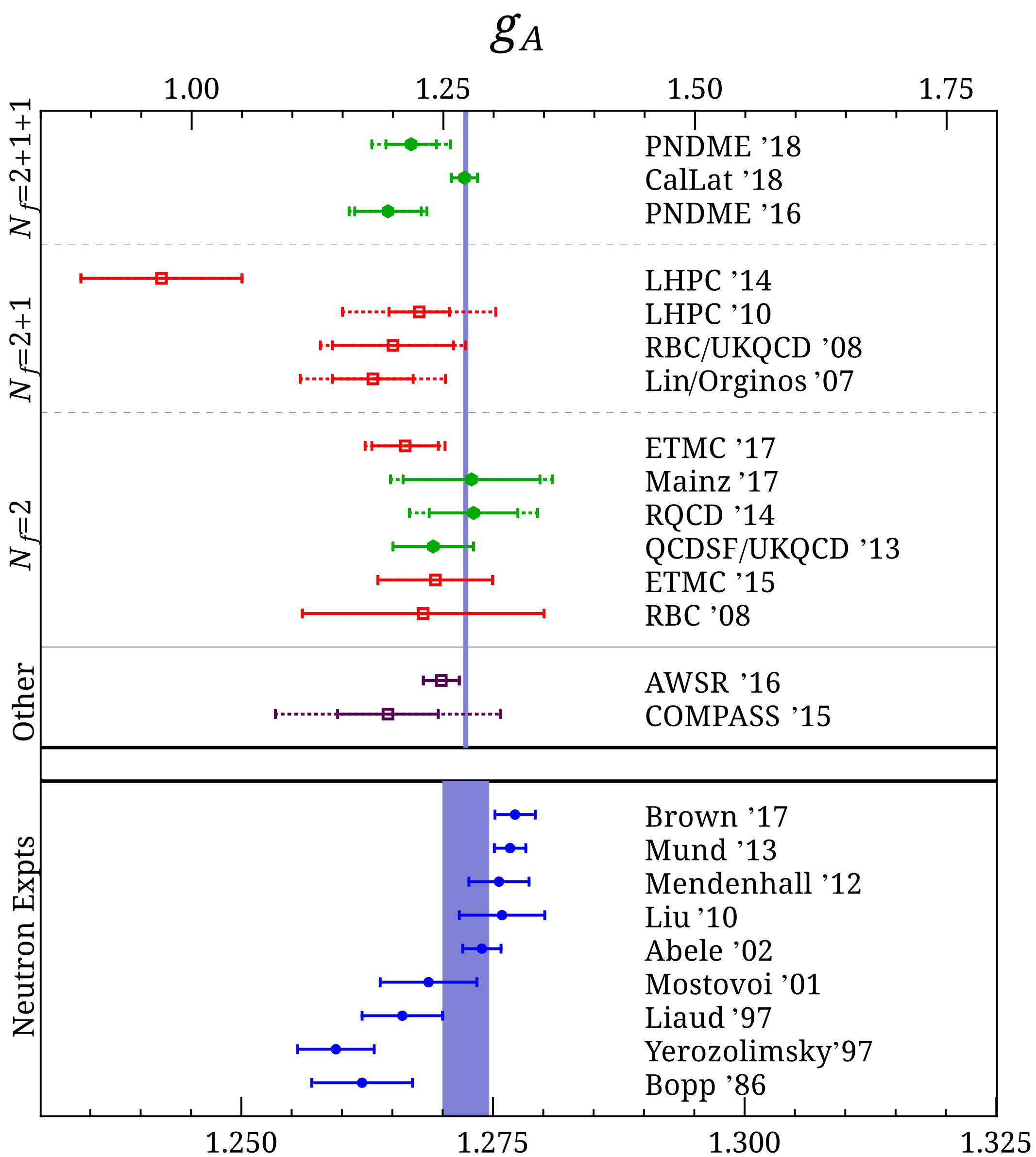
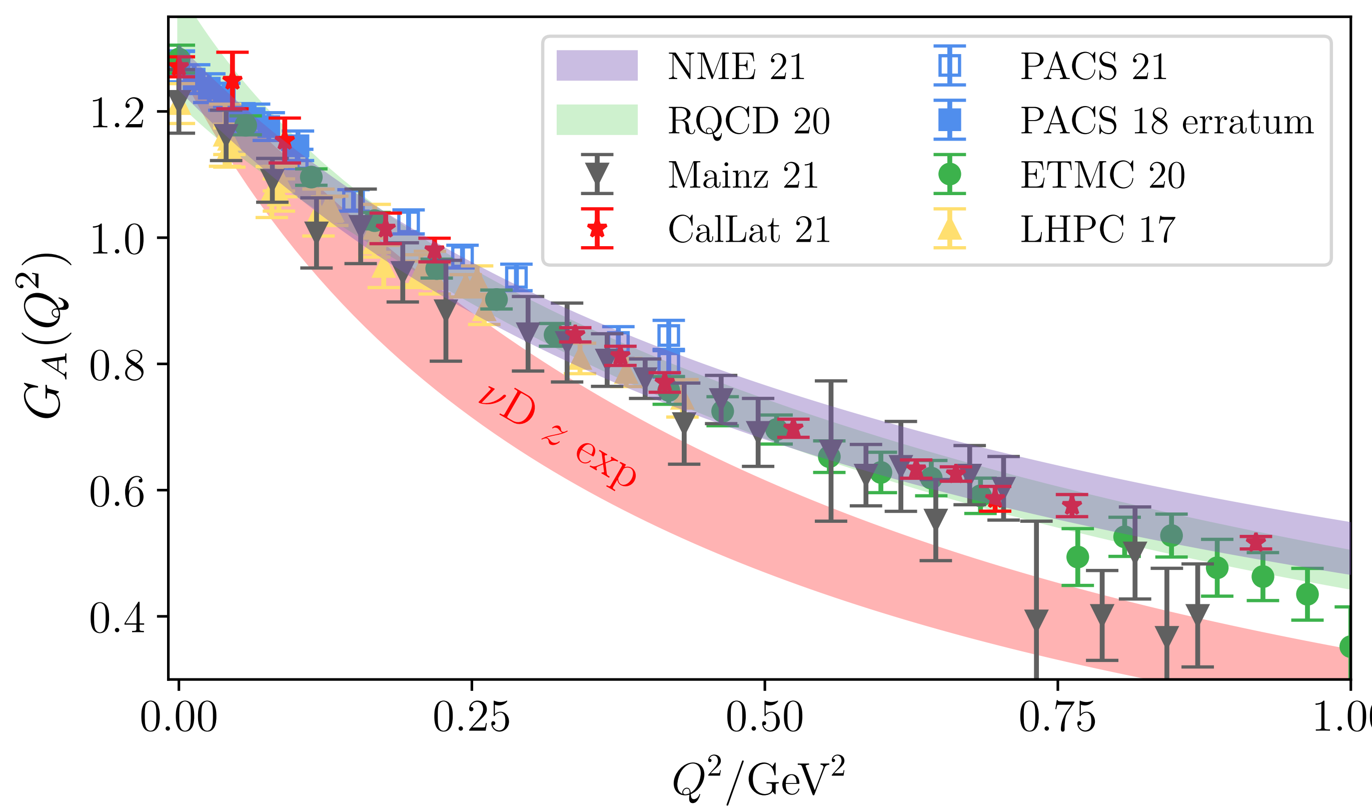
FLAG Review (2019), EPJC 80, 113 (2020).



Compilation of results

Meyer, Walker-Loud, and C. Wilkinson, arXiv:2201.01839 [hep-lat].



Isovector axial form factor results

For the status and future of multi-hadron spectroscopy and transitions from lattice QCD, see: Bulava et al, arXiv: 2203.03230 [hep-lat].

For the status and future of parton distribution functions from lattice QCD, see: Constantinou et al, arXiv: 2202.07193 [hep-lat].

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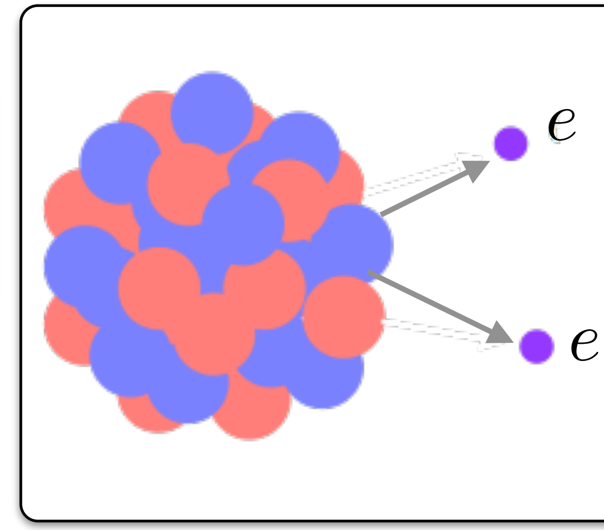
MOTIVATION AND TARGET OBSERVABLES



- Tonne-scale experiment planned in the U.S., design and interpretation of the results requires nuclear matrix elements in various scenarios.

- LNV from dimension-5 operator (light Majorana neutrino exchange)

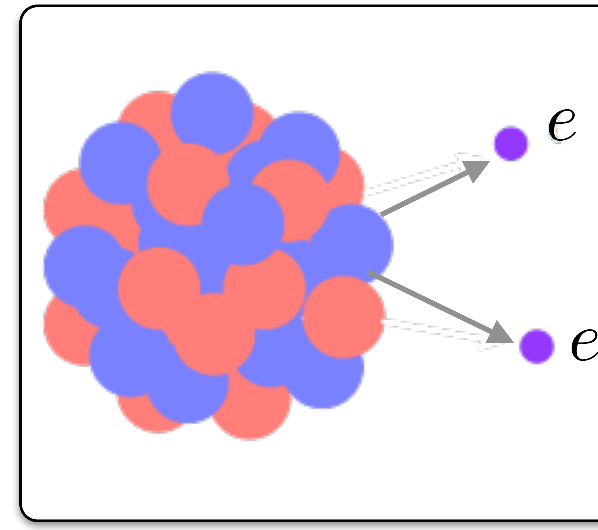
$$\langle \pi^+ | S_{NL} | \pi^- \rangle, \ \langle p\pi^+ | S_{NL} | n \rangle, \ \langle pp | S_{NL} | nn \rangle$$

$$S_{NL} = \int dx\, dy\, S_0(x-y)\; T\left(J^+_\alpha(x) J^+_\beta(y)\right)\; g^{\alpha\beta}$$

- LNV from dimension-9 operators ("short-distance" mechanisms). Requires matrix elements of 4-quark charge-changing operators

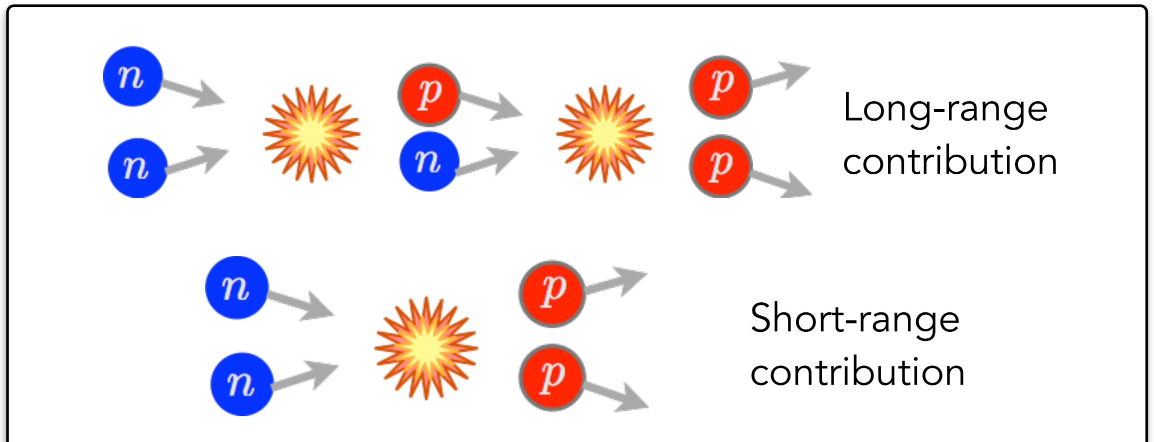
$$\langle \pi^+ | O_i | \pi^- \rangle, \langle p\pi^+ | O_i | n \rangle, \ \langle pp | O_i | nn \rangle$$

