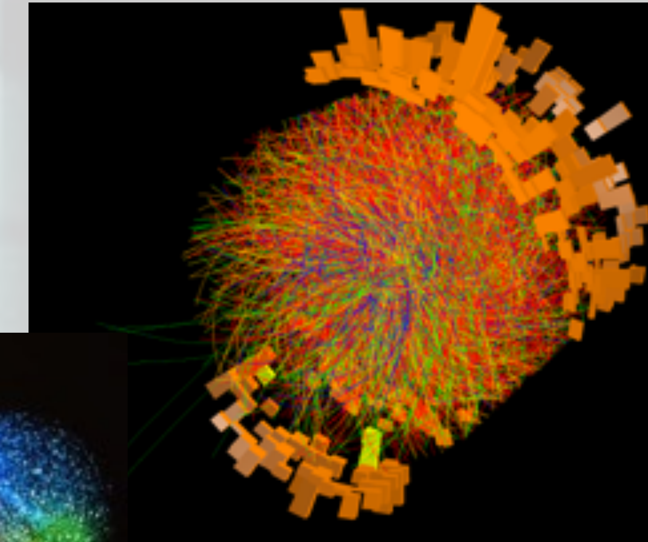
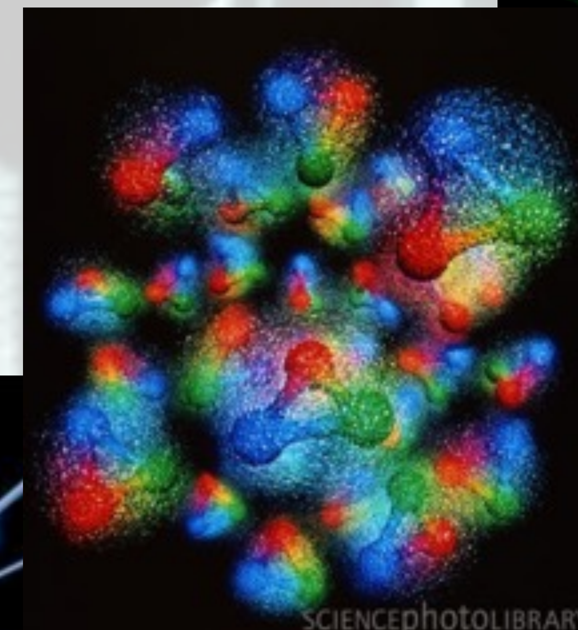
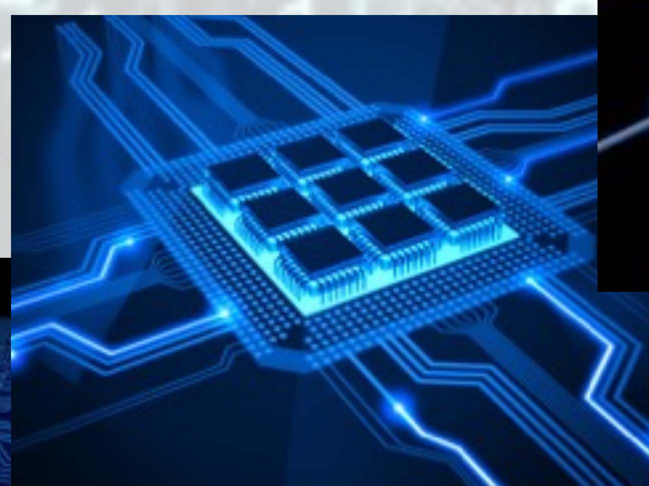
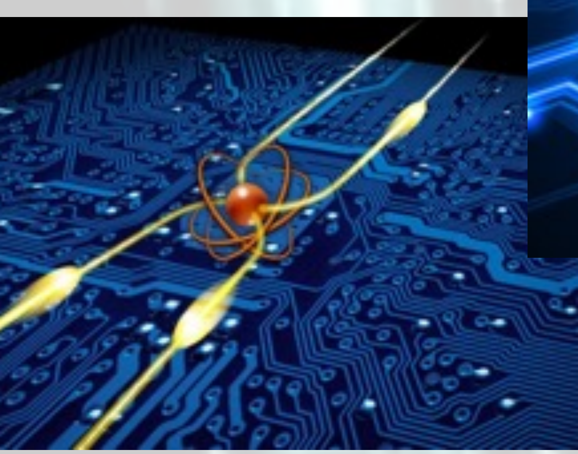






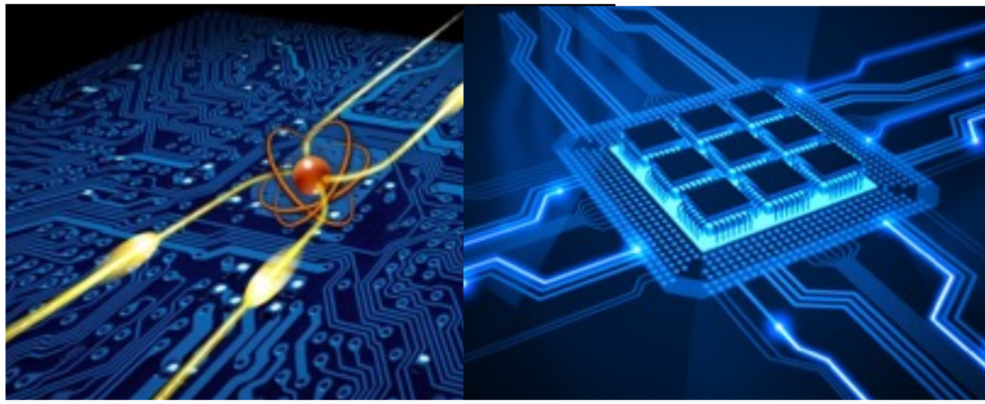


Quantum Chromodynamics in the Exascale Era with the Emergence of Quantum Computing

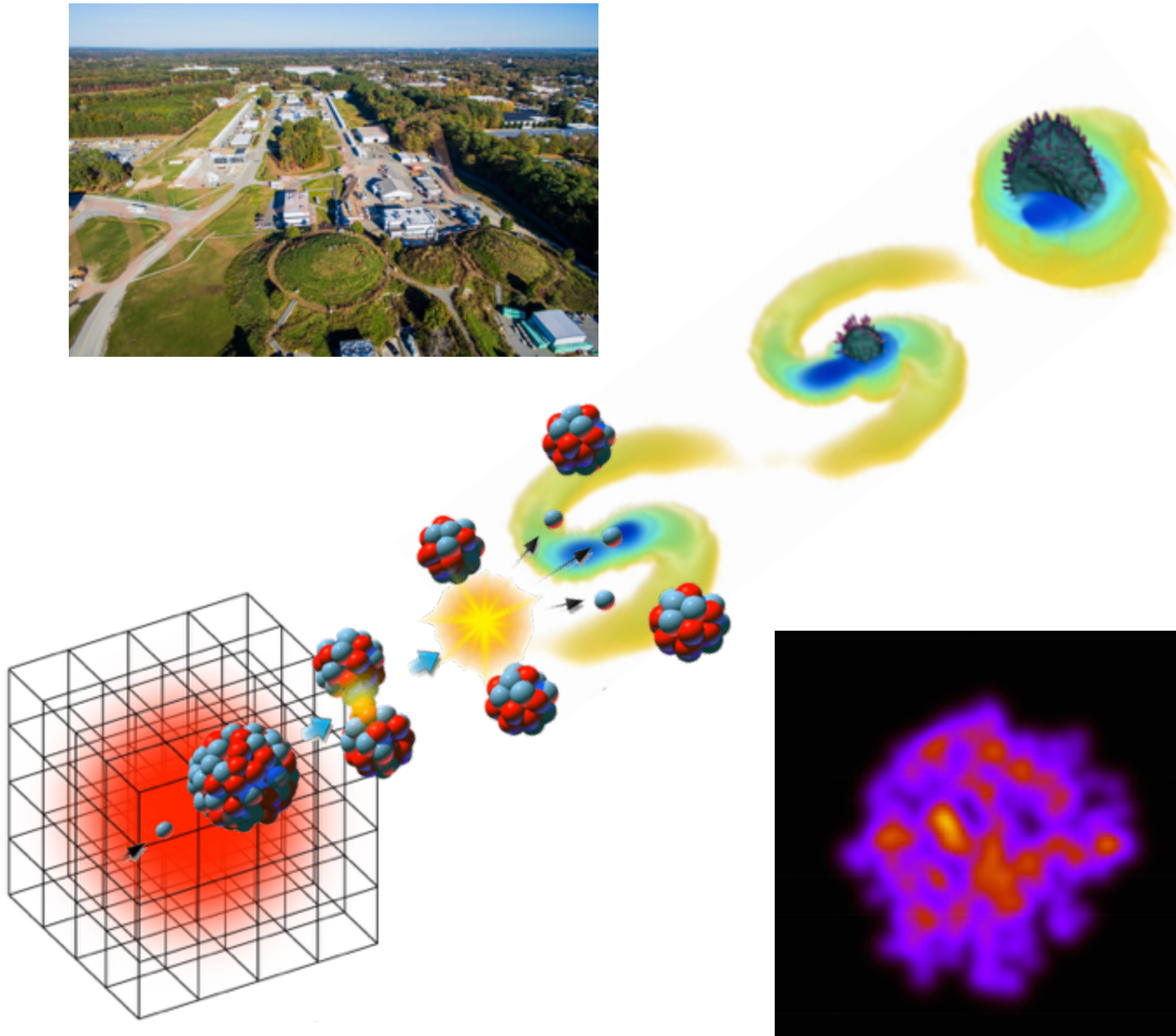
Workshop on Computational Complexity and High Energy Physics
Joint Center for Quantum Information and Computer Science
University of Maryland, July 31-Aug3 , 2017

Martin J Savage

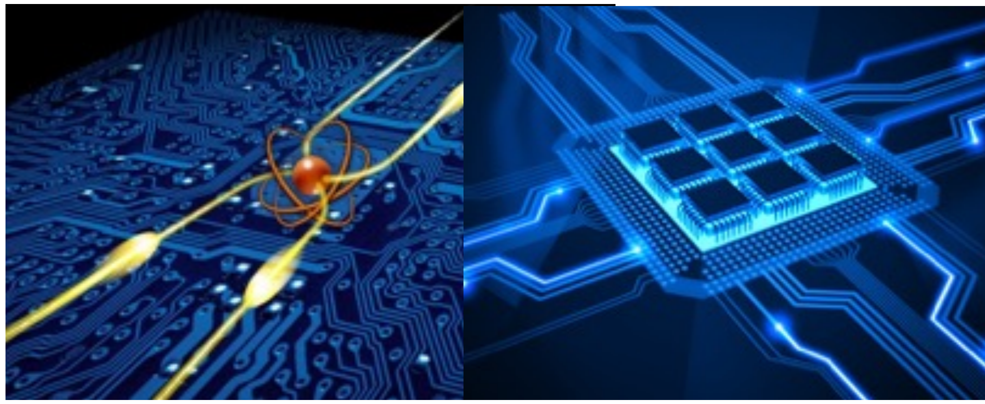
Institute for Nuclear Theory
University of Washington



