Title: Quantum simulators for nuclear and particle physics: progress, challenges, and future

Speakers: Zohreh Davoudi

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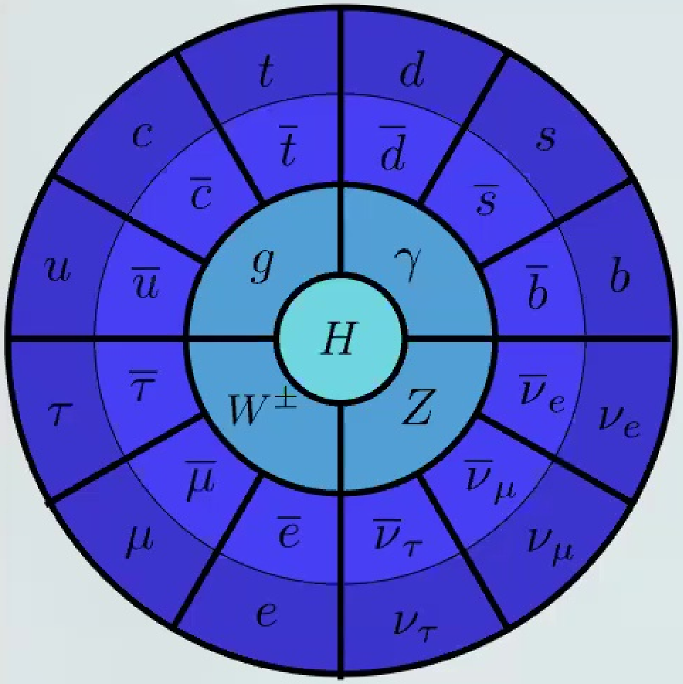
Abstract: A vibrant program has formed in recent years in various scientific disciplines to take advantage of near-term and future quantum-simulation and quantum-computing hardware to study complex quantum many-body systems, building upon the vision of Richard Feynman for quantum simulation. Such activities have recently started in nuclear and particle physics, hoping to bring new and powerful experimental and computational tools to eventually address a range of challenging problems in strongly interacting quantum field theories and nuclear many-body systems. In this talk, I review a number of important developments, including proposals for simulating strongly interacting field theories with the ultimate goal of studying strong dynamics of quarks and gluons, and of nucleons. Some of the requirements for hardware technologies that are expected to enable both the analog simulations and the digital quantum computations of these problems will be enumerated, and an experiment-theory co-development program will be motivated with an emphasis on trapped-ion platforms.

PHYSICS COLLOQUIUM
INSTITUTE FOR QUANTUM COMPUTING, UNIVERSITY OF WATERLOO
NOV 25, 2020

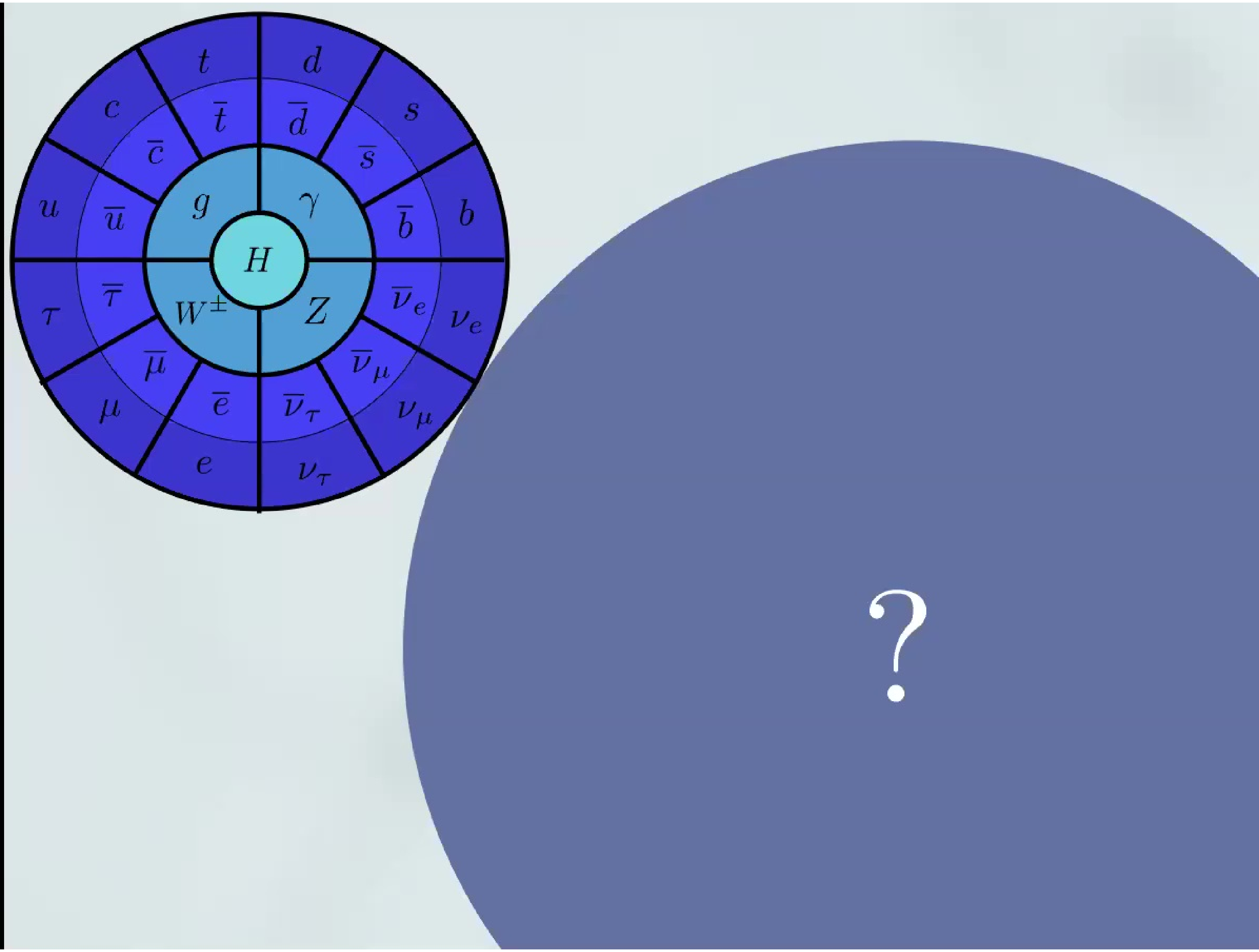
QUANTUM SIMULATORS FOR NUCLEAR AND PARTICLE PHYSICS: PROGRESS, CHALLENGES, AND FUTURE

ZOHREH DAVOUDI

UNIVERSITY OF MARYLAND, COLLEGE PARK
RIKEN FELLOW



WHAT ARE THE UNDERLYING RULES THAT GOVERN NATURE?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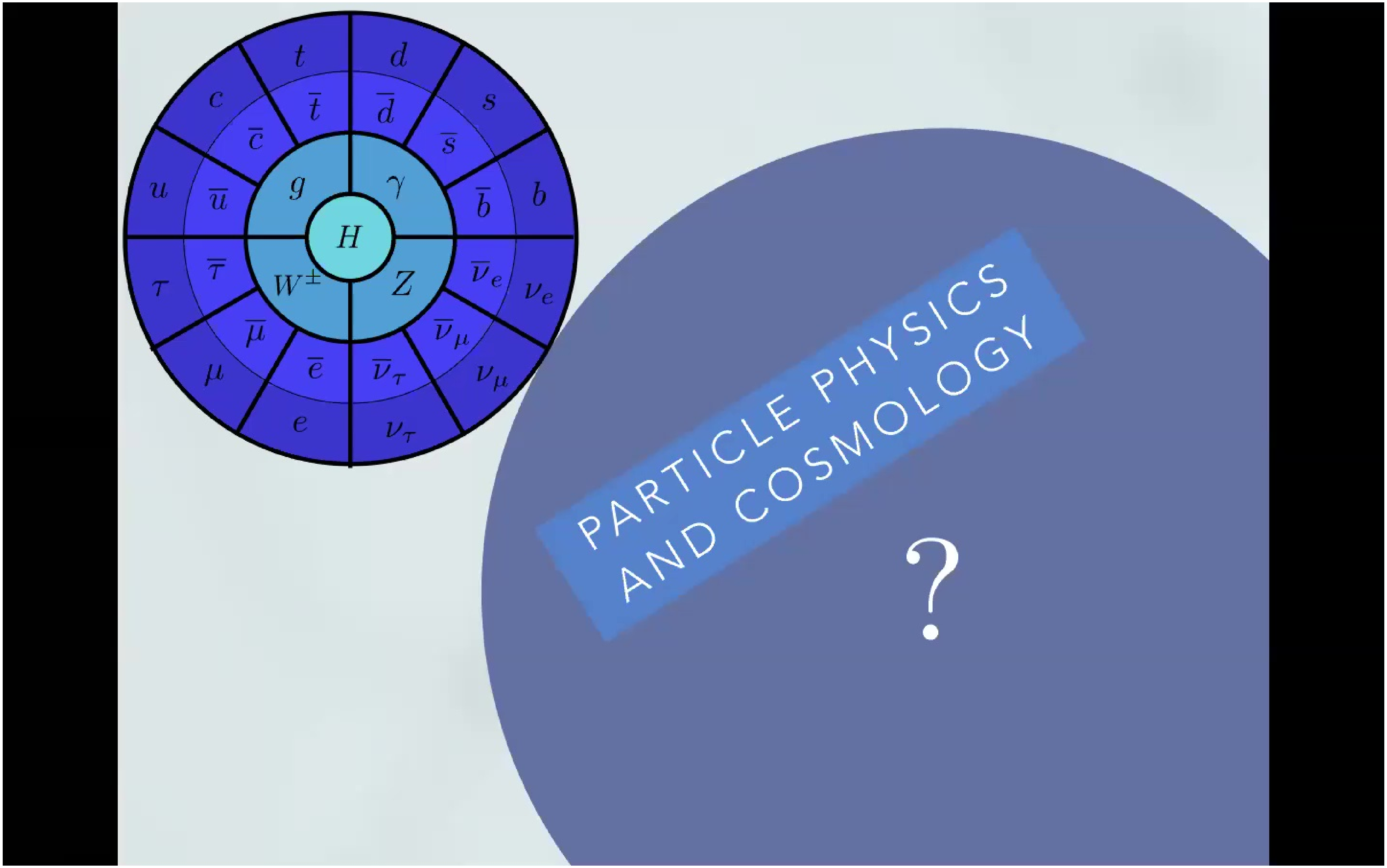
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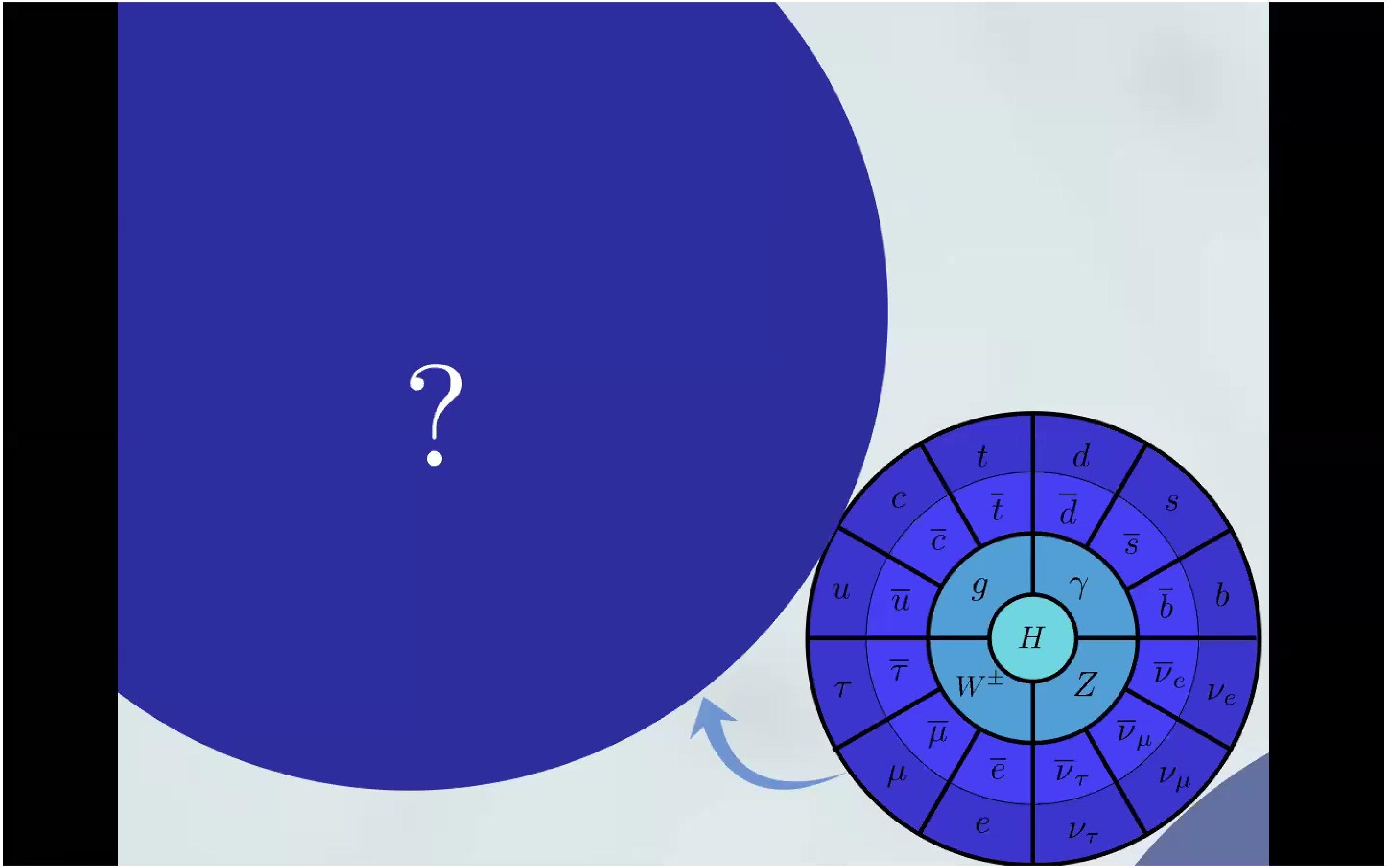
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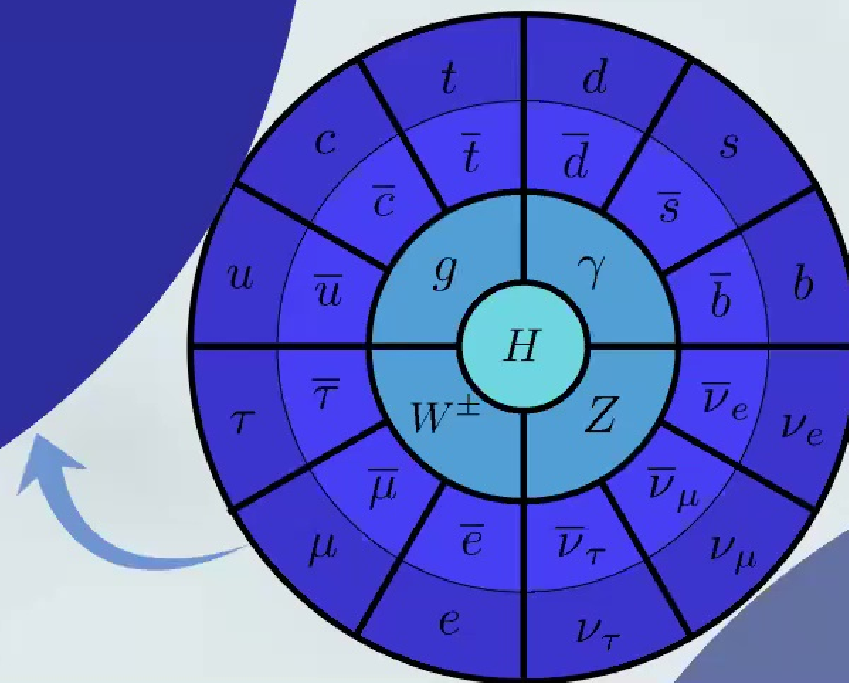
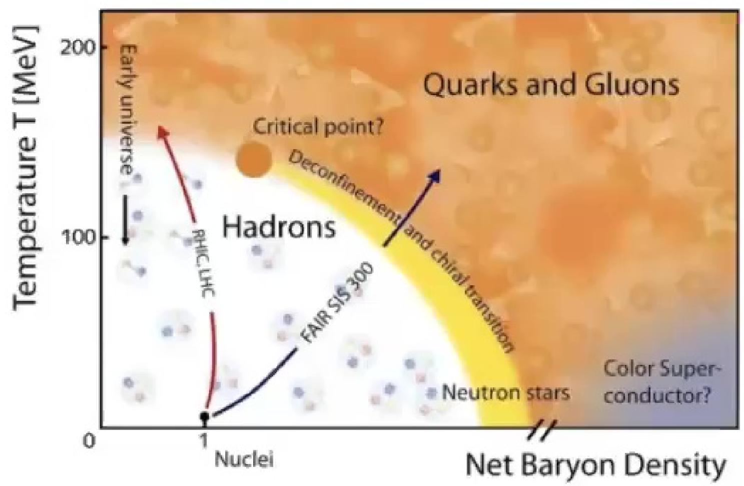
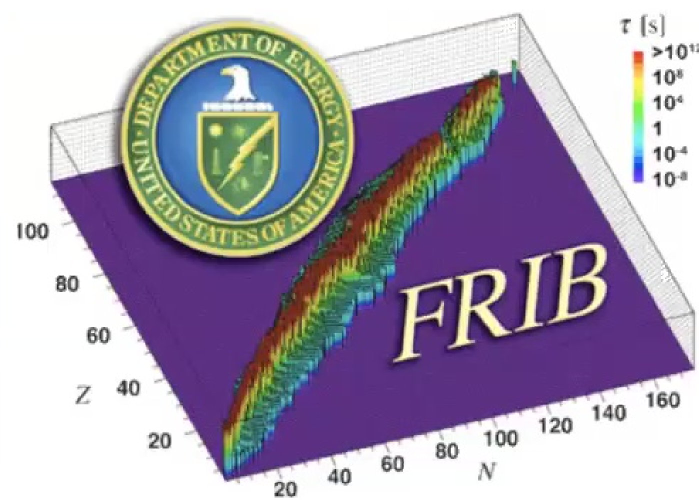
Q1) HOW DO COMPLEXITIES IN VISIBLE UNIVERSE EMERGE FROM STANDARD MODEL?



