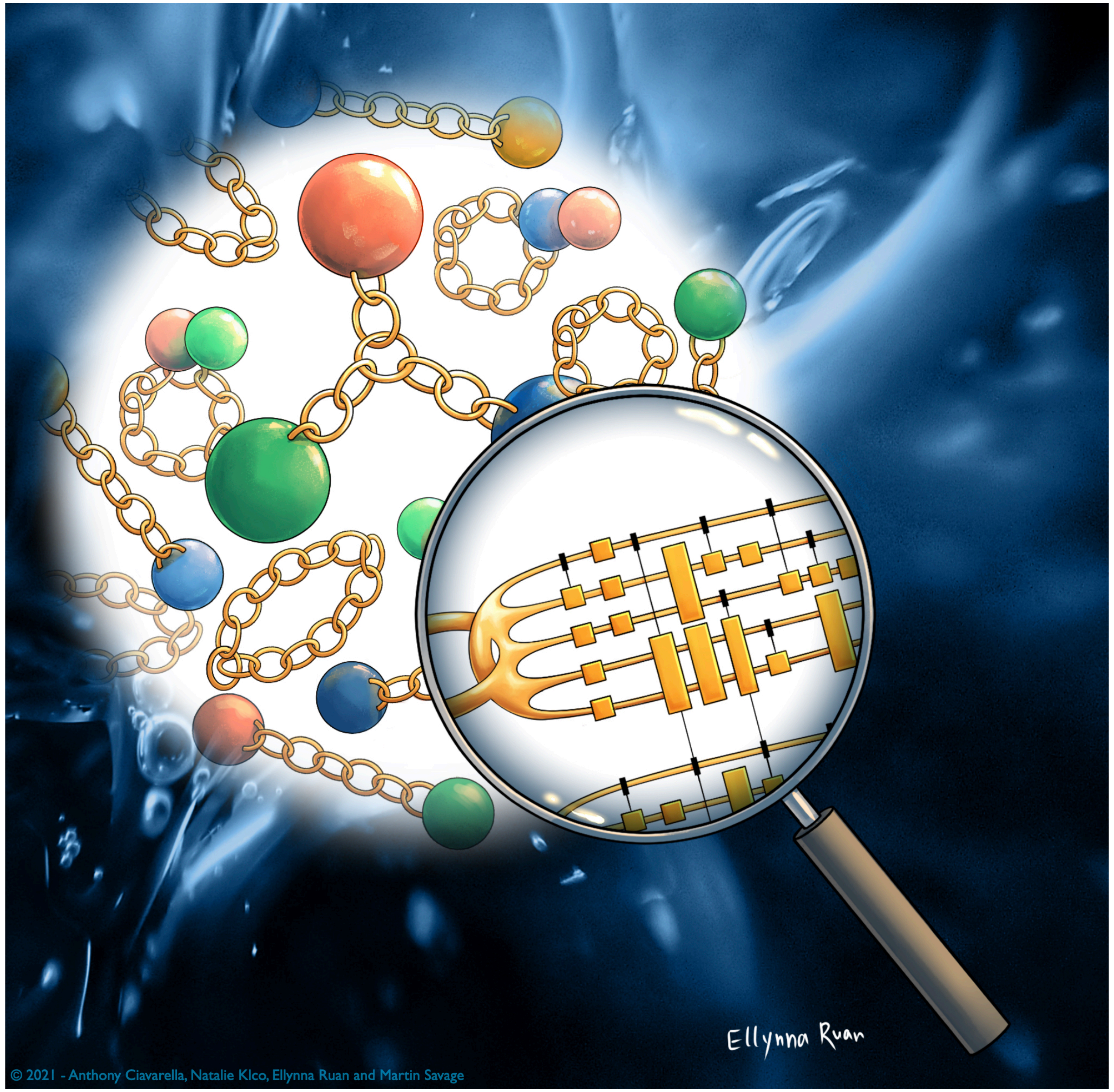


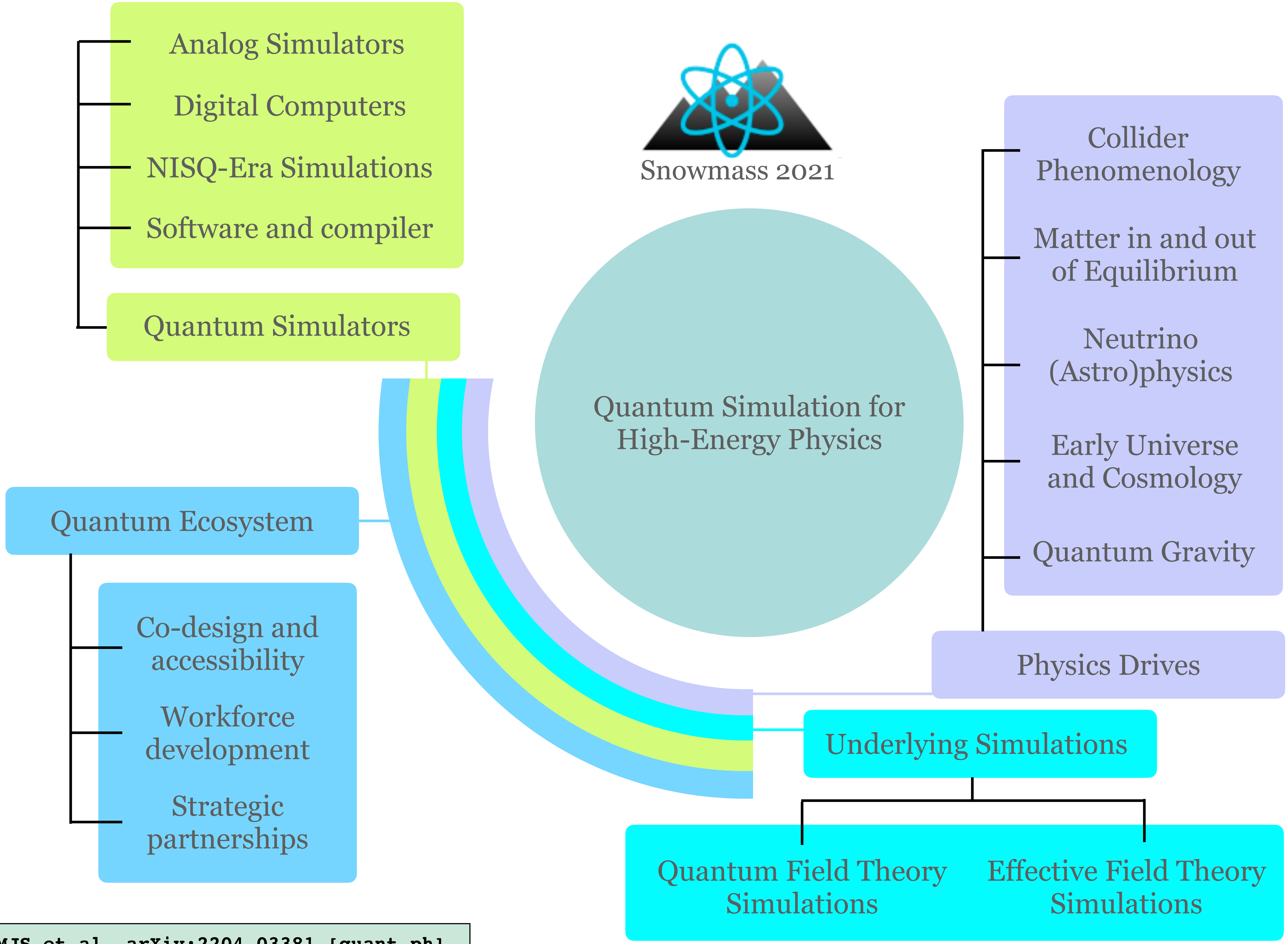
Quantum Simulations: Applications

Martin J Savage/Zohreh Davoudi

IQuS InQubator for Quantum Simulation
UNIVERSITY of WASHINGTON
Institute for Robust Quantum Simulation

Snowmass, CompF and TF
Friday, July 22, 10.00-12:00

For References and more Context, Please Check out the QS for HEP Whitepaper…

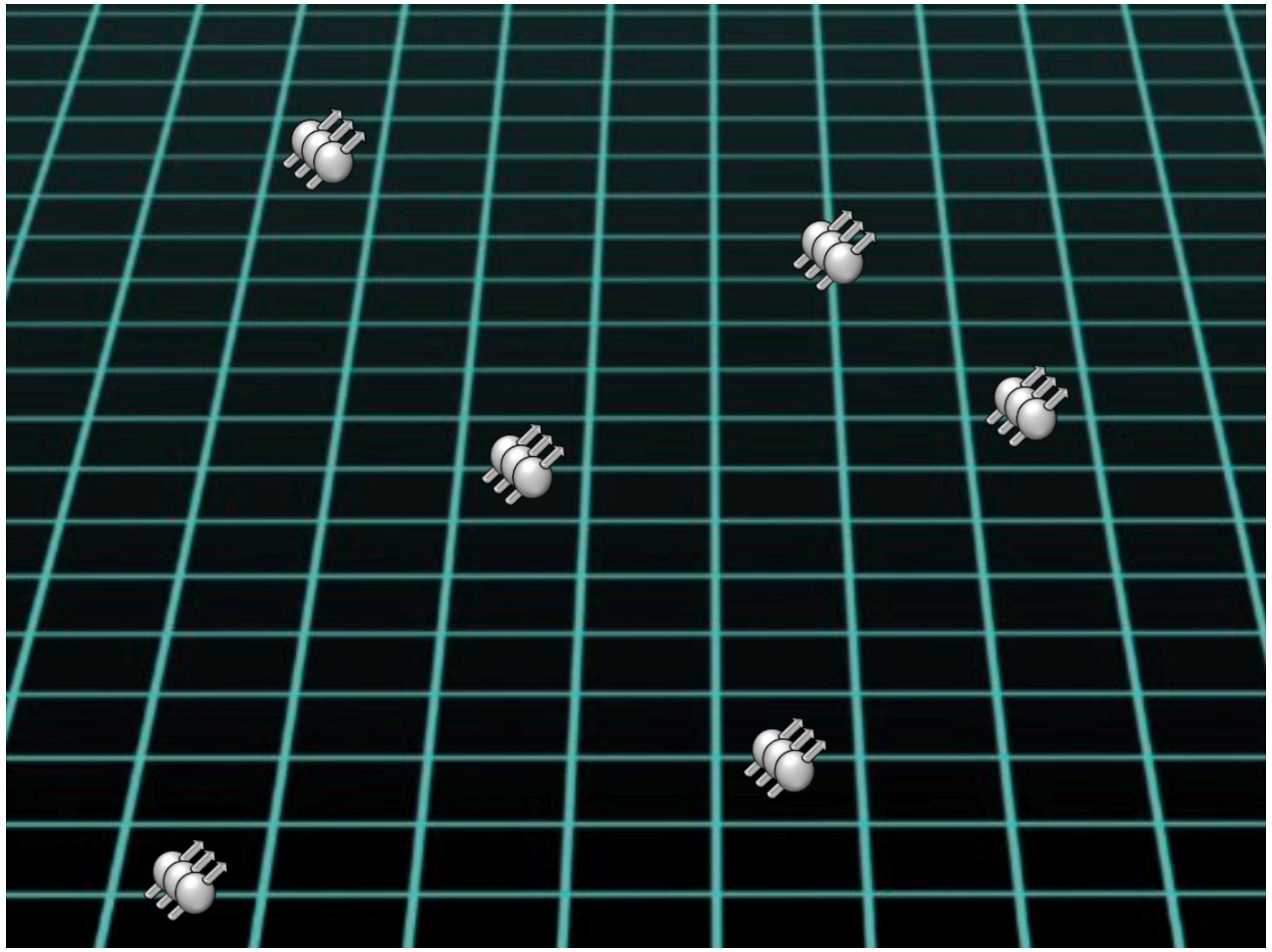


Bauer, ZD, MJS et al, arXiv:2204.03381 [quant-ph].

When will Applications Require Quantum Resources ?

If a classical computer can solve the problem, why "compete" using a quantum device?

e.g. pion mass can be computed with LQCD

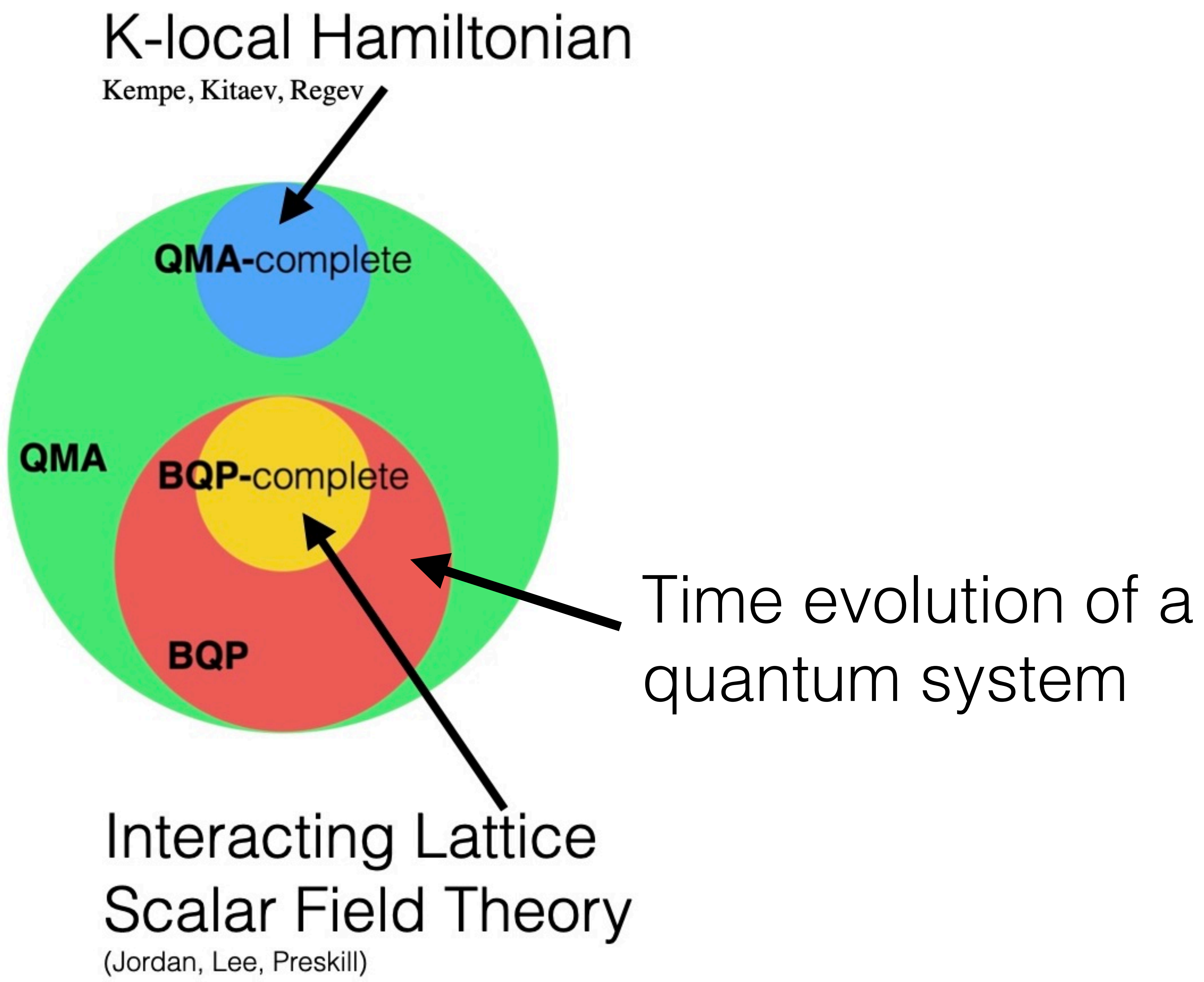


Entanglement is the "additional" attribute…

Use quantum devices to solve the (parts of) problems that classical computers can't.

"Gotta *know* your problems!"

Scaling of Quantum Resource Requirements and Complexity Classes



Far from "asymptotic resources" !!

"Useful Scalings":
The performance of our current circuits on current hardware, and "educated" extrapolations.

Complexity class indicates worst case
- can be much better, e.g. symmetries

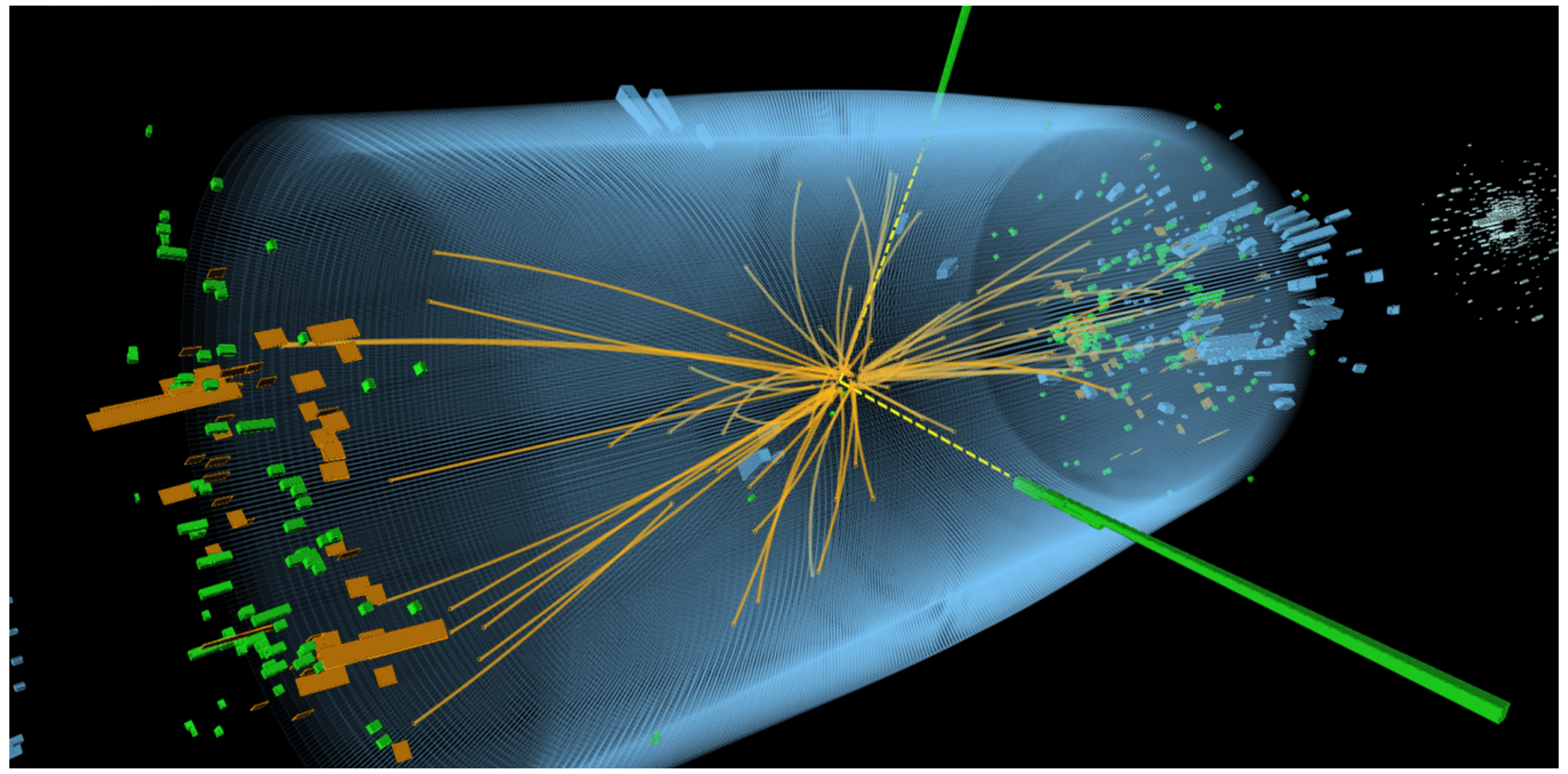
Expect enormous progress in applications that are in the "wrong" complexity classes

The "B" in BQP gives us latitude to change theories "a little"

With a target precision, perturbative expansions can potentially change problem difficulty

Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models



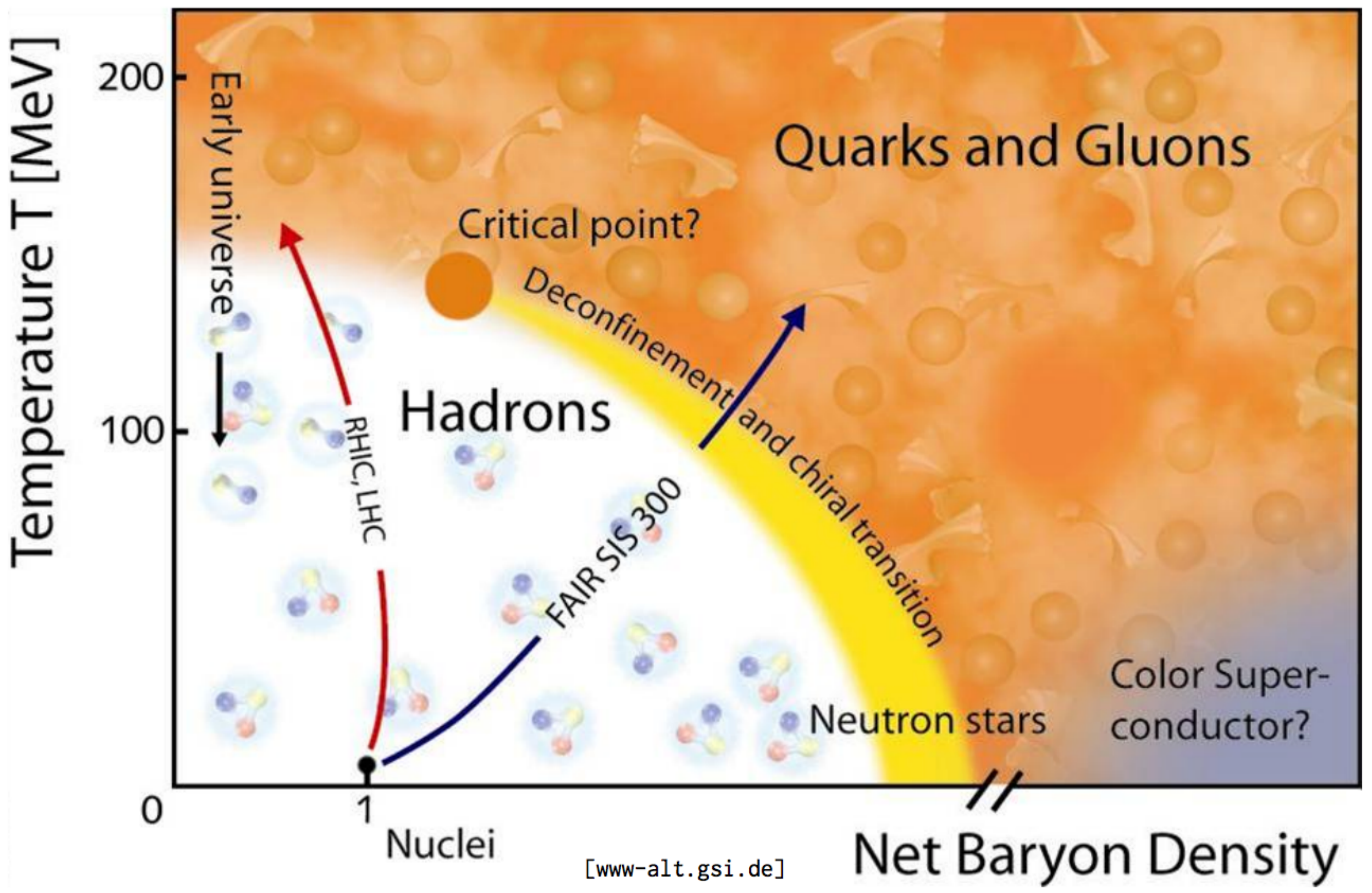
Real-time dynamics
  particle production, fragmentation
  vacuum and in medium

Low-energy reactions

Electroweak processes (e.g., nu-A)