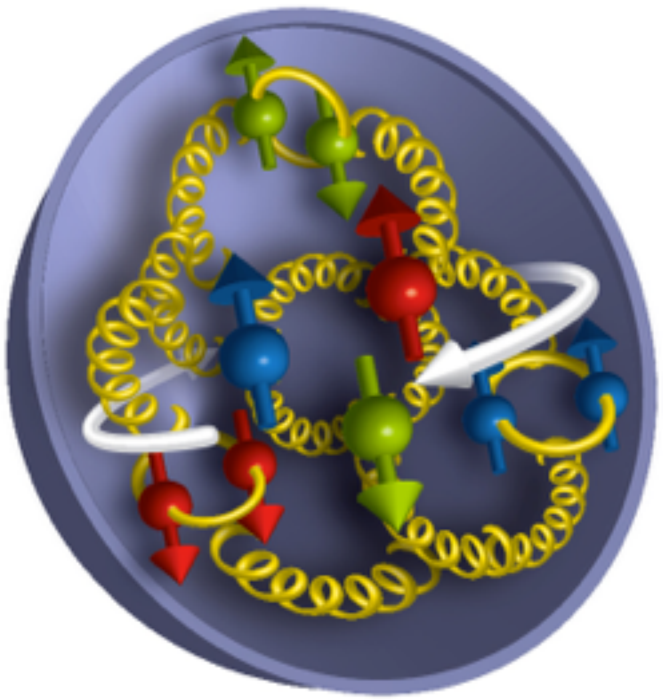
The Objective

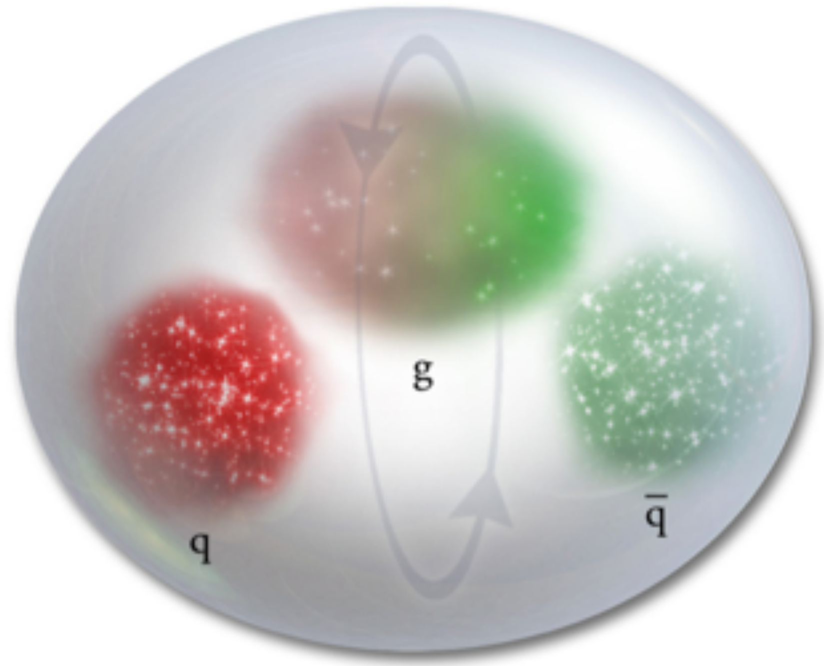


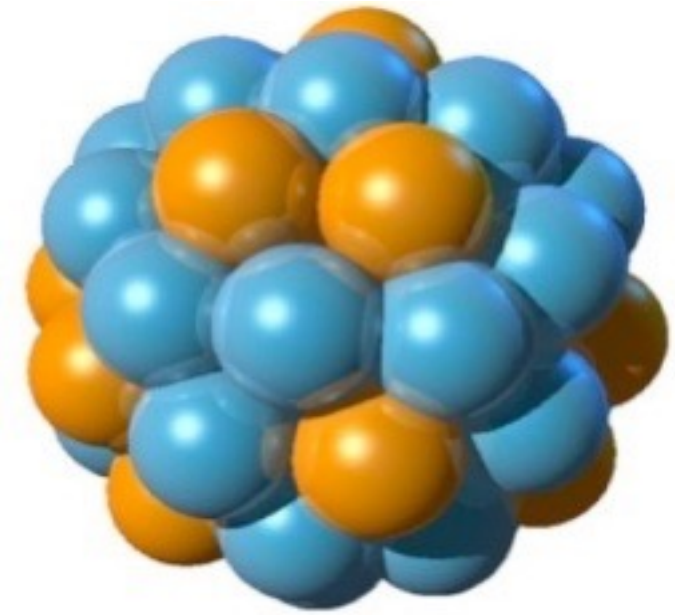
Imagine being able to predict — with unprecedented accuracy and precision — the structure of the proton and neutron, and the forces between them, directly from the dynamics of quarks and gluons, and then using this information in calculations of the structure and reactions of atomic nuclei and of the properties of dense neutron stars...