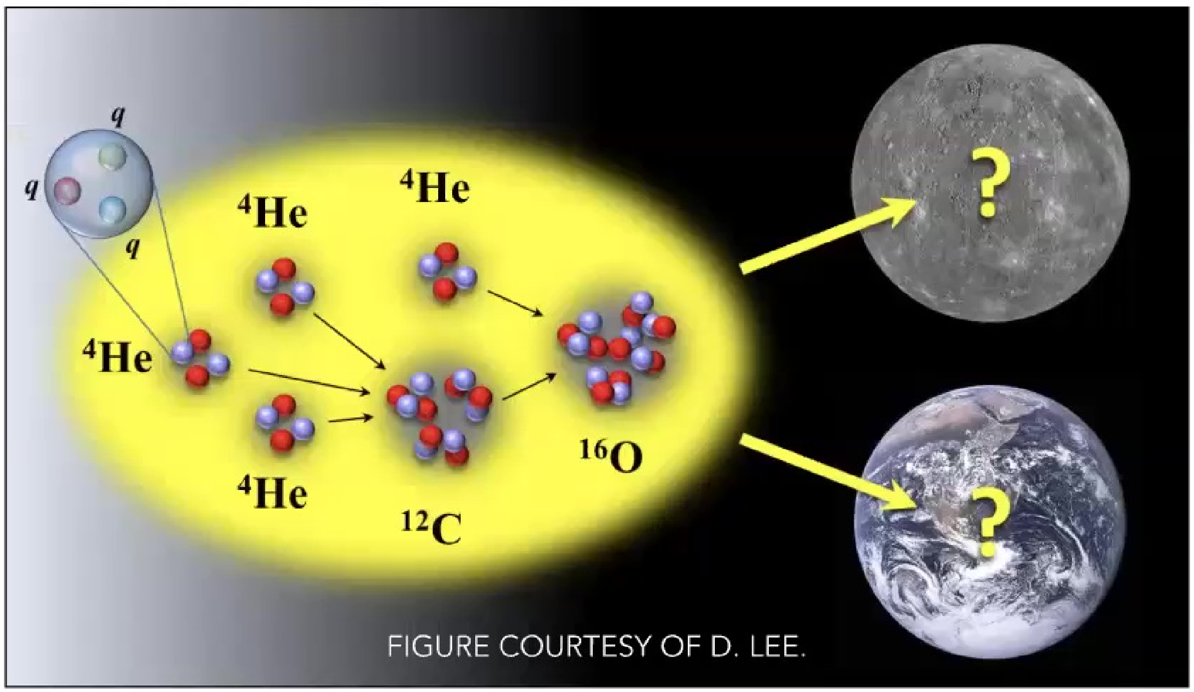
- What is the nature of dense matter in universe?
- What constitutes the interior of a neutron star?
- What are the phases of strongly interacting matter?
- Can rare exotic isotopes made in laboratories give some clues?
- Where do heavy elements on earth come from?



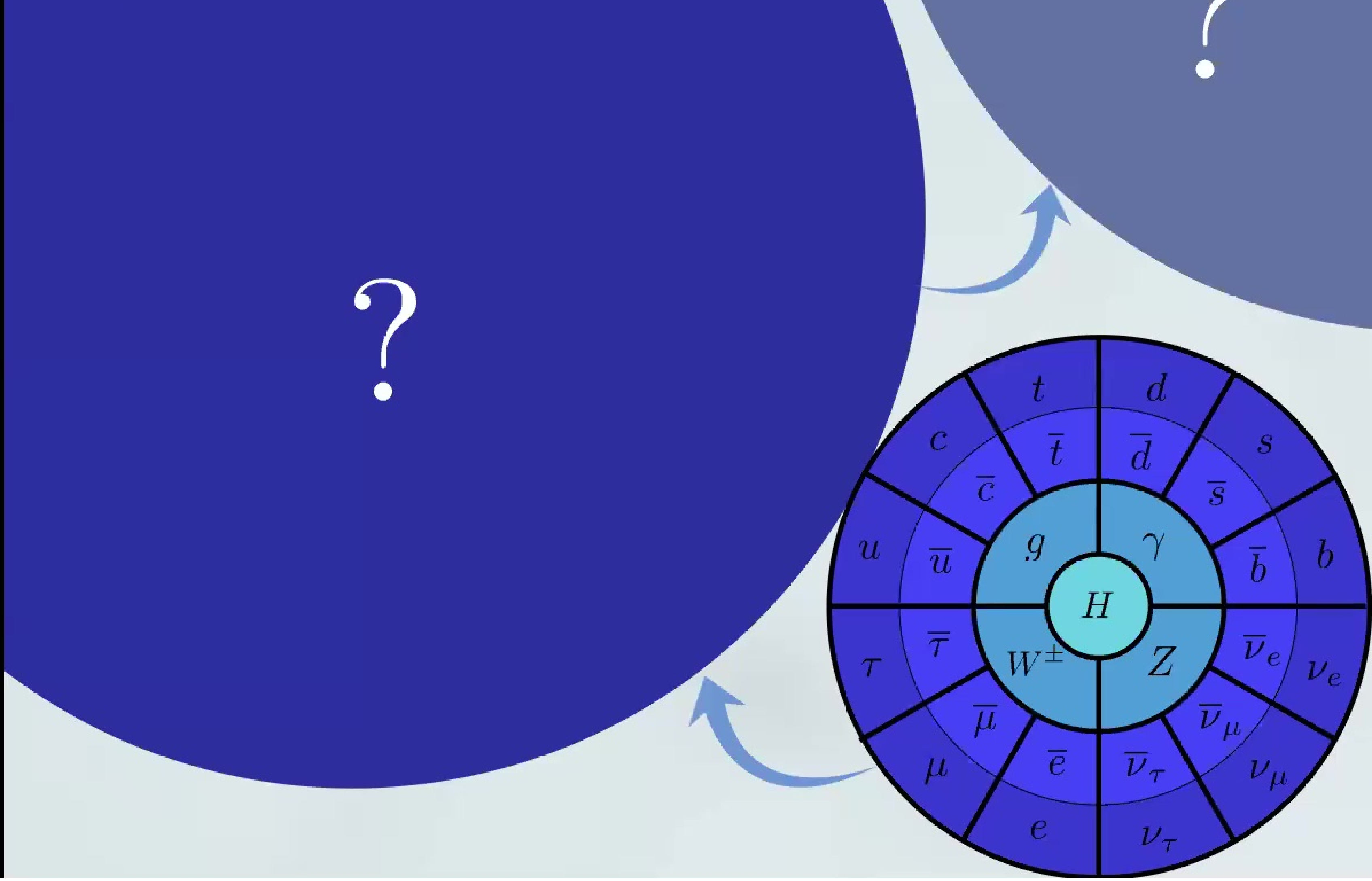
Source: The Facility for Antiproton and Ion Research (FAIR),GSI, Darmstadt, Germany.



- Would have we existed if the input parameters of the Standard Model had been set differently in nature?
- What would be the fate of stars and galaxies if quarks were lighter or heavier?



Q2) WHAT DOES IT TELL US ABOUT THE UNKNOWN PHYSICS BEYOND STANDARD MODEL?



- Are fundamental symmetries of the Standard Model violated?
- Are new interactions in play in nature?
- Nuclei serve as a laboratory to make discovery in this area, but do we know well how they interact with external probes?

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- Are new interactions in play in nature?
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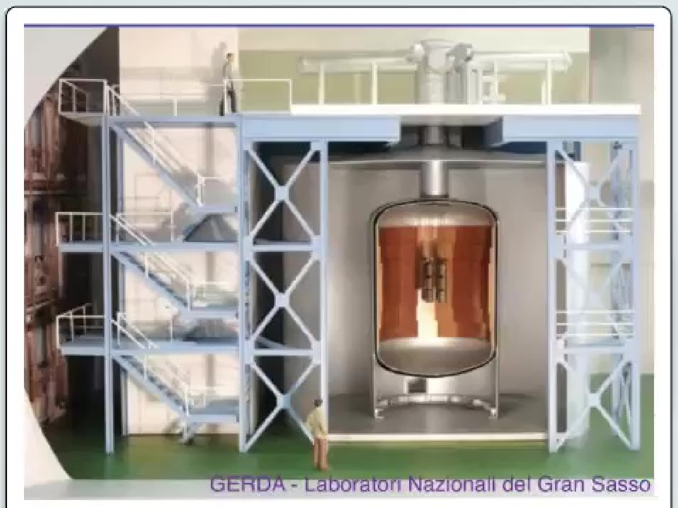
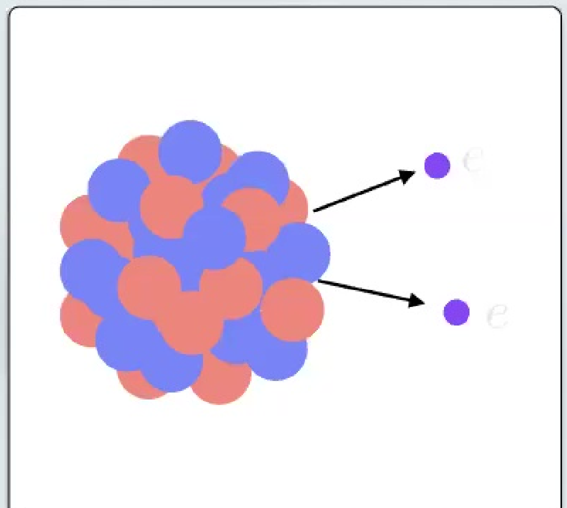
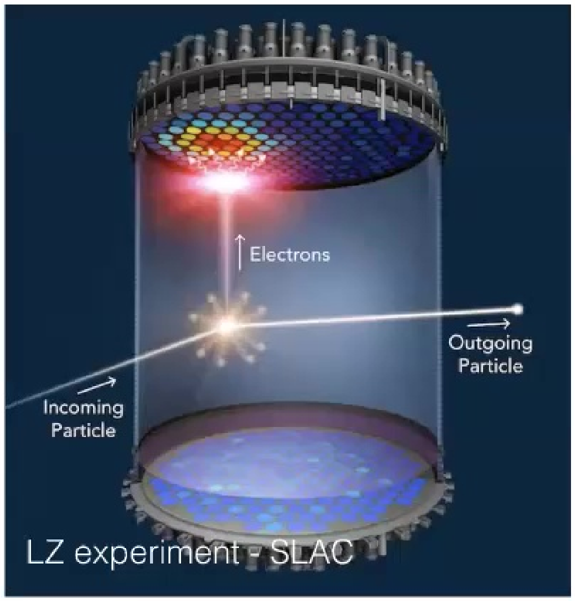
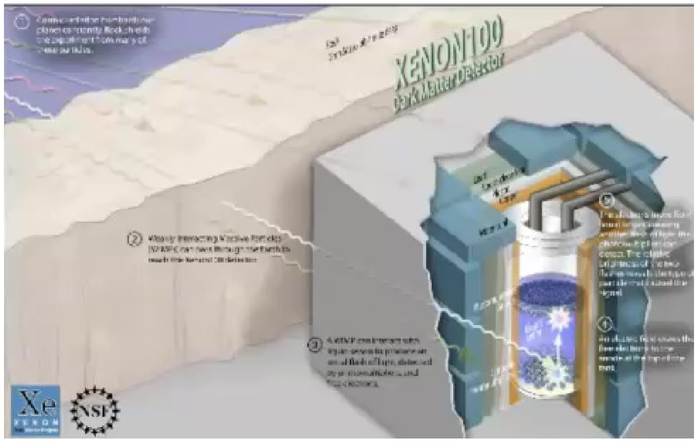
Example: Neutrinoless double-beta decay and lepton-number violation



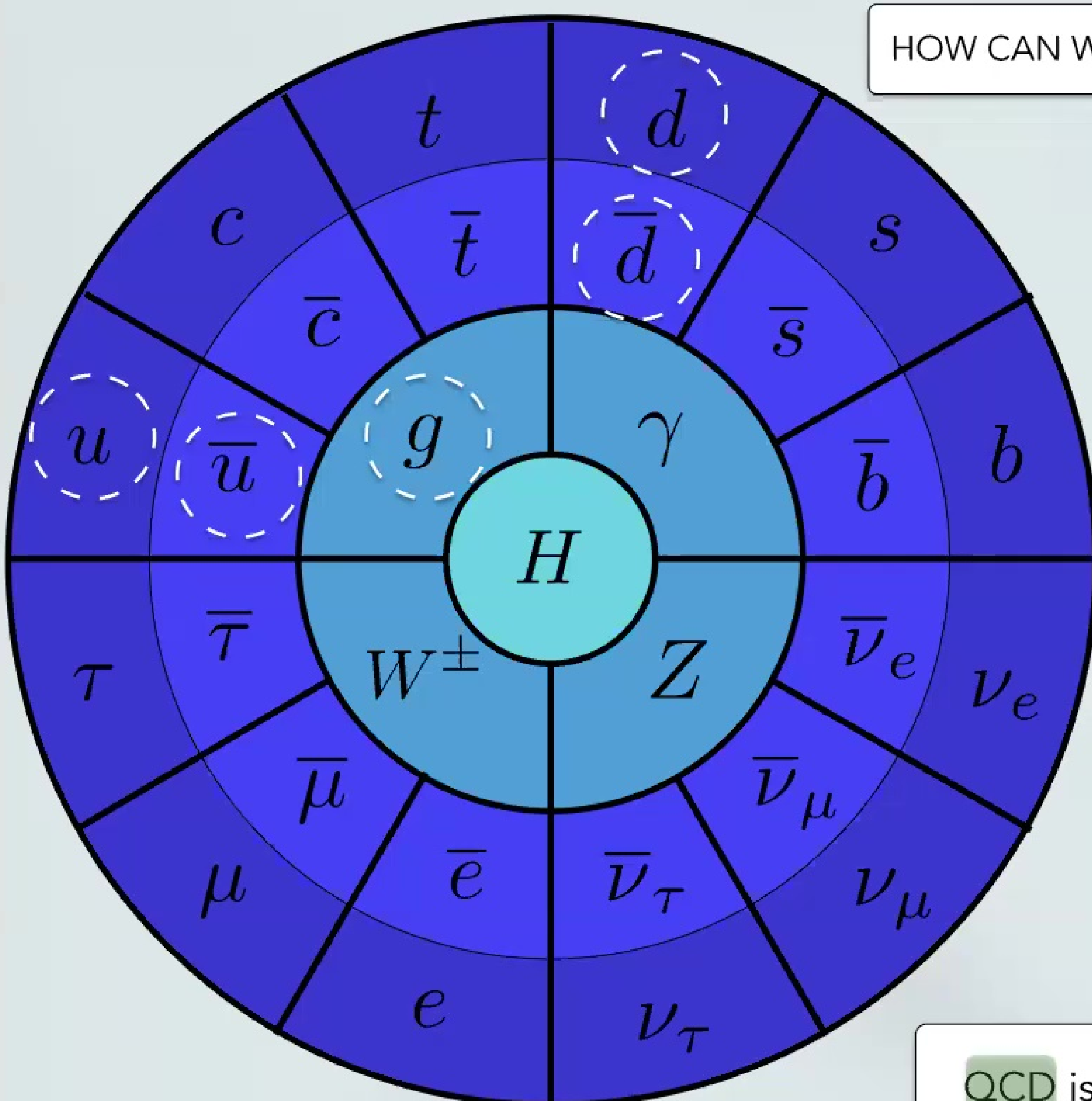


- Can dark matter candidates be discovered through their interactions with matter?
- How well can we predict potential dark matter-nucleus interactions?





HOW CAN WE APPROACH THESE PROBLEMS?



QCD is the fundamental theory, so ideally we should start from there…

QUANTUM CHROMODYNAMICS (QCD)

QCD is a SU(3) gauge theory augmented with several flavors of massive quarks:

$$\mathcal{L}_{QCD} = \sum_{f=1}^{N_f} \left[\bar{q}_f(i\gamma^\mu \partial_\mu - m_f)q_f - gA^i_\mu \bar{q}_f \gamma^\mu T^i q_f\right]$$

$$-\frac{1}{4}F^i_{\mu\nu}F^{i\mu\nu} + \frac{g}{2} f_{ijk} F^i_{\mu\nu} A^{i\mu} A^{j\nu} - \frac{g^2}{4} f_{ijk} f_{klm} A^j_\mu A^k_\nu A^{l\mu} A^{m\nu}$$

Features:

i) There are only $1 + N_f$ input parameters plus QED coupling. Fix them by few quantities and all nuclear physics is predicted (in principle)!

ii) QCD is asymptotically free and exhibits confinement.

WHAT CAN WE DO AT LOW ENERGIES?

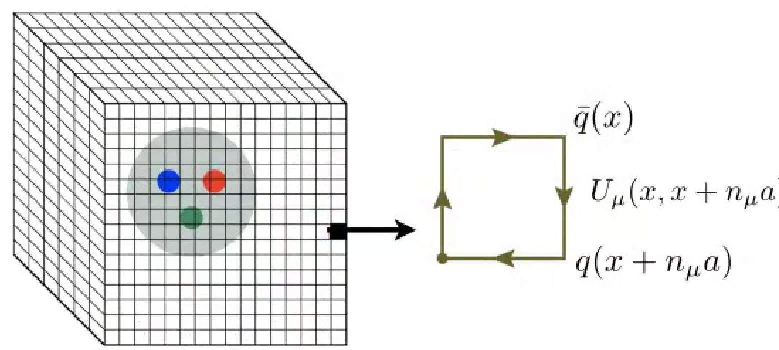
Solve it nonperturbatively: Lattice QCD

$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

$$\int d^4x \to a^4 \sum_{\mathbf{n}}$$

$$\mathcal{L}_{LQCD}[q, \bar{q}, U[A]; m_q a, \beta]$$

Extrapolate to infinite volume and zero lattice spacing



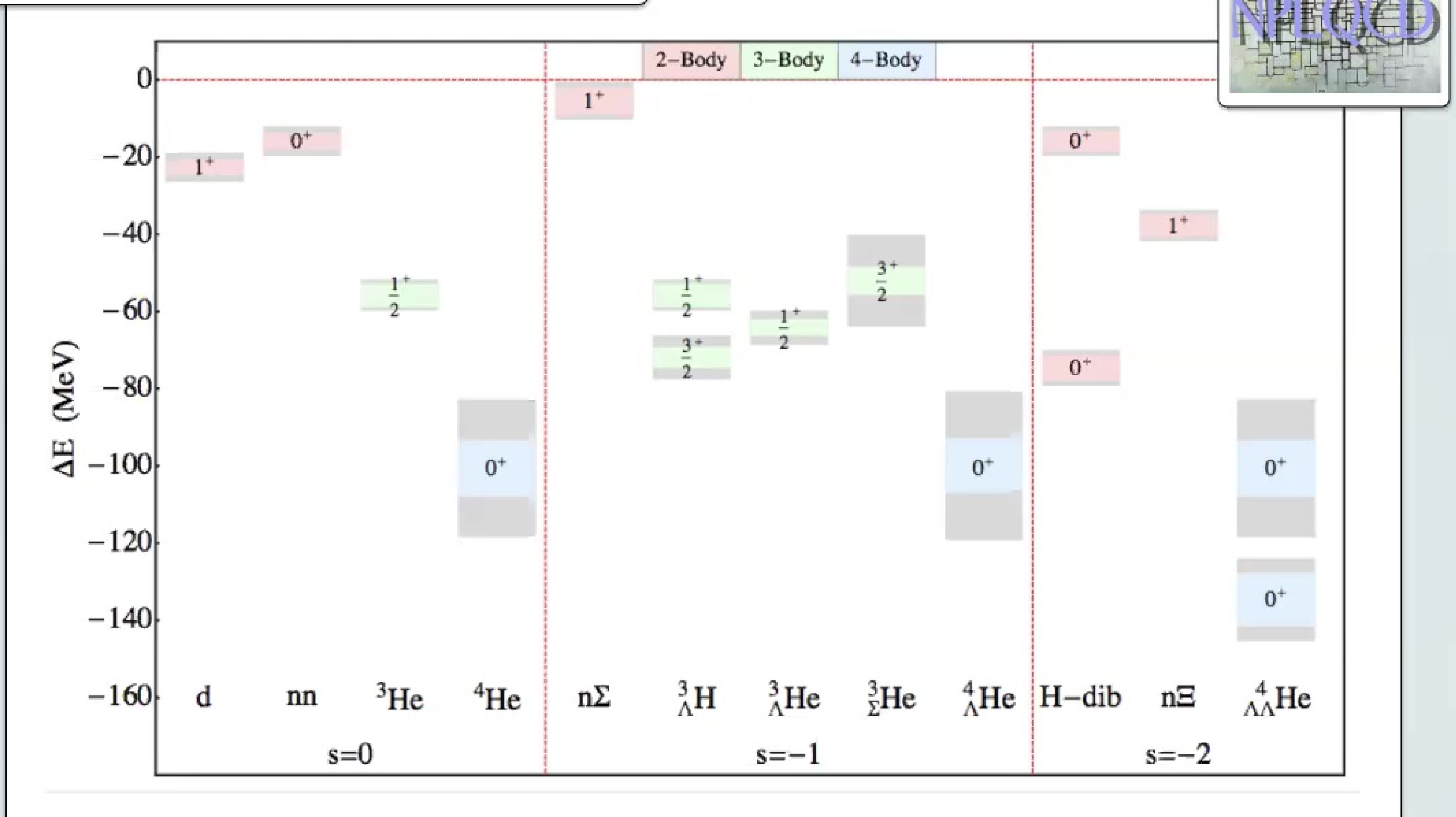
LATTICE QCD COMBINED WITH EFFECTIVE FIELD THEORIES IS ON TRACK TO DELIVER RESULTS ON IMPORTANT QUANTITIES IN NUCLEAR AND HIGH-ENERGY PHYSICS.

