THE XXVI EDITION OF OUR ANNUAL CHRISTMAS WORKSHOP
AT THE INSTITUTO DE FÍSICA TEÓRICA (IFT)
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TOWARD QUANTUM SIMULATION OF SYSTEMS OF RELEVANCE TO NUCLEAR AND PARTICLE PHYSICS

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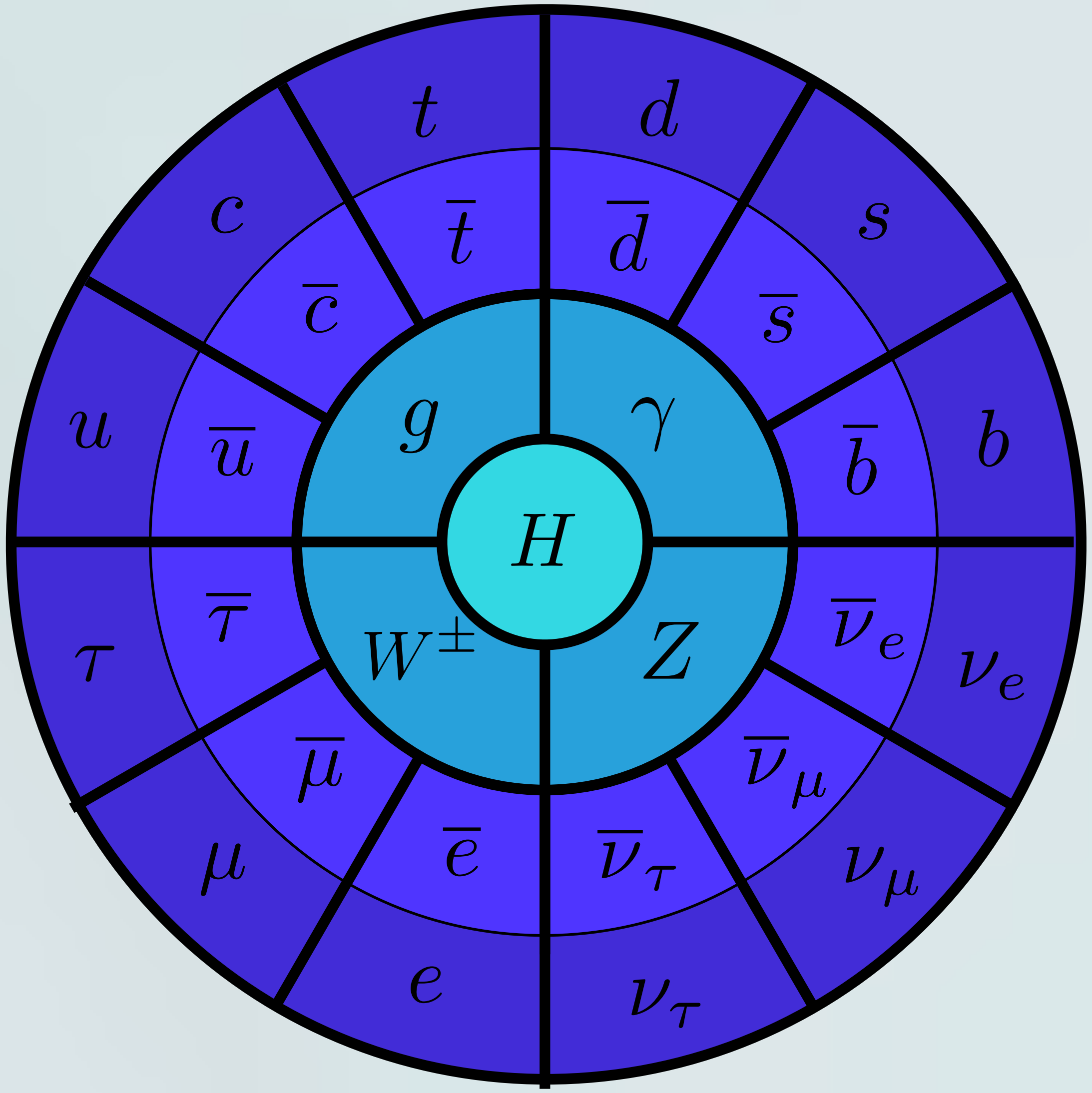
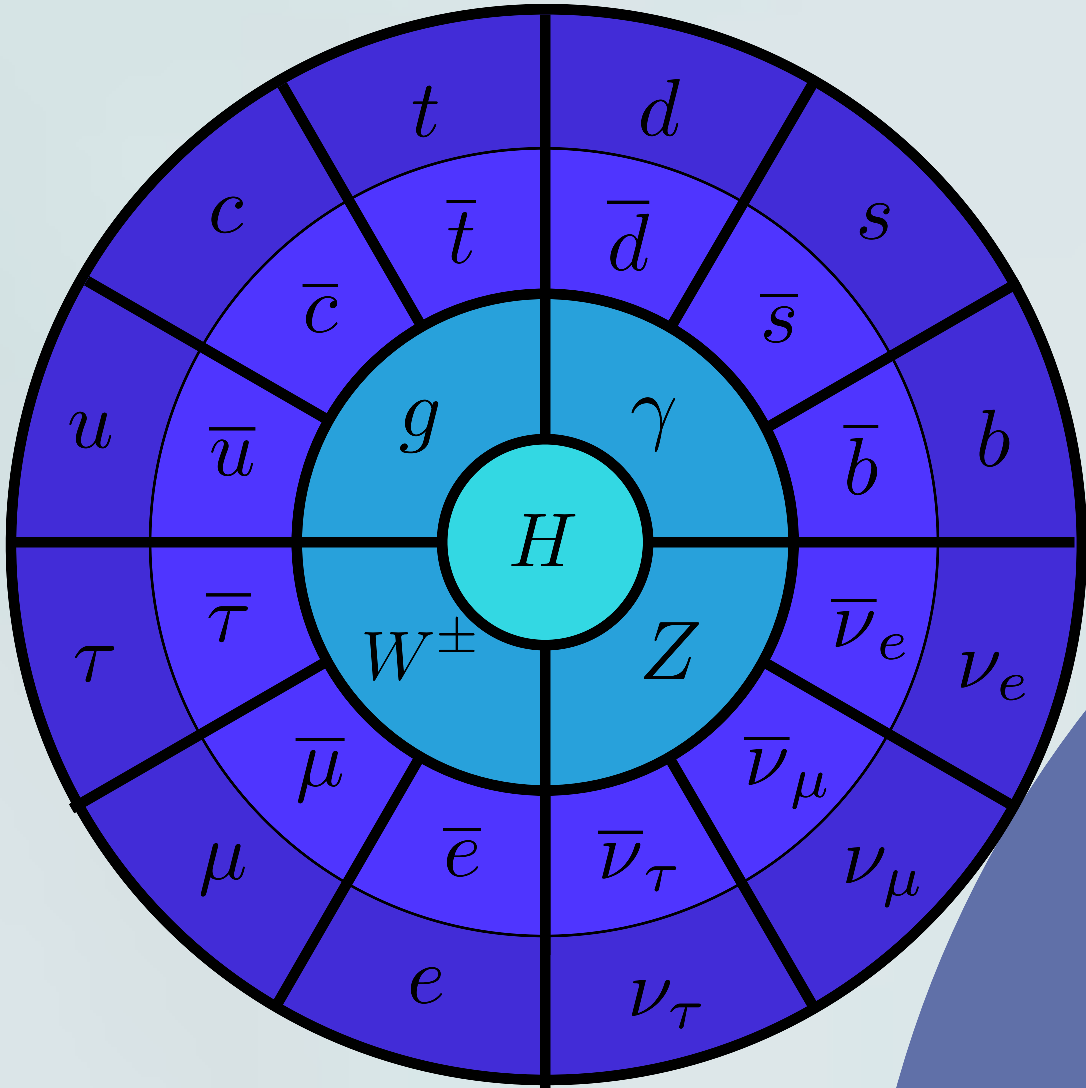
UNIVERSITY OF MARYLAND, COLLEGE PARK
RIKEN FELLOW



WHAT ARE THE UNDERLYING RULES THAT GOVERN NATURE?



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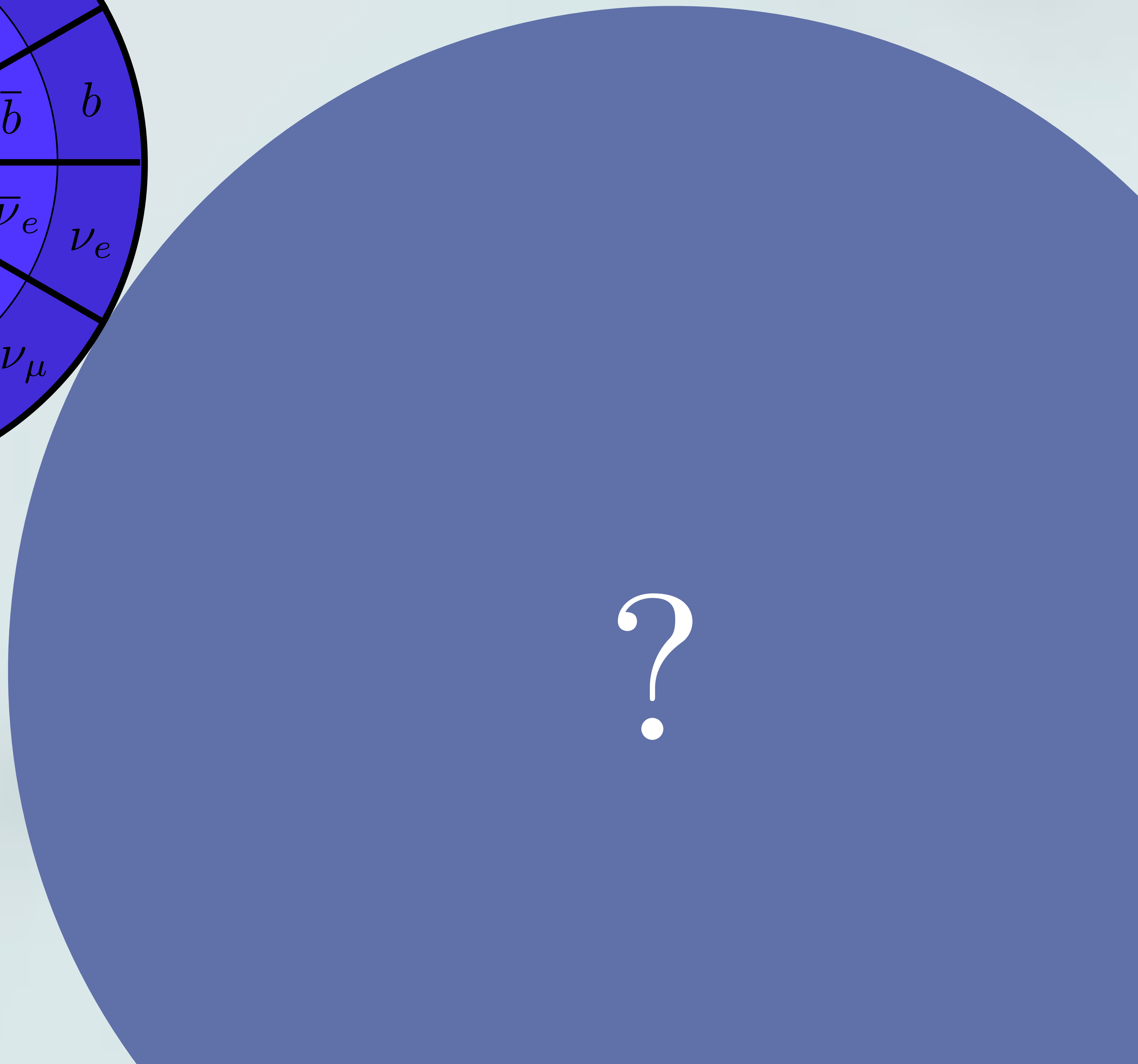

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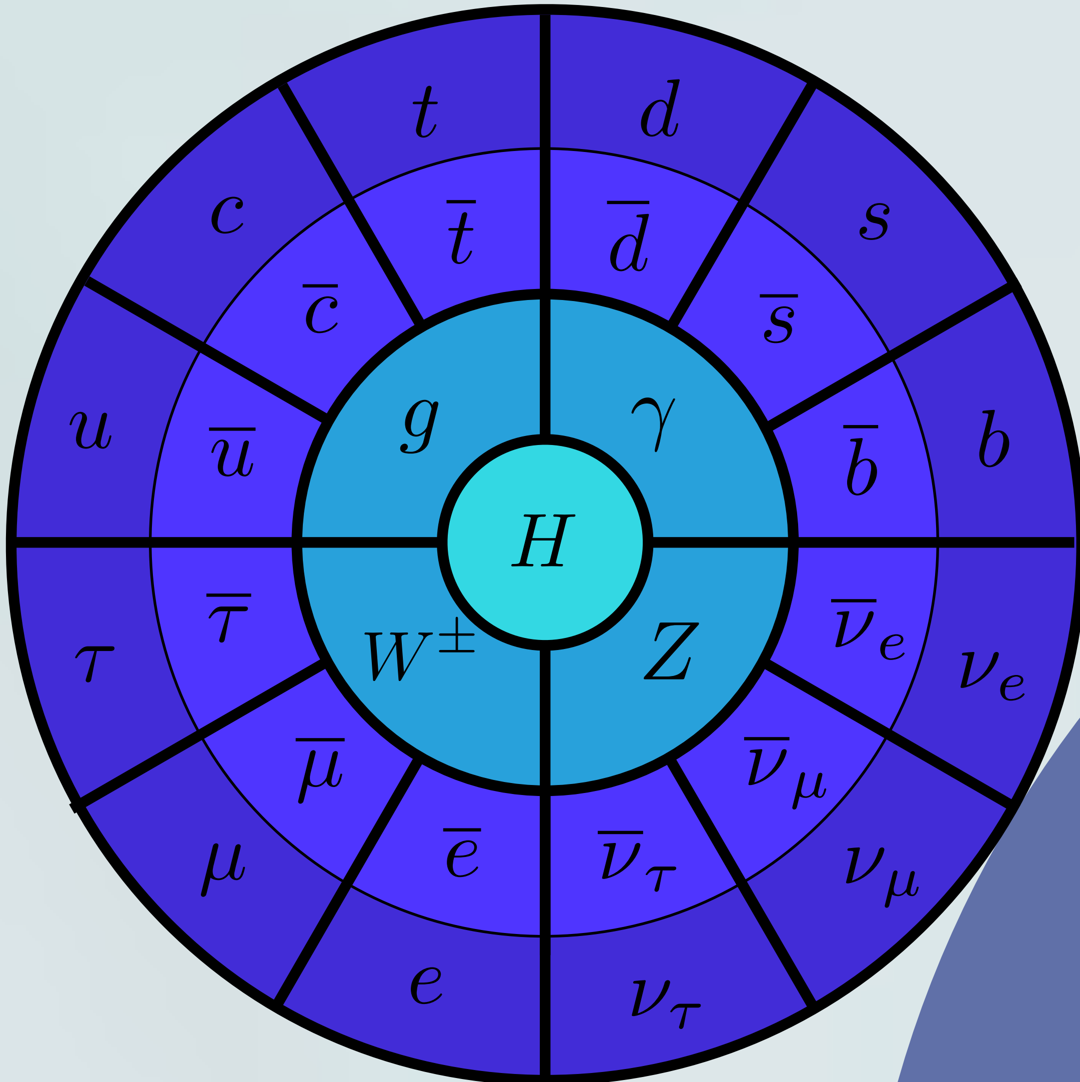

PARTICLE PHYSICS AND COSMOLOGY

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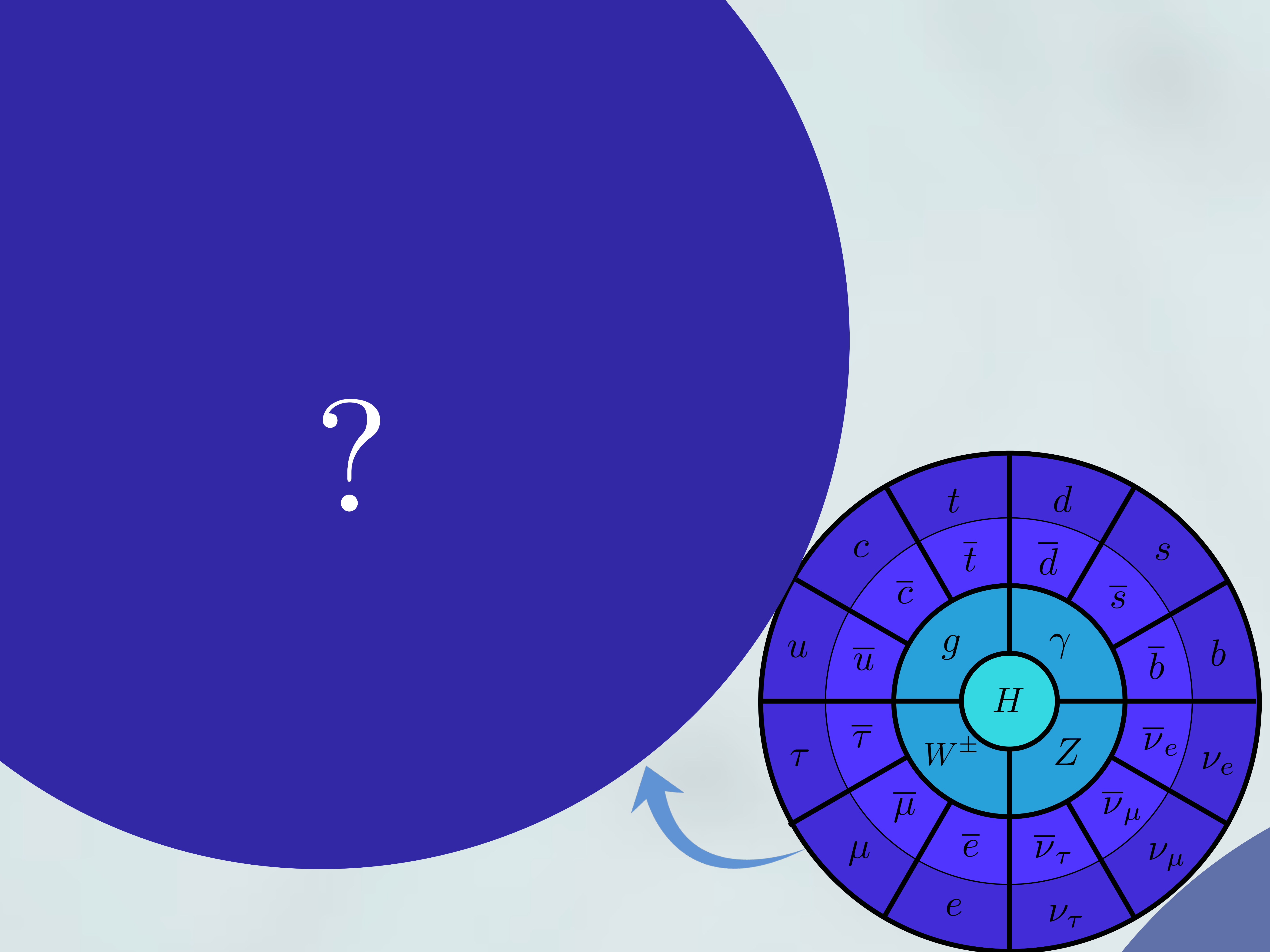
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NUCLEAR PHYSICS

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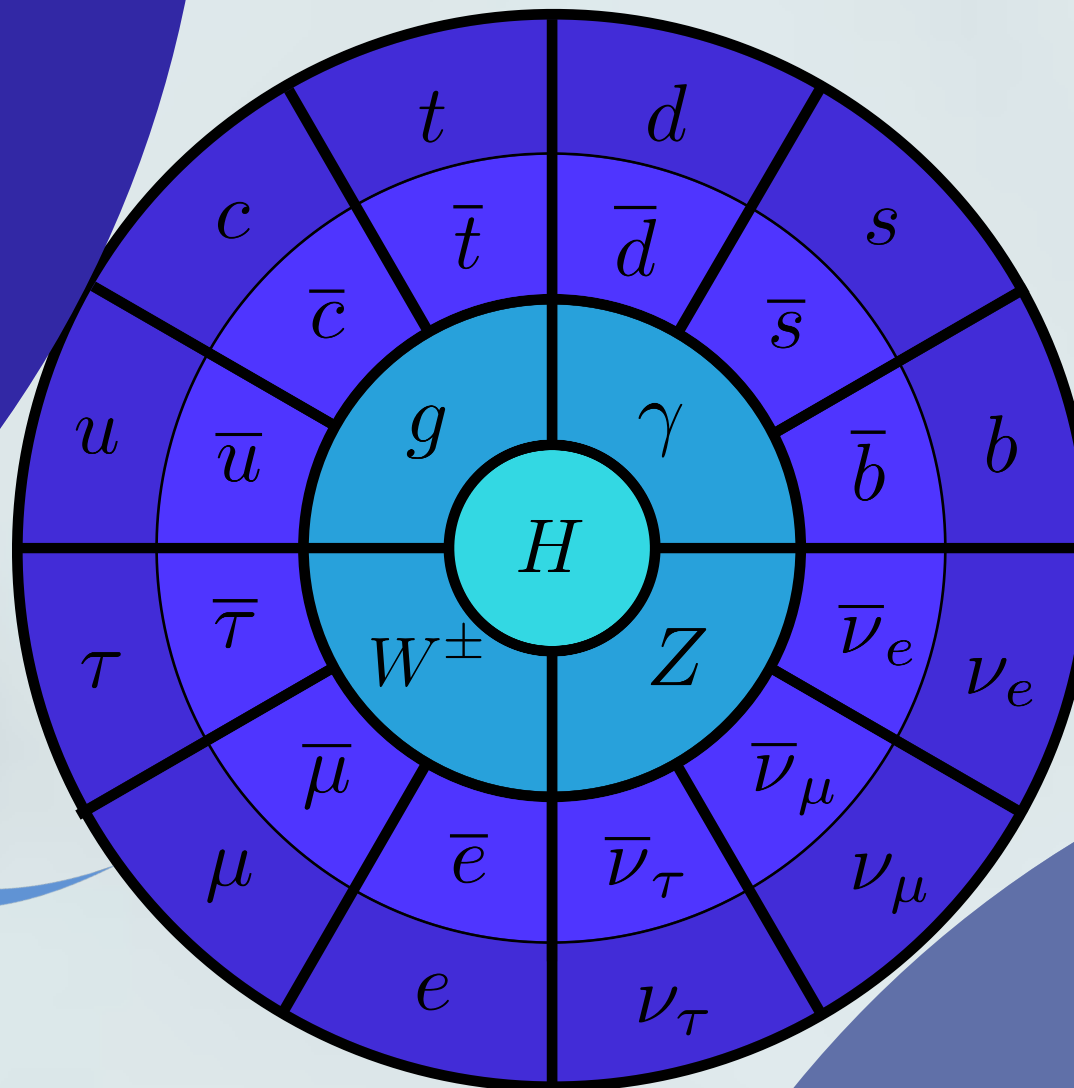
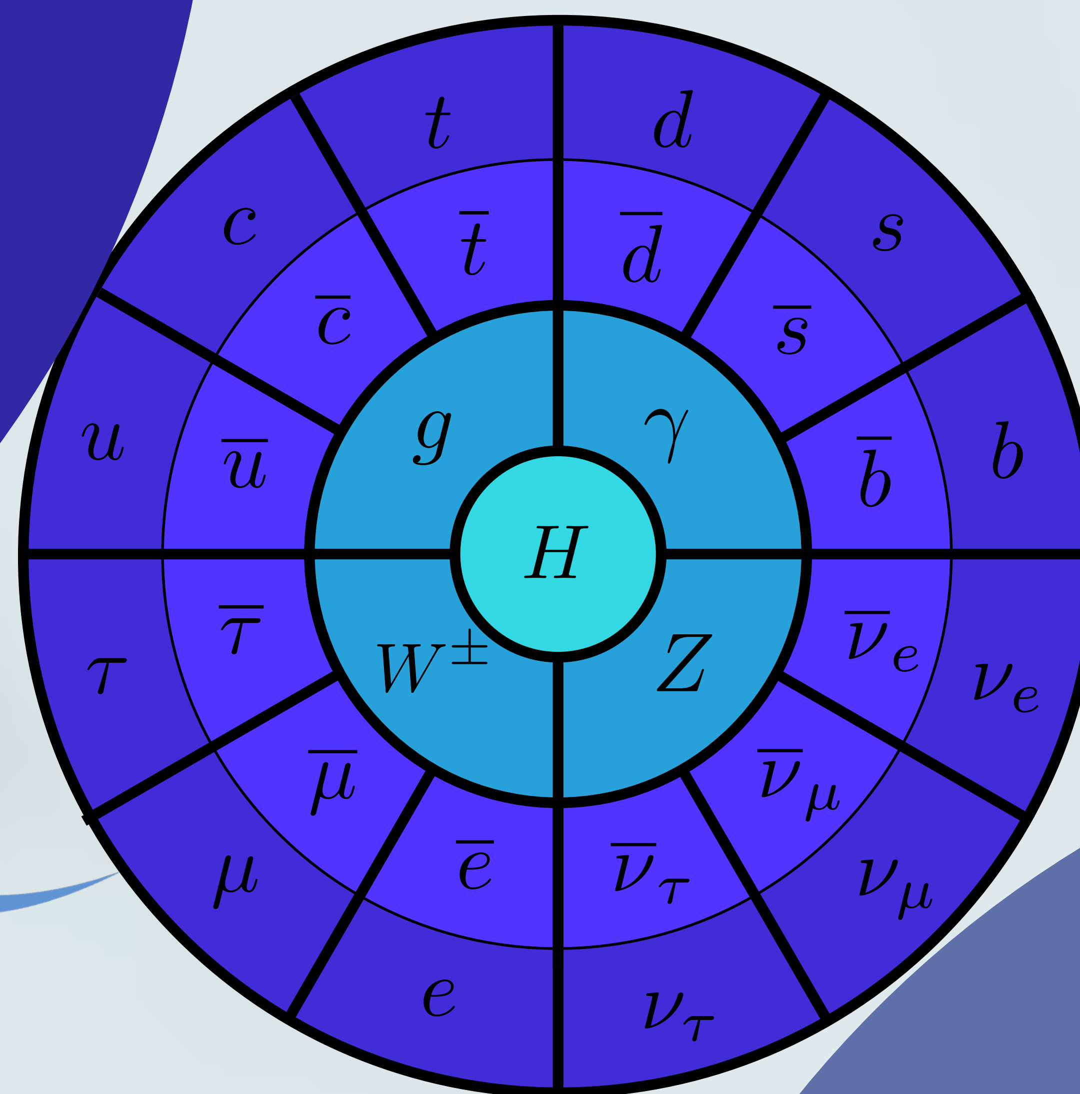
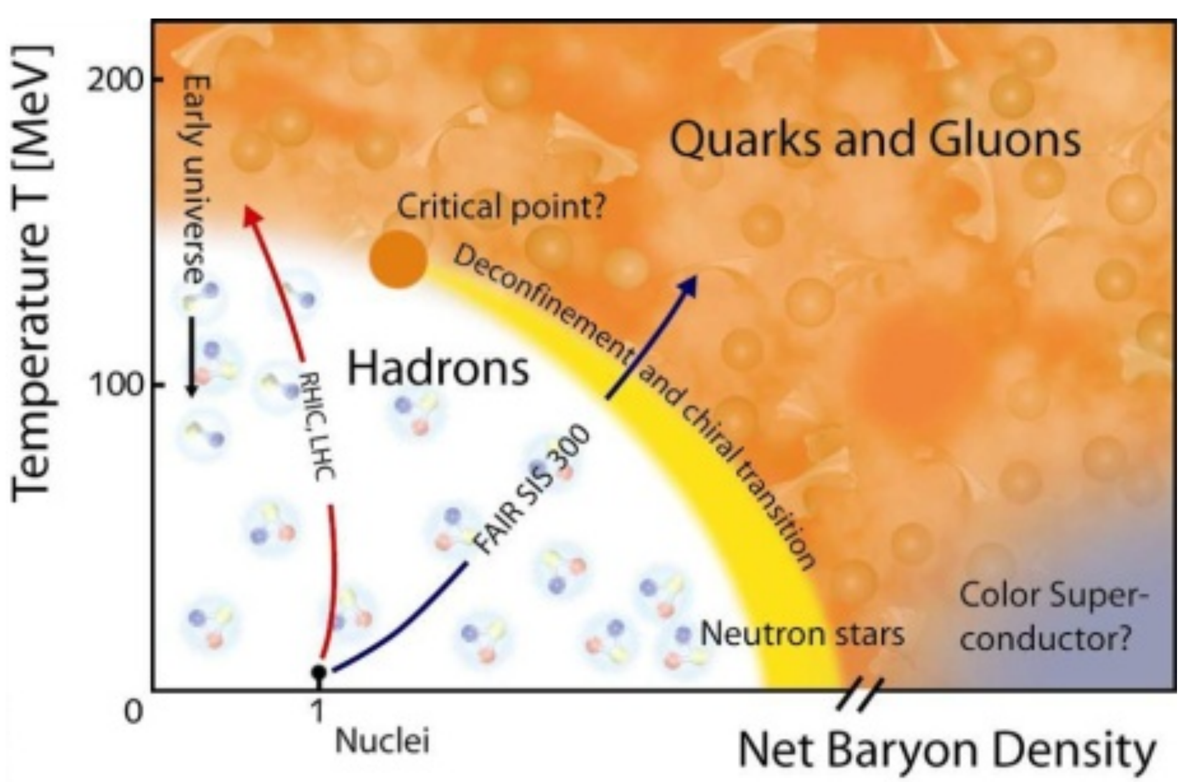


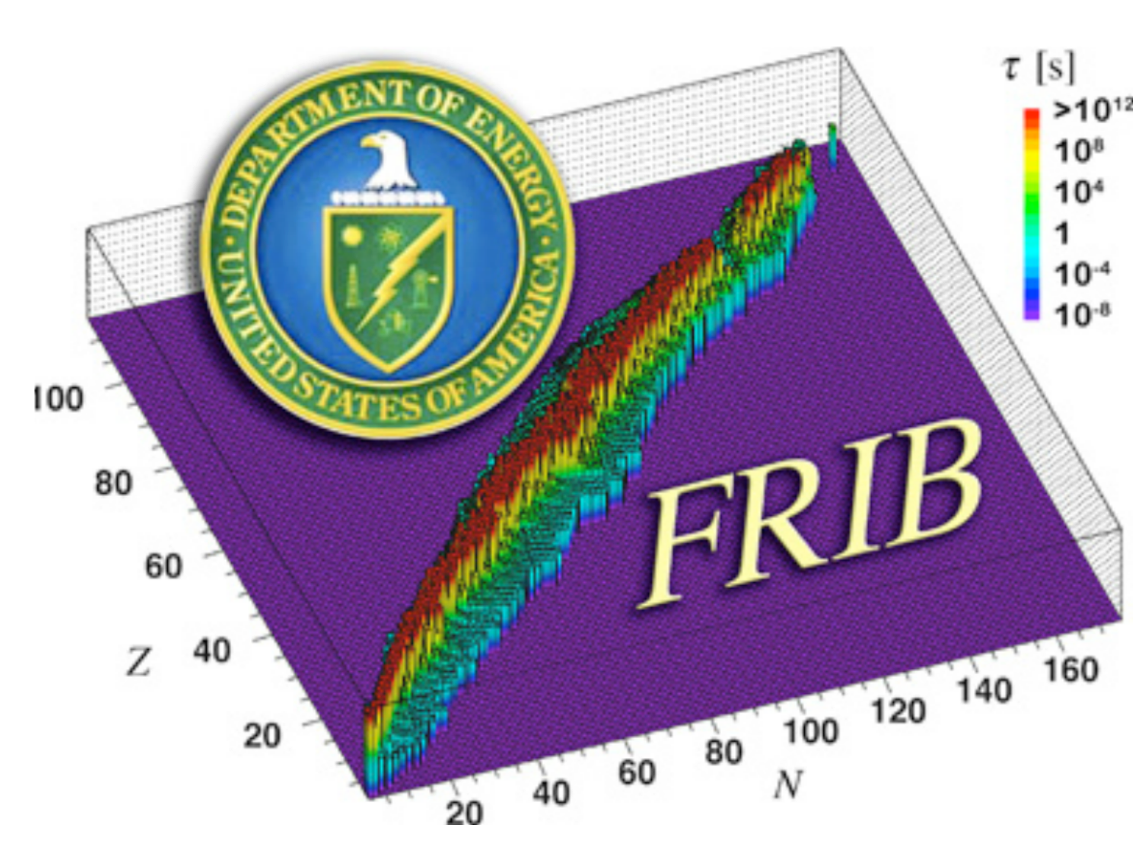
Q1) HOW DO COMPLEXITIES IN VISIBLE UNIVERSE EMERGE FROM STANDARD MODEL?



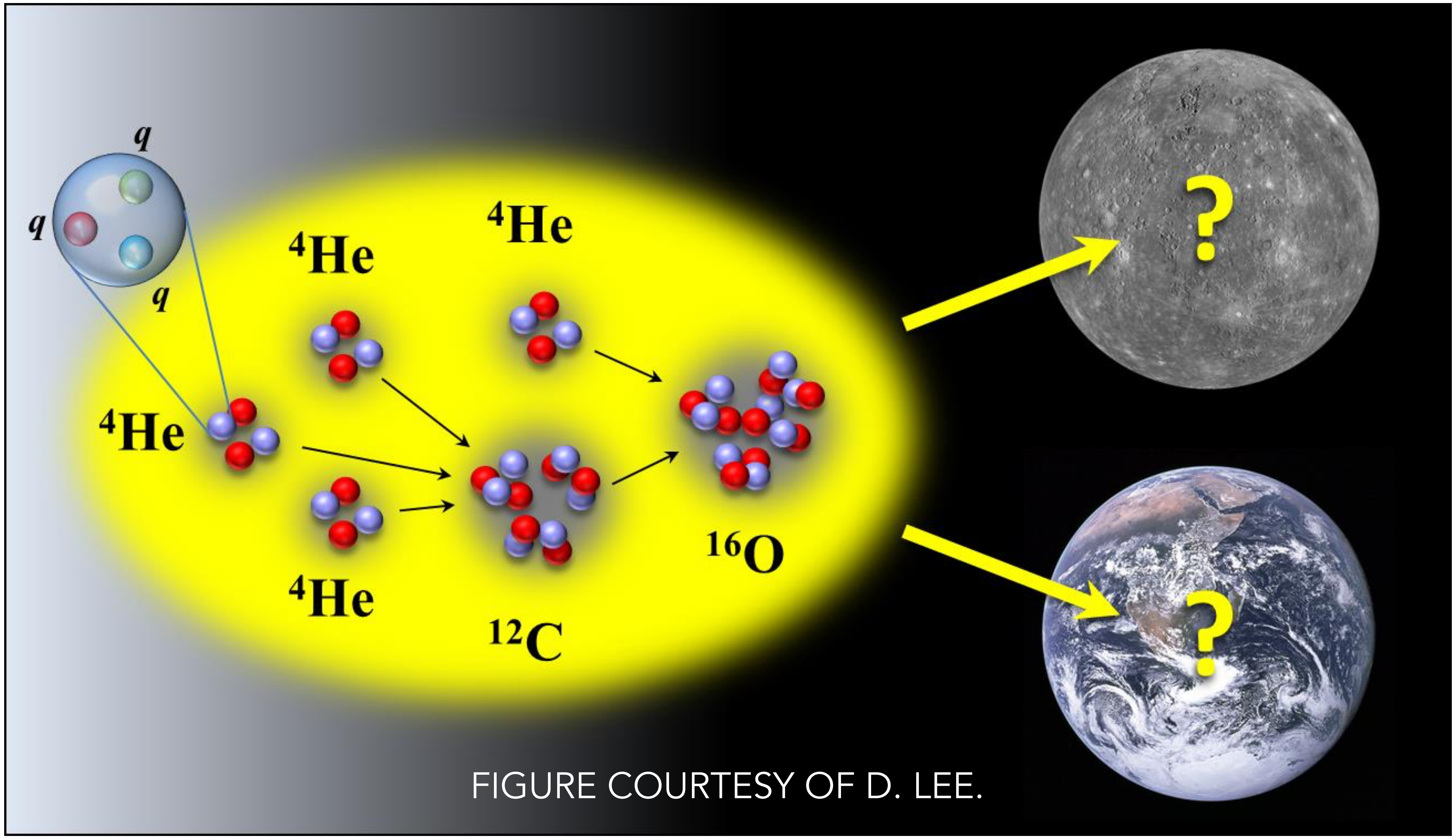
- What is the nature of dense matter in universe?
- What constitutes the interior of a neutron star?
- What are the phases of strongly interacting matter?
- Can rare exotic isotopes made in laboratories give some clues?
- Where do heavy elements on earth come from?