Neutrino dynamics

Matter-antimatter asymmetry

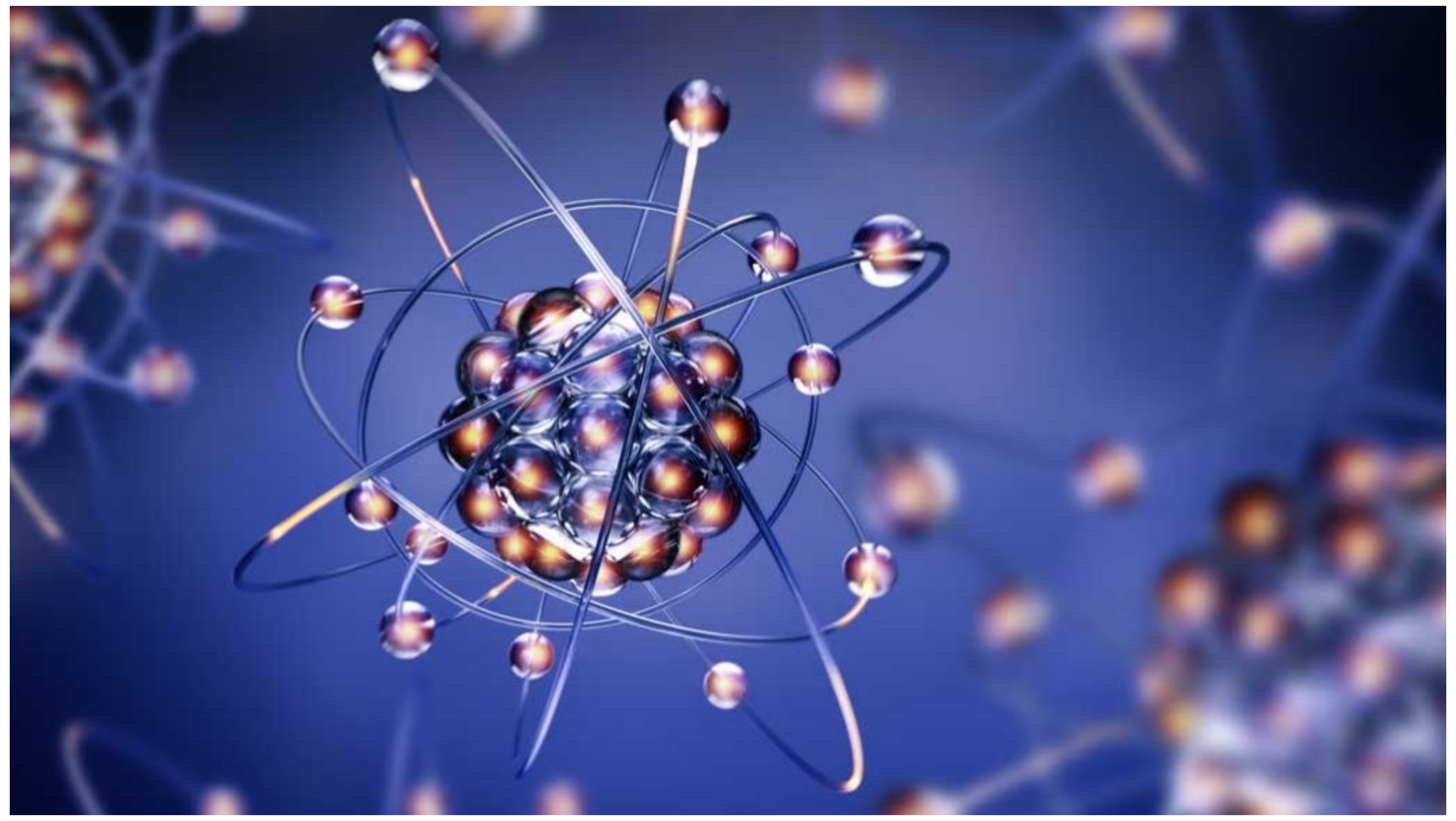


Equation of state of dense
  hot matter and dynamics

Conquering some "sign problems"

The early universe

Neutron stars

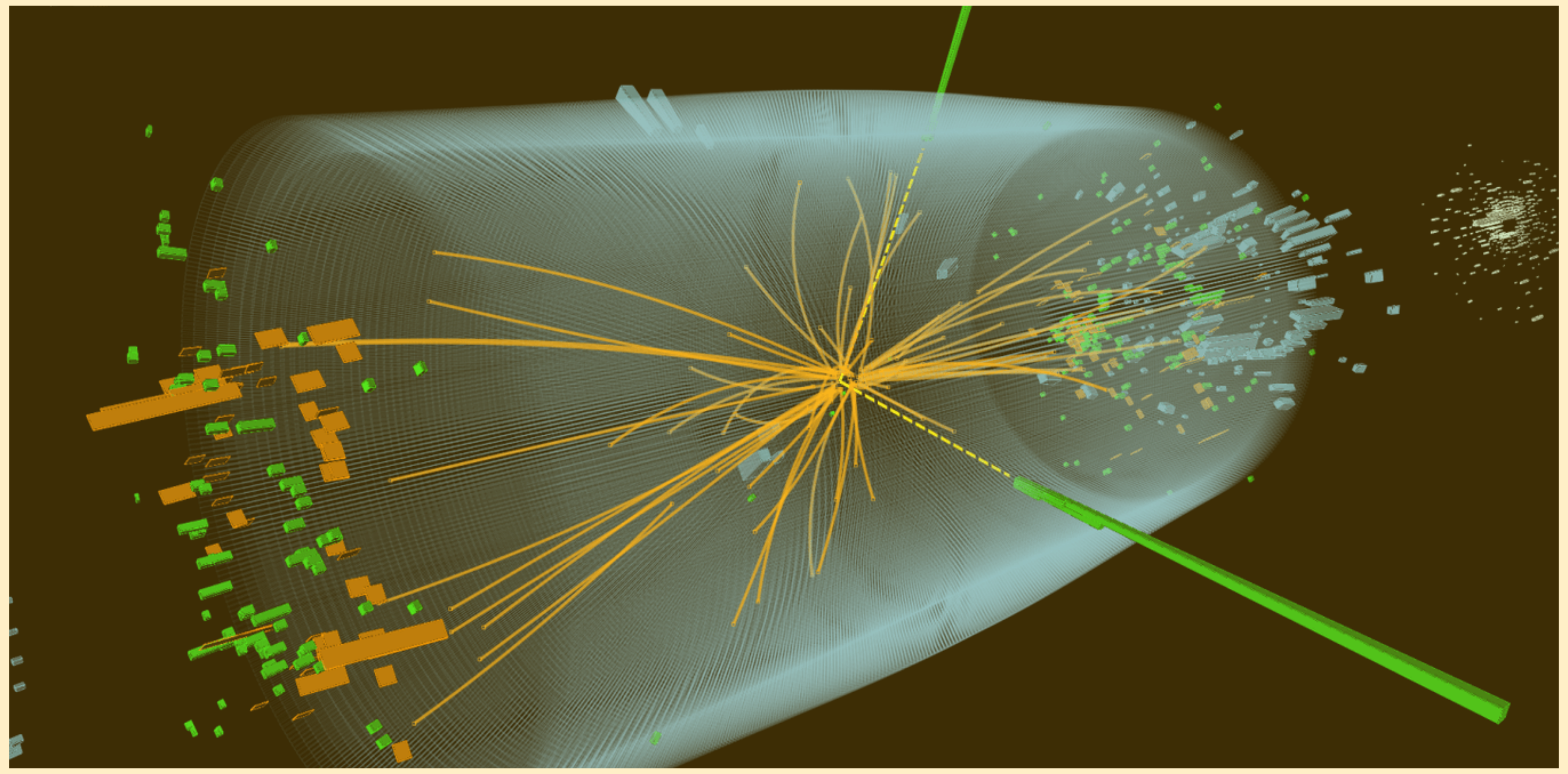


Precision structure and interactions
  of nuclei

Many-body systems

Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models



Real-time dynamics
particle production, fragmentation
vacuum and in medium

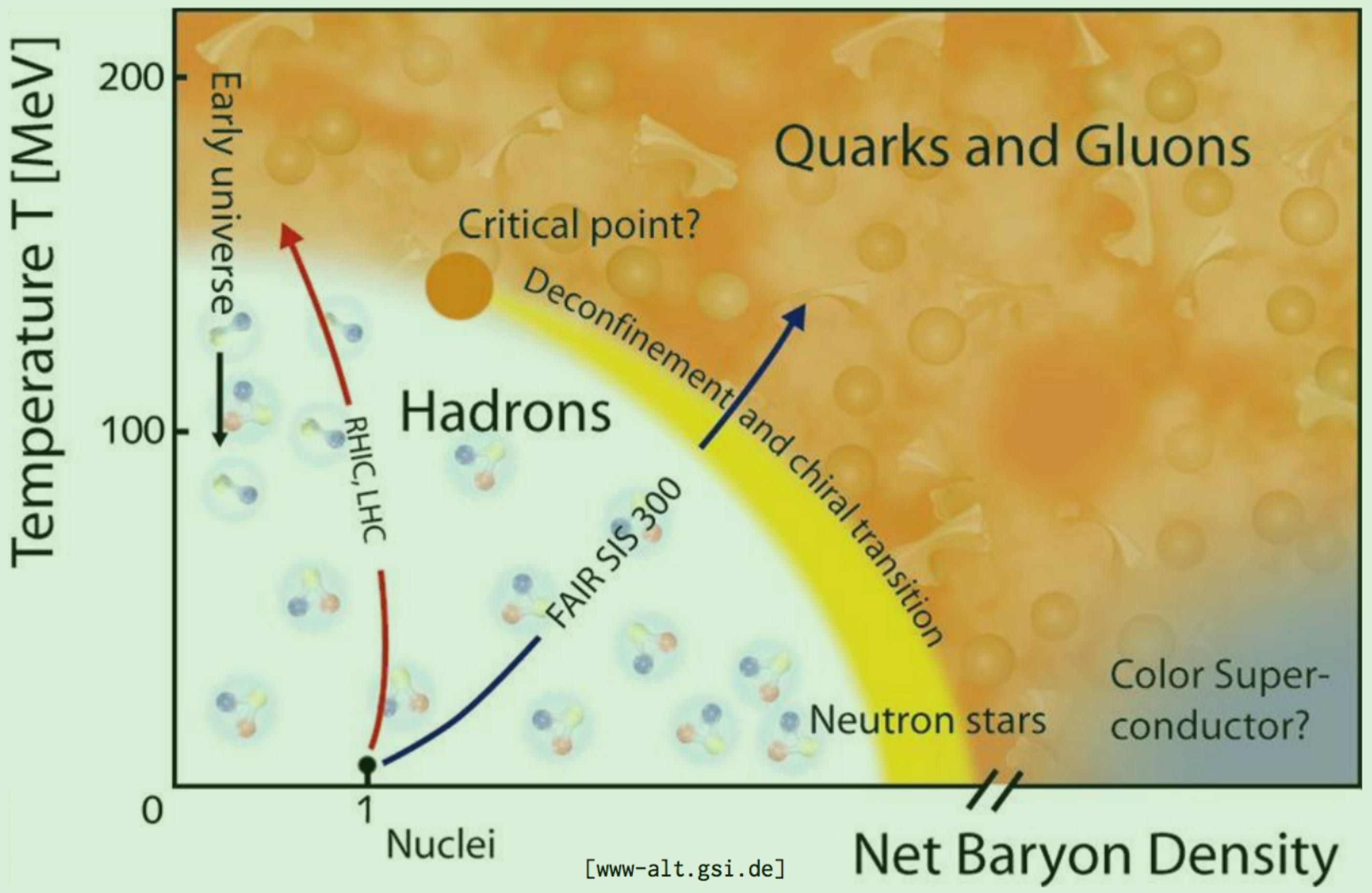
Low-energy reactions

Electroweak processes (e.g., nu-A)

Neutrino dynamics

BQP

Matter-antimatter asymmetry

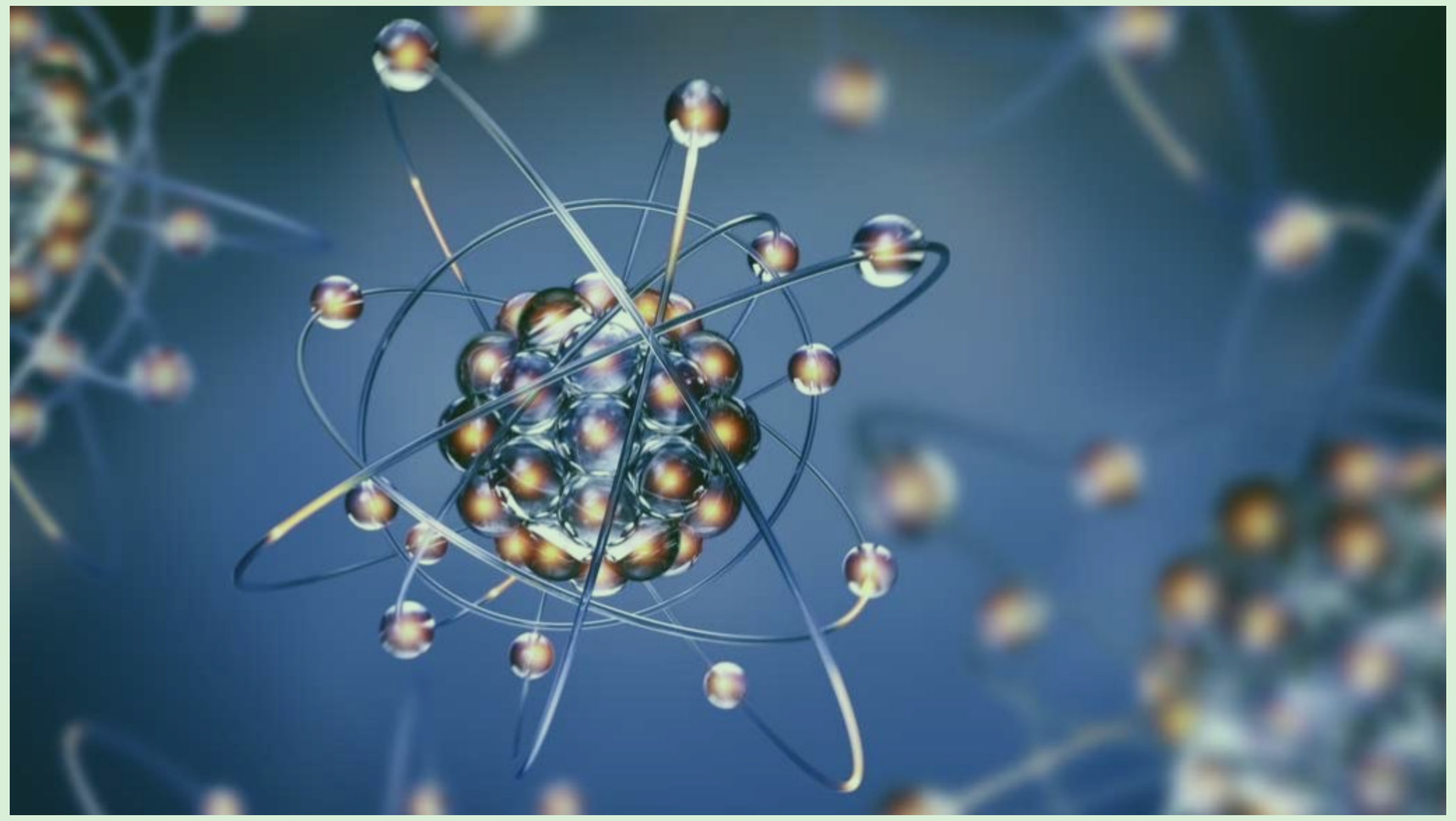


Equation of state of dense
hot matter and dynamics

Conquering some “sign problems”

The early universe

Neutron stars



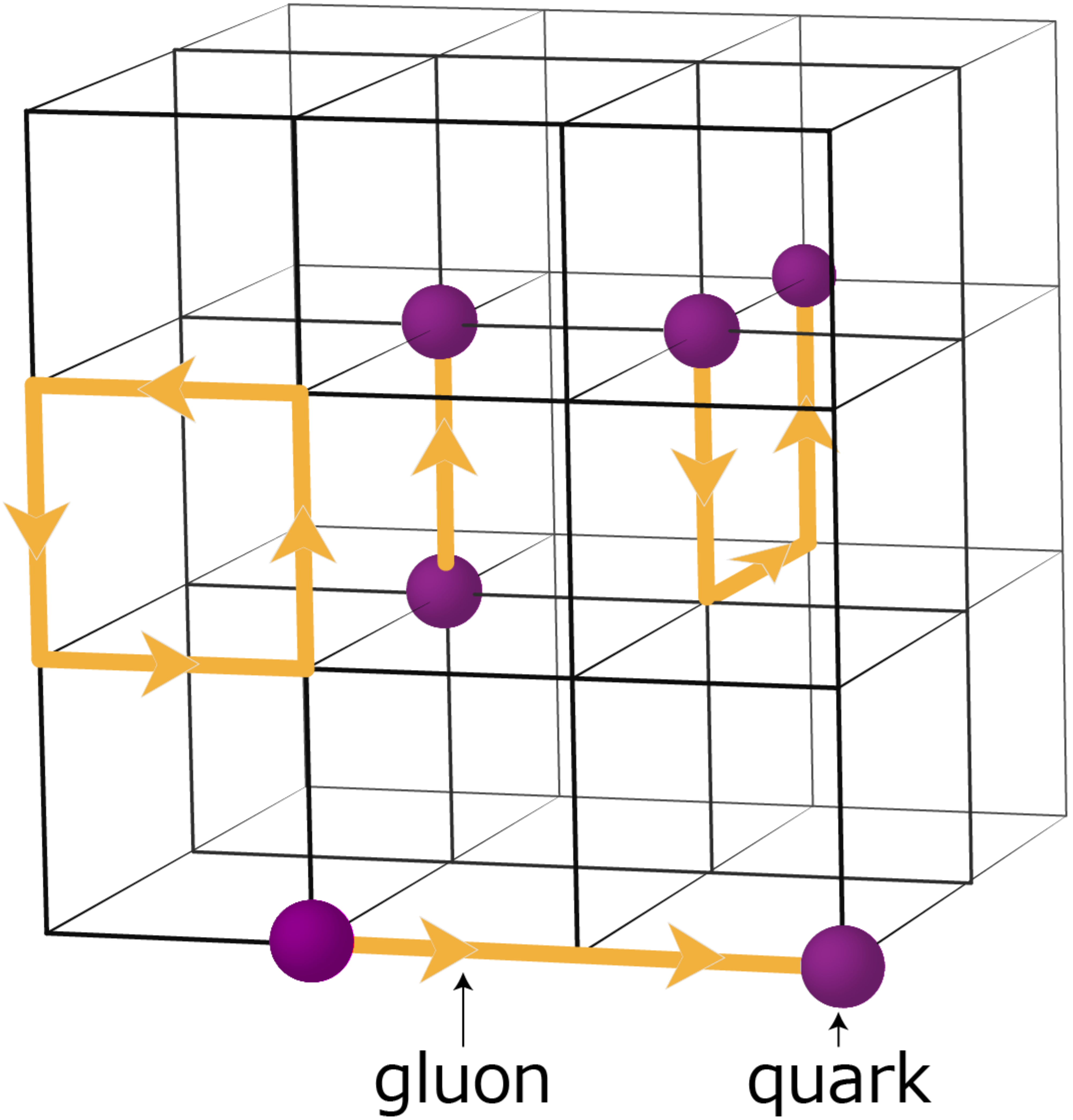
Precision structure and interactions
of nuclei

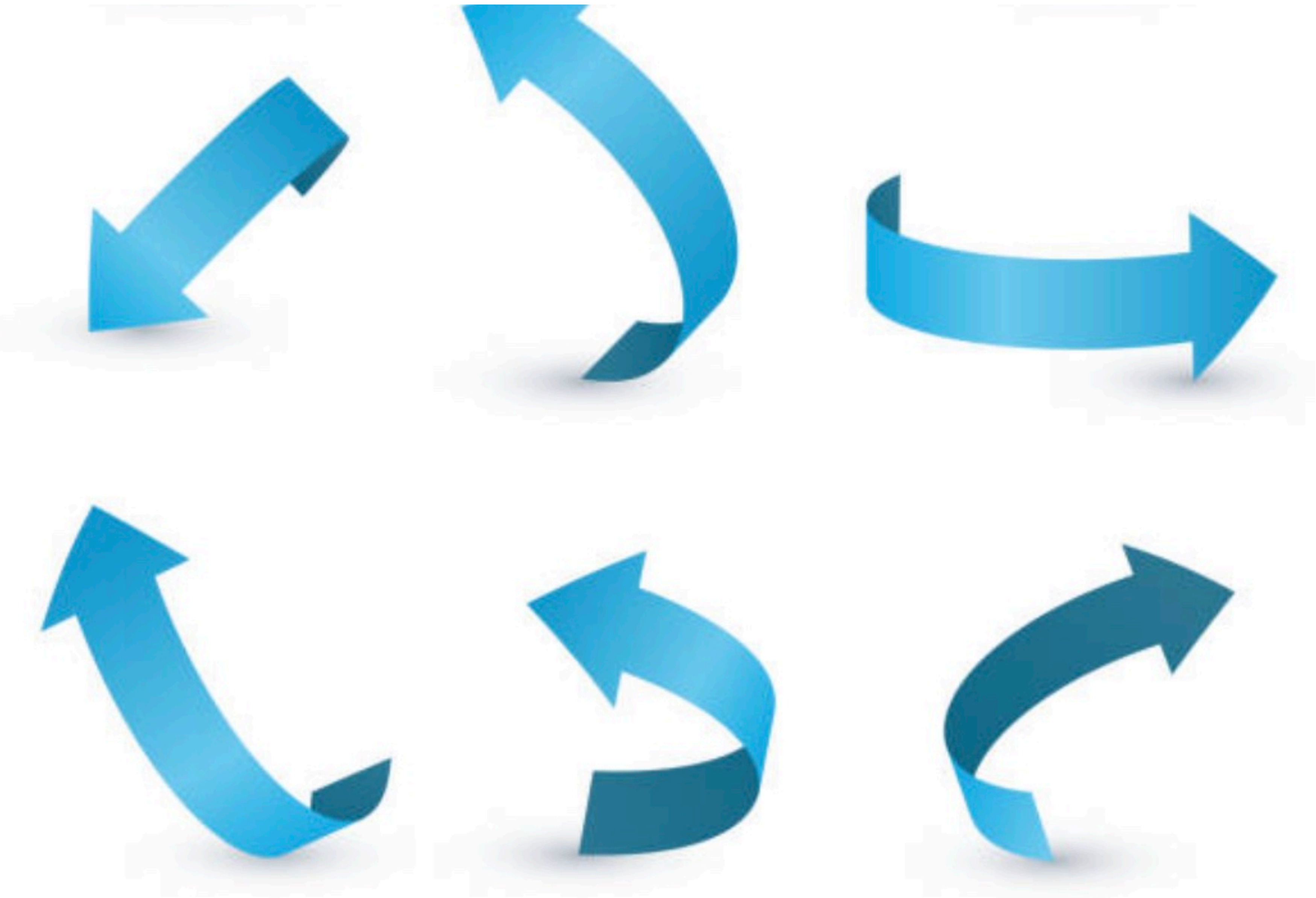
Many-body systems

QMA
– symmetries

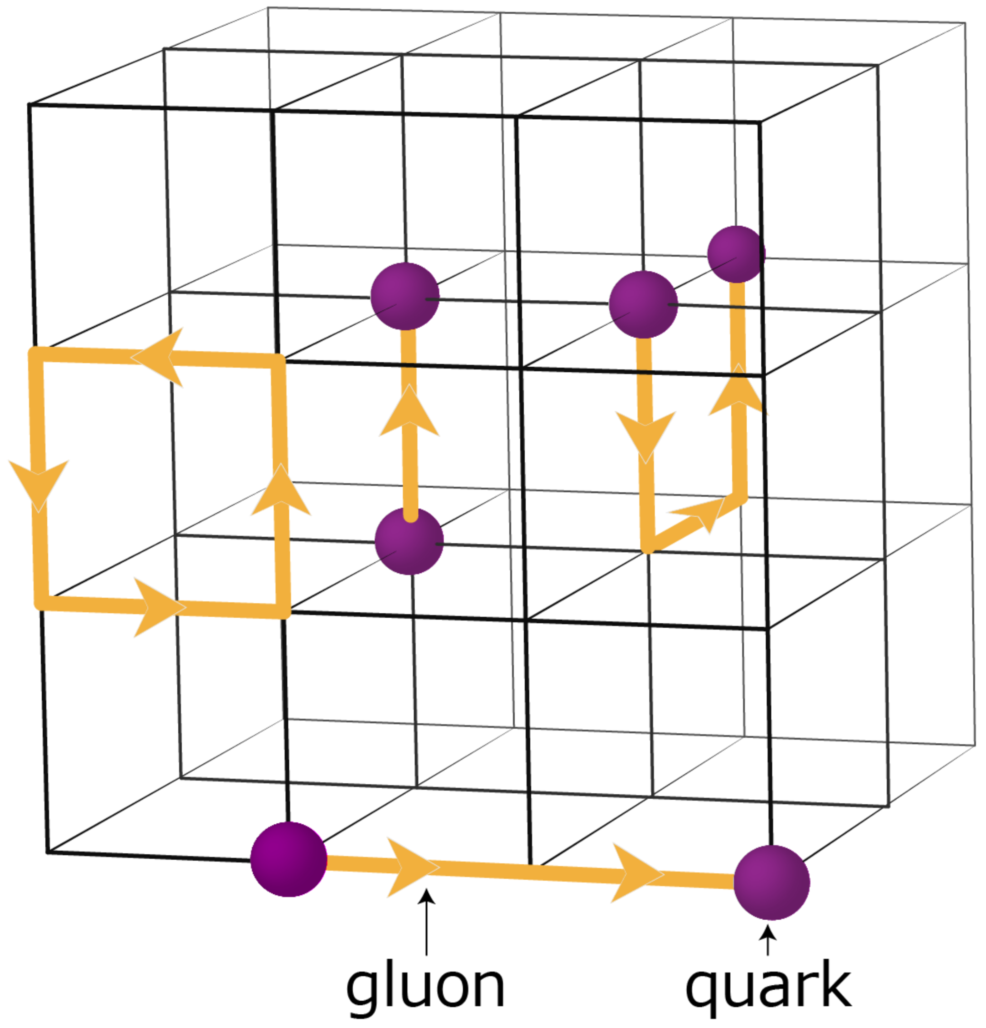
Simulation Objectives for the Standard Model and Beyond