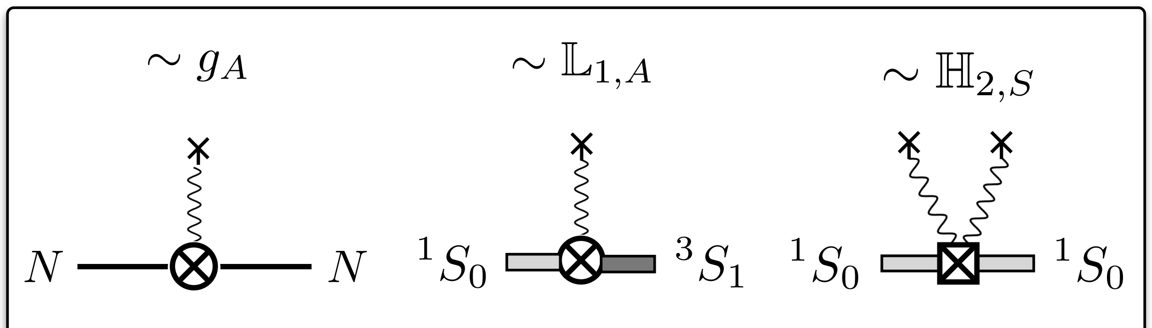
CURRENT STATUS



2vββ DECAY OF TWO NEUTRONS

$$nn \rightarrow pp\, ee\, \overline{\nu}_e \overline{\nu}_e$$



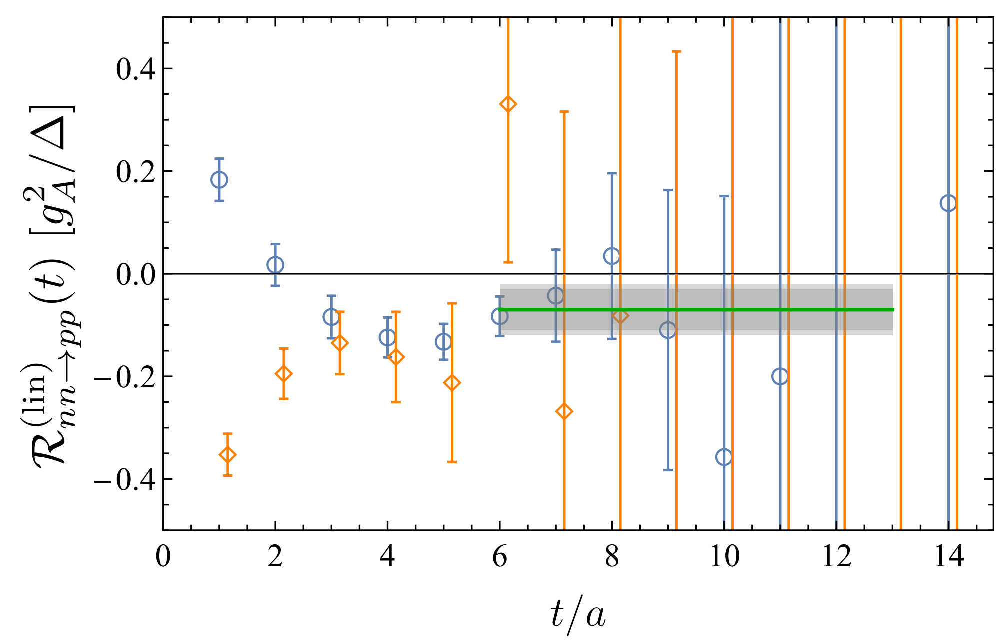


$$\mathbb{H}_{2,S} = 4.7(1.3)(1.8)\ \text{fm}$$

$@\ m_\pi \approx 800$ MeV

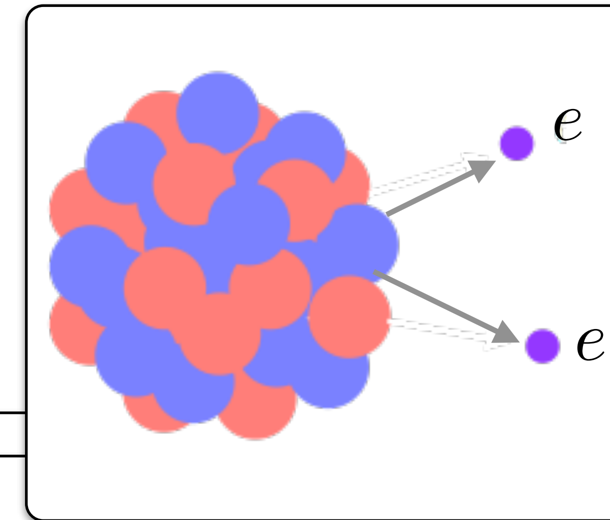
Constraint on the new short-range LEC.

$N_f = 3,\ m_\pi = 0.806$ GeV, $a = 0.145(2)$ fm

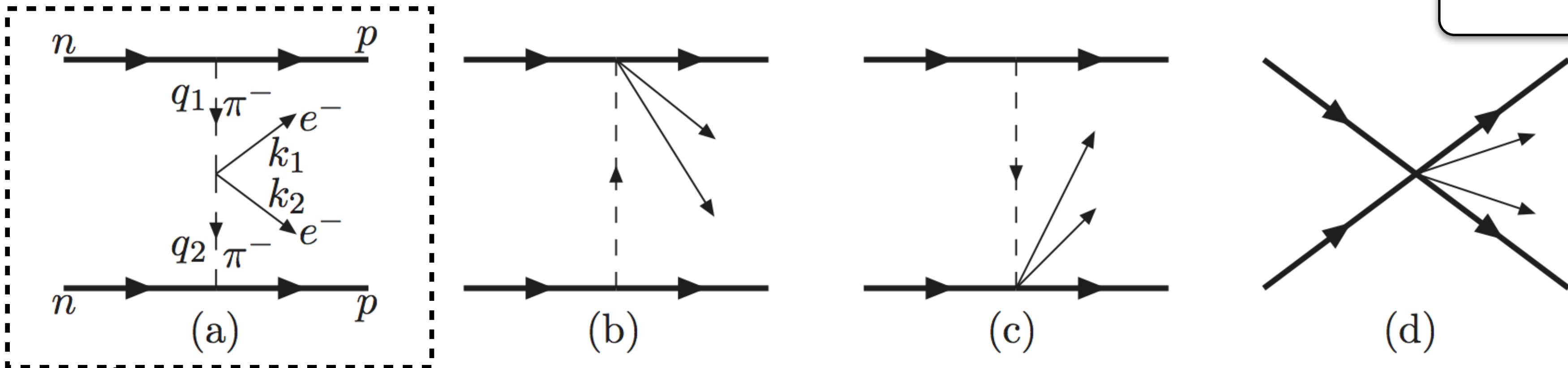


NPLQCD collaboration, Phys. Rev. Lett. 119, 062003 (2017), Phys. Rev. D 96, 054505 (2017). See also Feng et al, Phys. Rev. Lett. 122, 022001 (2019), and Detmold et al, arXiv:1811.05554 [hep-lat] for the $0\nu\beta\beta$ *decay of the pion.*

CURRENT STATUS

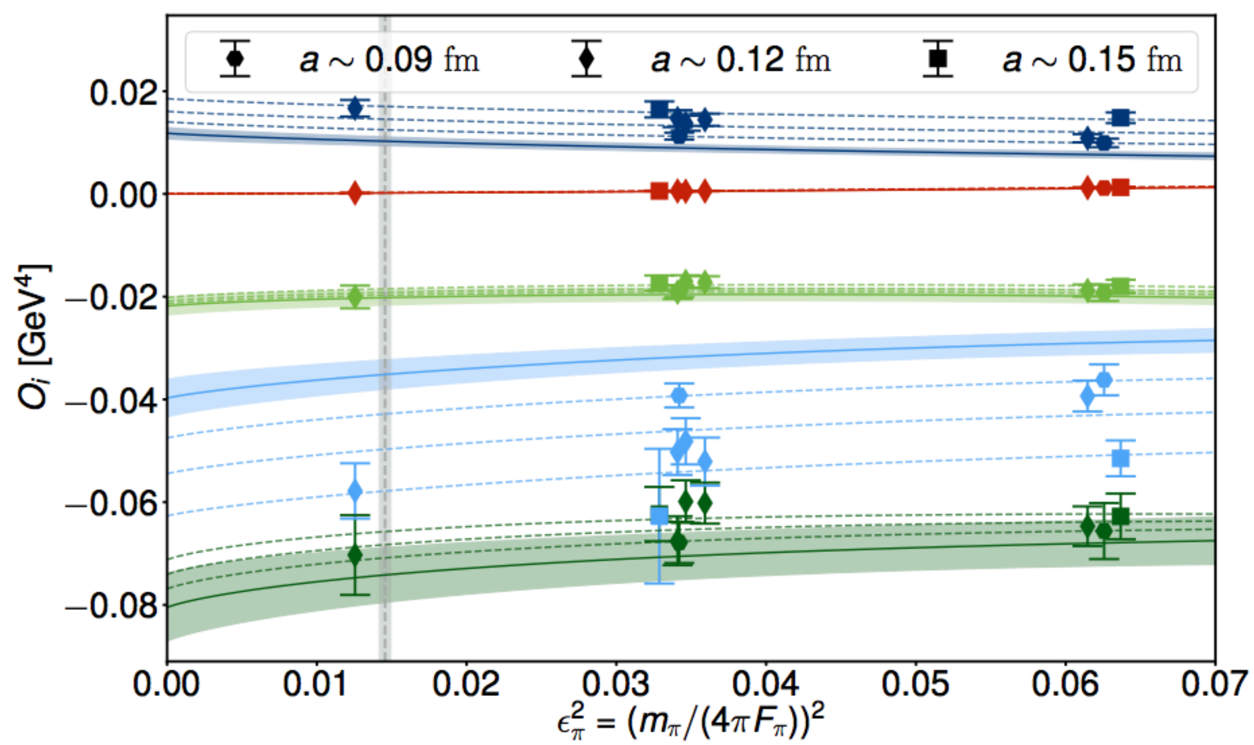


0νββ DECAY OF PIONS

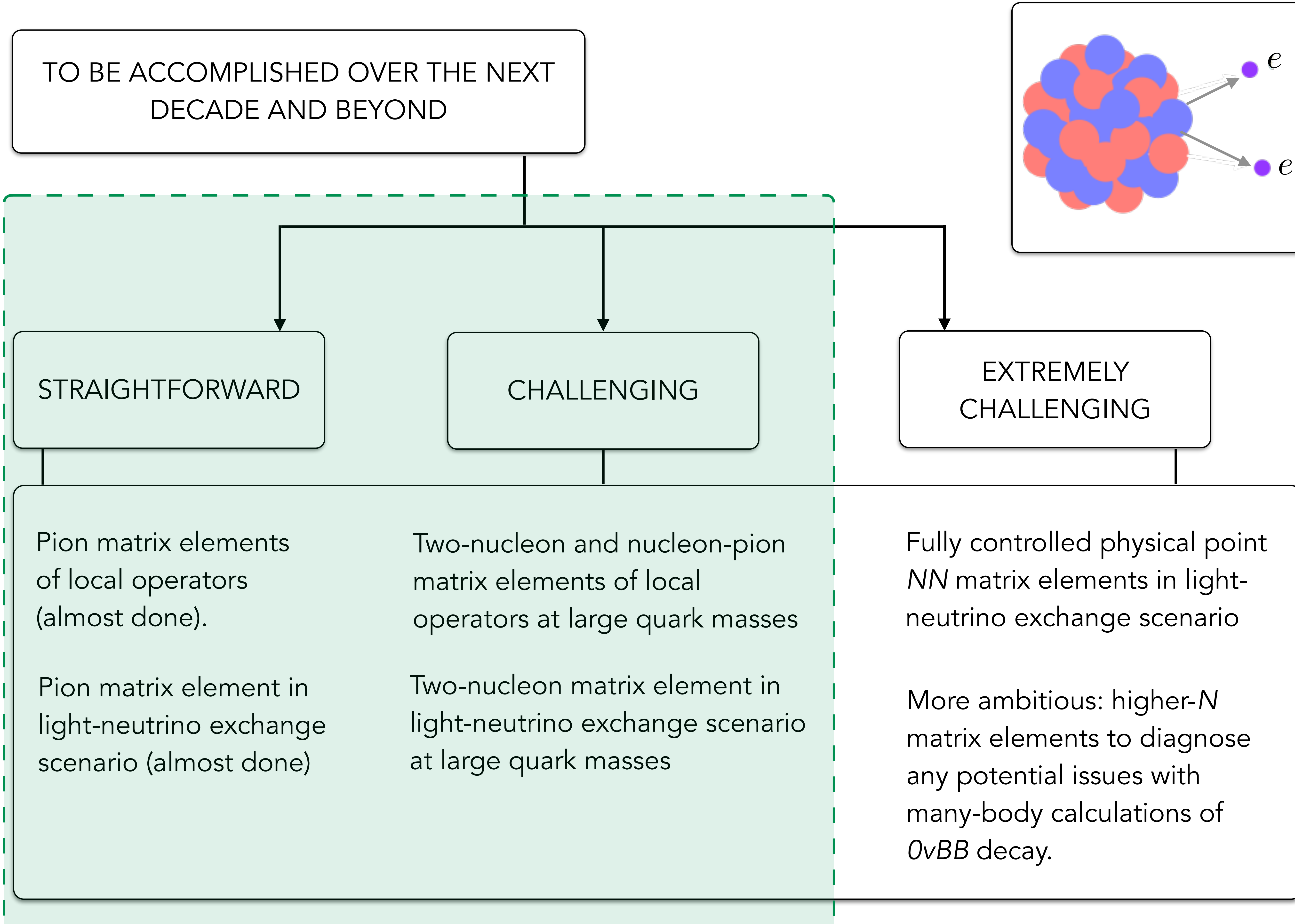


$$\langle\Omega|\Pi^+(t_f,\mathbf{p}_f)\mathcal{O}(0)\Pi^+(t_i,\mathbf{p}_i)|\Omega\rangle$$

$$\pi^- \to \pi^+ ee$$



Nicholson et al (CalLatt), Phys. Rev. Lett. 121, 172501 (2018).


TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND
STRAIGHTFORWARD
CHALLENGING
EXTREMELY CHALLENGING
Pion matrix elements of local operators (almost done).
Pion matrix element in light-neutrino exchange scenario (almost done)
Two-nucleon and nucleon-pion matrix elements of local operators at large quark masses
Two-nucleon matrix element in light-neutrino exchange scenario at large quark masses
Fully controlled physical point *NN* matrix elements in light-neutrino exchange scenario
More ambitious: higher-*N* matrix elements to diagnose any potential issues with many-body calculations of *0vBB* decay.
e
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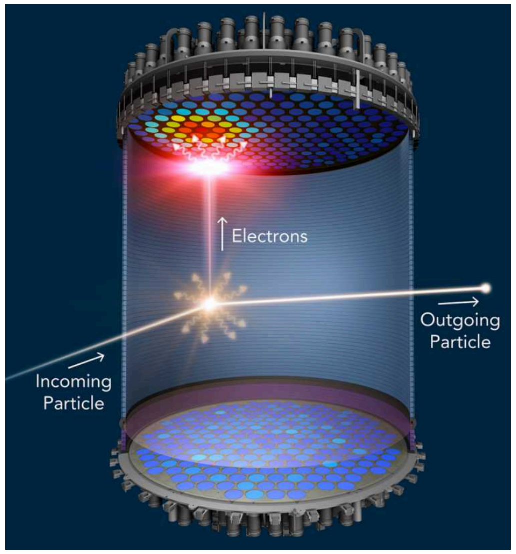
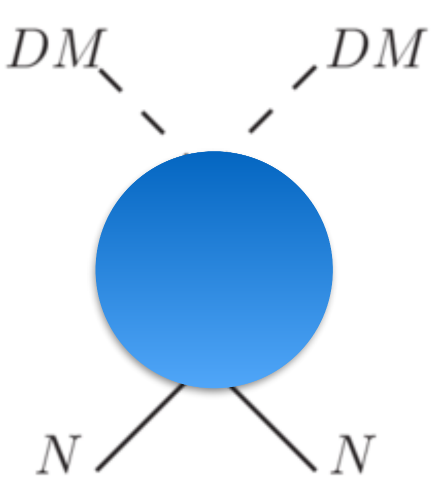
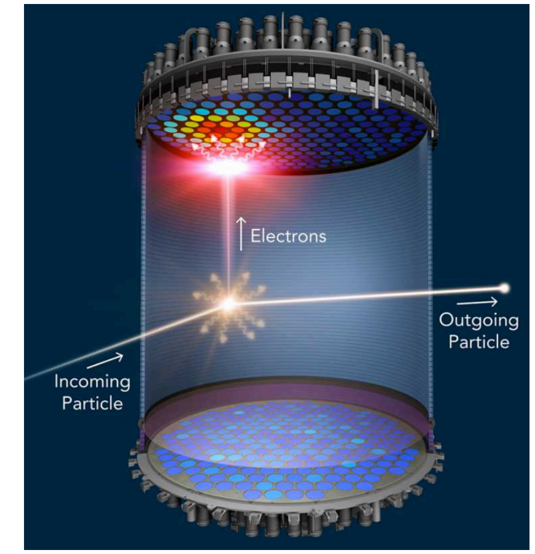


- Standard Model input is necessary to interpret the results of DM searches and translate these into limits on DM models.