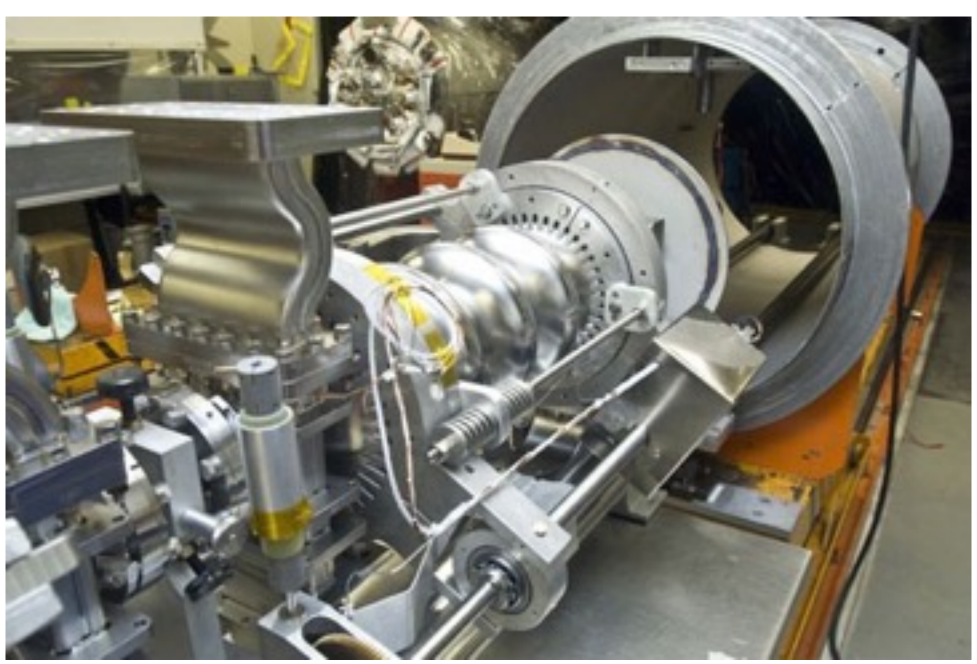


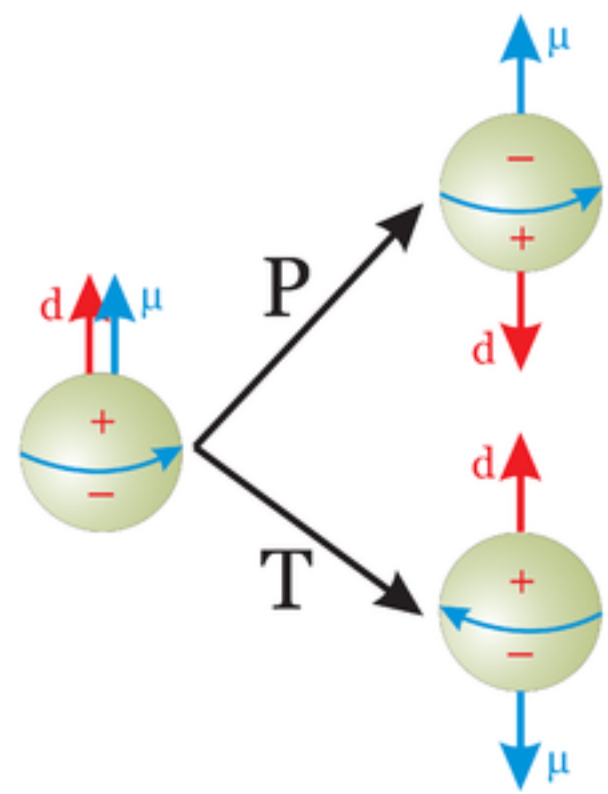
Hadrons and Nuclei

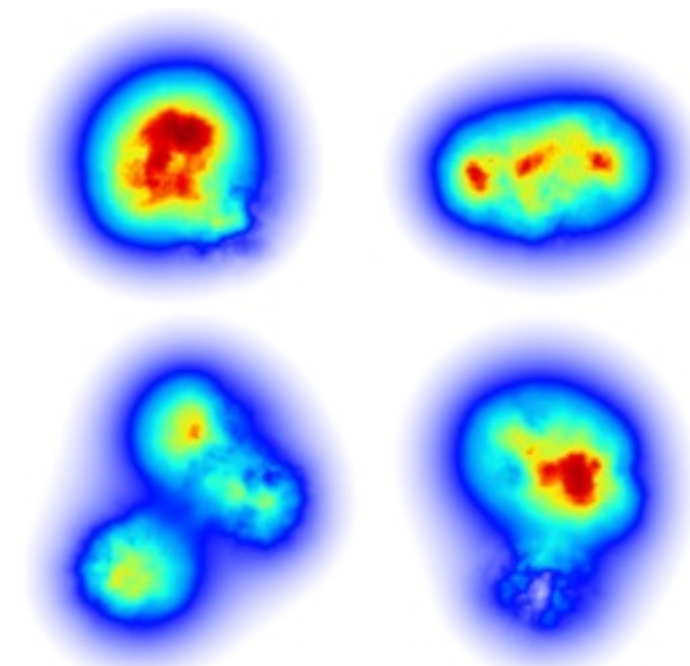


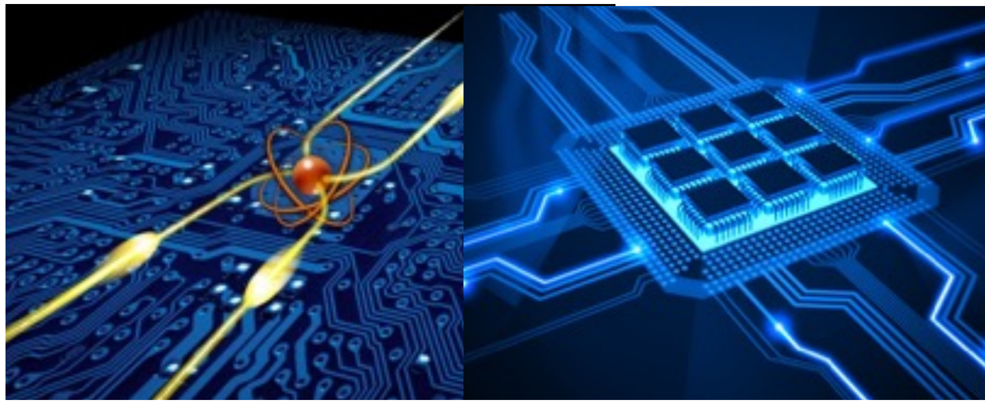




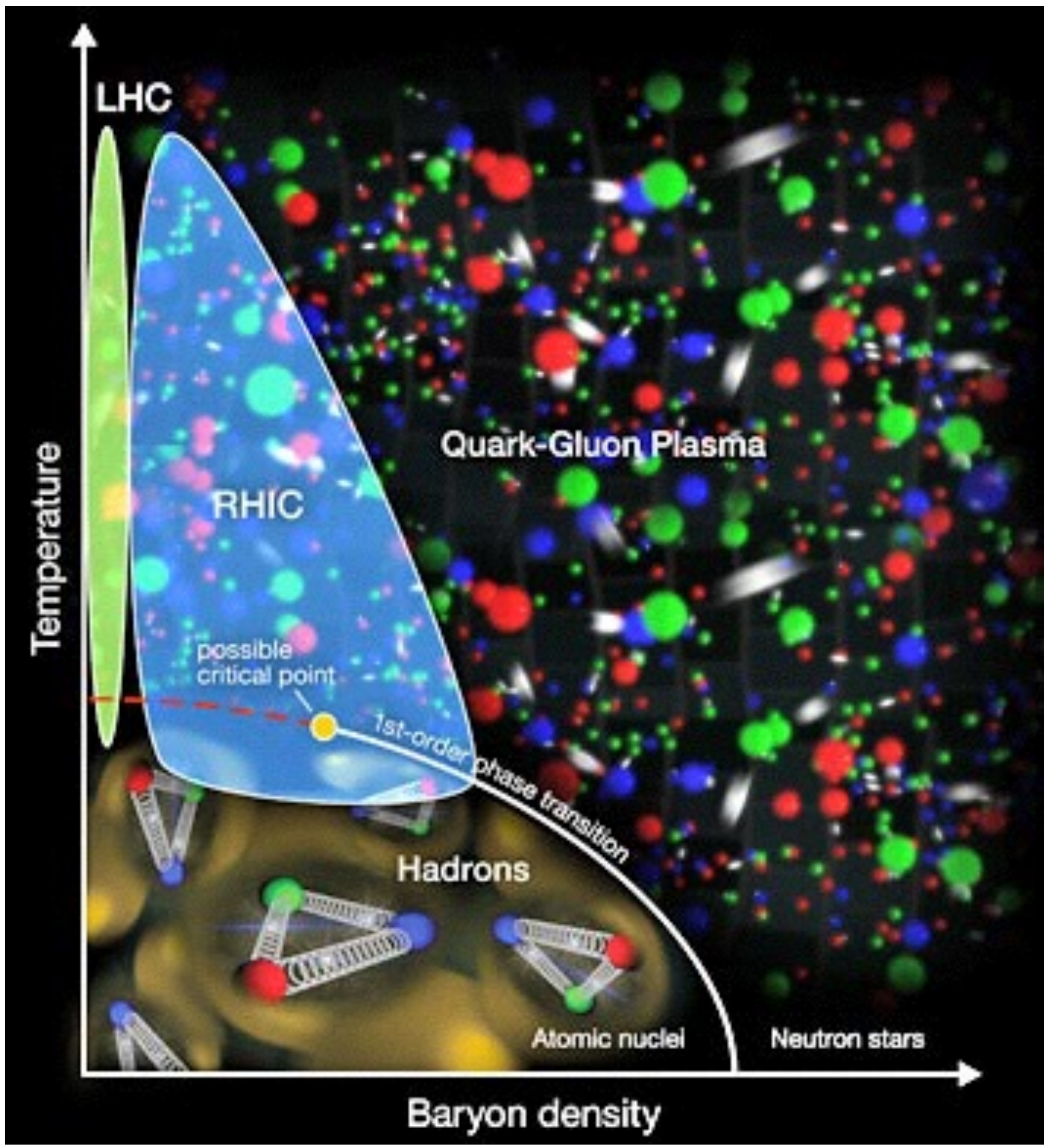


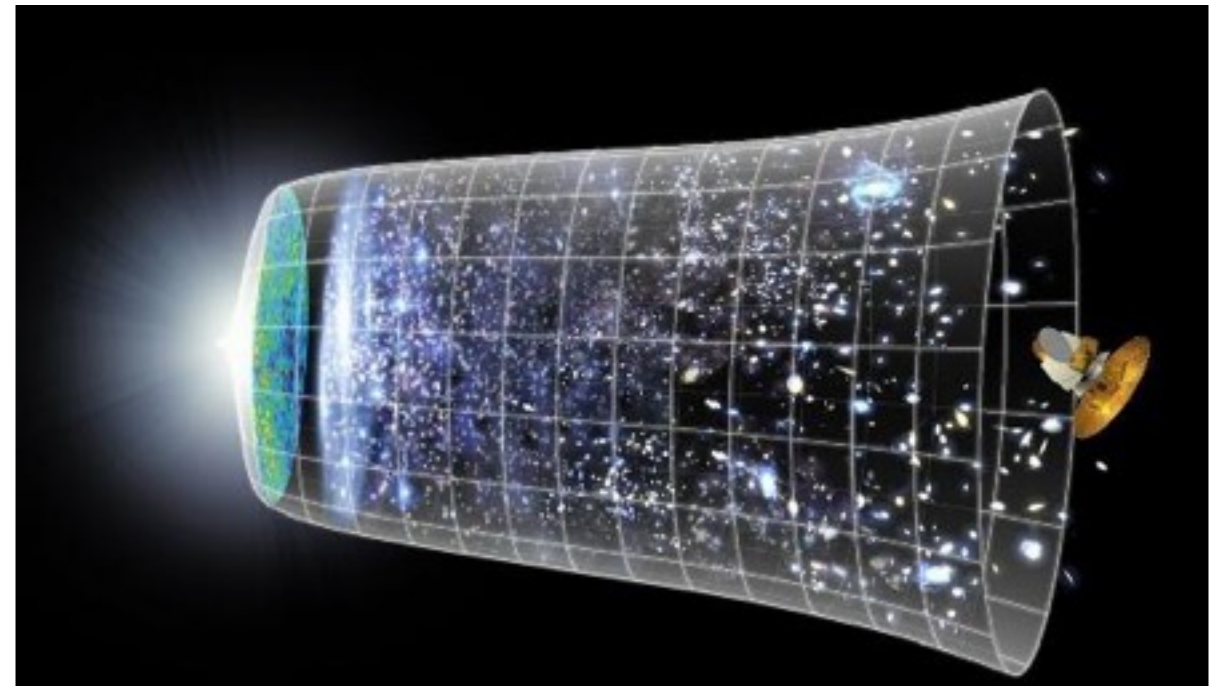


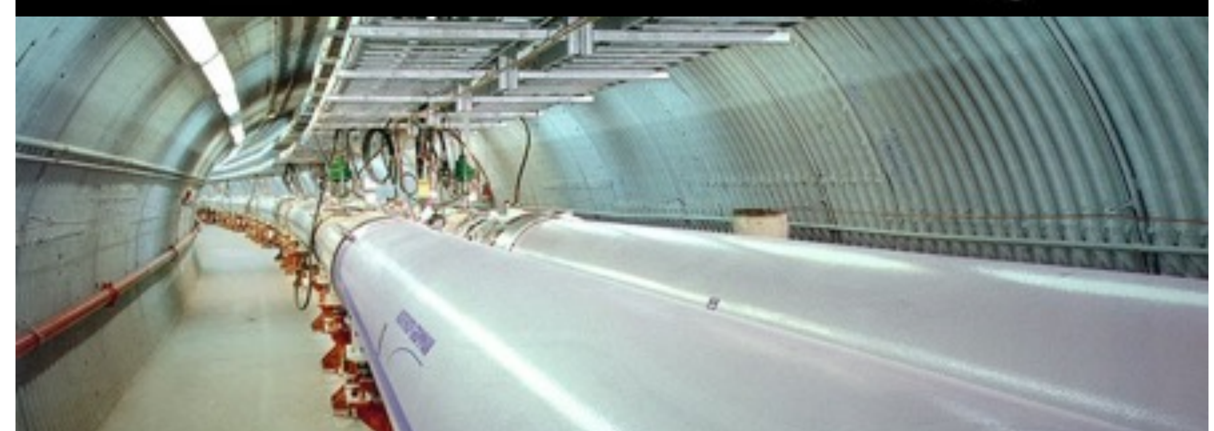


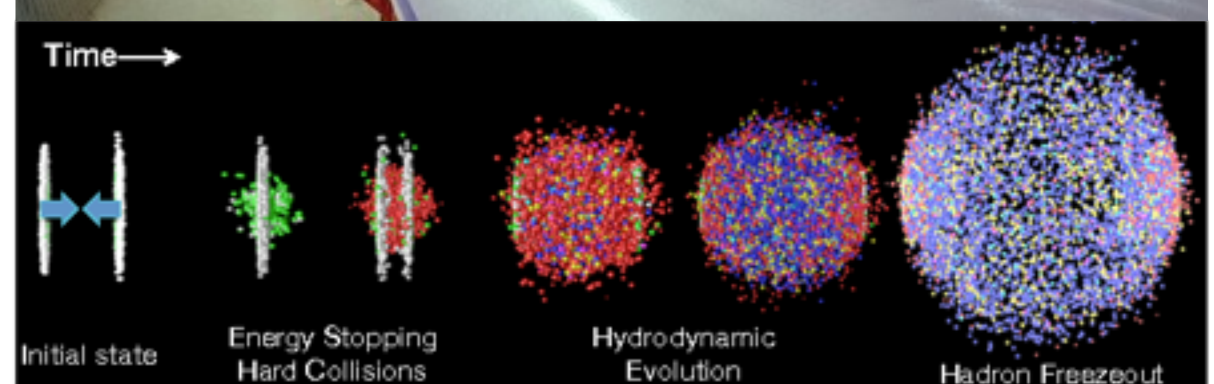