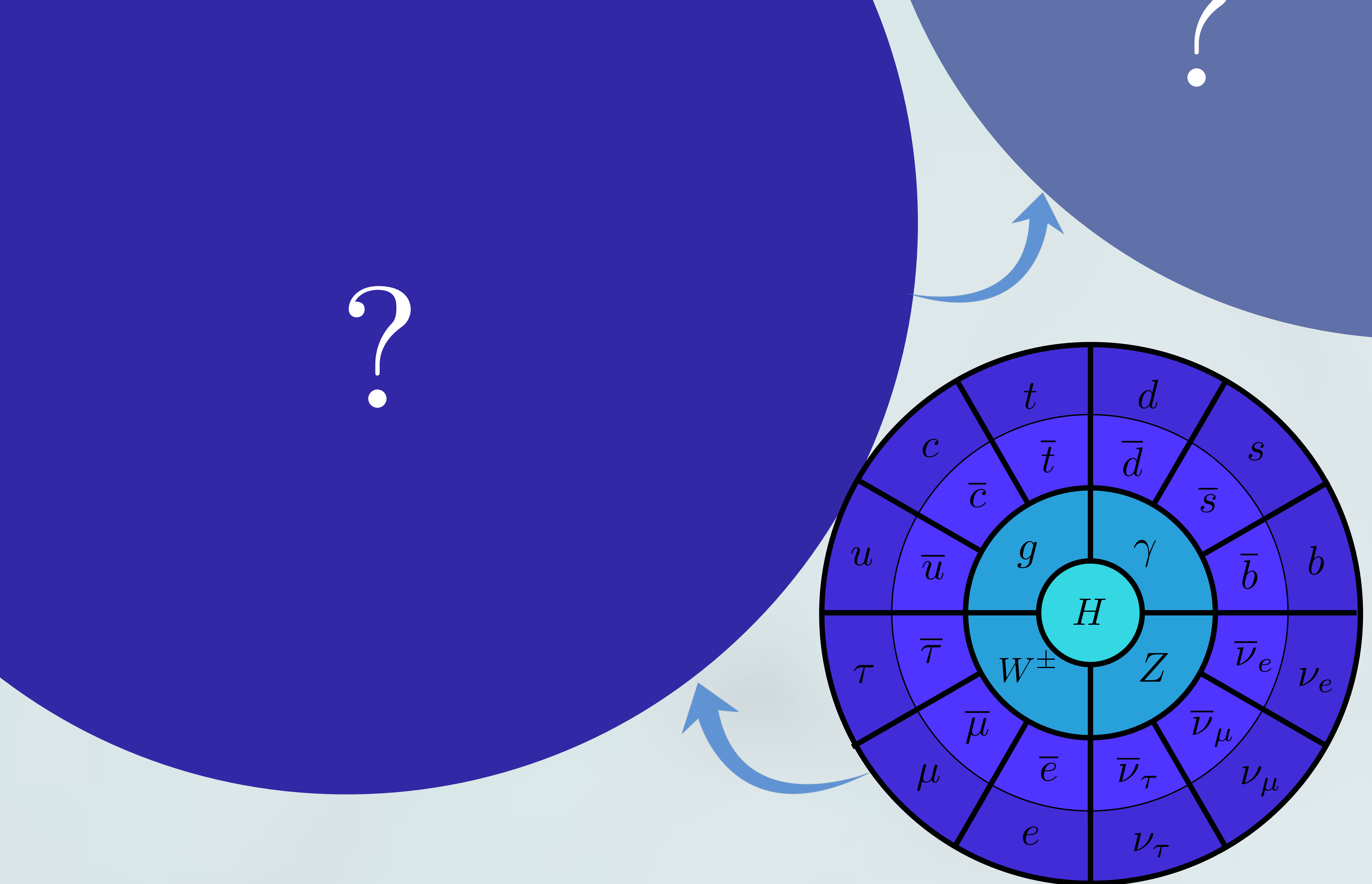
Source: The Facility for Antiproton and Ion Research (FAIR),GSI, Darmstadt, Germany.



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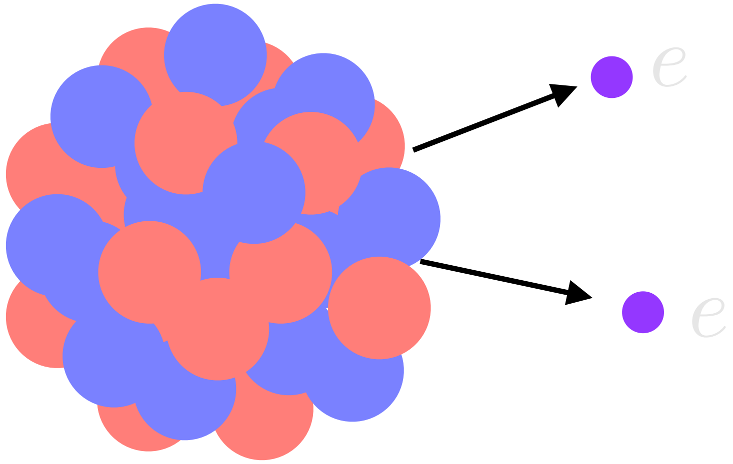
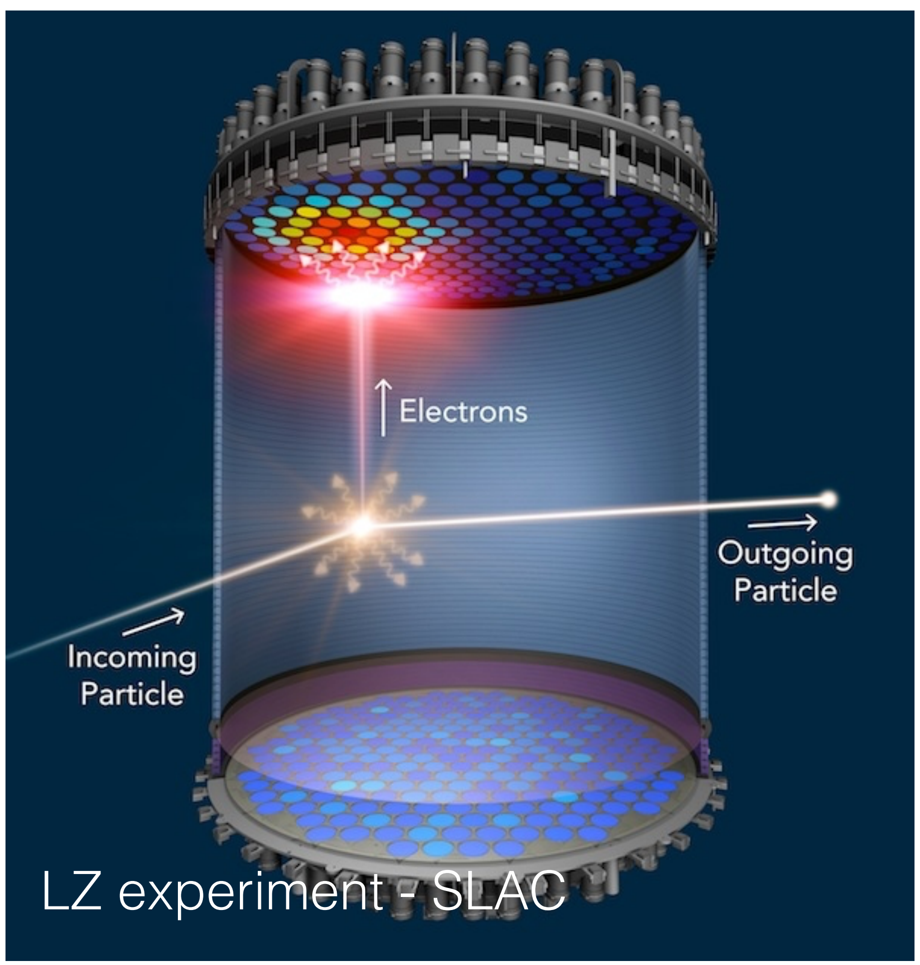
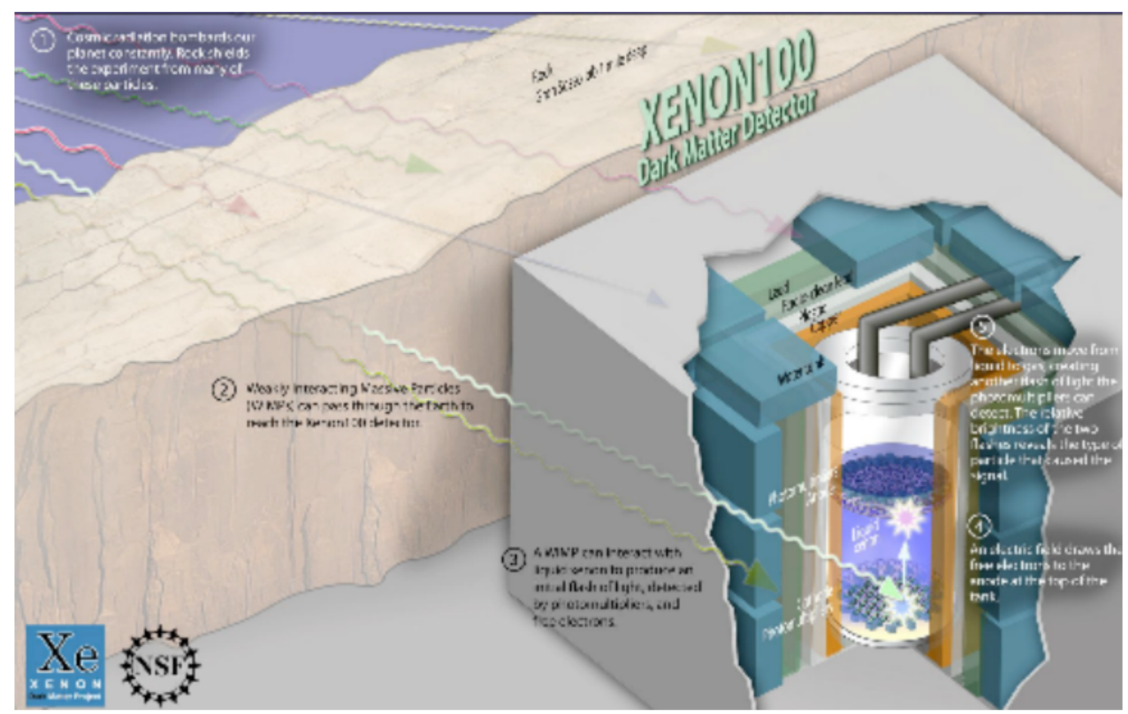
- Are new interactions in play in nature?
- Nuclei serve as a laboratory to make discovery in this area, but do we know well how they interact with external probes?

Example: Neutrinoless double-beta decay and lepton-number violation

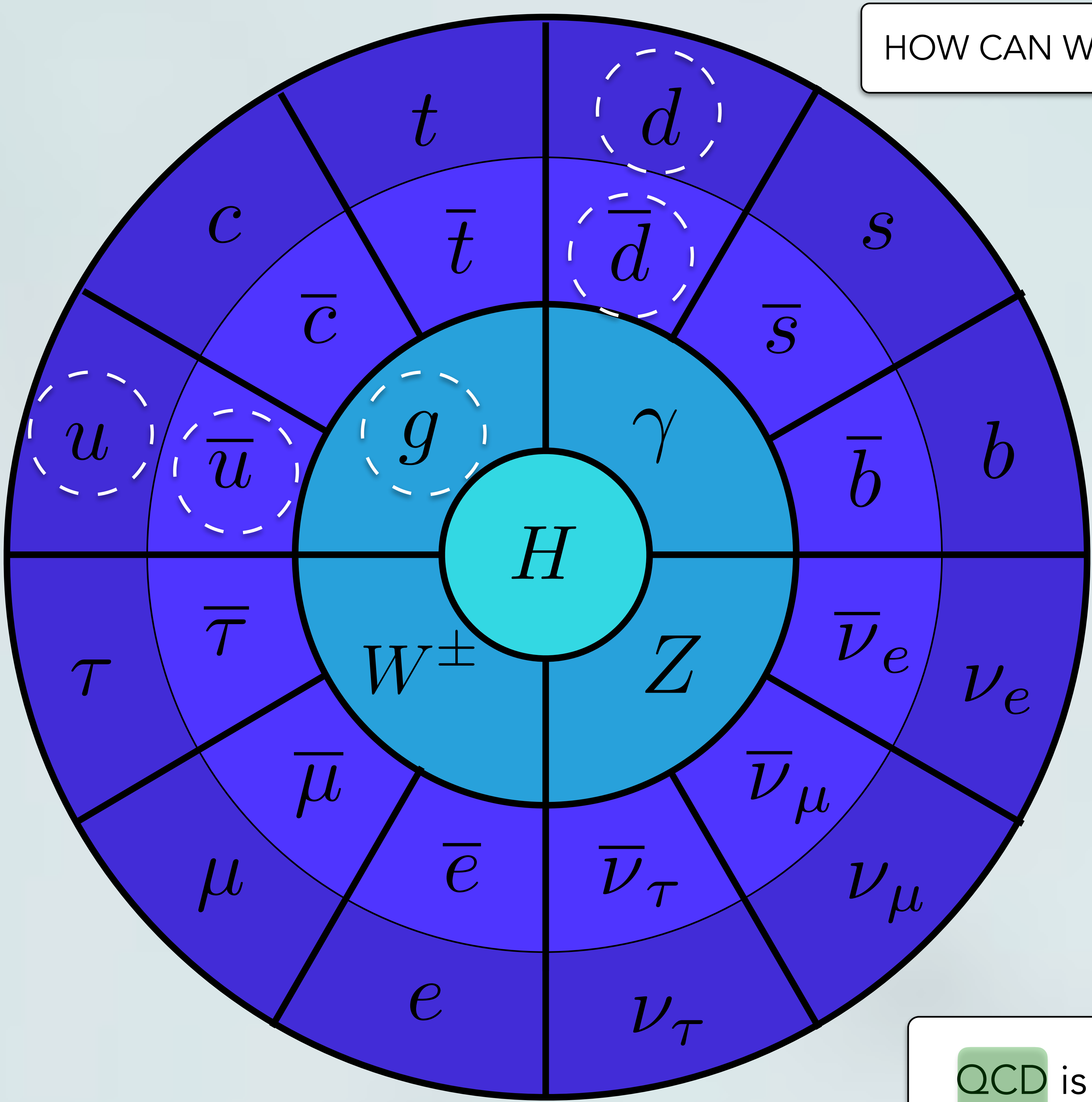


- Can dark matter candidates be discovered through their interactions with matter?
- How well can we predict potential dark matter-nucleus interactions?





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.

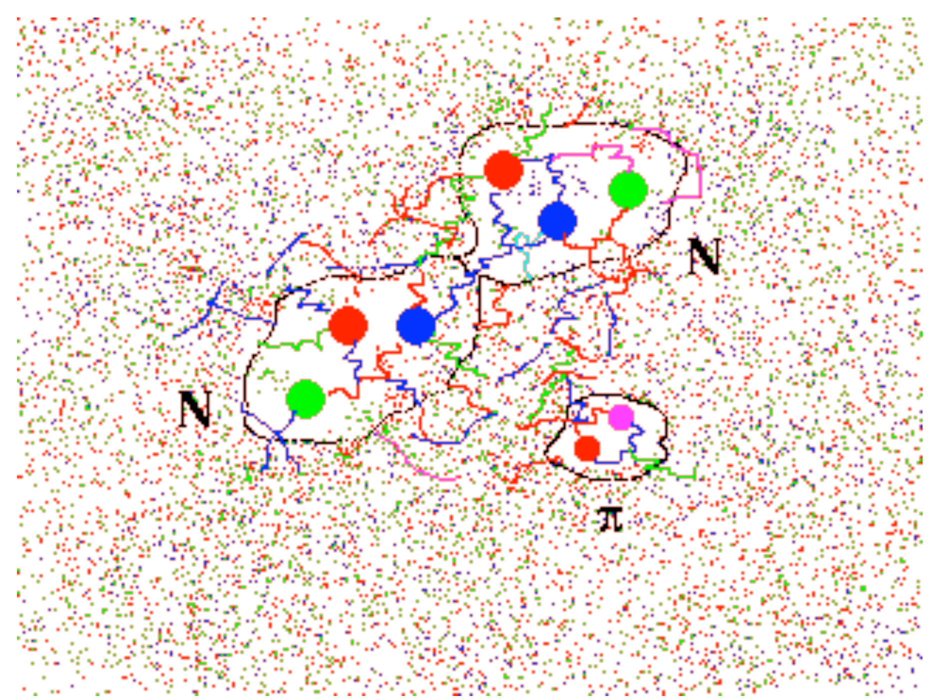
WHAT CAN WE DO AT LOW ENERGIES?

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

$$p, m << \Lambda$$

$$\mathcal{L}_{EFT}[\pi, N, ...; m_\pi, m_N, ..., C_i]$$

Low-energy constants



Write down effective interactions consistent with QCD: effective field theories

WHAT CAN WE DO AT LOW ENERGIES?

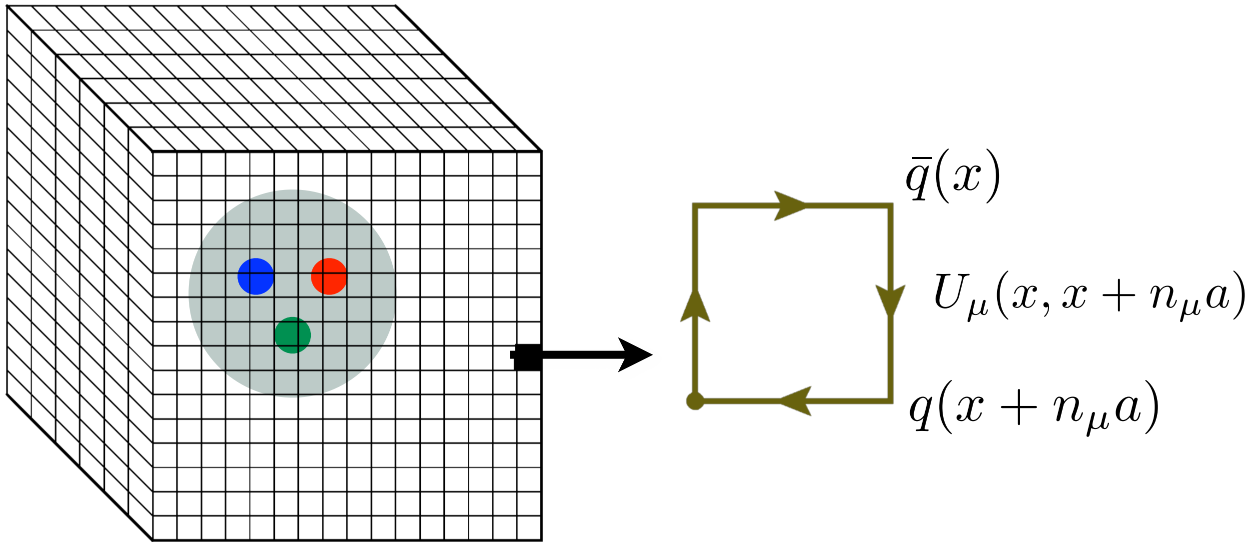
Solve it nonperturbatively: Lattice QCD

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

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

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

Extrapolate to infinite volume and zero lattice spacing



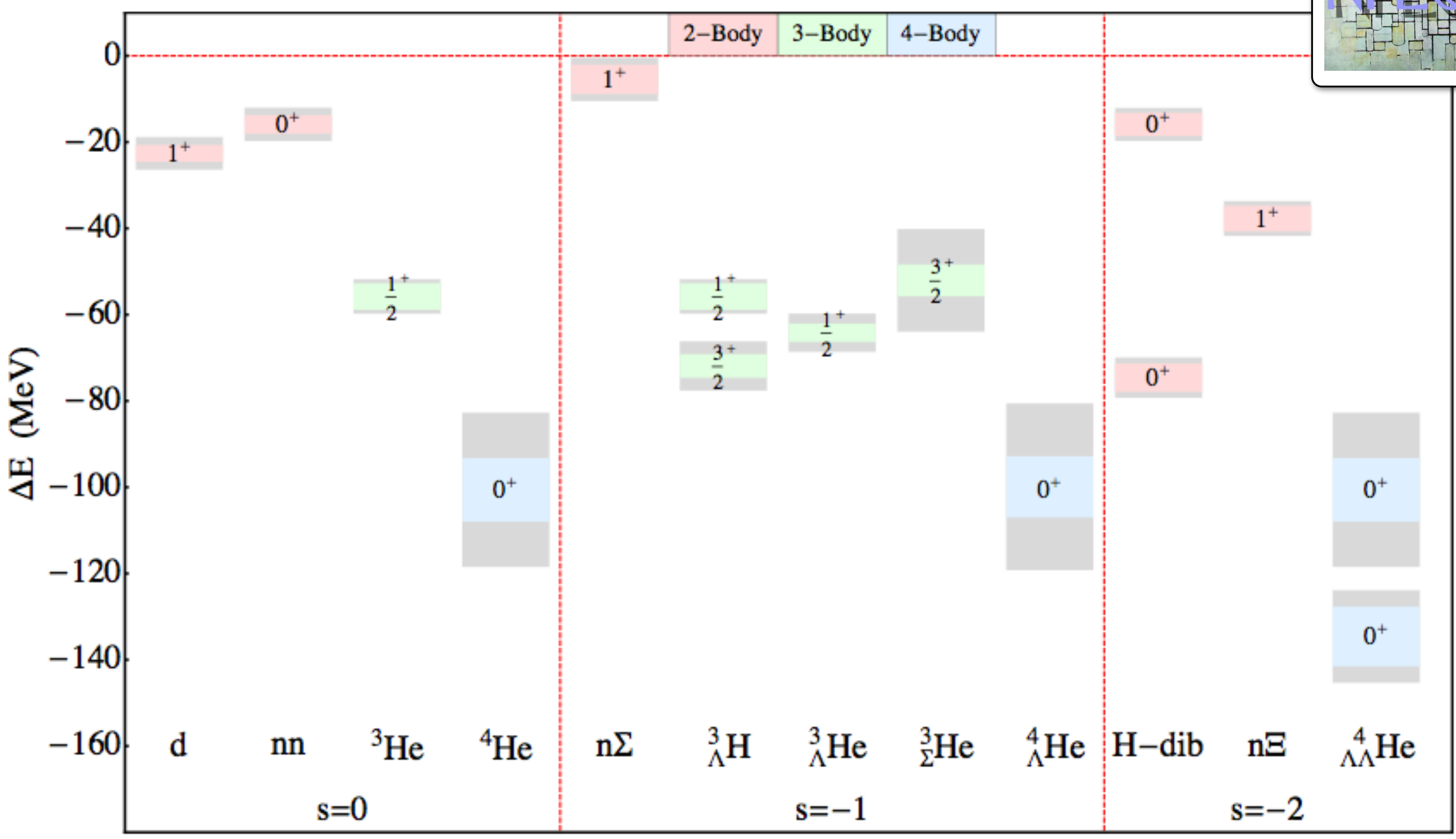
LATTICE QCD COMBINED WITH EFFECTIVE FIELD THEORIES IS ON TRACK TO DELIVER RESULTS ON IMPORTANT QUANTITIES IN NUCLEAR AND HIGH-ENERGY PHYSICS.

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

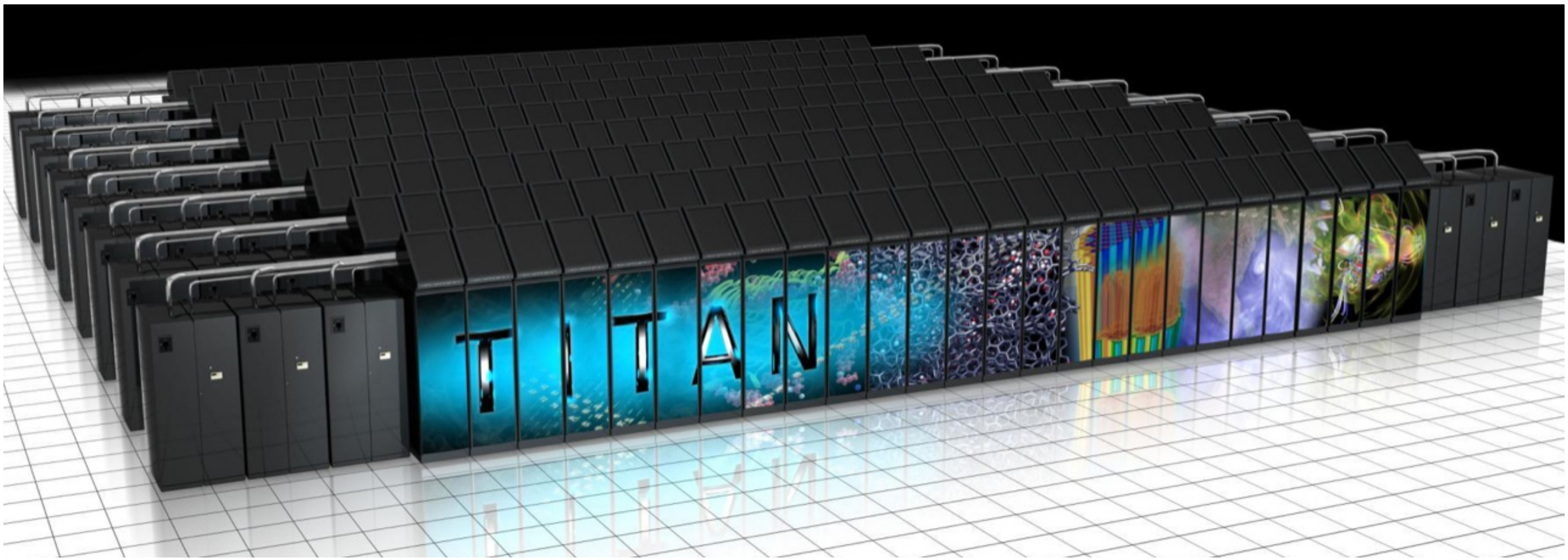
$N_f = 3,\ m_\pi = 0.806\ \text{GeV},\ a = 0.145(2)\ \text{fm}$



NPLQCD

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

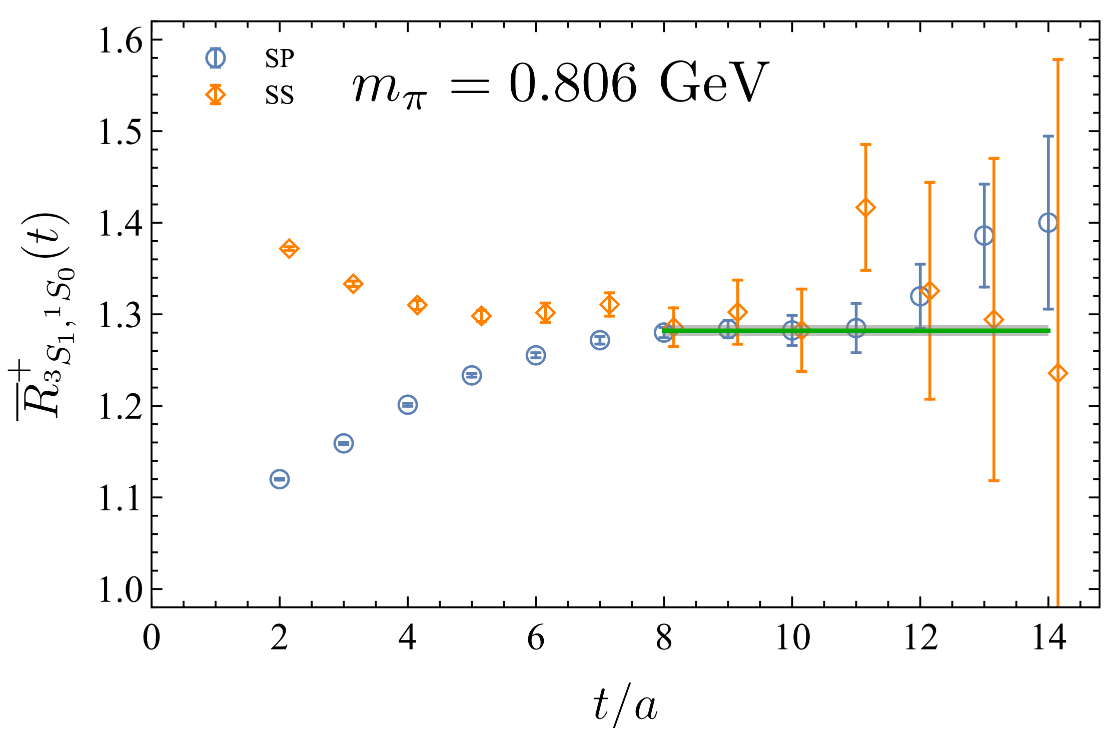
THIS STUDY TOOK ABOUT TWO YEARS AND A FEW HUNDRED MILLION CPU HOURS ON THE LARGEST SUPERCOMPUTERS IN THE U.S.!



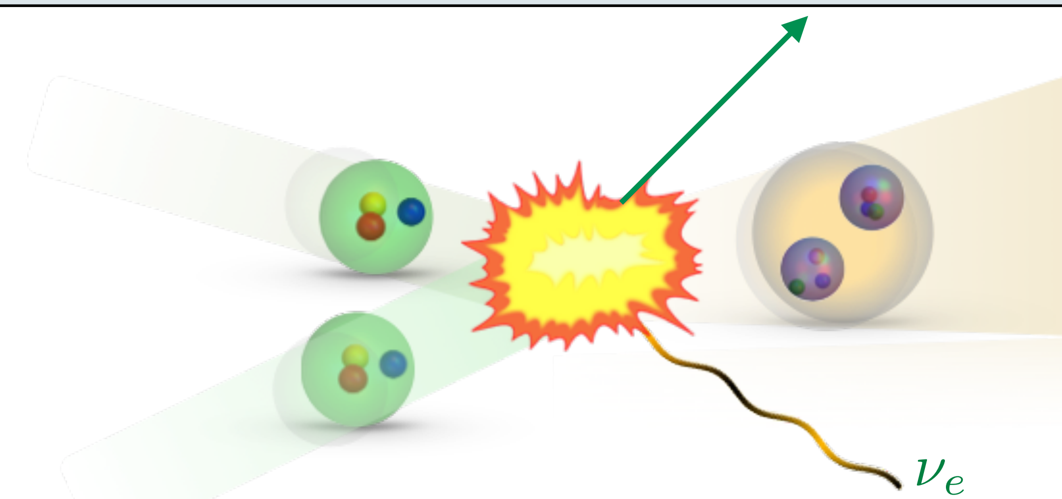
Titan supercomputer, Oak Ridge National Laboratory, USA

A SINGLE-WEAK PROCESS

$$pp \to de^+\nu_e$$



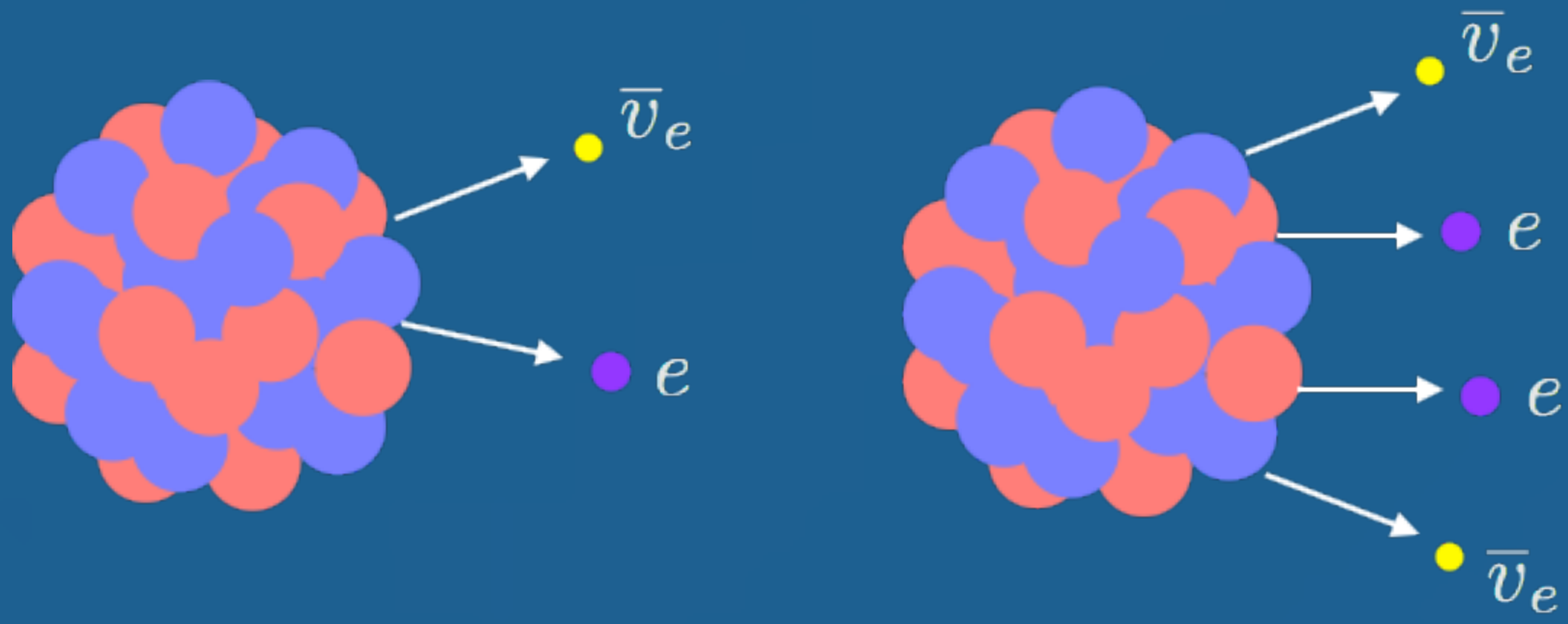
Savage, ZD et al, Phys.Rev.Lett.119,062002(2017).

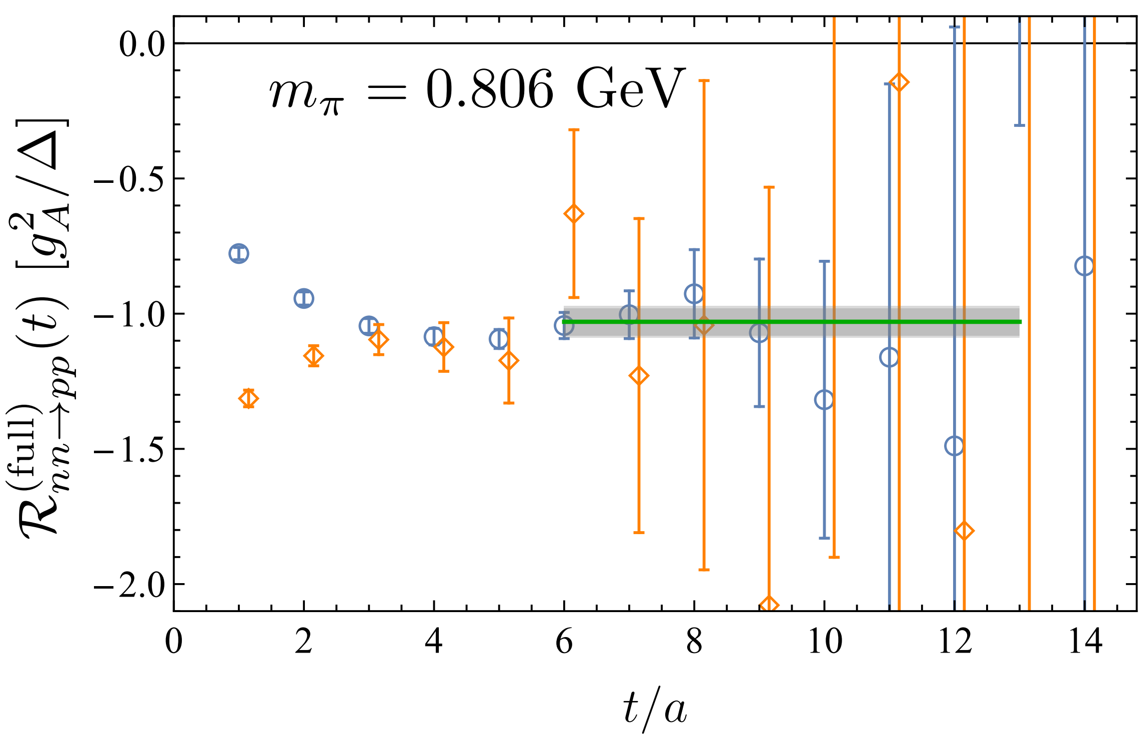


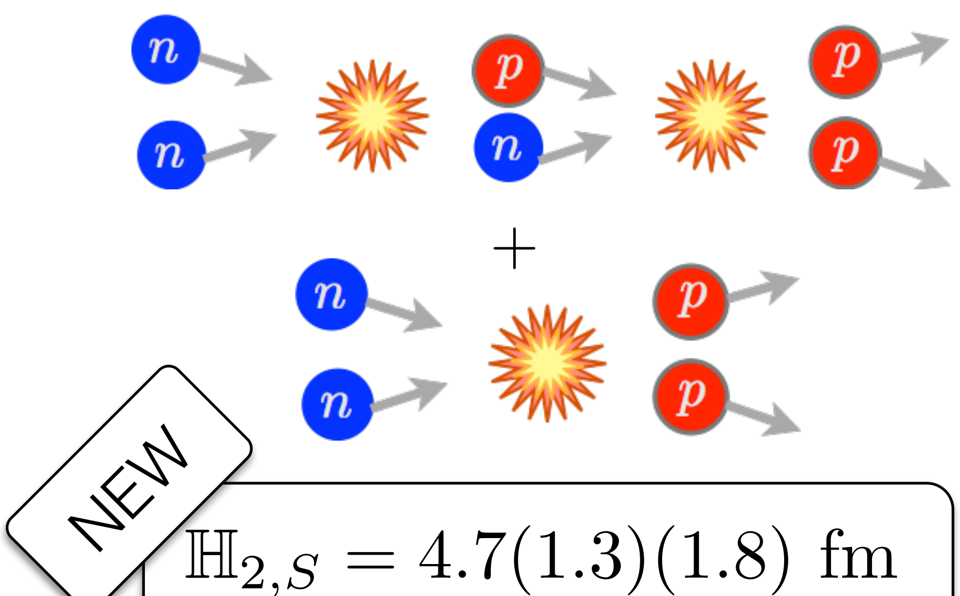
$L_{1,A} = 3.9(0.1)(1.0)(0.3)(0.9)\ \mathrm{fm}^3 \quad @\mu = m_\pi^{\mathrm{phys.}} = 140\ \mathrm{MeV}$

A DOUBLE-WEAK PROCESS

$$nn \to ppee\bar{\nu}_e\bar{\nu}_e$$







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

$@\ m_\pi = 806$ MeV

Tiburzi, ZD, et al (NPLQCD), Phys.Rev.D96,054505 (2017), Shanahan, ZD, et al (NPLQCD), Phys. Rev. Lett. 119,062003 (2017).