- The low-energy limit of a generic spin-independent interaction is scalar coupling to any quark flavor.
- Lattice QCD is the key tool to obtain the strange contributions.
- Spin-dependent couplings and other interactions require knowledge of parton structure of nuclei.

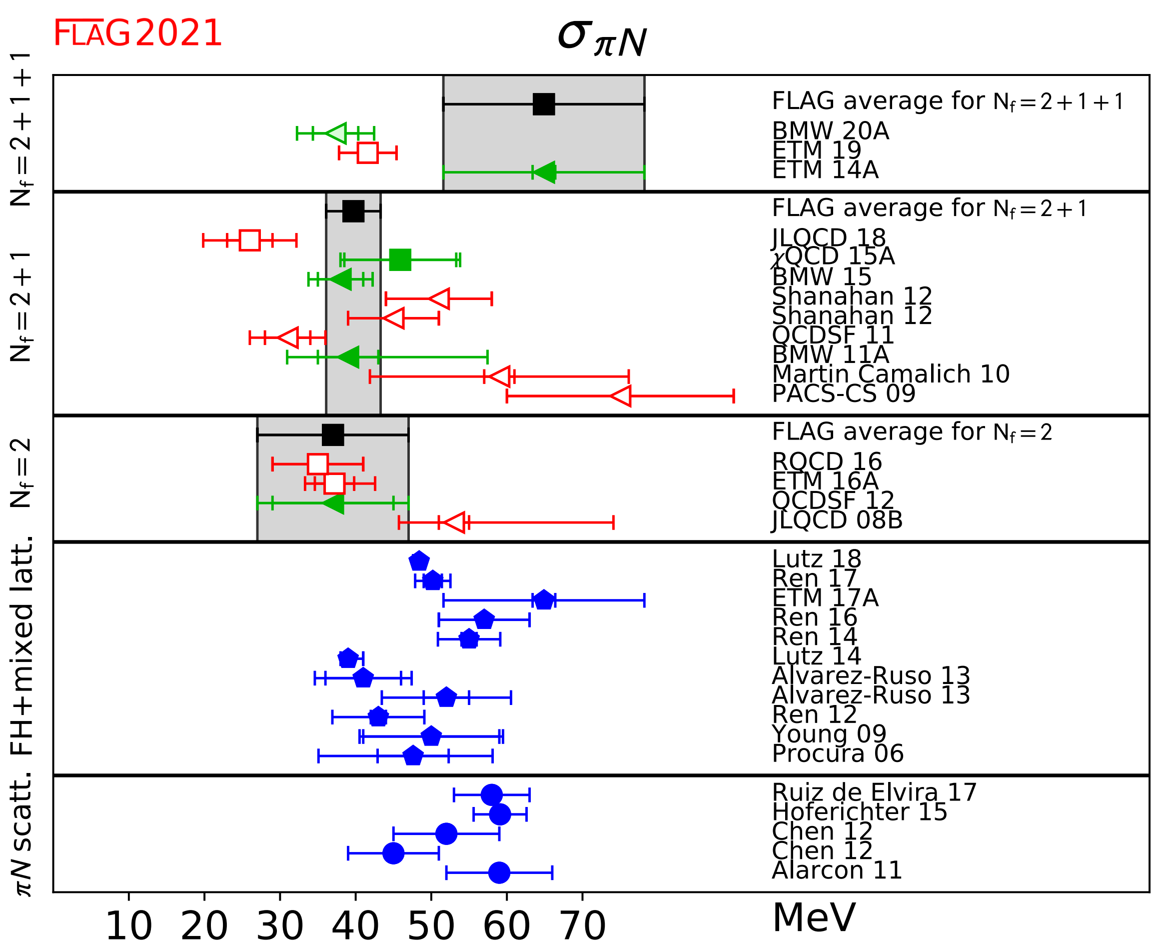
CURRENT STATUS

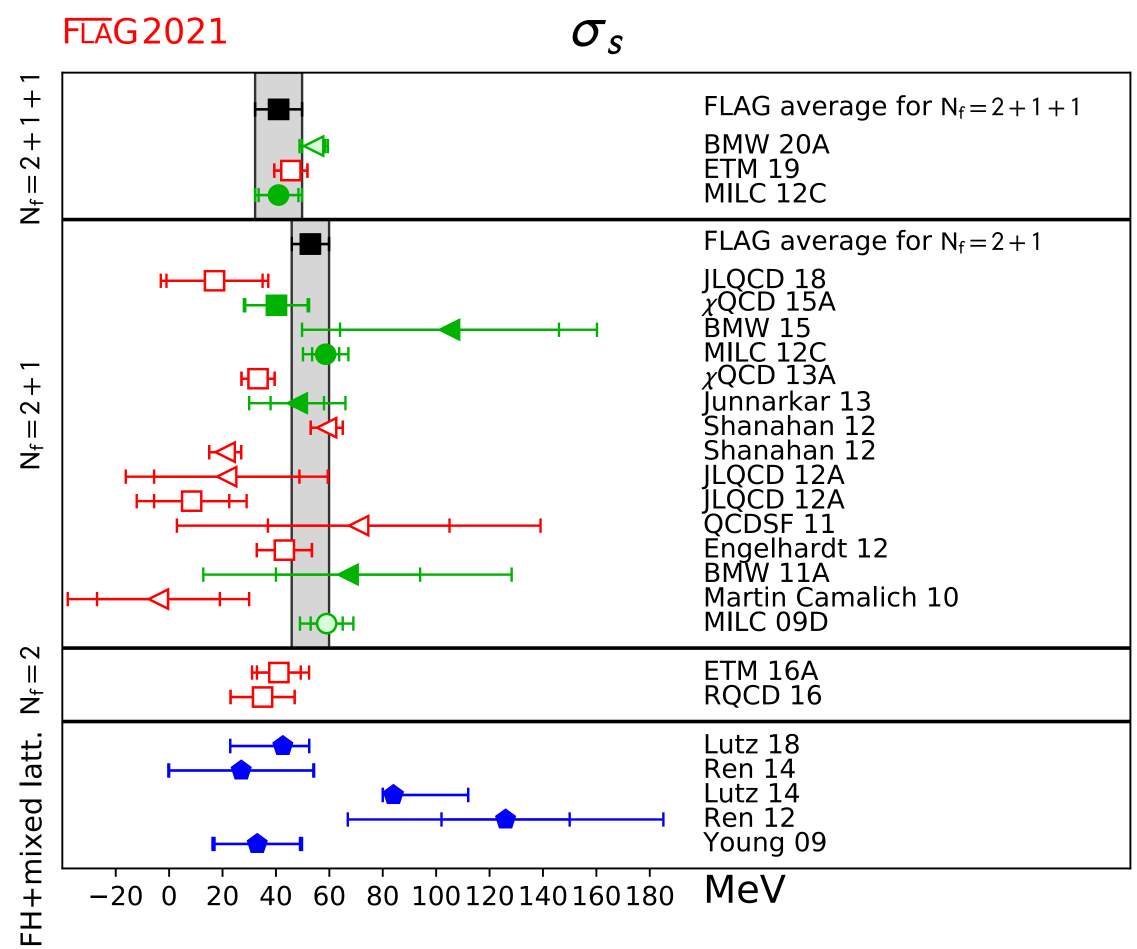


SIGMA TERMS IN NUCLEON

$$\sigma_{\pi N} = \frac{1}{2}(m_u + m_d)\langle N|\bar{u}u + \bar{d}d|N\rangle$$

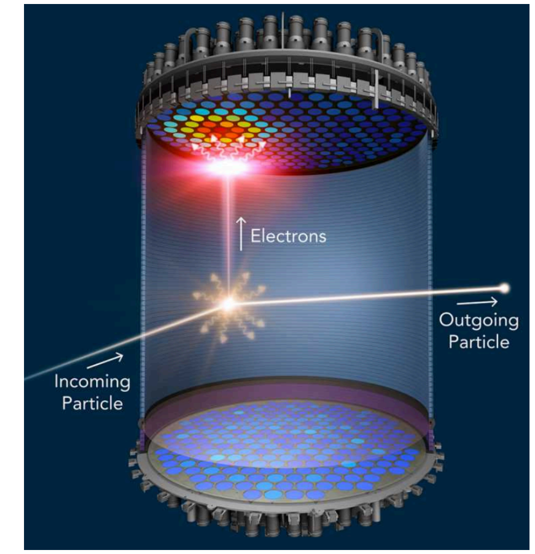
$$\sigma_s = m_s\langle N|\bar{s}s|N\rangle$$





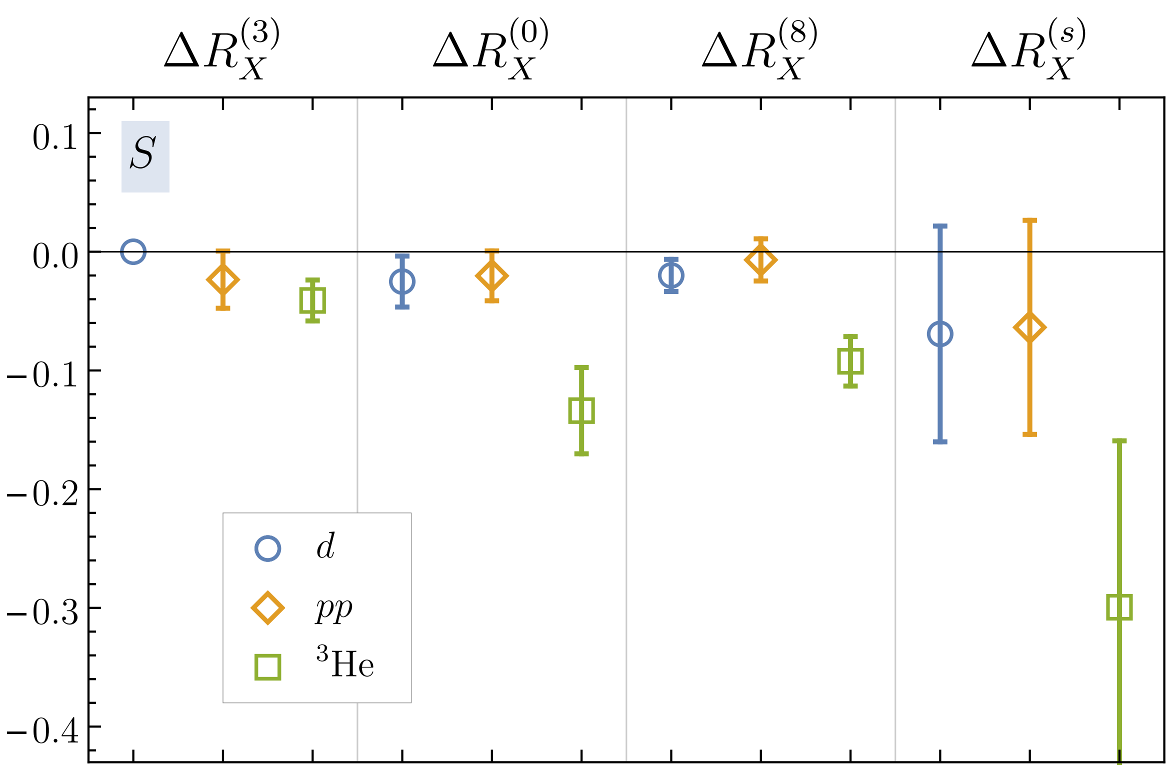
Aoki et al (Flavor Lattice Averaging Group), FLAG Review (2021).