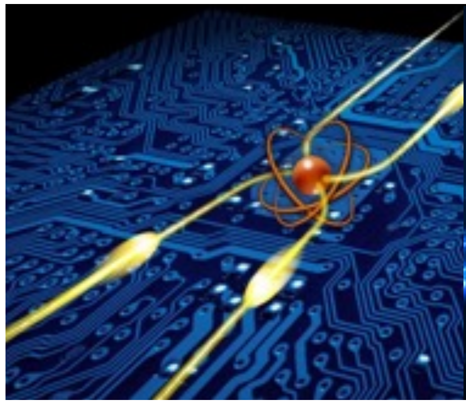
Hot and Dense Matter

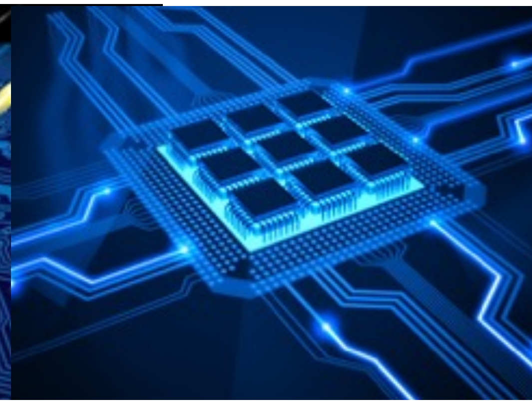




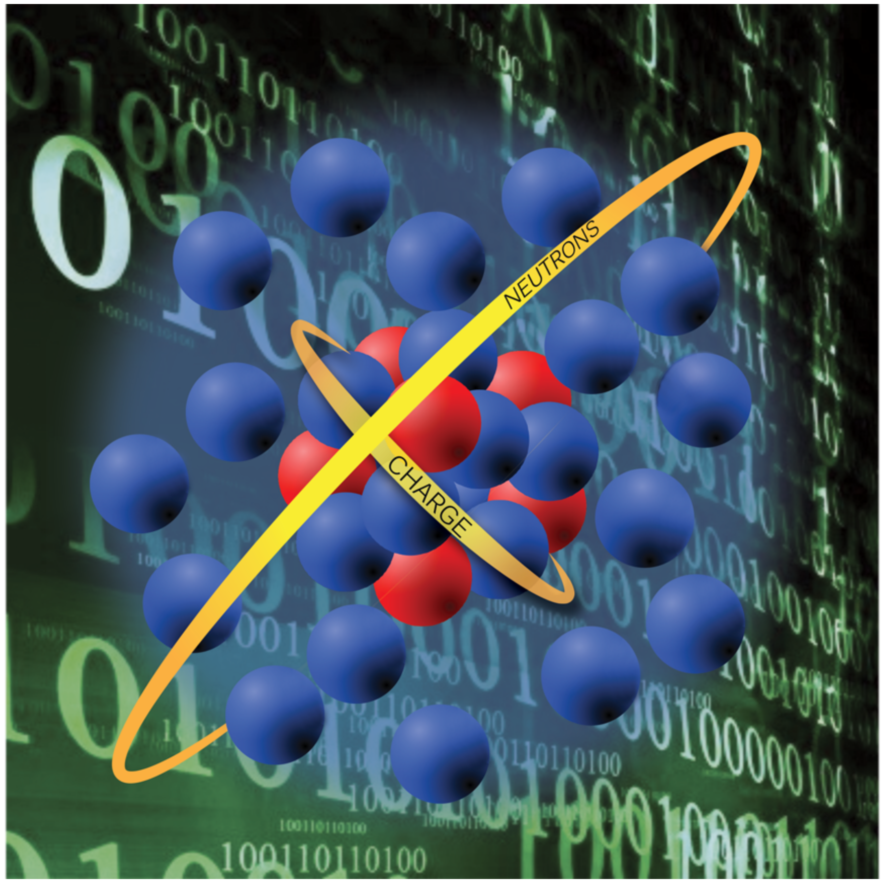


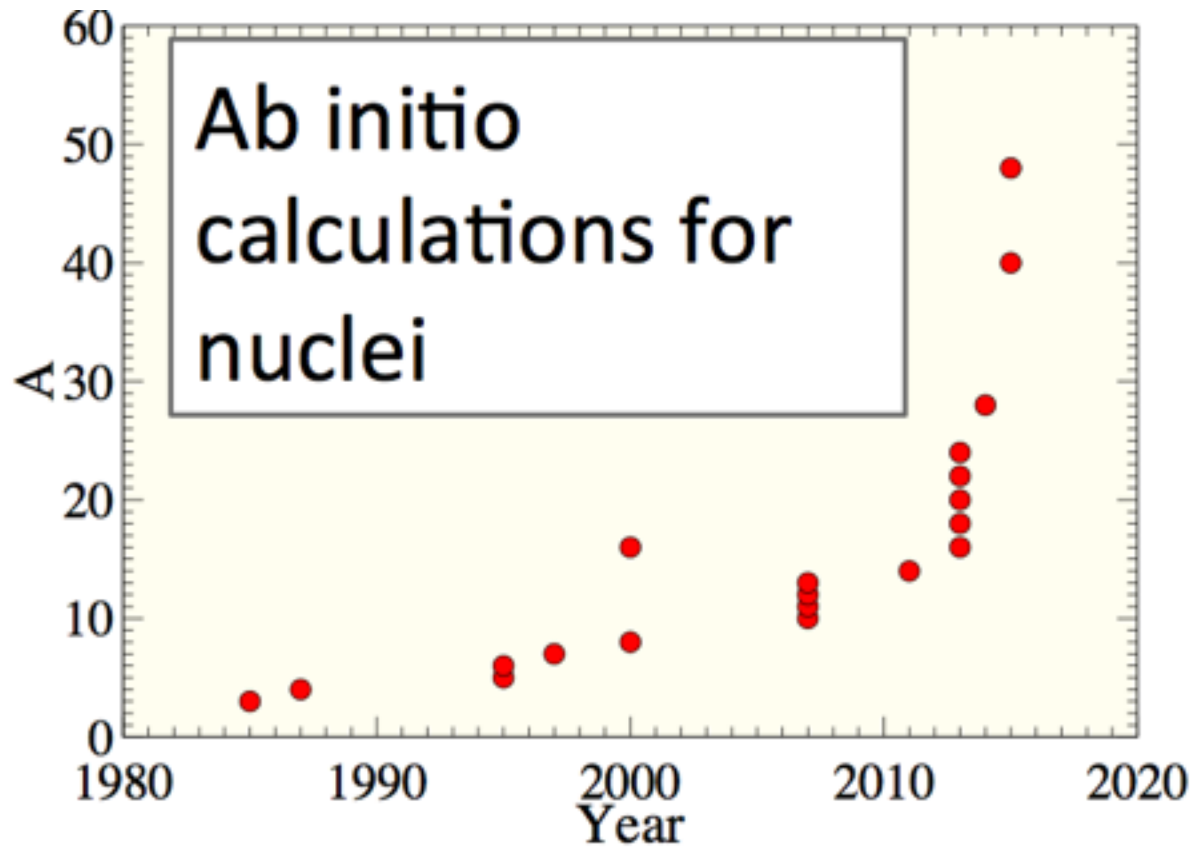




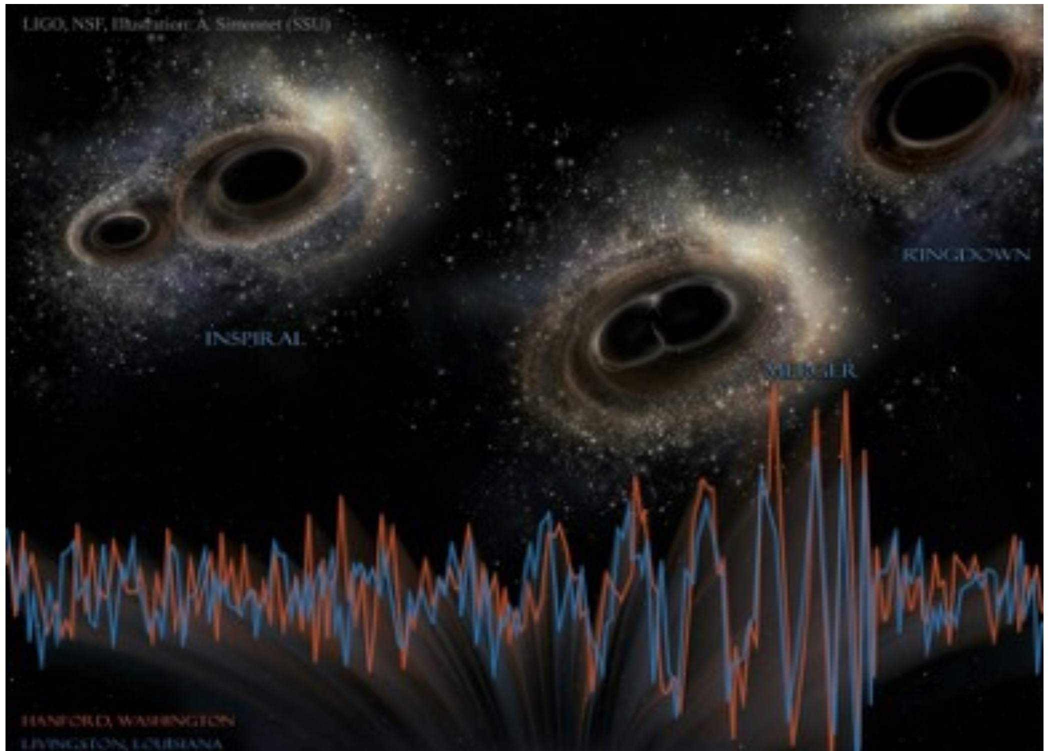


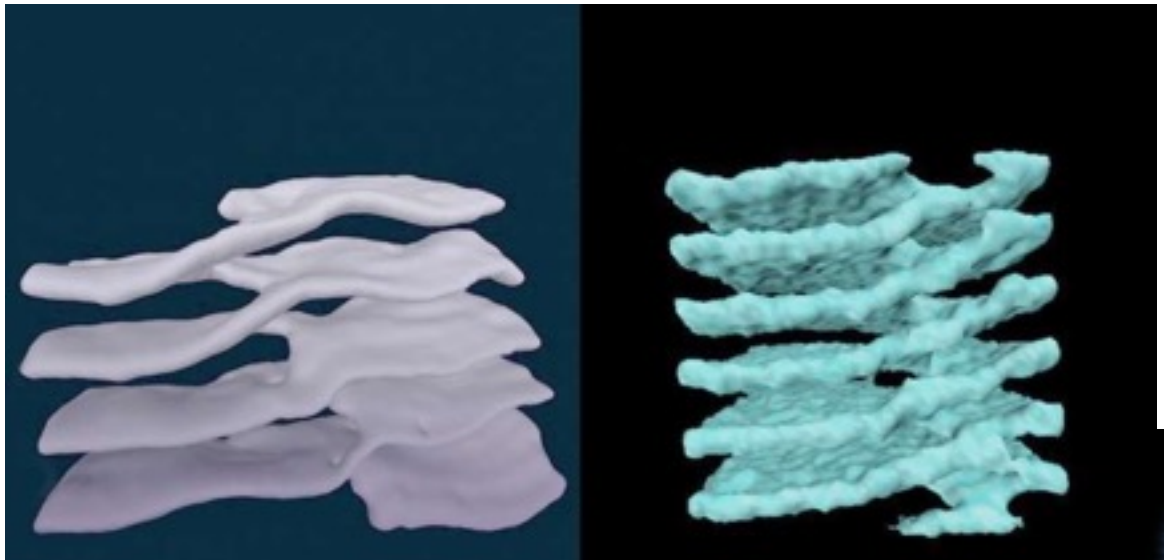
Nuclei and Nuclear Matter



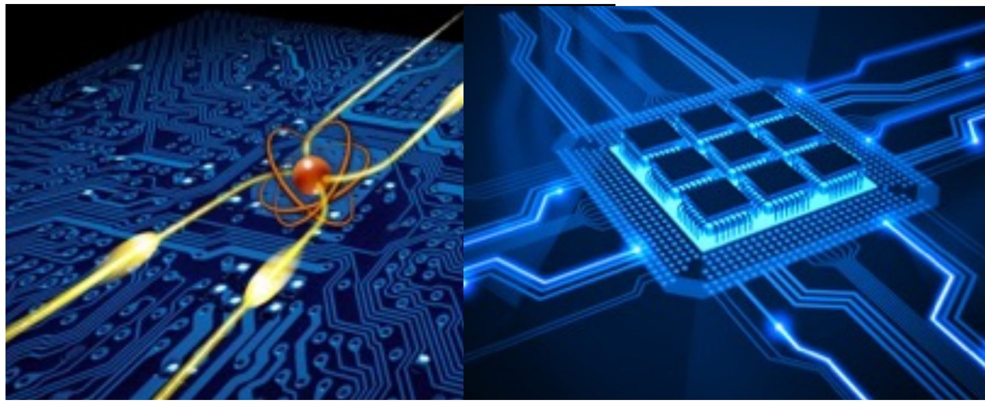


HPC, algorithm and RG-techniques