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

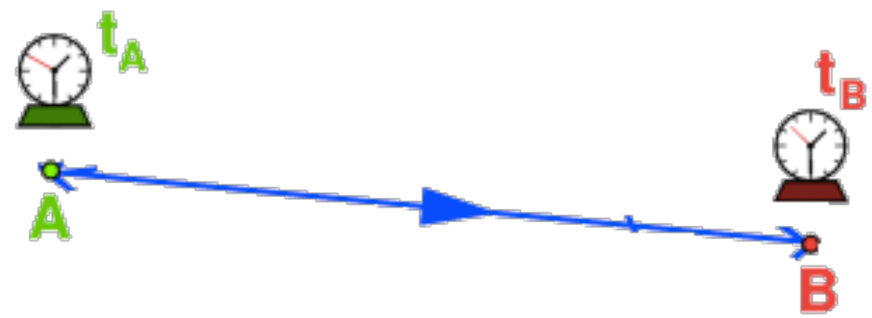
Slide content courtesy of Martin Savage.

LET US SEE WHAT IS INVOLVED IN (CLASSICAL) SIMULATIONS OF QUANTUM FIELD THEORY OF THE STRONG FORCE, i.e., LATTICE QCD.

STRIKING FEATURE OF QUANTUM MECHANICS:

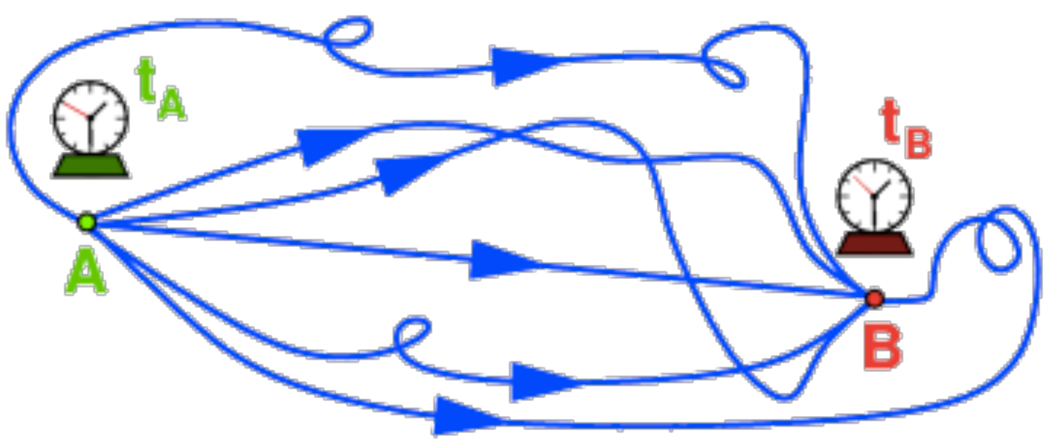
Given all the interactions of the system, what is the probability for transition from A to B?

Classical:



The principle of least action

Quantum mechanical:

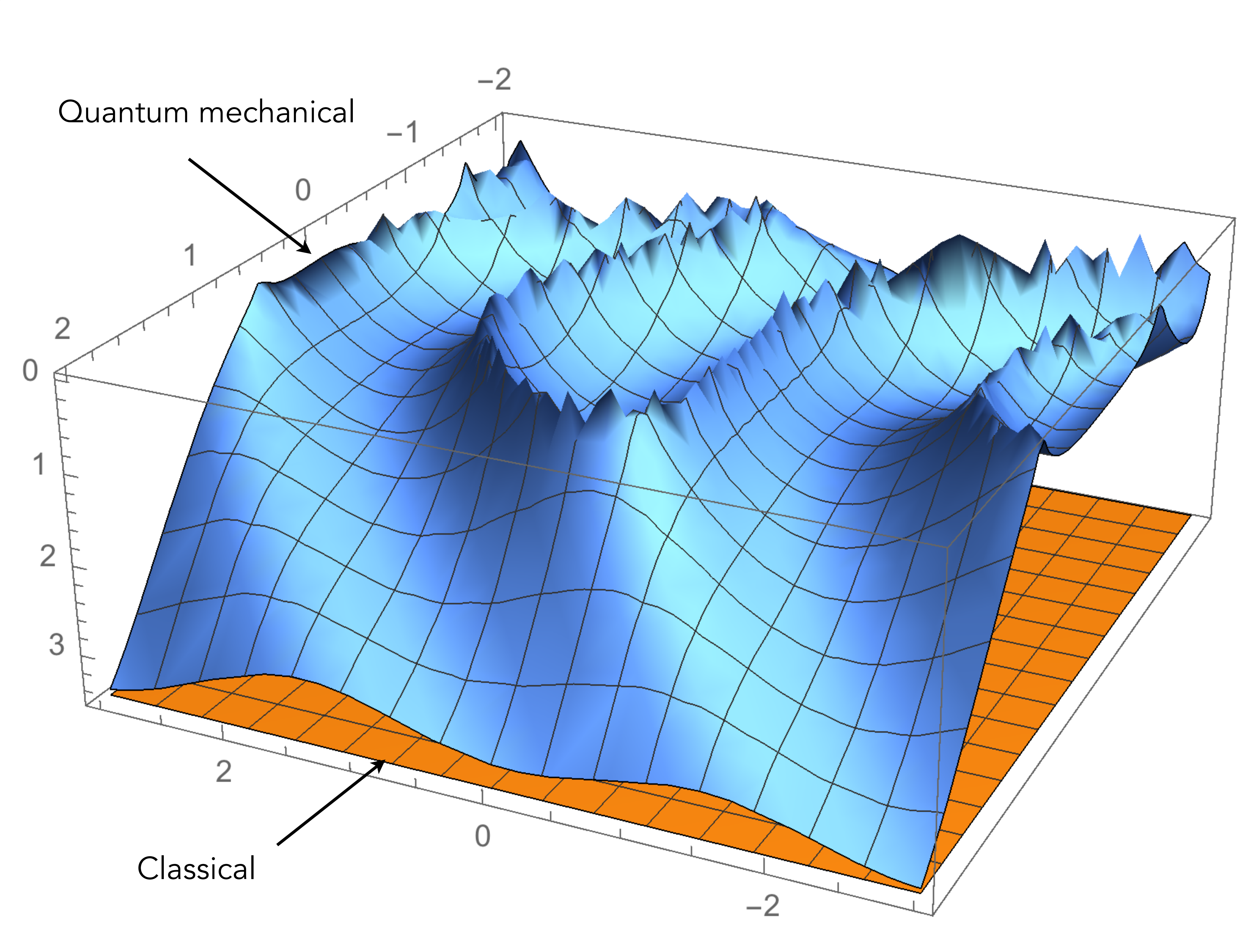


Every trajectory is explored!

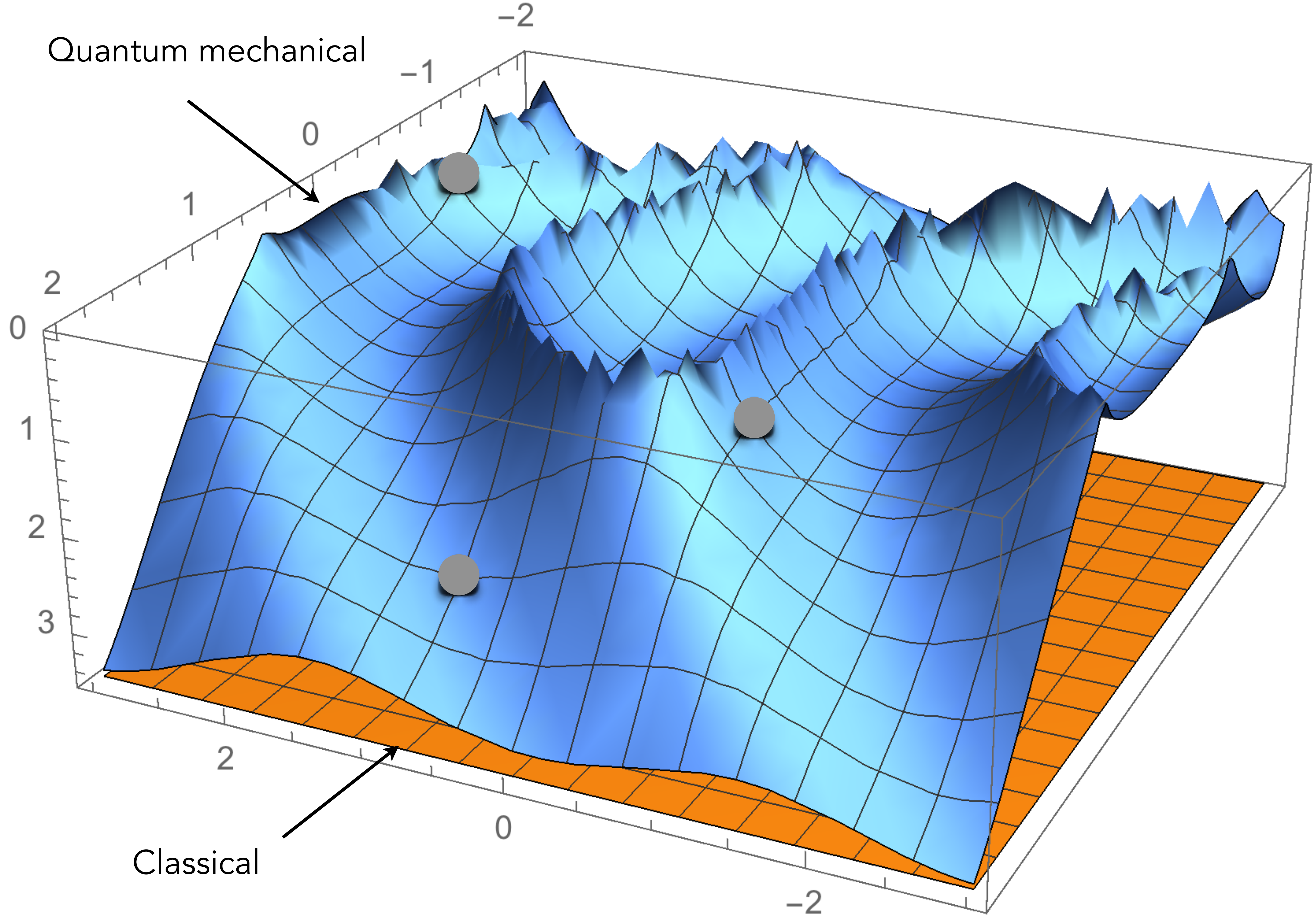
Quantum probability amplitude:

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

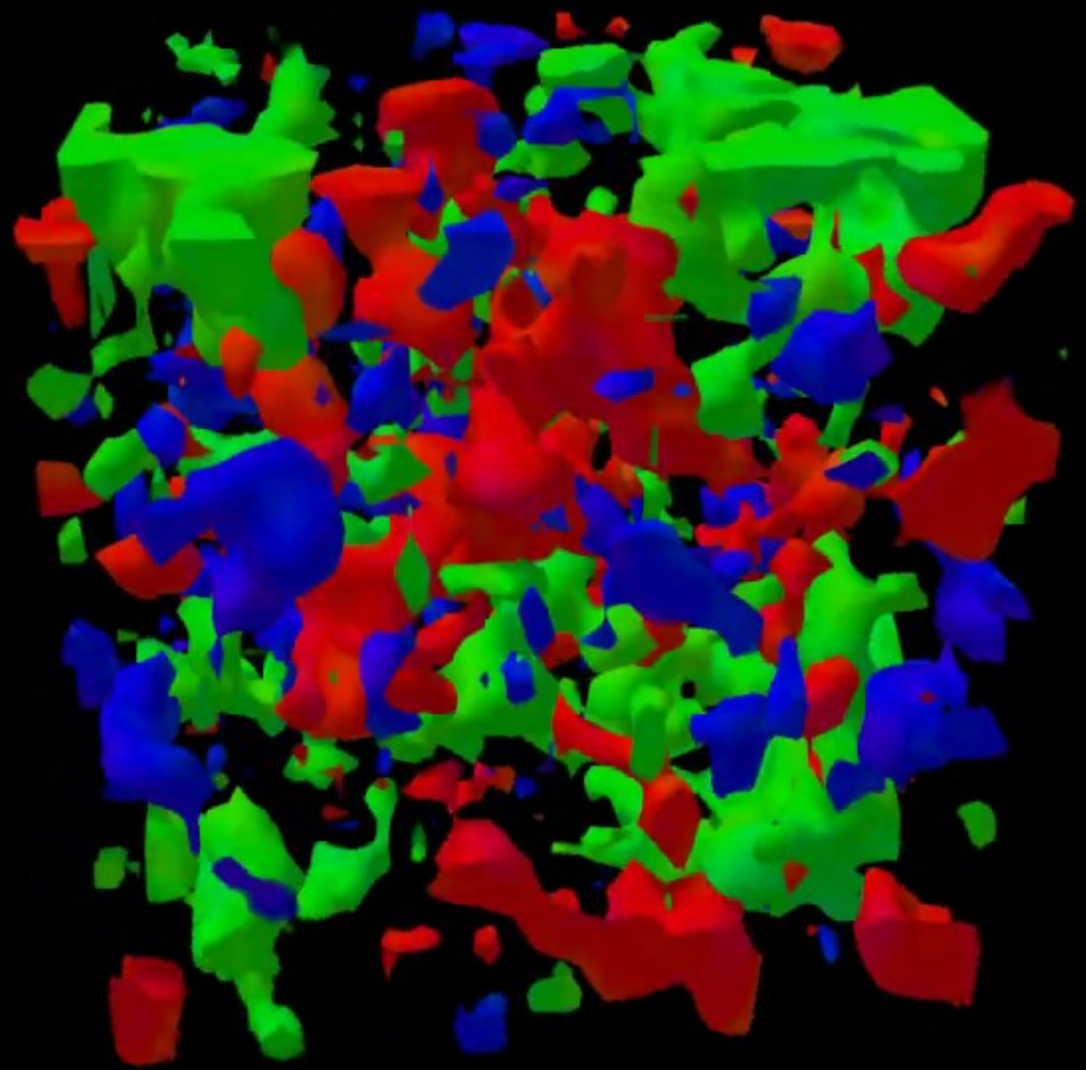
PROBABLITY AMPLITUDE FOR A=VACUUM TO B=VACUUM!



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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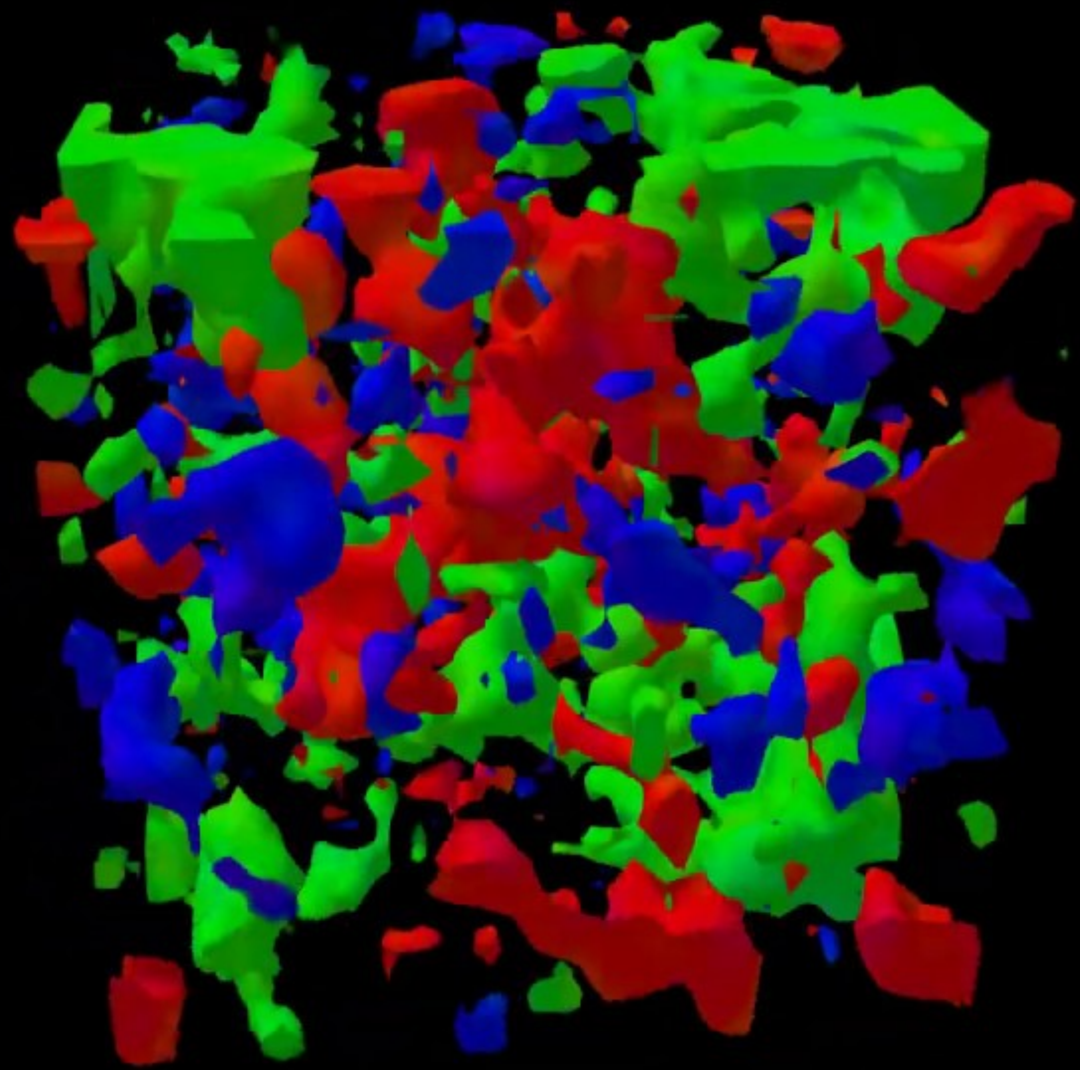


BY CSSM VISUALISATION

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

$$\Downarrow$$

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

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

COMPUTATIONAL COST?

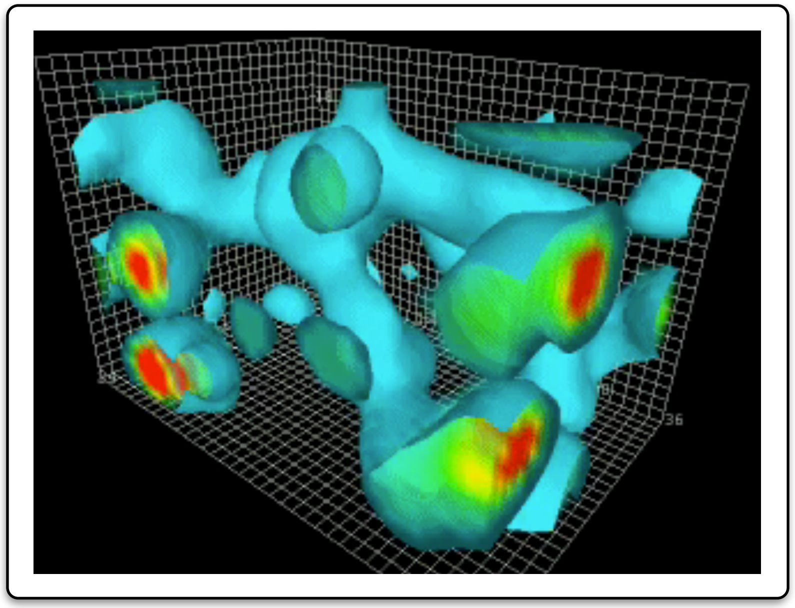
Example: Consider a lattice with: $L/a = 48, \; T/a = 256$

Sampling SU(3) matrices. Only a single sample requires storing

$$8 \times 48^3 \times 256 = 226,492,416$$

c-numbers in the computer!

Requires tens of thousands of uncorrelated samples. molecular-inspired HMC sampling used.



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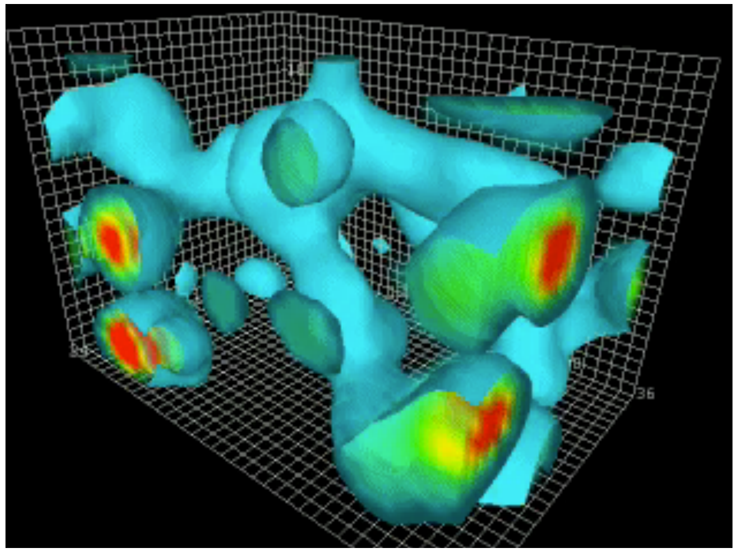


Solving

$$[D(U)]_{X,Y}[S(U)]_{Y,X_0} = G_{X,X_0}$$

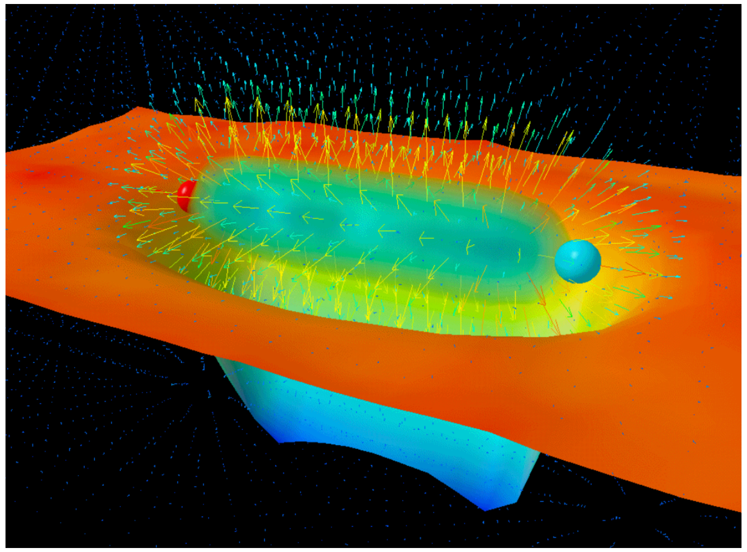
Dirac matrix

Quark propagator

Source

Requires inverting a matrix with dimensions:

$$(4 \times 3 \times 48^3 \times 256)^2 = 339,738,624 \times 339,738,624$$



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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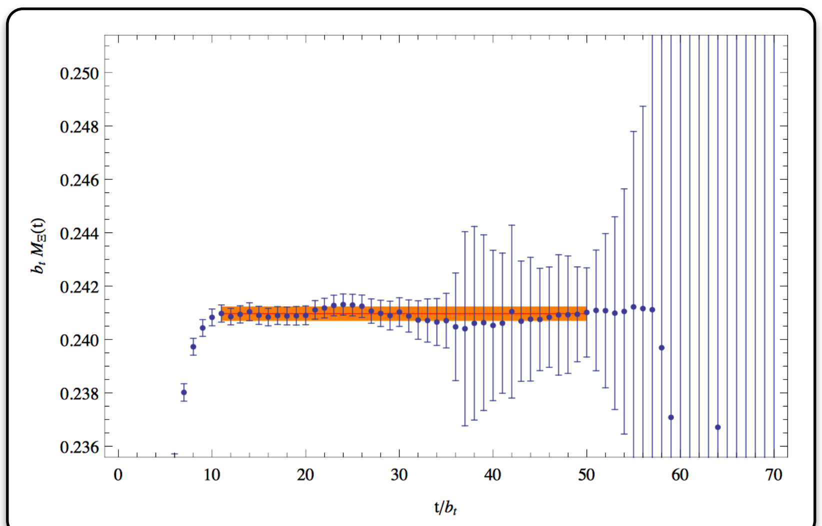

ii) There is a severe signal-to-noise degradation.