CURRENT STATUS

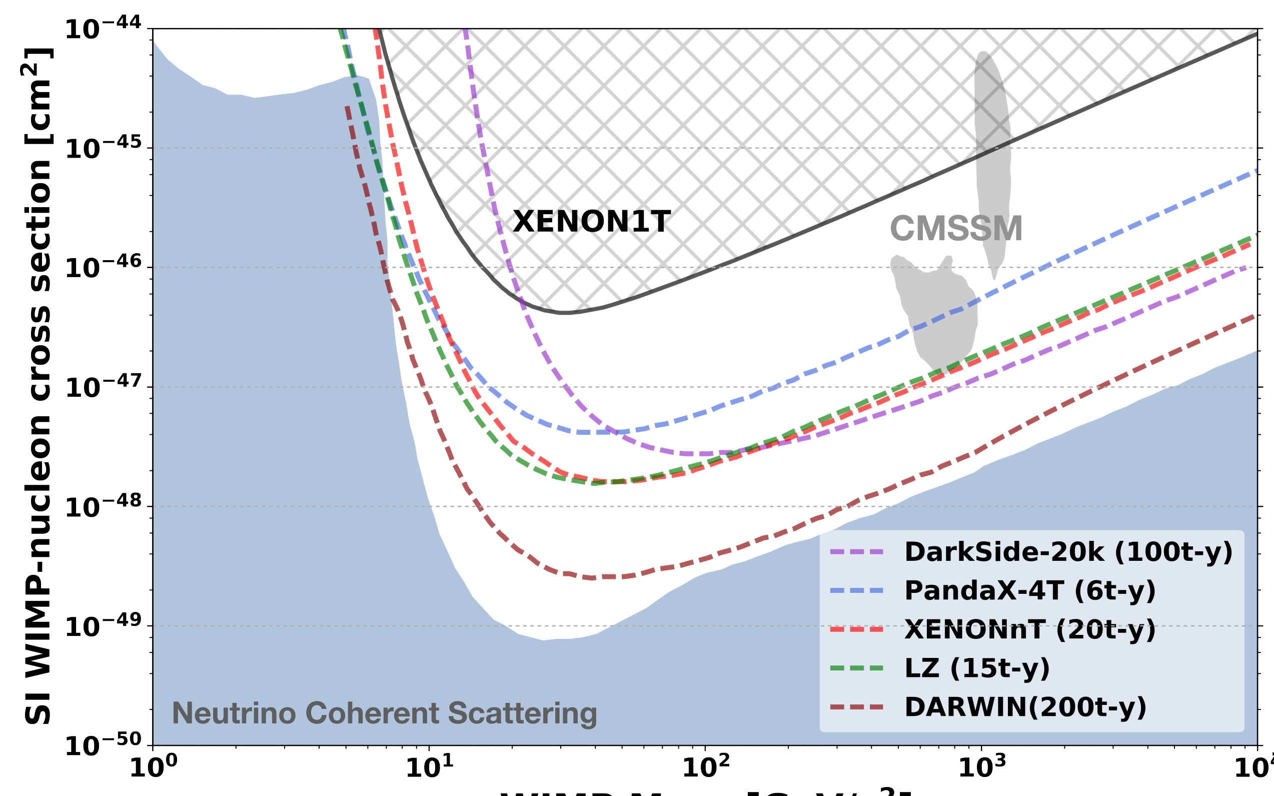


SCALAR RESPONSE OF LIGHT NUCLEI

$$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$$



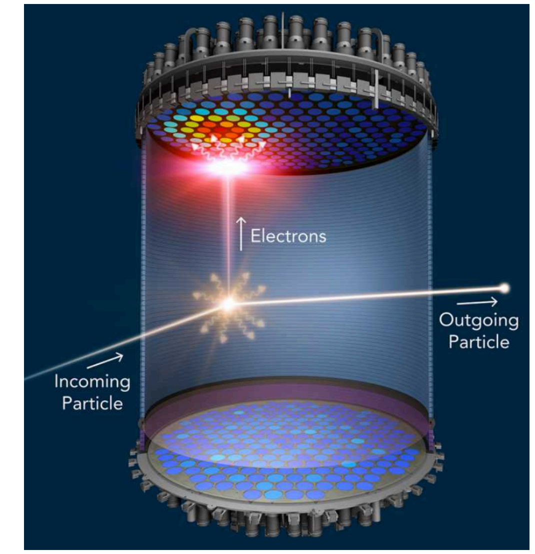
Status of direct detection of WIMP by 2025



Courtesy of Kaixuan Ni

Chang et al (NPLQCD), Phys. Rev. Lett. 120, 152002 (2018).

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

CHALLENGING

EXTREMELY CHALLENGING

Few-percent precision on nucleon matrix elements

Spin-dependent interactions, PDF of nucleons, etc.

Fully controlled 2 and 3 nucleon matrix elements (disconnected, multiple lattice spacings, volumes, chiral extrapolation). Scalar matrix elements are the priority.

Direct and controlled evaluation in (light) nuclei

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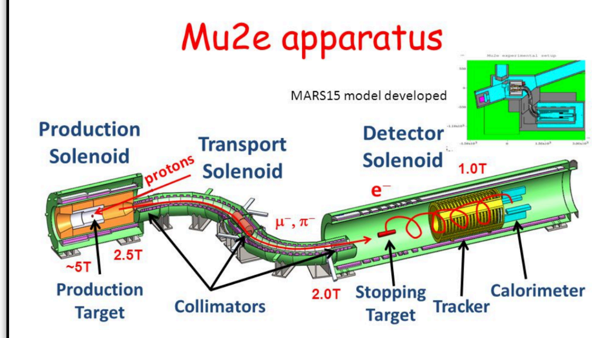
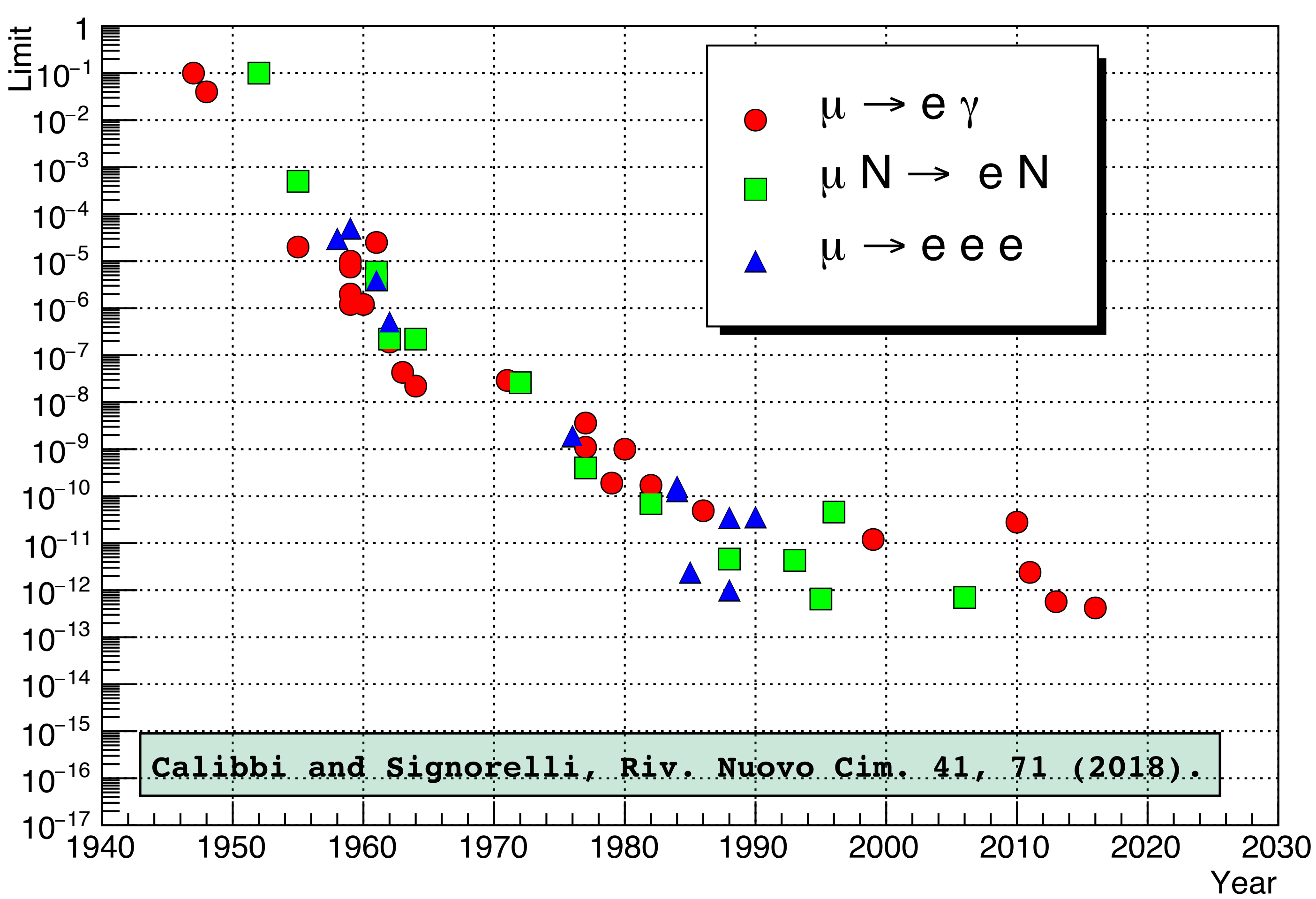
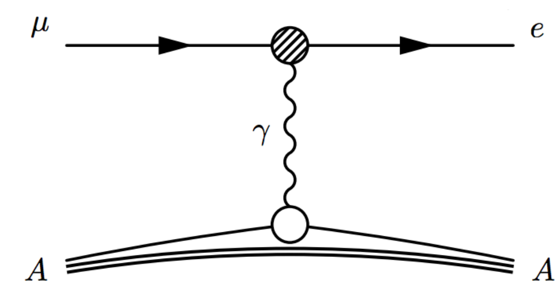


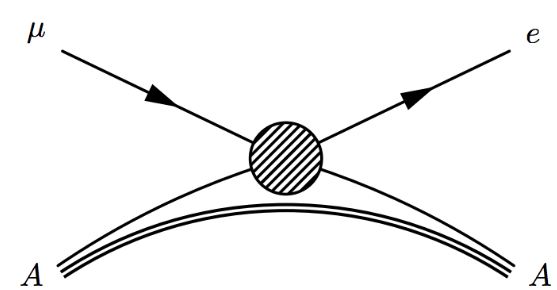
MOTIVATION AND TARGET OBSERVABLES

Reliable matrix elements will help establish pattern of LFV signatures in various decay channels depending on the underlying mechanism.



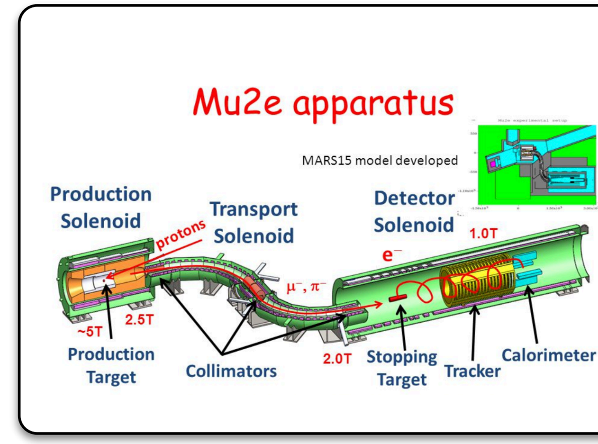


$$\mathcal{L}_d \sim \frac{1}{\Lambda^2} m_\mu \bar{\mu}_L \sigma_{\mu\nu} e_R F^{\mu\nu}$$



$$\mathcal{L}_4 \sim \frac{1}{\Lambda^2} \bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L \right)$$

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

Nucleon form factors (scalar, vector, axial, tensor, pseudoscalar) at $q^2 = m_\mu^2$.

Most relevant is the set of scalar form factors (with *u*, *d*, *s* flavor) and *GG* gluonic operator.

CHALLENGING

Few-percent precision on nucleon form factors

Going beyond impulse approx: directly evaluating matrix elements in nuclei (2 and 3 body contributions)

EXTREMELY CHALLENGING

Directly evaluating matrix elements in (light) nuclei with controlled uncertainties.

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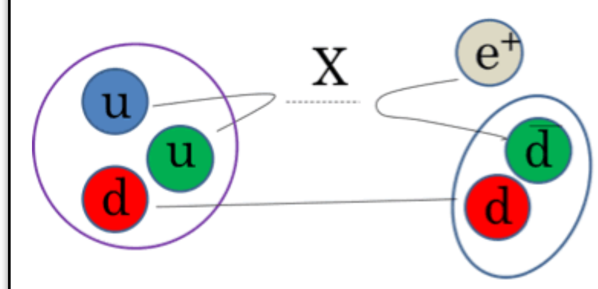
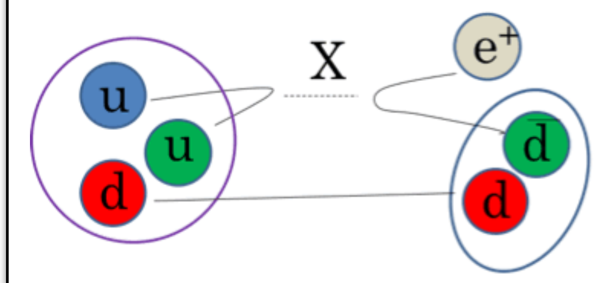
MOTIVATION AND TARGET OBSERVABLES



- GUT and SUSY-GUT constraints require $p \to$ meson matrix elements. Some models predict suppression of p decay matrix elements due to nonperturbative dynamics.
- Upcoming DUNE will examine $p \to K l \nu$ and $p \to \pi\pi e^+$ decays with better precision, future hyper-K will further improve p-decay constraints.