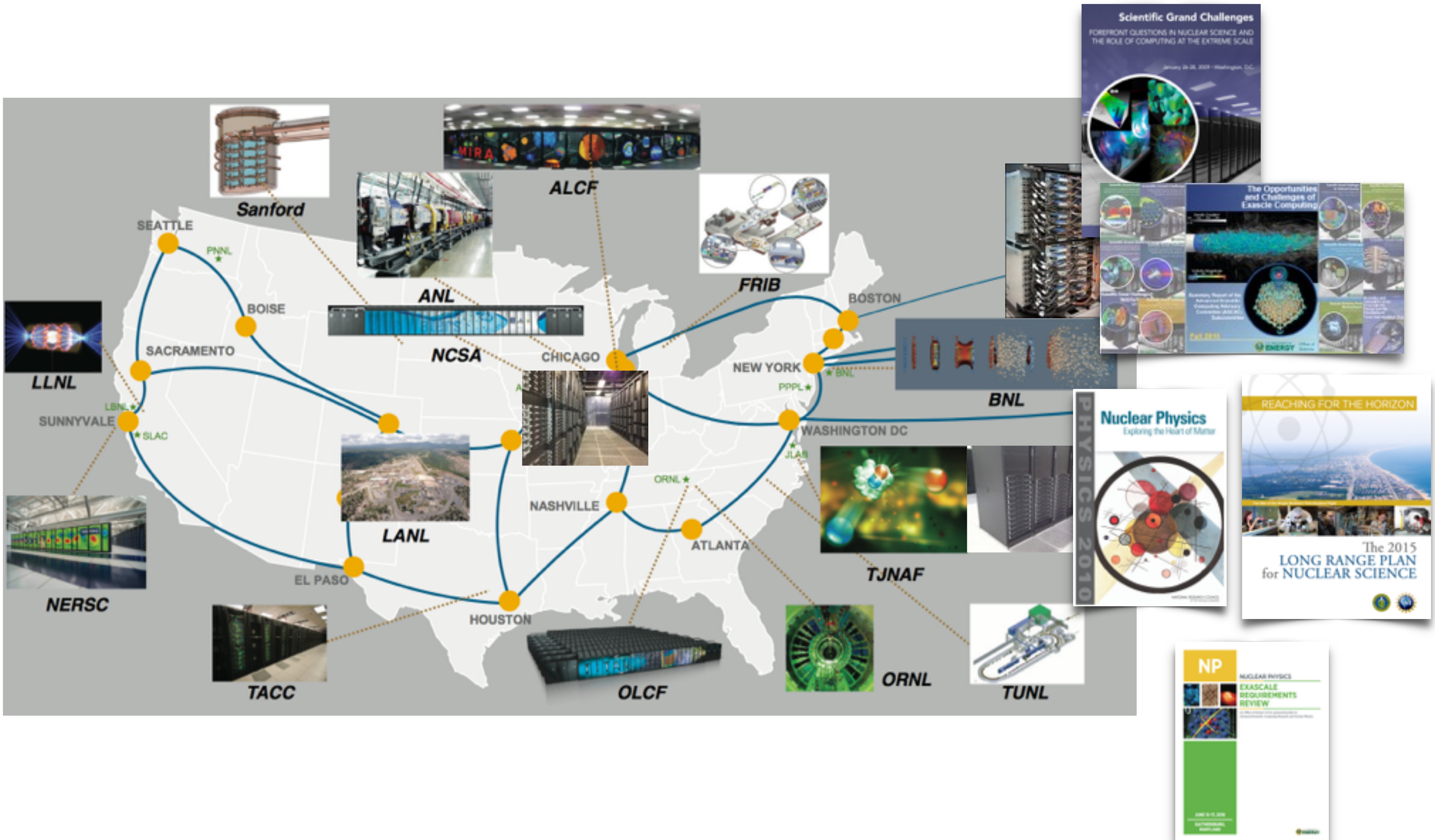


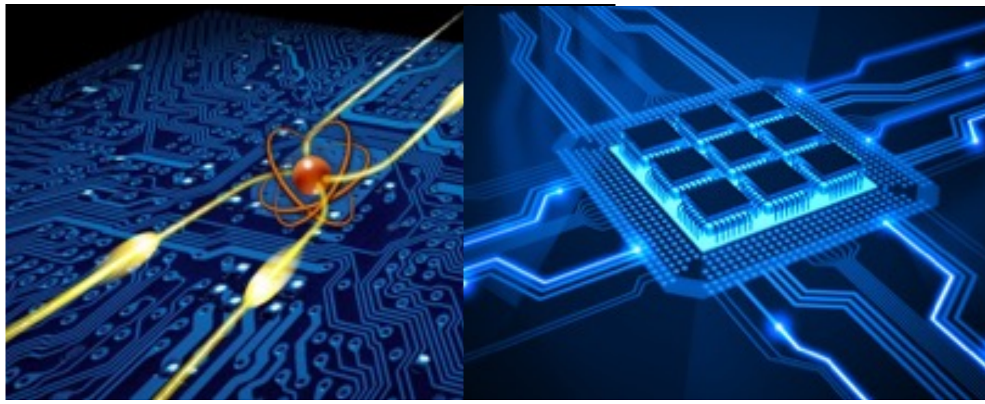


"Parking-garage" structures in nuclear astrophysics and cellular biophysics
D.K. Berry, M.E. Caplan, C.J. Horowitz, Greg Huber, A.S. Schneider.
Phys.Rev. C94 (2016) no.5, 055801



Nuclear Physics Scientific Objectives and Applications Rely on High-Performance Computing