Gauge Theories and Descendent Effective Field Theories and Models





Lattice Gauge Theories



Formal Framework - Byrne and Yamamoto in 2006
Building upon Kogut-Susskind

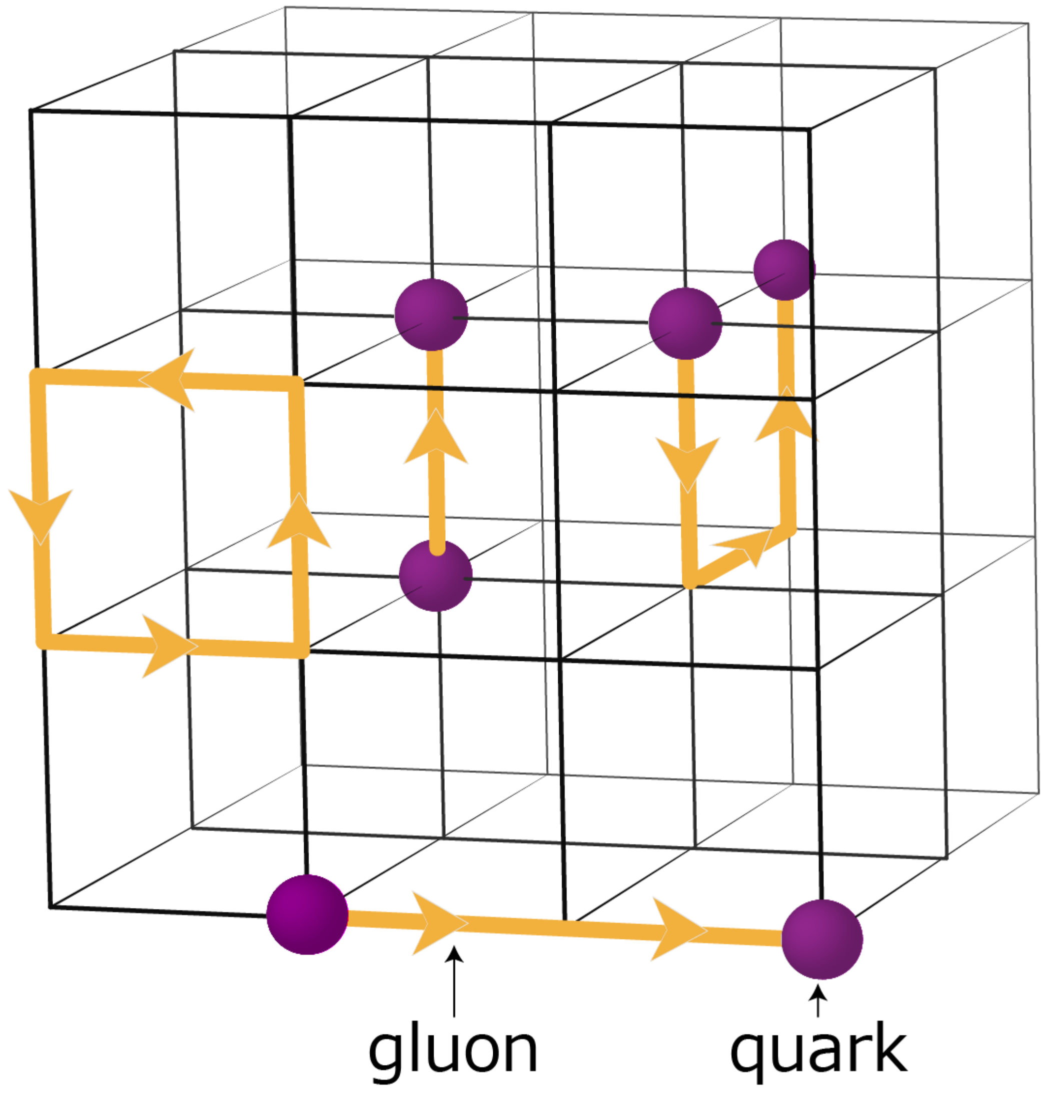
First concrete implementation proposals by Zohar, Cirac, Resnick (2012)
and Quantum Link models by Banerjee et al (2012) and Tagliacozzo et al (2012)

Different gauge field digitizations
U(1), SU(2), SU(3)
Kogut-Susskind in electric basis
Quantum Link Models

Digitized sampling in gauge basis
Loop-string-hadron basis
Schwinger Bosons
“Dynamical” magnetic basis

Lessons from Euclidean-Space Lattice QCD Calculations

A low-energy non-perturbative predictive effective field theory for computation of QCD



Lattice Spacing : $a << 1/\Lambda\chi$ (Nearly Continuum)

Lattice Volume : $m_\pi L >> 2\pi$ (Nearly Infinite Volume)

Extrapolation to $a = 0$ and $L = \infty$

Systematically remove non-QCD parts of calculation through the Symanzik action and p-regime effective field theories

- Asymptotic Freedom in the UV (small coupling constant at short-distances)
  - systematic perturbative calculations to match QCD to LQCD
  - controlled extrapolation to the continuum with uncertainty quantification.

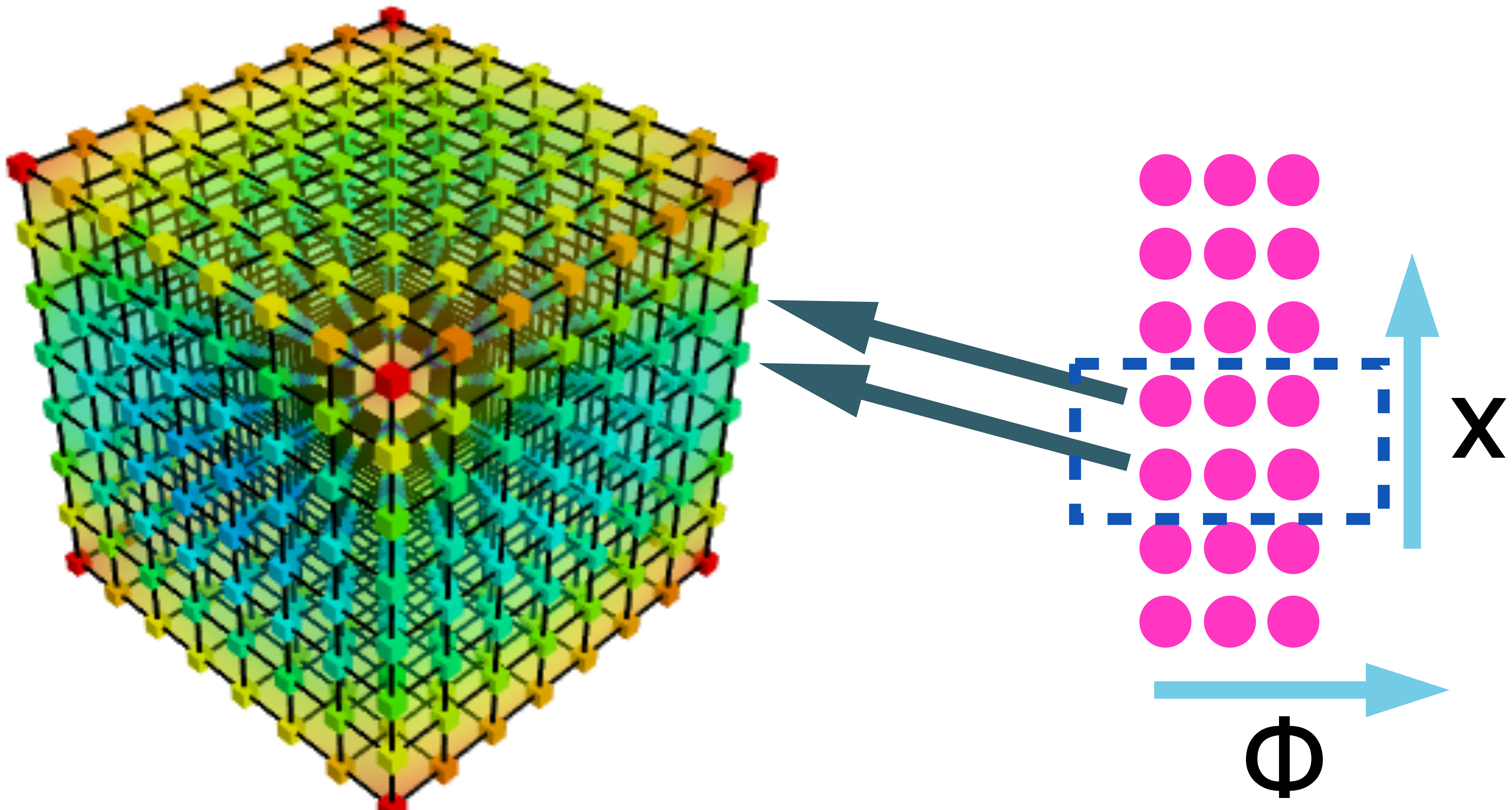
- Lattices large enough to contain correlation lengths supported over many lattice sites
  - control over IR (non-perturbative) observables with uncertainty quantification.

- Time evolution?

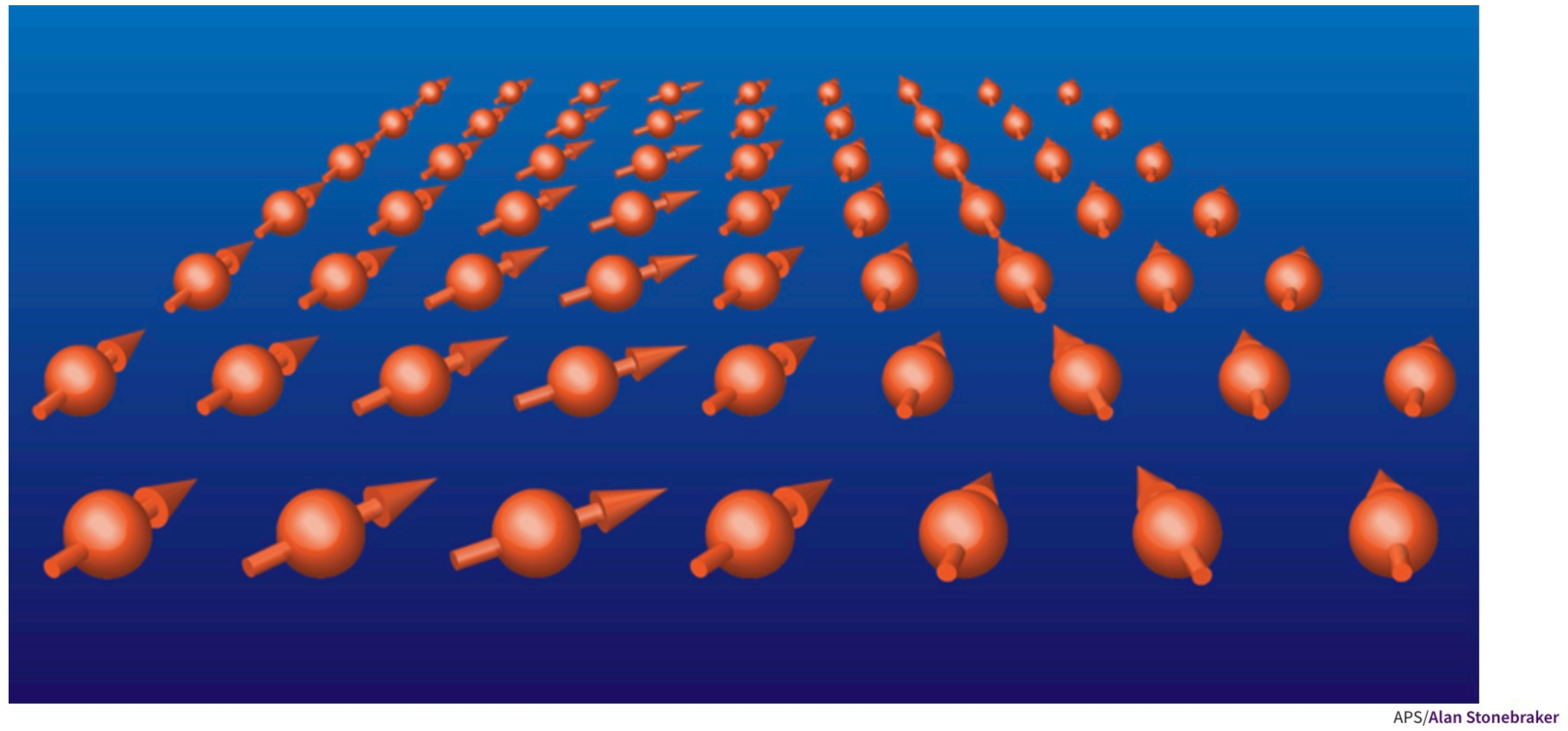
Many great ideas, papers,...

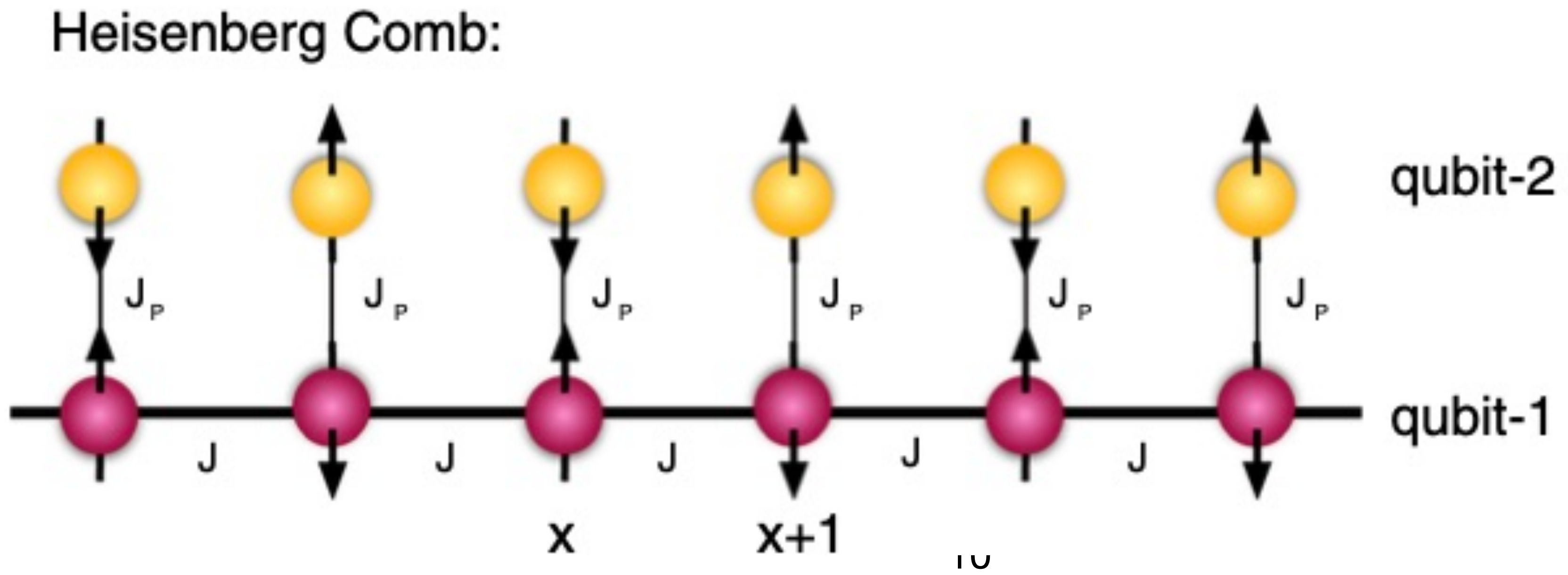
Universality
Creativity in the UV (to Recover the IR)
Entanglement Motivated

Parallelizes easily at the circuit level
- dual layer application per Trotter step



Mappings to spin-systems





Light Front (Dimensional Reduction), or Quantum Links, or Dual Mappings, or ...... ? Many paths to explore

Mesons, baryons, nuclei

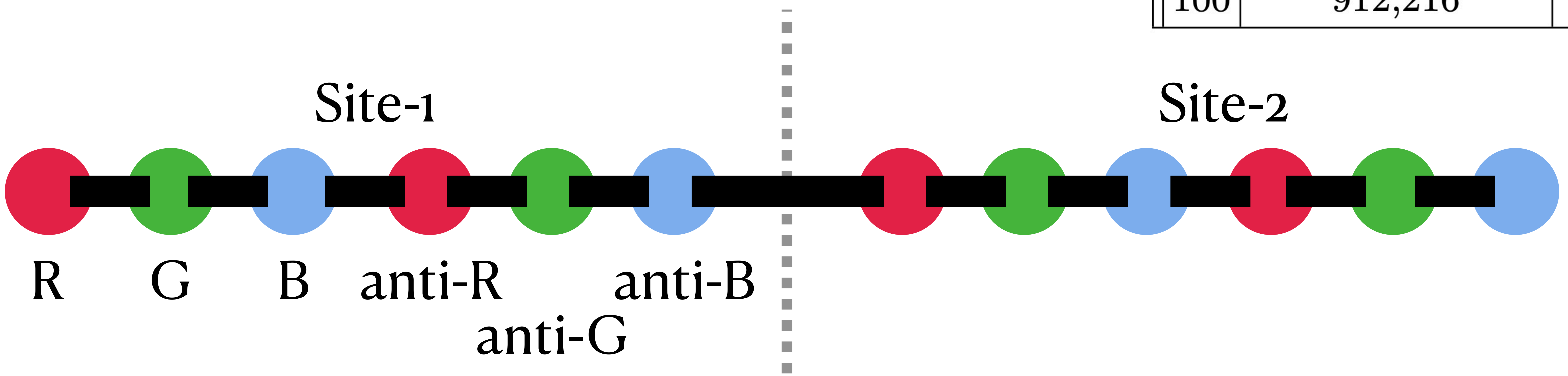
SU(N) : 1+1 Gauge Theories

Non-dynamical gauge fields

$$H = \frac{1}{2} \sum_{n=0}^{N_{fs}-1} \left(\phi_n^\dagger U_n \phi_{n+1} + \text{h.c.} \right) + m \sum_{n=0}^{N_{fs}-1} (-1)^n \, \phi_n^\dagger \phi_n + \frac{g^2}{2} \sum_{n=0}^{N_{fs}-2} |\mathbf{L}_n|^2$$

$$H_K \to +\frac{1}{2} \sum_{n=0}^{N_{fs}-1} \Big[\sigma^+_{n,r}\sigma^z_{n,g}\sigma^z_{n,b}\sigma^-_{n+1,r} + \sigma^+_{n,g}\sigma^z_{n,b}\sigma^z_{n+1,r}\sigma^-_{n+1,g} + \sigma^+_{n,b}\sigma^z_{n+1,r}\sigma^z_{n+1,g}\sigma^-_{n+1,b} + \sigma^-_{n,r}\sigma^z_{n,g}\sigma^z_{n,b}\sigma^+_{n+1,r} + \sigma^-_{n,g}\sigma^z_{n,b}\sigma^z_{n+1,r}\sigma^+_{n+1,g} + \sigma^-_{n,b}\sigma^z_{n+1,r}\sigma^z_{n+1,g}\sigma^+_{n+1,b} \Big] ,$$

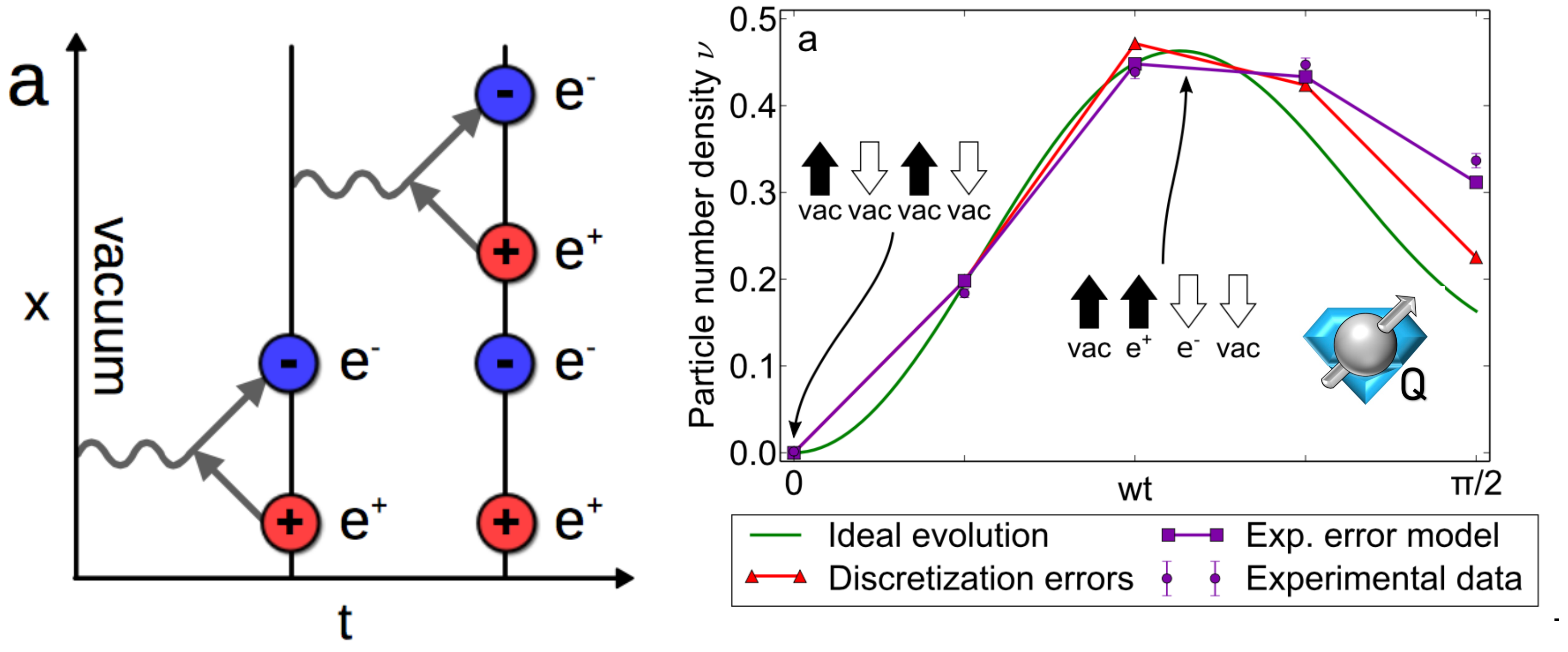
Number of CNOT gates for one Trotter step of $SU(3)$			
L	$N_f = 1$	$N_f = 2$	$N_f = 3$
1	30	114	242
2	228	878	1,940
5	1,926	7,586	16,970
10	8,436	33,486	75,140
100	912,216	3,646,086	8,201,600



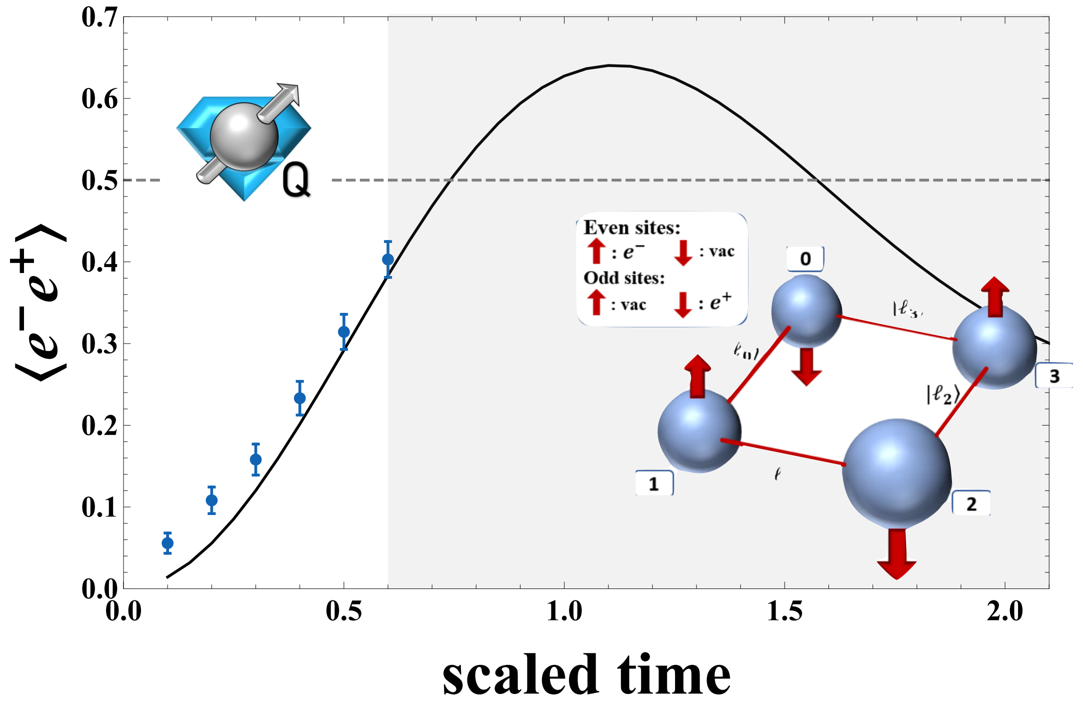
Dynamics in the Schwinger Model - Abelian Gauge Theory