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Paris (1984) and Lepage (1989)
Wagman and Savage (2017, 2018)
```

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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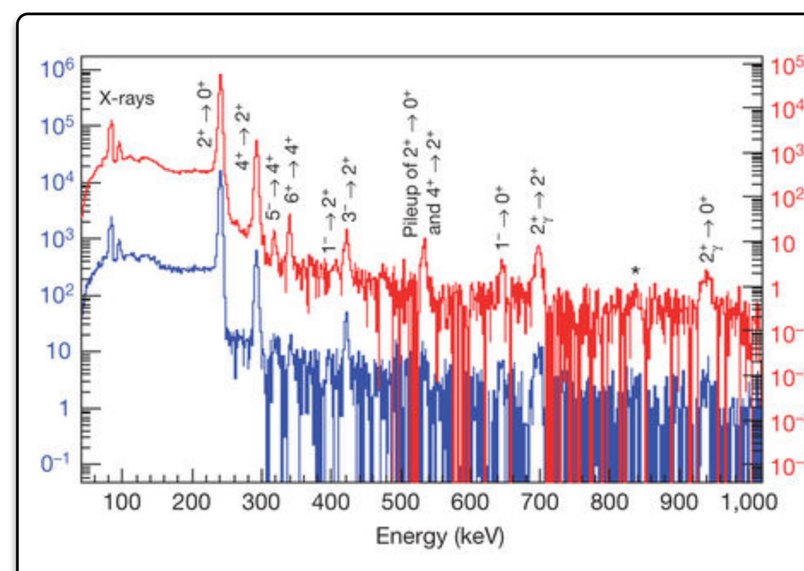
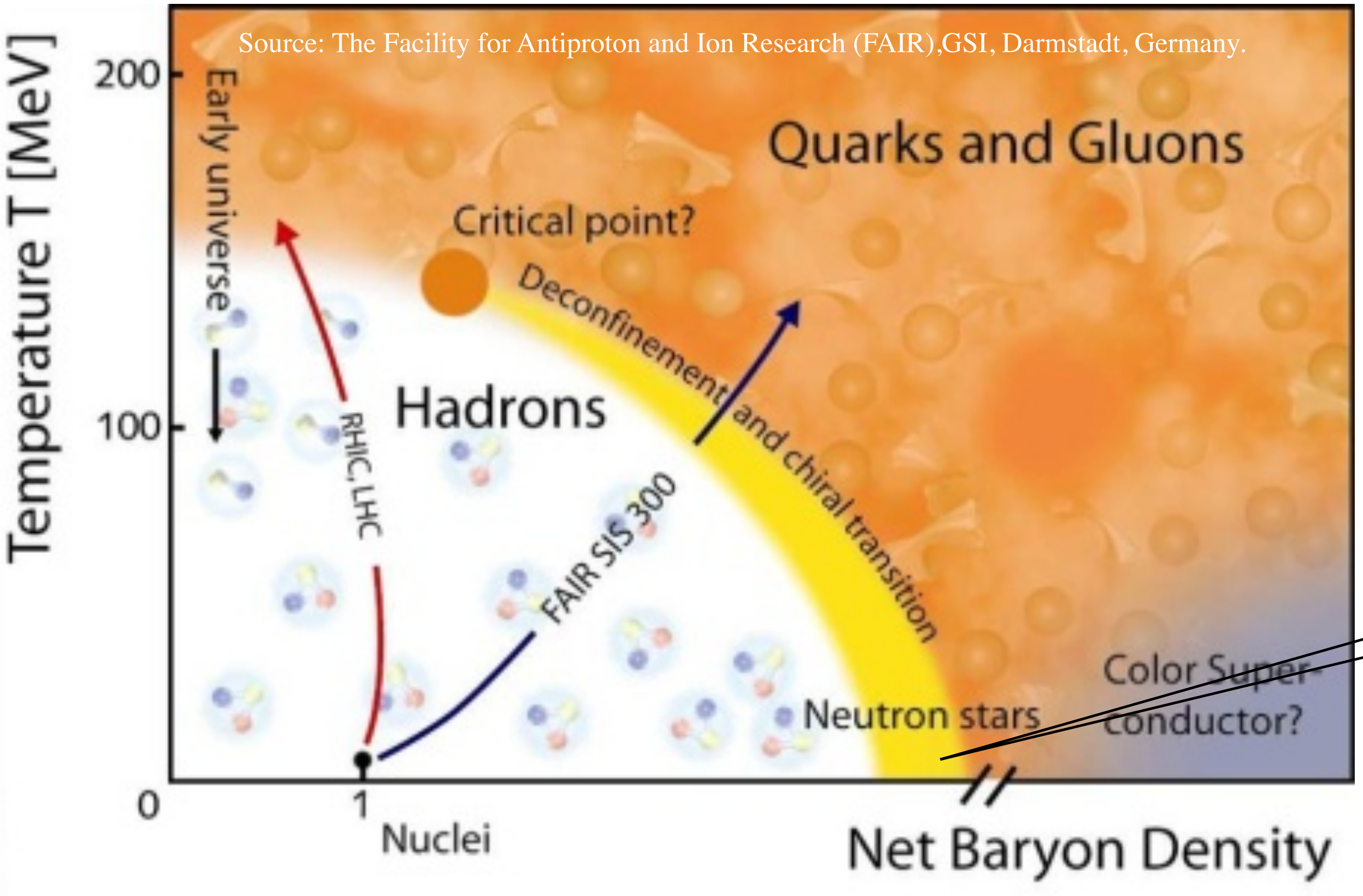
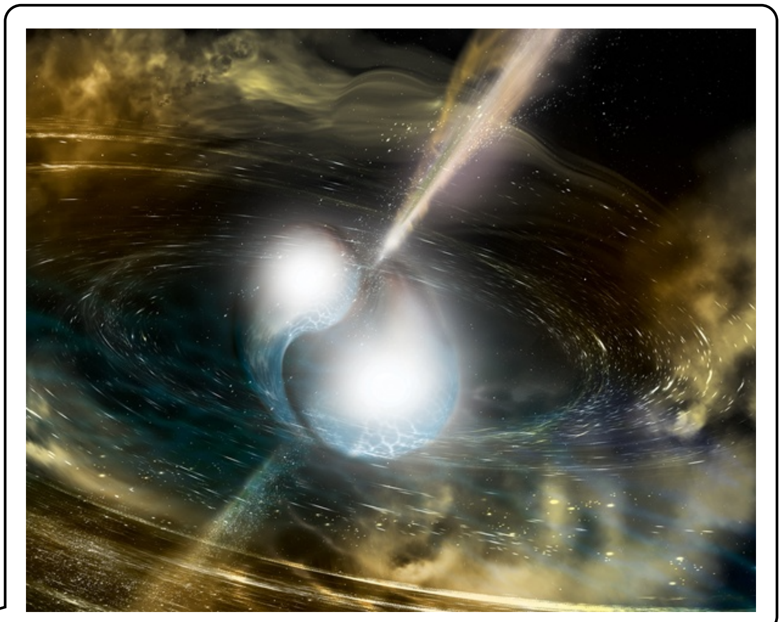


ADDITIONALLY THE SIGN PROBLEM FORBIDS:

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:

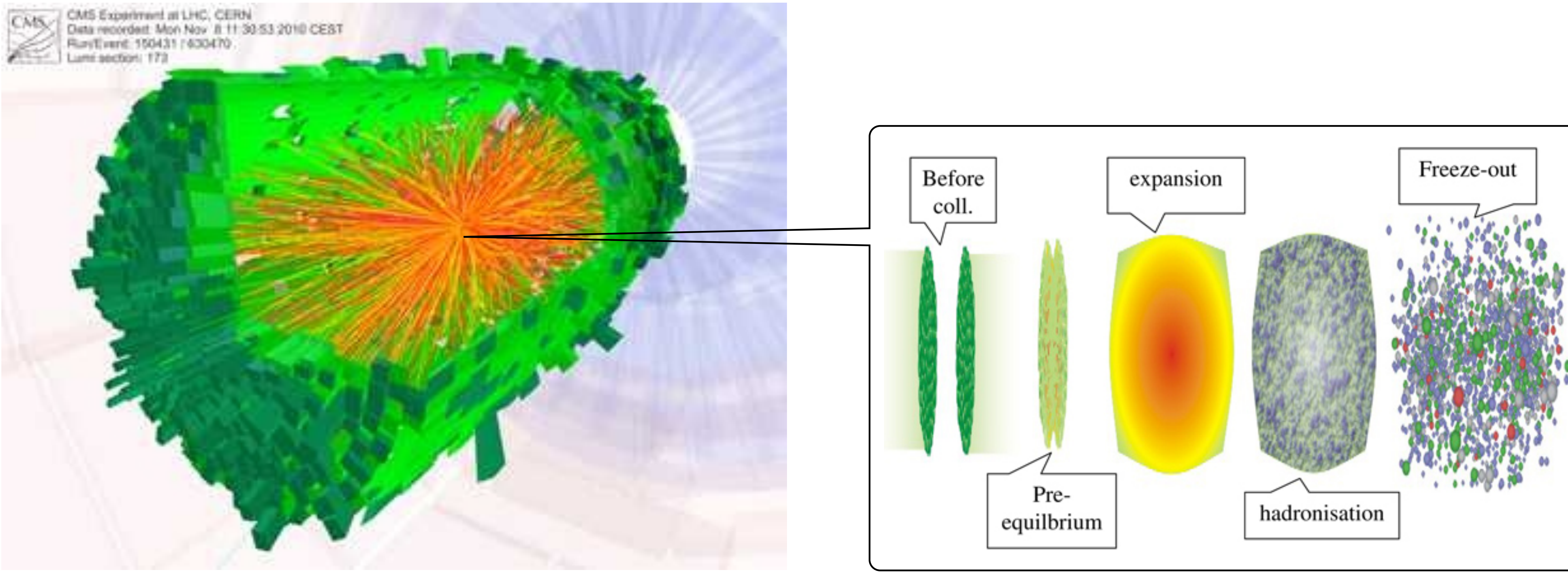
$$\boxed{e^{-S[U,q,\bar{q}]}}$$

with a complex action:

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

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:

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

Hamiltonian evolution:

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

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

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

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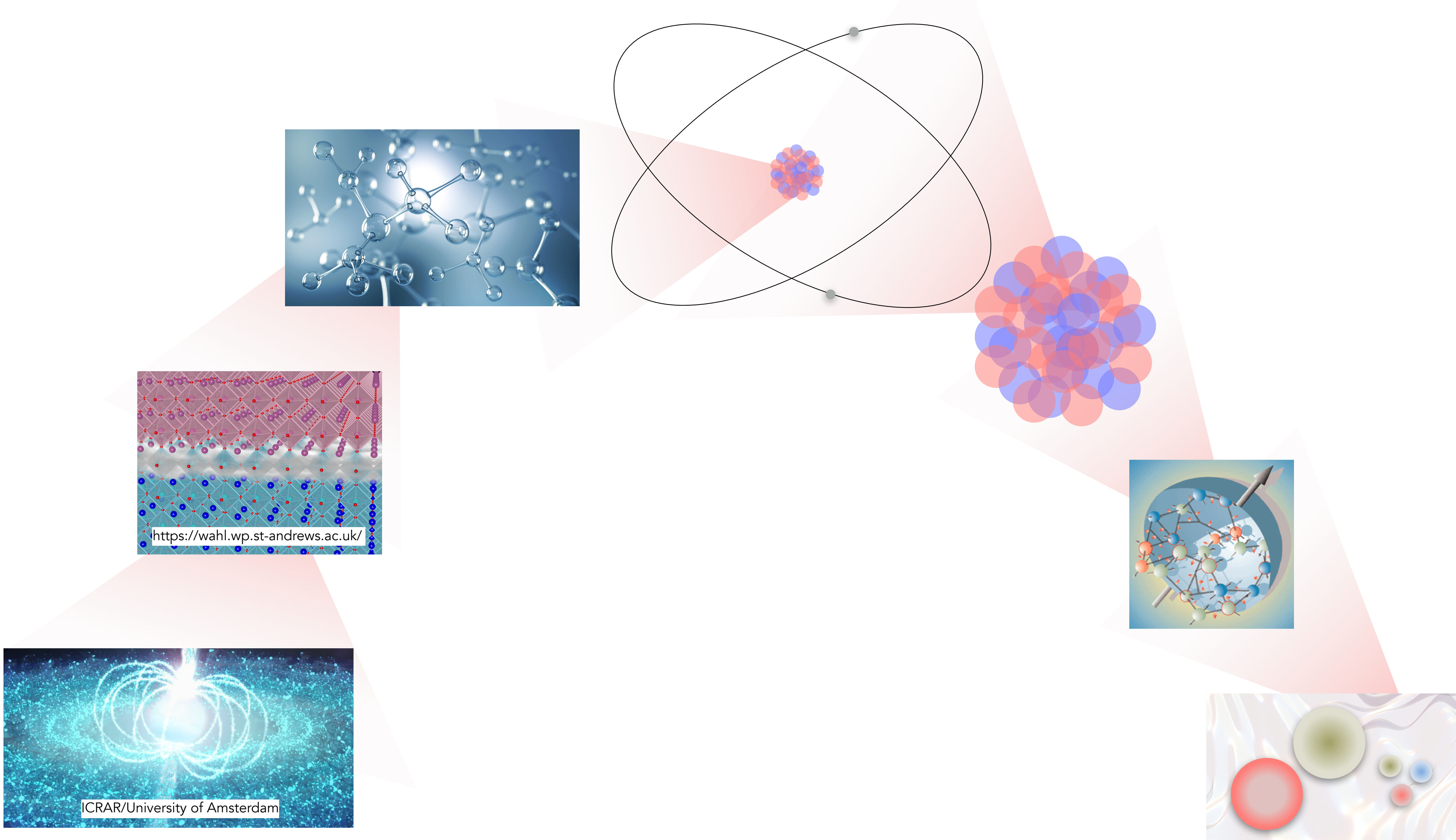
Quantum simulation amounts to leveraging a quantum system that can be controlled to study another quantum systems that is more elusive, experimentally or computationally.



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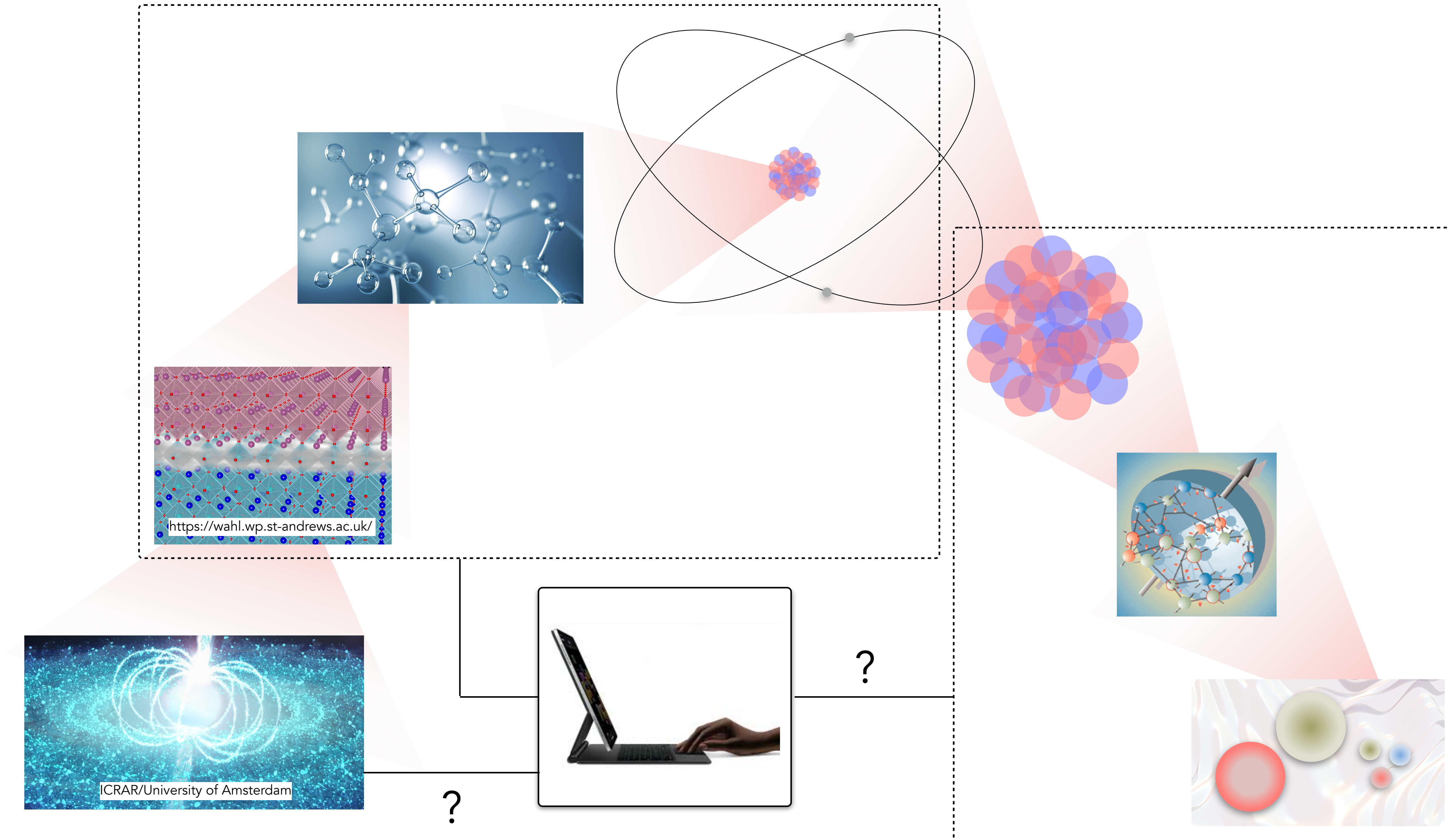

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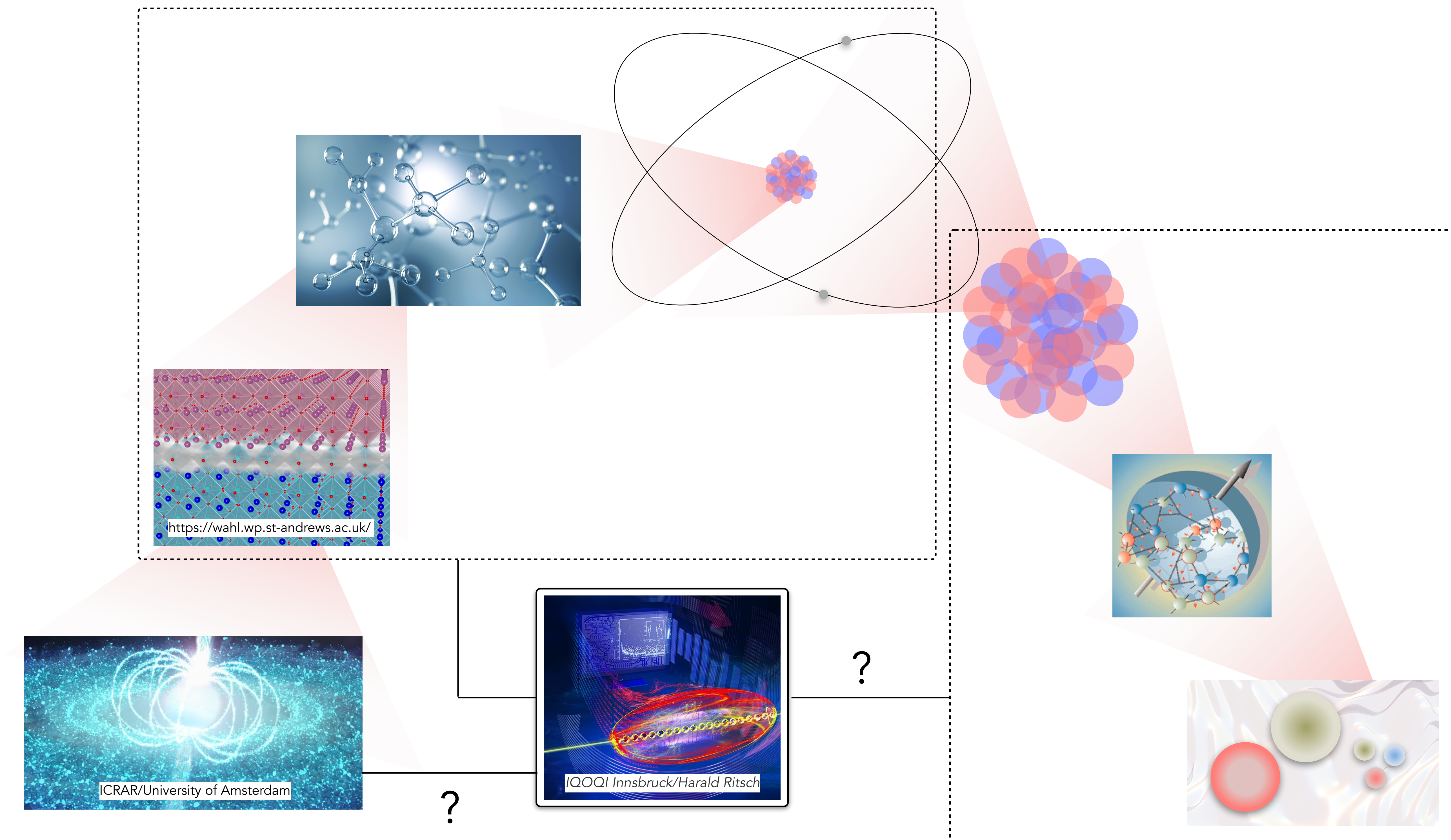
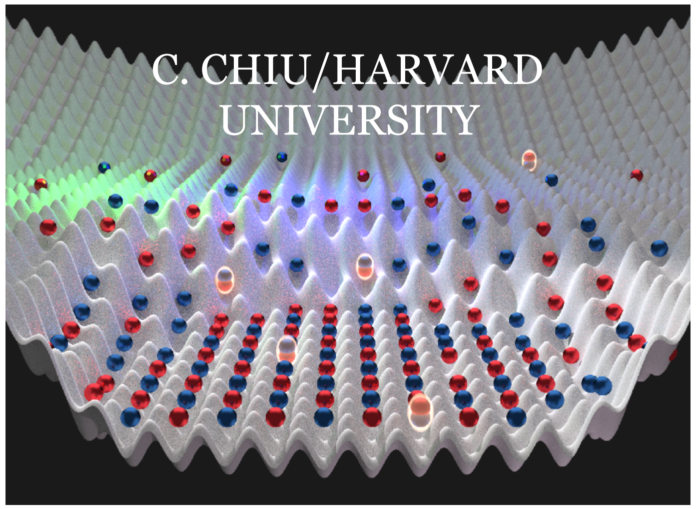
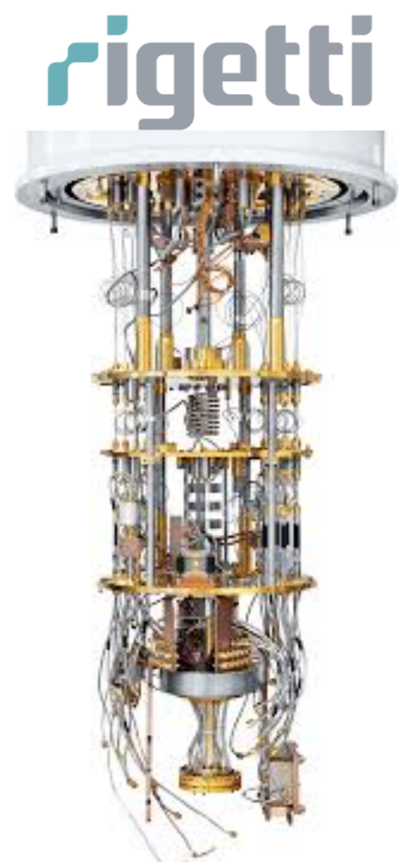
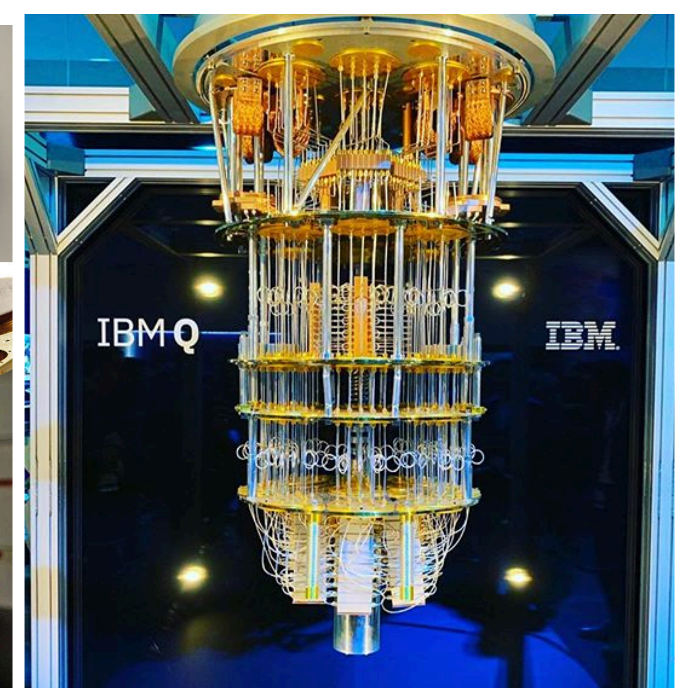


A RANGE OF QUANTUM SIMULATORS WITH VARING CAPACITY AND CAPABILITY IS AVAILABLE!

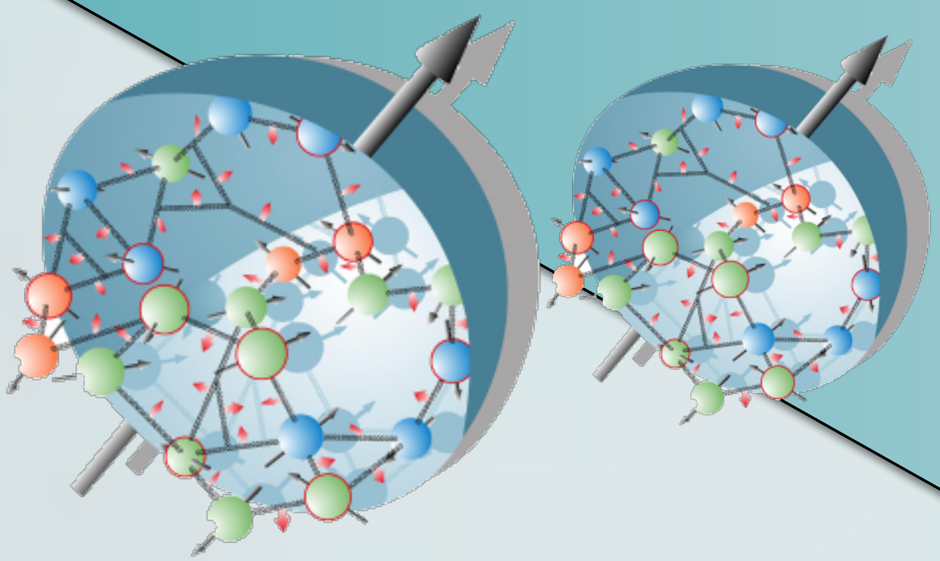




UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing



SOME SIMILARITIES BUT MAJOR DIFFERENCES

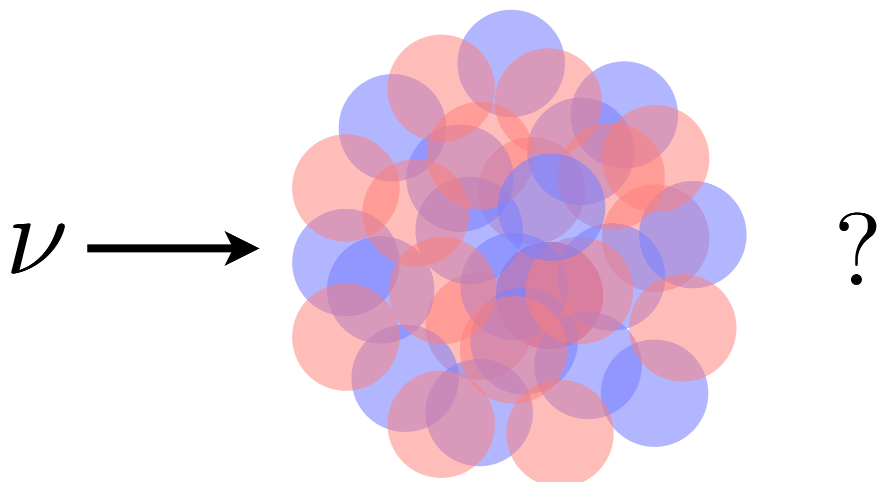


Starting from the nucelar Hamiltonian

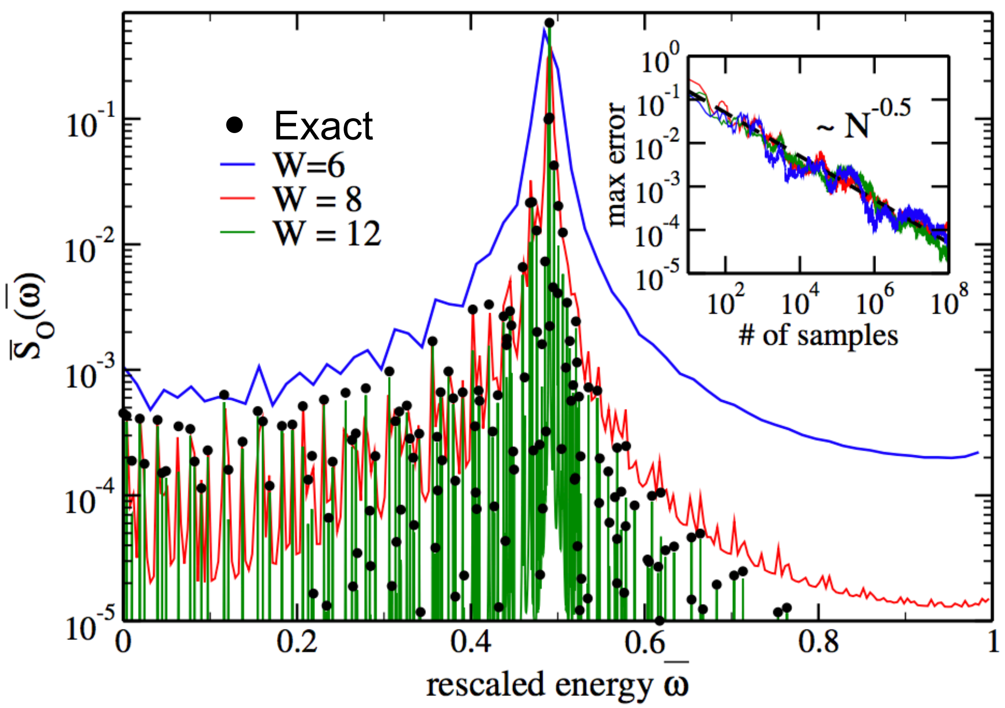
More complex Hamiltonian, itself unknown with arbitrary accuracy, short, intermediate, and long-range interactions, three and multi-body interactions, pions (bosons) and other hadrons can become dynamical.

QUANTUM SIMULATION FOR NUCLEAR ASTROPHYSICS: TWO EXAMPLES

Dynamical response functions needed for ν-nucleus cross sections



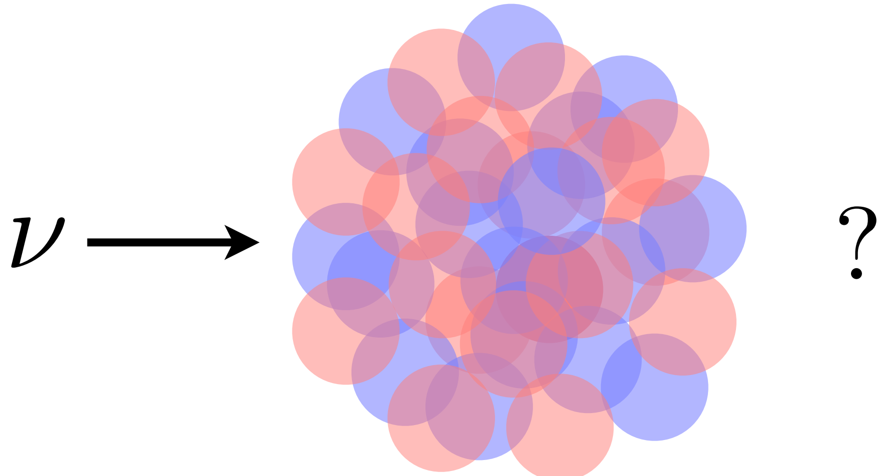
A quantum computation of response function in Fermi-Hubbard model



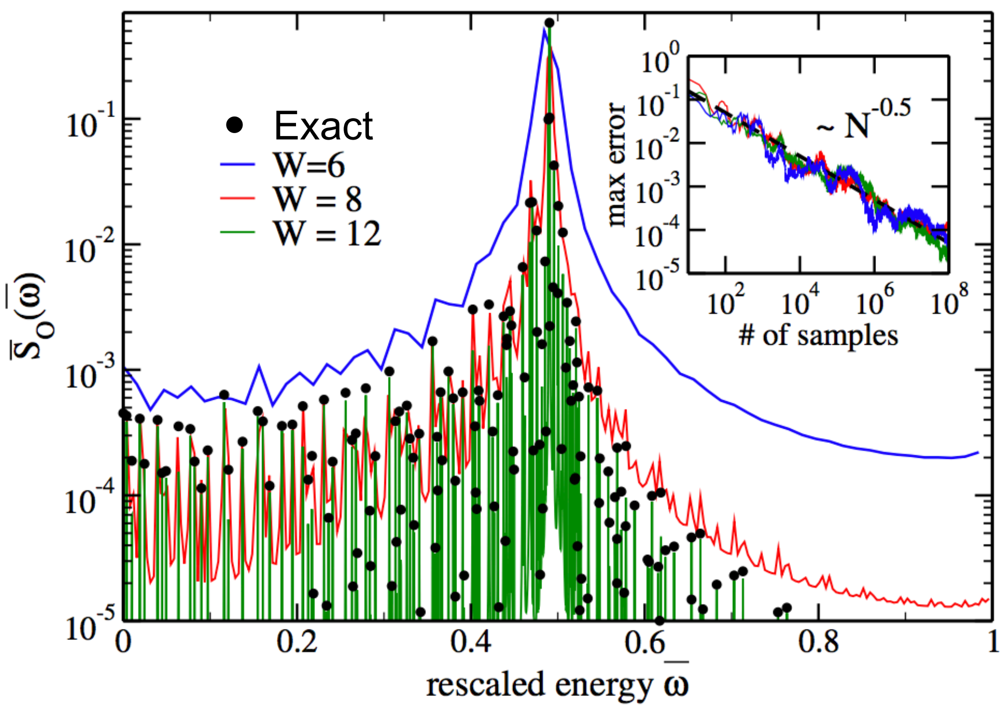
Roggero, Carlson, Phys. Rev. C 100, 034610 (2019)

QUANTUM SIMULATION FOR NUCLEAR ASTROPHYSICS: TWO EXAMPLES

Dynamical response functions needed for ν-nucleus cross sections



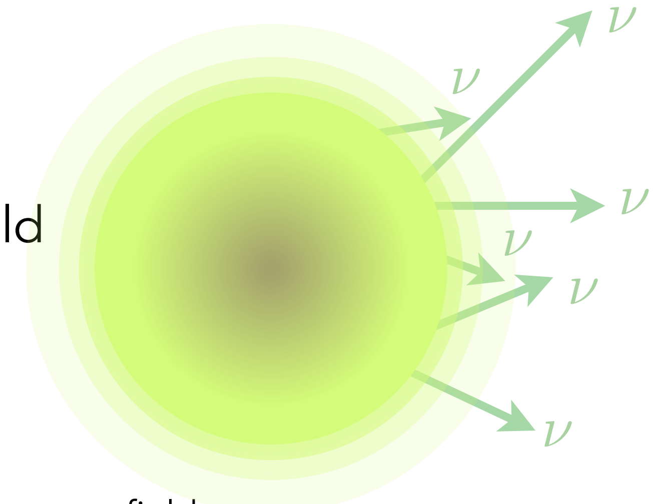
A quantum computation of response function in Fermi-Hubbard model



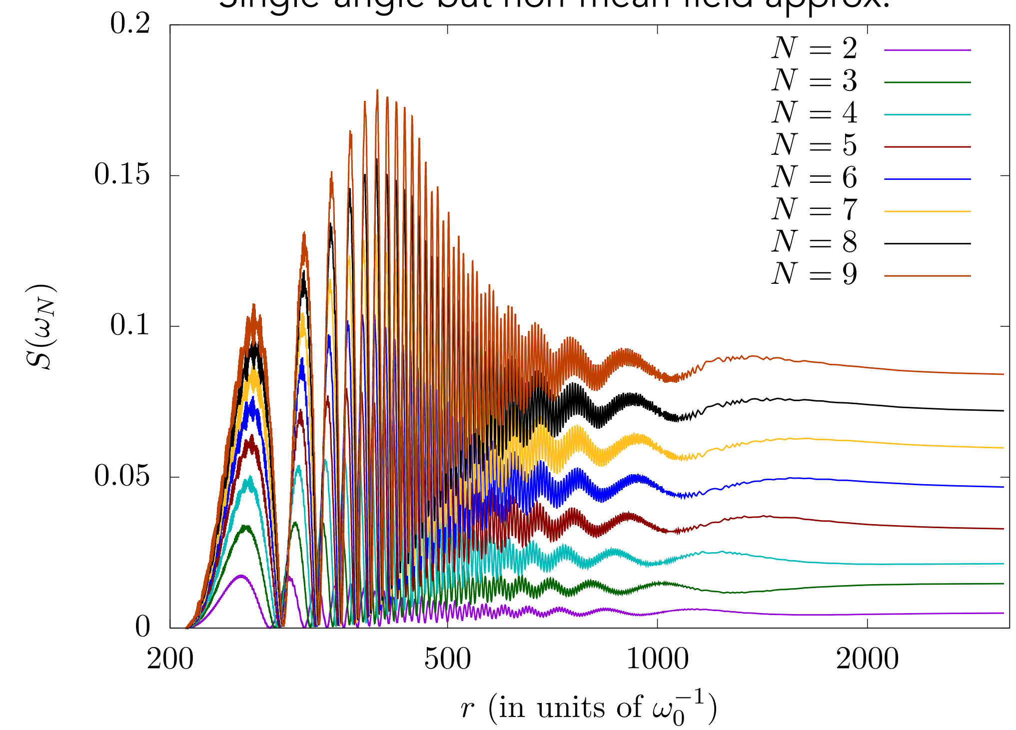
Roggero, Carlson, Phys. Rev. C 100, 034610 (2019)

Collective neutrino oscillations

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



Single-angle but non-mean field approx.

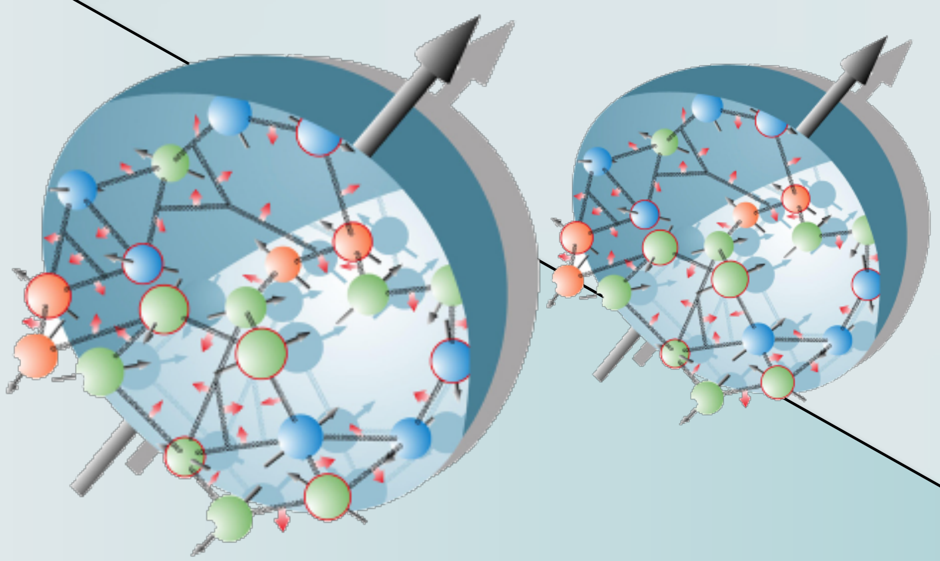


Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, Phys. Rev. D 100, 083001 (2019)

Would need quantum simulation!

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

SOME SIMILARITIES BUT MAJOR DIFFERENCES

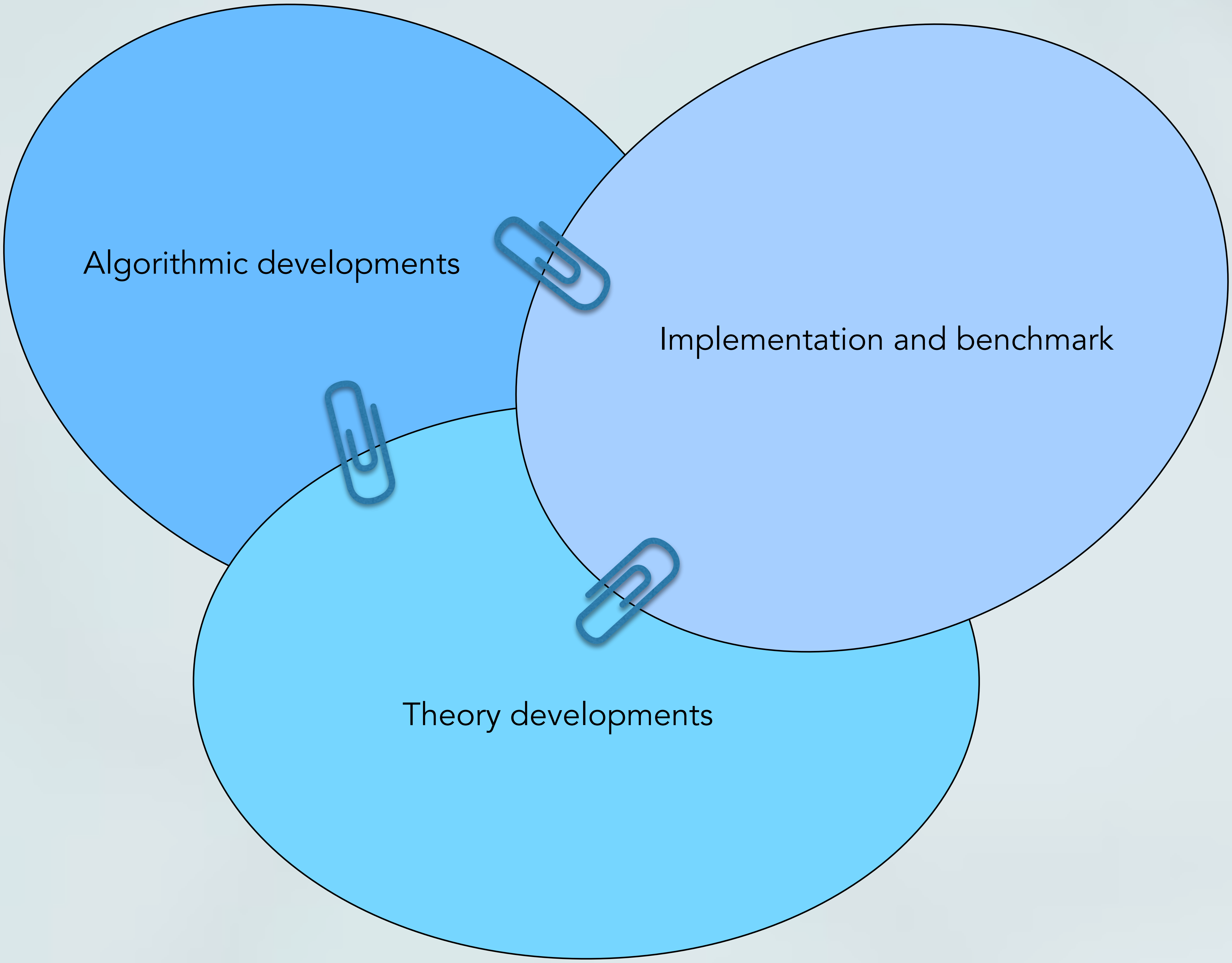


Starting from the Standard Model

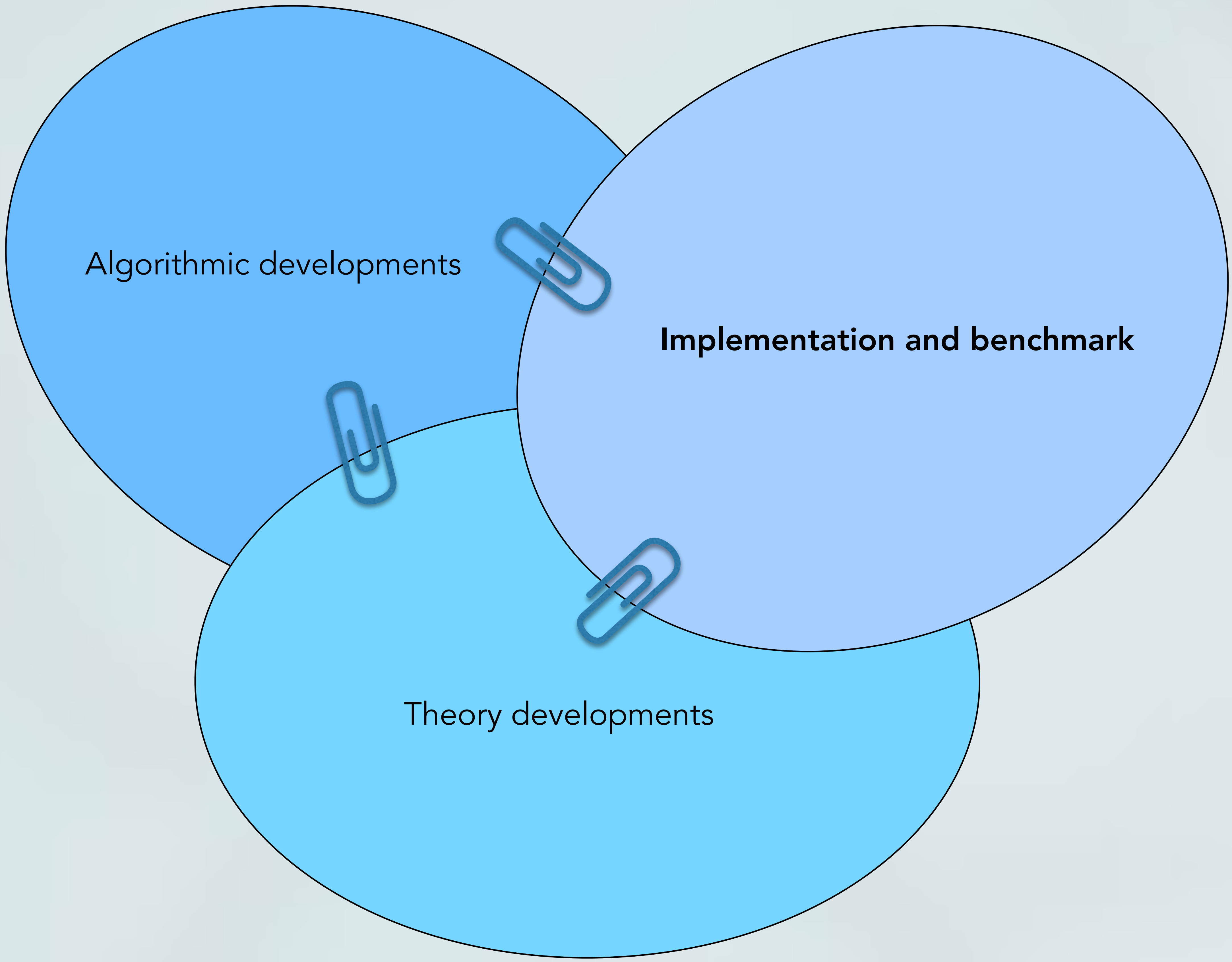