A recent review on low-energy nuclear physics from lattice QCD:

ZD et al (NPLQCD), arXiv: 2008.11160 [hep-lat], accepted to Physics Reports.

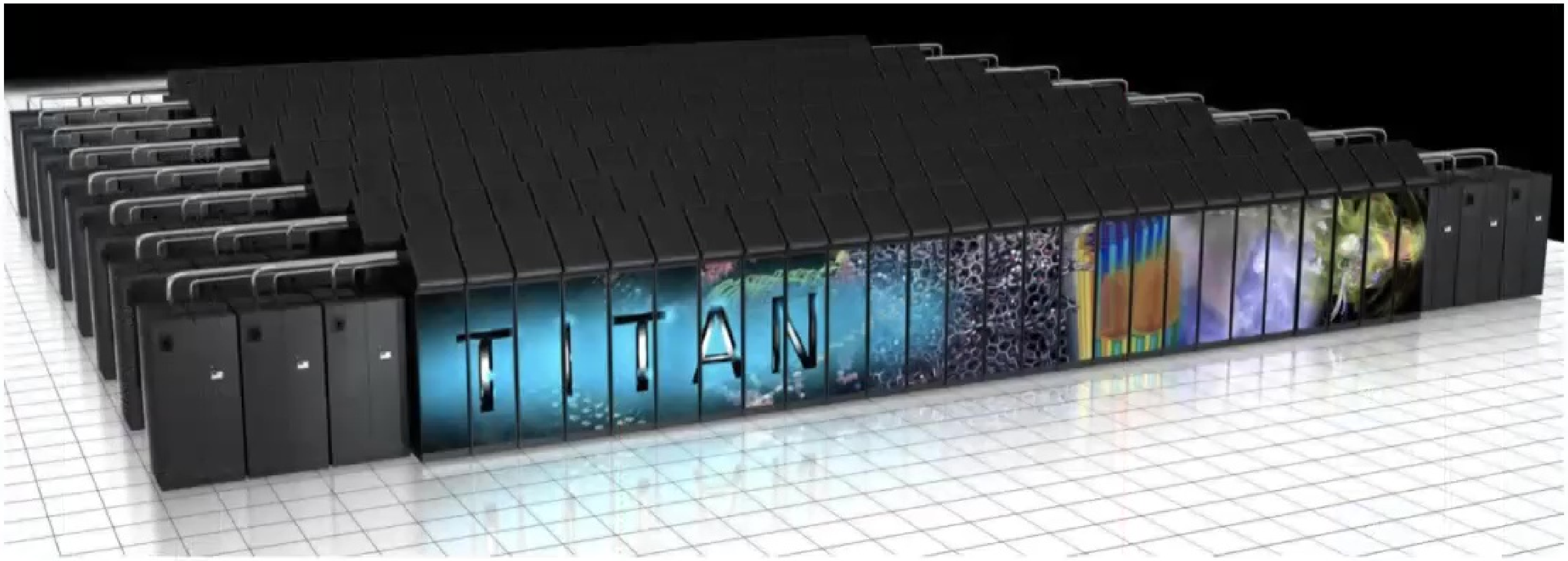
A MILESTONE: NUCLEI FROM QCD IN A WORLD WITH HEAVIER QUARKS THAN THOSE IN NATURE

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

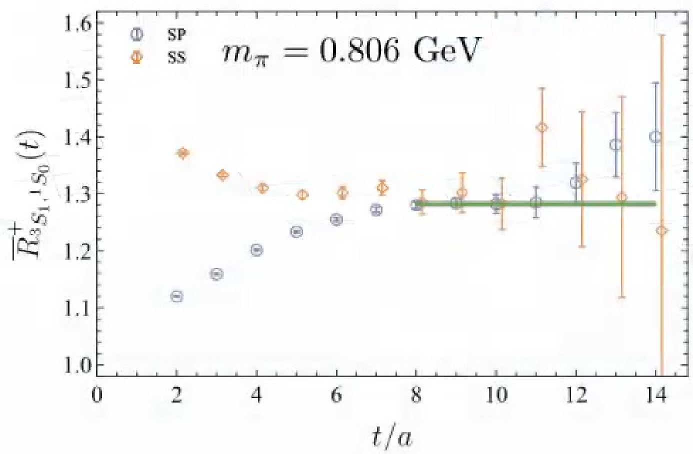


Beane, et al. (NPLQCD), Phys.Rev. D87 (2013), Phys.Rev. C88 (2013)

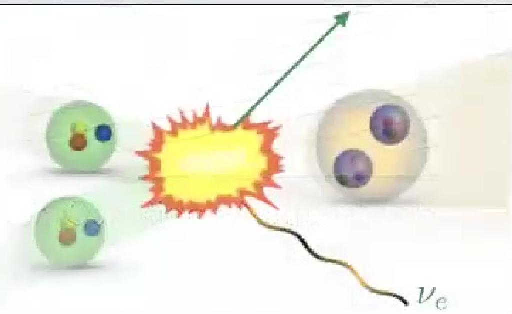
THIS STUDY TOOK ABOUT TWO YEARS AND A FEW HUNDRED MILLION CPU HOURS ON THE LARGEST SUPERCOMPUTERS IN THE U.S.!



Titan supercomputer, Oak Ridge National Laboratory, USA



Savage, ZD et al, Phys.Rev.Lett.119,062002(2017).

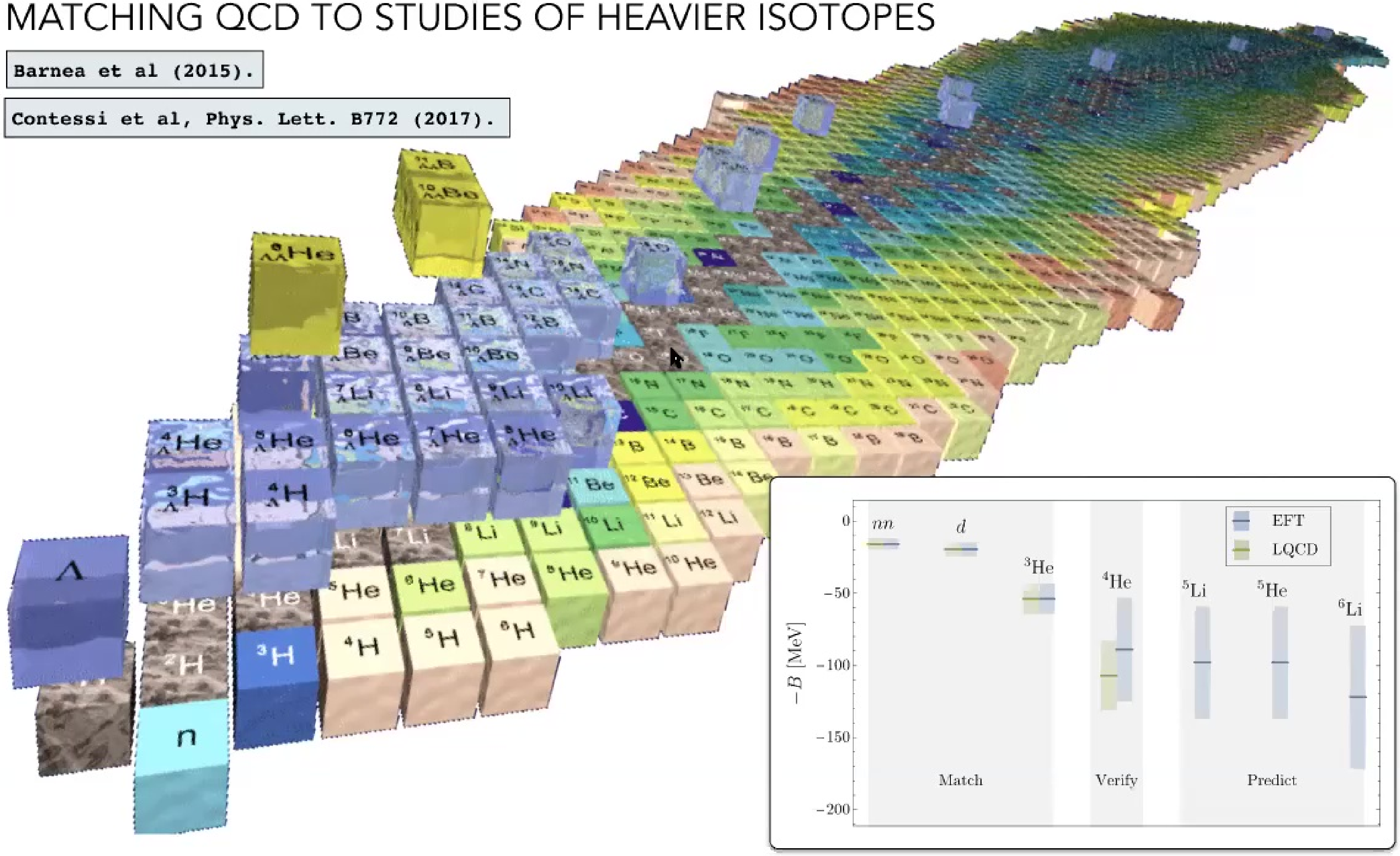


$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3$ @ $\mu = m_\pi^{\mathrm{phys.}} = 140$ MeV

MATCHING QCD TO STUDIES OF HEAVIER ISOTOPES

Barnea et al (2015).

Contessi et al, Phys. Lett. B772 (2017).



QCD input → Few-body EFT interactions → Many-body calculations of nuclei and hypernuclei

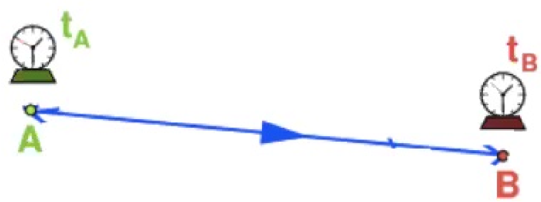
LATTICE QCD IS SUPPORTING A MULTI-BILLION DOLLAR EXPERIMENTAL PROGRAM!

Slide content courtesy of Martin Savage.

STRIKING FEATURE OF QUANTUM MECHANICS:

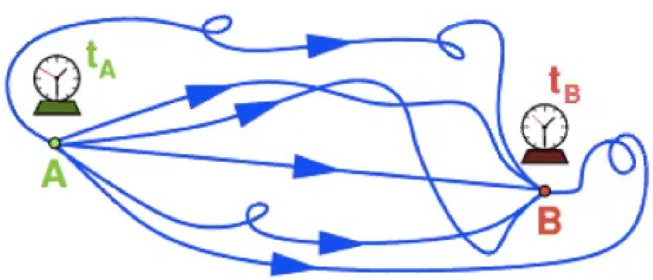
Given all the interactions of the system, what is the probability for transition from A to B?

Classical:



The principle of least action

Quantum mechanical:

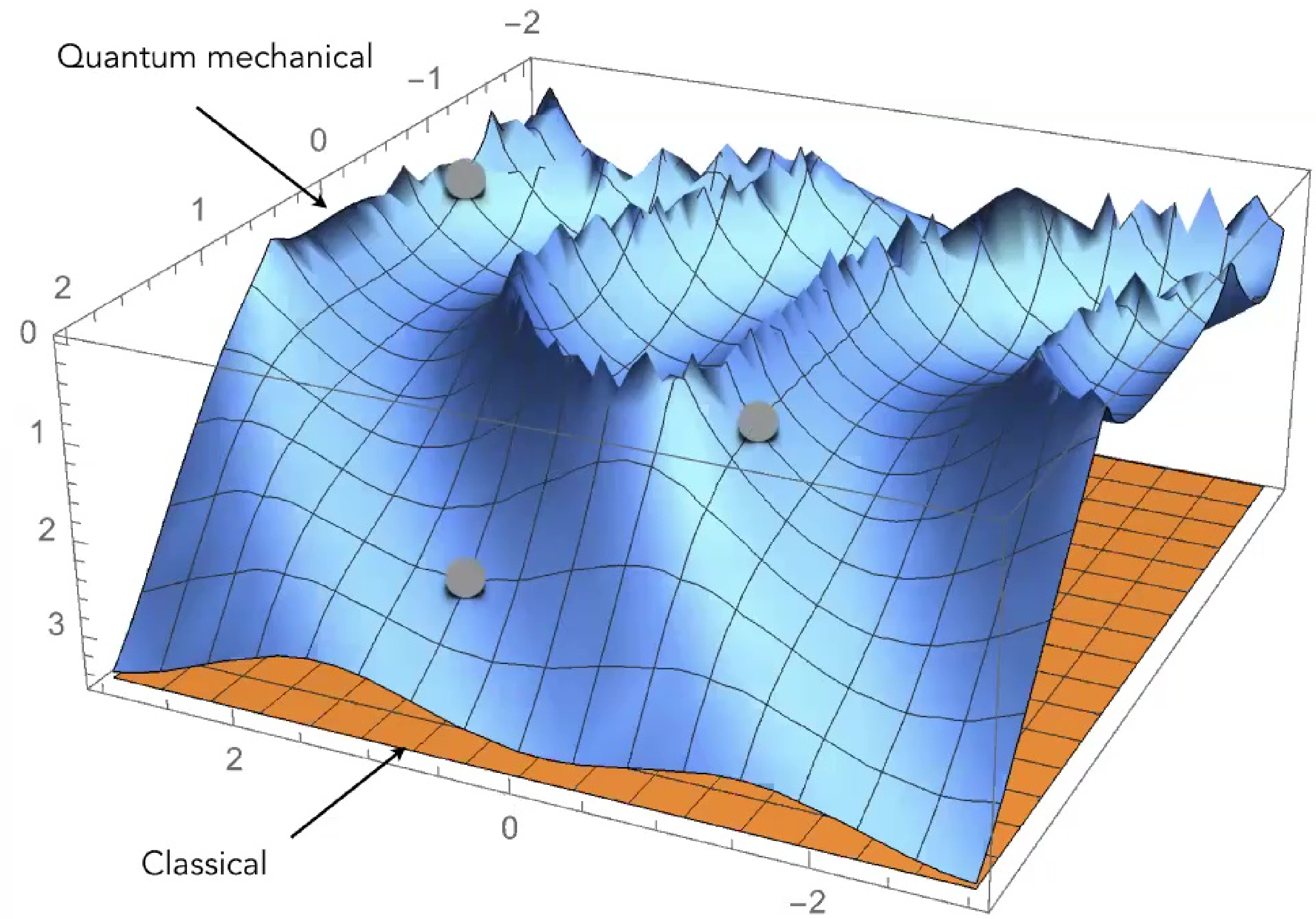


Every trajectory is explored!

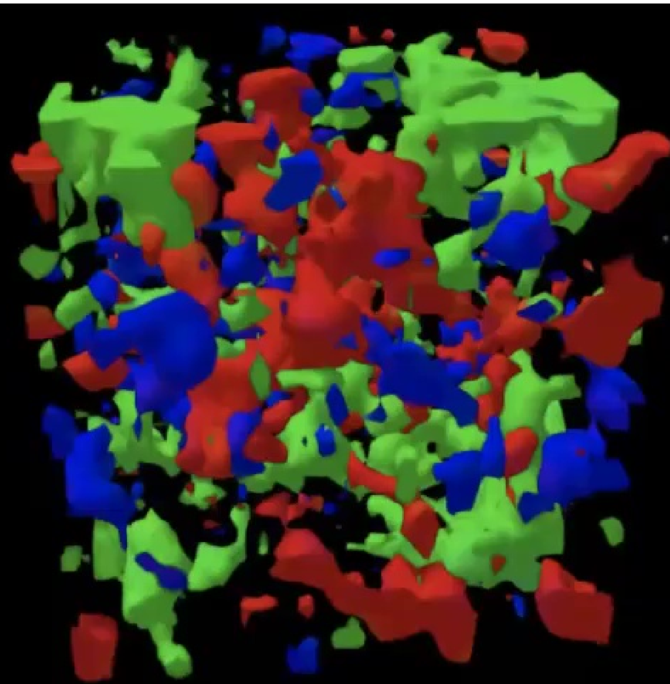
Quantum probability amplitude:

1. Give each path a weight where the classical path has the largest weight.
2. Sum over all infinite number of trajectories!

CORRELATION AMONG e.g., THREE "FIELDS"?