— 1+1 dim QED —

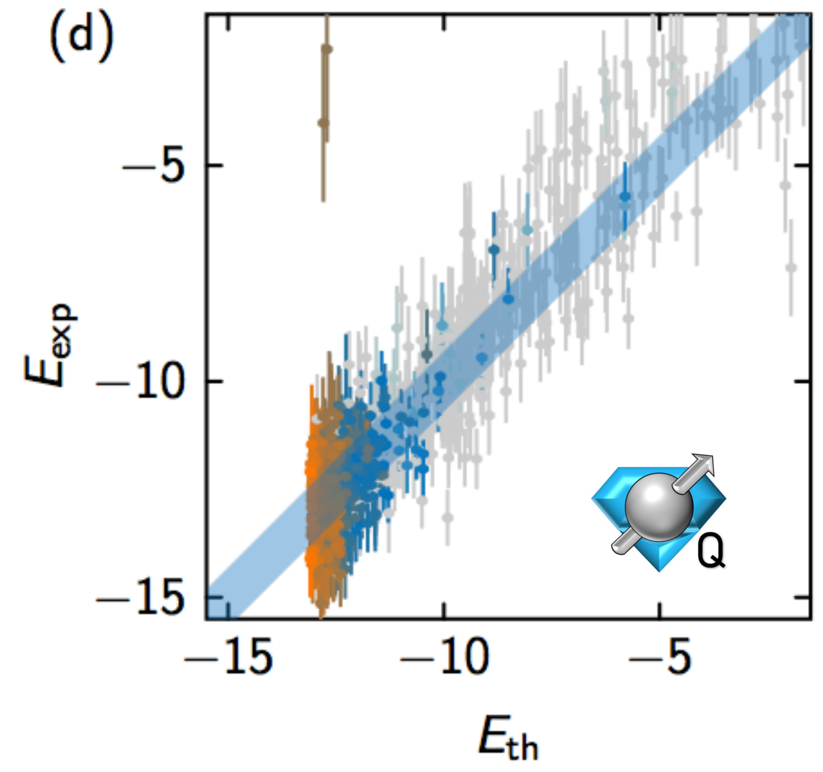
Innesbruck

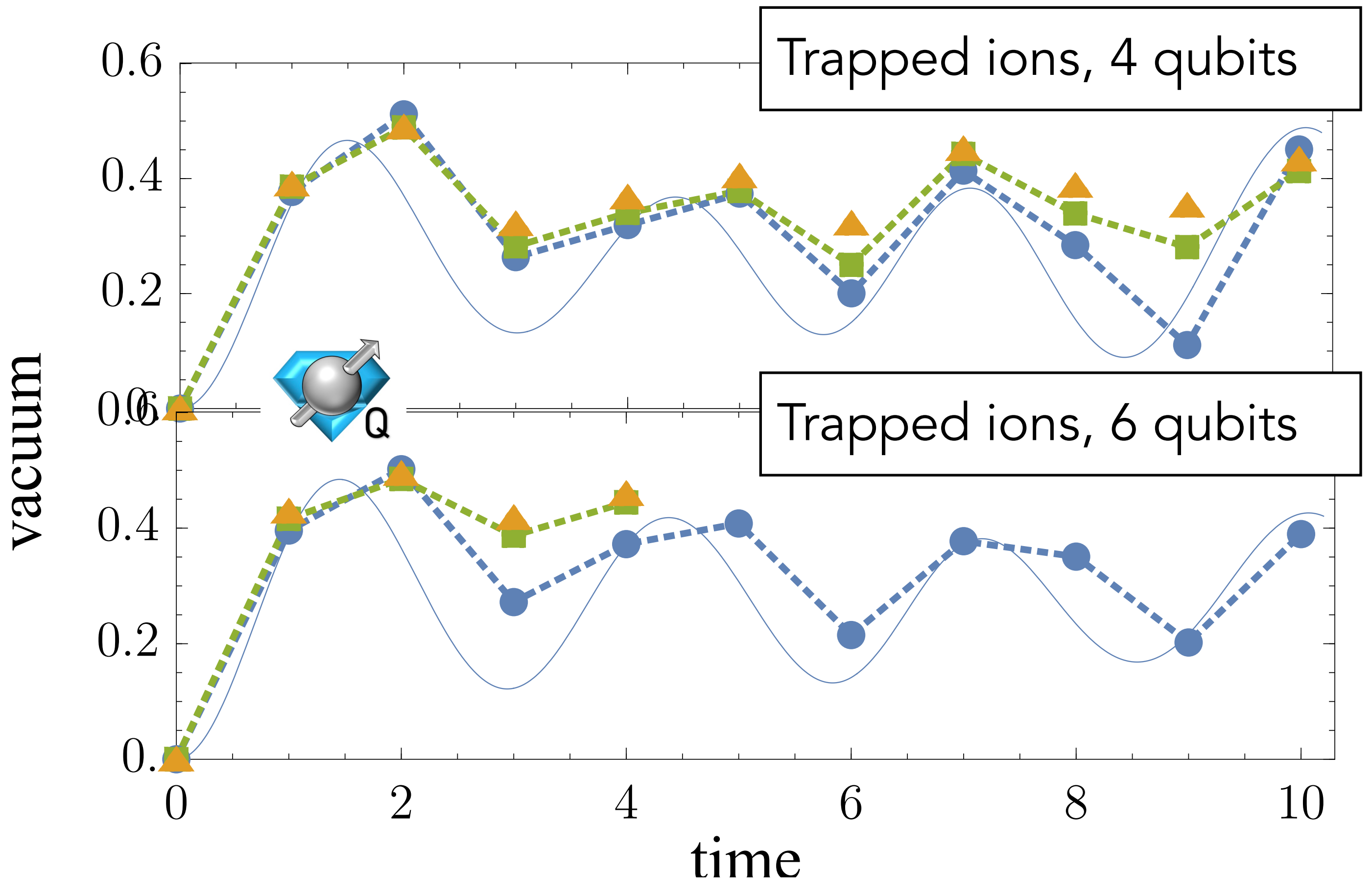


ORNL-Washington-Basque

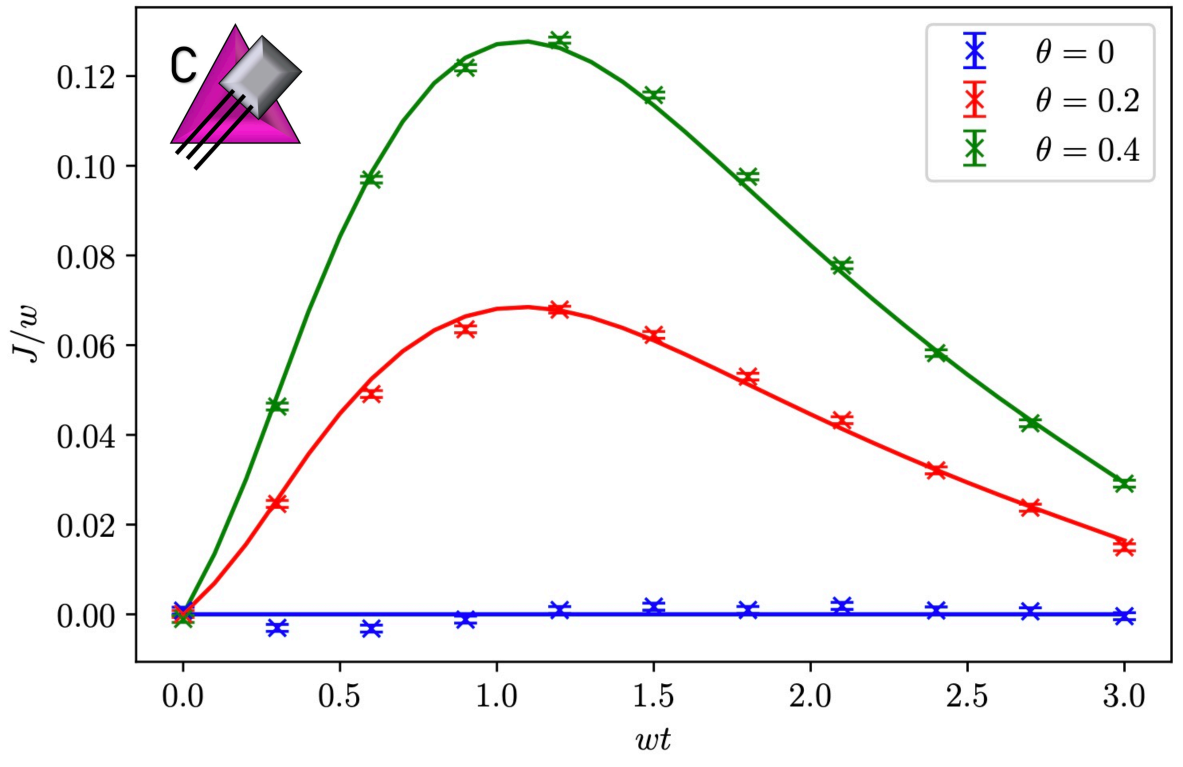


Innesbruck

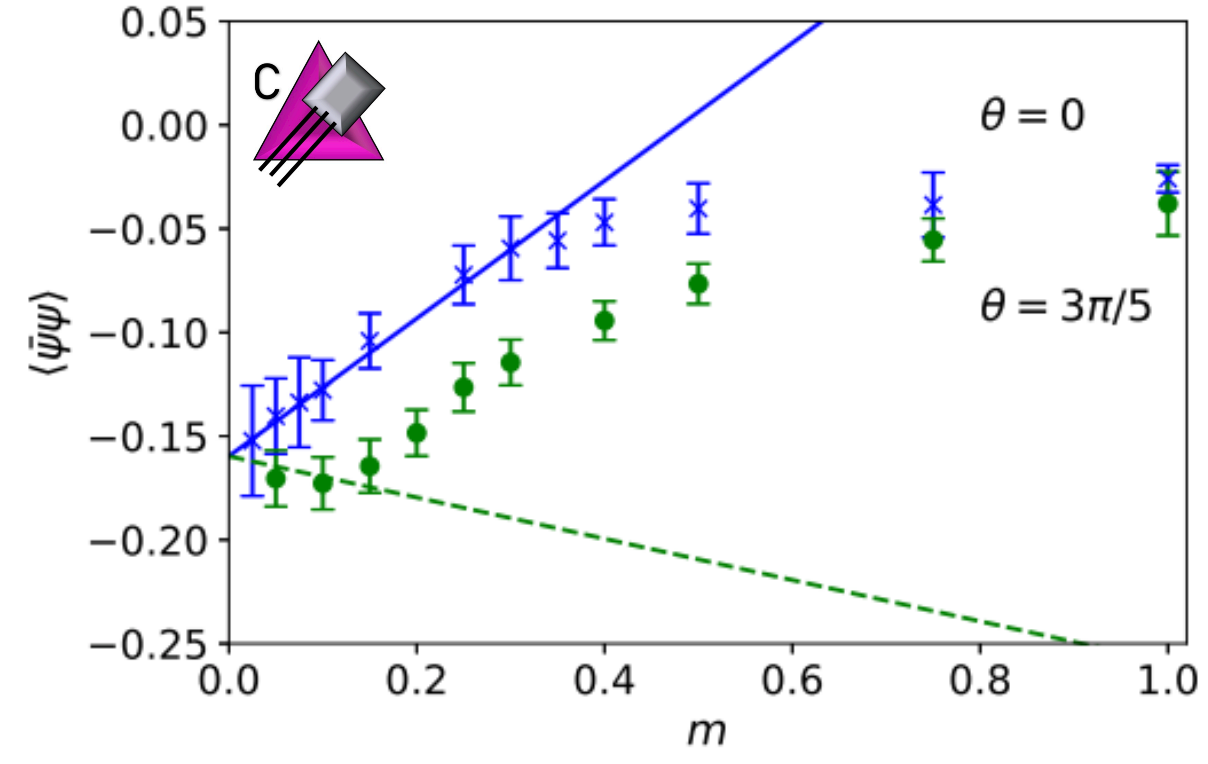




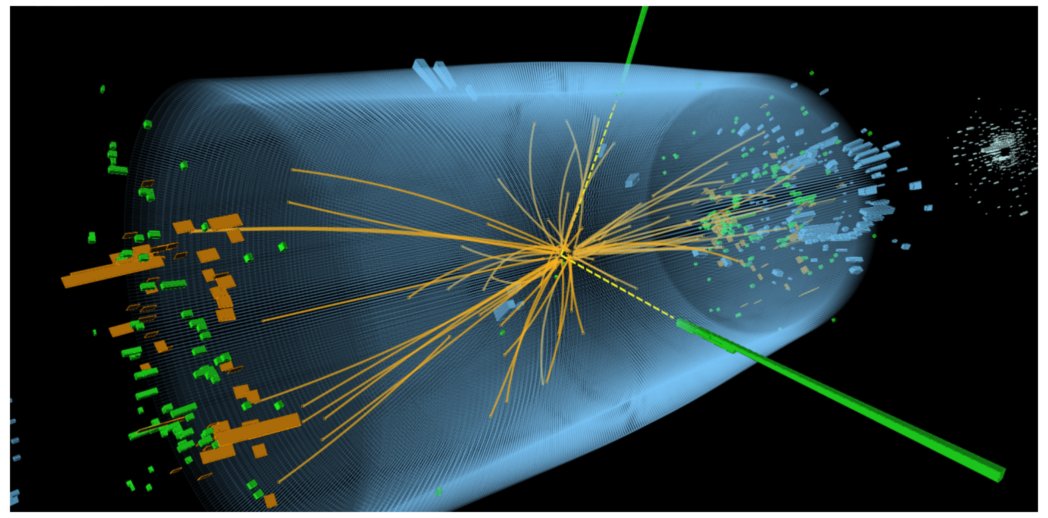
Maryland



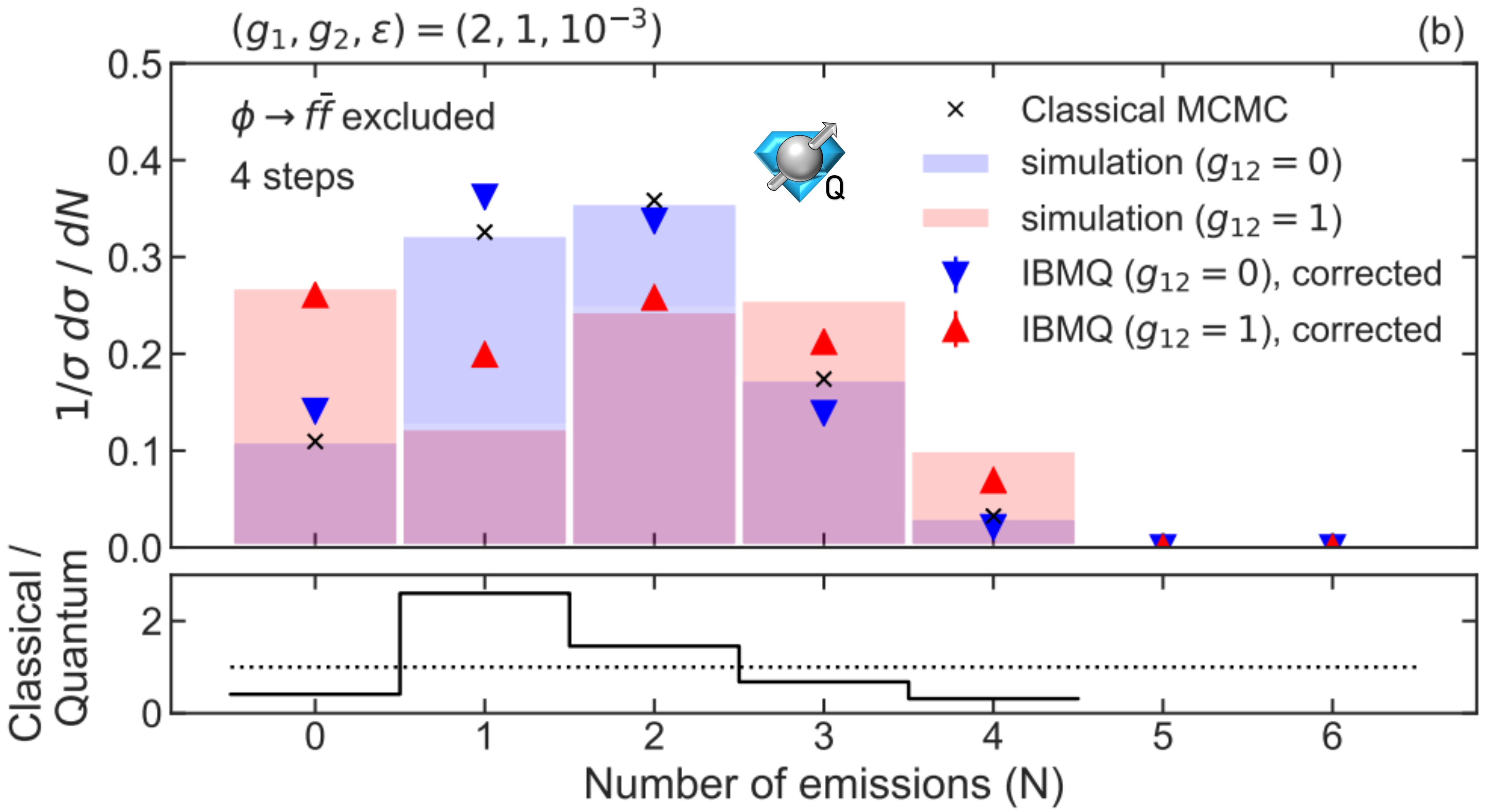
Kharzeev-Kikuchi



Chakraborty, Honda, Izubuchi, Tomiya

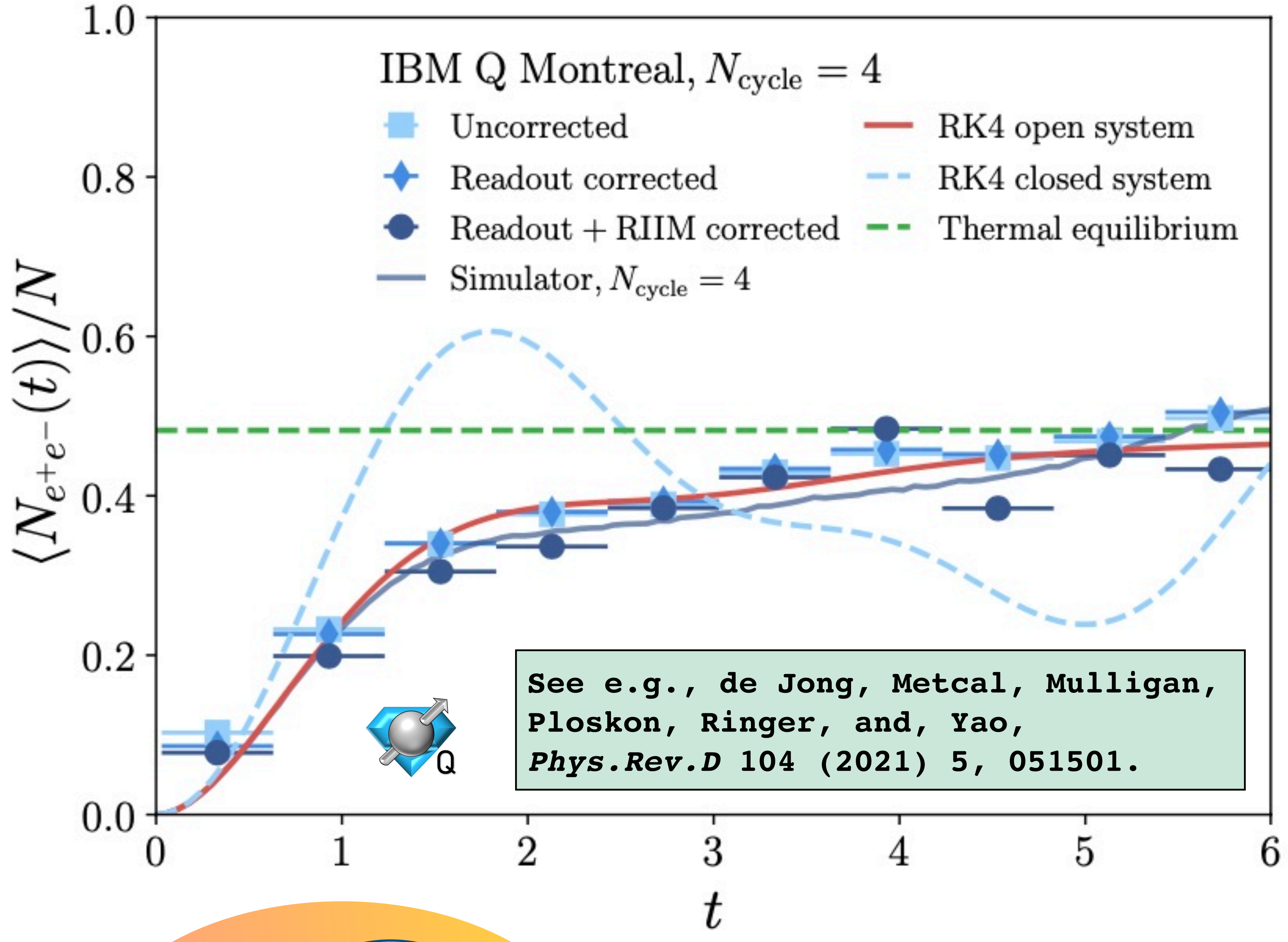


Fragmentation and Collisions
Vacuum and In-Medium

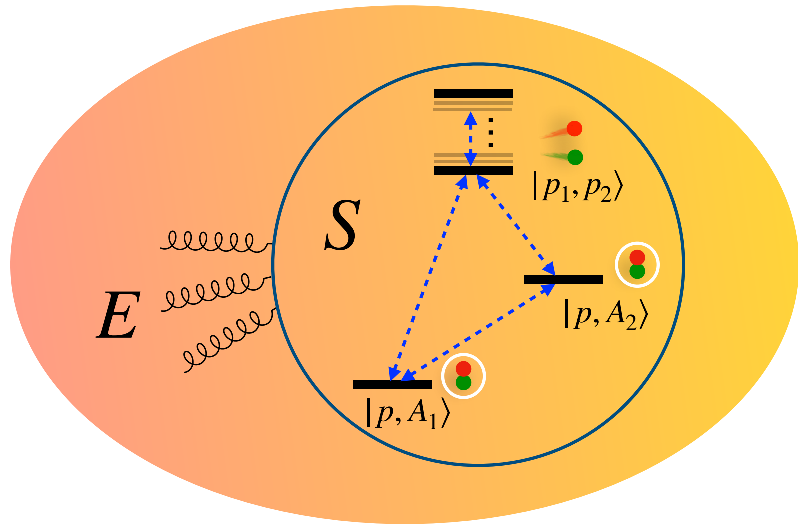


Nachman, Provasoli, and Bauer‡, *Phys. Rev. Lett.* 126 (2021) 6, 062001.

A polynomial time quantum final state shower algorithm that accurately models the effects of intermediate spin states similar to those present in electroweak showers.

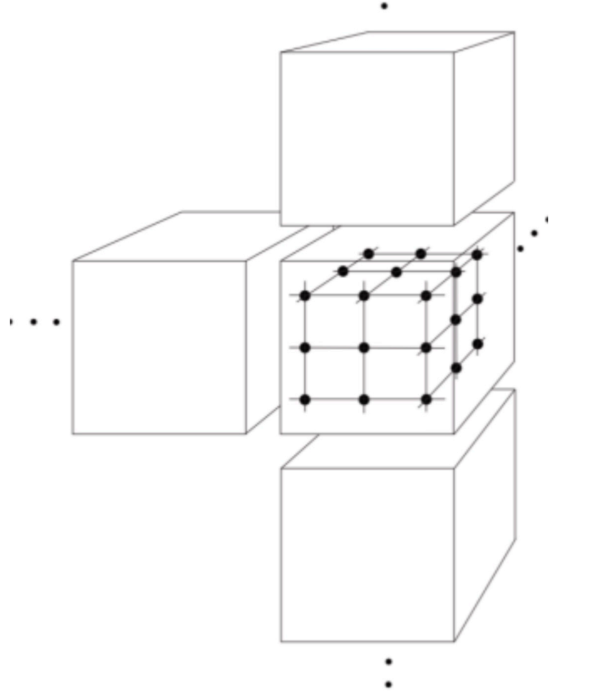


See e.g., de Jong, Metcal, Mulligan, Ploskon, Ringer, and, Yao, *Phys.Rev.D* 104 (2021) 5, 051501.