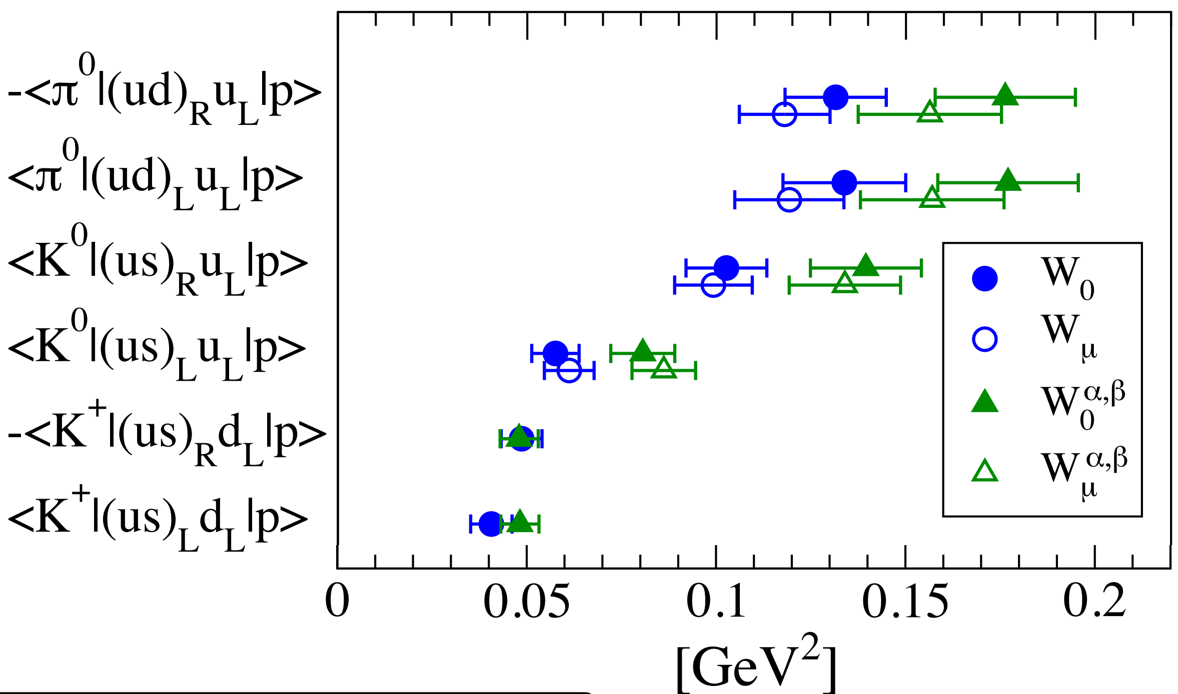
$$\langle \pi^0 | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L u^k | p \rangle$$
$$\langle \pi^+ | \epsilon_{ijk} (u^{iT} C P_{R,L} d^j) P_L d^k | p \rangle$$

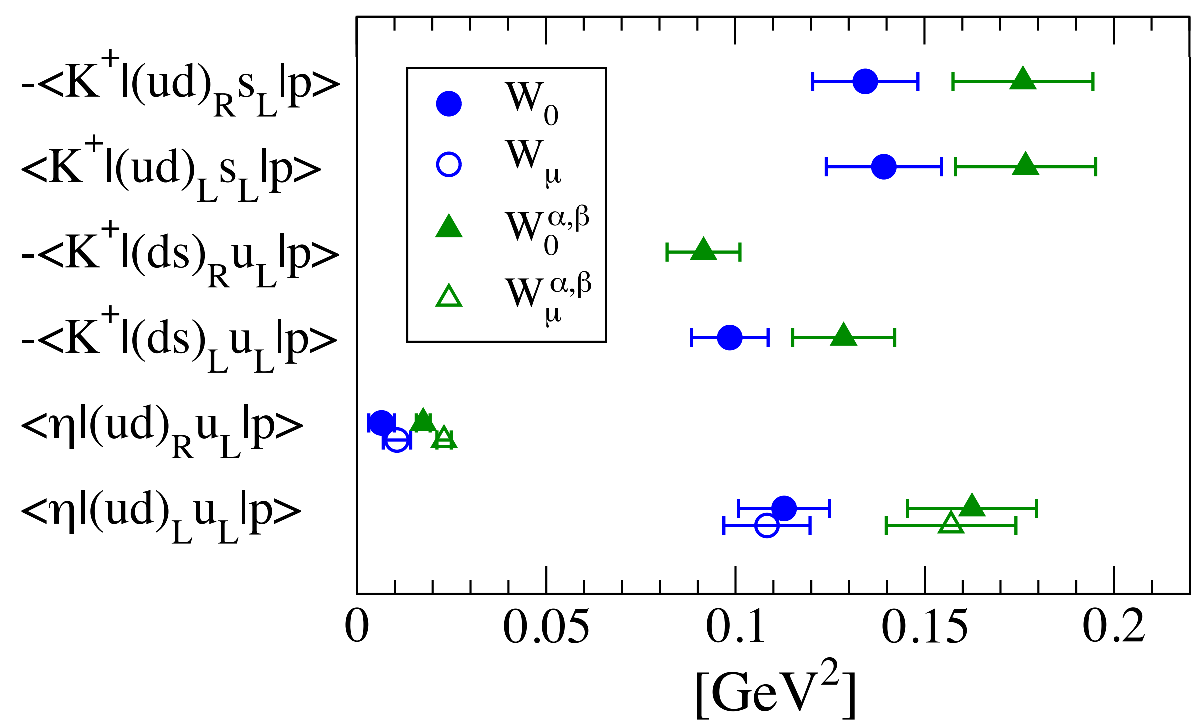
CURRENT STATUS

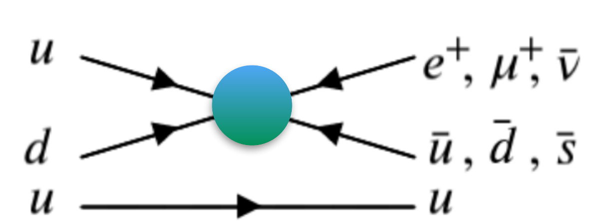


www.hyper-k.org

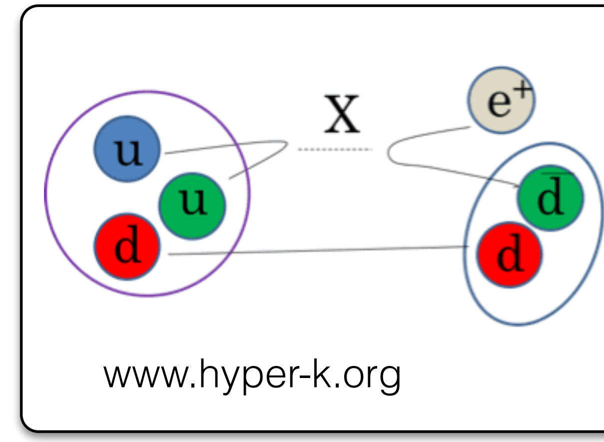
Form factors parametrizing the shown normalized matrix elements at given values of momentum transfer:







Y. Aoki et al (RBC-UKQCD), Phys. Rev. D 96, 014506 (2017).



TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND

STRAIGHTFORWARD

Physical-point calculations of $p \rightarrow$ meson with controlled systematic (multiple volumes, lattice spacing, etc.)

CHALLENGING

Matrix elements for $p \rightarrow \pi\pi e^+$ at a range of quark masses and at the physical point

EXTREMELY CHALLENGING

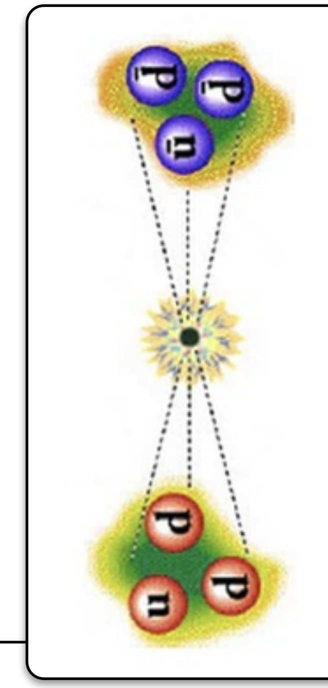
Proton decay in nuclear medium, i.e., $NN \rightarrow NP$ with P being the pseudo-scalar meson.

UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI

Physics	Target Quantity	Experiments
CP Violation and Neutrino Phenomenology	Neutrino-nucleus Scattering Cross Sections	DUNE, other Long-baseline Neutrino Experiments
Baryon Number Violation and Grand Unified Theories	Proton Decay Matrix Elements	DUNE, Hyper-Kamiokande
Baryon Number minus Lepton Number Violation	Neutron-antineutron Matrix Elements	ILL, ESS Super-K, DUNE and other reactors
Lepton Flavor Violation	Nucleon and Nuclei Form Factors	Mu2e, COMET
Lepton Number Violation	$0\nu\beta\beta$ Matrix Elements	EXO, Tonne-scale $0\nu\beta\beta$
CP Violation and Baryon Asymmetry in Universe	Electric Dipole Moment	Hg, Ra, *n* EDM at SNS and LANL
Dark Matter and New Physics Searches	Nucleon and Nuclei Form Factors	Dark Matter Experiments, Precision Measurements

Cirigliano, ZD et al (USQCD), Eur. Phys. J. A (2019) 55: 197, Kronfeld et al (USQCD), Eur. Phys. J. A 55 (2019) 11, 196.

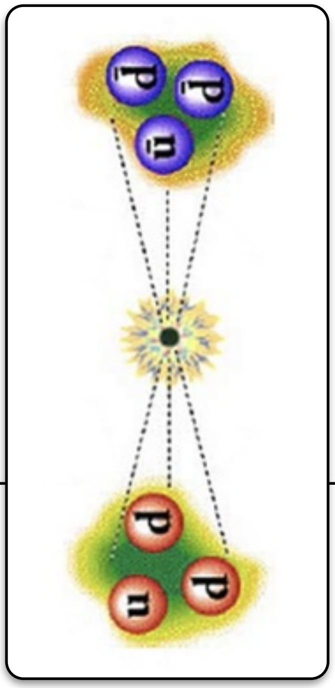
MOTIVATION AND TARGET OBSERVABLES



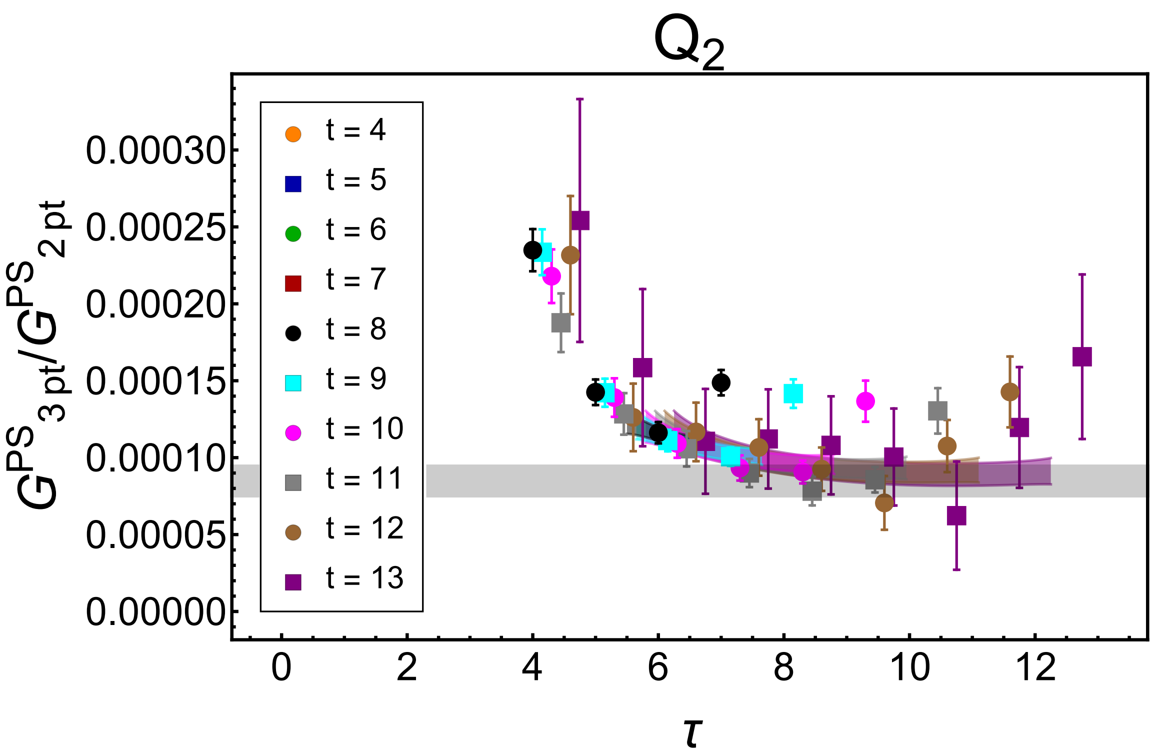
- Some models of B-L violation do not allow the proton decay, therefore, neutron-antineutron oscillation bounds can provide powerful constraints.
- Two types of experiments: slow neutron beams and oscillation in nuclear medium with a distinct 5-pion final state.
- Theoretical uncertainties in neutron beam expts easier to control. Bounds could be improved by a factor of 1000 in next experiments.
- Lattice QCD evaluates matrix elements of 6-quark operators that convert a neutron to an antineutron.

$$\boxed{\frac{1}{\tau_{n\bar{n}}} = \delta m = c_{BSM}(\mu_{BSM}, \mu_W) c_{QCD}(\mu_W, \Lambda_{QCD}) \langle \bar{n} | \mathscr{O} | n \rangle}$$

CURRENT STATUS

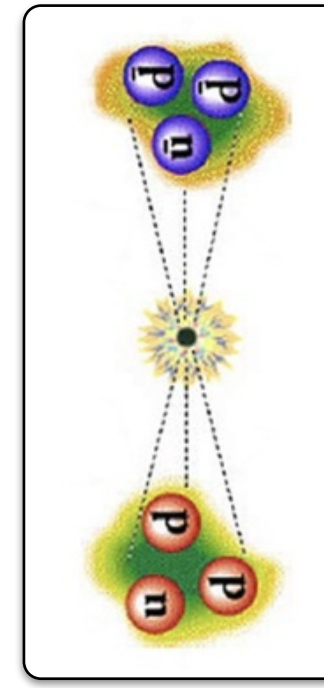


Normalized six-quark operators matrix elements obtained from lattice QCD at the physical point:



Operator	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (2 GeV)	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (700 TeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag A}}$ (2 GeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag B}}$ (2 GeV)
Q_1	$-46(13)$	$-26(7)$	4.2	5.2
Q_2	$95(17)$	$144(26)$	7.5	8.7
Q_3	$-50(12)$	$-47(11)$	5.1	6.1
Q_5	$-1.06(48)$	$-0.23(10)$	-0.8	1.6

Rinaldi et al., Phys. Rev. Lett. 122, 162001 (2019).



TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND

STRAIGHTFORWARD

CHALLENGING

EXTREMELY CHALLENGING

Precision single-neutron matrix elements (sensitive to discretization, chiral symmetry is important).