Both bosonic and fermionic DOF are dynamical and coupled, exhibit both global and local (gauge) symmetries, relativistic hence particle number not conserved, vacuum state nontrivial in strongly interacting theories.

Attempts to cast QFT problems in a language closer to quantum chemistry and NR simulations:
Kreshchuk, Kirby, Goldstein, Beauchemin, Love, arXiv:2002.04016 [quant-ph]
Liu, Xin, arXiv:2004.13234 [hep-th]
Barata , Mueller, Tarasov, Venugopalan (2020)

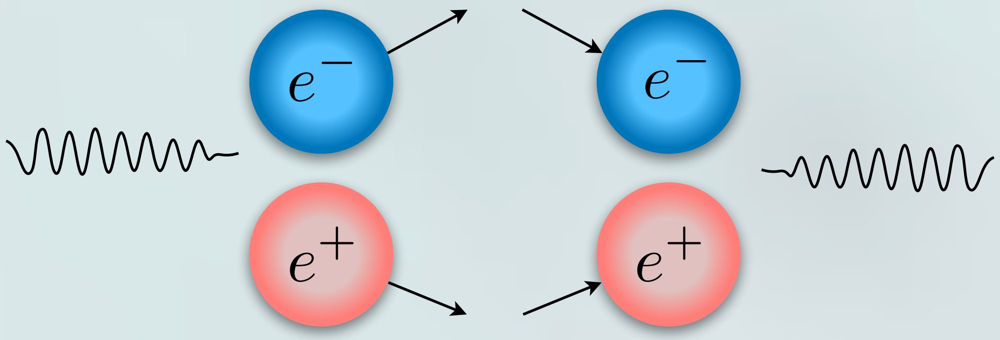
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A FEW EXAMPLES

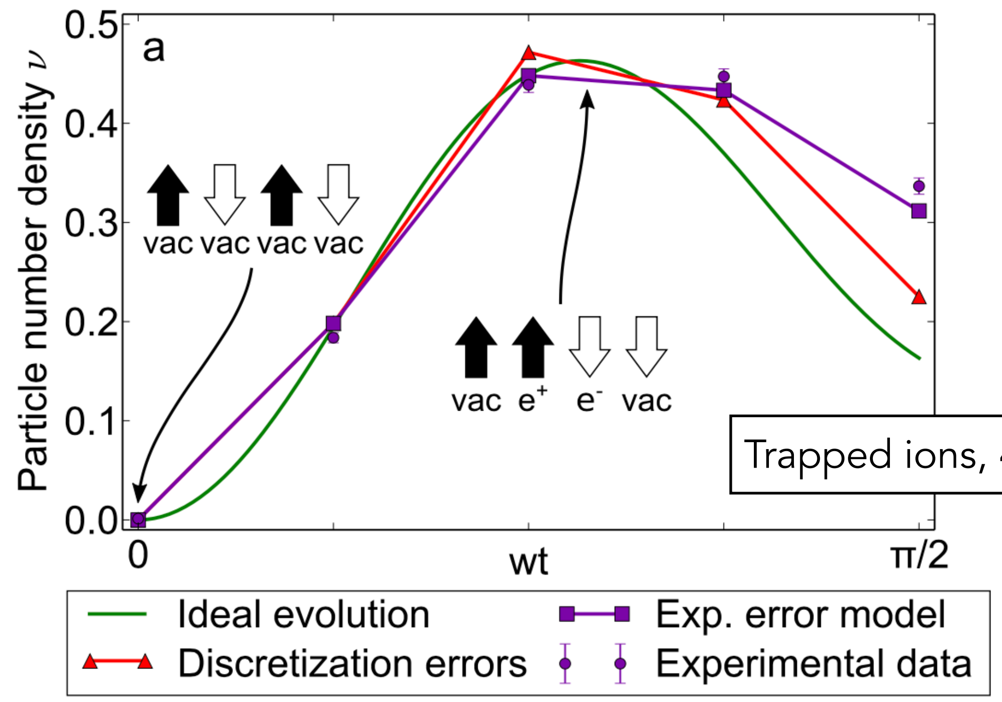


QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A FEW EXAMPLES



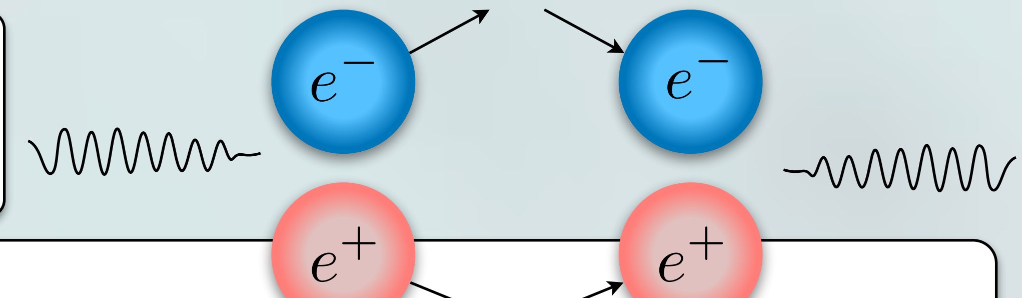
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK DIGITAL EXAMPLES

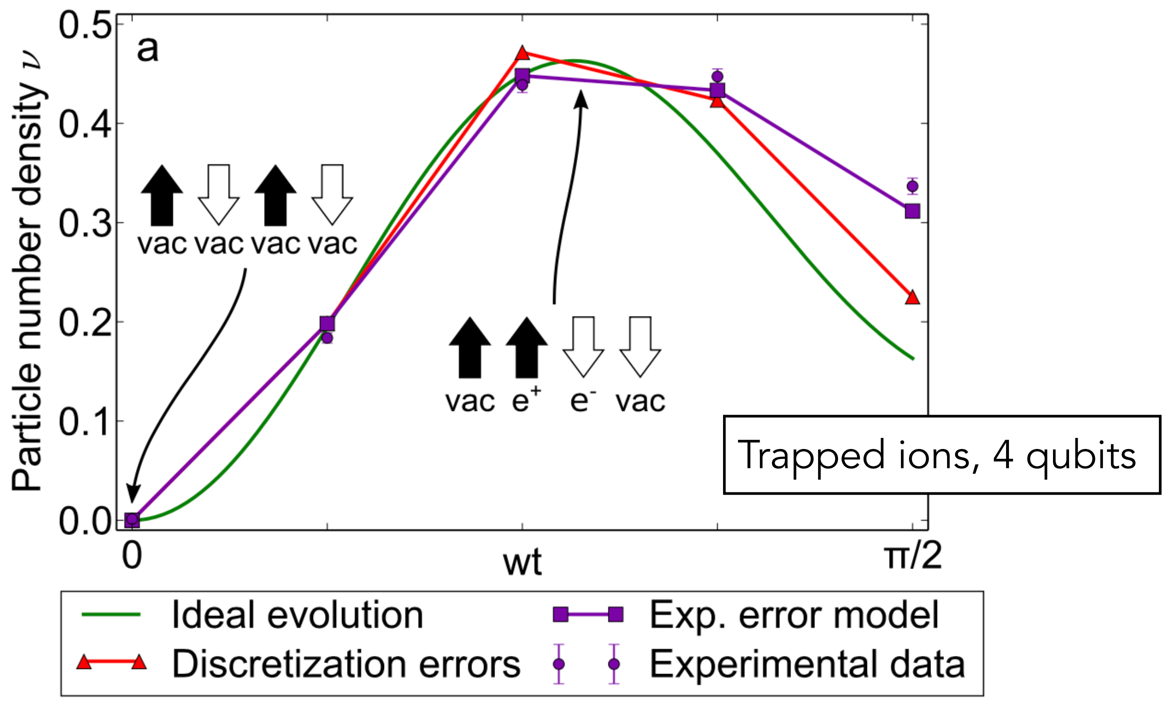




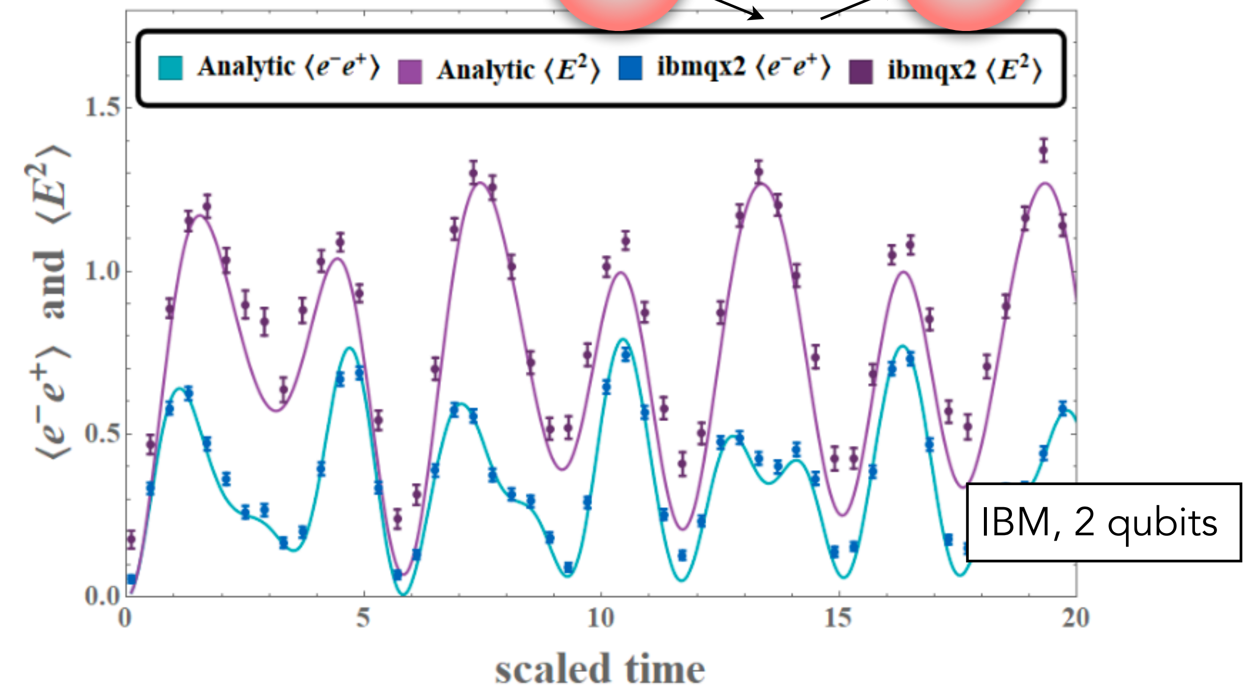
Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)

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

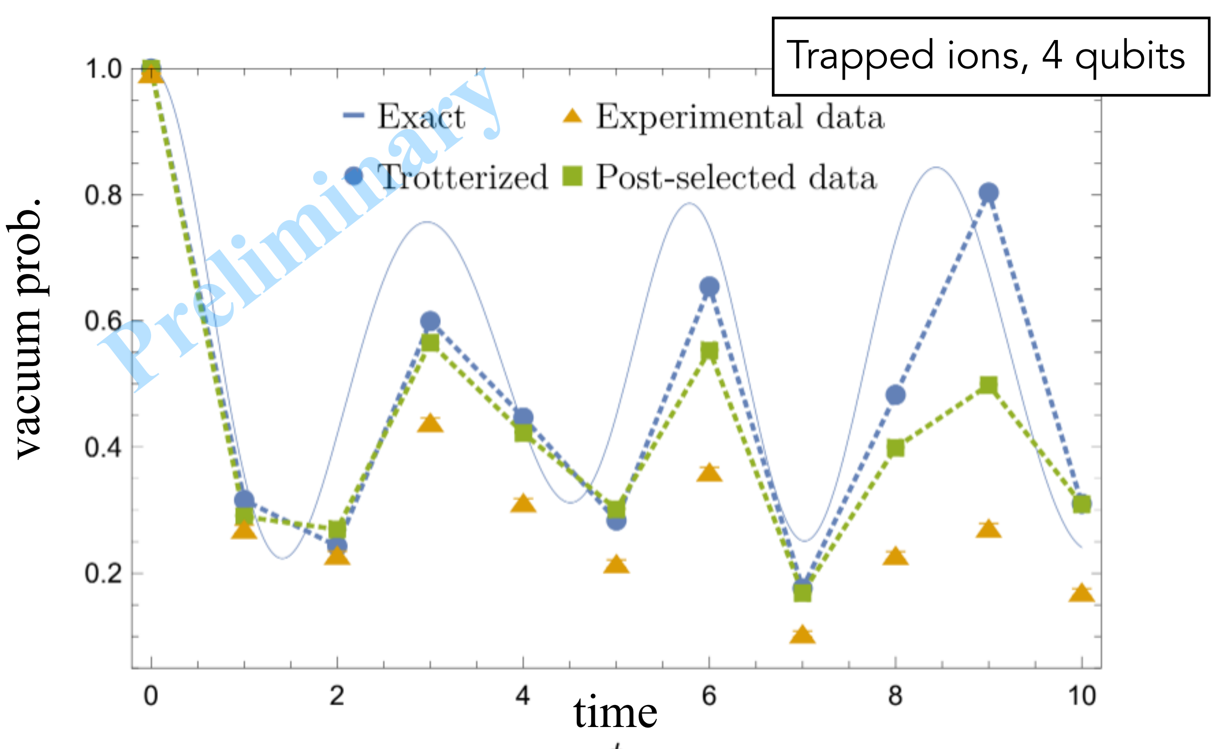




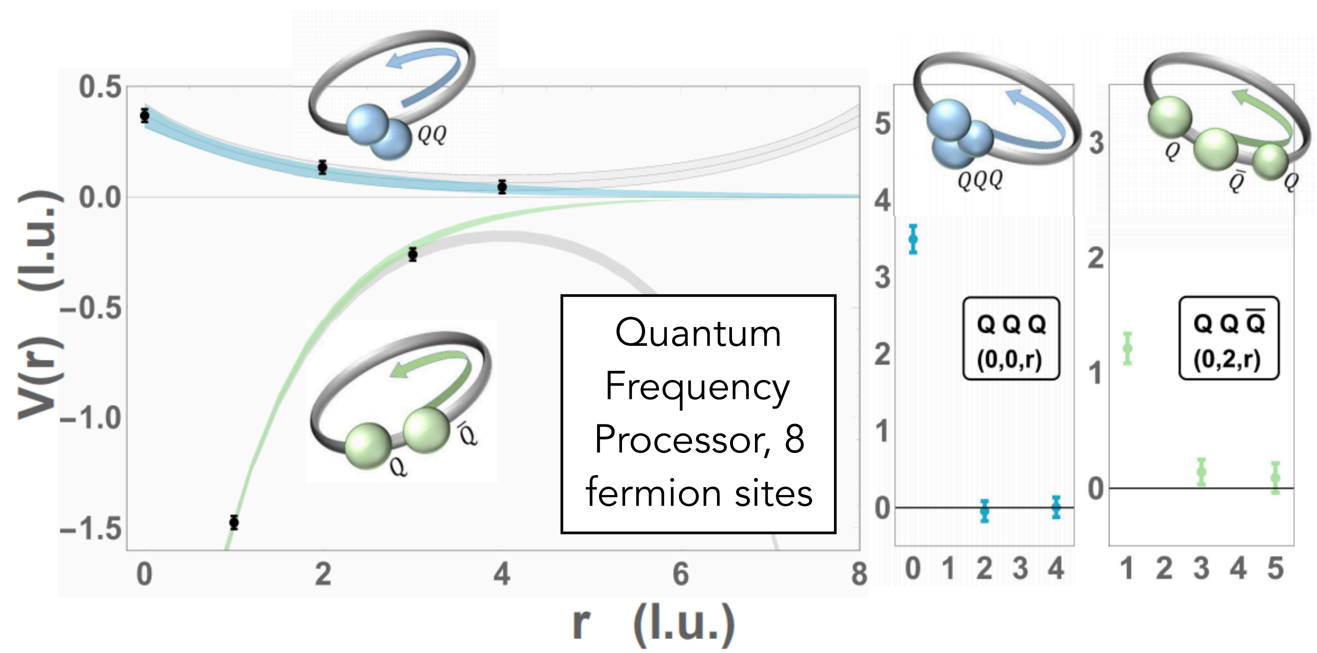
Martinez, Muschik, Schindler, Nigg, Erhard, Heyl, Hauke, Dalmonte, Monz, Zoller, Blatt, Nature 534, 516-519 (2016)



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

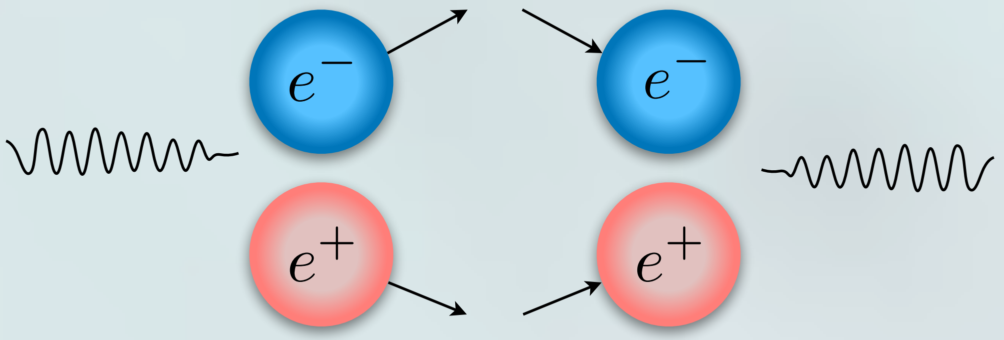


Nguyen, Shaw, Zhu, Huerta Alderete, ZD, Linke (2020)

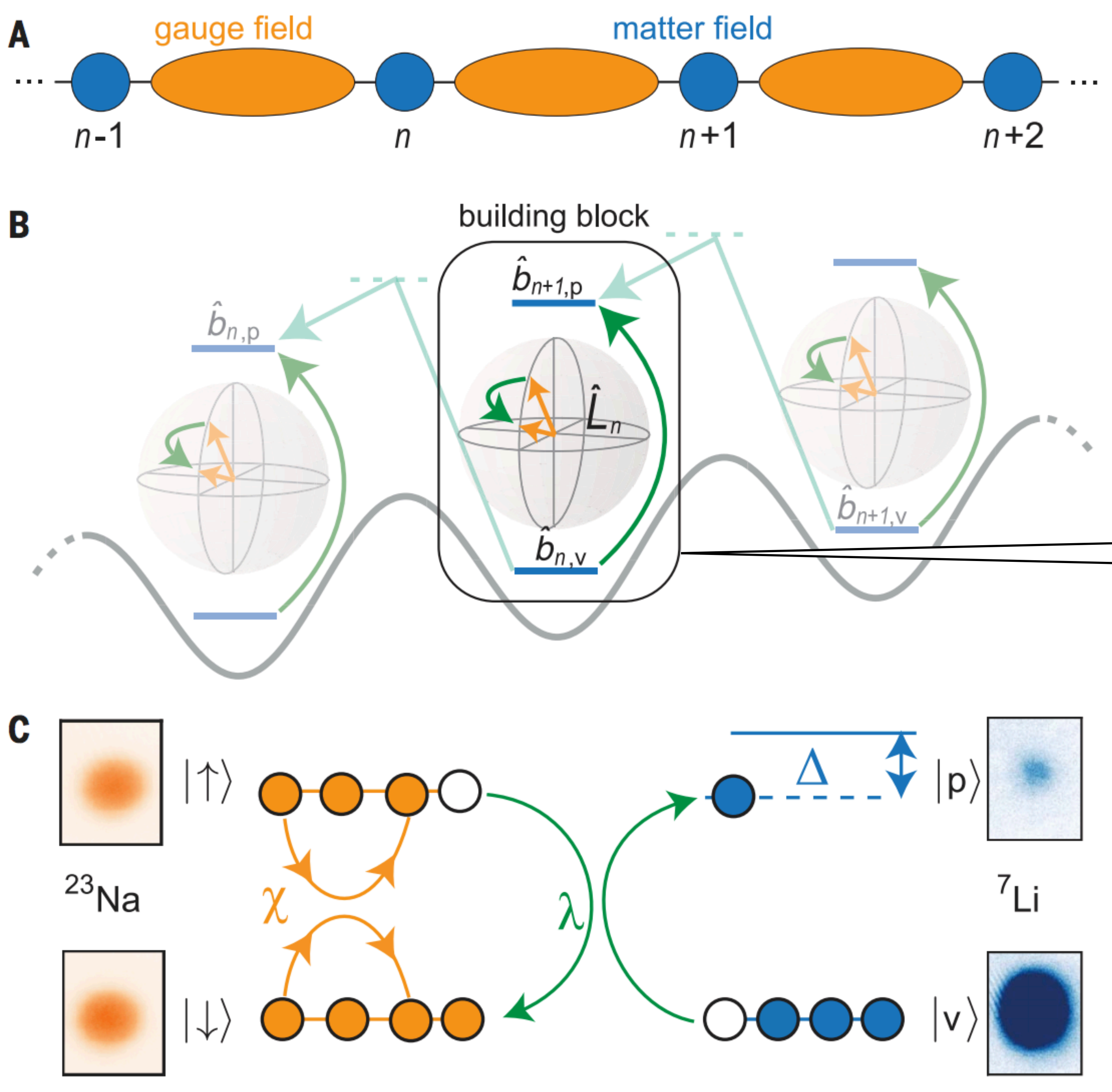


Lu, **Klco**, Lukens, Morris, Bansal, Ekström, Hagen, Papenbrock, Weiner, Savage, Lougovski, Phys. Rev. A 100, 012320 (2019)

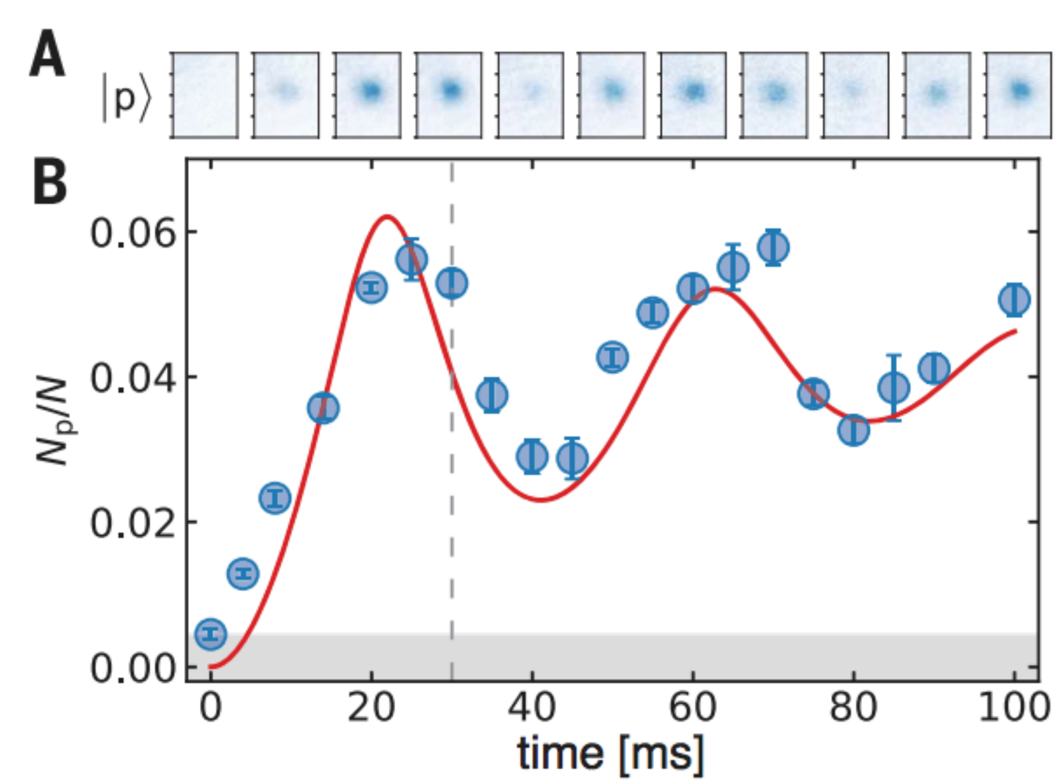
QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: IMPLEMENTATION AND BENCHMARK ANALOG EXAMPLE



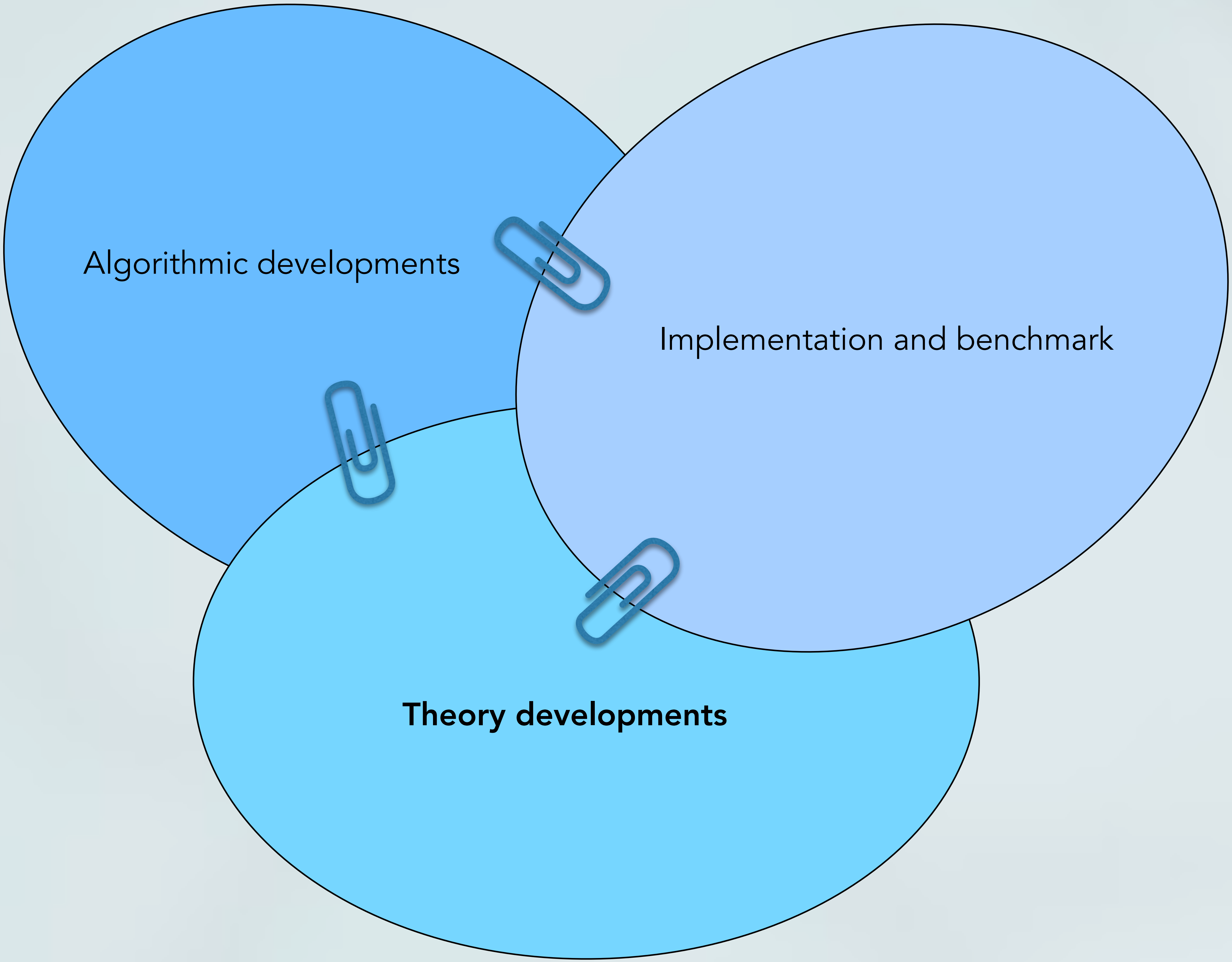
A realization of lattice Schwinger model within QLM with cold atoms in a trapping potential



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



QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A FEW EXAMPLES



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

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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

Kogut and Susskind formulation:

$$H_{\mathrm{QCD}} = \underbrace{-t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right)}_{\text{Fermion hopping term}} + \underbrace{m\sum_x s_x \psi_x^\dagger \psi_x}_{\text{Fermion mass}} + \underbrace{\frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right)}_{\text{Energy of color electric field}} - \underbrace{\frac{1}{4g^2}\sum_{\Box}\mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)}_{\text{Energy of color magnetic field}}.$$

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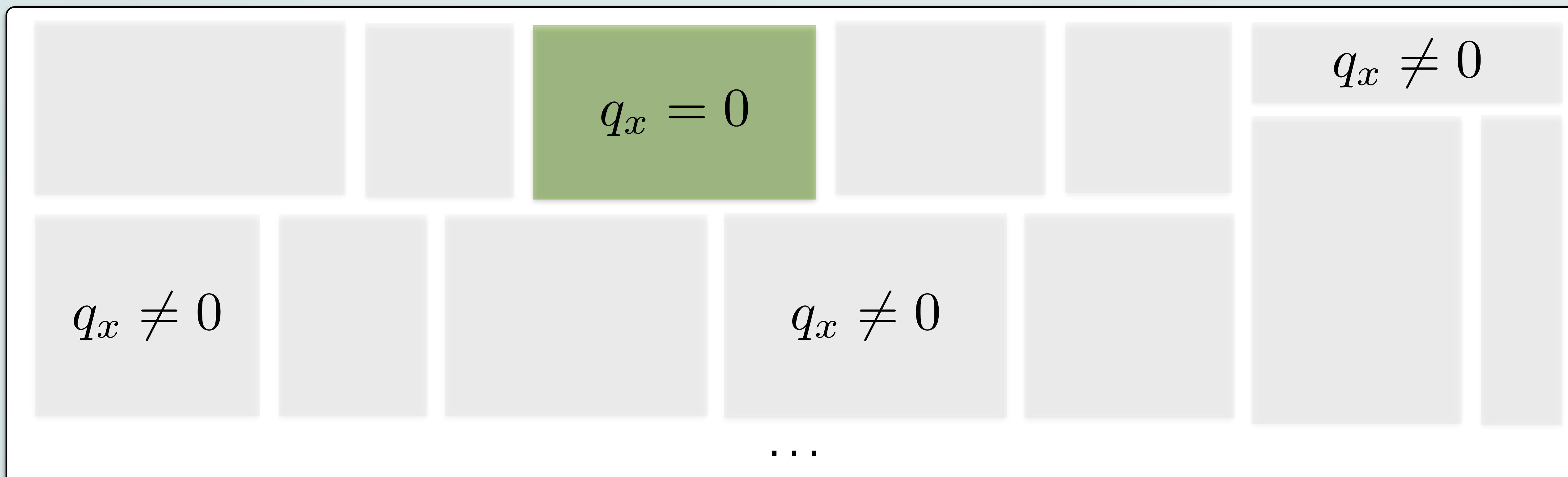

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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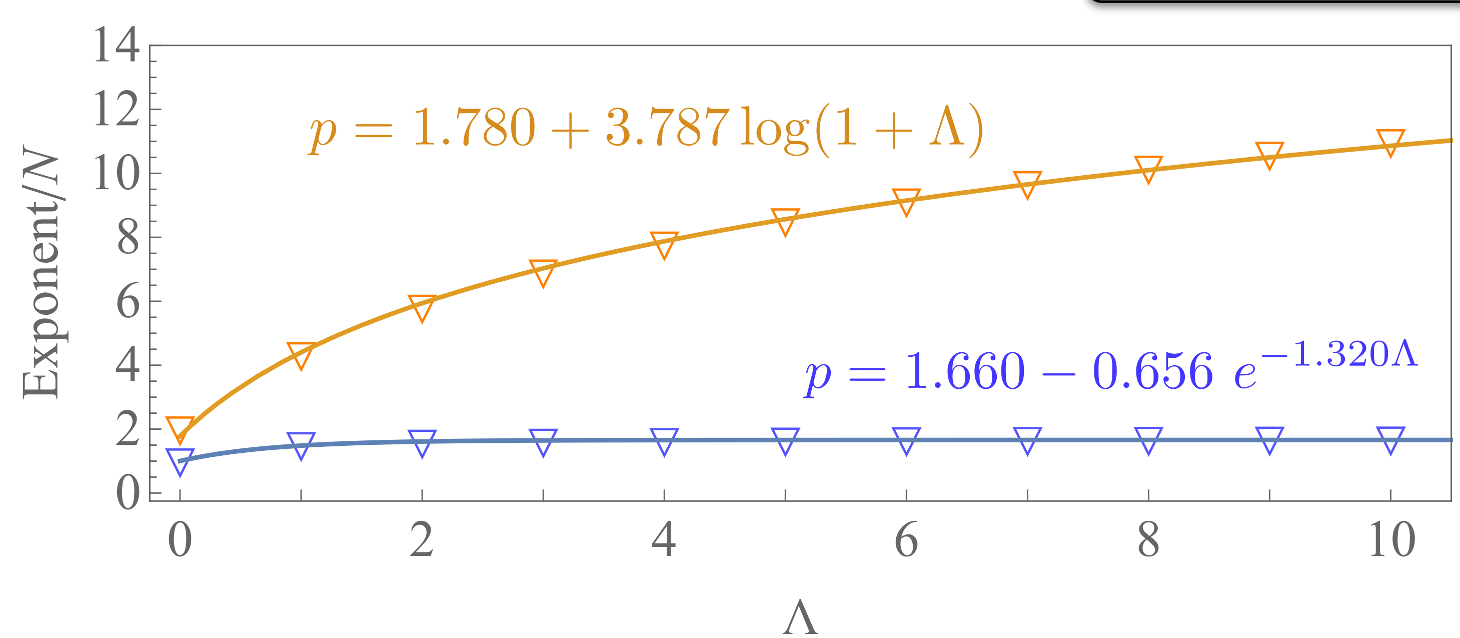
$$H_{\rm QCD} = \underbrace{-t\sum_{\langle xy\rangle} s_{xy}\left(\psi_x^\dagger U_{xy}\psi_y + \psi_y^\dagger U_{xy}^\dagger \psi_x\right)}_{\text{Fermion hopping term}} + \underbrace{m\sum_x s_x \psi_x^\dagger \psi_x}_{\text{Fermion mass}} + \underbrace{\frac{g^2}{2}\sum_{\langle xy\rangle}\left(L_{xy}^2 + R_{xy}^2\right)}_{\text{Energy of color electric field}} - \underbrace{\frac{1}{4g^2}\sum_{\Box}\mathrm{Tr}\left(U_\Box + U_\Box^\dagger\right)}_{\text{Energy of color magnetic field}}.$$