QQbar moving in medium

Yang- Mills and QCD Beyond 1+1 Dim
— Dynamical Gauge Fields —



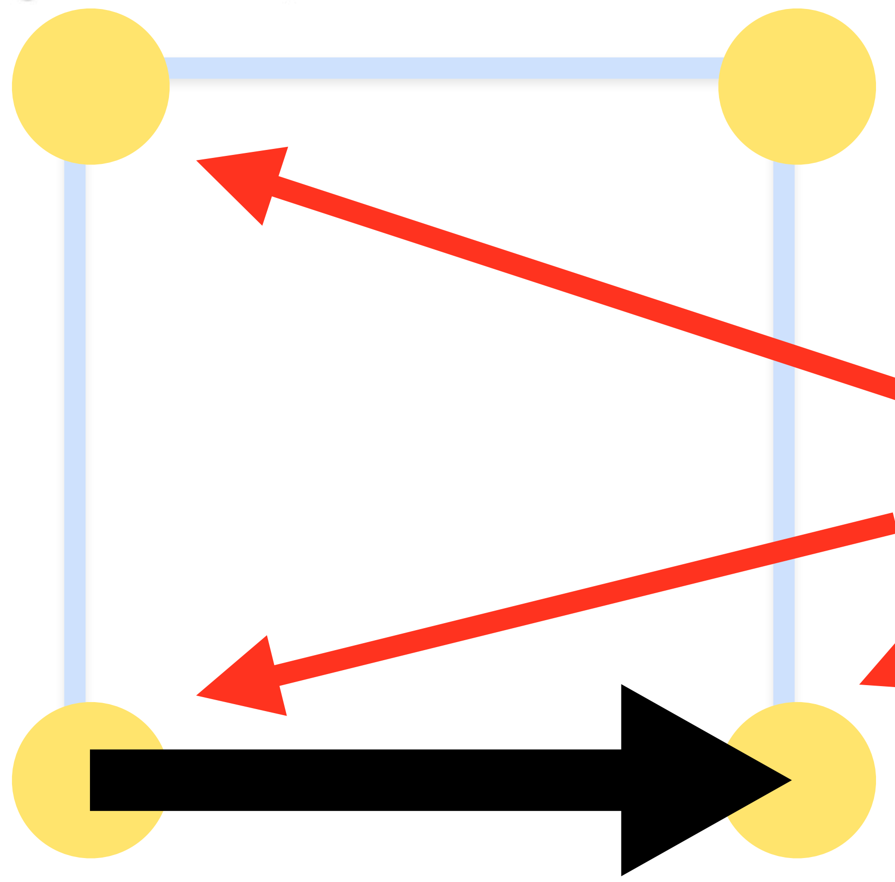
Consider the Kogut-Susskind basis = electric basis ....

$$\hat{H} = \frac{g^2}{2}\sum_{\text{links}} \hat{E}^2 - \frac{1}{2g^2}\sum_{\square}\left(\hat{\square} + \hat{\square}^\dagger\right)$$

Electric Field Casimir operator

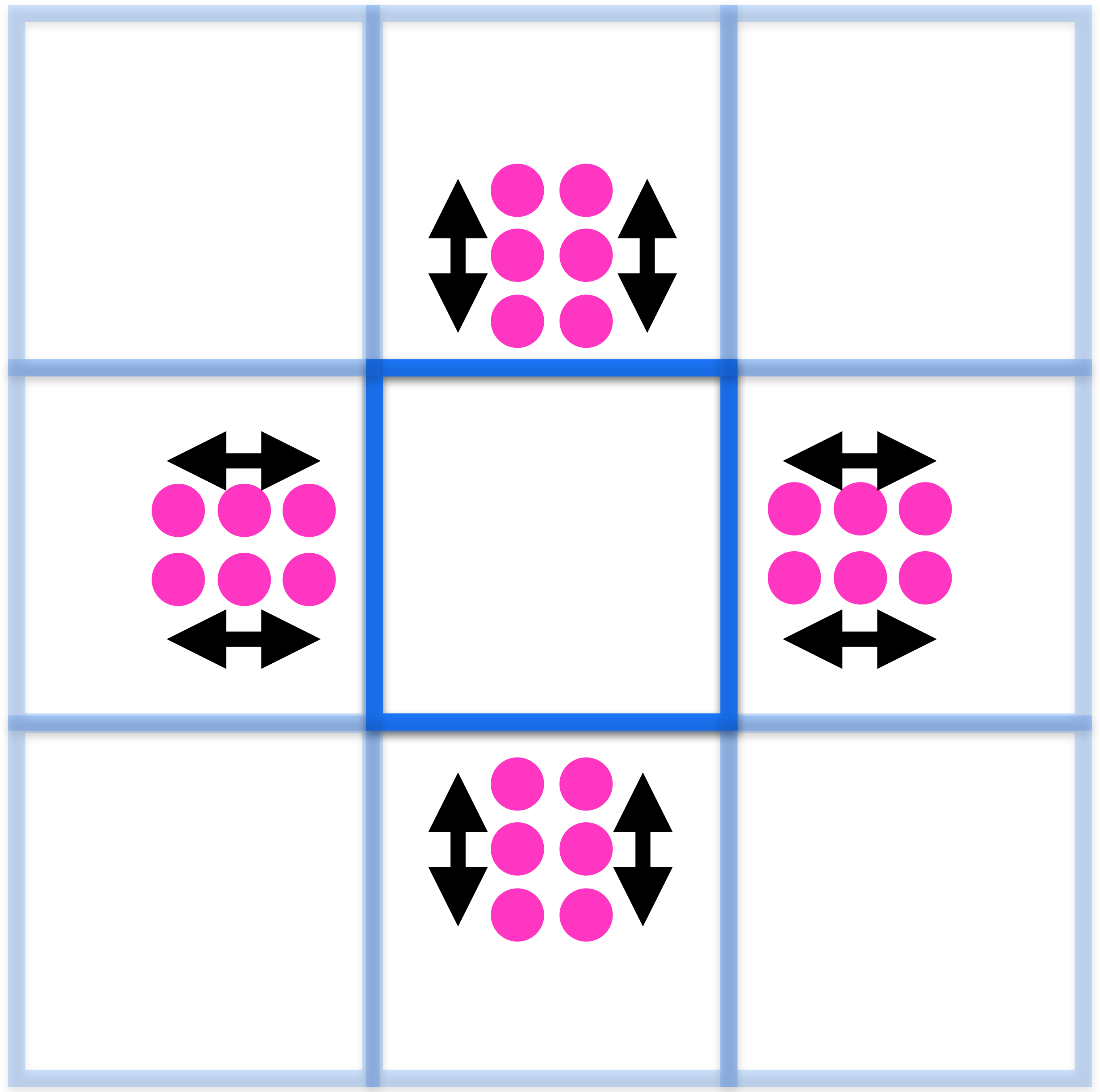
$|p, q, T_L, T_L^z, Y_L, T_R, T_R^z, Y_R\rangle$

Magnetic Field operator
Off-diagonal on electric basis



SU(N) Gauge invariant
Hilbert space

$T^{a_1 \ldots a_p}_{b_1 \ldots b_q}$ $T^{c_1 \ldots c_p}_{d_1 \ldots d_q}$

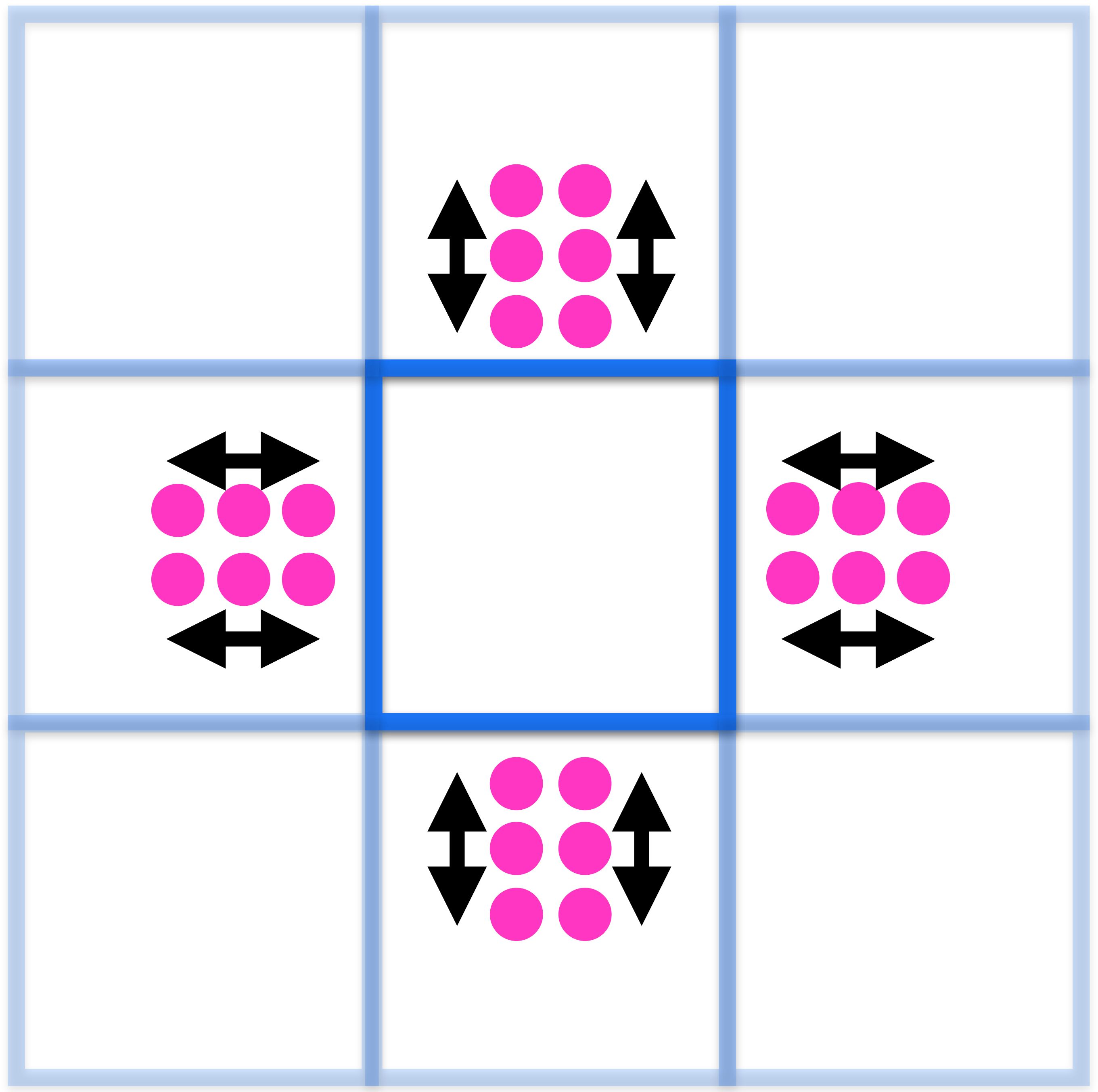


Truncate in Casimir
= dimensionality of irrep

Continuum limit

Resource Estimates for “Modest” Truncation of SU(3)

$\mathbf{1}, \mathbf{3}, \overline{\mathbf{3}}, \mathbf{8}$ e.g., Truncation in color space



Integrating over each vertex gauge space:

- 2 qubits per link
- 8 qubits for 1 plaquette
- 12 qubits for 2 plaquettes with PBC
- 24 qubits for 1 x 1 x 1 cube

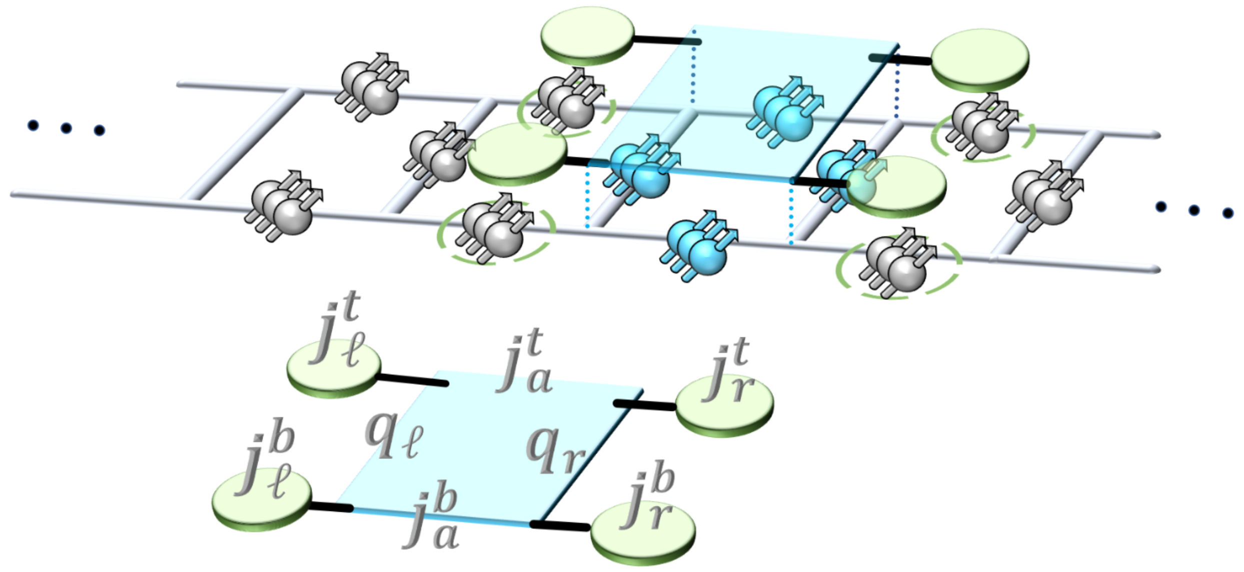
NOT integrating over gauge space (pure Byrnes+Yamamoto):

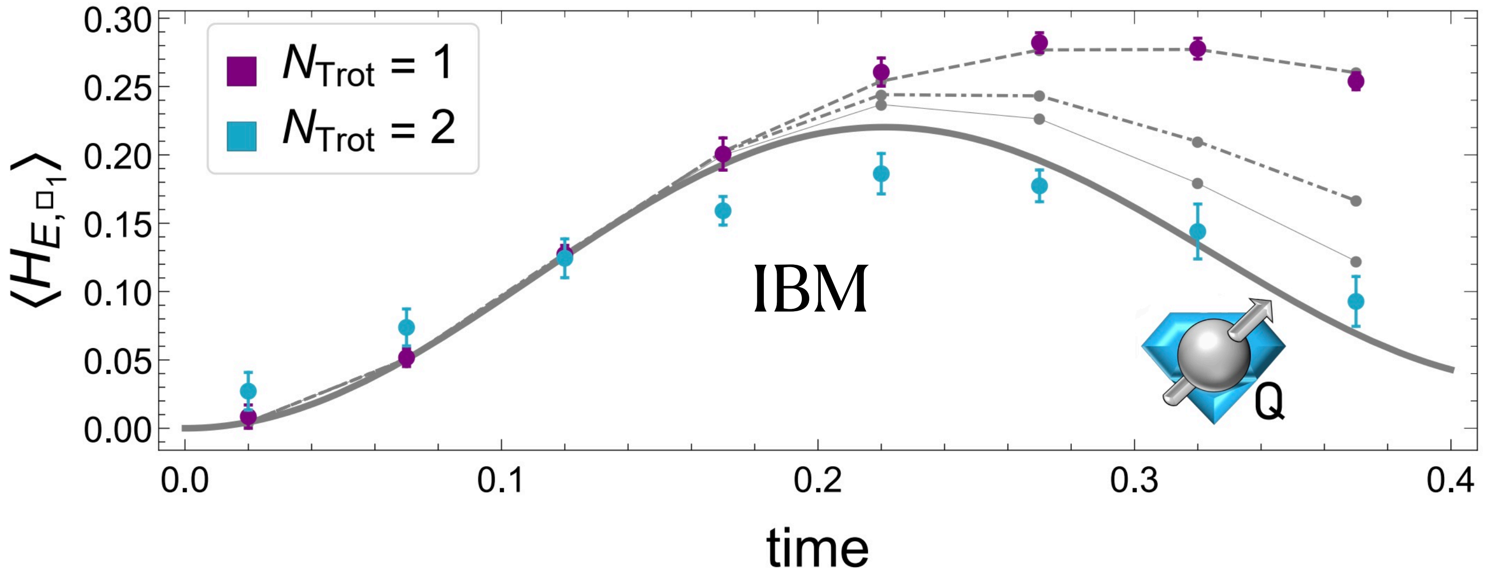
- 18 qubits per link
- 72 qubits for 1 plaquette
- 108 qubits for 2 plaquettes with PBC
- 156 qubits for 1 x 1 x 1 cube

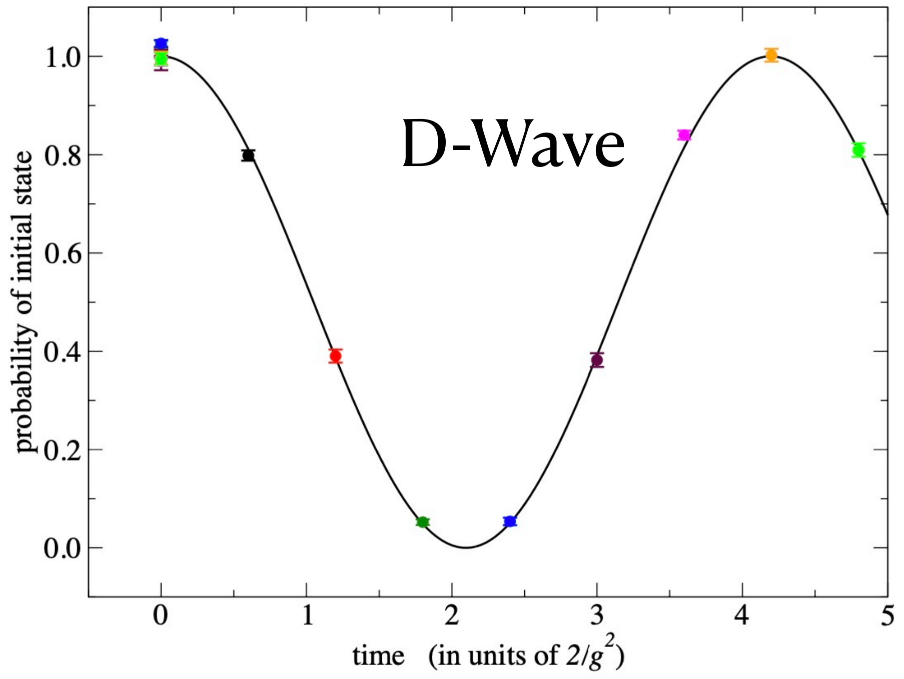
SU(N) : Results in Low Dimensions

SU(2), pure Yang-Mills, 2-D
Dynamical gauge fields

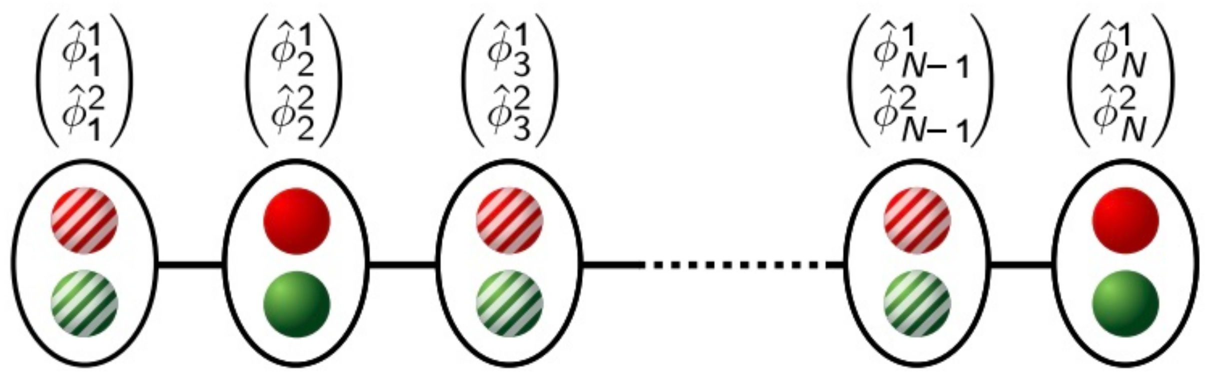
See e.g., Klco, Savage, and Stryker, Phys. Rev. D 101, 074512 (2020).