MEs of 6-quark operators including EM current insertions

Neutron-antineutron annihilation matrix element

Neutron-antineutron annihilation matrix element in nuclei (deuteron?) for SNO

Multi-nucleon contributions for DUNE/super-K

UNCOVERING NEW-PHYSICS SIGNALS IN NUCLEONS AND NUCLEI

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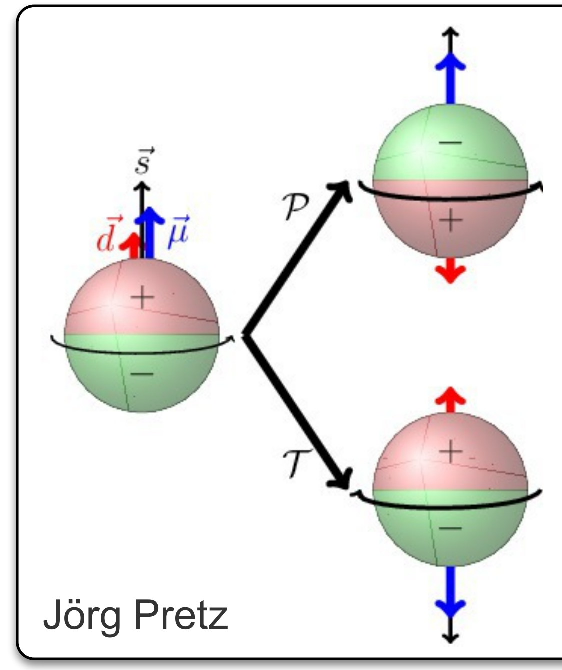
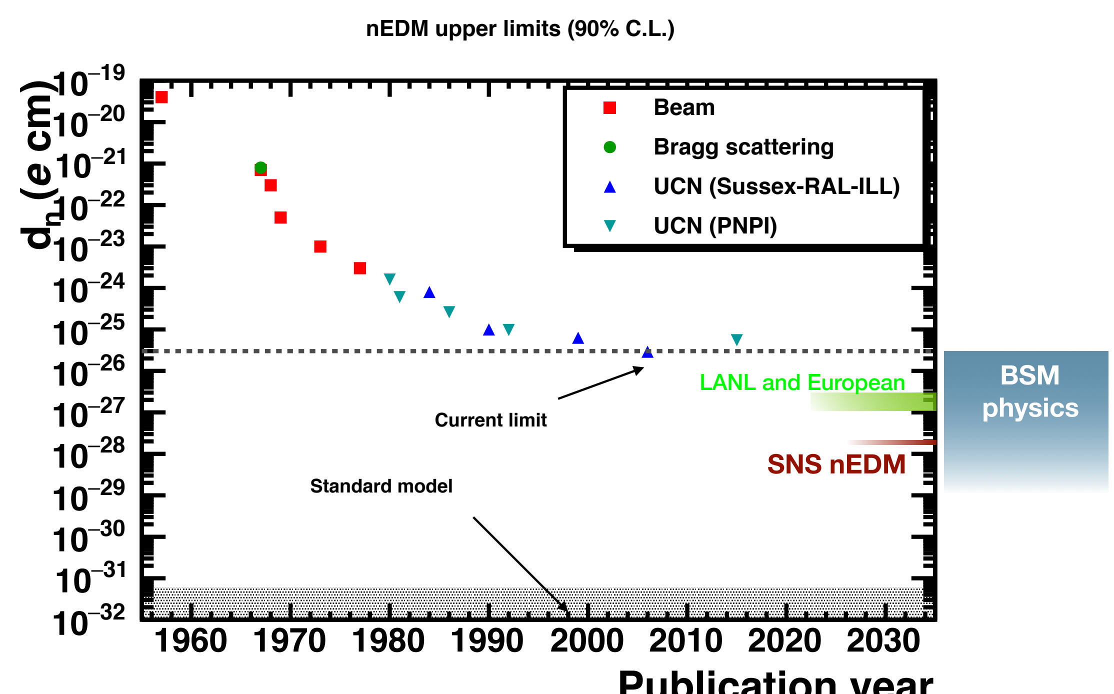
MOTIVATION AND TARGET OBSERVABLES



- Permanent EDM of protons, neutrons and nuclei would be the best evidence for CP violation beyond the SM.
- Several neutron EDM experiments are planned (SNS and LANL in the U.S.), improving the limits by 2 orders of magnitude.

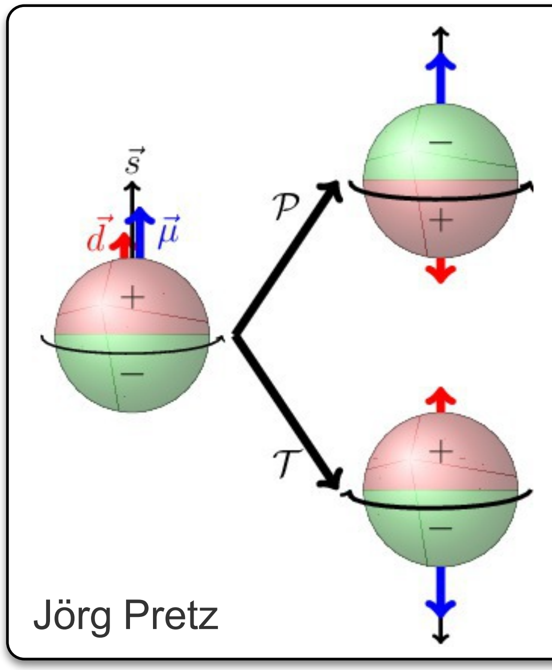
	Current	SM
e	10^{-29}	10^{-38}
μ	10^{-19}	10^{-35}
τ	10^{-16}	10^{-34}
n	10^{-26}	10^{-31}
p	10^{-23}	10^{-31}
^{199}Hg	10^{-29}	10^{-33}
^{129}Xe	10^{-27}	10^{-33}
^{225}Ra	10^{-23}	10^{-33}

Experimental landscape



Plot courtesy of T. Ito.

MOTIVATION AND TARGET OBSERVABLES



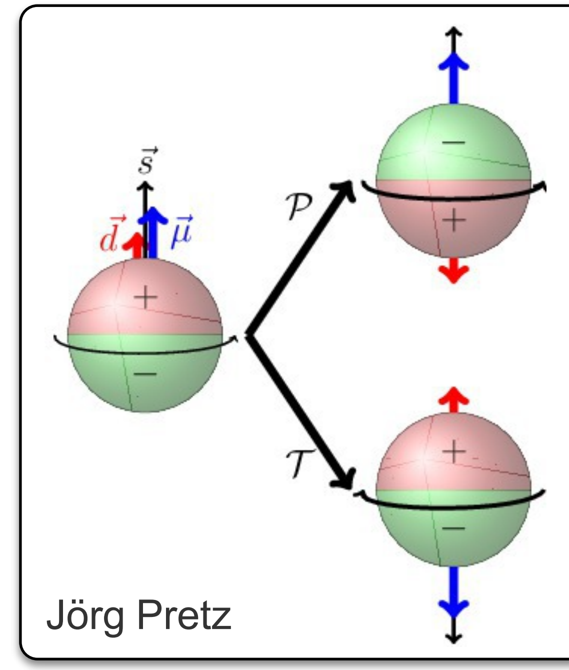
- Constraining BSM requires combining different non-zero EDM results and matching between nuclear-level EDM and quark/gluon effective CP violating operators.
- Quark EDM and tensor charges essentially done, more on isoscalar and strange/charm to be done. the rest of EDM contributions yet unconstrained.

$$\mathcal{L}_6^{CPV} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, g_s\, \bar{q}\sigma\cdot G\gamma_5 q + d_W \frac{g_s}{6} G\tilde{G}G + \sum_i C_i^{(4f)} O_i^{(4f)}$$

See e.g., Bhattacharya et al, Phys. Rev. Lett. 115, 212002.

Alarcon et al, arXiv:2203.08103 [hep-ph].

TO BE ACCOMPLISHED OVER THE NEXT DECADE AND BEYOND



STRAIGHTFORWARD

- θ_{QCD}-induced *p*/*n*EDM at large quark masses
- Isovector *q*chromo-EDM-induced *n*EDM at the physical point
- Weinberg *GGG*-induced *p*/*n*EDM at large quark masses

CHALLENGING

- θ_{QCD}-induced *p*/*n*EDM at physical point
- Isoscalar *q*chromo-EDM-induced *n*EDM at the physical point, requires subtraction of the first item
- Weinberg *GGG*-induced *p*/*n*EDM at the physical point, again mixing with the first item

EXTREMELY CHALLENGING

- 4-quark-induced *p*/*n*EDM requires 4pt functions, and often disconnecteds contb.
- πNN and *NNNN* CP-violating interactions
- EDM in deuteron and light nuclei

EXPECTATIONS FOR THE NEXT DECADE

Category	Milestone	Target precision	Experiment(s)
Nucleon matrix elements	Nucleon g_A^{u-d}	1%*	Neutron lifetime puzzle
	Nucleon g_T^{u-d}	1%	UCNB, Nab
	Nucleon g_S^{u-d}	3%	UCNB, Nab
	$\sigma_{\pi N}$, σ_s	5%	Mu2e, LZ, CDMS
	Nucleon r_E, r_A	5%	DUNE, MicroBooNE, NOvA, T2K
	Nucleon $F_A(q^2)$	8%	DUNE, MicroBooNE, NOvA, T2K
	Nucleon tensor	20%	DUNE, MicroBooNE, NOvA, T2K
	Nucleon PDFs	12%*	ATLAS, CMS, DUNE, EIC expts
	Proton decay	10%	DUNE, HyperK
	$nn \to pp$	50%*	EXO, other $0\nu\beta\beta$ experiments
	Nucleon EDM	10%*	Neutron, proton EDM experiments
	$g_{A,T,S}$, $1 < A \leq 4$	20%*	All neutrino, DM, EDM, ...

Single-nucleon
Multi-nucleon

Kronfeld at al, USQCD Snowmass whitepaper (2022).

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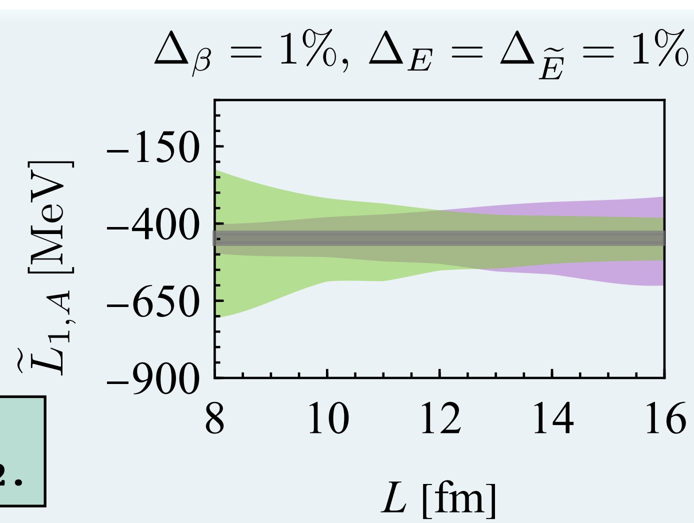
Single-nucleon
Multi-nucleon

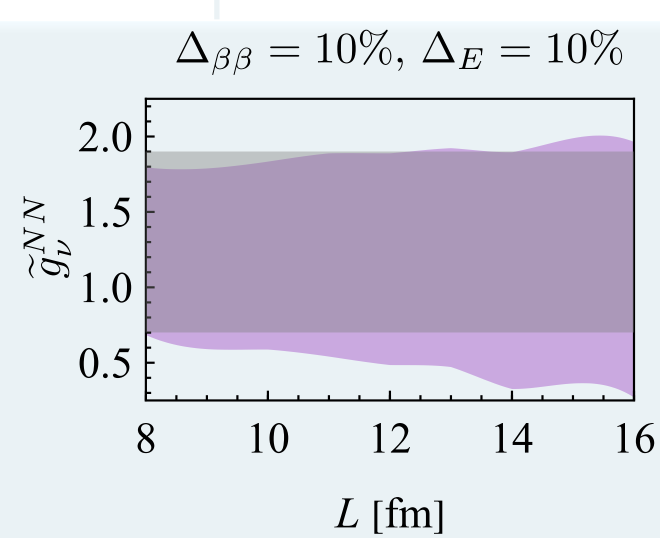
Kronfeld at al, USQCD Snowmass whitepaper (2022).

Need more resource assessments and sensitivity analysis using synthetic data for nuclear matrix elements.

Leading-order two-nucleon correlated axial coupling



ZD, Kadam, Phys. Rev. D 105 (2022) 9, 094502.



Leading-order $0\nu\beta\beta$ coupling with light Majorana neutrinos

Three features make lattice QCD calculations of nuclei hard:

i) The complexity of systems grows rapidly with the number of quarks.

Detmold and Orginos, Phys. Rev. D 87, 114512 (2013).

See also: Detmold and Savage, Phys.Rev.D82 014511 (2010).
Doi and Endres, Comput. Phys. Commun. 184 (2013) 117.

ii) Excitation energies of nuclei are much smaller than the QCD scale.