LET'S HAVE A
LOOK AT HOW
CONVENTIONAL
LATTICE QCD
SIMULATIONS
ARE DONE…



BY CSSM VISUALISATION

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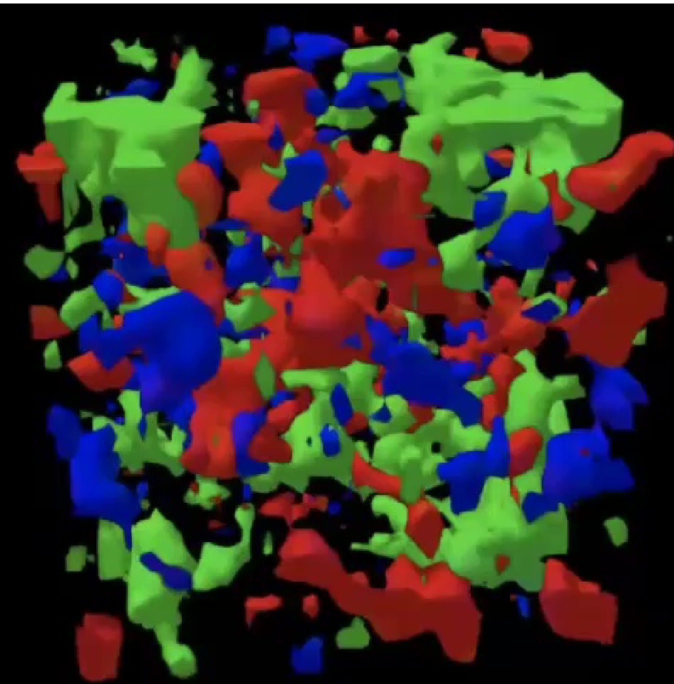

BY CSSM VISUALISATION

$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{\mathcal{Z}} \int \mathcal{D}U_\mu \mathcal{D}q\mathcal{D}\bar{q}\, e^{-S^{(G)}_{\text{lattice}}[U] - S^{(F)}_{\text{lattice}}[U,q,\bar{q}]}\, \hat{\mathcal{O}}[U,q,\bar{q}]$$

$$\Downarrow$$

$$\langle \hat{\mathcal{O}} \rangle = \frac{1}{N} \sum_i^N \langle \hat{\mathcal{O}} \rangle_F [U^{(i)}]$$

$U^{(i)}$ sampled from the distribution: $\boxed{\frac{1}{\mathcal{Z}} e^{-S^{(G)}_{\text{lattice}}[U]} \prod_f \det D_f}$

THREE FEATURES MAKE LATTICE QCD CALCULATIONS OF NUCLEI HARD:

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

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Detmold and Orginos (2013)
Detmold and Savage (2010)
Doi and Endres (2013)
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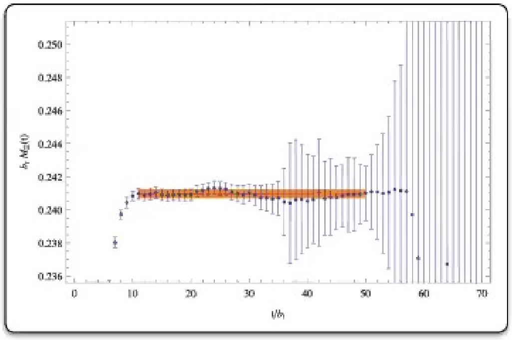

ii) There is a severe signal-to-noise degradation.

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Paris (1984) and Lepage (1989)
Wagman and Savage (2017, 2018)
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iii) Excitation energies of nuclei are much smaller than the QCD scale.

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Beane at al (NPLQCD) (2009)
Beane, Detmold, Orginos, Savage (2011)
ZD (2018)
Briceno, Dudek and Young (2018)
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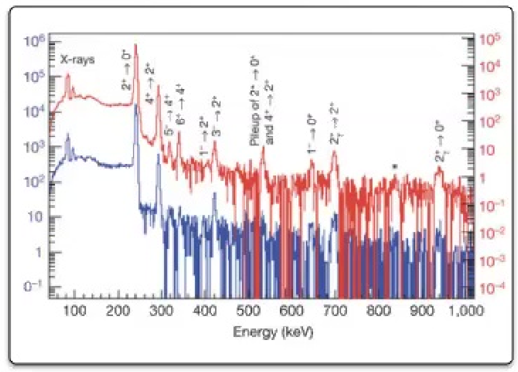
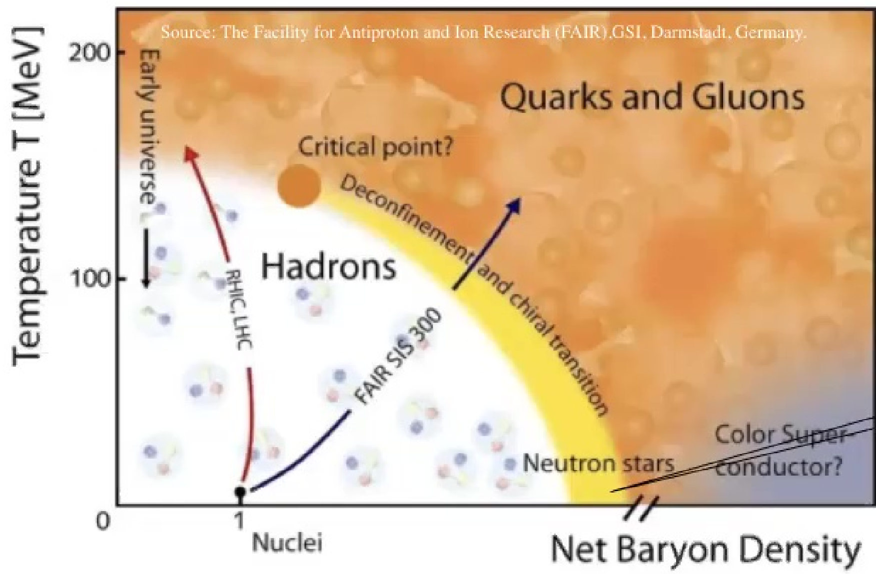
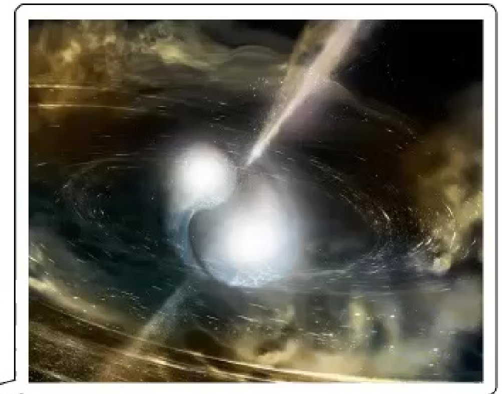


ADDITIONALLY THE SIGN PROBLEM FORBIDS:

i) Studies of nuclear isotopes, dense matter, and phase diagram of QCD… both with lattice QCD and with ab initio nuclear many-body methods.





Path integral formulation:

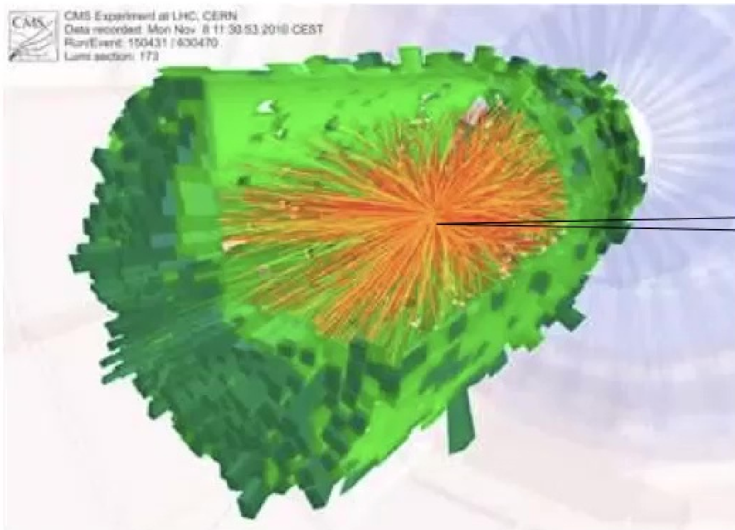
$$e^{-S[U,q,\bar{q}]}$$

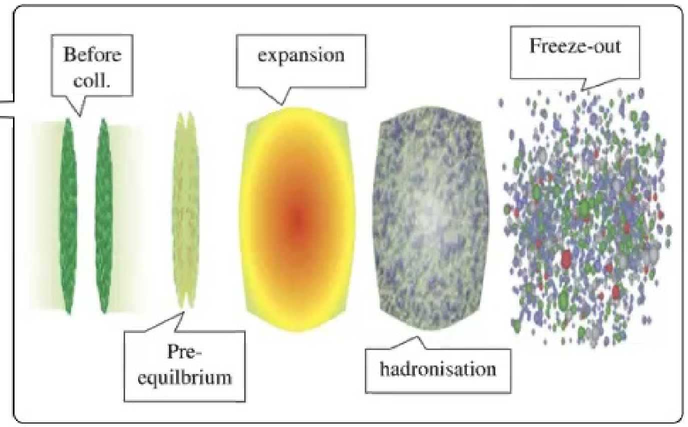
with a complex action:

$$\mathcal{L}_{\text{QCD}} \rightarrow \mathcal{L}_{\text{QCD}} - i\mu \sum_f \bar{q}_f \gamma^0 q_f$$

ADDITIONALLY THE SIGN PROBLEM FORBIDS:

ii) Real-time dynamics of matter in heavy-ion collisions or after Big Bang…





…and a wealth of dynamical response functions, transport properties, hadron distribution functions, and non-equilibrium physics of QCD.

Path integral formulation:

$$e^{iS[U,q\bar{q}]}$$

Hamiltonian evolution:

$$U(t) = e^{-iHt}$$

AN OPPORTUNITY TO EXPLORE NEW PARADIGMS AND NEW TECHNOLOGIES IN SIMULATION: QUANTUM SIMULATION?

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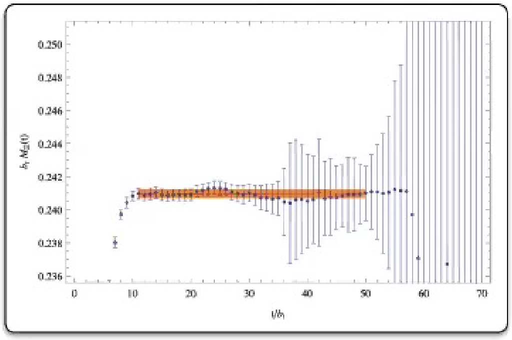

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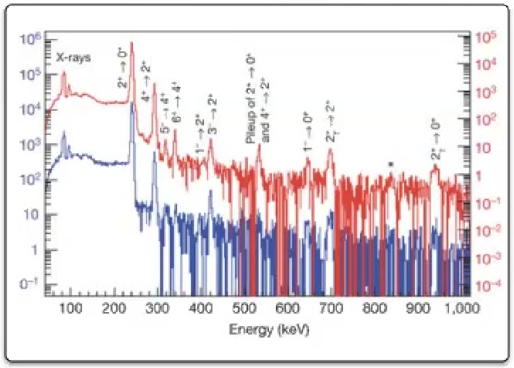
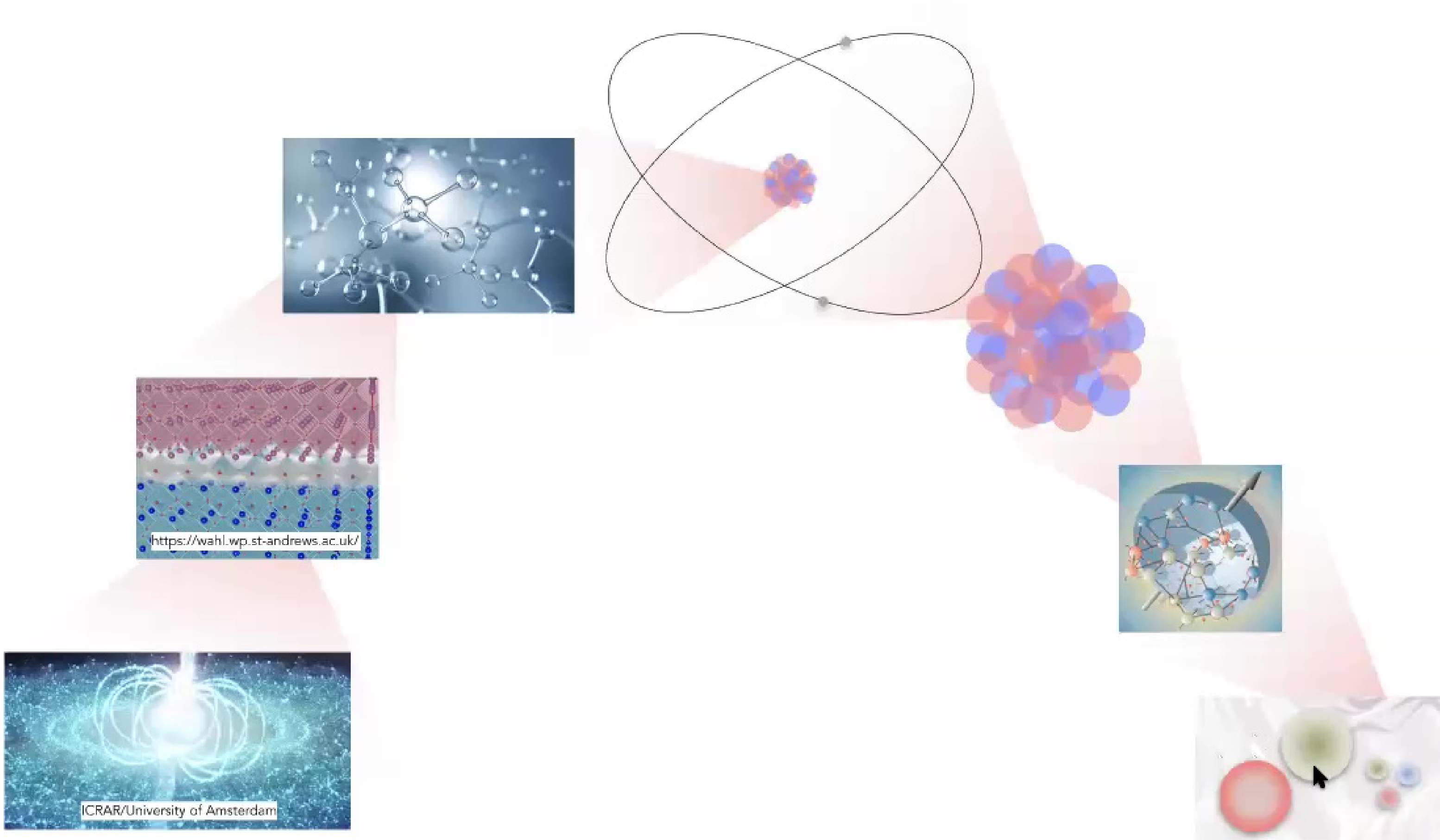


AN OPPORTUNITY TO EXPLORE NEW PARADIGMS AND NEW TECHNOLOGIES IN SIMULATION: QUANTUM SIMULATION?

QUANTUM SIMULATION FOR NUCLEAR AND HIGH-ENERGY PHYSICS: WHAT IT IMPLIES.

Quantum simulation amounts to leveraging a quantum system that can be controlled to study another quantum systems that is more elusive, experimentally or computationally.



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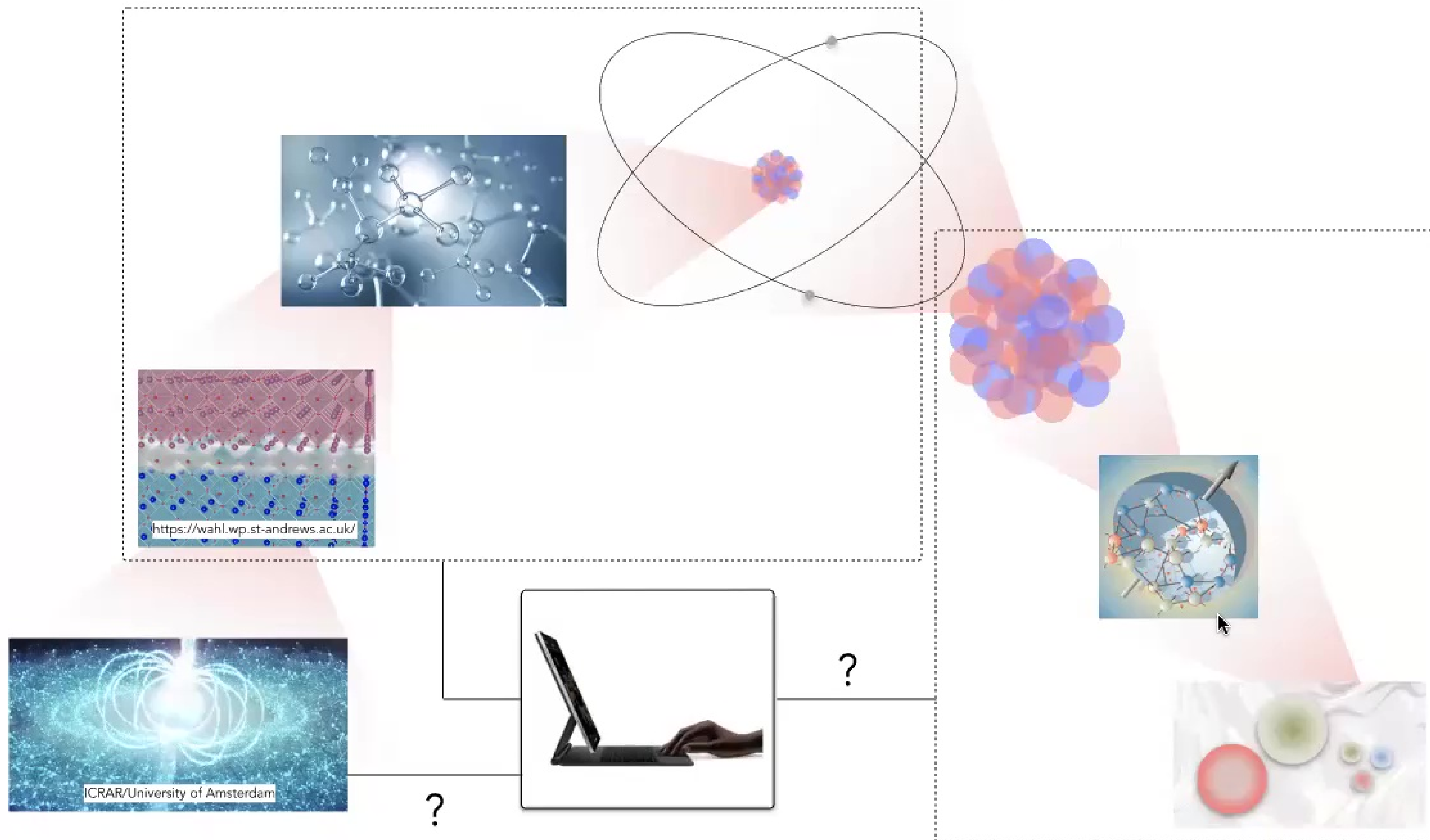
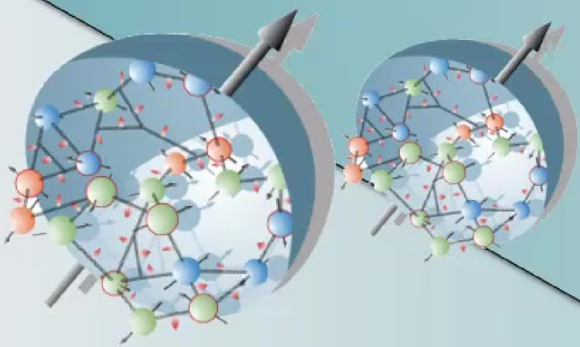


A RANGE OF QUANTUM SIMULATORS WITH VARING CAPACITY AND CAPABILITY IS AVAILABLE!