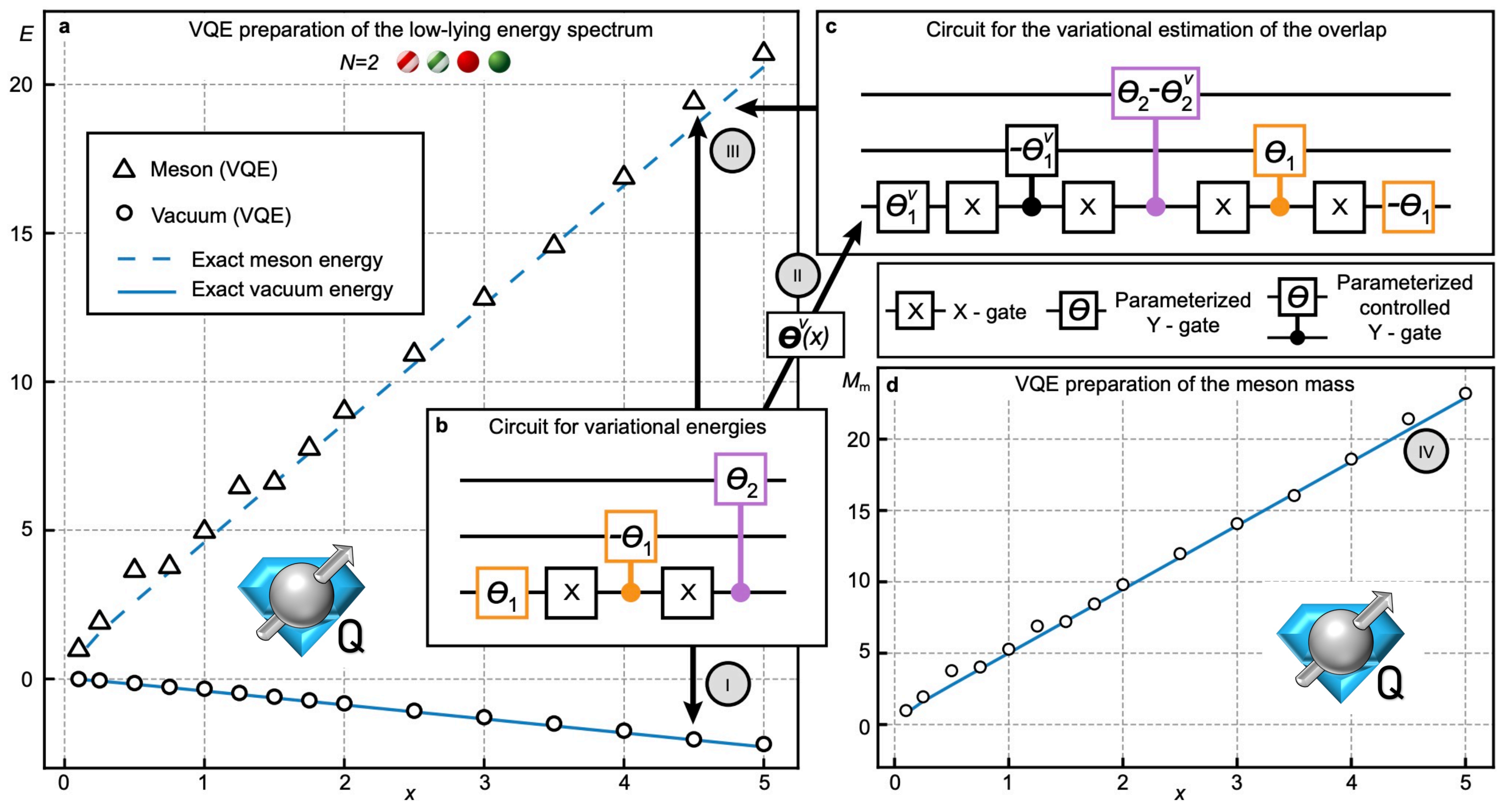




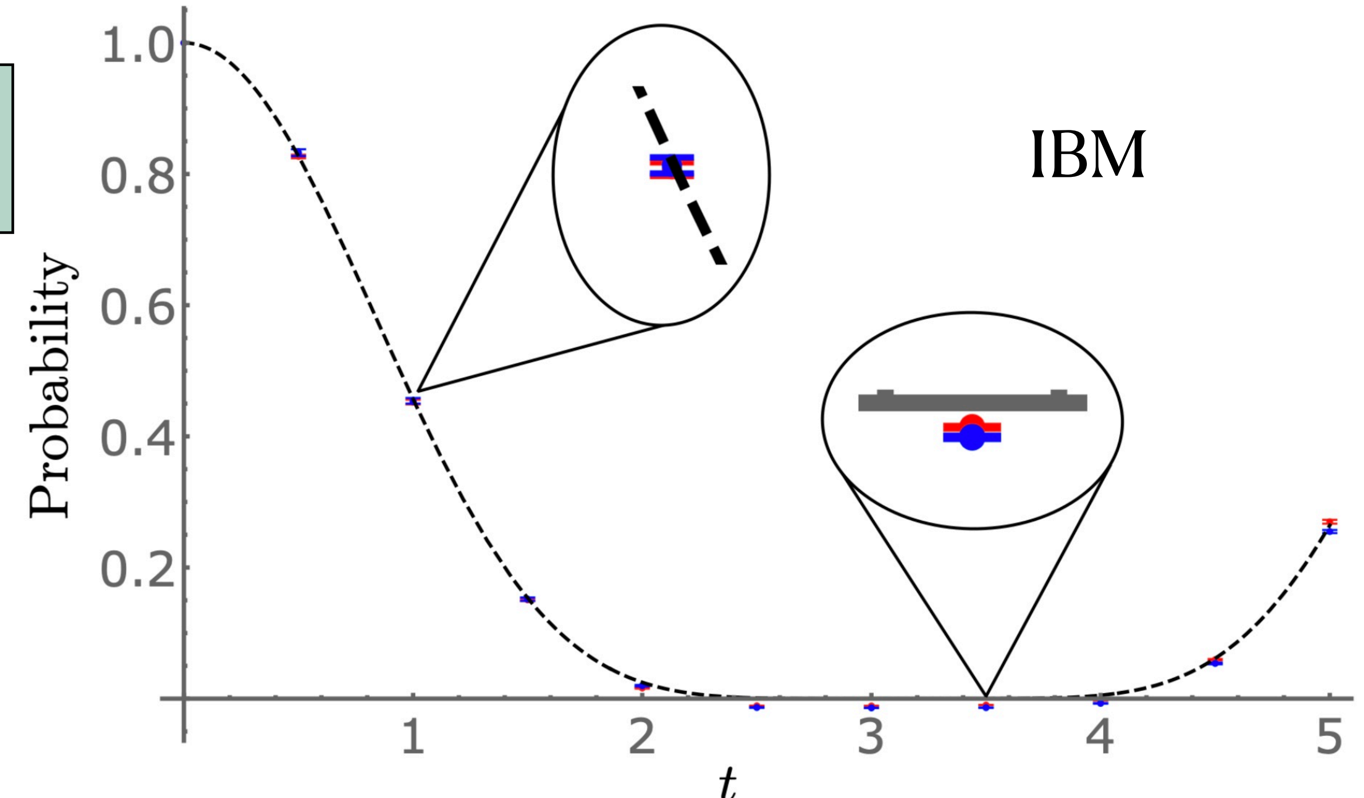


SU(N), Yang-Mills and fermions, 1-D
Non-dynamical gauge fields

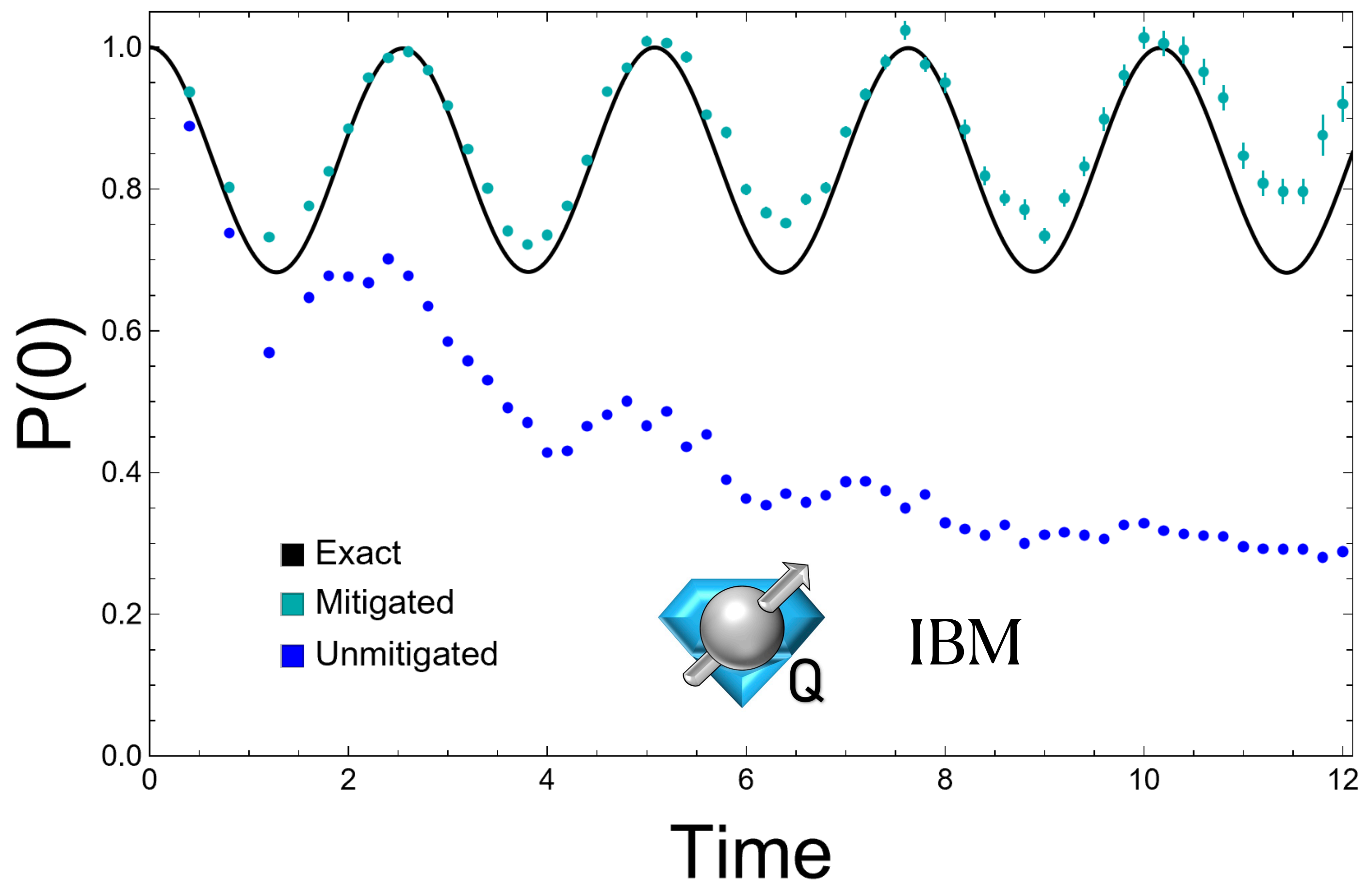




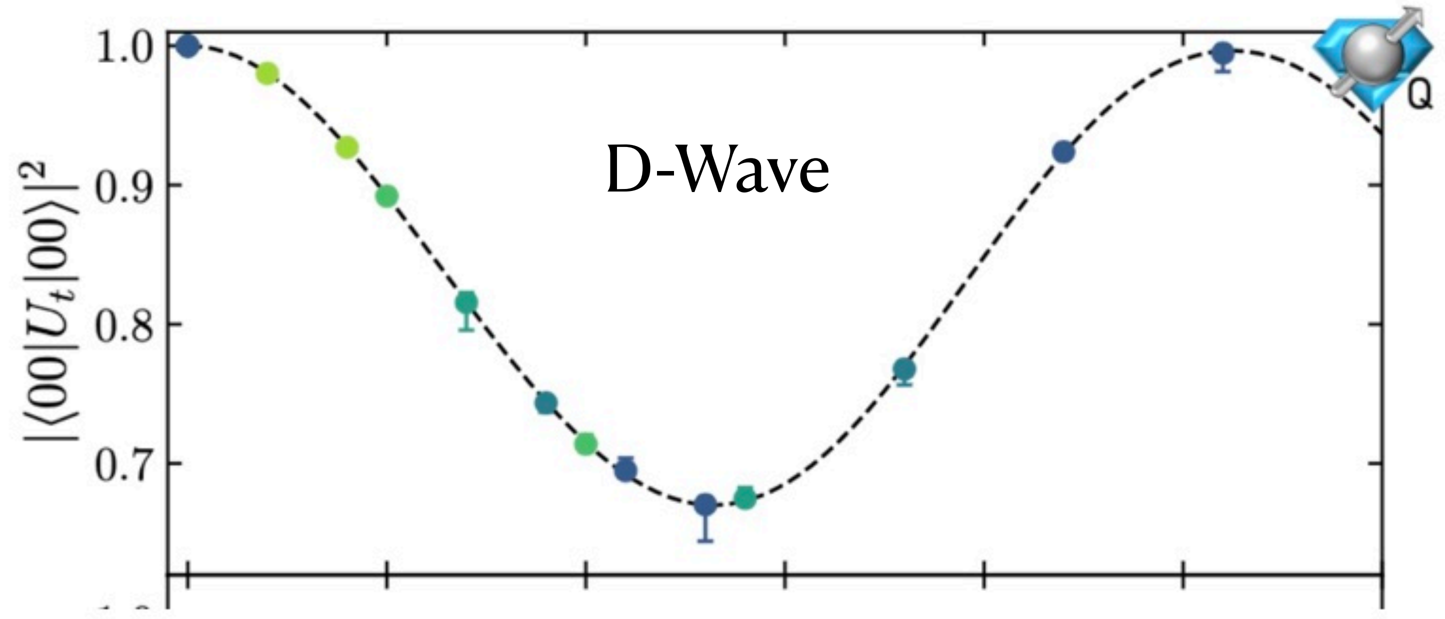
See e.g., Atas et al, Nature Communications 12, 6499 (2021).



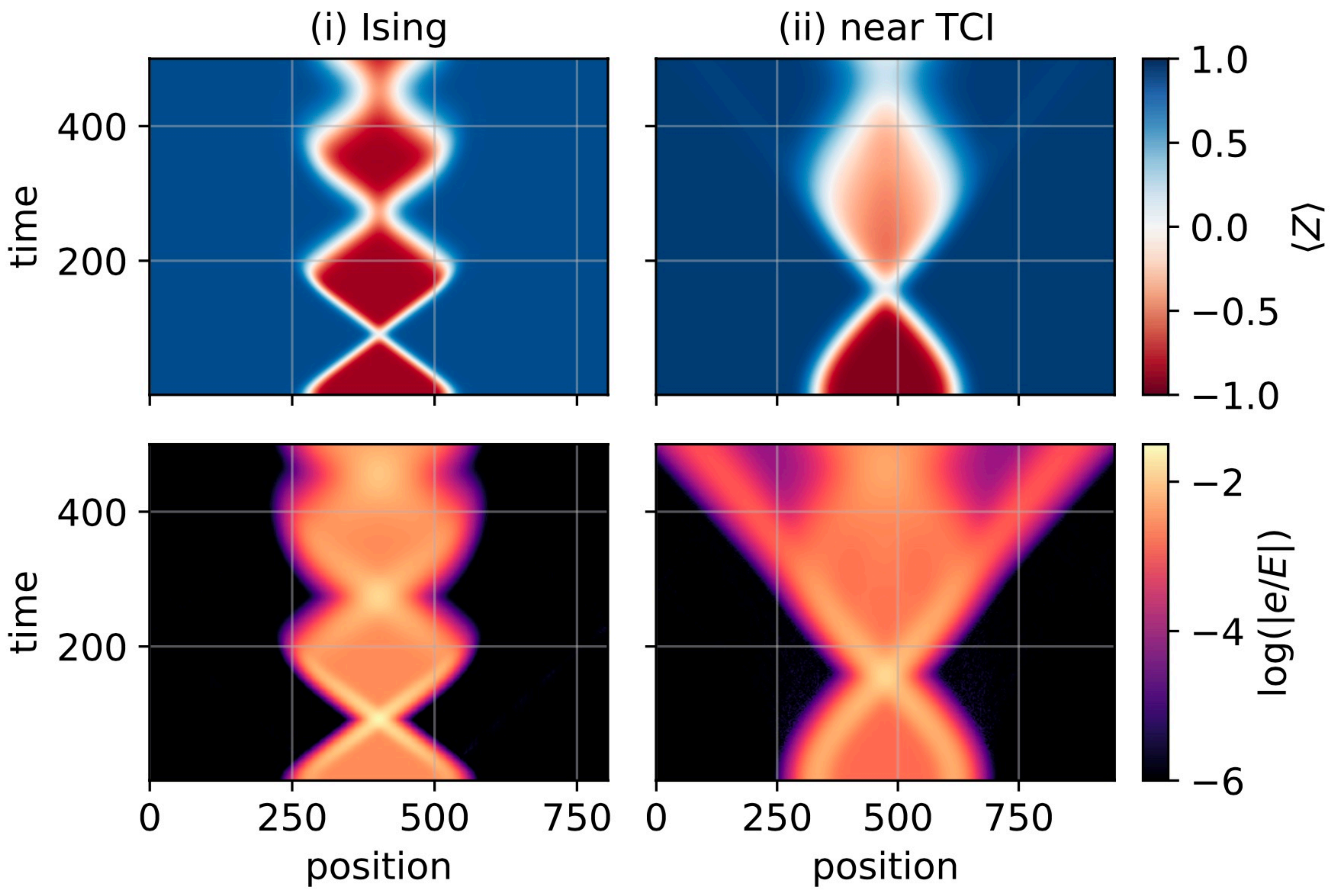
SU(3), pure Yang-Mills, 2-D
Dynamical gauge fields



See e.g., Ciavarella, Klco, and Savage, Phys. Rev. D 103, 094501 (2021), Atas et al, arXiv:2207.03473 [quant-ph]. Farrel MJS et al, arXiv:2207.01731 [quant-ph].

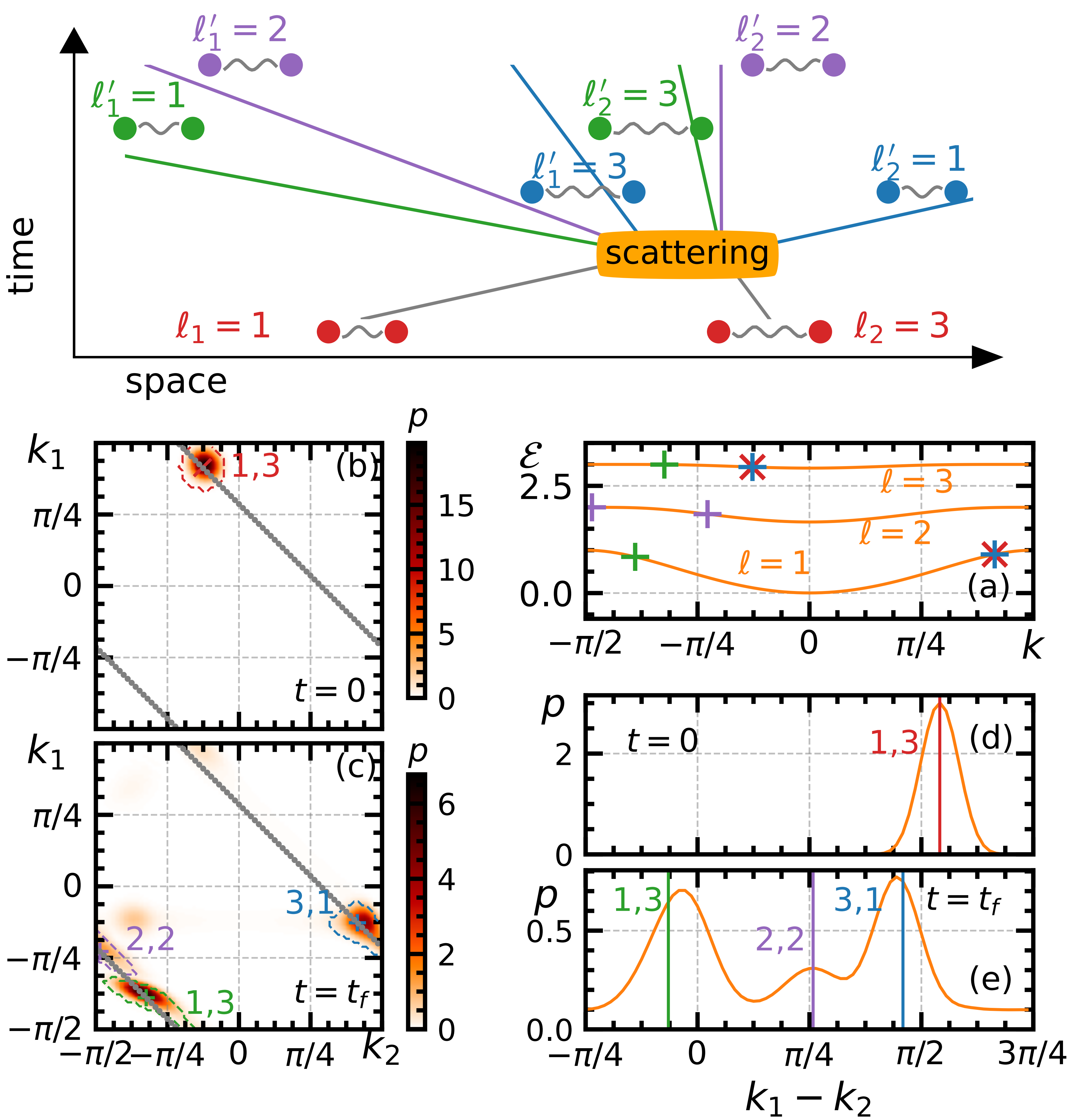


First Steps Toward Scattering in Spin Systems — Numerical Simulations —



Ashley Milsted, Liu, John Preskill, and Vidal, PRX Quantum 3 (2022) 2, 020316.

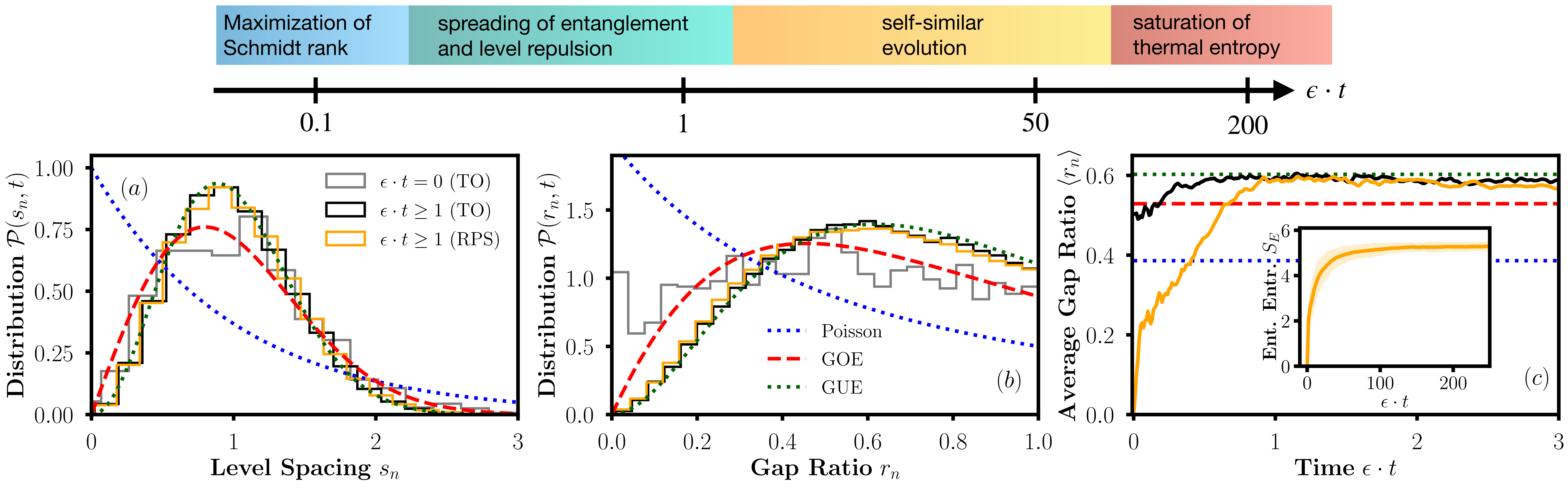
Surace, Lerose, New J. Phys. 23 (2021) 062001.



Emerging Understanding of Thermalization in Simple Gauge Theories

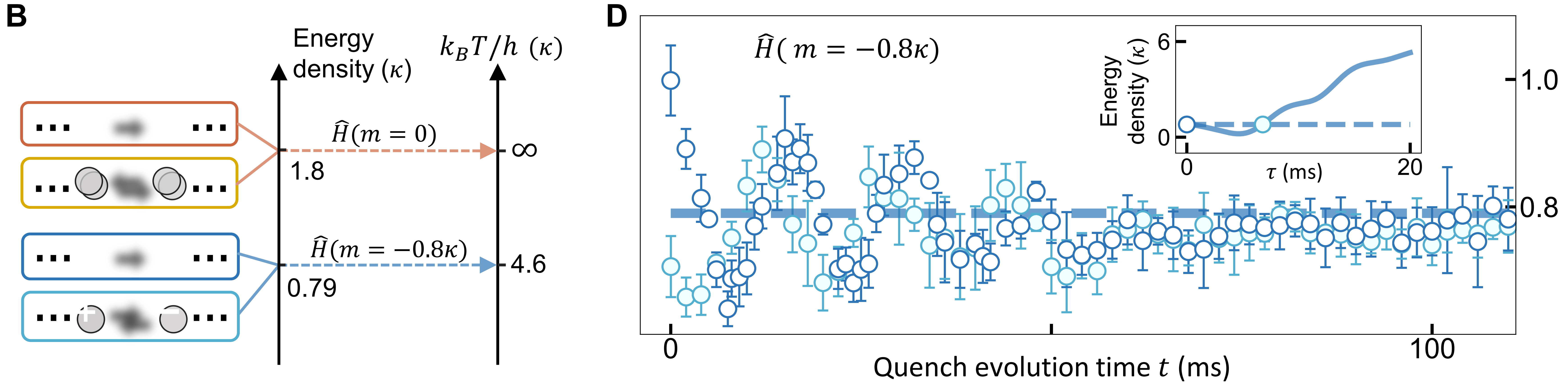
Numerical study of Z2 lattice gauge theory in 2+1 D

Mueller, Zache, Ott, Phys. Rev. Lett. 129, 011601 (2022).



Quantum Link Model in a 70-site analog simulator

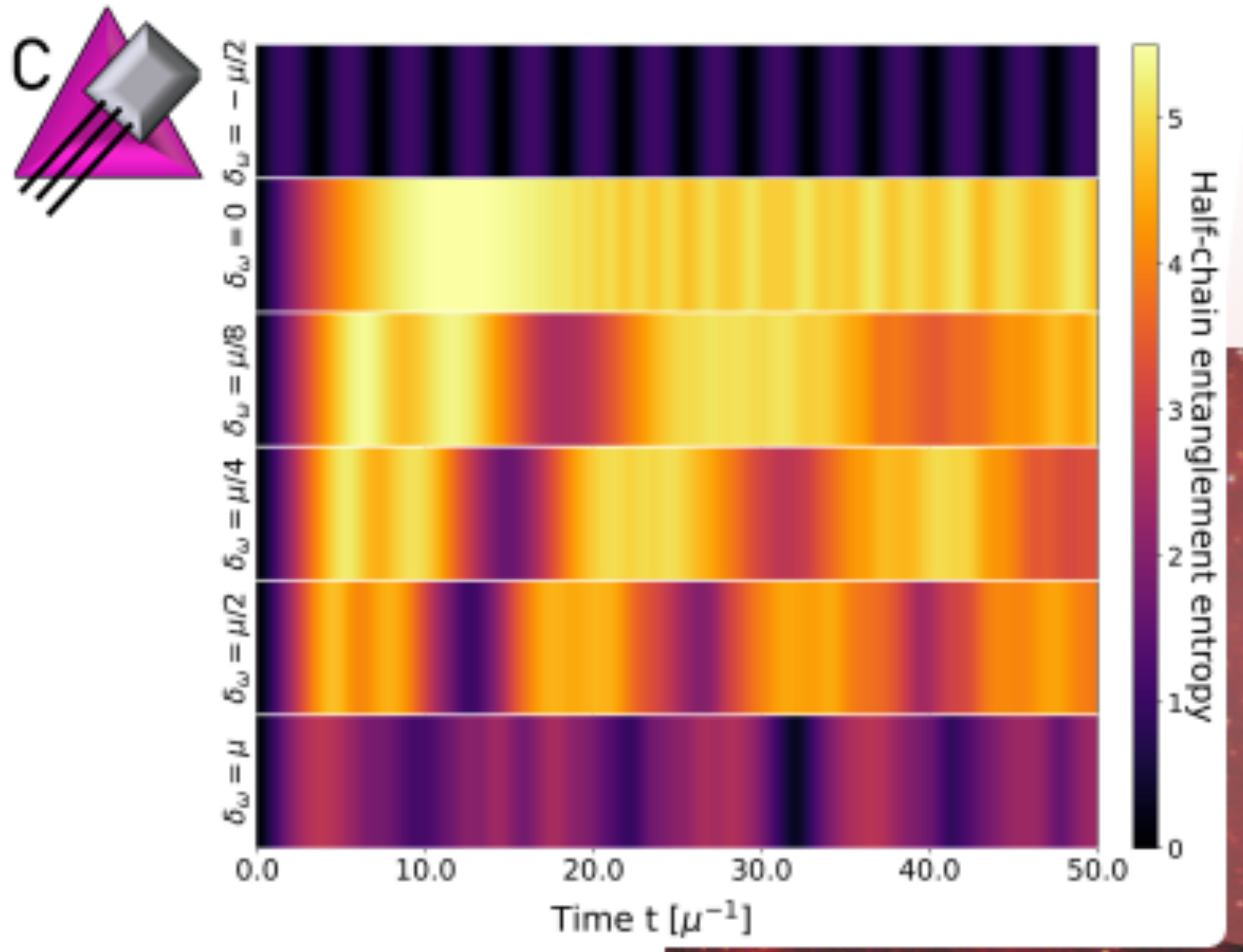
Zhou et al, *Science* 377 (2022) 6603.