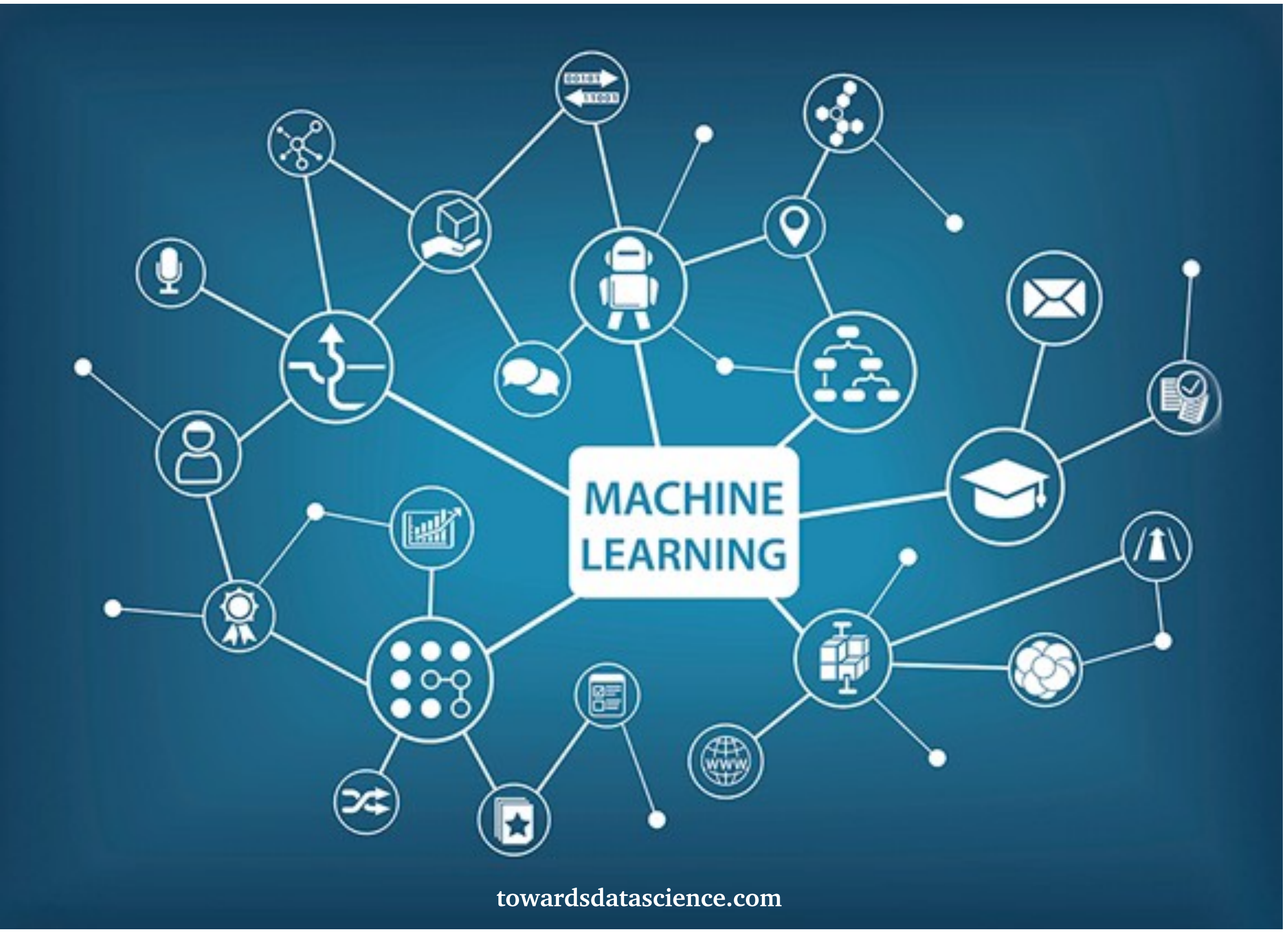
Beane at al (NPLQCD), Phys.Rev.D79 114502 (2009).
Beane, Detmold, Orginos, Savage, Prog. Part. Nucl. Phys. 66 (2011).
Junnakar and Walker-Loud, Phys.Rev. D87 (2013) 114510.
Briceno, Dudek and Young, Rev. Mod. Phys. 90 025001.

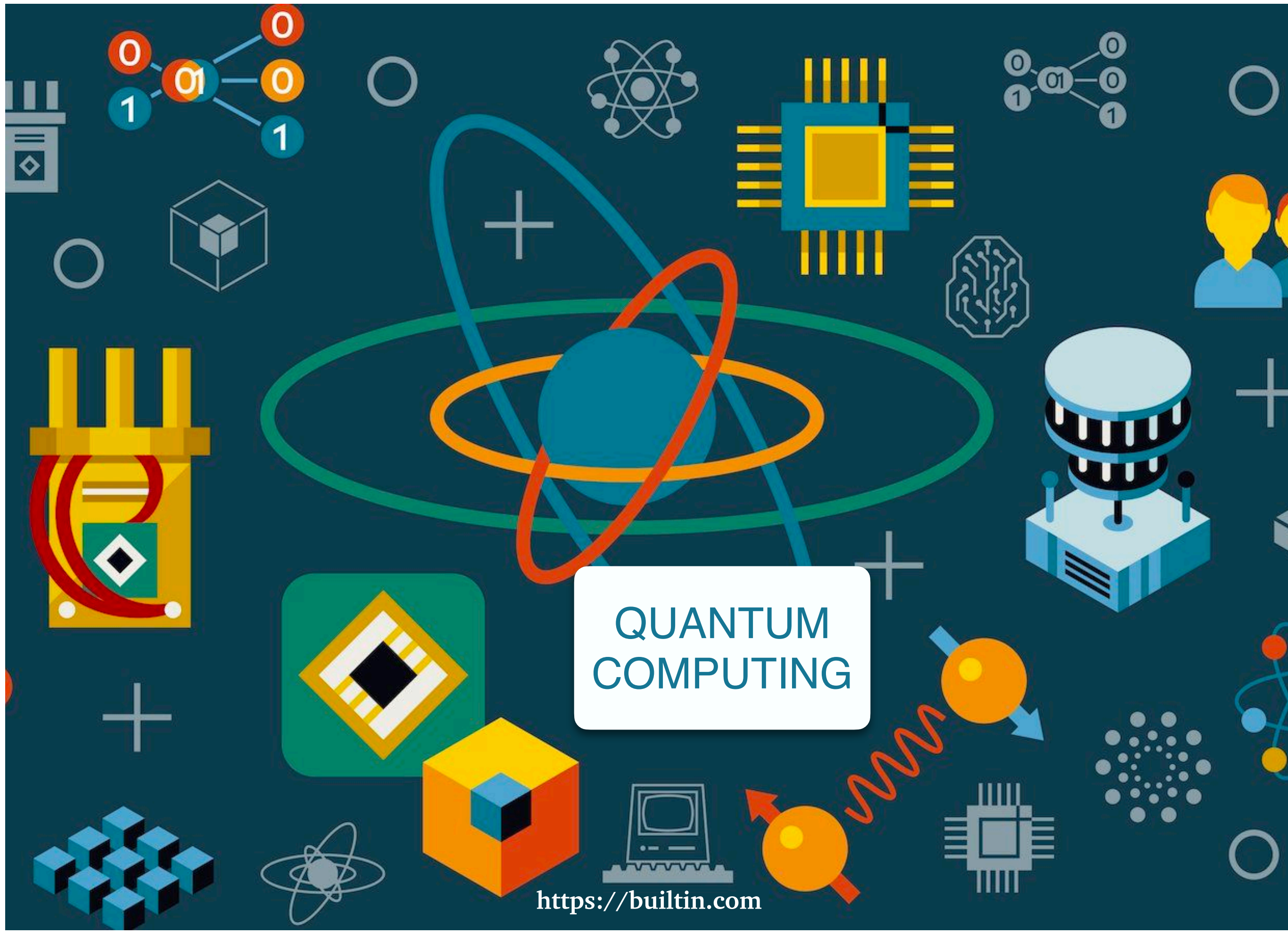
iii) There is a severe signal-to-noise degradation.

Paris (1984) and Lepage (1989).

Wagman and Savage, Phys. Rev. D 96, 114508 (2017).
Wagman and Savage, arXiv:1704.07356 [hep-lat].

CAN WE COMBAT SIGNAL-TO-NOISE AND SIGN PROBLEMS IN MONTE CARLO LATTICE QCD SIMULATIONS WITH NEW COMPUTATIONAL PARADIGMS?





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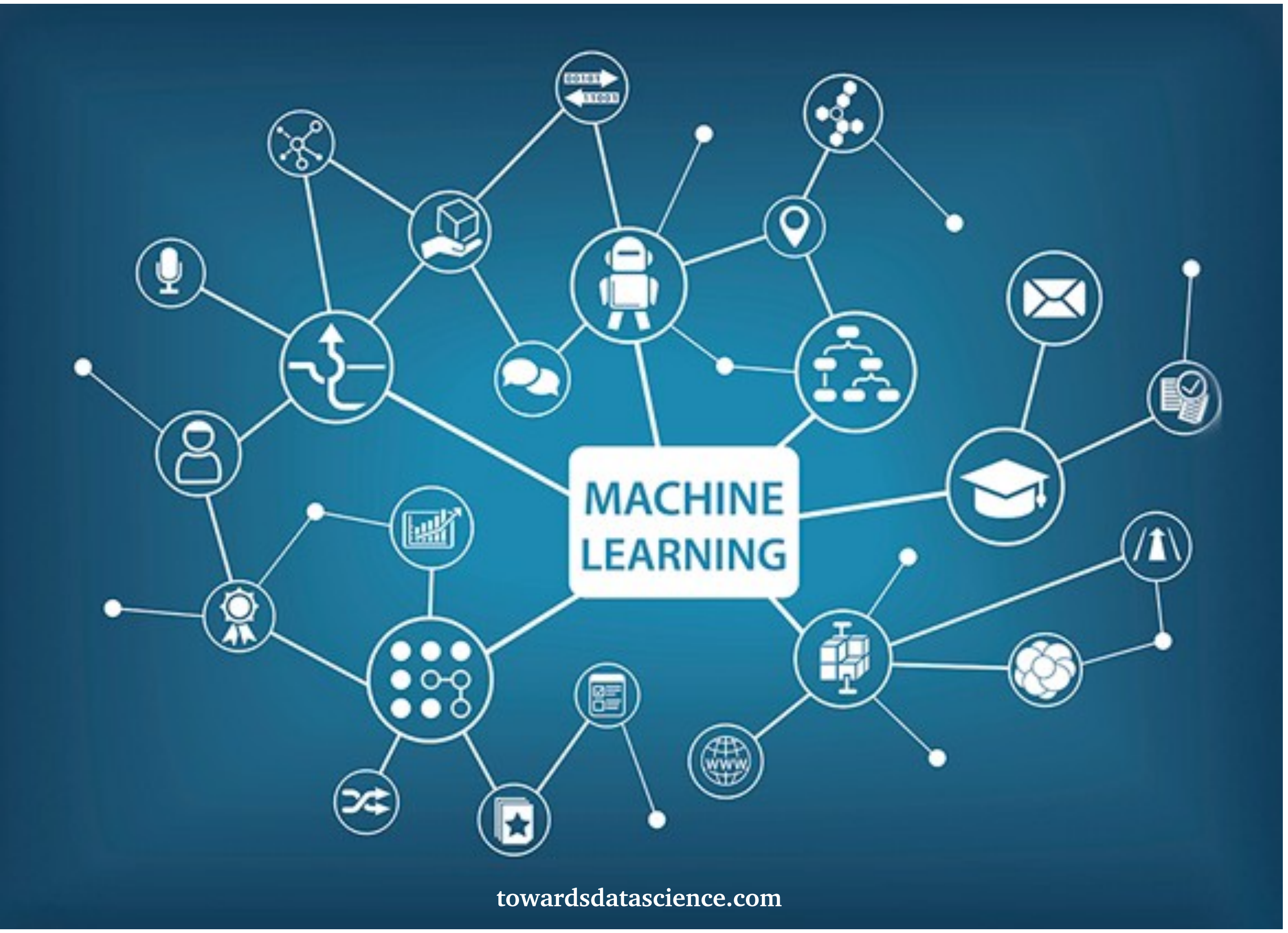