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

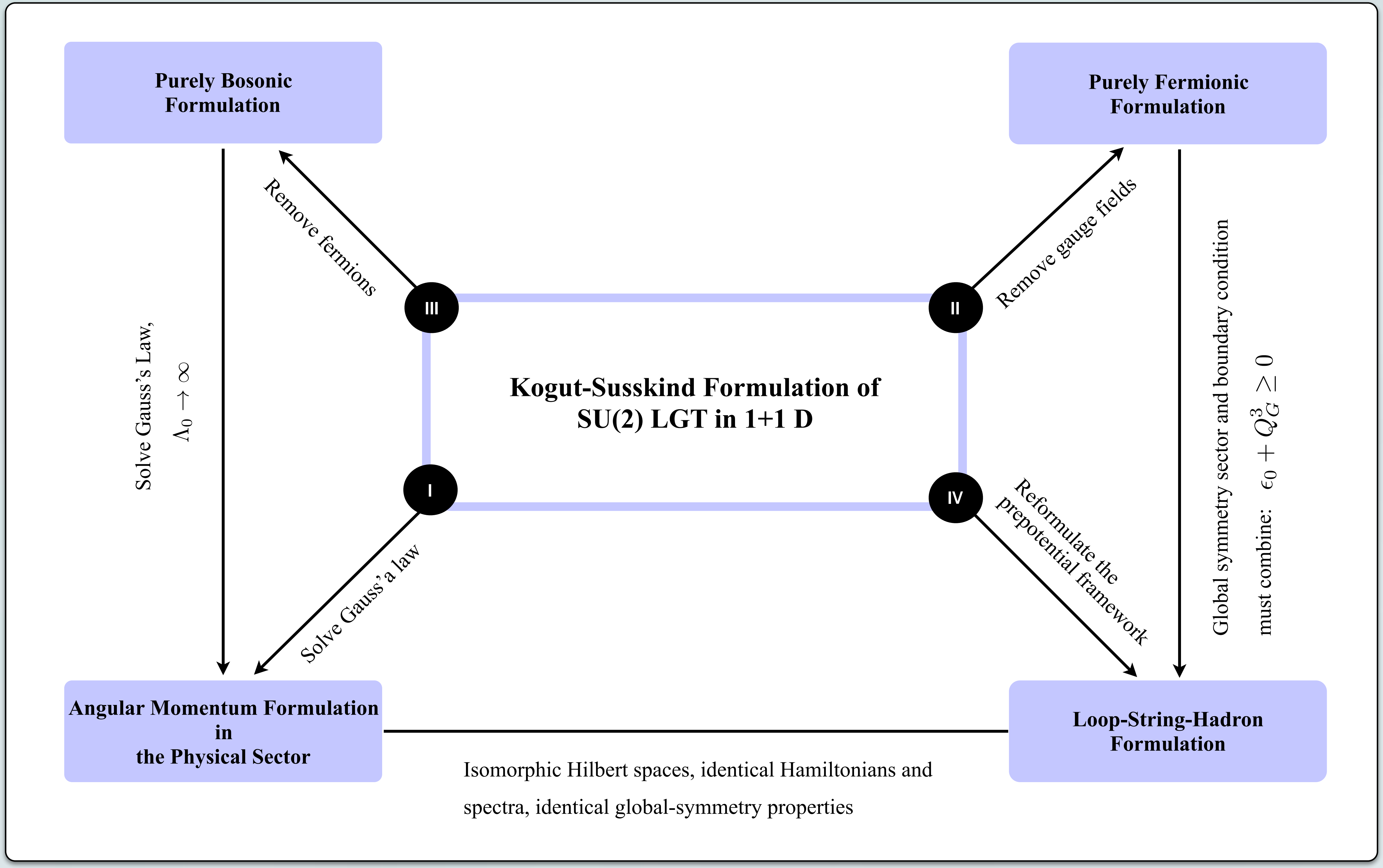
$N_{\rm state} \sim e^{pN}$

SU(2) gauge theory with matter in 1+1D



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

QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS



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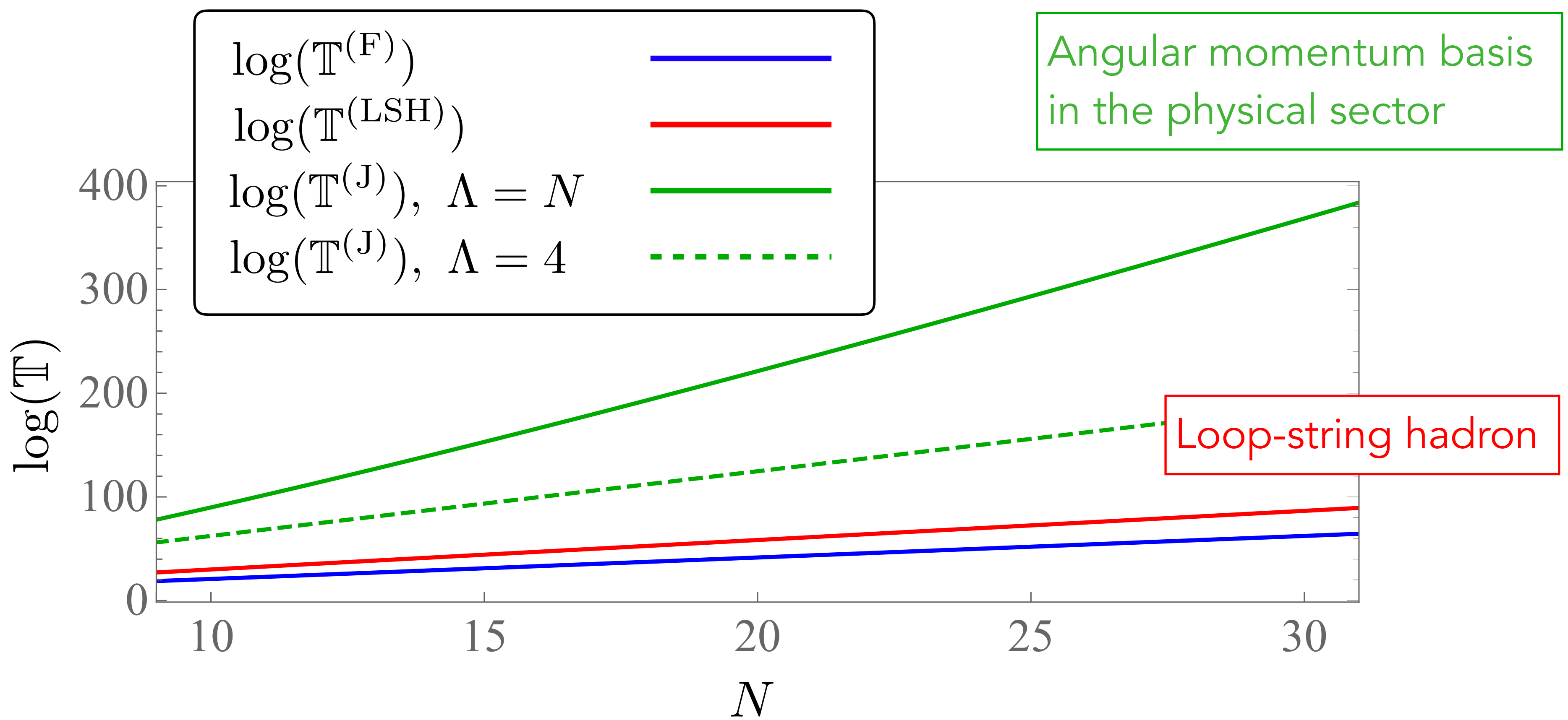
QUANTUM SIMULATION OF GAUGE FIELD THEORIES: THEORY DEVELOPMENTS

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



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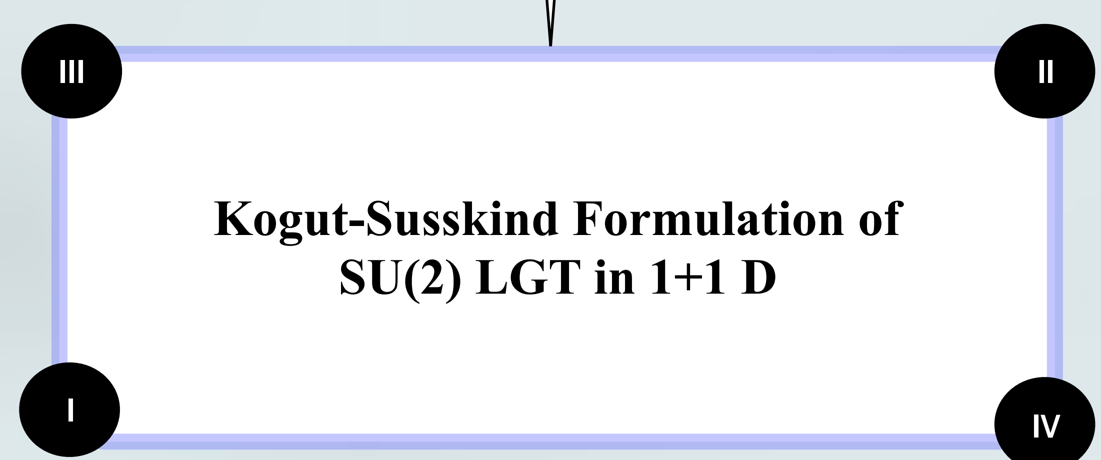
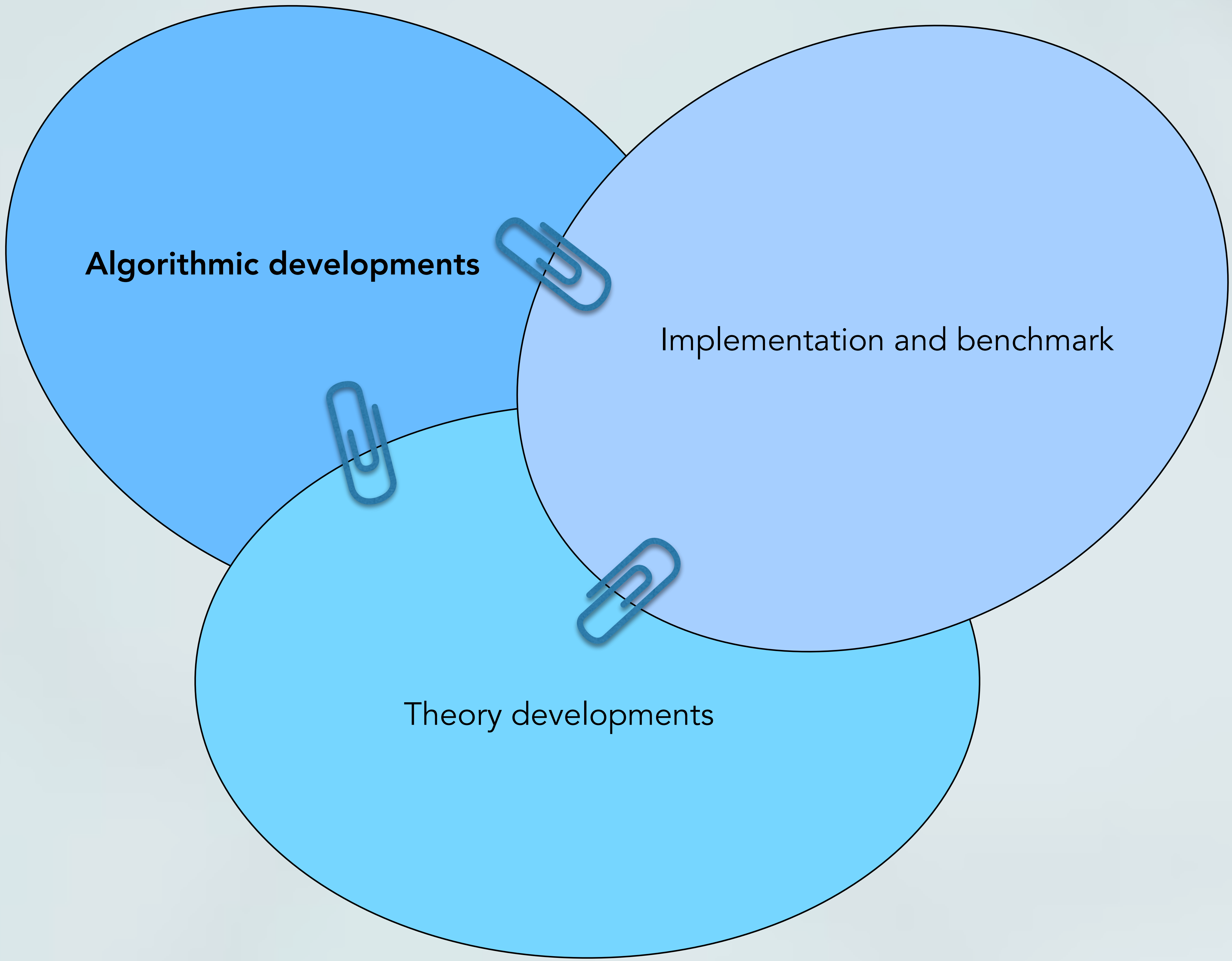


Raychowdhury, Stryker, Phys. Rev. D 101, 114502 (2020).

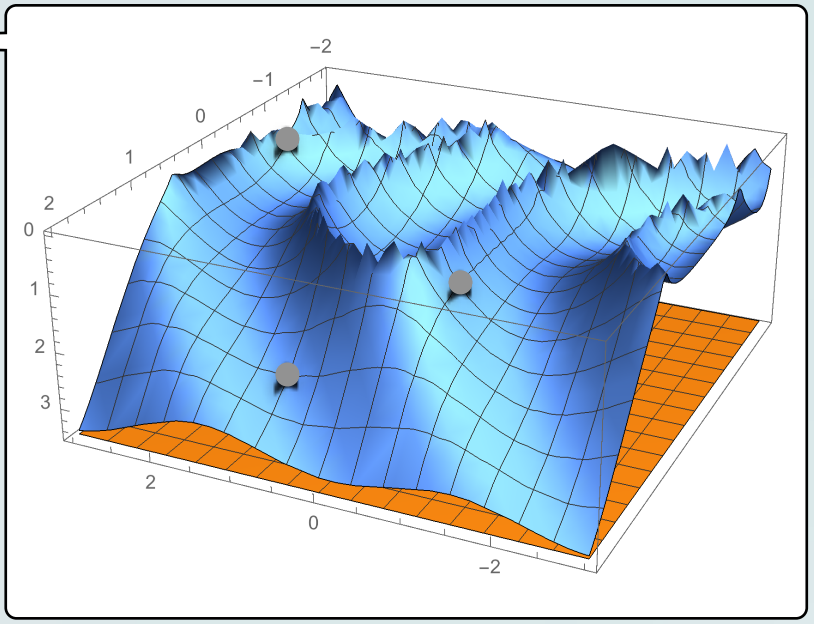
For progress in 2+1 D U(1) gauge theory, see:
Haase, Dellantonio, Celi, Paulson, Kan, Jansen, Muschik, arXiv:2006.14160 [quant-ph]
Paulson, Dellantonio, Haase, Celi, Kan, Jena, Kokail, van Bijnen, Jansen, Zoller, Muschik, arXiv: 2008.09252 [quant-ph].

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: A FEW EXAMPLES



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).

QUANTUM SIMULATION OF QUANTUM FIELD THEORIES: ALGORITHMIC DEVELOPMENTS

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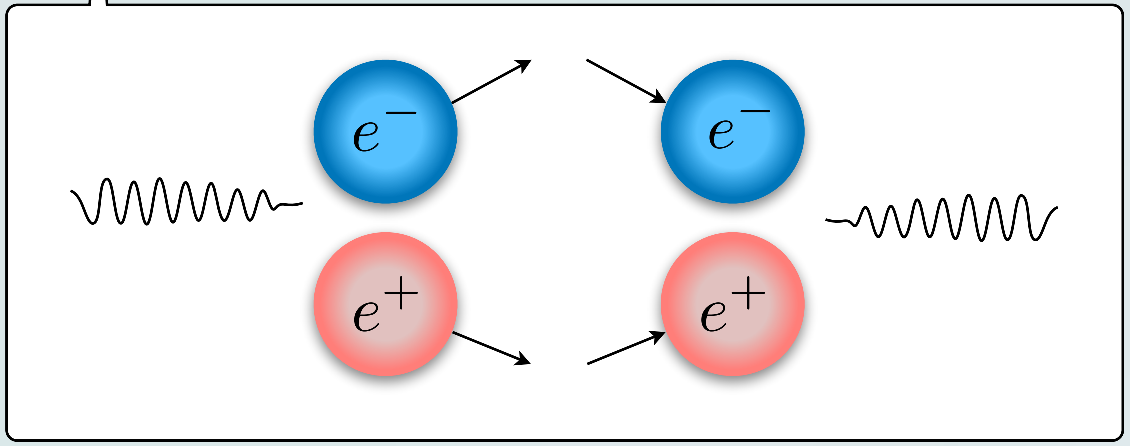
Klco, Savage, Phys. Rev. A 99, 052335 (2019).

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)



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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 ($\mu = 1,\ \tilde{\epsilon}^2 = 0.1$)

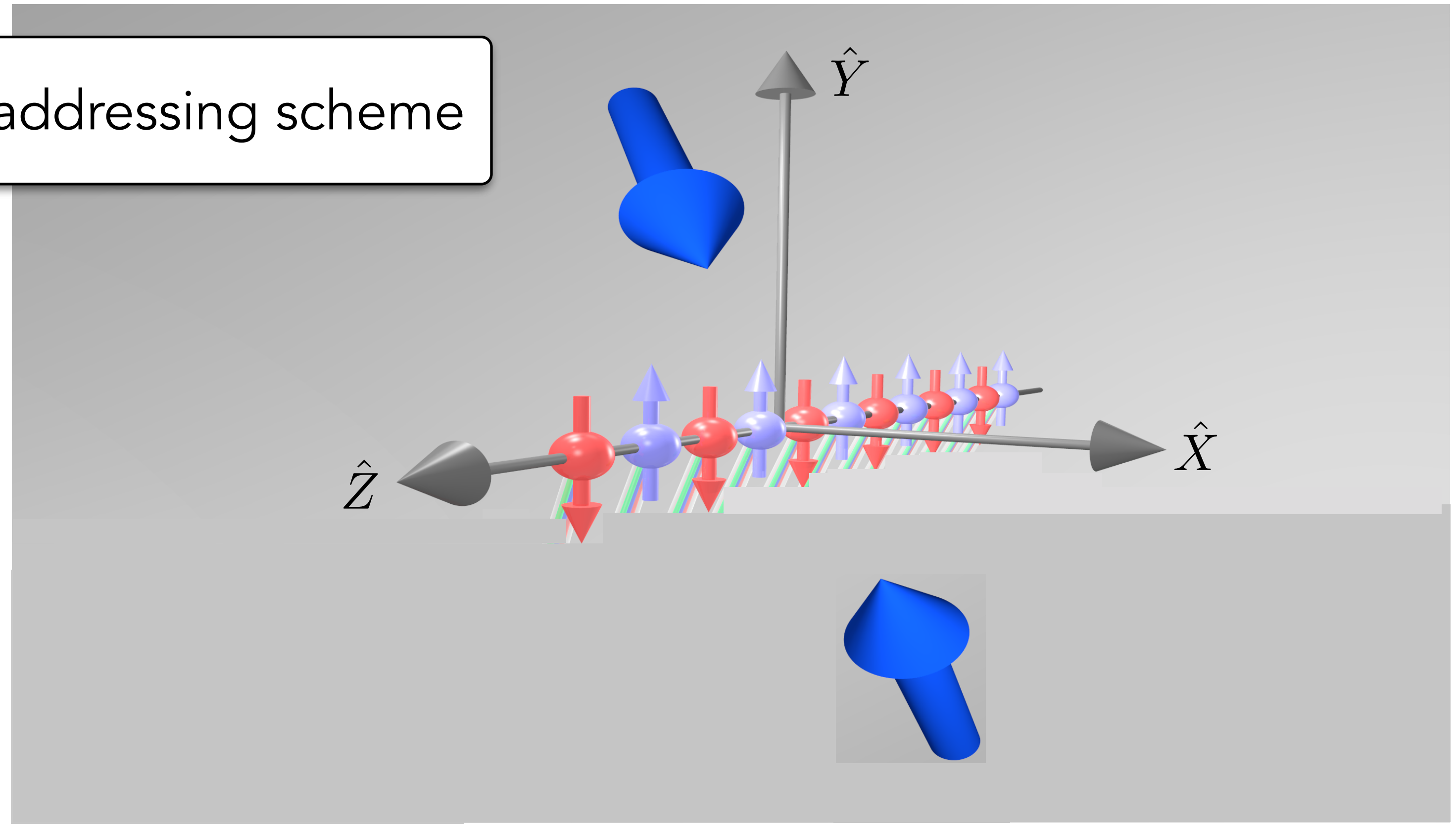
	Short Time ($T = 10/x$)		Long Time ($T = 1000/x$)	
	Sampling	Estimating	Sampling	Estimating
$N = 4,\ \Lambda = 2$				
Strong Coupling ($x = 0.1$)	$6.5 \cdot 10^7$	$2.4 \cdot 10^{11}$	$8.8 \cdot 10^{10}$	$3.3 \cdot 10^{14}$
Weak Coupling ($x = 10$)	$5.0 \cdot 10^6$	$1.8 \cdot 10^{10}$	$7.0 \cdot 10^9$	$2.6 \cdot 10^{13}$
$N = 16,\ \Lambda = 2$				
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?

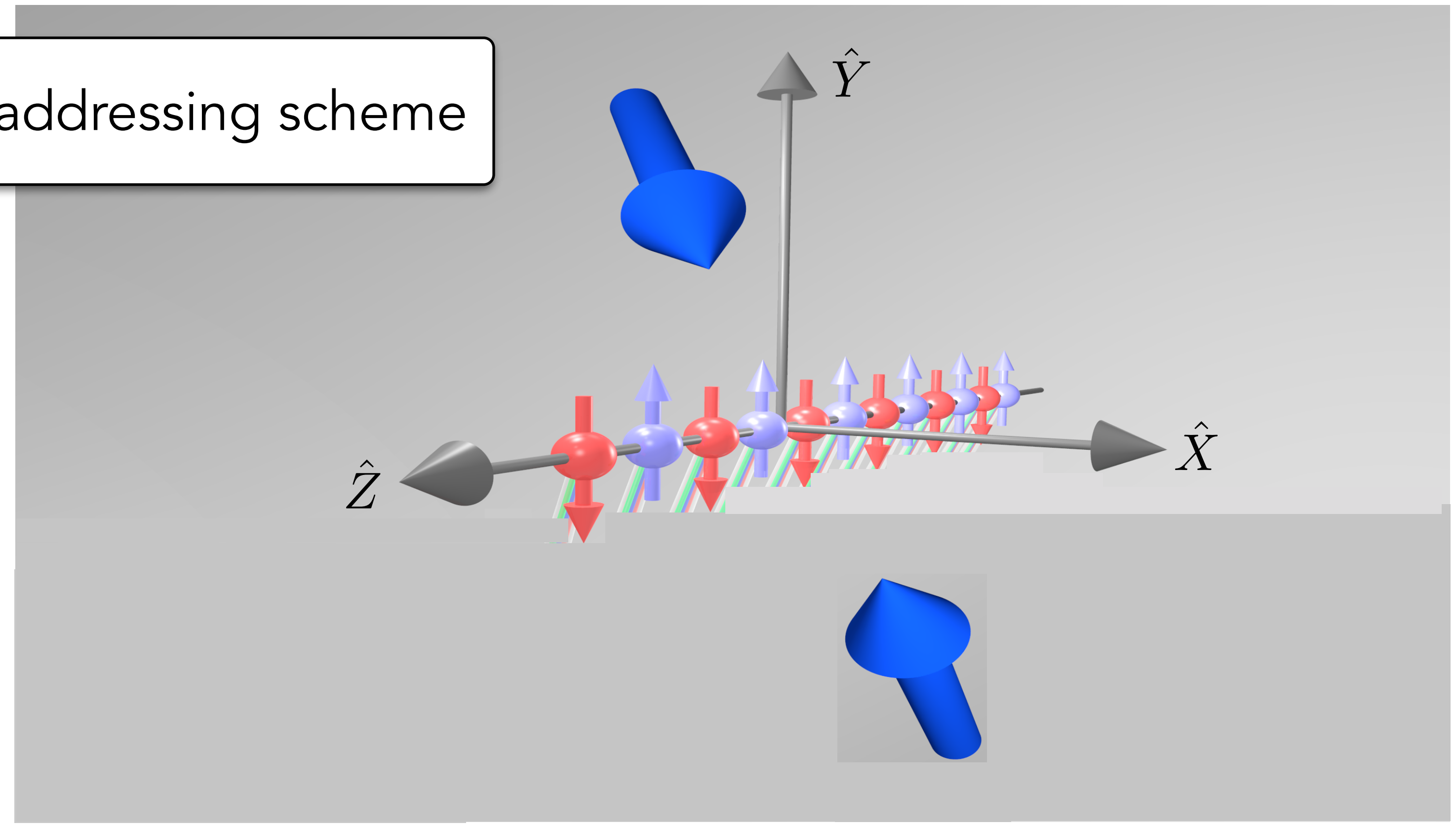
EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

A global addressing scheme



EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

A global addressing scheme

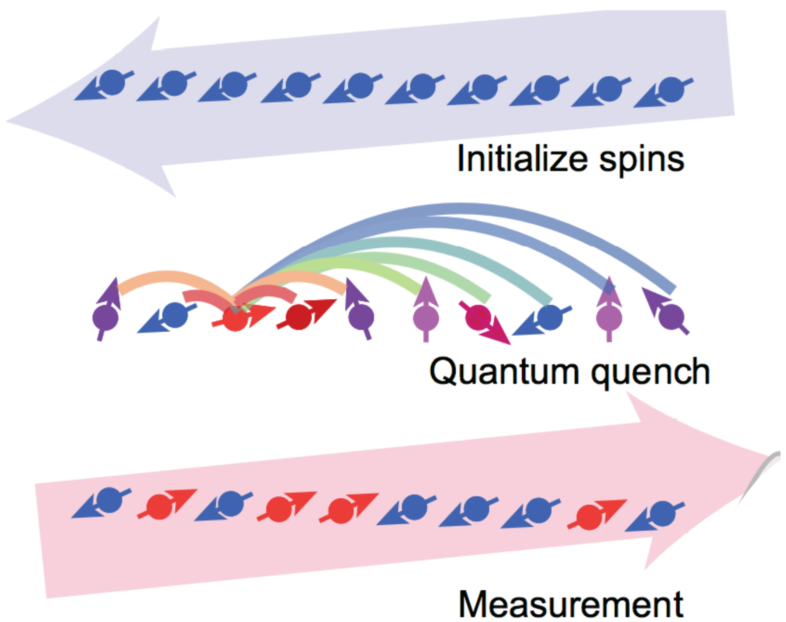


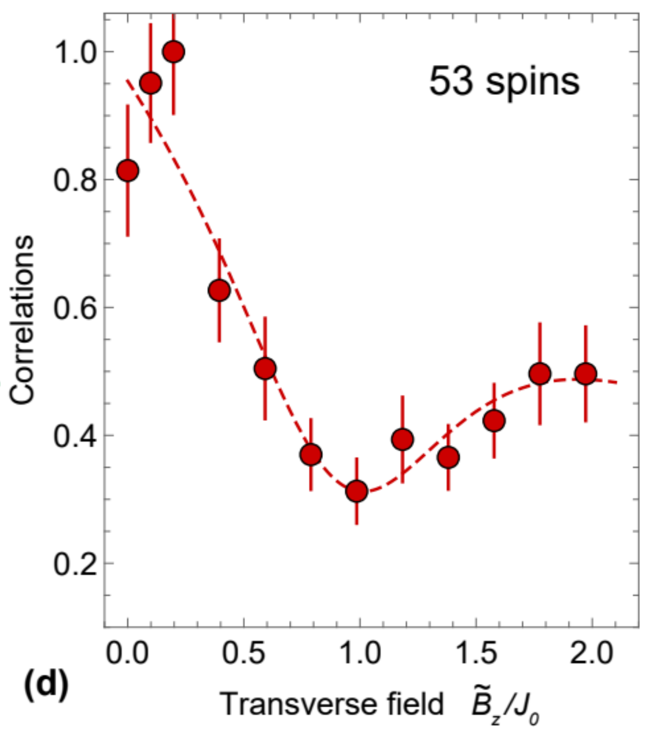
Effective Hamiltonian

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

with coupling:

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

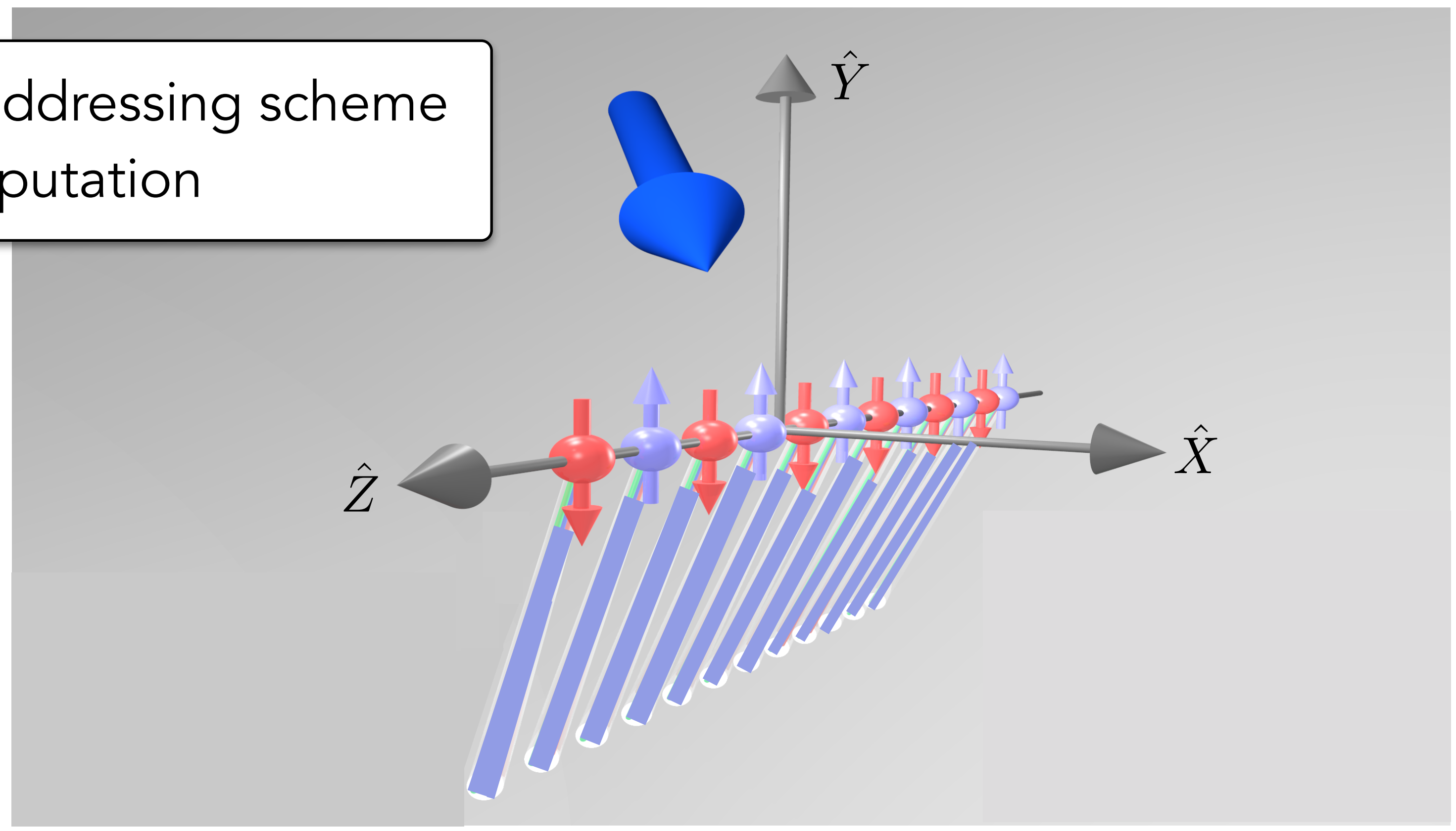




Zhang et al, Nature 551, 601–604 (2017).

EXAMPLE: A TRAPPED-ION DIGITAL SIMULATOR

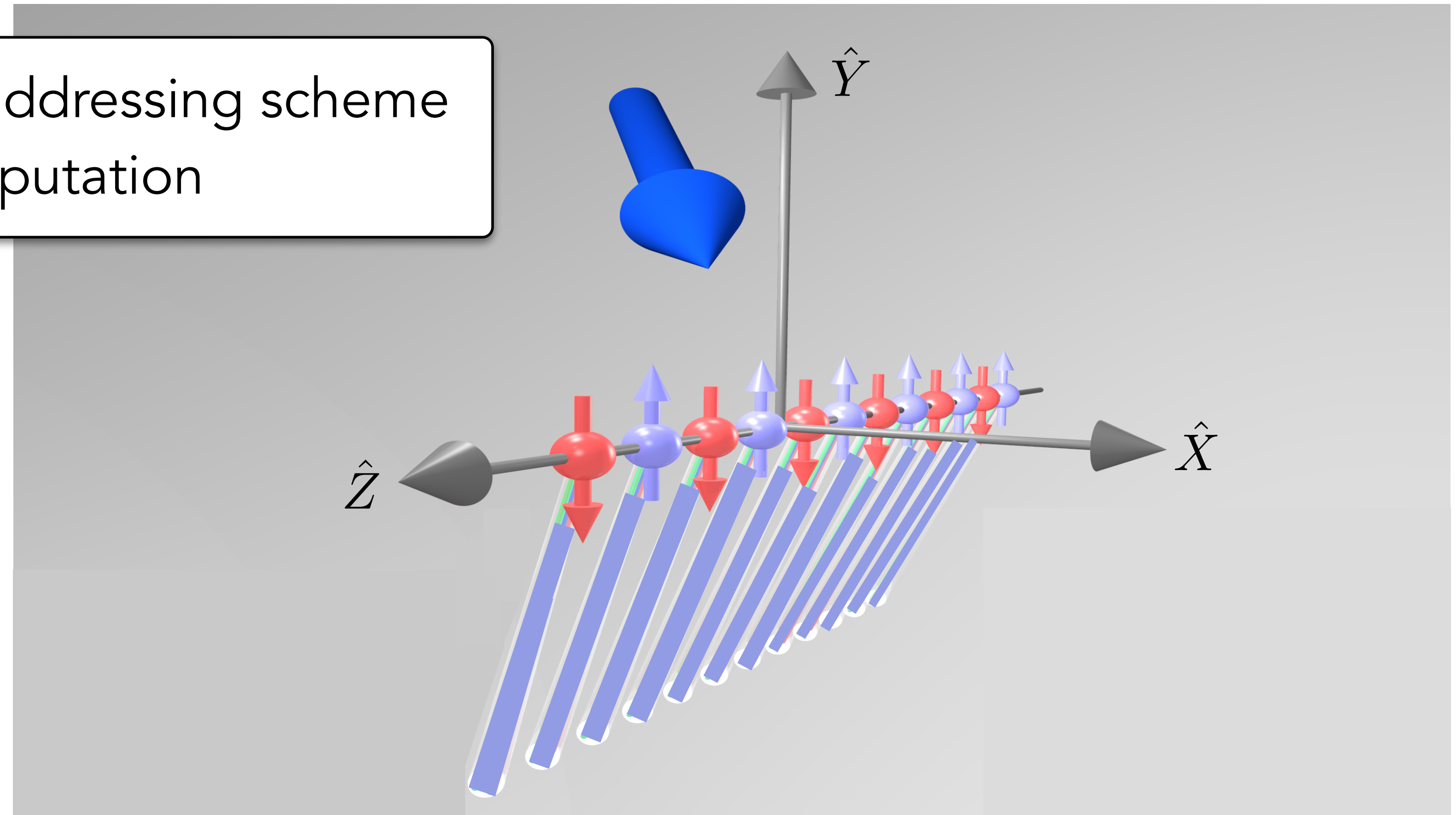
An individual addressing scheme for digital computation



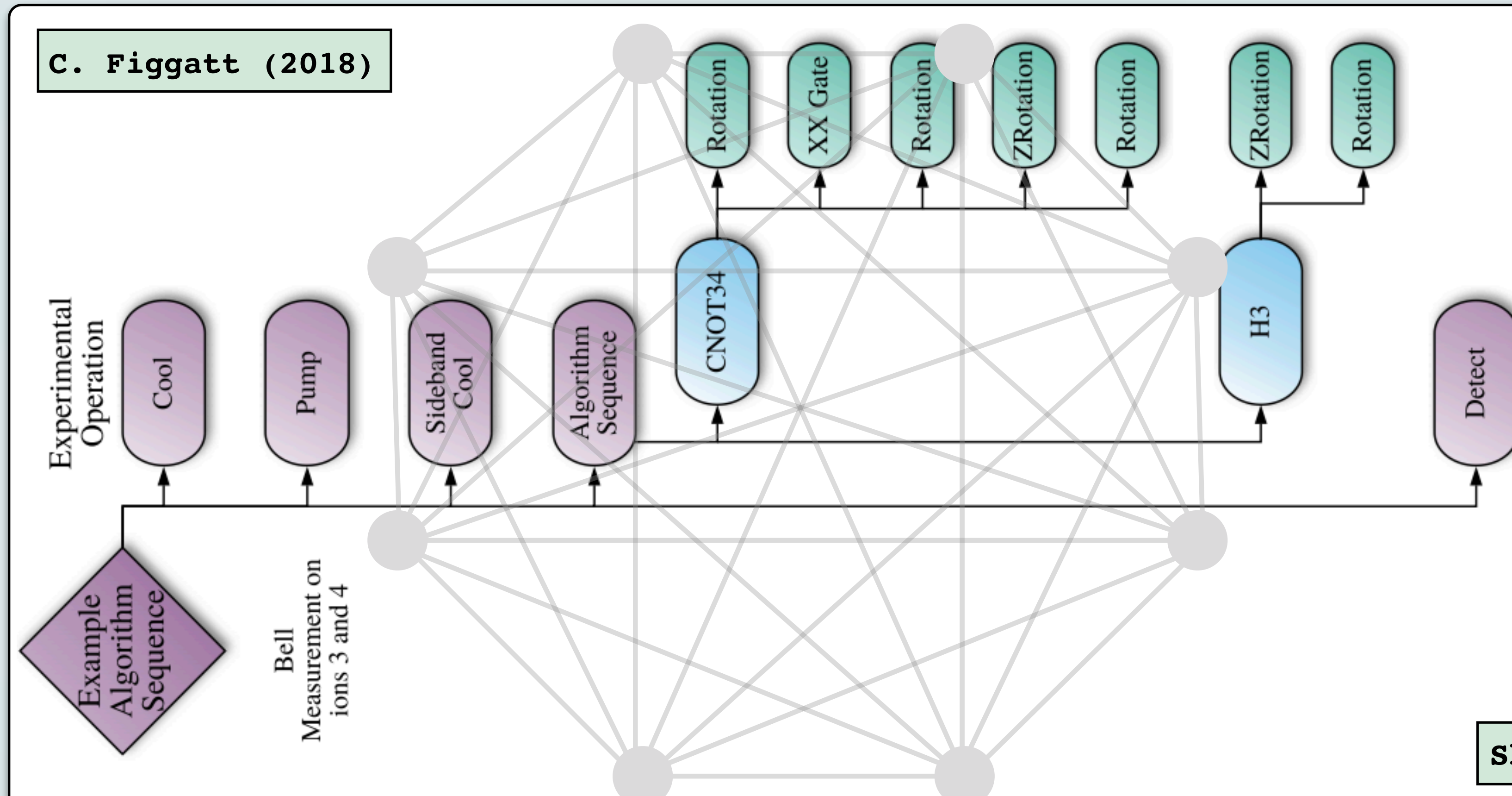
A highly tunable analog simulator is achievable with this set up too: Teoh, Drygala, Melko, Islam arXiv:1910.02496 [quant-ph], Korenblit, Islam, Monroe et al, New Journal of Physics 14, 095024 (2012).

EXAMPLE: A TRAPPED-ION DIGITAL SIMULATOR

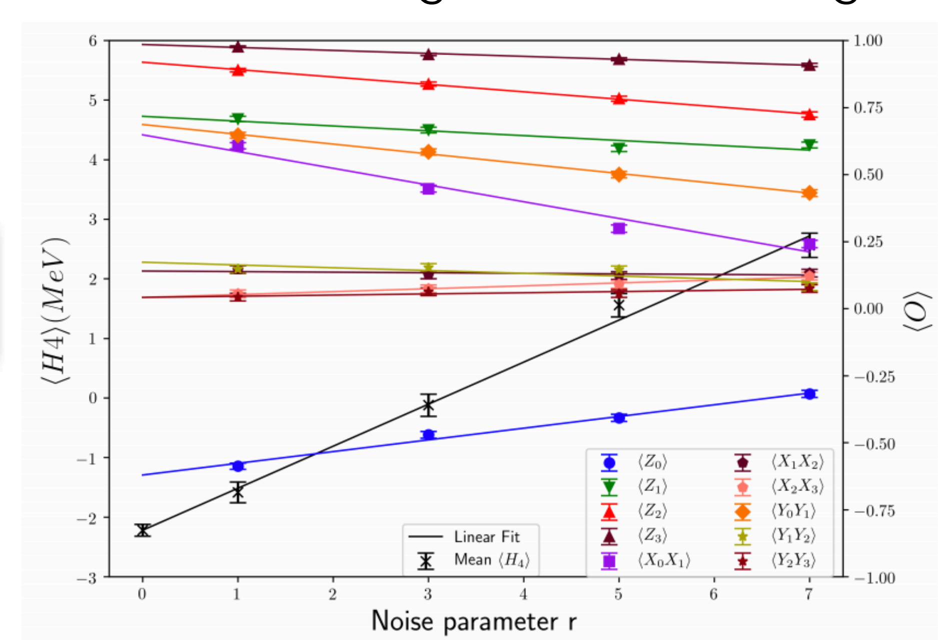
An individual addressing scheme for digital computation



C. Figgatt (2018)



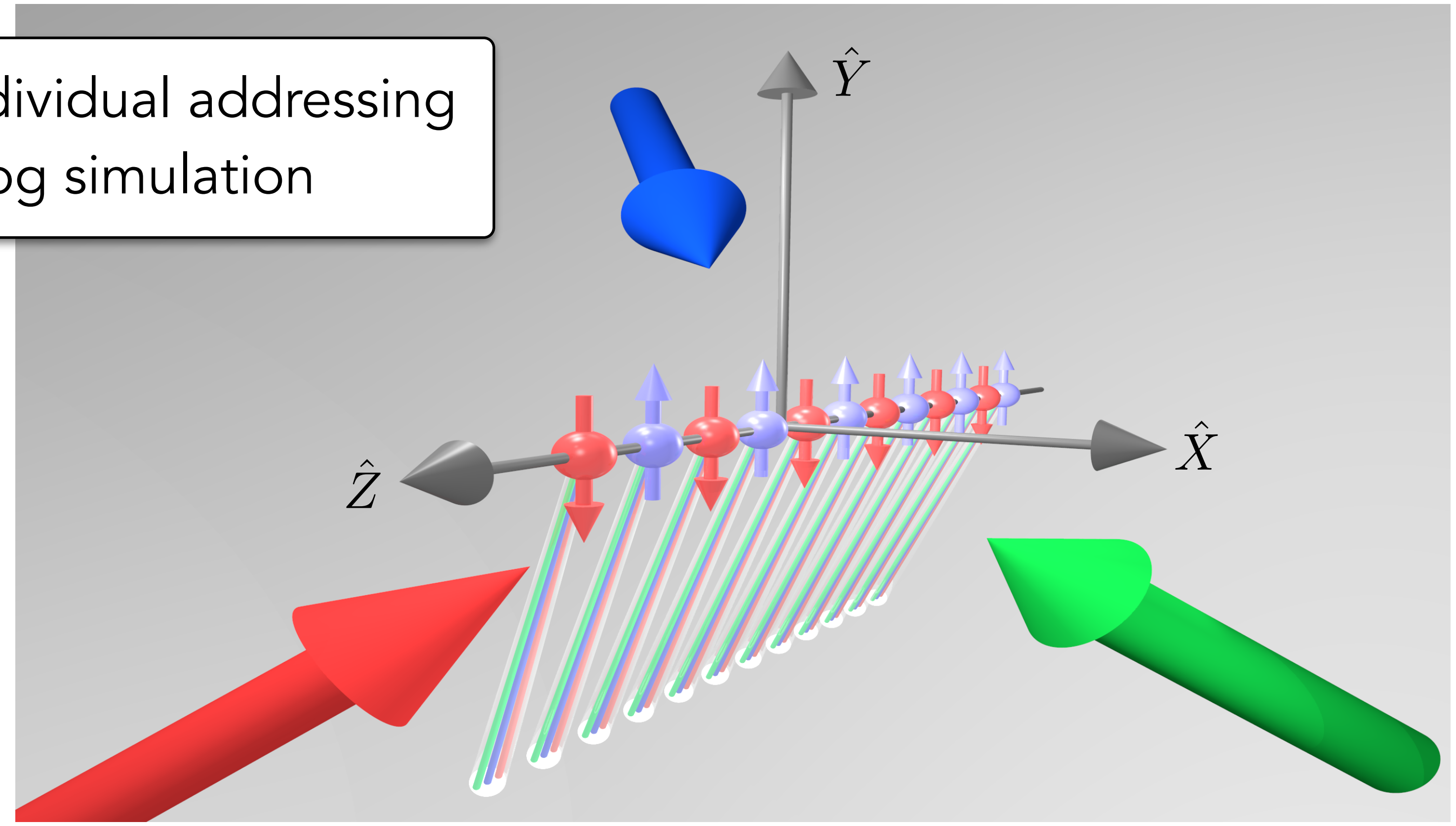