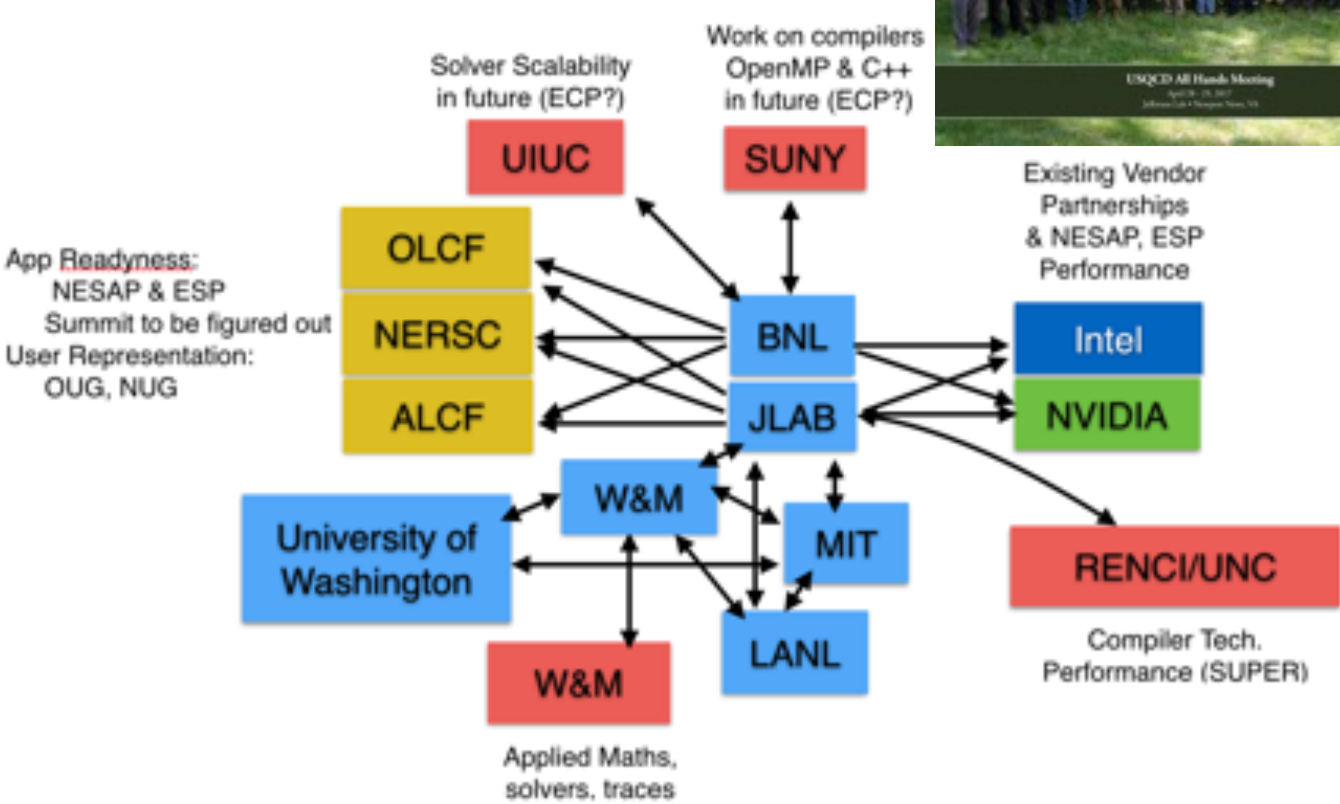
Essential, Extensive Collaboration

SciDAC
Scientific Discovery through Advanced Computing

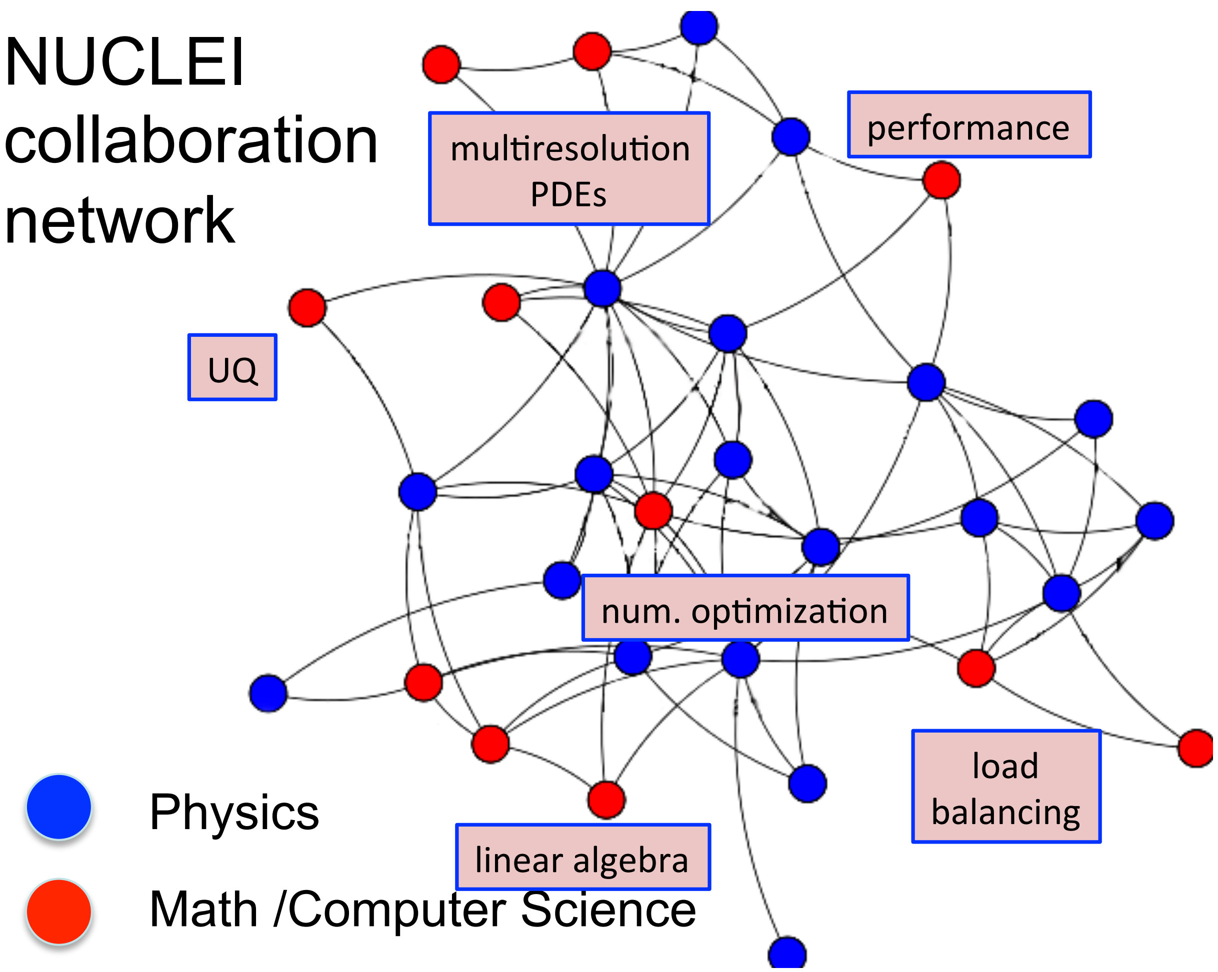
ECP
EXASCALE COMPUTING PROJECT

USQCD

USQCD-Joint NP-HEP



NUCLEI collaboration network



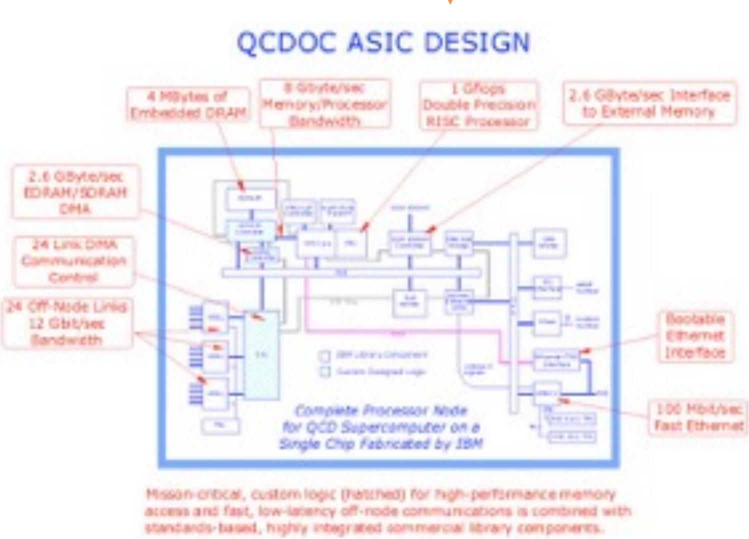
Necessity is the Mother of Invention

2009

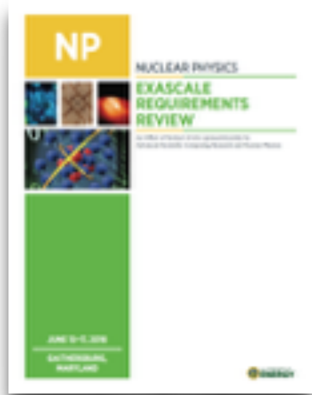
Mid-scale GPU-accelerated Cluster
Precursor to Exascale Architectures

QCDSP : 1998 Gordon Bell Prize

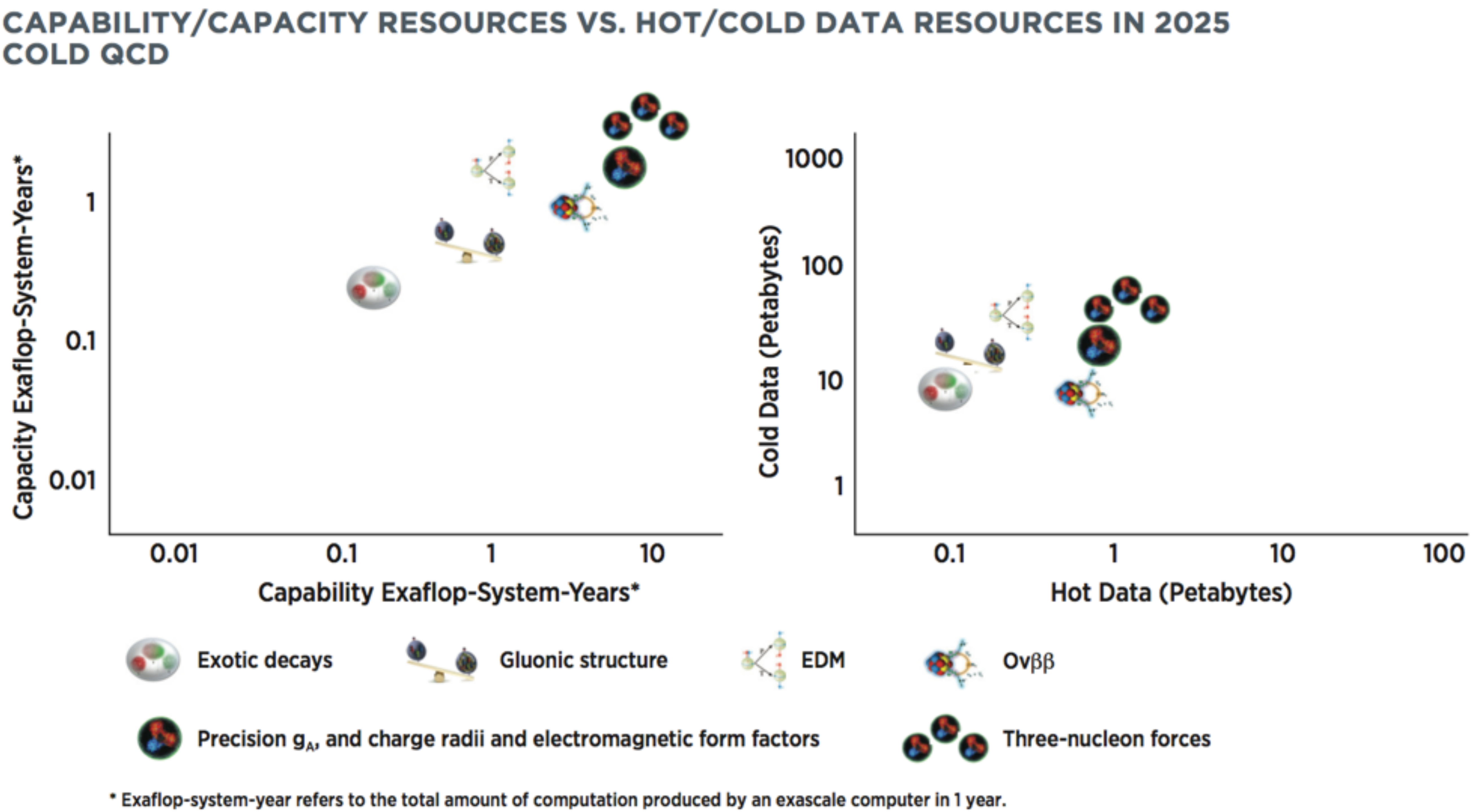
HEP-NP collaboration has been essential to NP program



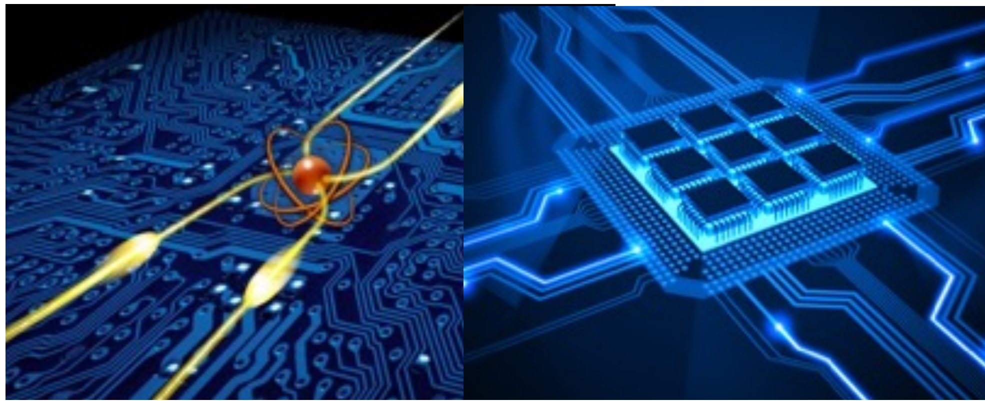
SciDAC
Scientific Discovery through Advanced Computing