SOME SIMILARITIES BUT MAJOR DIFFERENCES



Starting from the nucelar Hamiltonian

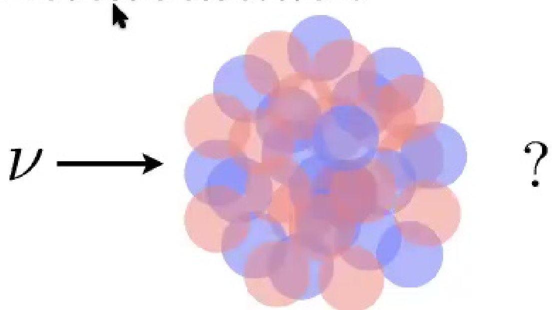
More complex Hamiltonian, itself unknown with arbitrary accuracy, short, intermediate, and long-range interactions, three and multi-body interactions, pions (bosons) and other hadrons can become dynamical.

Starting from the Standard Model

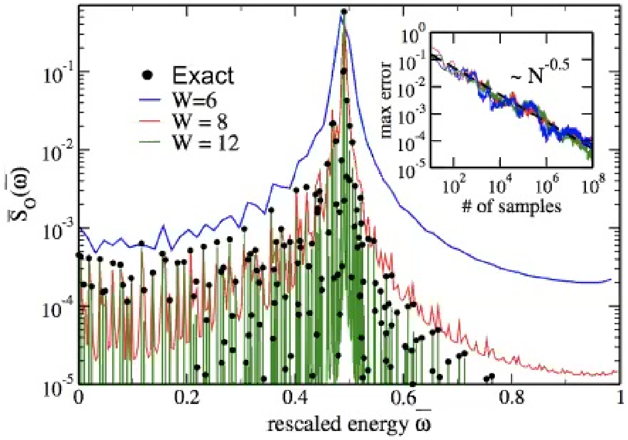
Both bosonic and fermionic DOF are dynamical and coupled, exhibit both global and local (gauge) symmetries, relativistic hence particle number not conserved, vacuum state nontrivial in strongly interacting theories.

QUANTUM SIMULATION FOR NUCLEAR ASTROPHYSICS: TWO EXAMPLES

Dynamical response functions needed for ν-nucleus cross sections



A quantum computation of response function in Fermi-Hubbard model



Roggero, Carlson, Phys. Rev. C 100, 034610 (2019)

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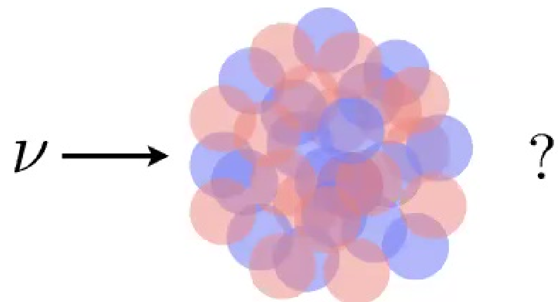

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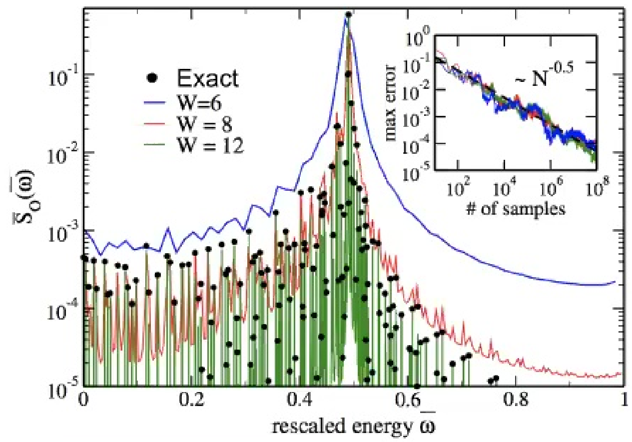
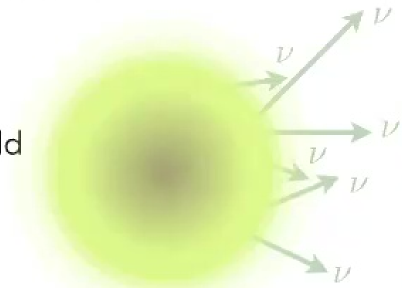
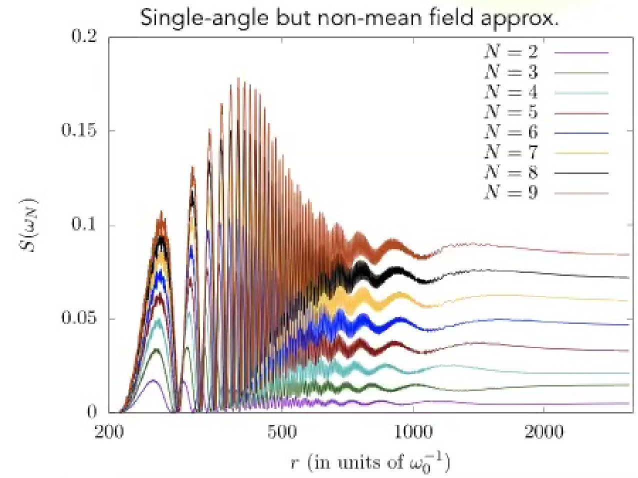


Roggero, Carlson, Phys. Rev. C 100, 034610 (2019)

Collective neutrino oscillations

Quantum entanglement measures tell us mean-field approximation this might not be good enough.



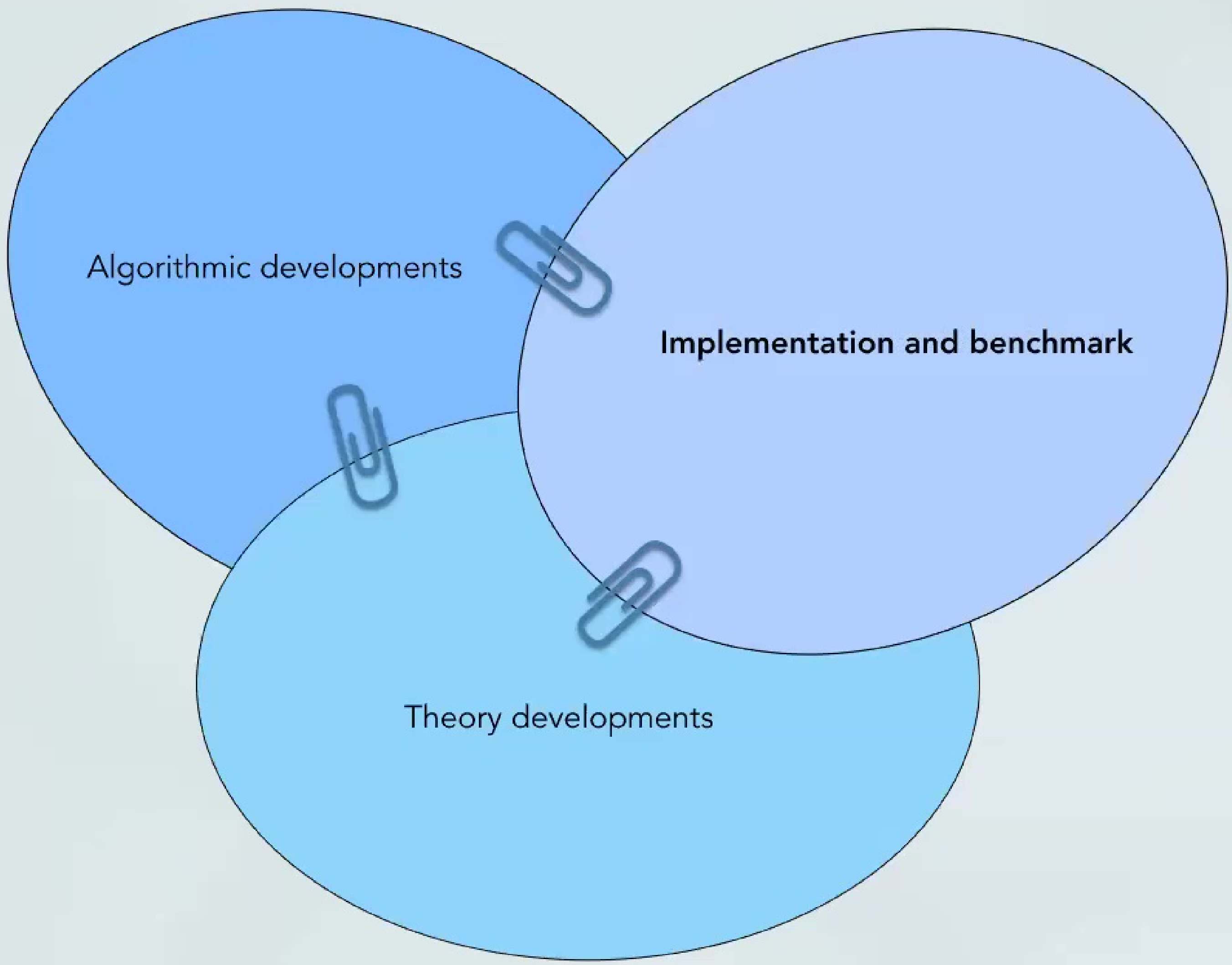


Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, Phys. Rev. D 100, 083001 (2019)

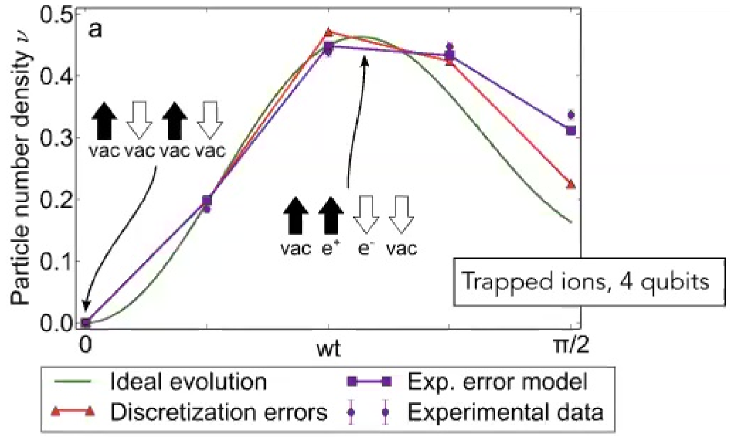
Would need quantum simulation!

Ongoing work by Baroni, Carlson, Hall, Roggero (2020).

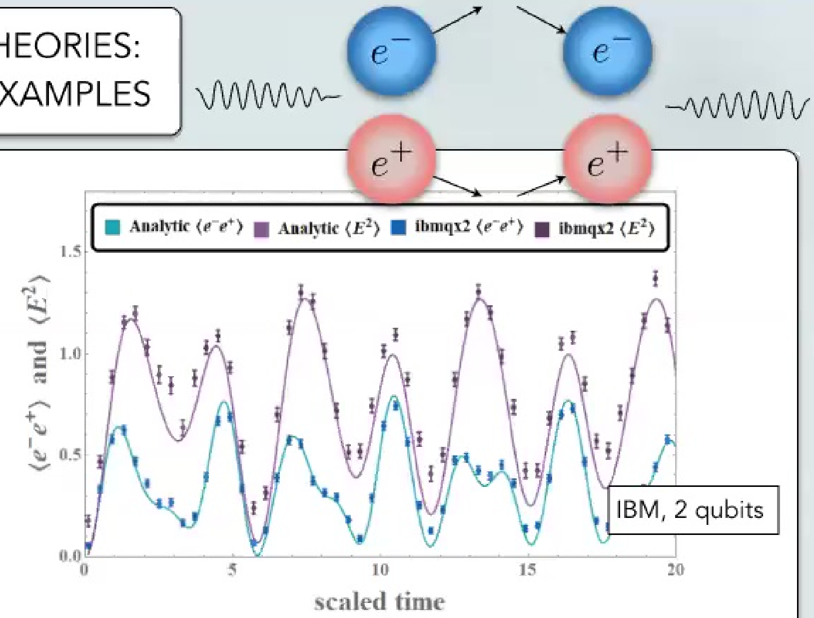
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A FEW EXAMPLES



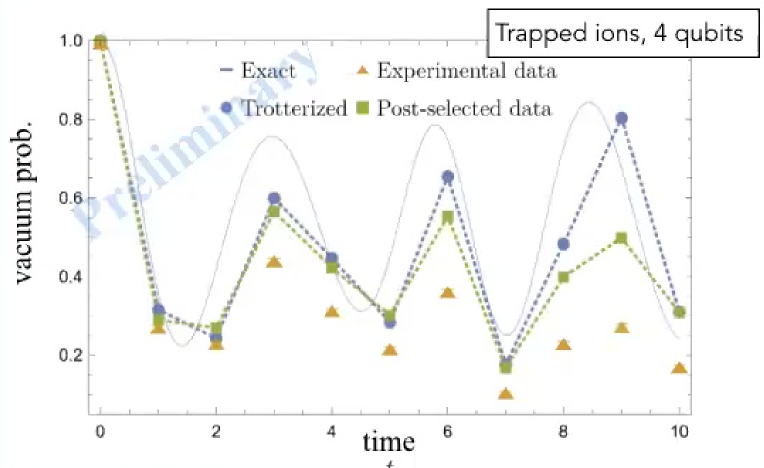
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK DIGITAL EXAMPLES



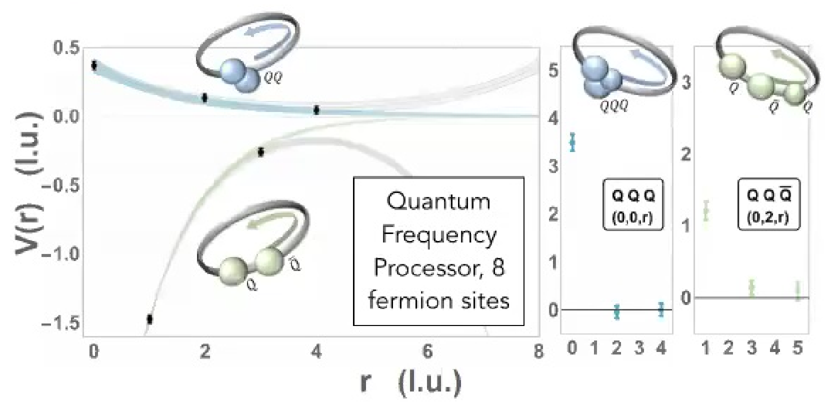
Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



Klco, Dumitrescu, McCaskey, Morris, Pooser, Sanz, Solano, Lougovski, Savage, Phys. Rev. A 98, 032331 (2018)

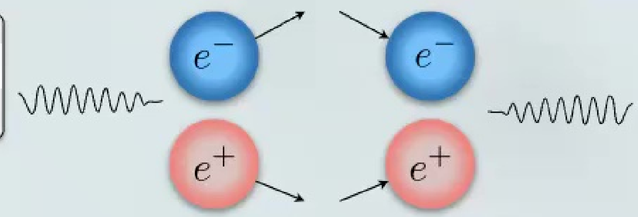


Nguyen, Shaw, Zhu, Huerta Alderete, ZD, Linke (2020)

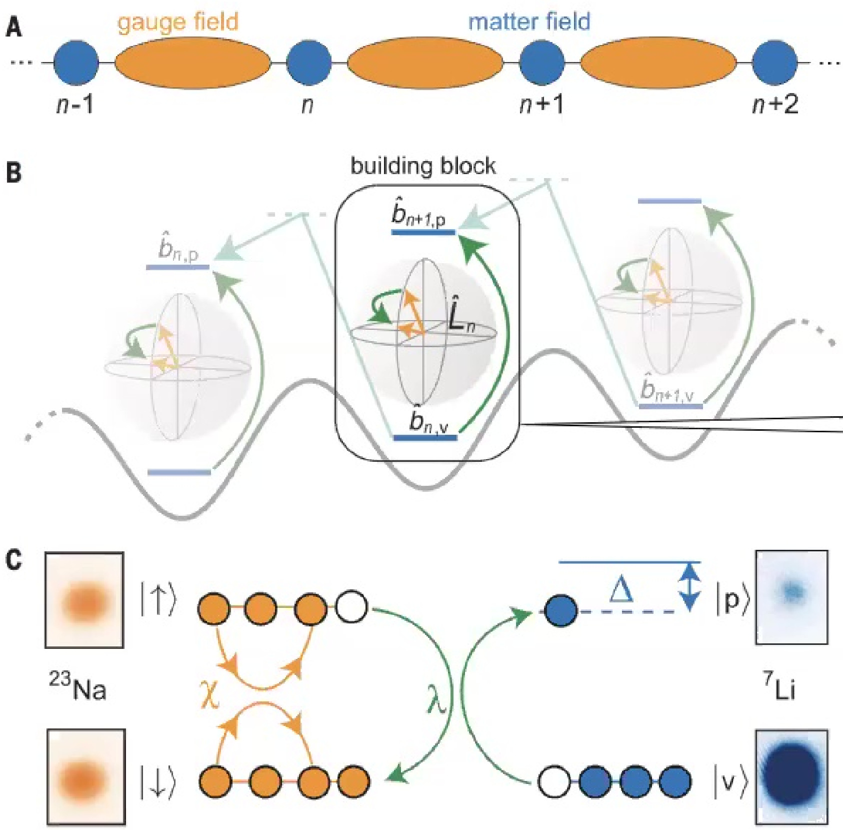


Lu, Klco, Lukens, Morris, Bansal, Ekström, Hagen, Papenbrock, Weiner, Savage, Lougovski, Phys. Rev. A 100, 012320 (2019)

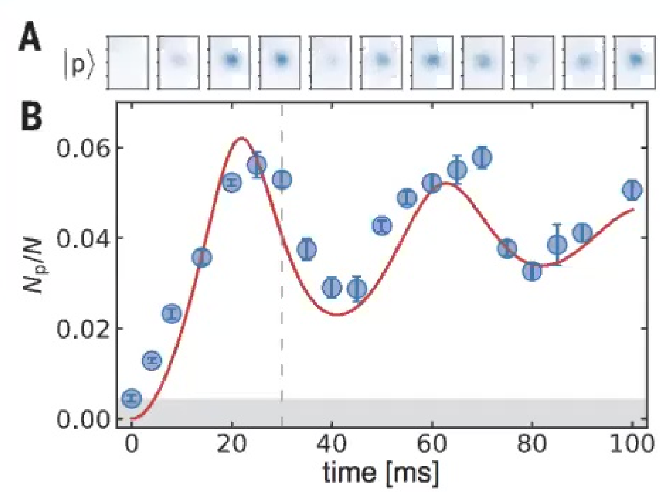
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK ANALOG EXAMPLE