VQE for finding deuteron's binding



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

EXAMPLE: A TRAPPED-ION ANALOG SIMULATOR

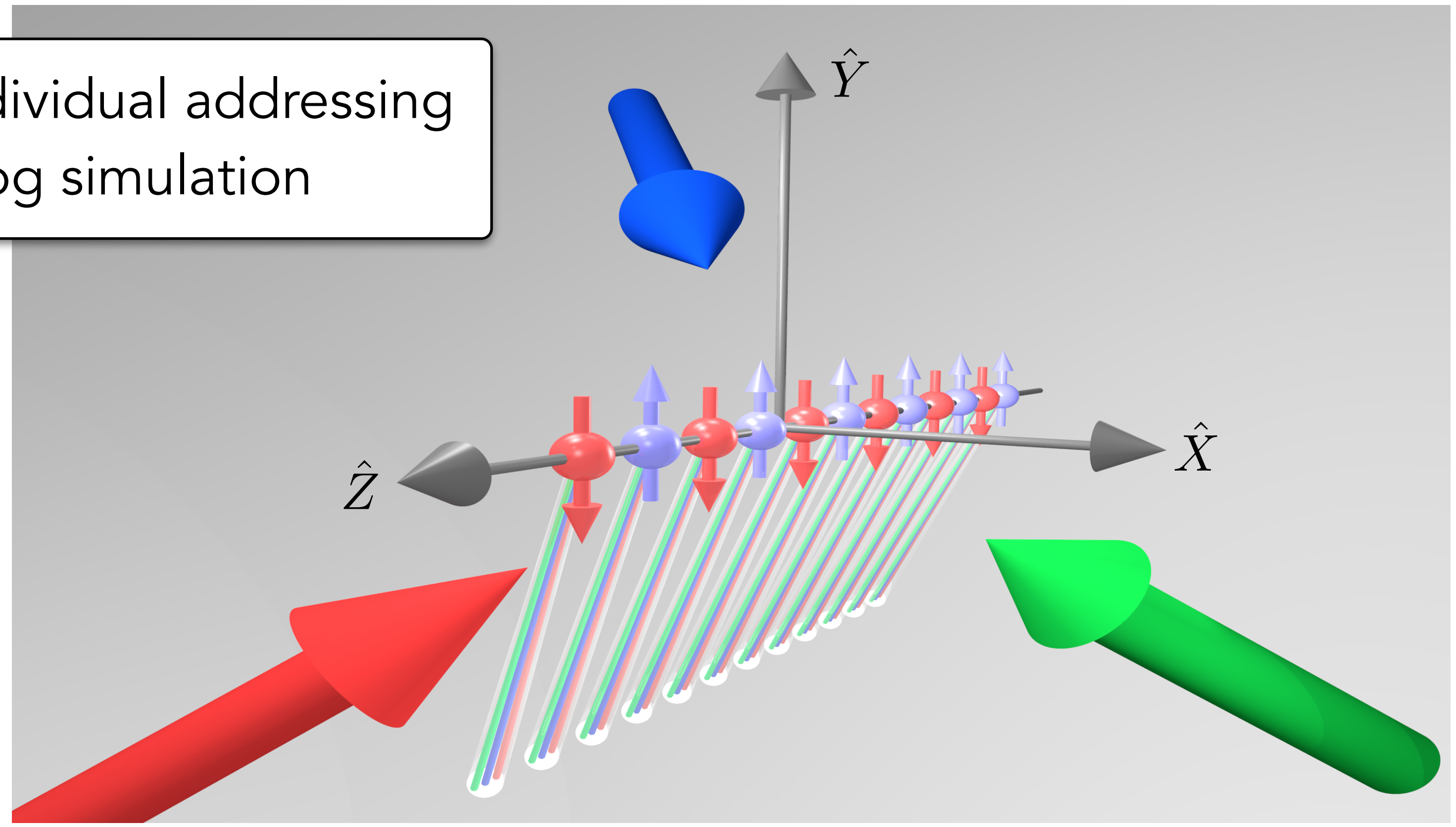
An enhanced individual addressing scheme for analog simulation



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

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:

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

This can be matched to the Hamiltonian of Schwinger Model

$$\hat{H}_s = \frac{\mu}{2}\sum_{n=1}^{N}(-1)^n\sigma_n^z + x\sum_{n=1}^{N-1}\{\sigma_n^+\sigma_{n+1}^- + \text{h.c.}\} + \frac{1}{4}\sum_{n=1}^{N-1}\left\{\sum_{m=1}^{n}\left[\sigma_m^z + (-1)^m\right]\right\}^2$$

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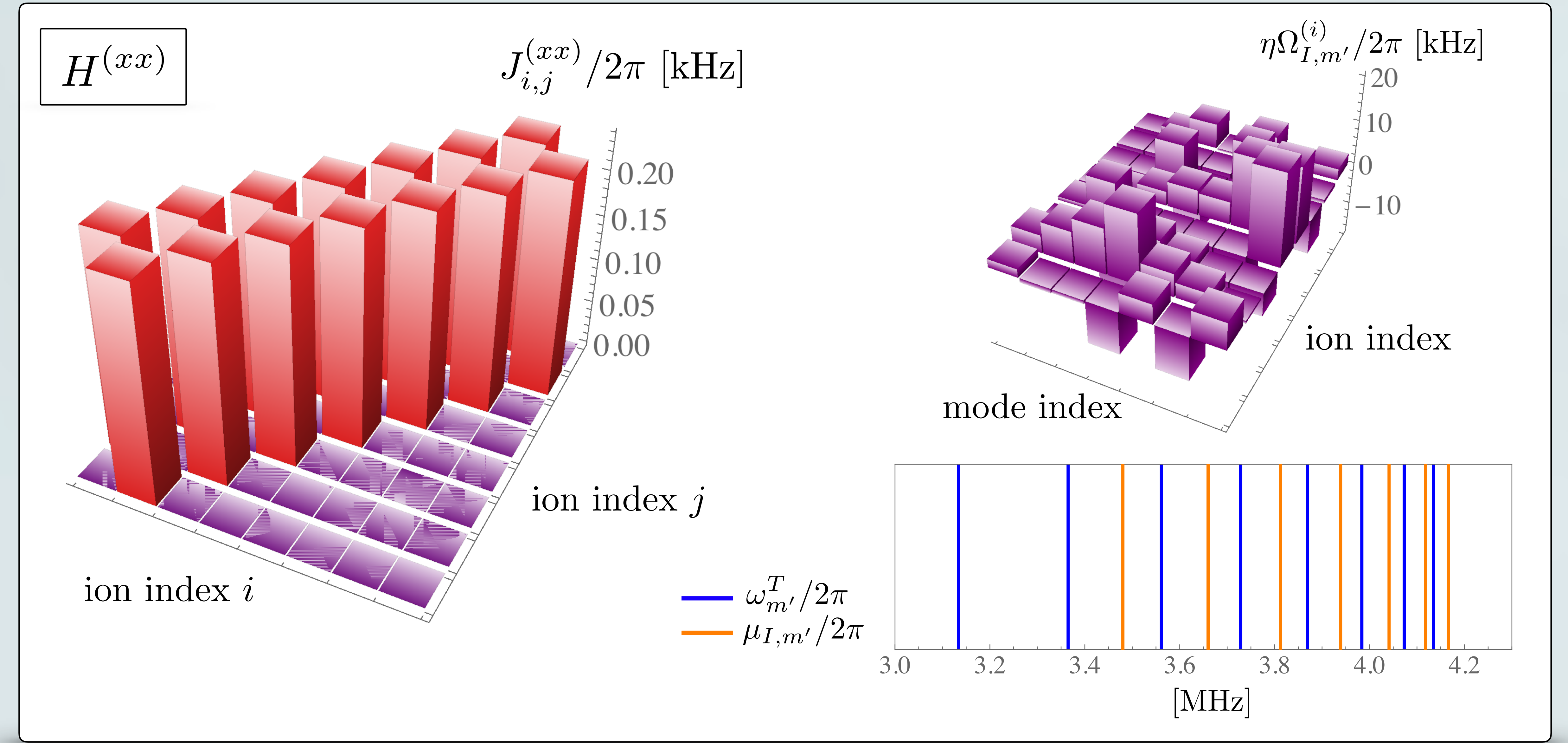

Eight-fermion site theory

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

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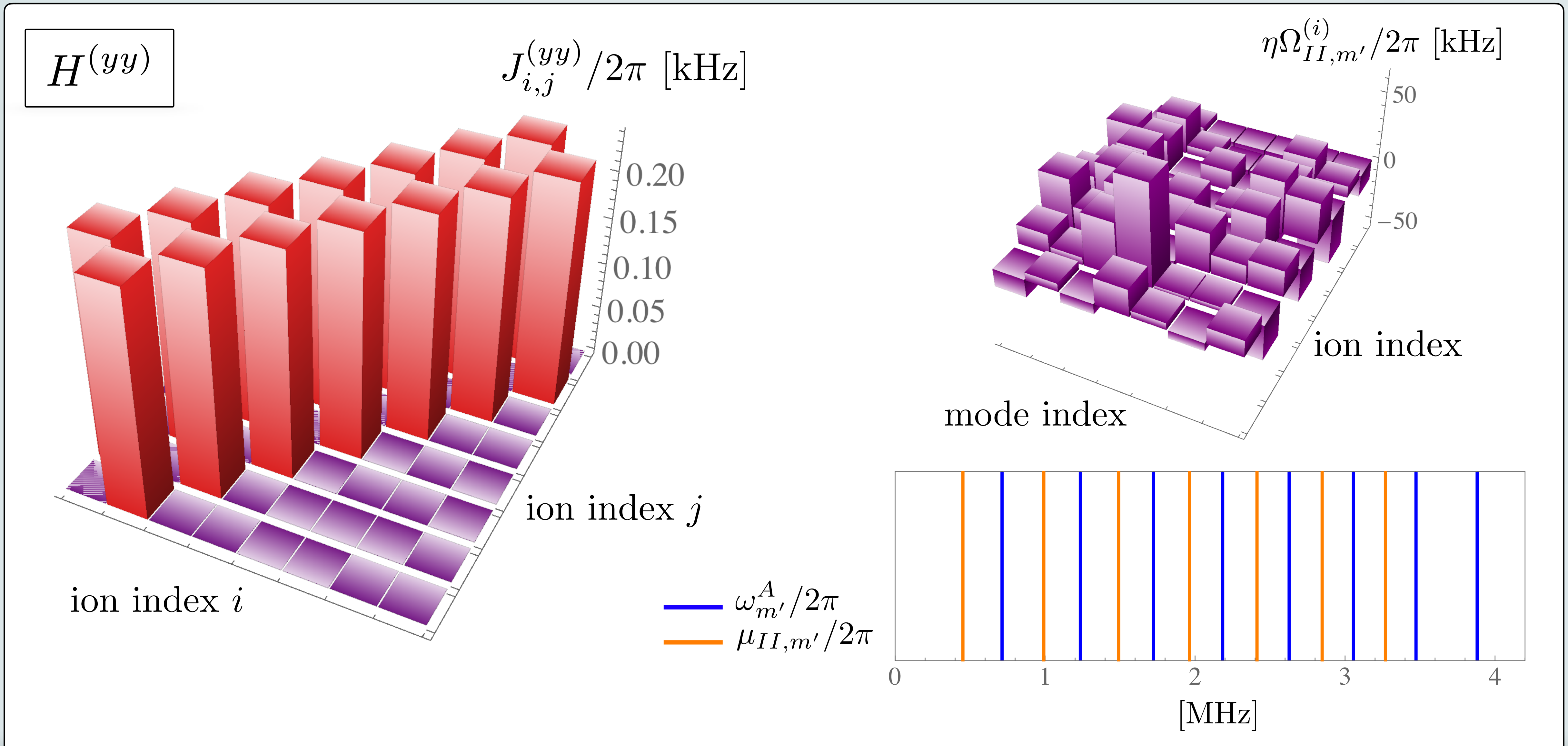

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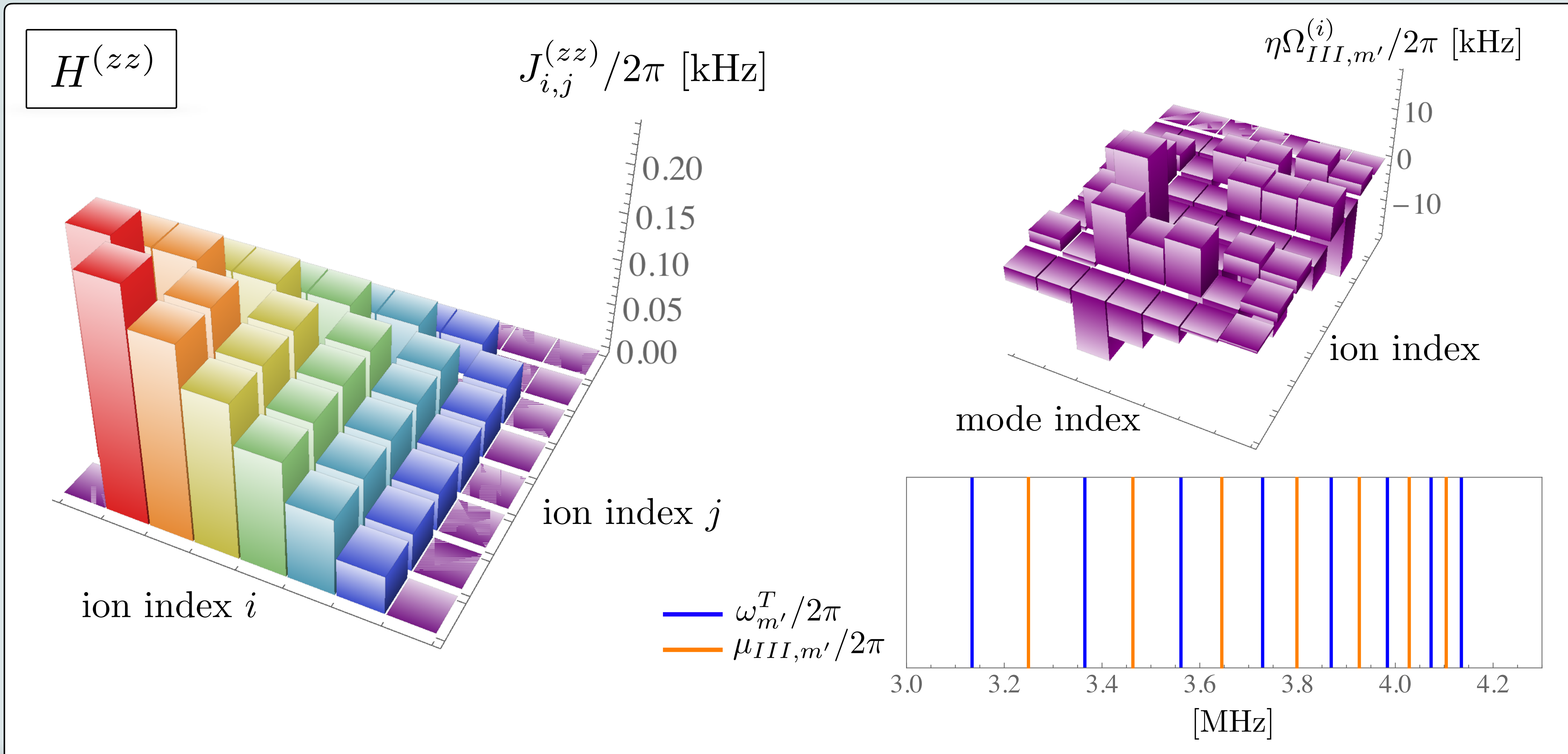


Eight-fermion site theory

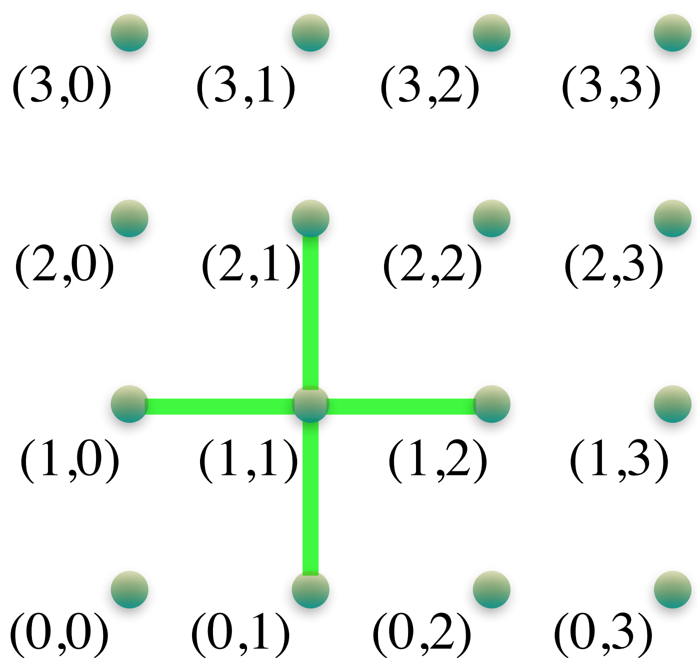
ZD, HAFEZI, MONROE, PAGANO, SEIF AND SHAW, Phys. Rev. R 2, 023015 (2020)

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

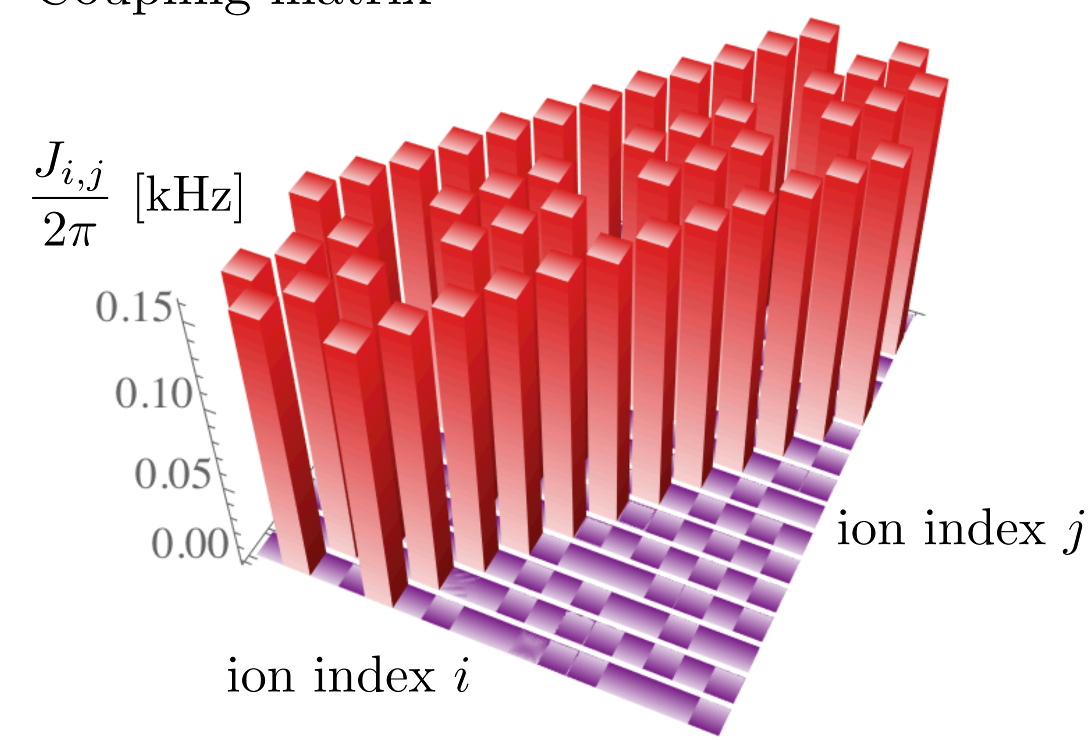
$$\mathcal{L}_{\rm CS} = a^\dagger(x) i D_0 a(x) - \sum_{j=1,2} \left[a^\dagger(x) e^{iA_j(x)} a(x+\hat{\boldsymbol{n}}_j) + \text{h.c.} \right] - \frac{\theta}{4} \epsilon^{\mu\nu\lambda} A_\mu(x) F_{\nu\lambda}(x) \quad (24)$$

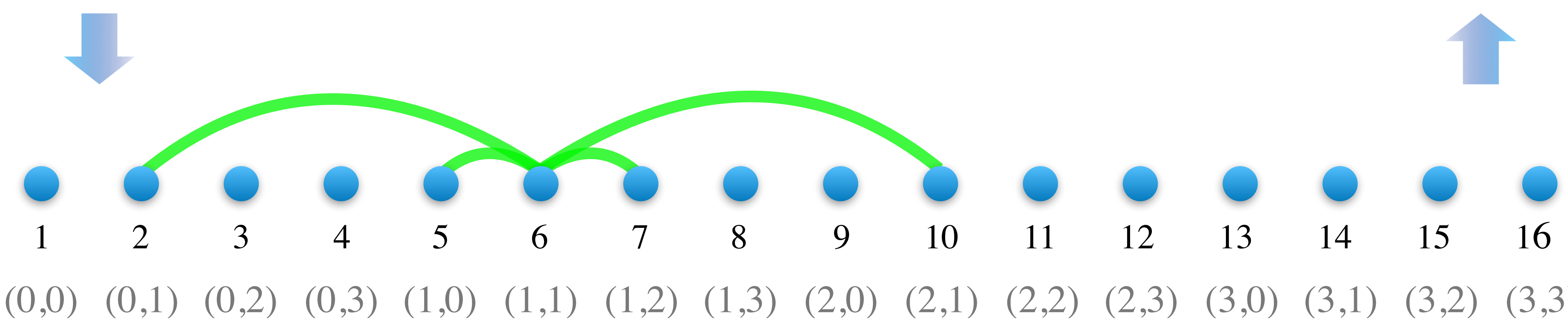
$$H_{\rm CS} = \sum_{\boldsymbol{n}} \sum_{j=1,2} \left[\sigma_+^{(\boldsymbol{n})} \sigma_-^{(\boldsymbol{n}+\hat{\boldsymbol{n}}_j)} + \text{h.c.} \right]$$

2D lattice



Coupling matrix

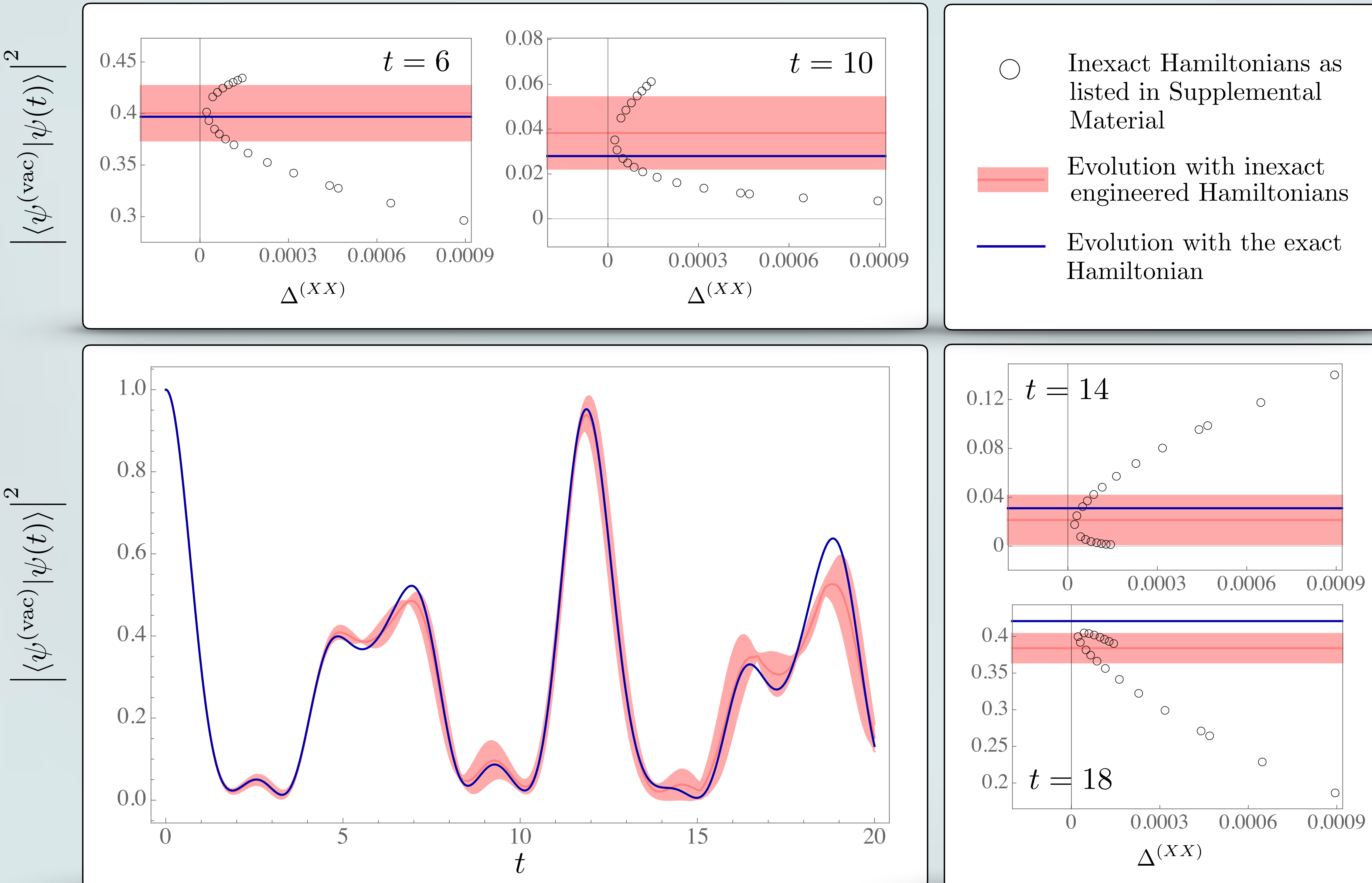




Ion chain

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

HOW IS WE COULD NOT HAVE SIMULATED THE HAMILTONIAN PERFECTLY?

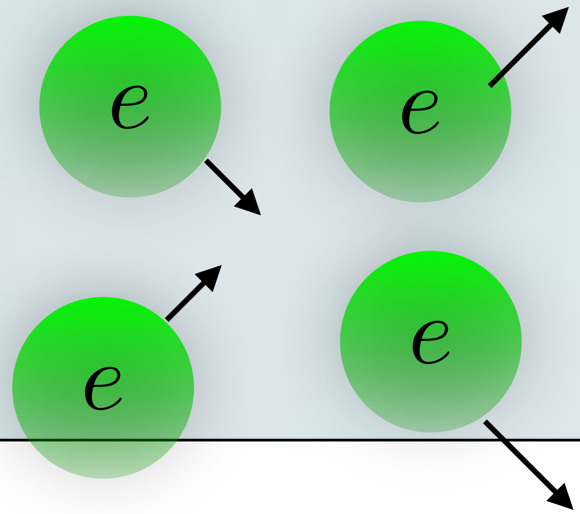


CAN WE DISCOVER DEEPER CONNECTIONS IN NUCLEAR AND PARTICLE PHENOMENOLOGY BY QUANTUM-INFORMATION TOOLS? CAN PROTOTYPES PROVIDE INSIGHT?

SOME EXAMPLES TO DEMONSTRATE THIS POINT…

EXAMPLE I: QUANTUM ENTANGLEMENT IN HIGH-ENERGY ELECTROWEAK INTERACTIONS

Do QED (and weak) processes generate maximal entanglement in scattering? Yes!



Cervera-Lierta, Latorre, Rojo, and Luca Rottoli, SciPost Phys. 3, 036 (2017).

$$|\Phi^{\pm}\rangle \sim |RR\rangle \pm |LL\rangle \text{ and } |\Psi^{\pm}\rangle \sim |RL\rangle \pm |LR\rangle$$

Process		Initial state $\|RR\rangle$		Initial state $\|RL\rangle$	
		High Energy	Low Energy	High Energy	Low Energy
Mott scattering	$e^-\mu^- \to e^-\mu^-$	–	–	–	–
e^-e^+ annihilation into muons	$e^-e^+ \to \mu^-\mu^+$	–	$(\cos\theta\|\Phi^-\rangle - \sin\theta\|\Psi^+\rangle)_{\forall\theta}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	–
Møller scattering	$e^-e^- \to e^-e^-$	–	$\|\Phi^-\rangle_{\theta=\pi/2}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	$\|\Psi^-\rangle_{\theta=\pi/2}$
Bhabha scattering	$e^-e^+ \to e^-e^+$	–	–	$\|\Psi^+\rangle_{\theta=\pi/2}$	–
Pair annihilation	$e^-e^+ \to \gamma\gamma$	–	$\|\Phi^-\rangle_{\forall\theta}$	$\|\Psi^-\rangle_{\theta=\pi/2}$	–

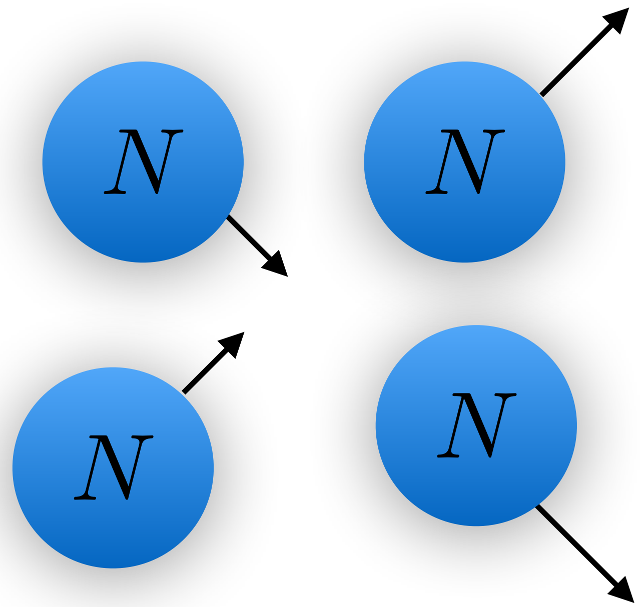