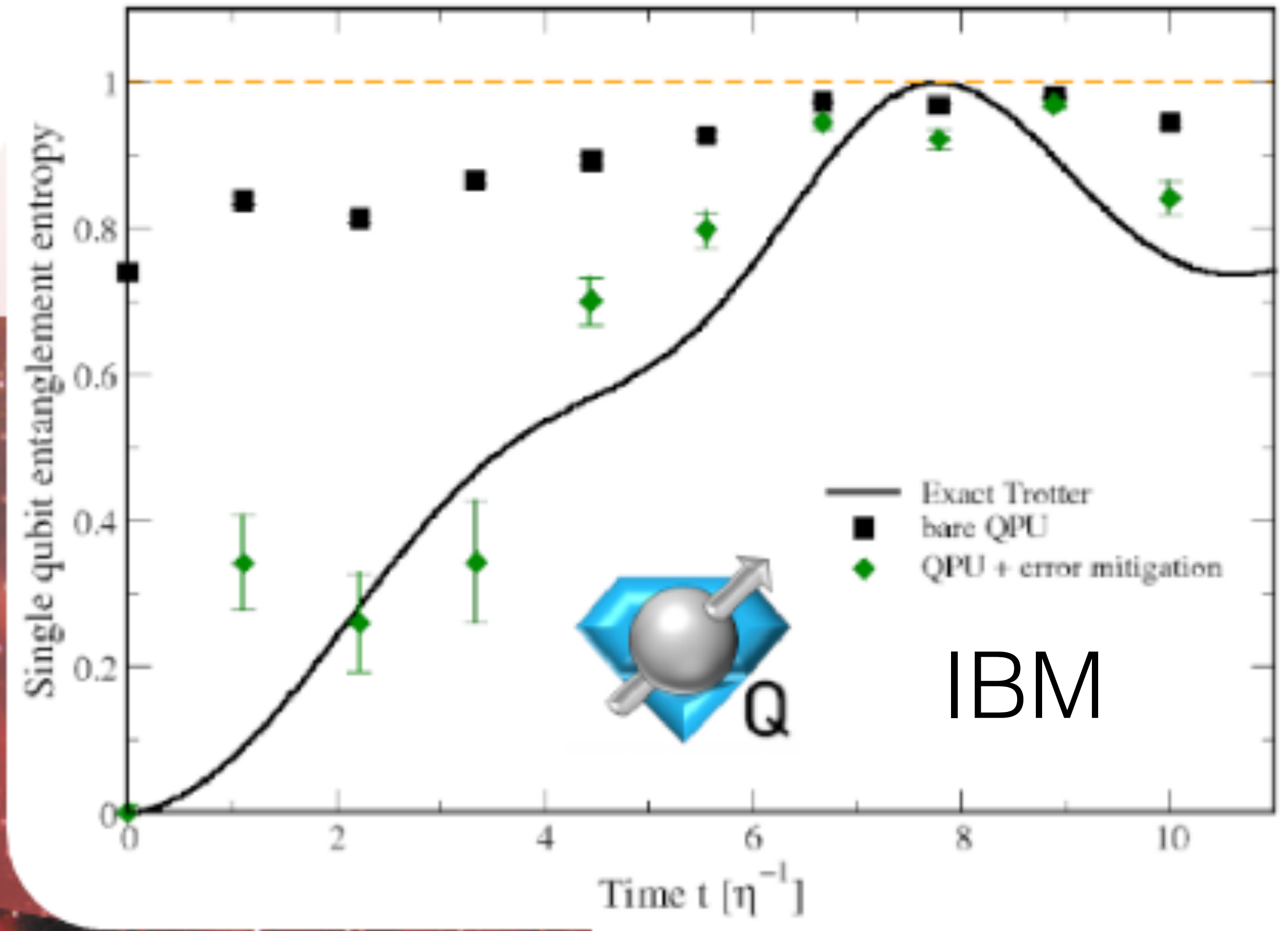


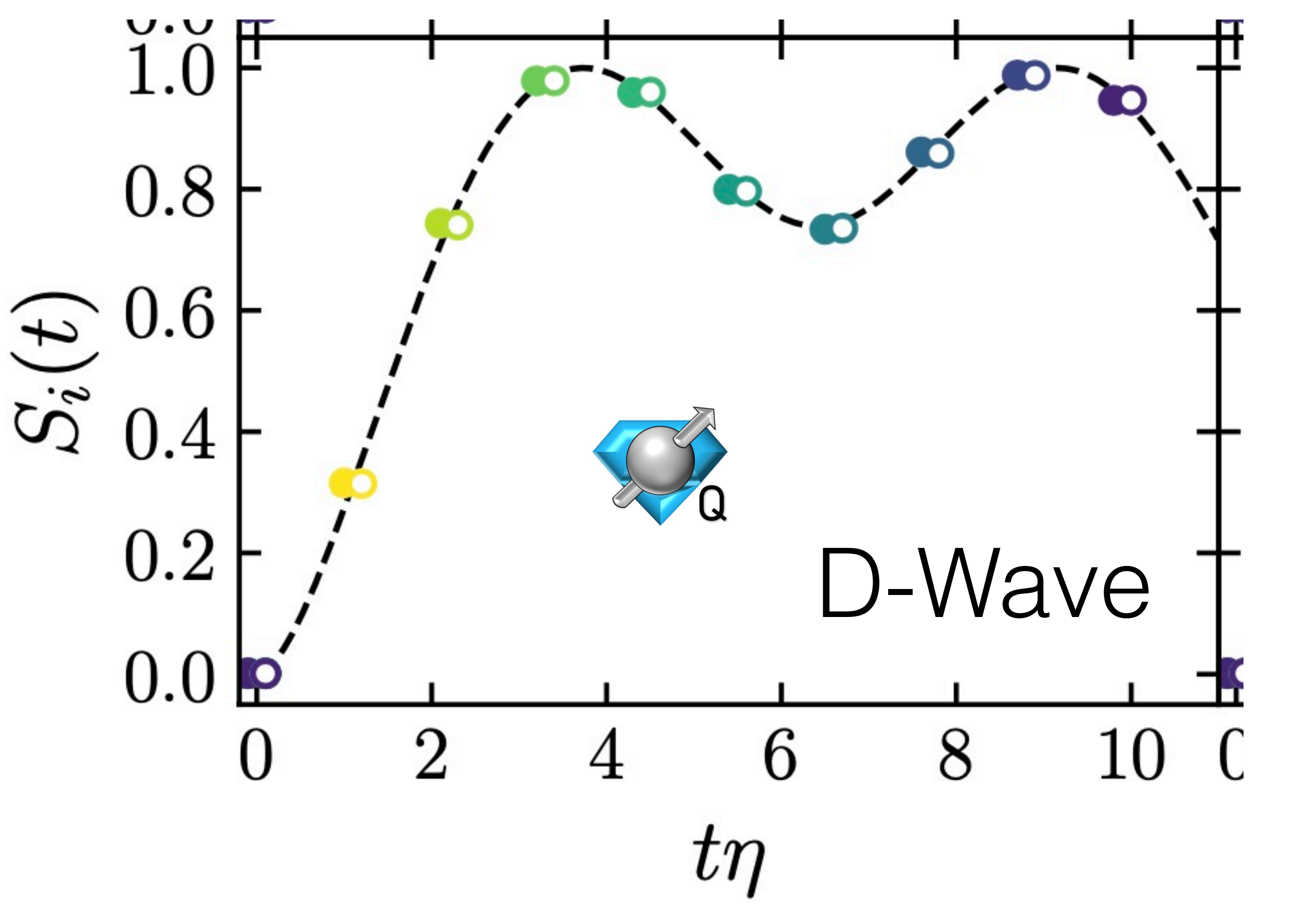
$$H_{FS} = -\sum_{k=1}^{N} \frac{\omega_k}{2} \sigma_k^z + \frac{\mu}{2N} \sum_{i<j}^{N} \mathcal{J}_{ij} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

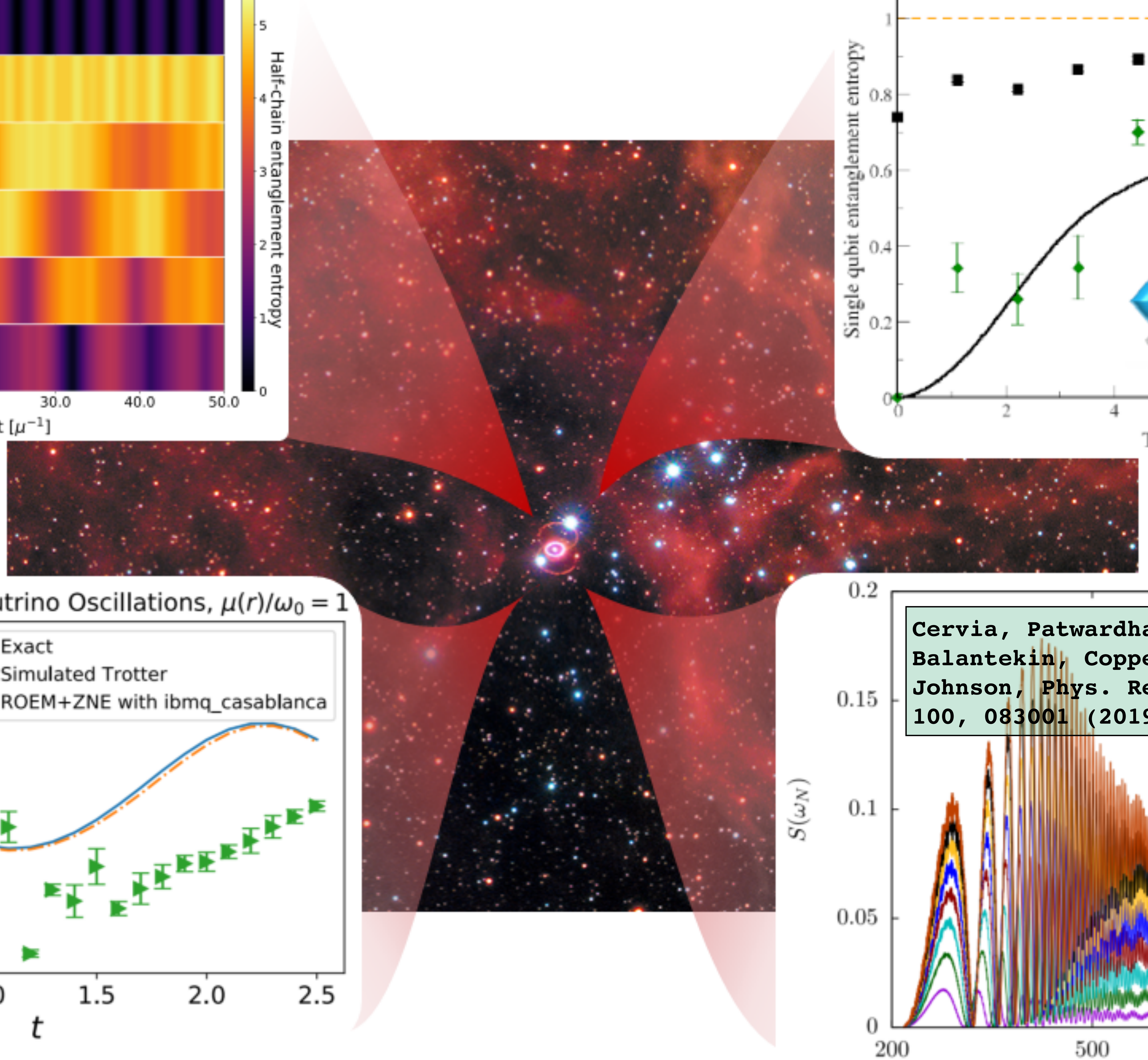
Neutrino Flavor Dynamics Supernova and Early Universe

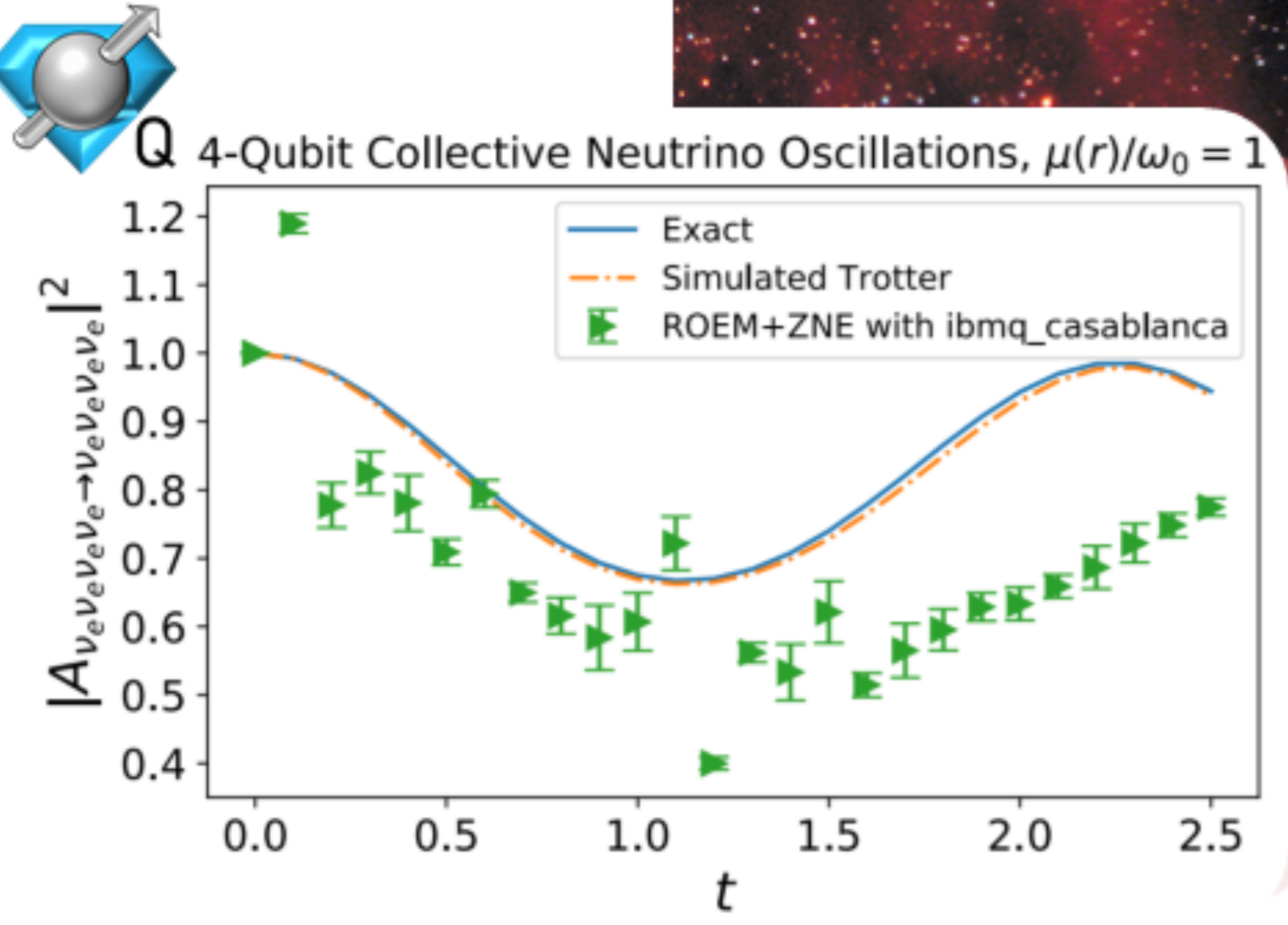
See e.g., Amitrano, Roggero, Luchi, Francesco Turro, Vespucci, Pederiva, arXiv:2207.03189 [quant-ph].

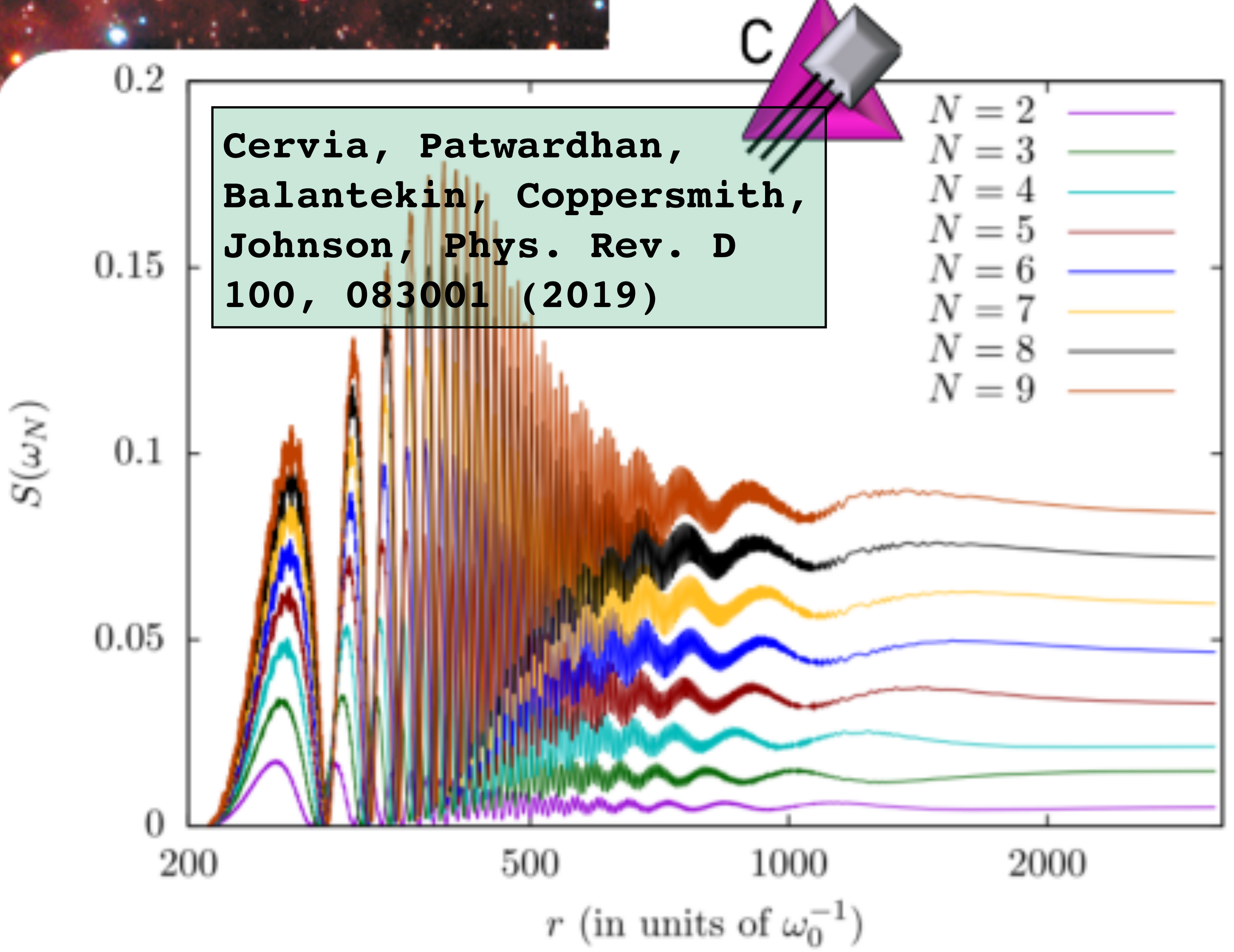




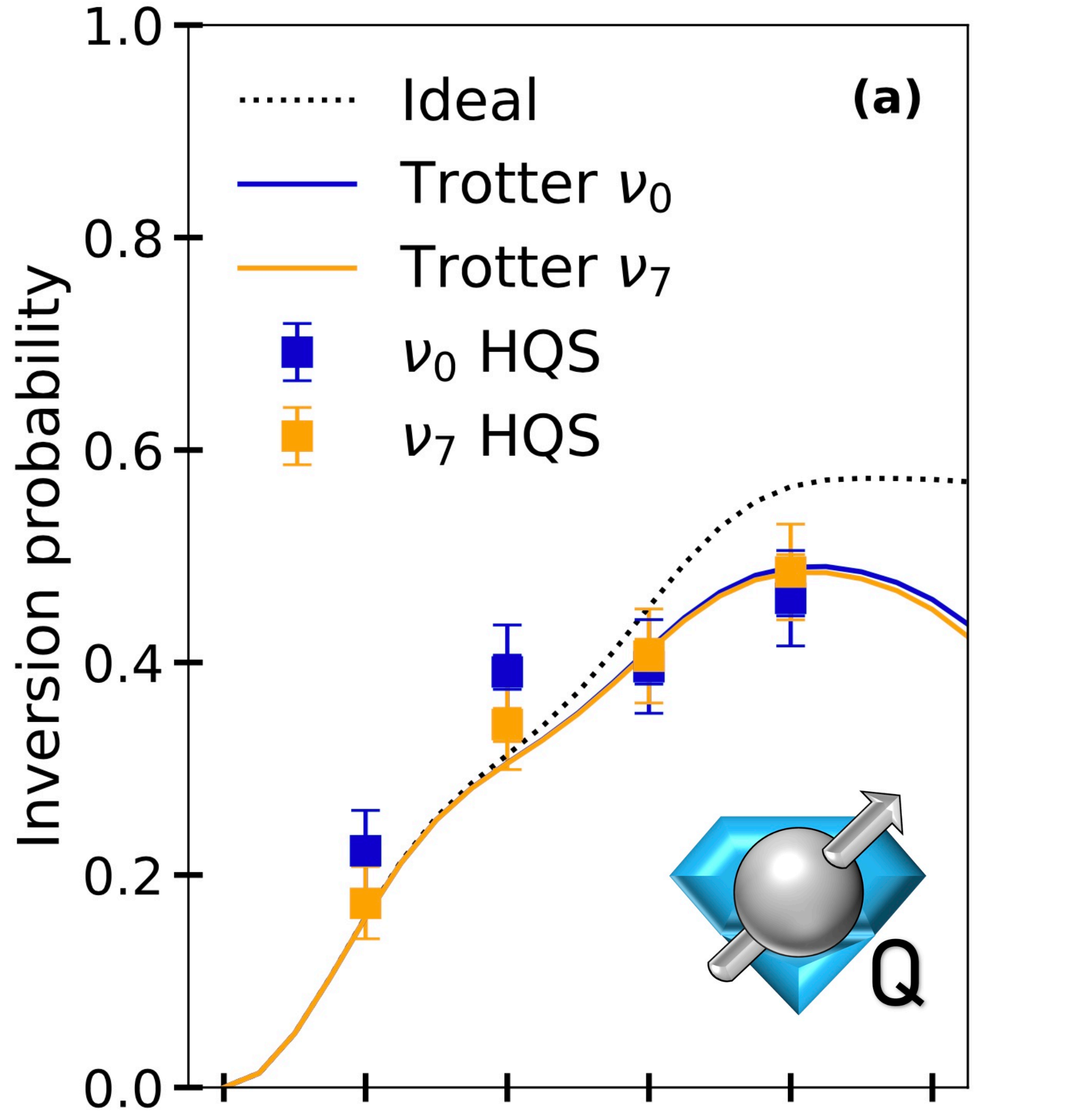






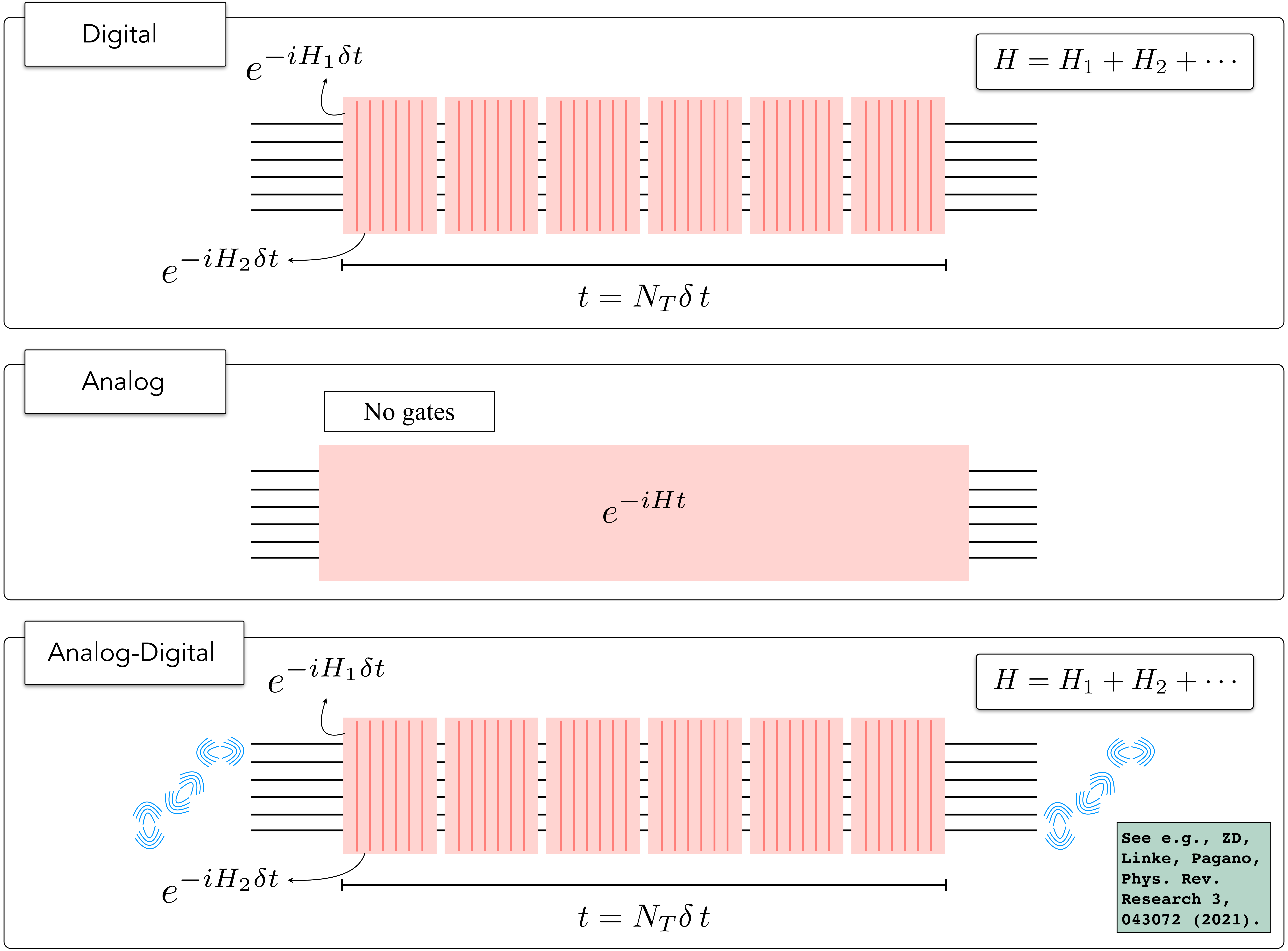


Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, Phys. Rev. D 100, 083001 (2019)