A realization of lattice Schwinger model within QLM with cold atoms in a trapping potential



Mil, Zache, Hegde, Xia, Bhatt, Oberthaler, Hauke, Berges, Jendrzejewski, Science 367, 1128-1130 (2020)



QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

Hamiltonian formalism maybe more natural than the path integral formalism for quantum simulation/computation:

Kogut and Susskind formulation:

$$H_{\mathrm{QCD}} = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right) - \frac{1}{4g^2}\sum_{\Box}\mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right).$$

Fermion hopping term | Fermion mass | Energy of color electric field | Energy of color magnetic field

Generator of infinitesimal gauge transformation $G_x^a = \psi_x^{i\dagger}\lambda_{ij}^a\psi_x^j + \sum_k \left(L_{x,x+\hat{k}}^a + R_{x-\hat{k},x}^a\right) \Rightarrow G_x^i|\psi(\{q_x^{(i)}\})\rangle = q_x^{(i)}|\psi(\{q_x^{(i)}\})\rangle$

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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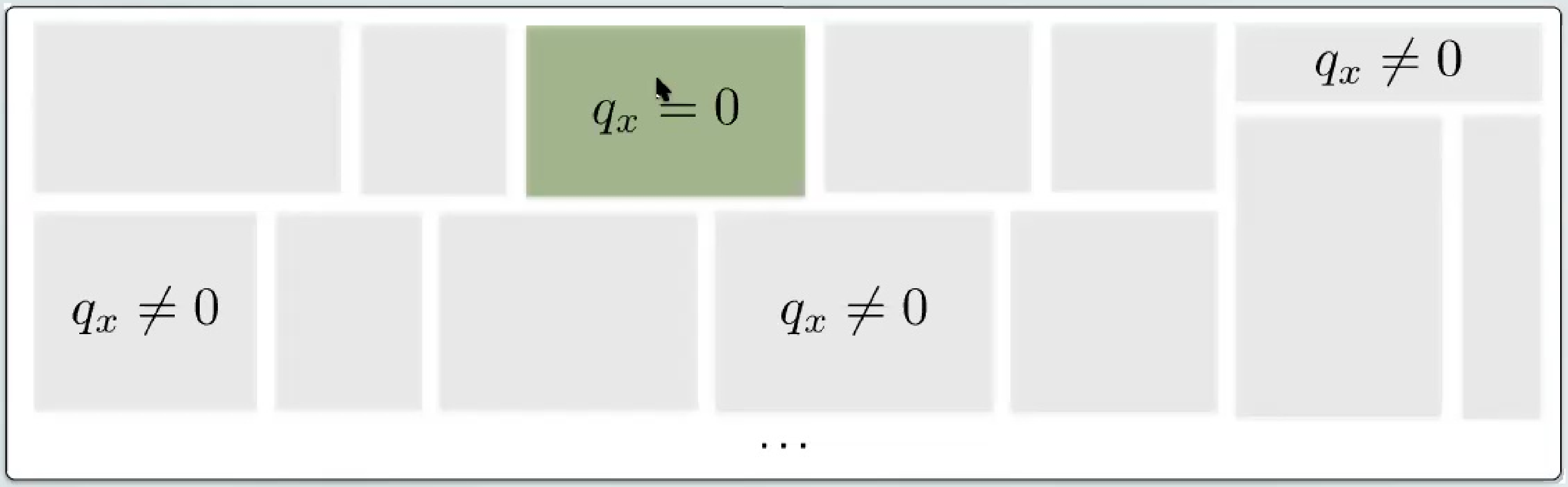
Fermion hopping term | Fermion mass | Energy of color electric field | Energy of color magnetic field

Generator of infinitesimal gauge transformation $G_x^a = \psi_x^{i\dagger}\lambda_{ij}^a\psi_x^j + \sum_k \left(L^a_{x,x+k} + R^a_{x-\hat{k},x}\right) \Longrightarrow G_x^i|\psi(\{q_x^{(i)}\})\rangle = q_x^{(i)}|\psi(\{q_x^{(i)}\})\rangle$



QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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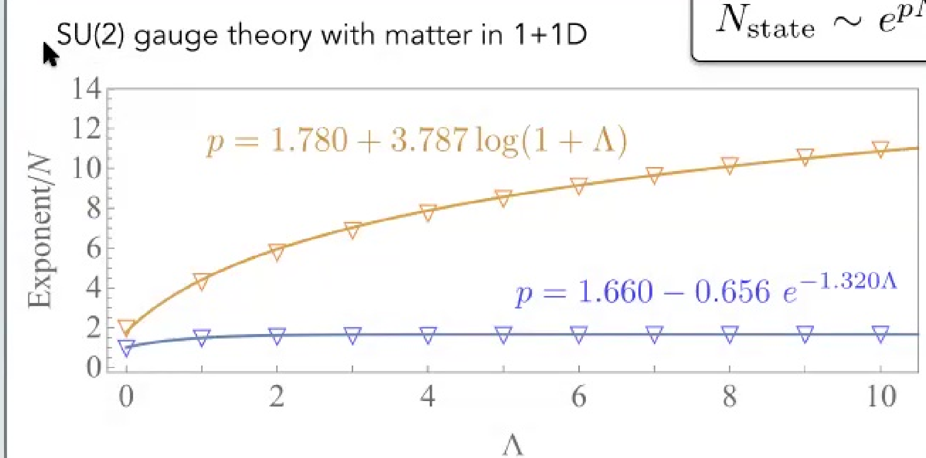
Kogut and Susskind formulation:

$$H_{\rm QCD} = -t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right) + m\sum_x s_x \psi_x^\dagger \psi_x + \frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right) - \frac{1}{4g^2}\sum_{\Box}{\rm Tr}\left(U_\Box + U_\Box^\dagger\right).$$

Fermion hopping term | Fermion mass | Energy of color electric field | Energy of color magnetic field

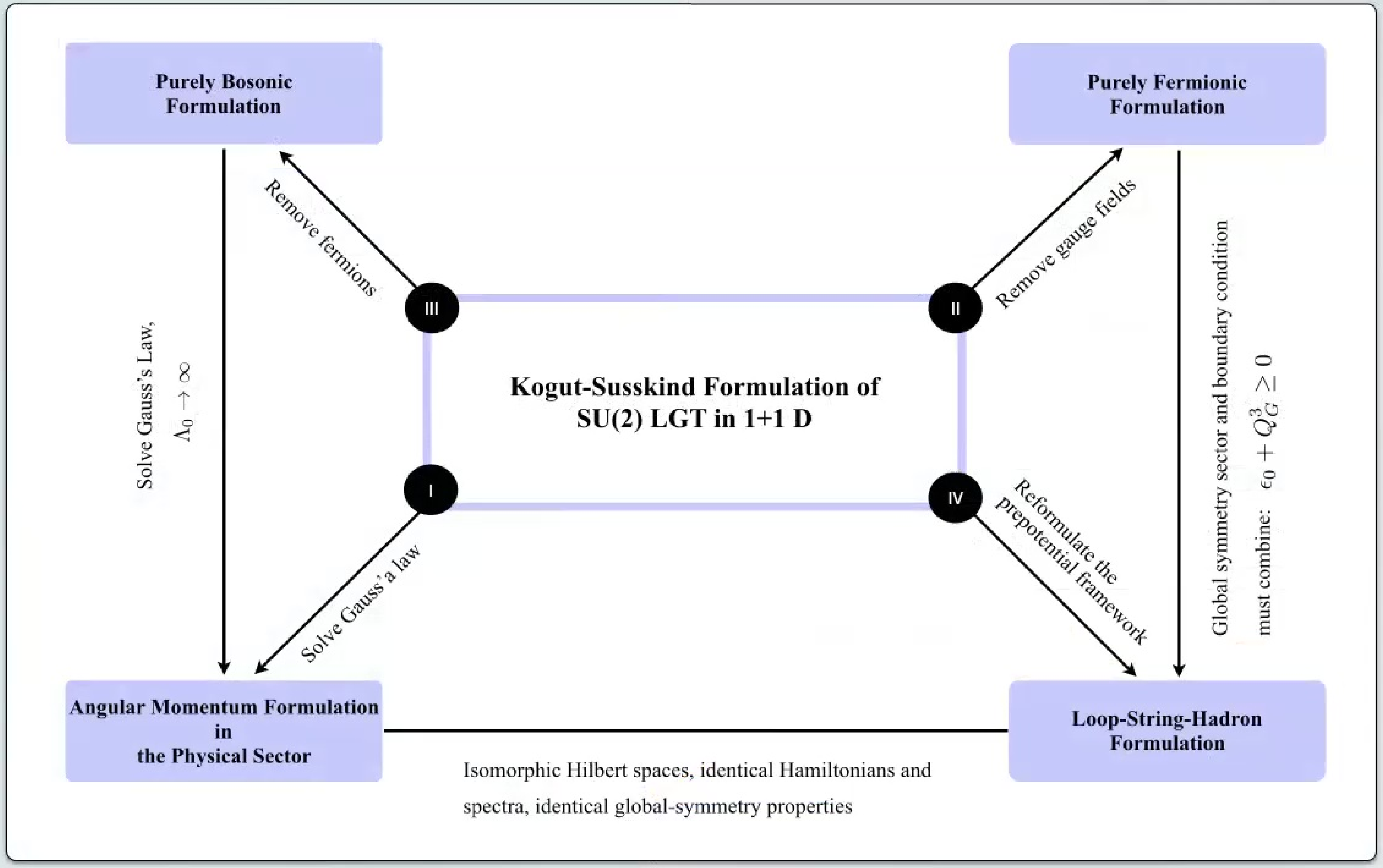
Generator of infinitesimal gauge transformation $G_x^a = \psi_x^{i\dagger}\lambda_{ij}^a\psi_x^j + \sum_k \left(L_{x,x+\hat{k}}^a + R_{x-\hat{k},x}^a\right) \Longrightarrow G_x^i|\psi(\{q_x^{(i)}\})\rangle = q_x^{(i)}|\psi(\{q_x^{(i)}\})\rangle$

$N_{\rm state} \sim e^{pN}$



ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

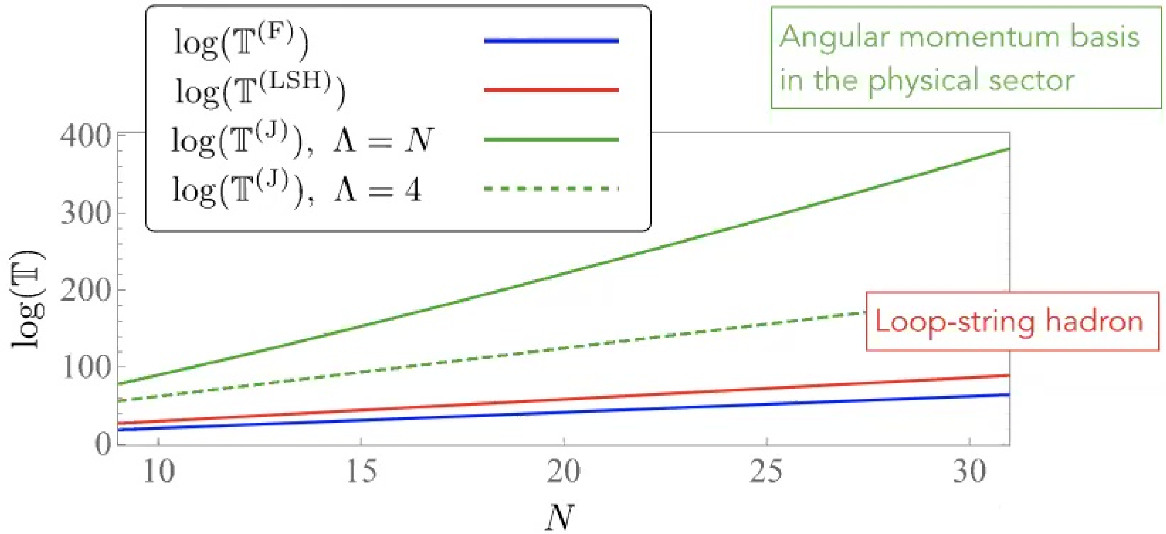
QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS



ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

The time complexity of classical Hamiltonian-simulation algorithms for each formulation.



ZD, Raychowdhury, and Shaw, arXiv:2009.11802 [hep-lat]

III

II

Kogut-Susskind Formulation of SU(2) LGT in 1+1 D

I

IV

Raychowdhury, Stryker, Phys. Rev. D 101, 114502 (2020).

For progress in 2+1 D U(1) gauge theory, see:
Haase, Dellantonio, Celi, Paulson, Kan, Jansen, Muschik, arXiv:2006.14160 [quant-ph]
Paulson, Dellantonio, Haase, Celi, Kan, Jena, Kokail, van Bijnen, Jansen, Zoller, Muschik, arXiv: 2008.09252 [quant-ph].

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: ALGORITHMIC DEVELOPMENTS

Scalar field theory

Jordan, Lee, and Preskill, Quant. Inf. Comput.14,1014(2014)

Klco, Savage, Phys. Rev. A 99, 052335 (2019).

Barata , Mueller, Tarasov, Venugopalan (2020).

1+1 D quantum electrodynamics

$$\hat{H}_{\text{spin}} = w \sum_{n=1}^{N-1} \left[\hat{\sigma}_n^+ e^{i\hat{\theta}_n} \hat{\sigma}_{n+1}^- + \text{H.c.} \right] + \frac{m}{2} \sum_{n=1}^{N} (-1)^n \hat{\sigma}_n^z + J \sum_{n=1}^{N-1} \hat{L}_n^2.$$

Shaw, Lougovski, Stryker, Wiebe, Quantum 4, 306 (2020)

Recourse analysis for lattice Schwinger model

Near term

	$\delta_g = 10^{-3}$		$\delta_g = 10^{-4}$		$\delta_g = 10^{-5}$		$\delta_g = 10^{-6}$		$\delta_g = 10^{-7}$	
	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT	$\tilde{\epsilon}^2$	CNOT
$x = 10^{-2}$	—	7.3e4	—	1.6e5	—	3.4e5	—	7.3e5	5.6e-2	1.6e6
$x = 10^{-1}$	—	1.6e4	—	3.5e4	—	7.5e4	5.9e-2	1.6e5	2.7e-3	3.5e5
$x = 1$	—	4.6e3	—	9.9e3	1.0e-1	2.1e4	4.7e-3	4.6e4	2.2e-4	9.9e4
$x = 10^2$	—	2.8e3	8.3e-1	6.1e3	3.8e-2	1.3e4	1.8e-3	2.8e4	8.2e-5	6.0e4

Far term

Upper Bounds on T-gate Cost of Specific Simulations ($\mu = 1,\ \tilde{\epsilon}^2 = 0.1$)

	Short Time ($T = 10/x$)		Long Time ($T = 1000/x$)	
	Sampling	Estimating	Sampling	Estimating
$N = 4,\ \Lambda = 2$				
Strong Coupling ($x = 0.1$)	$6.5 \cdot 10^7$	$2.4 \cdot 10^{11}$	$8.8 \cdot 10^{10}$	$3.3 \cdot 10^{14}$
Weak Coupling ($x = 10$)	$5.0 \cdot 10^6$	$1.8 \cdot 10^{10}$	$7.0 \cdot 10^9$	$2.6 \cdot 10^{13}$
$N = 16,\ \Lambda = 2$				
Strong Coupling ($x = 0.1$)	$7.2 \cdot 10^8$	$2.5 \cdot 10^{12}$	$9.4 \cdot 10^{11}$	$3.3 \cdot 10^{15}$
Weak Coupling ($x = 10$)	$5.6 \cdot 10^7$	$1.9 \cdot 10^{11}$	$7.6 \cdot 10^{10}$	$2.7 \cdot 10^{14}$
$N = 16,\ \Lambda = 4$				
Strong Coupling ($x = 0.1$)	$1.9 \cdot 10^9$	$6.3 \cdot 10^{12}$	$2.3 \cdot 10^{12}$	$8.1 \cdot 10^{15}$
Weak Coupling ($x = 10$)	$9.6 \cdot 10^7$	$3.2 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$4.2 \cdot 10^{14}$

THEORY-EXPERIMENT CO-DEVELOPMENT IS
A KEY TO PROGRESS.

CAN NUCLEAR AND HIGH-ENERGY IMPACT
QUANTUM-SIMULATION HARDWARE
DEVELOPMENTS?