Product state (not entangled)

Maximally-entangled state

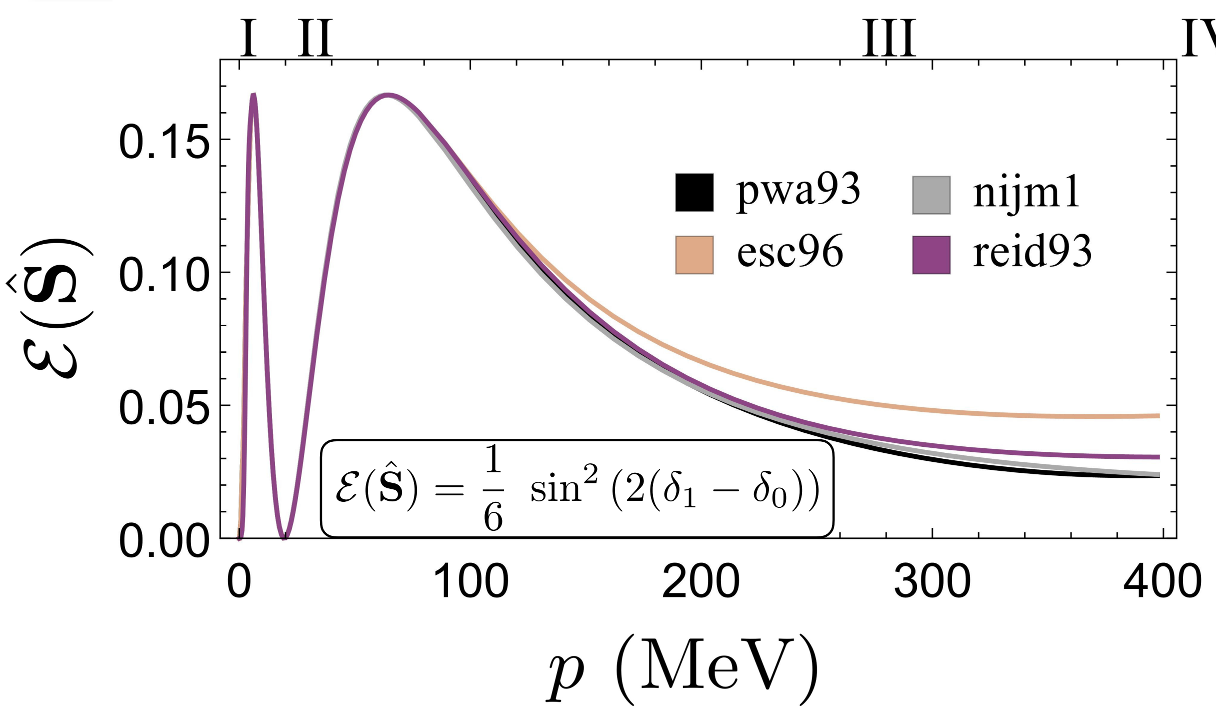
The principle of maximal entanglement constrains the QED gauge-matter form, as well as the Weinberg angle of weak interactions!

EXAMPLE II: QUANTUM ENTANGLEMENT IN LOW-ENERGY NUCLEAR PHYSICS

NN interactions at low energies are consistent with vanishing entanglement…



$SU(4)$



Beane, Kaplan, Klco and Savage, Phys. Rev. Lett. 122, 102001 (2019)

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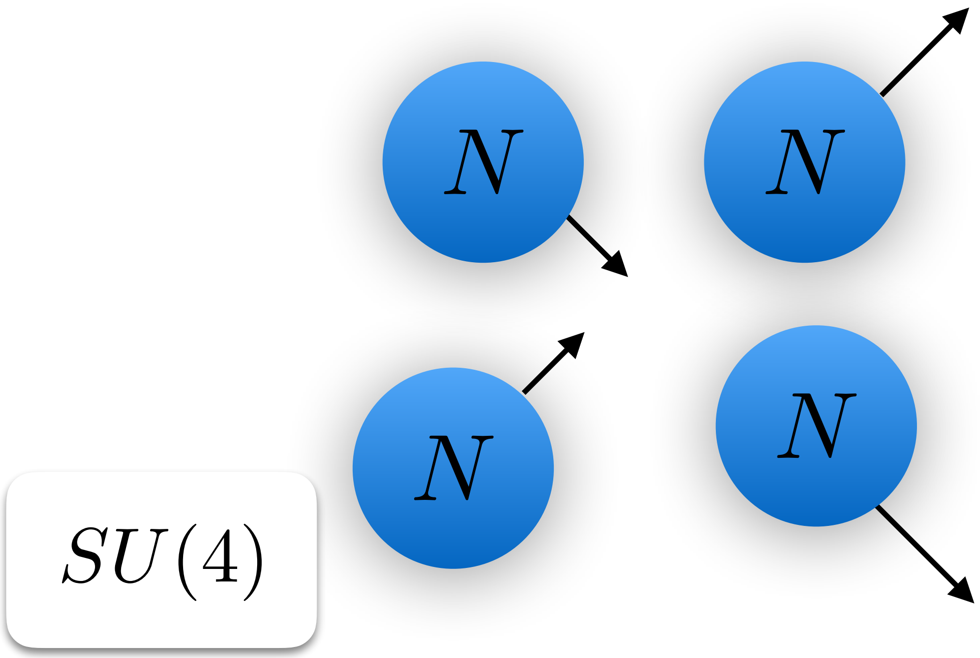
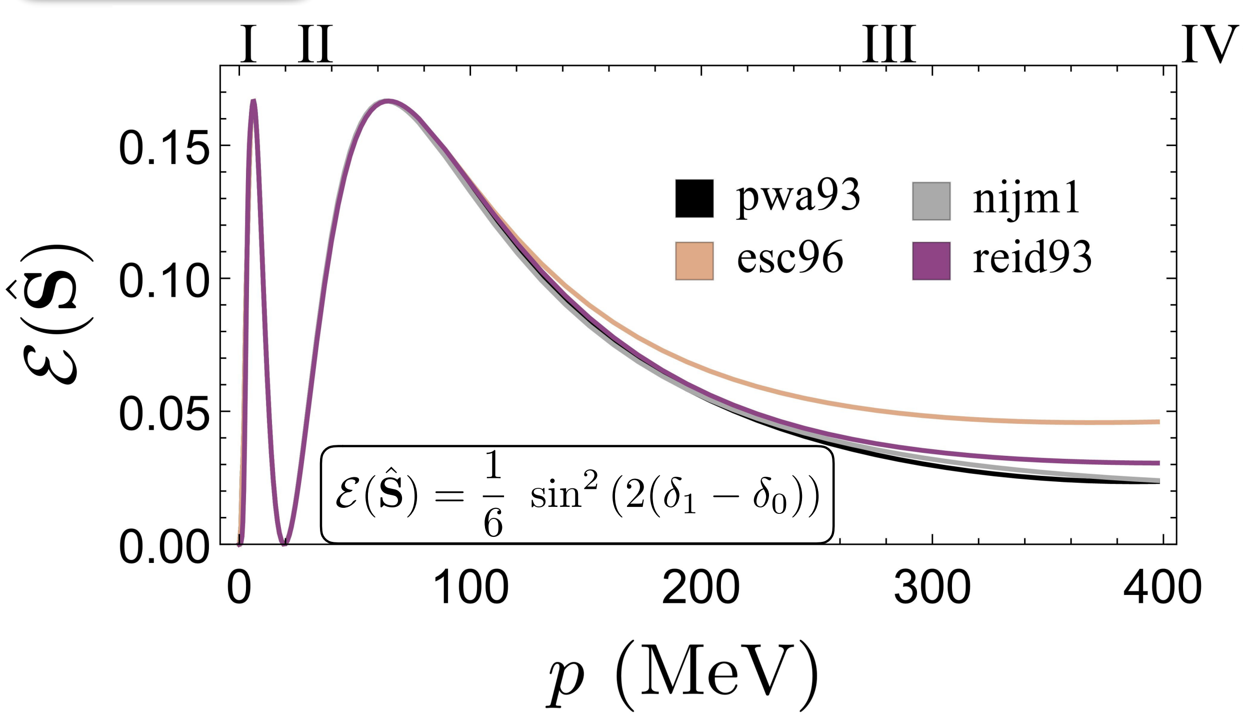
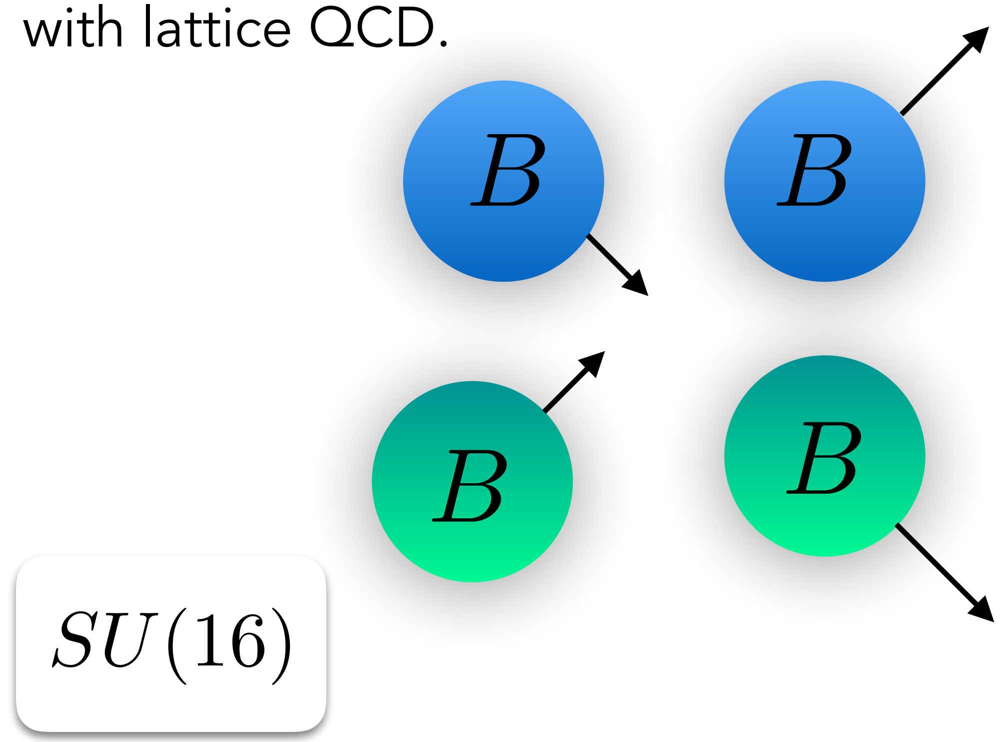
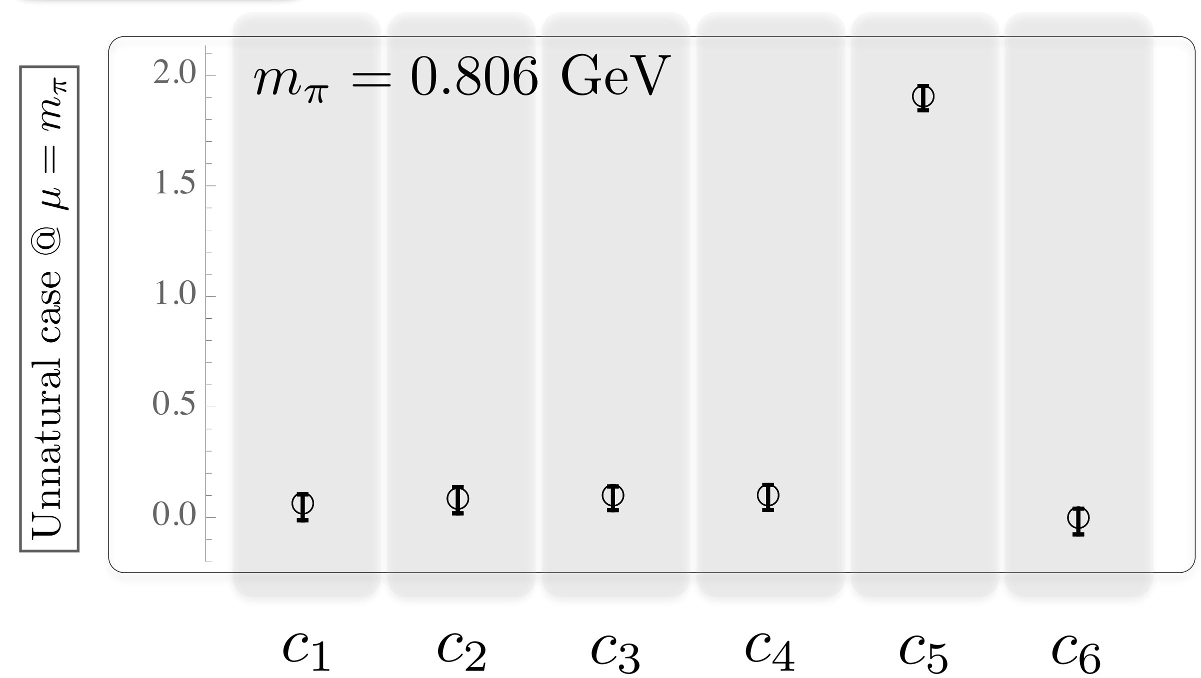




Beane, Kaplan, Klco and Savage, Phys. Rev. Lett. 122, 102001 (2019)

…as are low-energy BB interactions as obtained with lattice QCD.





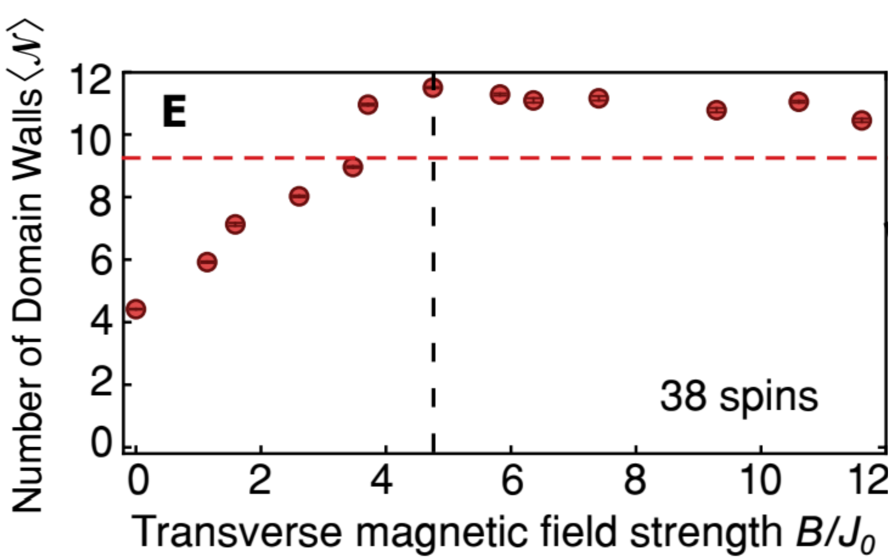
Wagman, Winter, Chang, ZD, Detmold, Orginos, Savage, Shanahan (NPLQCD), Phys. Rev. D 96, 114510 (2017)

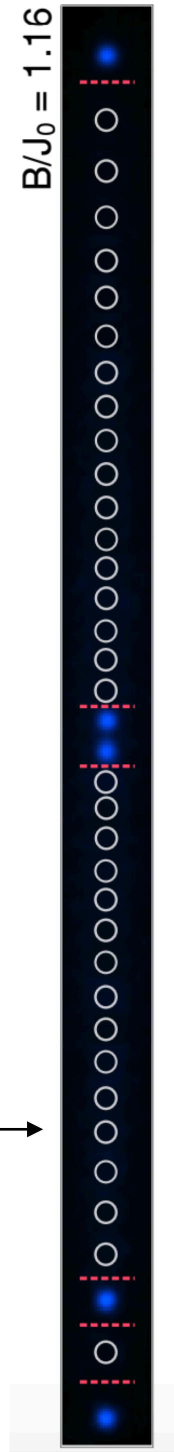
EXAMPLE III: SPIN MODELS AS PROTOTYPES OF QCD? CAN THEY REVEAL ENTANGLEMENT ASPECTS OF CONFINEMENT AND COLLISIONS?

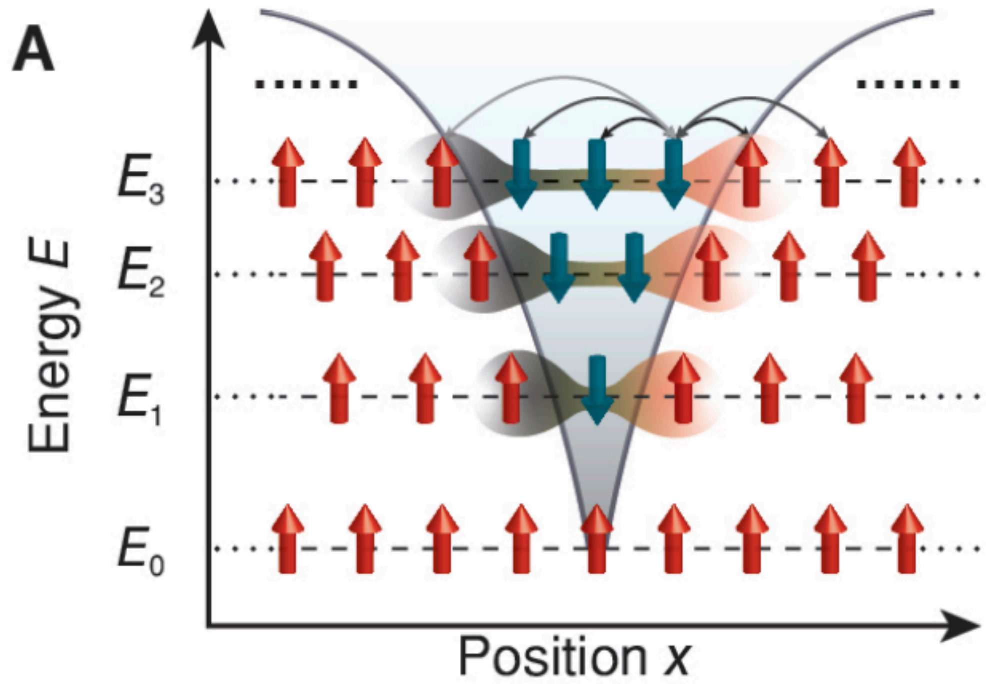
Transverse-field Ising model with long-range interactions in 1+1D exhibits an effective confining potential among domain walls: the "mesons"!

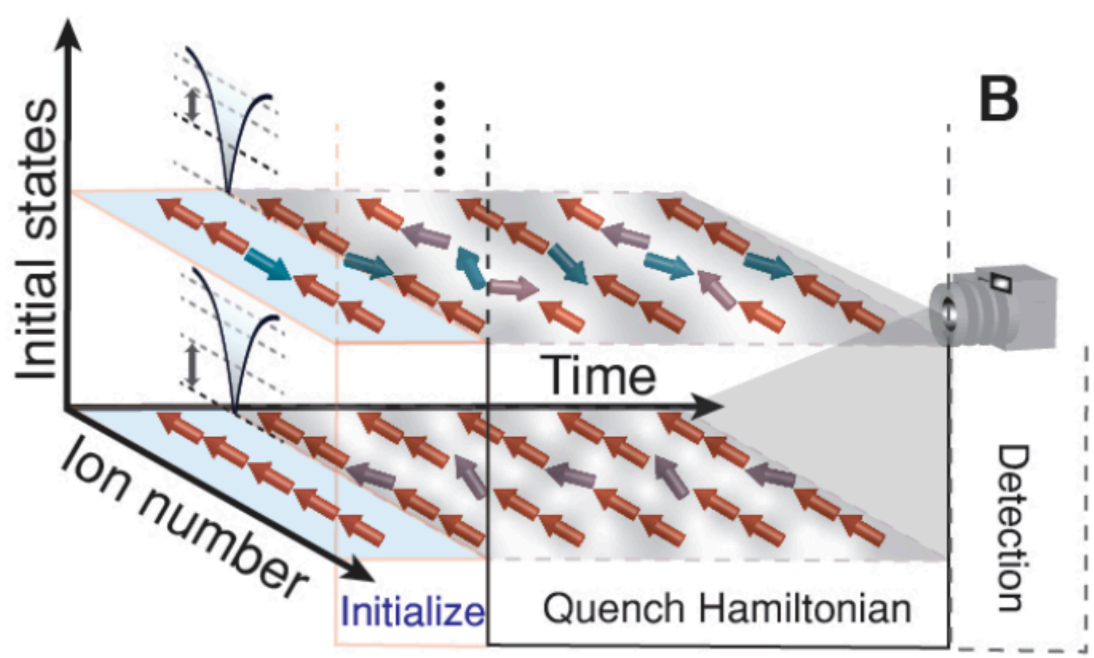
$$H = -\sum_{i<j}^{L} J_{i,j}\sigma_i^x\sigma_j^x - B\sum_{i}^{L}\sigma_i^z.$$

Native Hamiltonian in a trapped-ion simulator!









Tan, Becker, Liu, Pagano, Collins, De, Feng, Kaplan, Kyprianidis, Lundgren, Morong, Whitsitt, Gorshkov, Monroe, arXiv:1912.11117 [quant-ph]

See also: Milsted, Liu, Preskill, Vidal, arXiv: 2012.07243 [quant-ph]

TO SUMMARIZE…

A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES

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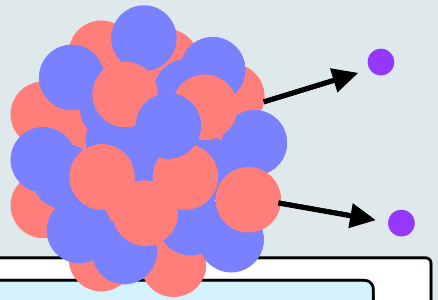
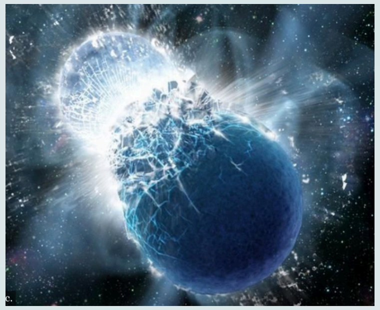


Dana Berry, Skyworks Digital, Inc.

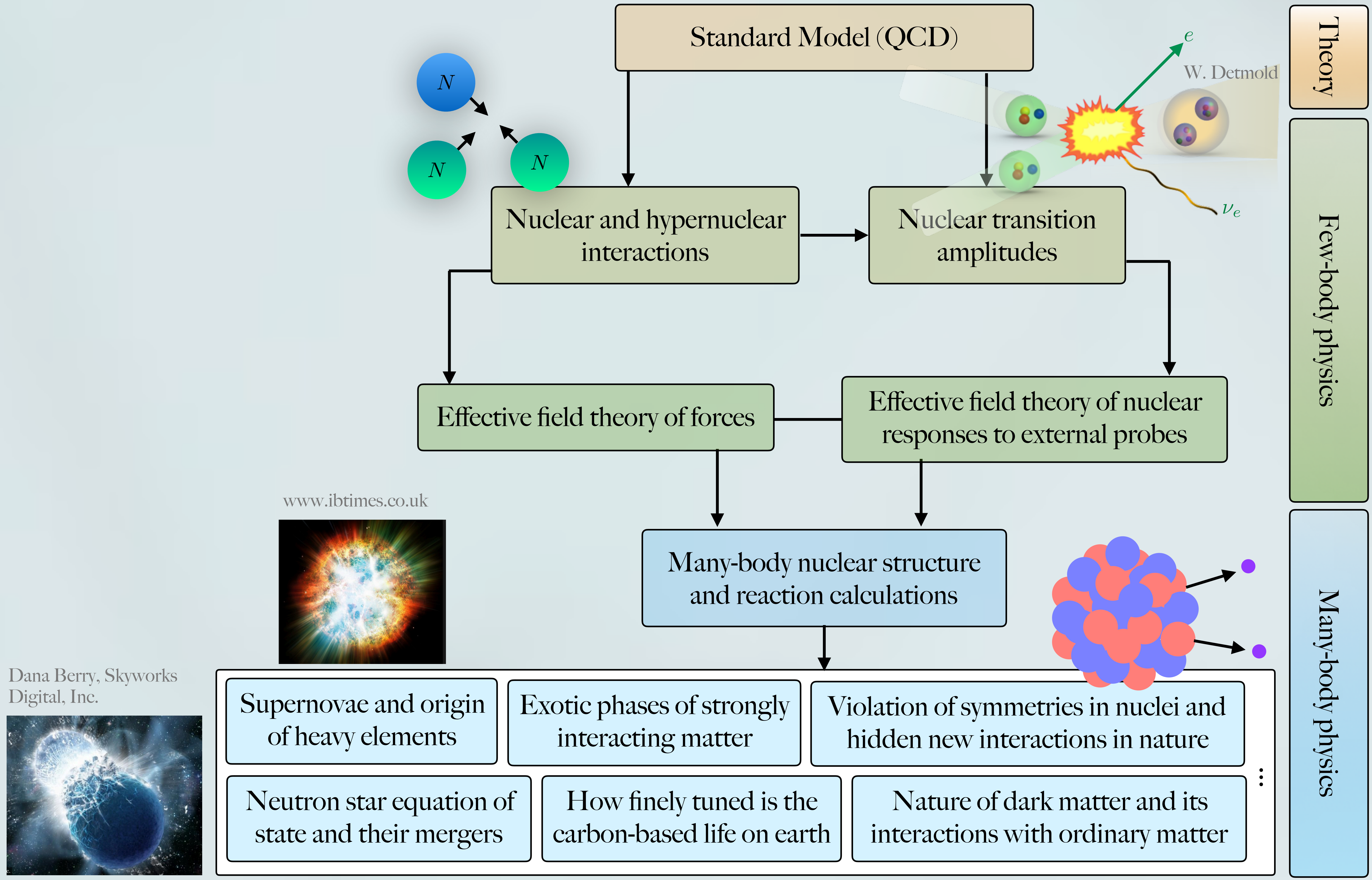


Supernovae and origin of heavy elements	Exotic phases of strongly interacting matter	Violation of symmetries in nuclei and hidden new interactions in nature
Neutron star equation of state and their mergers	How finely tuned is the carbon-based life on earth	Nature of dark matter and its interactions with ordinary matter

⋮

Many-body physics

A NUCLEAR PHYSICS ROADMAP FOR LEVERAGING QUANTUM TECHNOLOGIES



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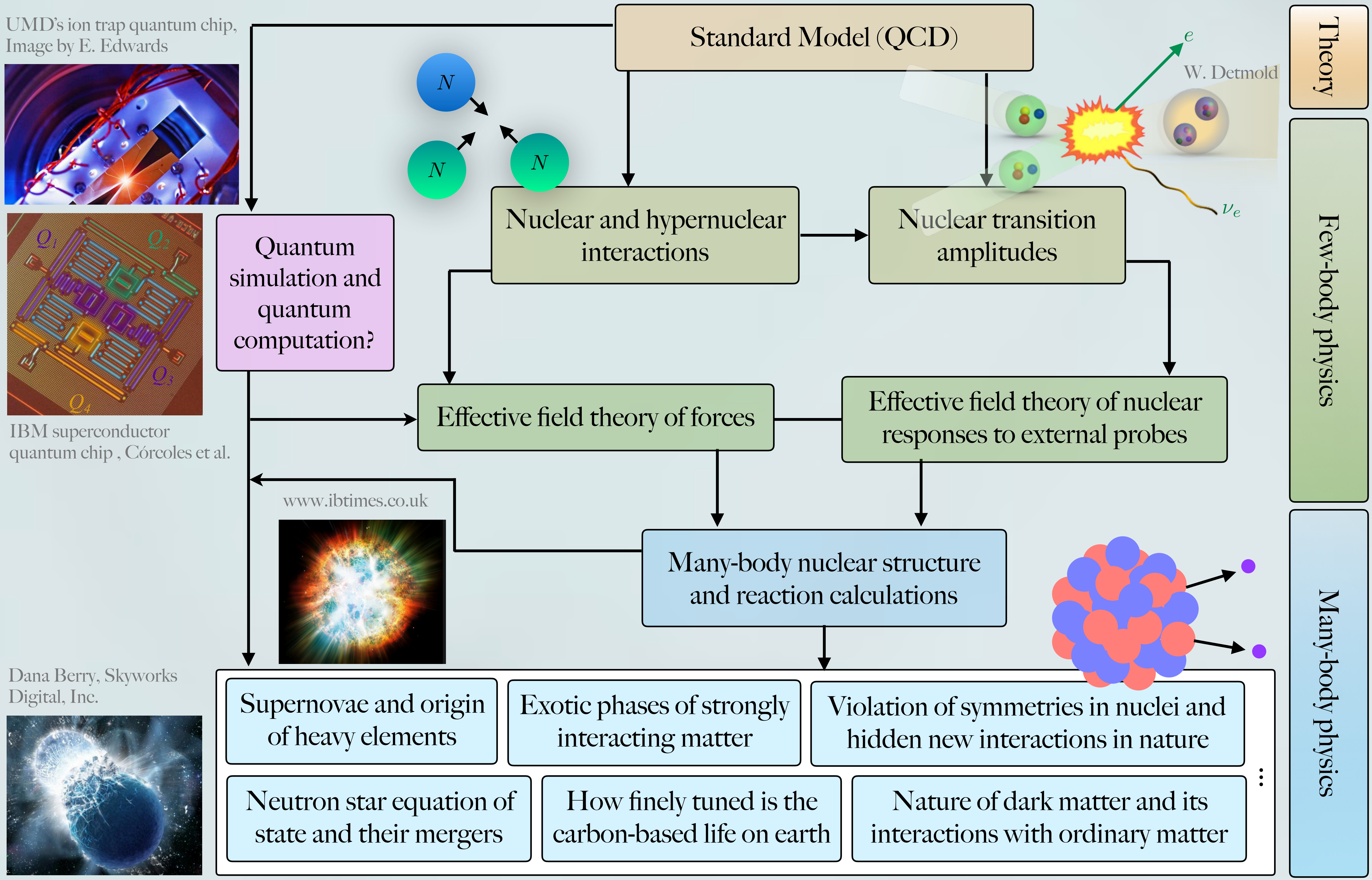

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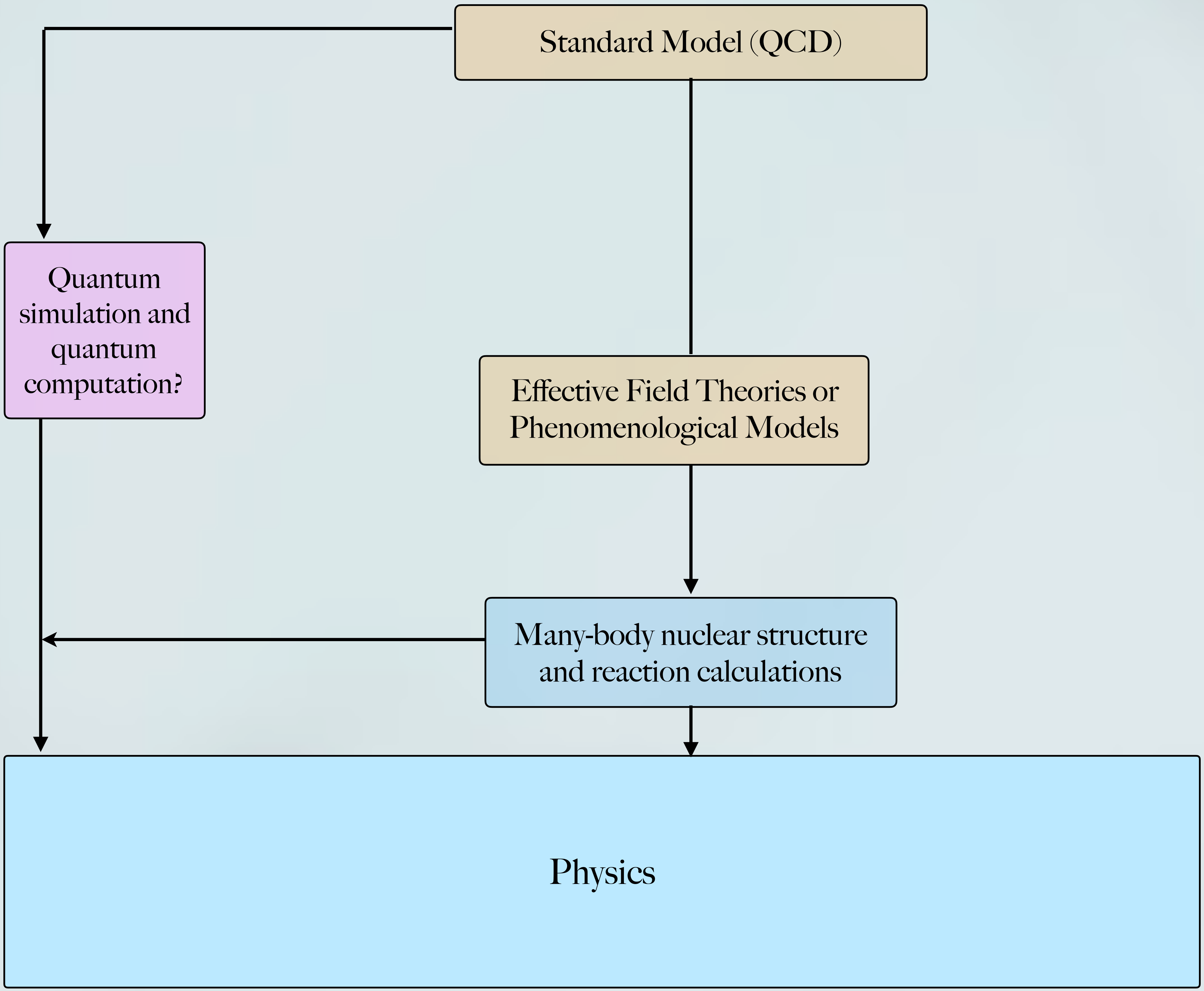
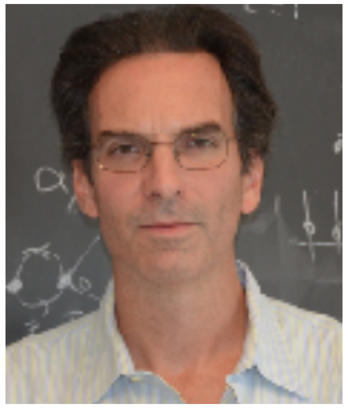


MANY THANKS TO…

MY COLLABORATORS IN LATTICE QCD



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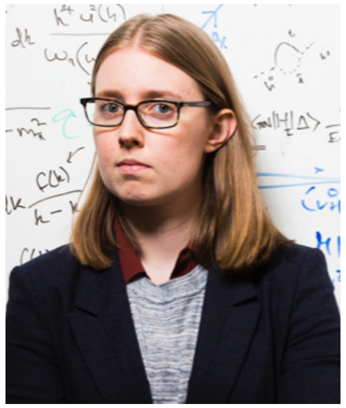

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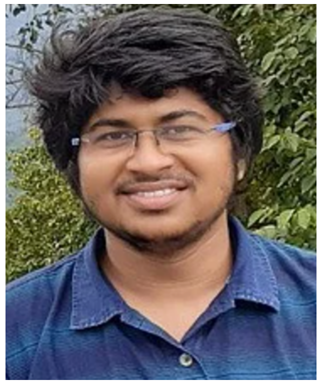

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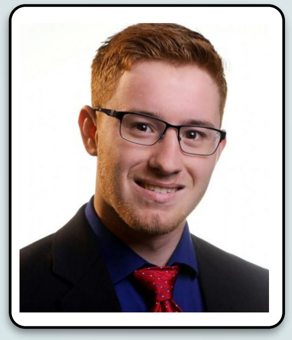

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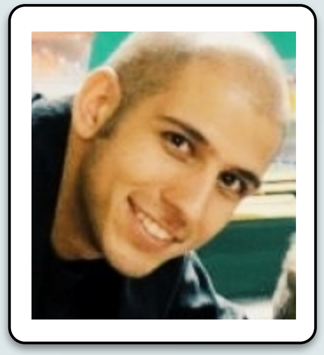

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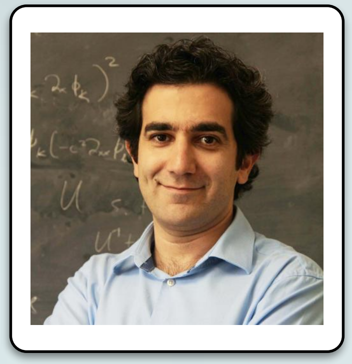

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