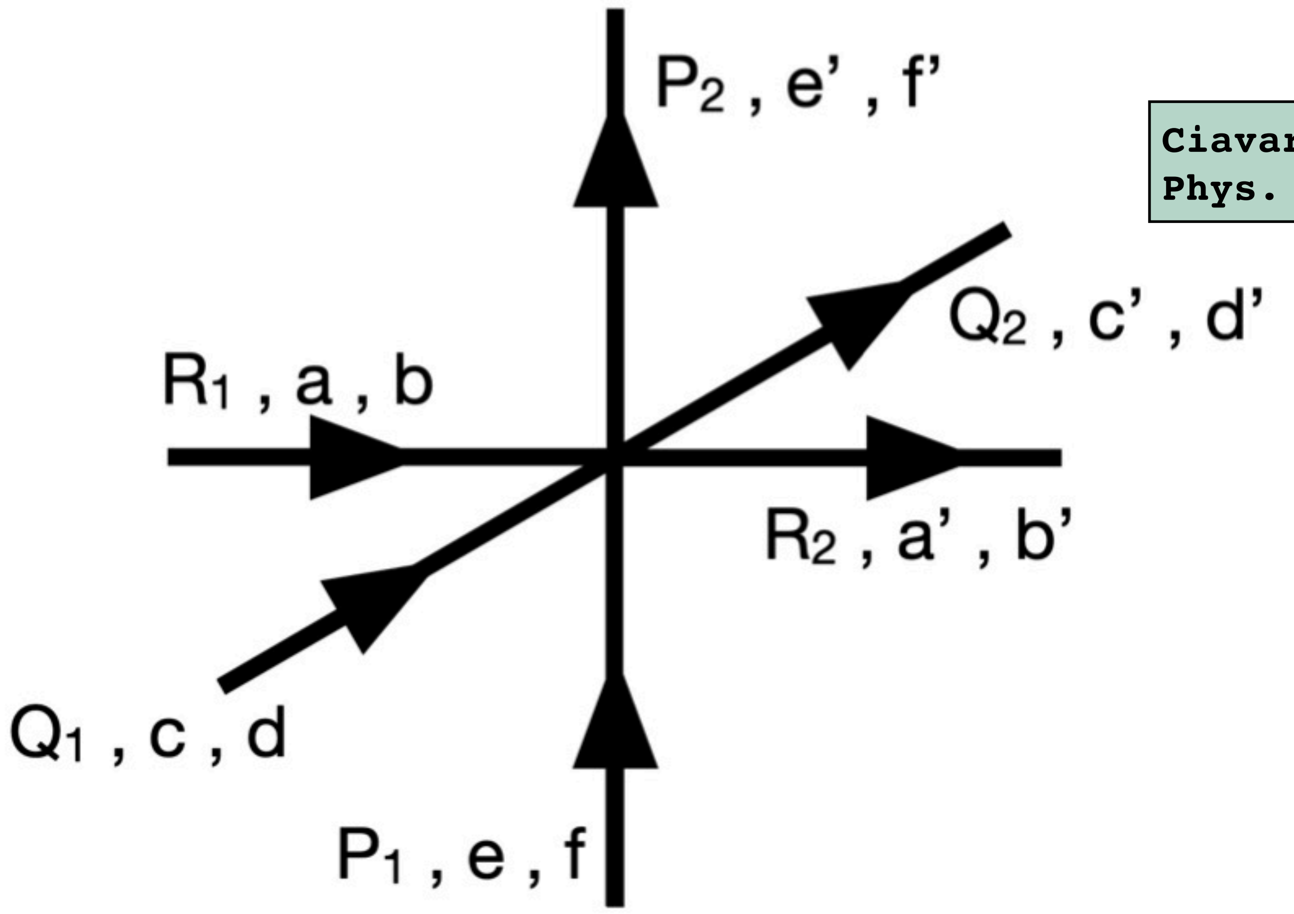


Implementation, benchmark, and co-design

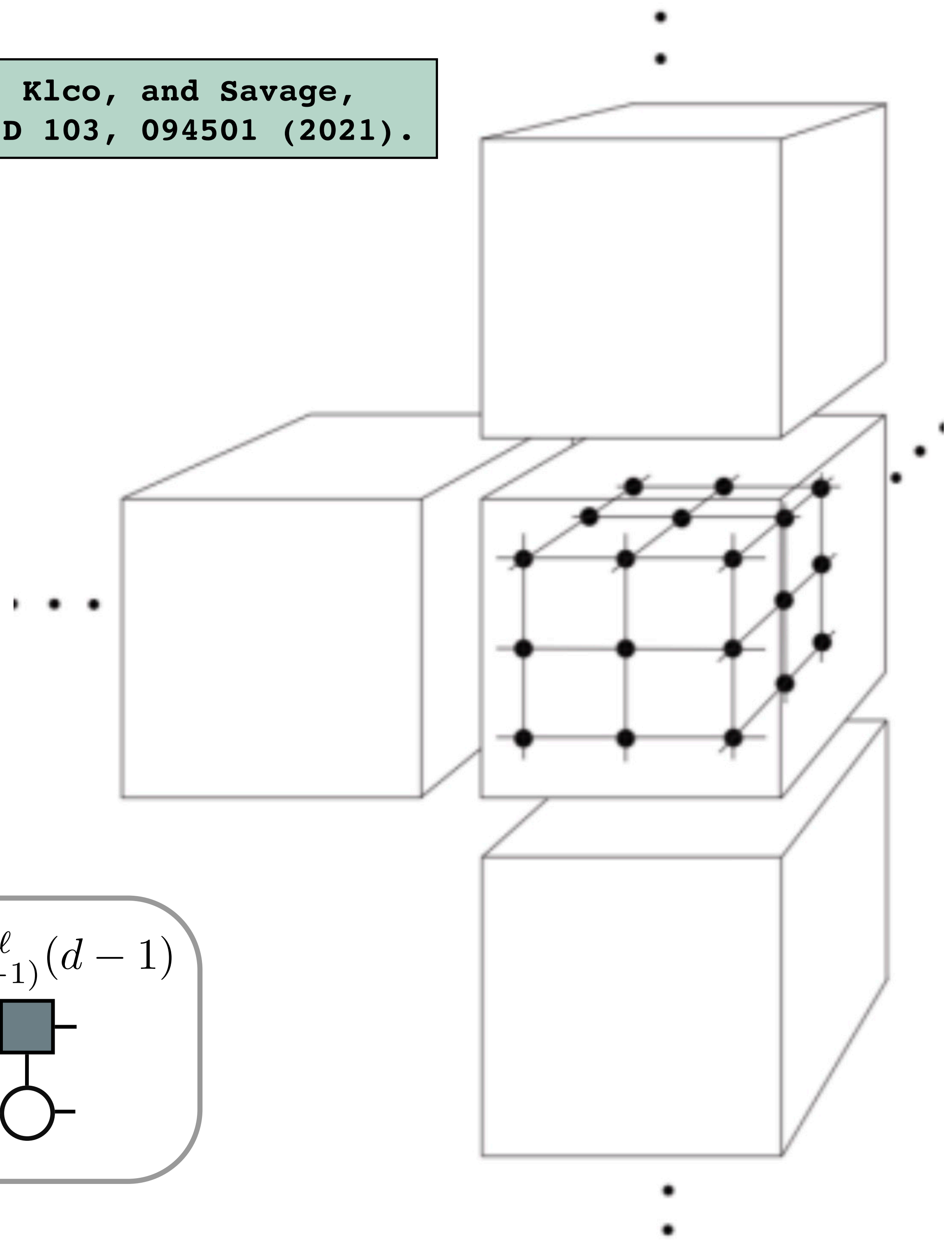
- What is the capability limit of the hardware for gauge-theory simulations so far?
- What is the nature of noise in hardware and how can it best be mitigated?
- Can we co-design dedicated systems for gauge-theory simulations?
- Can digital and analog ideas be combined to facilitate simulations of field theories?
- Can we simulate higher-dimensional gauge theories?
- Can non-Abelian gauge theories be realized in an analog simulator?

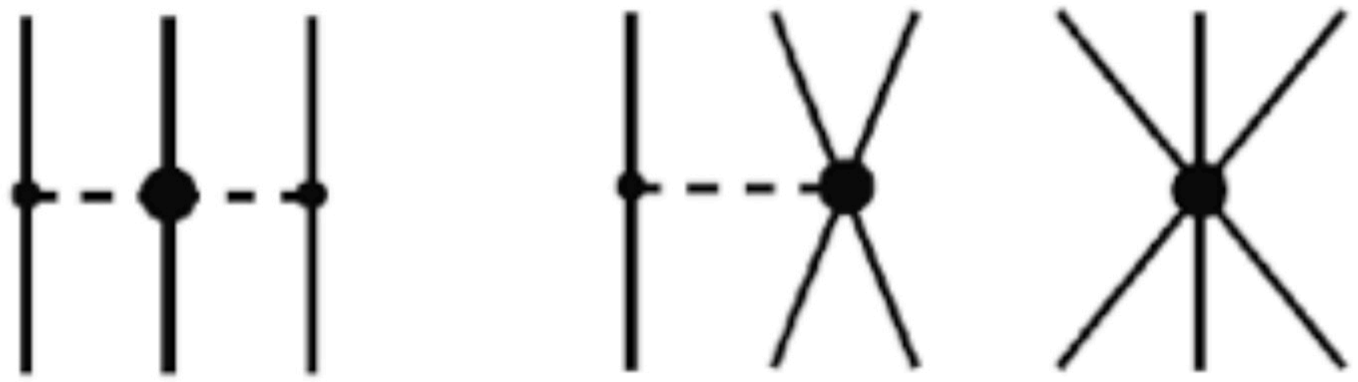

Digital
$e^{-iH_1\delta t}$
$H = H_1 + H_2 + \cdots$
$e^{-iH_2\delta t}$
$t = N_T\delta t$
Analog
No gates
e^{-iHt}
Analog-Digital
$e^{-iH_1\delta t}$
$H = H_1 + H_2 + \cdots$
$e^{-iH_2\delta t}$
$t = N_T\delta t$
See e.g., ZD, Linke, Pagano, Phys. Rev. Research 3, 043072 (2021).

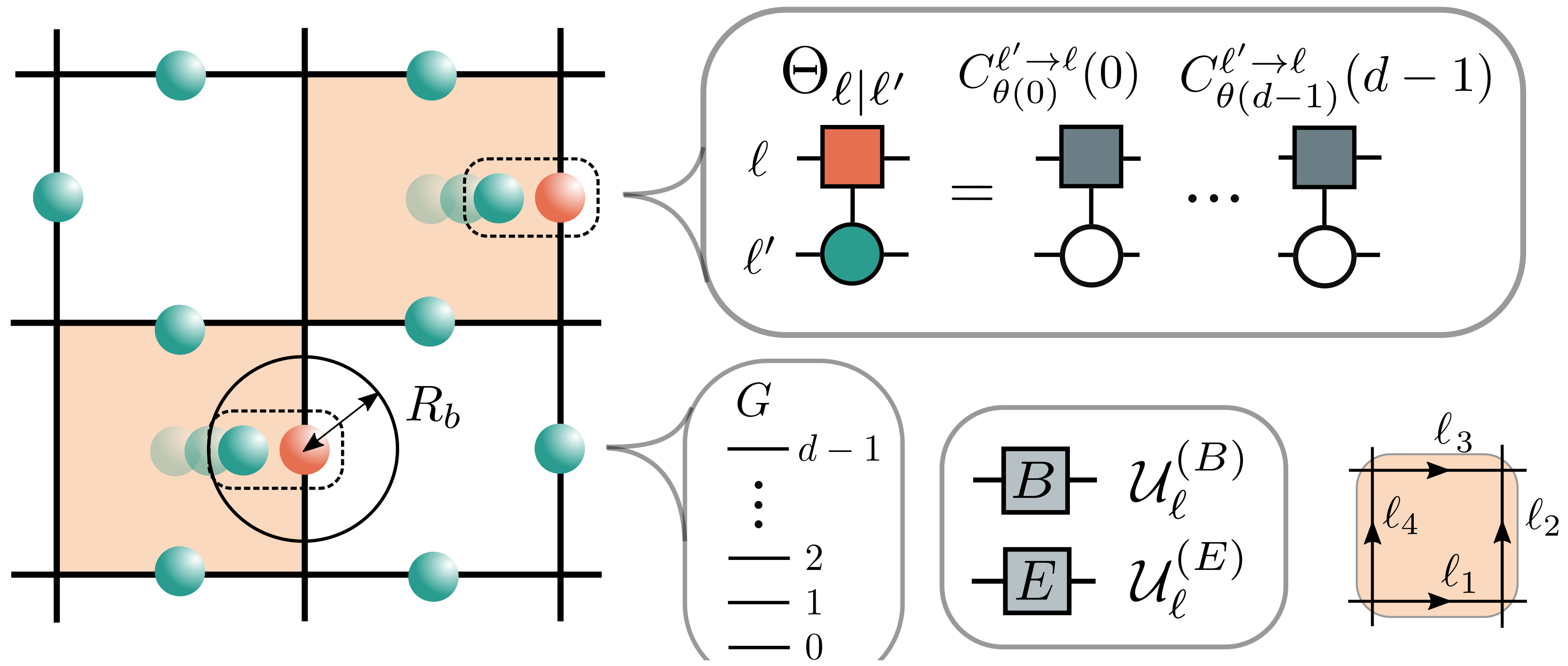
Co-Design for Standard Model Physics
An example: Multi-dim local Hilbert spaces and multi-mode interactions



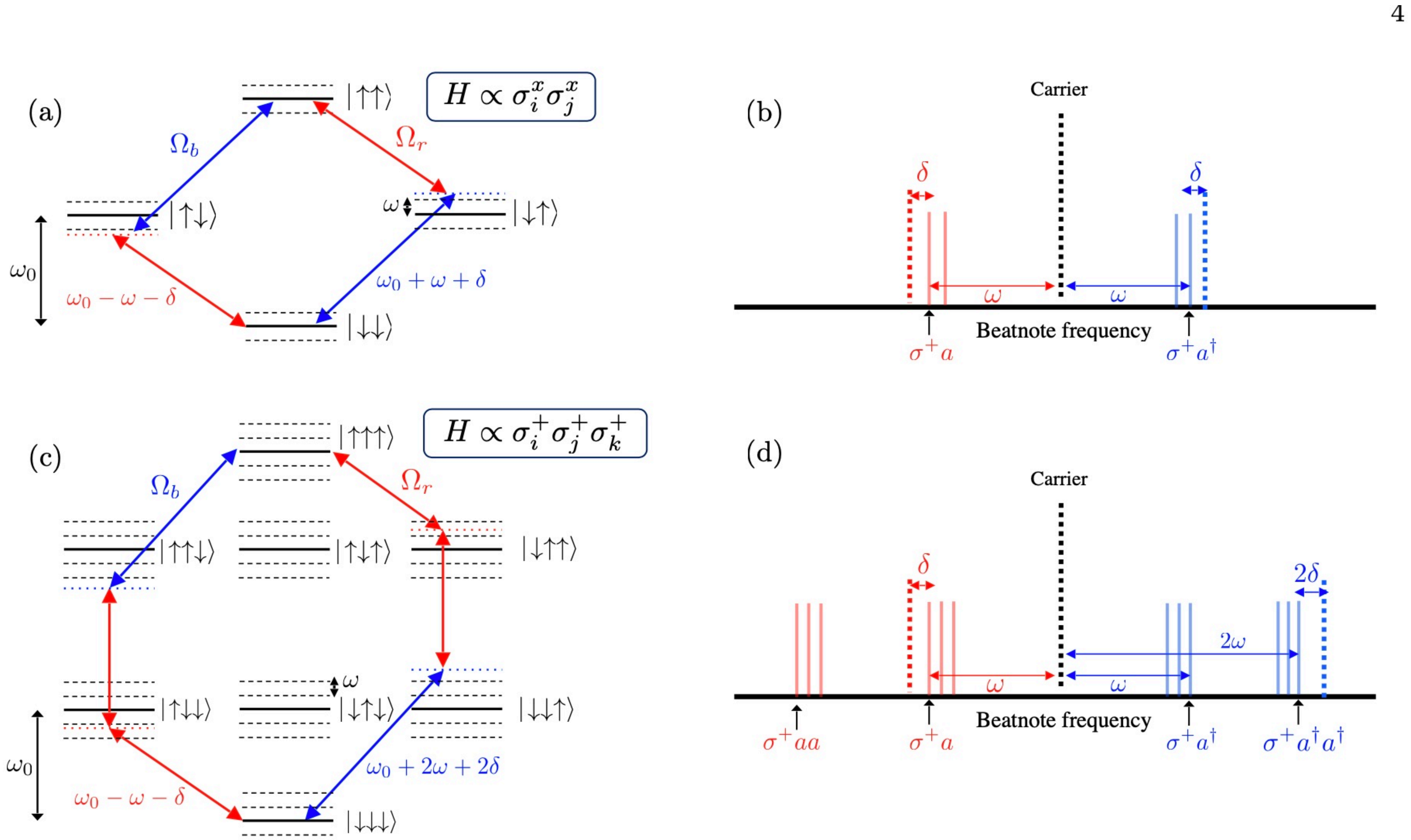
Ciavarella, Klco, and Savage,
Phys. Rev. D 103, 094501 (2021).







González-Cuadra, Zache, Carrasco, Kraus, Zoller,
arXiv:2203.15541 [quant-ph].

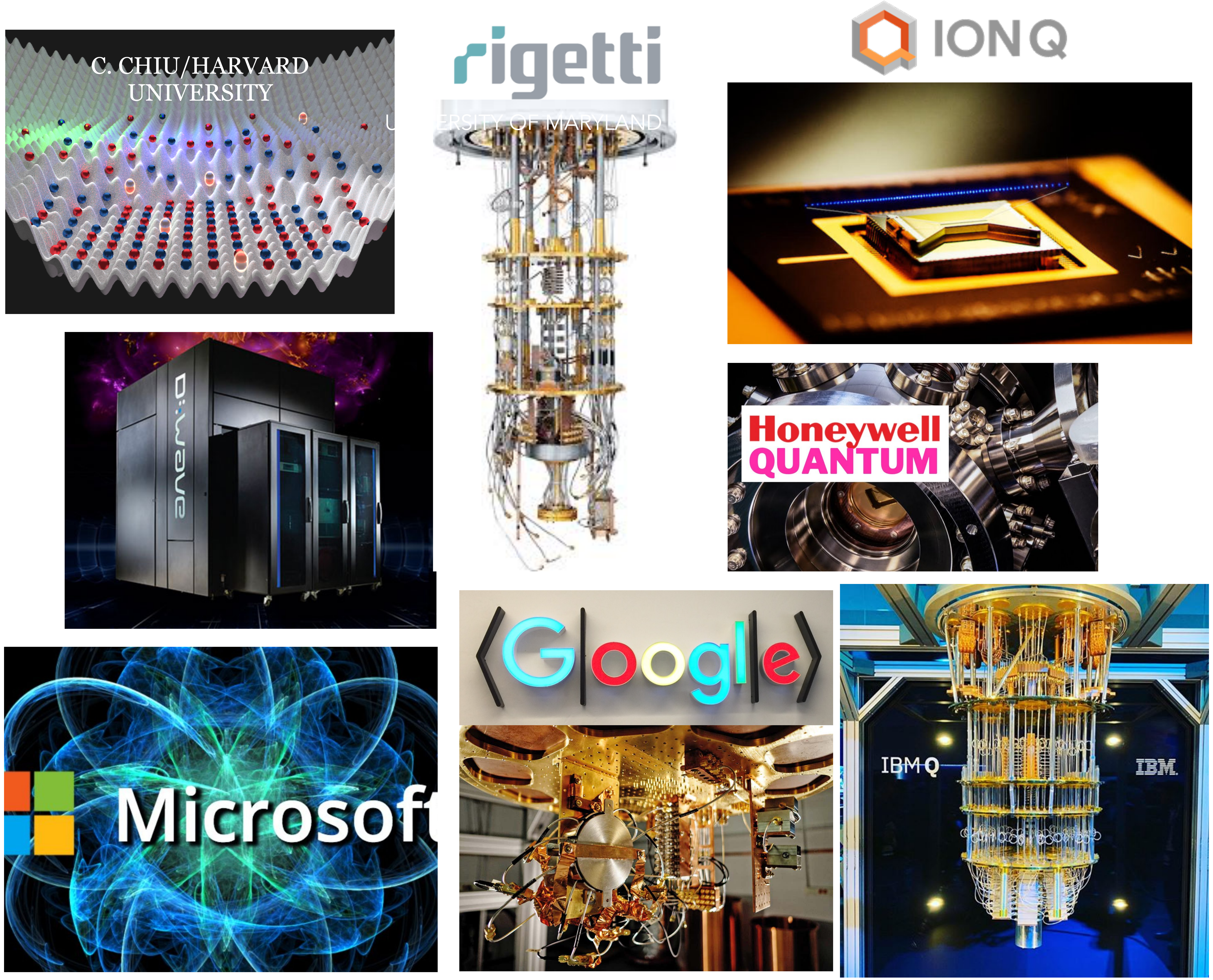


Andrade, ZD, Grass, Hafezi, Pagano, Seif,
arXiv:2108.01022 [quant-ph], Bermudez et al, Pays.Rev.A79, 060303
R (2009), Katz, Centina, Monroe, arXiv:2202.04230 [quant-ph].

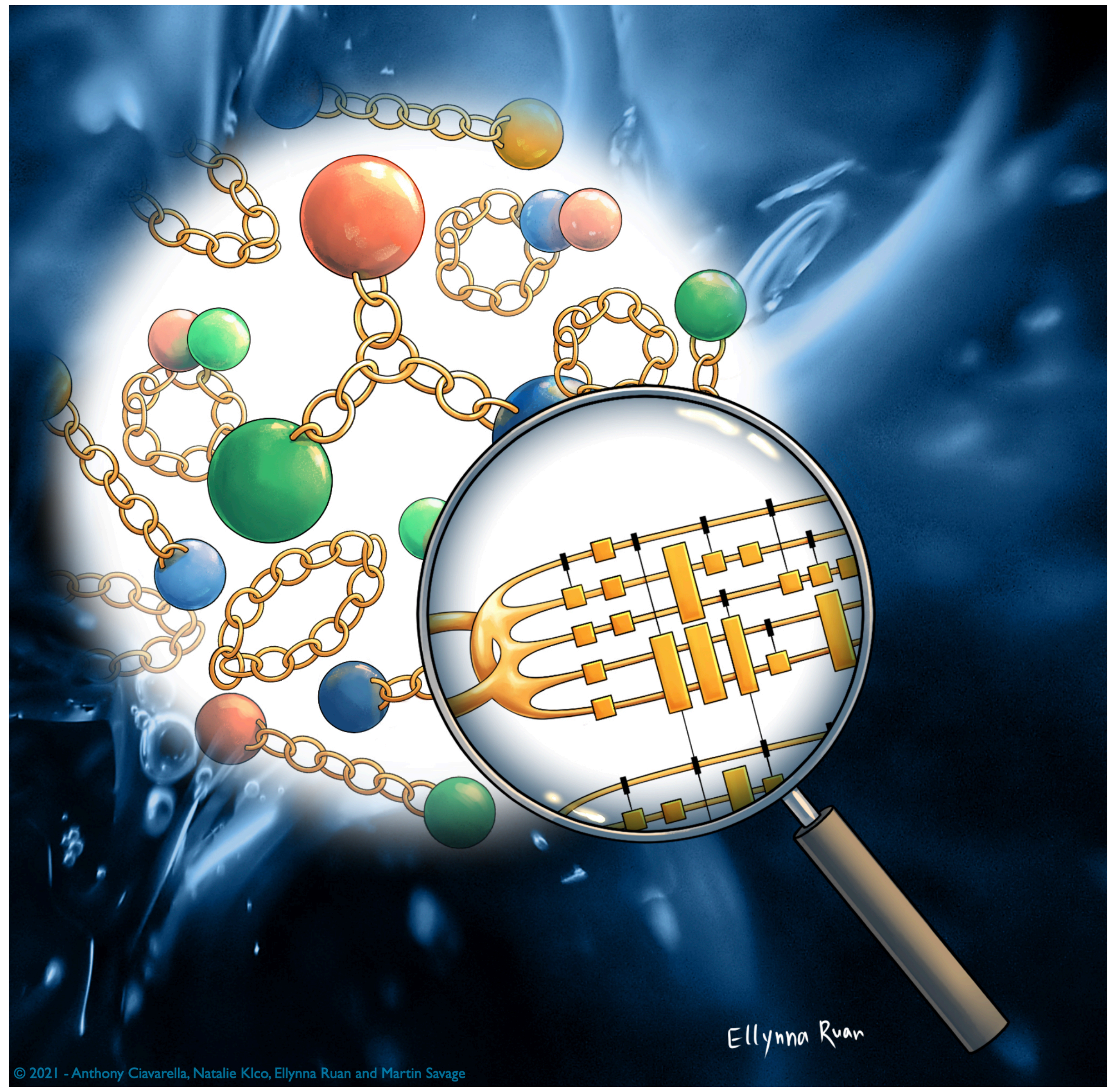
Platforms Explored

- Atomic systems (trapped ions, cold atoms, Rydbergs)
- Condensed matter systems (superconducting circuits, dopants in semiconductors such as in Silicon, NV centers in diamond)
- Laser-cooled polar molecules
- Optical systems (cavity quantum electrodynamics)

Need to study which system(s) suit HEP problems best.



Summary



Quantum Simulation is essential for addressing key questions in High-Energy Physics

- Key Applications to pursue during the next decade

-Multiple paths to explore. The optimal simulation strategy and simulator architecture not known. They will likely be determined in a co-design process involving HEP and QIS researchers.

* Examples in this talk were just to showcase the progress. Not comprehensive by any means. Please check out references in Snowmass (**HEP**) Whitepaper : **Quantum Simulation for High Energy Physics** `Bauer, ZD, MJS et al, arXiv:2204.03381 [quant-ph].`

FIN