Ion-laser Hamiltonian

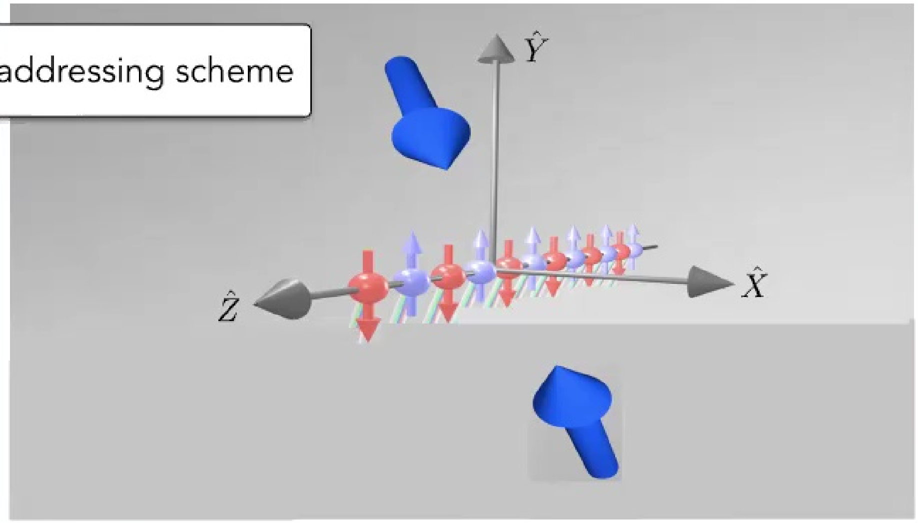
Wineland et al, J.Res.Natl.Inst.Stand.Tech. 103 (1998) 259, Schneider et al, Rep. Prog. Phys. 75 024401 (2012)

$$H_I = \sum_{i=1}^{N} \left[\left(\sum_{I=1}^{n_L} \frac{1}{2} \Omega_I^{(i)} e^{-i(\omega_I - \omega_{\uparrow\downarrow})t + i\phi_I^{(i)}} \right) \left(e^{i \sum_{m=1}^{3N} \eta_m^{(i)} (a_m e^{-i\omega_m t} + a_m^\dagger e^{i\omega_m t})} \right) (\alpha_0 \mathbb{I} + \alpha_1 \sigma_x^{(i)} + \alpha_2 \sigma_y^{(i)} + \alpha_3 \sigma_z^{(i)}) \right]$$

$$H_I = -\mu \cdot \mathbf{E}$$

EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

A global addressing scheme

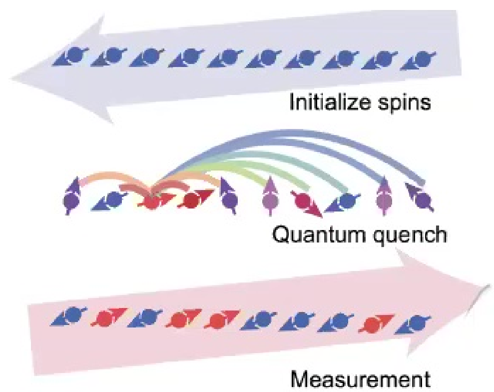


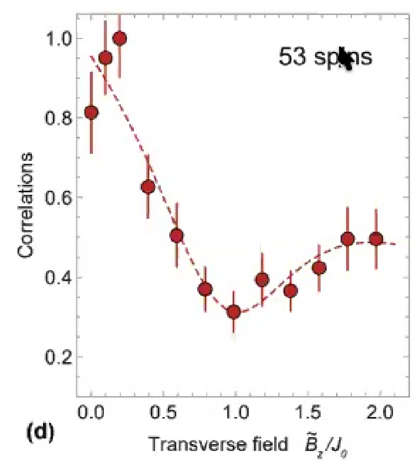
Effective Hamiltonian

$$H_{\text{eff}} = \sum_{i,j} J_{i,j}^{(xx)} \sigma_x^{(i)} \otimes \sigma_x^{(j)} - \frac{B_z}{2} \sum_i \sigma_z^{(i)}$$

with coupling:

$$J_{i,j}^{(xx)} \sim \frac{1}{|i-j|^{\alpha}}, \; 0 < \alpha < 3$$

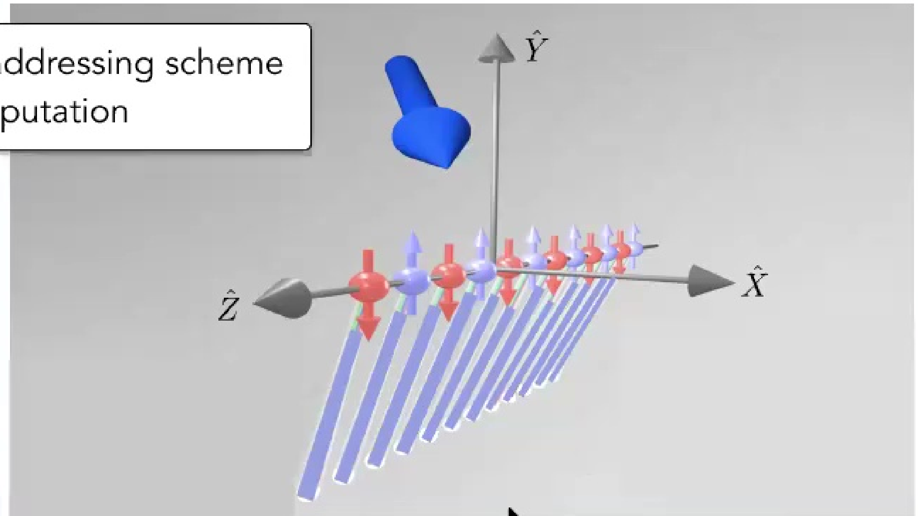




Zhang et al, Nature 551, 601–604 (2017).

EXAMPLE: A TRAPPED-ION DIGITAL SIMULATOR

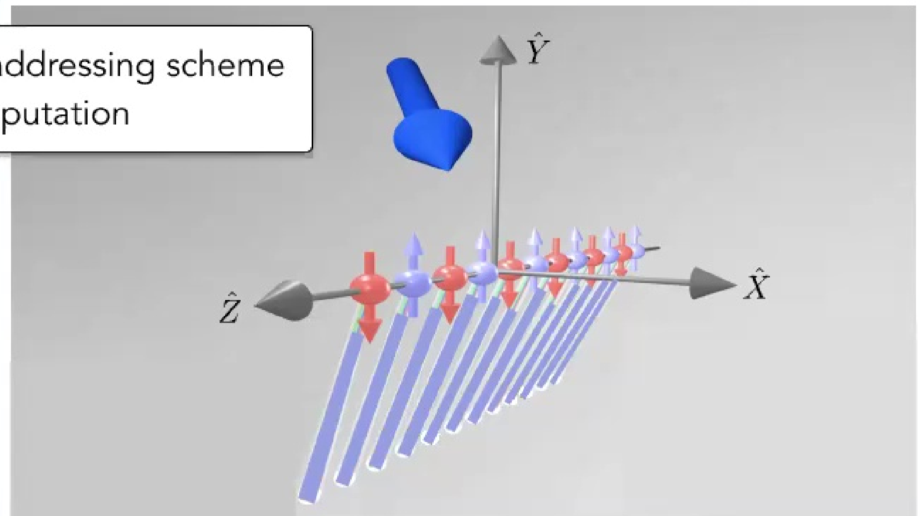
An individual addressing scheme
for digital computation



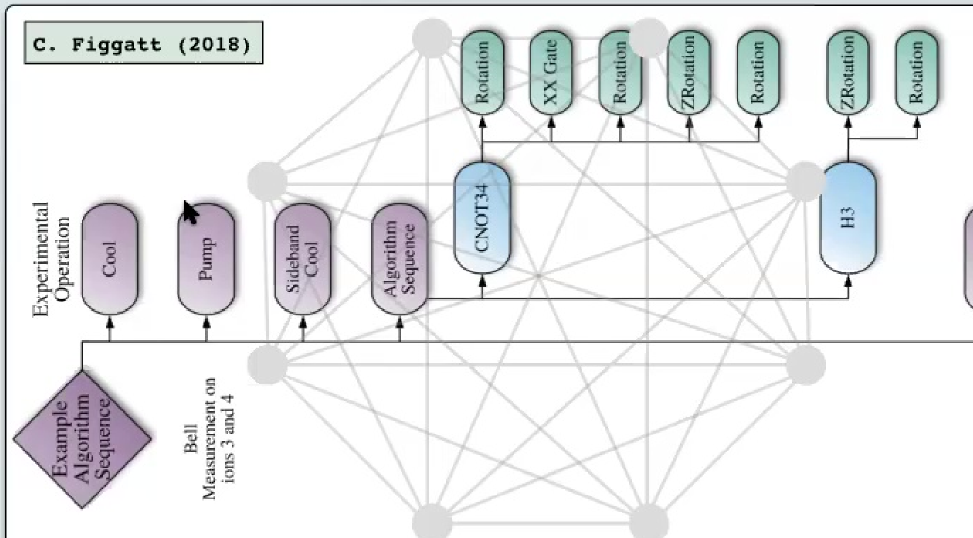
A highly tunable analog simulator is achievable with this set up too: Teoh, Drygala, Melko, Islam arXiv:1910.02496 [quant-ph], Korenblit, Islam, Monroe et al, New Journal of Physics 14, 095024 (2012).

EXAMPLE: A TRAPPED-ION DIGITAL SIMULATOR

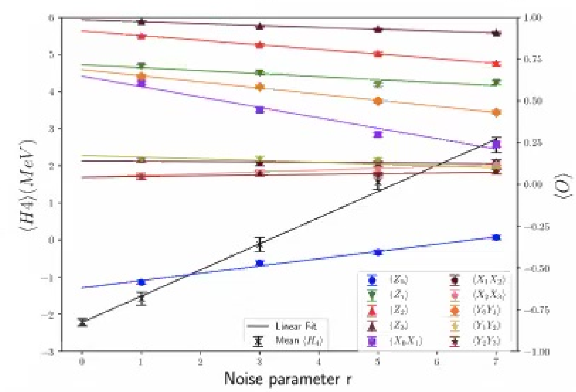
An individual addressing scheme for digital computation



C. Figgatt (2018)



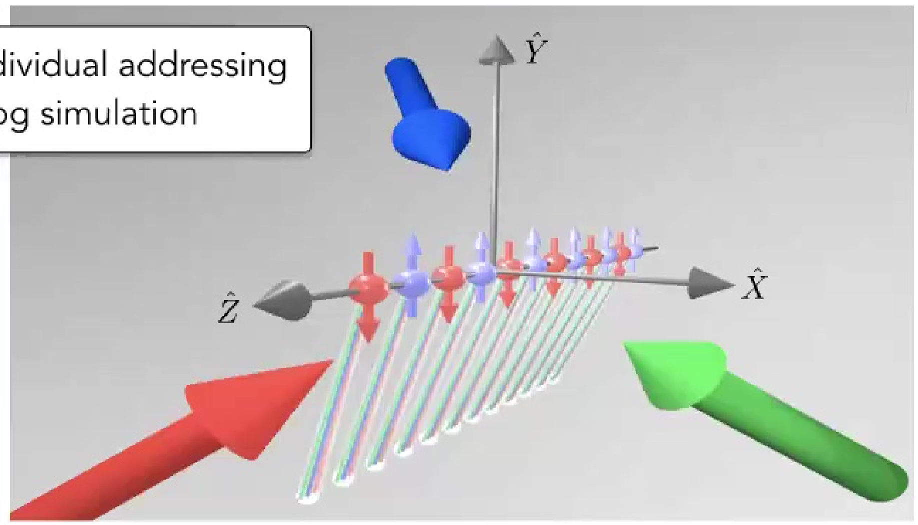
VQE for finding deuteron's binding



Shehab et al, Phys. Rev. A 100, 062319 (2019)

EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

An enhanced individual addressing scheme for analog simulation



ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

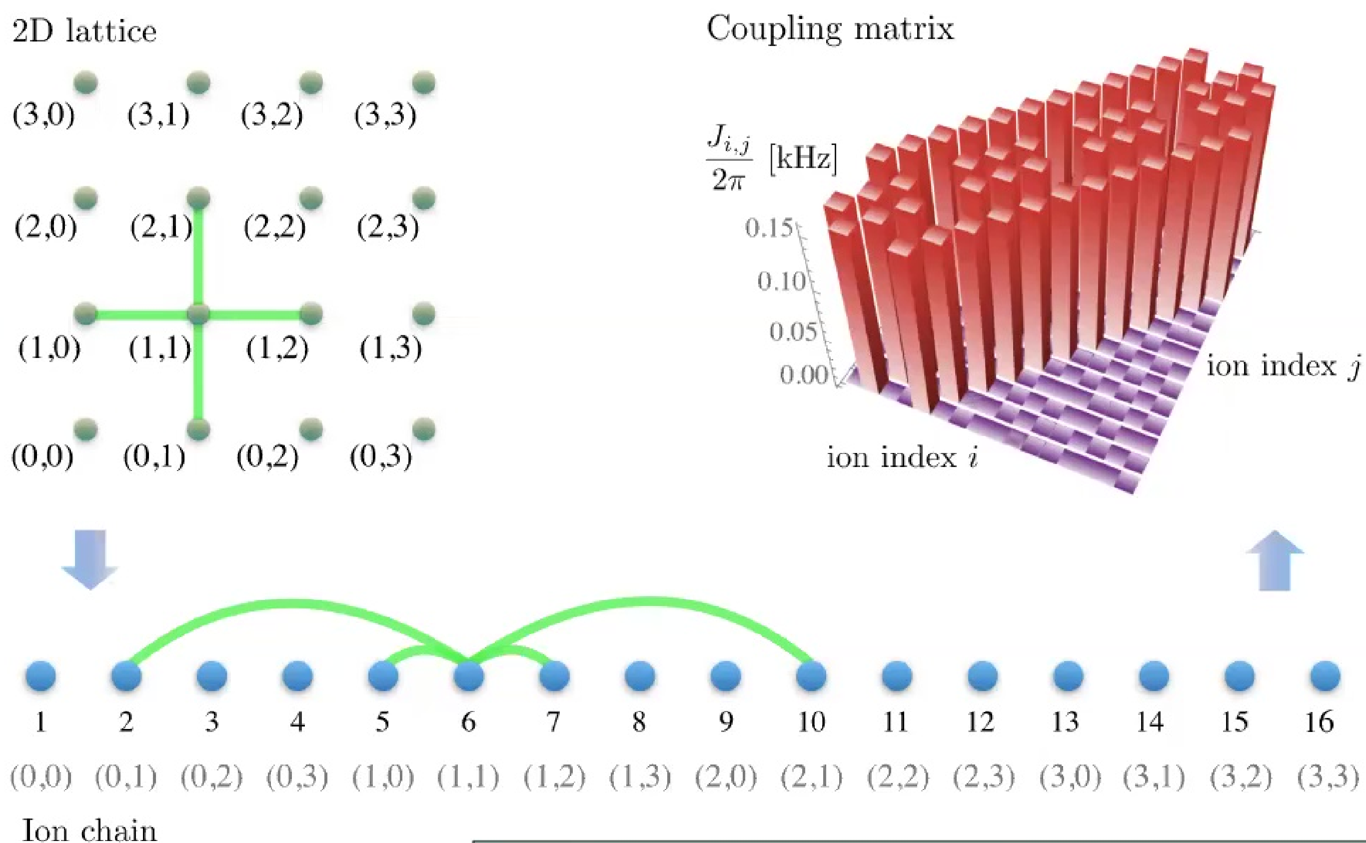
Heisenberg model Hamiltonian can be obtained under certain conditions:

$$H_{\text{eff}} = \sum_{\substack{i,j \\ j<i}} \left[J_{i,j}^{(xx)} \sigma_x^{(i)} \otimes \sigma_x^{(j)} + J_{i,j}^{(yy)} \sigma_y^{(i)} \otimes \sigma_y^{(j)} + J_{i,j}^{(zz)} \sigma_z^{(i)} \otimes \sigma_z^{(j)} \right] - \frac{1}{2} \sum_{i=1}^{N} B_z^{(i)} \sigma_z^{(i)}.$$

The same scheme can be applied to Chern-Simons theory in 2+1 d:

$$\mathcal{L}_{\text{CS}} = a^\dagger(x) i D_0 a(x) - \sum_{j=1,2} \left[a^\dagger(x) e^{iA_j(x)} a(x+\hat{\boldsymbol{n}}_j) + \text{h.c.} \right] - \frac{\theta}{4} \epsilon^{\mu\nu\lambda} A_\mu(x) F_{\nu\lambda}(x) \qquad (24)$$

$$H_{\text{CS}} = \sum_{\boldsymbol{n}} \sum_{j=1,2} \left[\sigma_+^{(\boldsymbol{n})} \sigma_-^{(\boldsymbol{n}+\hat{\boldsymbol{n}}_j)} + \text{h.c.} \right]$$

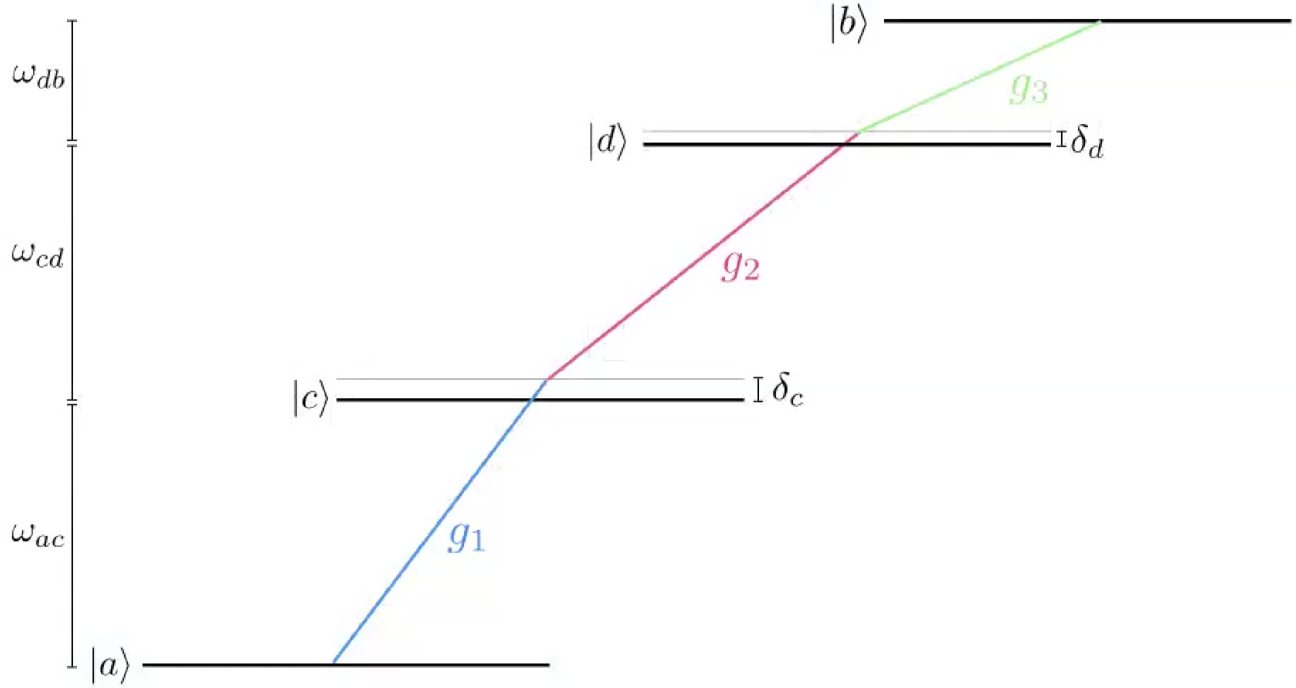


ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

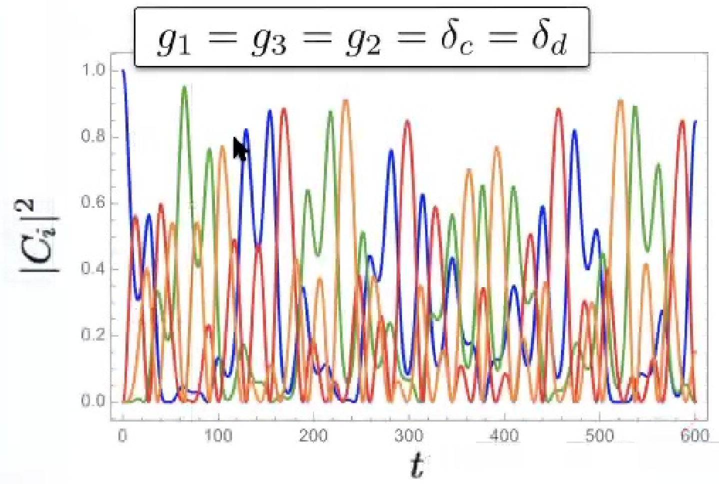
HOW OTHER GAUGE THEORIES? OR NUCLEAR HAMILTONIAN?