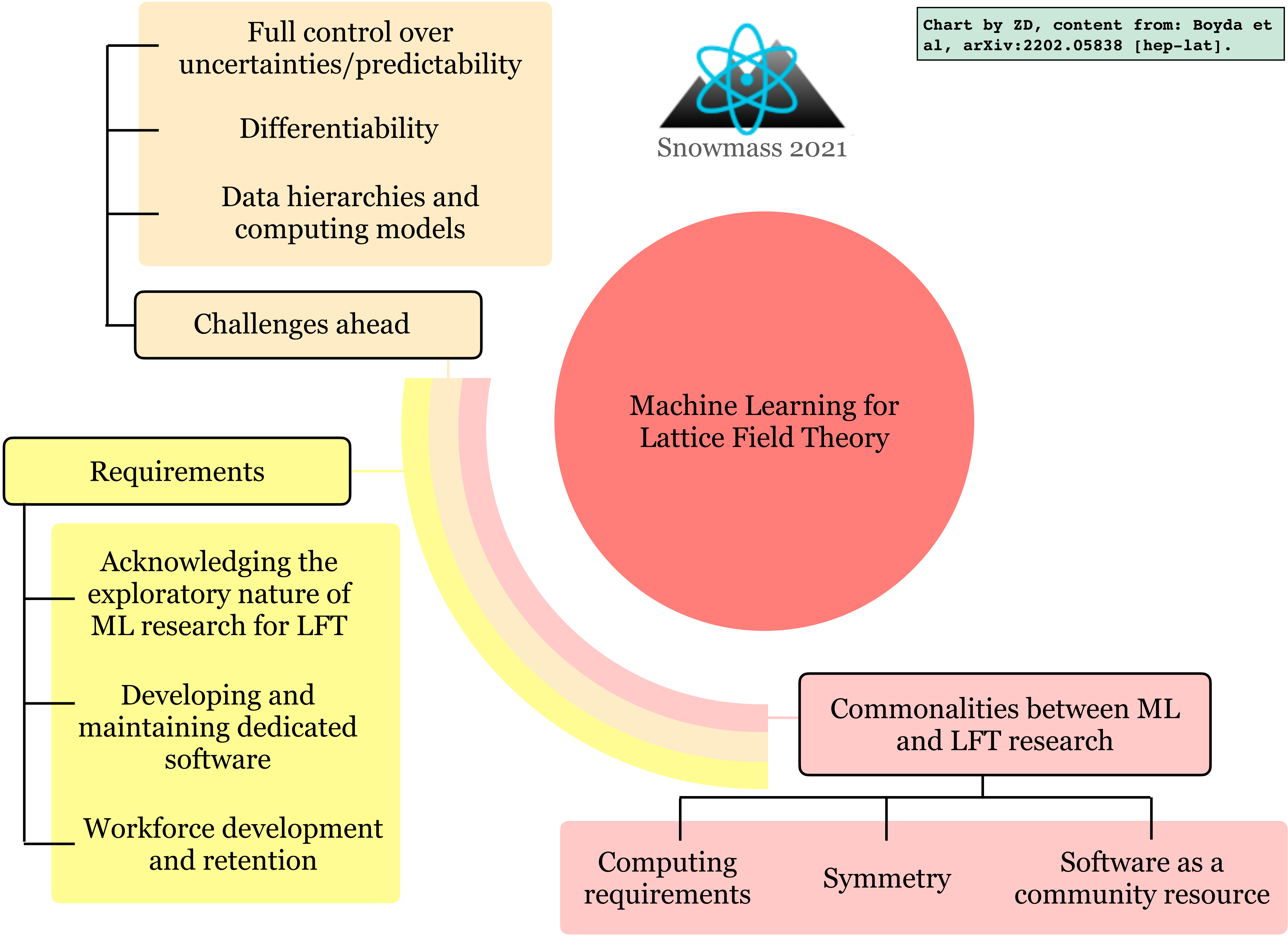
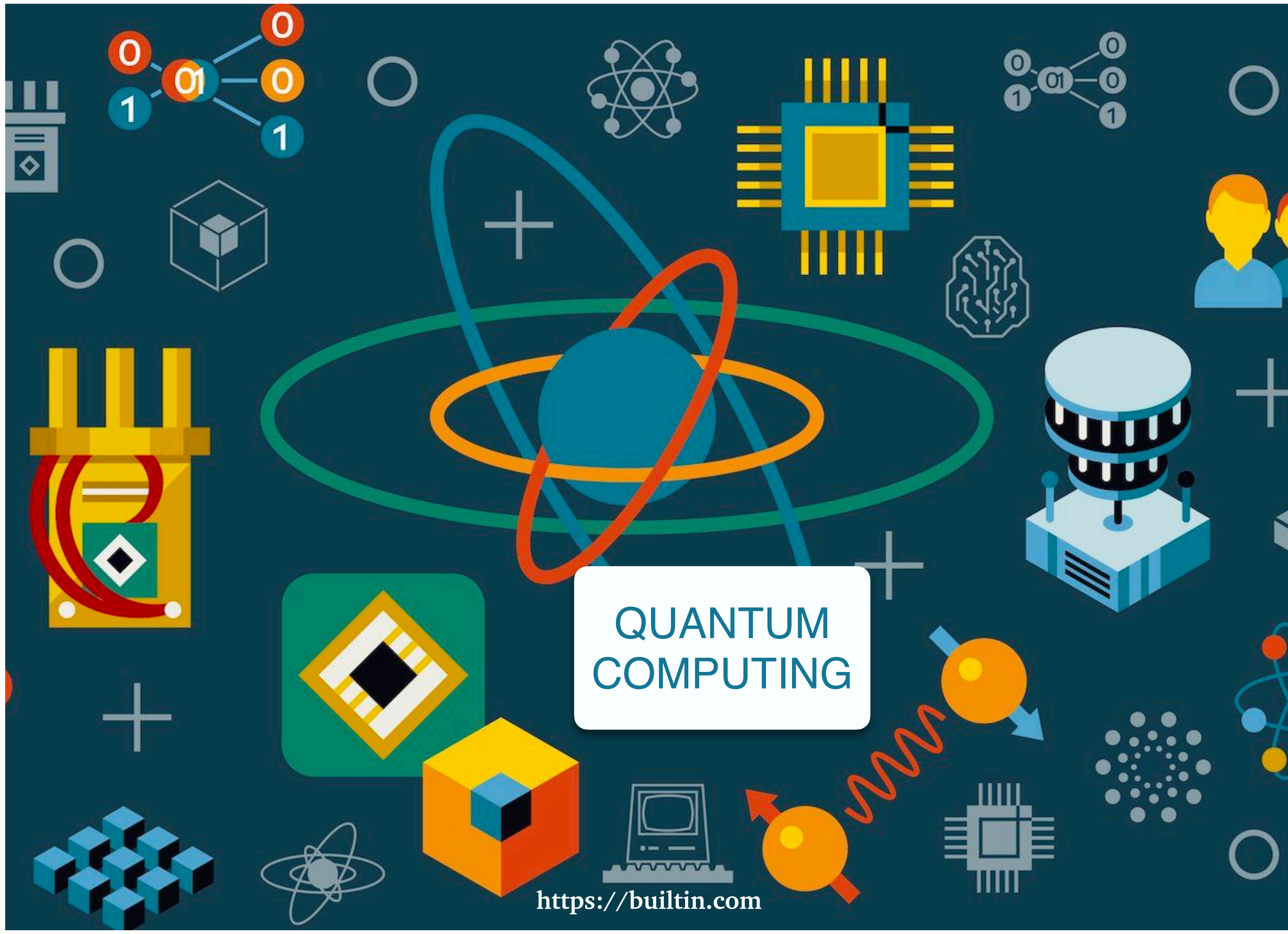
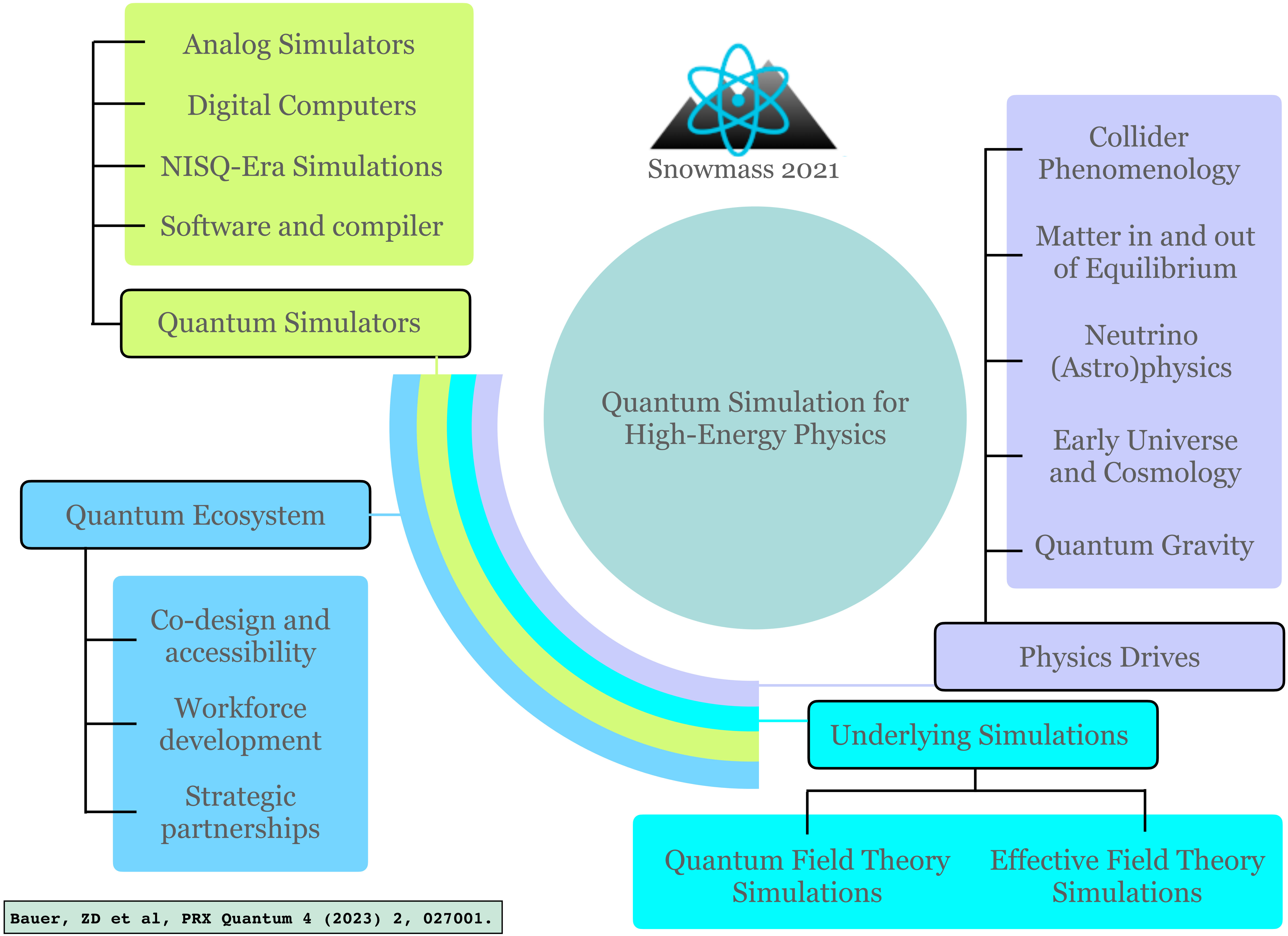
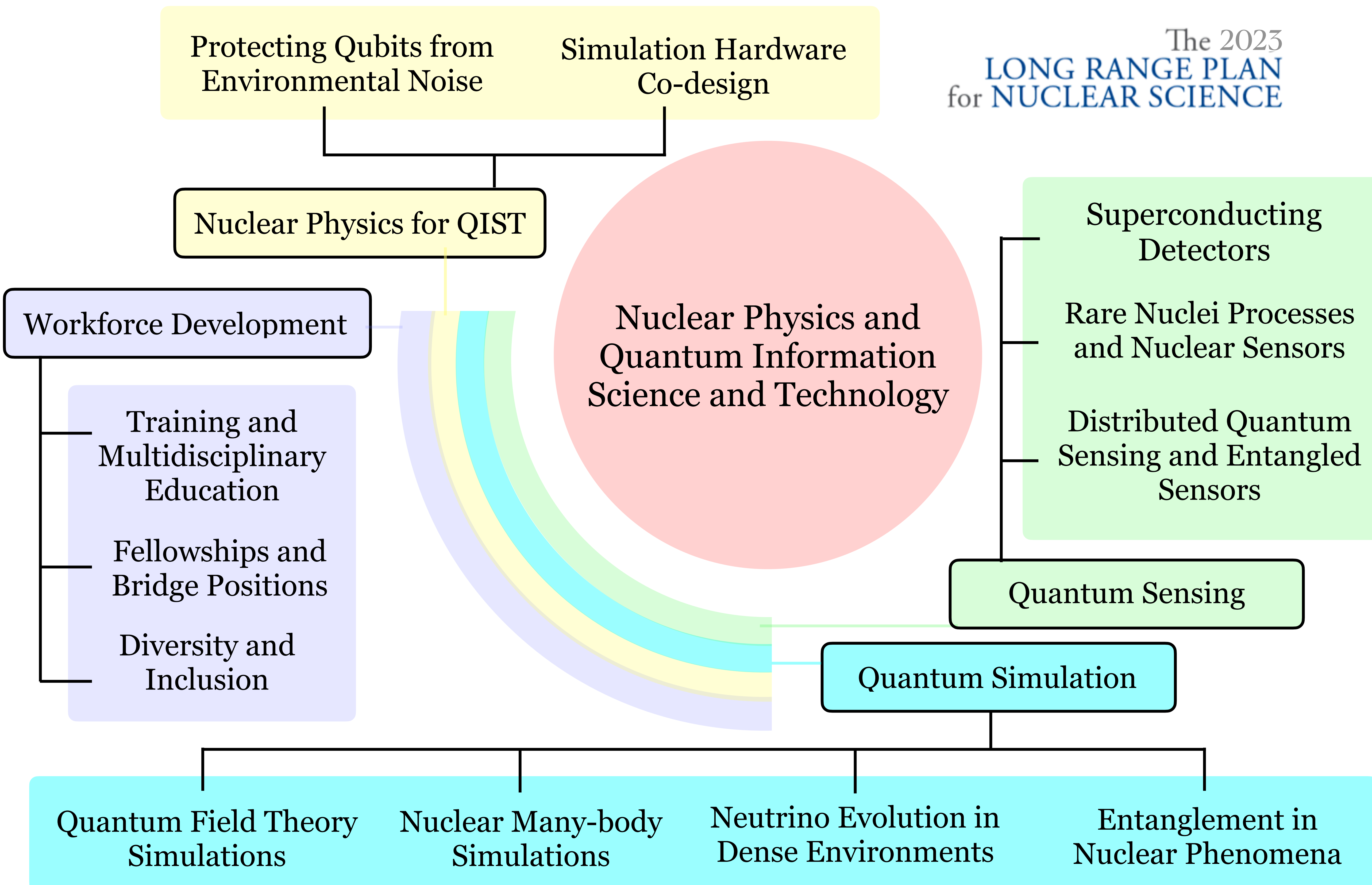


Chart by ZD, content from: Boyda et al, arXiv:2202.05838 [hep-lat].
Snowmass 2021
Machine Learning for Lattice Field Theory
Challenges ahead
Full control over uncertainties/predictability
Differentiability
Data hierarchies and computing models
Requirements
Acknowledging the exploratory nature of ML research for LFT
Developing and maintaining dedicated software
Workforce development and retention
Commonalities between ML and LFT research
Computing requirements
Symmetry
Software as a community resource

CAN WE COMBAT SIGNAL-TO-NOISE AND SIGN PROBLEMS IN MONTE CARLO LATTICE QCD SIMULATIONS WITH NEW COMPUTATIONAL PARADIGMS?




Analog Simulators
Digital Computers
NISQ-Era Simulations
Software and compiler
Quantum Simulators
Snowmass 2021
Quantum Simulation for High-Energy Physics
Collider Phenomenology
Matter in and out of Equilibrium
Neutrino (Astro)physics
Early Universe and Cosmology
Quantum Gravity
Physics Drives
Quantum Ecosystem
Co-design and accessibility
Workforce development
Strategic partnerships
Underlying Simulations
Quantum Field Theory Simulations
Effective Field Theory Simulations
Bauer, ZD et al, PRX Quantum 4 (2023) 2, 027001.



Quantum Information Science and Technology for Nuclear Physics, Beck, Carlson, Davoudi, Formaggio, Quaglioni, Savage, et al, arXiv:2303.00113 [nucl-ex].

Physics
CP Violation and Neutrino Phenomenology
Baryon Number Violation and Grand Unified Theories
Baryon Number minus Lepton Number Violation
Lepton Flavor Violation
Lepton Number Violation
CP Violation and Baryon Asymmetry in Universe
Dark Matter and New Physics Searches

TO SUMMARIZE:

Theorists supporting the research program in searches for new physics in rare processes in nucleon and nuclei include high-energy physicists building the high-scale models, QCD physicists matching high-scale models to hadronic-scale quantities, and nuclear physicists matching the hadronic quantities to nuclear-scale quantities for experiment. The synergy among these communities will be essential.

Lattice field theorists have long identified the impactful calculations in this area and are pushing the frontiers of exploratory as well as mature full-scale computations of quantities of relevance to this program.

The quantities of interest are a set of local (and bi-local) nucleon and nuclear matrix elements associated with SM or beyond the SM quark- and gluon-level currents. Few percent uncertainties in nucleon matrix elements and <50% uncertainties in few-nucleon matrix elements are achievable goals of this program over the next decade.

To expedite the computations and combat signal-to-noise and sign problems associated with finite-density systems and/or dynamical quantities, lattice field theorists are exploring new computational paradigms such as machine learning and quantum computing.

THANK YOU

MARYLAND CENTER for Fundamental Physics

JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE

Institute for Robust Quantum Simulation

U.S. DEPARTMENT OF ENERGY | Office of Science

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QUESTIONS?