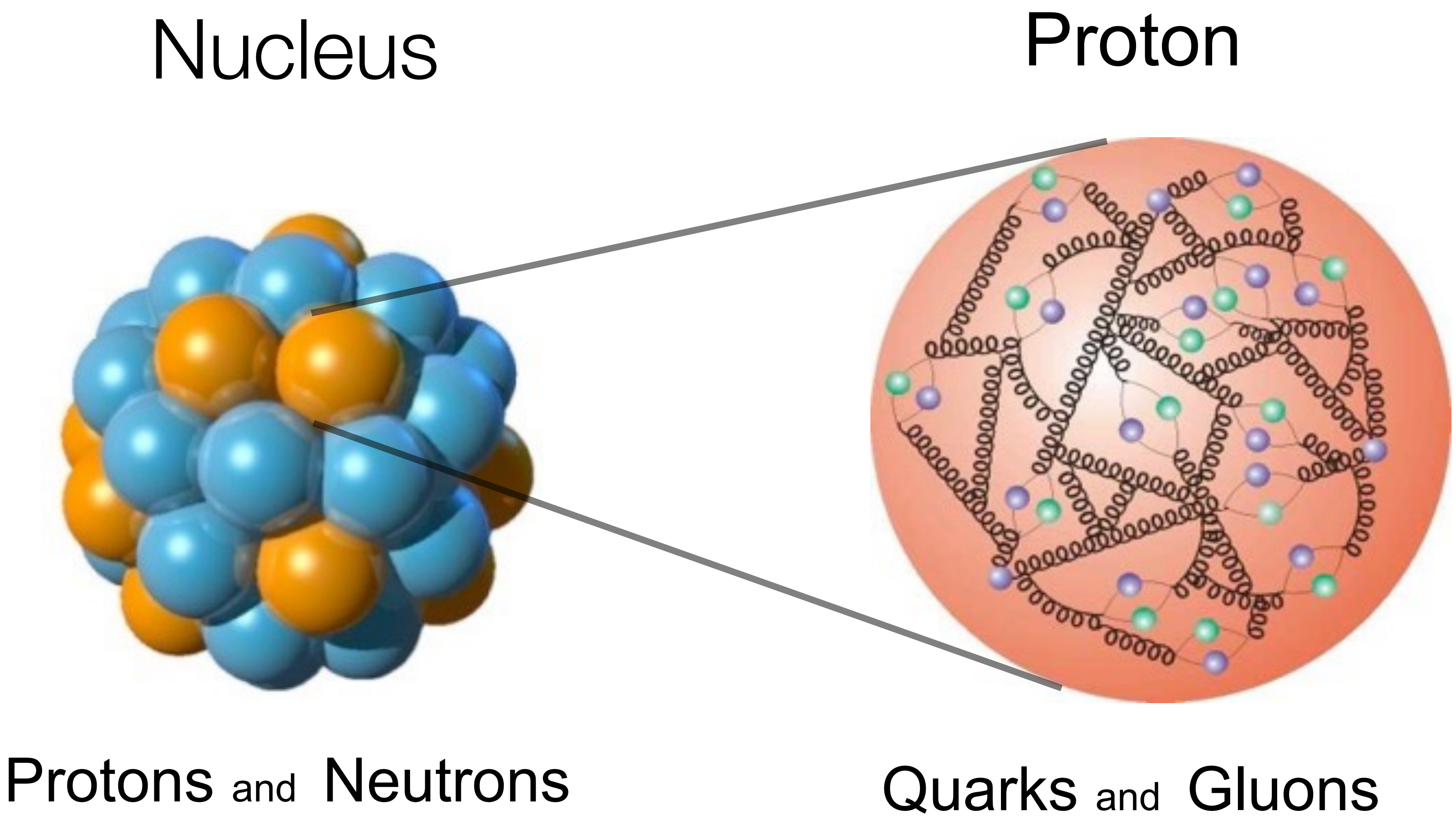
Exascale Ecosystem for Nuclear Physics

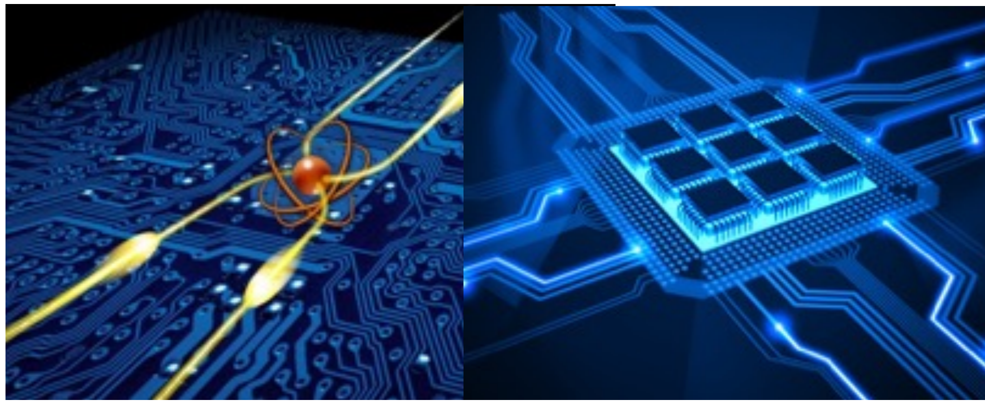


A single Exascale machine will be immediately oversubscribed by a large factor



Quantum Chromodynamics and NP



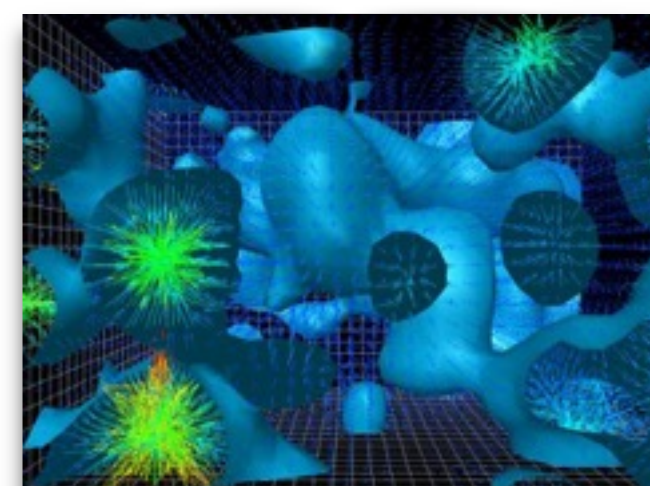


Quantum Chromodynamics
Path Integrals and Lattice QCD

Minkowski Space - probability amplitudes of unit norm

$$Z \;\propto \int \mathcal{D}A^a_\mu \mathcal{D}\overline{q}_i \mathcal{D}q_i \; e^{\frac{i}{\hbar}\int d^4x \;\mathcal{L}+\mathcal{L}_{g.f.}+\mathcal{L}_{\mathrm{ghosts}}}$$

$$\mathcal{L} \;=\; \sum_{i=u,d,s,c,b,t} \overline{q}_i \,[\; i\not{D} - m_i \;]\, q_i \;-\; \frac{1}{4} \sum_{a=1,\ldots,8} G^a_{\mu\nu} G^{\mu\nu,a}$$



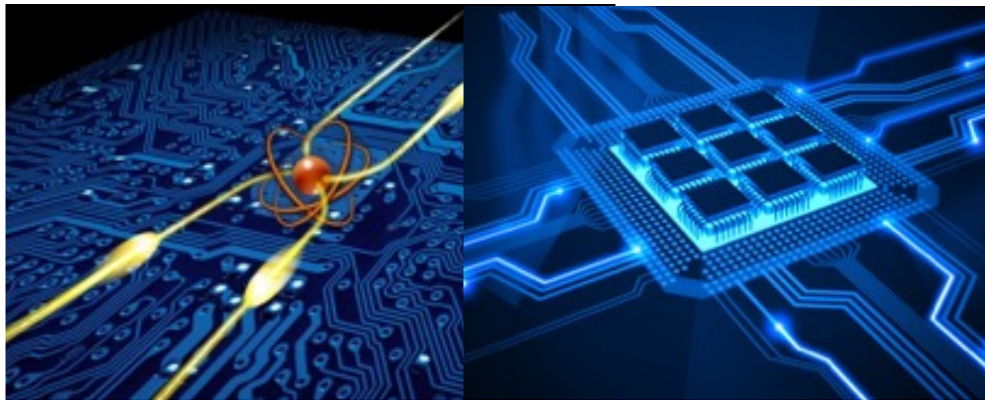
Euclidean Space - probability distribution

$$\langle\hat{\theta}\rangle \sim \int \mathcal{D}\mathcal{U}_\mu \;\hat{\theta}[\mathcal{U}_\mu]\; \det[\kappa[\mathcal{U}_\mu]]\; e^{-S_{YM}}$$

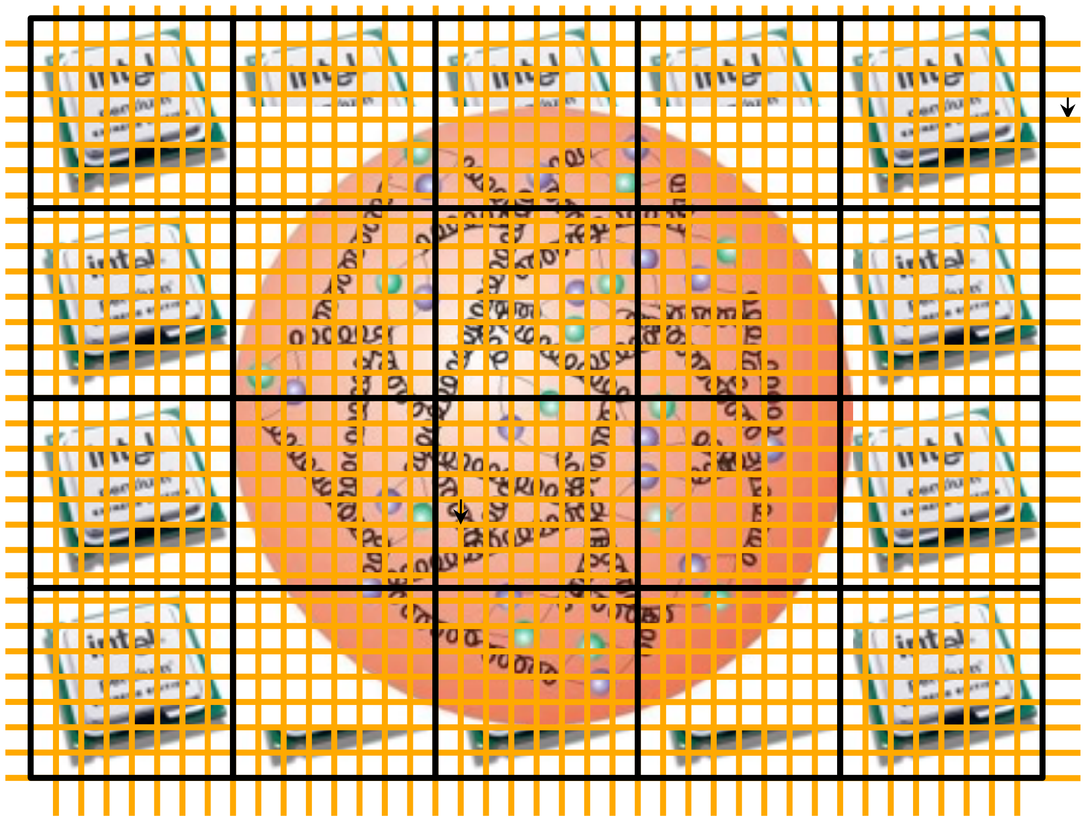
$$\rightarrow \frac{1}{N} \sum_{\mathrm{gluon\;\;cfgs}}^{N} \hat{\theta}\,[\mathcal{U}_\mu]$$