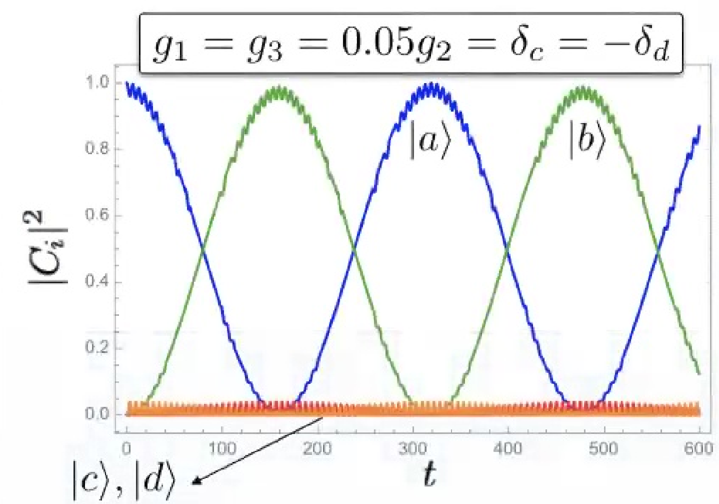
CAN WE EXPAND THE TRAPPED-ION TOOLKIT EVEN FURTHER FOR ANALOG SIMULATIONS OF NUCLEAR AND HIGH-ENERGY PHYSICS?

Adiabatic elimination technique for a four-level system

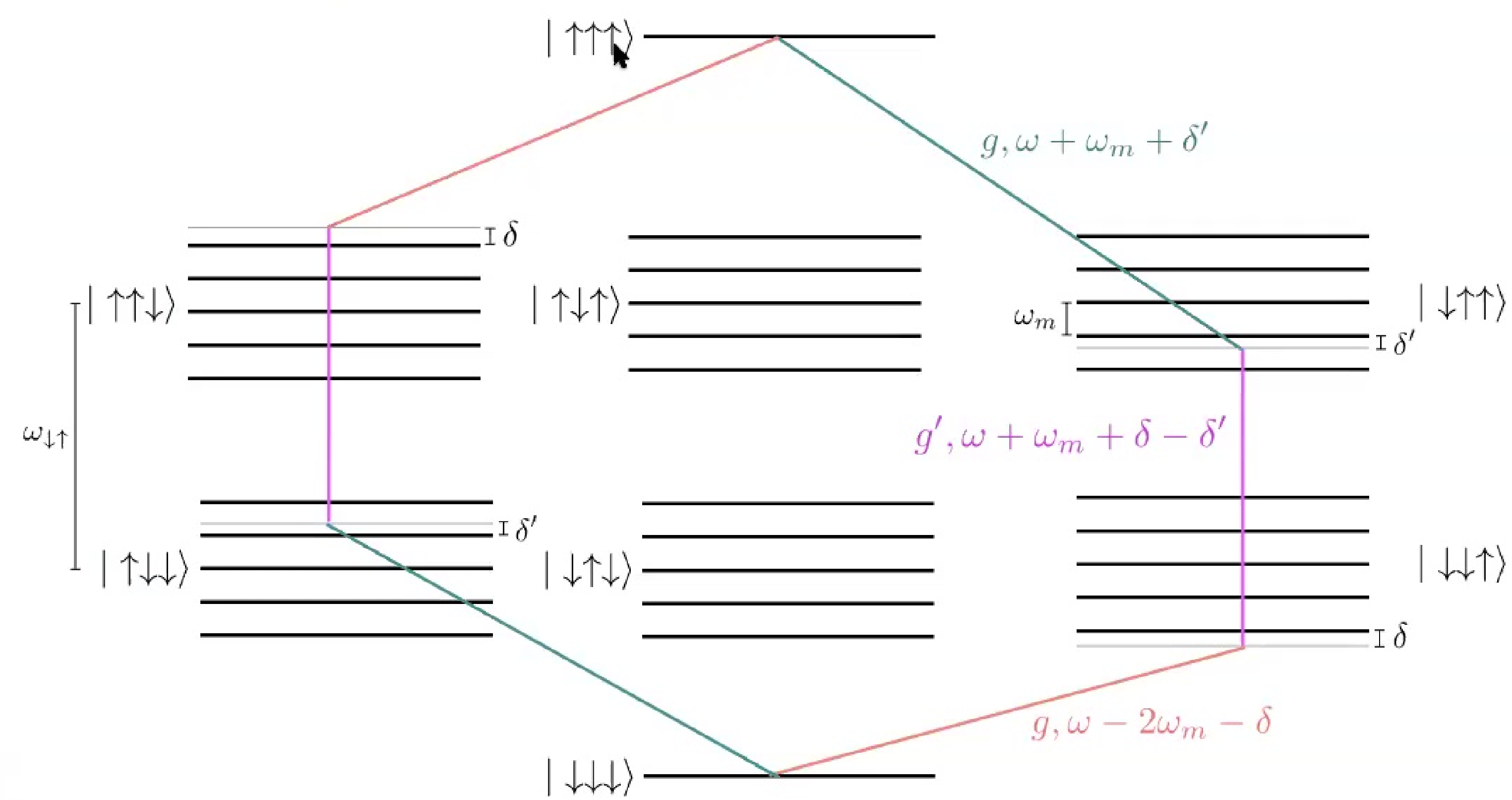


Adiabatic elimination technique
for a four-level system





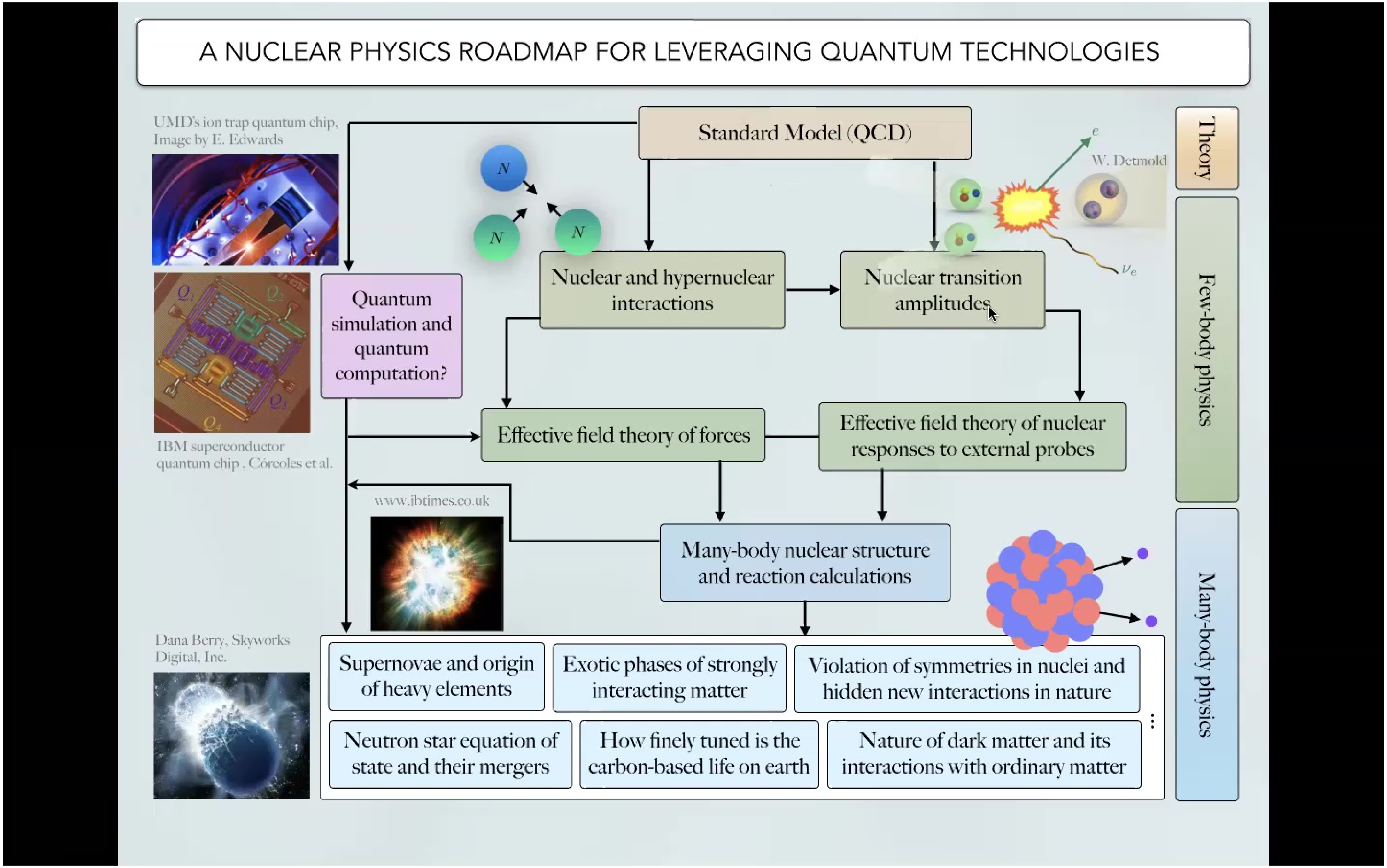
A BICHROMATIC LASER PLUS A MONOCHROMATIC LASER OFF-TUNED FROM SINGLE AND DOUBLE SIDEBANDS CAN INDUCE THREE-SPIN INTERACTIONS.



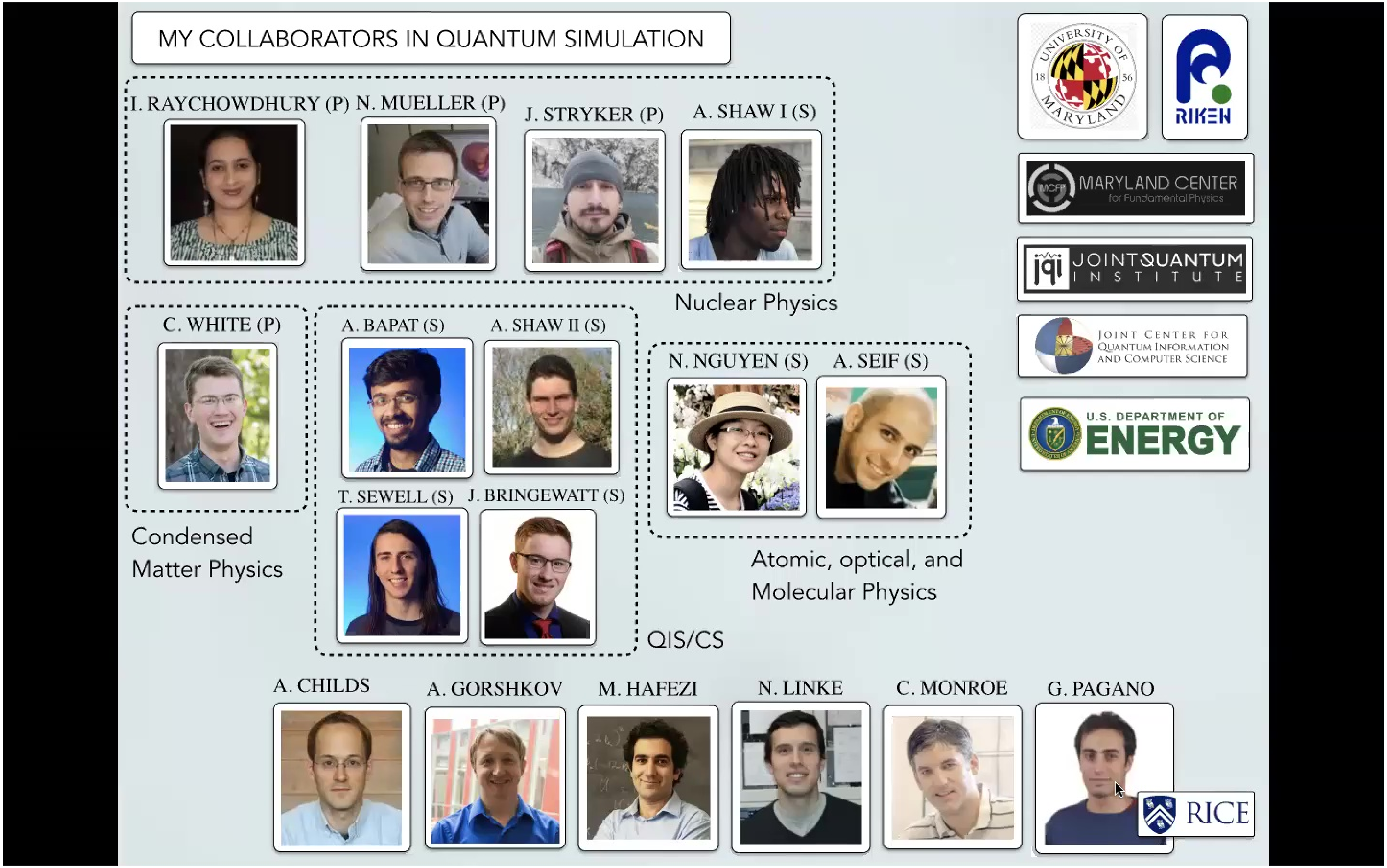
18 paths contribute! $\delta = 2\delta'$ eliminates dependence on phonon occupation and makes it very robust.

Can augment it with multi-level ion simulators in
Low, White, Cox, Day, Senko, Phys. Rev. Research 2, 033128 (2020)

See also: Bermudez et al,
Pays.Rev.A79, 060303 R (2009)



A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES
UMD's ion trap quantum chip, Image by E. Edwards
IBM superconductor quantum chip , Córcoles et al.
Dana Berry, Skyworks Digital, Inc.
www.ibtimes.co.uk
W. Detmold
Standard Model (QCD)
Quantum simulation and quantum computation?
Nuclear and hypernuclear interactions
Nuclear transition amplitudes
Effective field theory of forces
Effective field theory of nuclear responses to external probes
Many-body nuclear structure and reaction calculations
Supernovae and origin of heavy elements
Exotic phases of strongly interacting matter
Violation of symmetries in nuclei and hidden new interactions in nature
Neutron star equation of state and their mergers
How finely tuned is the carbon-based life on earth
Nature of dark matter and its interactions with ordinary matter
Theory
Few-body physics
Many-body physics


MY COLLABORATORS IN QUANTUM SIMULATION
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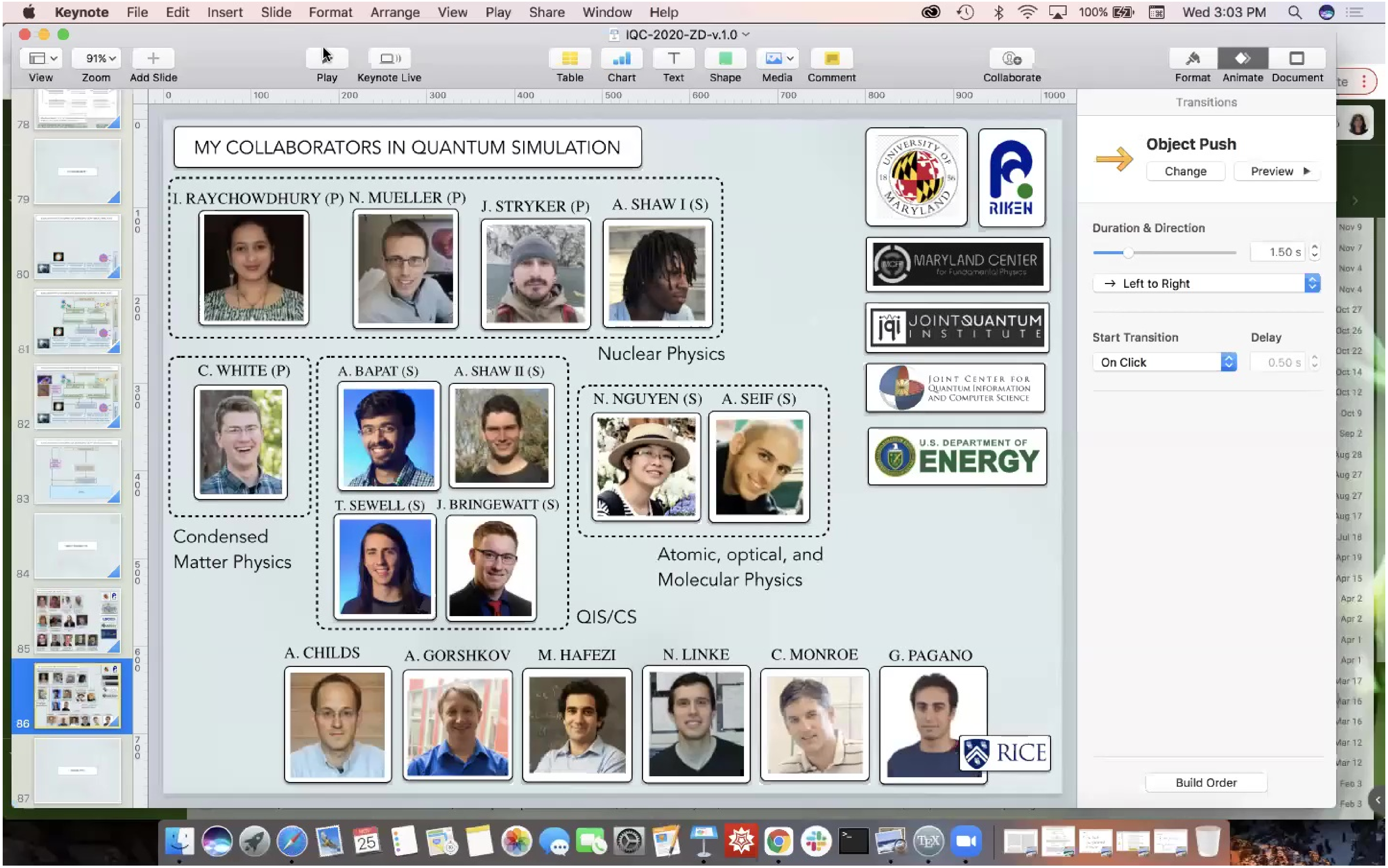
N. MUELLER (P)
J. STRYKER (P)
A. SHAW I (S)
Nuclear Physics
C. WHITE (P)
Condensed Matter Physics
A. BAPAT (S)
A. SHAW II (S)
T. SEWELL (S)
J. BRINGEWATT (S)
QIS/CS
N. NGUYEN (S)
A. SEIF (S)
Atomic, optical, and Molecular Physics
A. CHILDS
A. GORSHKOV
M. HAFEZI
N. LINKE
C. MONROE
G. PAGANO
UNIVERSITY OF MARYLAND 18 56
RIKEN
MARYLAND CENTER for Fundamental Physics
JOINT QUANTUM INSTITUTE
JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE
U.S. DEPARTMENT OF ENERGY
RICE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U.S. DEPARTMENT OF ENERGY
IQC-2020-ZD-v.1.0
Object Push
Duration & Direction
Left to Right
Start Transition
On Click
Delay
Build Order