Gauge fields sampled

Fermion integrals can be performed analytically



Lattice Quantum Chromodynamics - Discretized Euclidean Spacetime

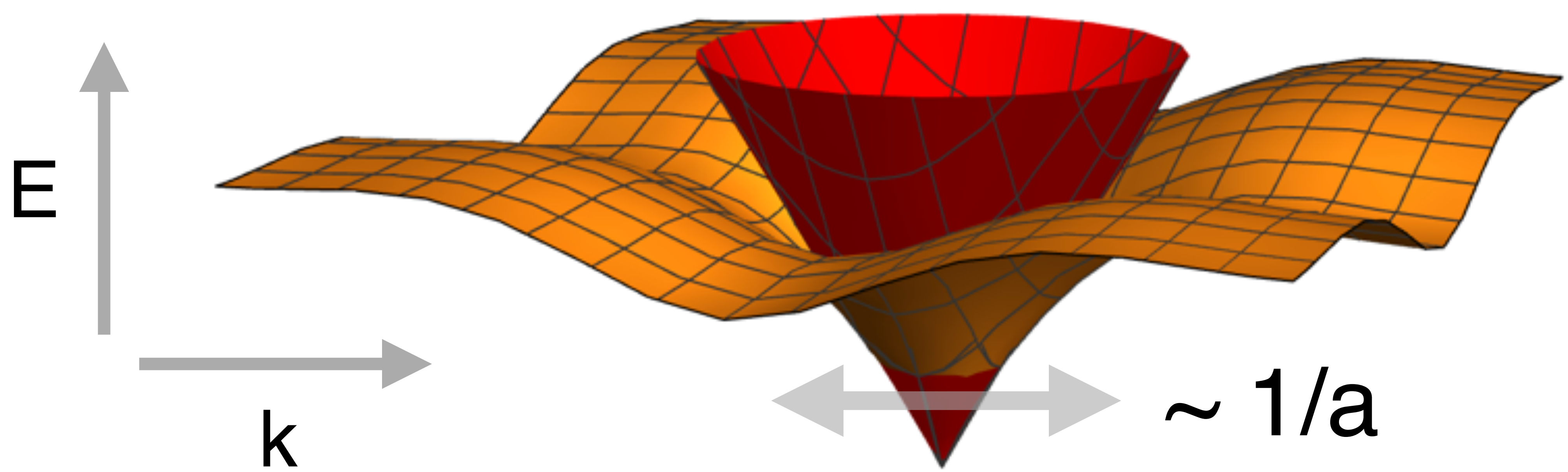


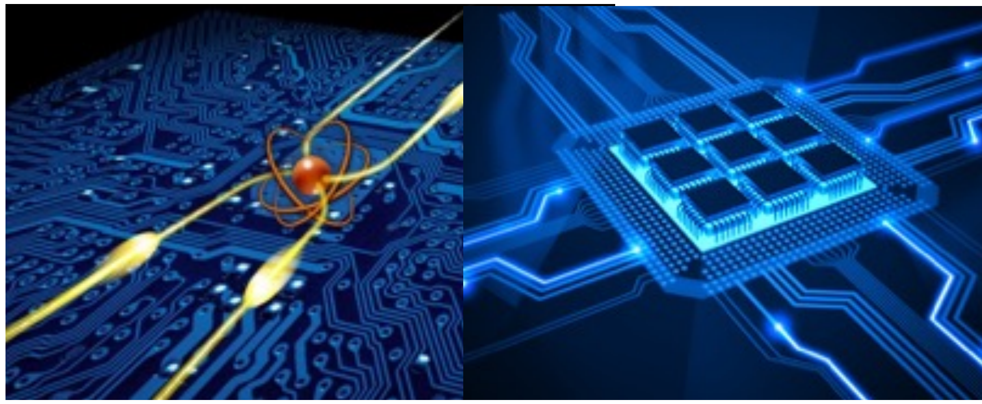
Lattice Spacing :
a << $1/\Lambda\chi$
(Nearly Continuum)

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

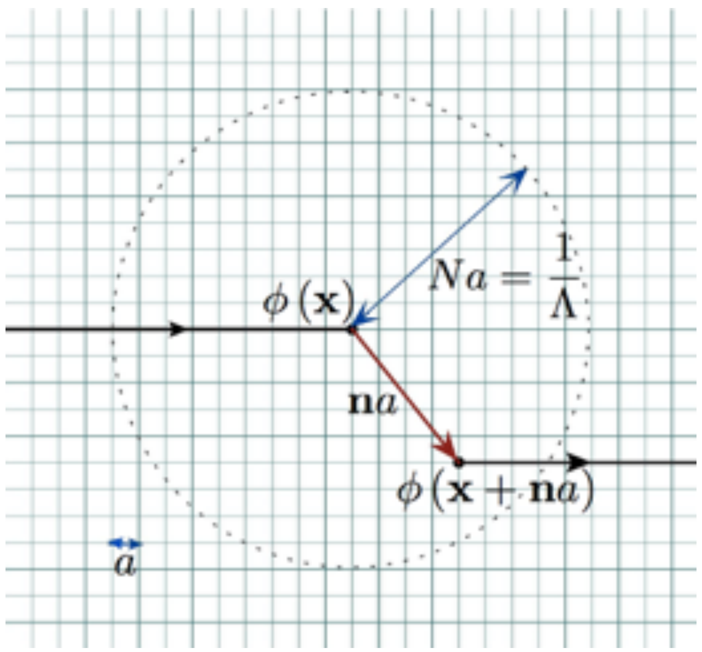
Extrapolation to $a = 0$ and $L = \infty$

Systematically remove non-QCD parts of calculation through effective field theories





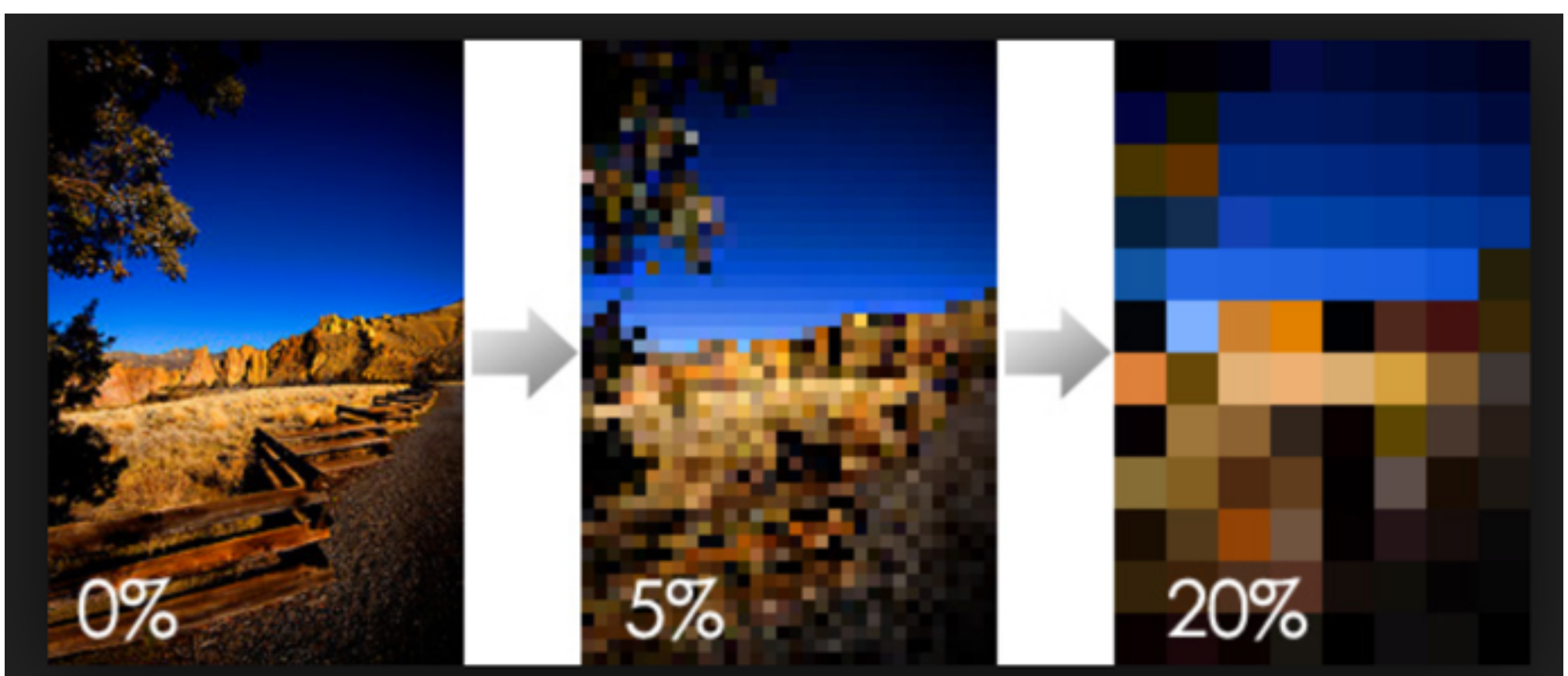
Recovering SO(3) from H(3)

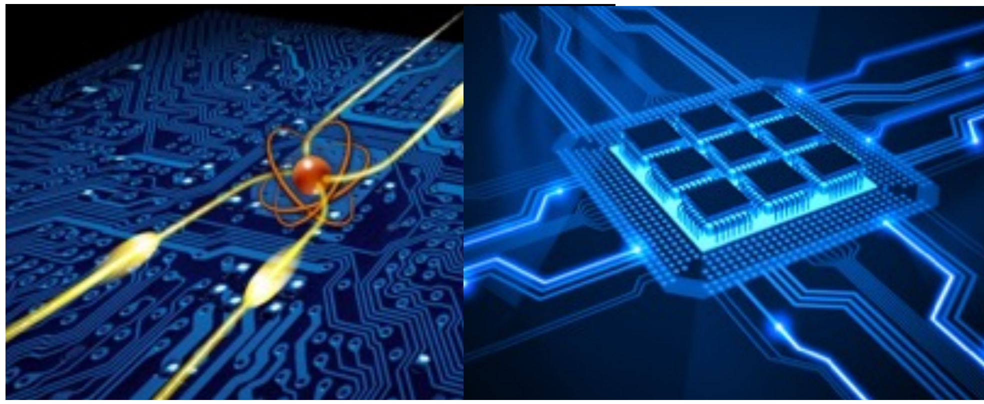


Hold all physical scales, and the renormalization scale fixed when taking lattice spacing to zero

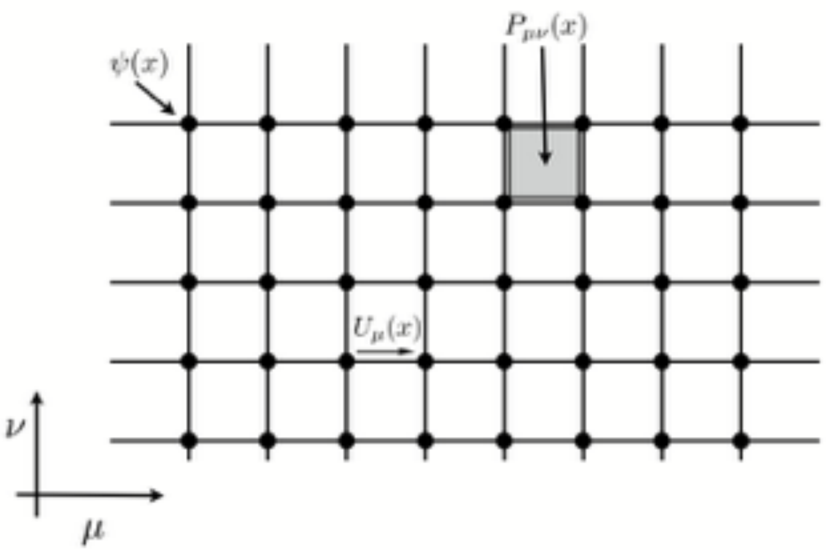
Survives at quantum level in QCD - smearing is critical so as not to ``see'' the UV cubic structure

Multiplicity of irreps of H(3) allow for combinations to approach SO(3) states - both in position space (a) and momentum space (L)





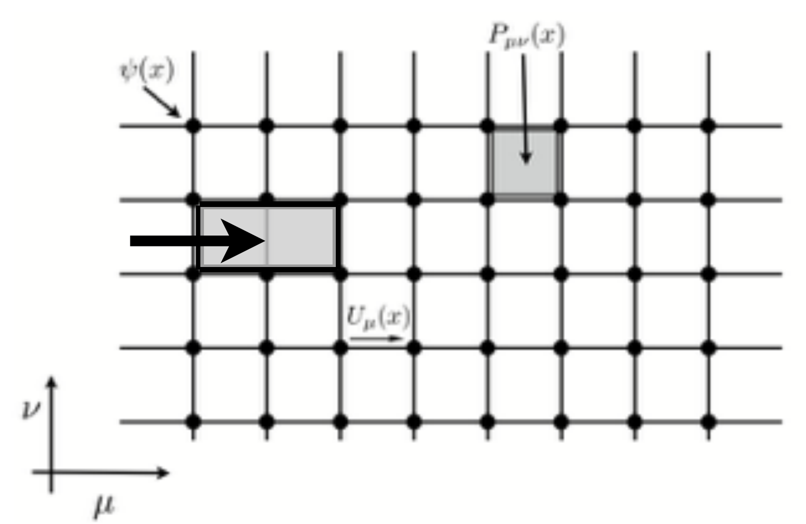
Lattice QCD
The Discretized Action



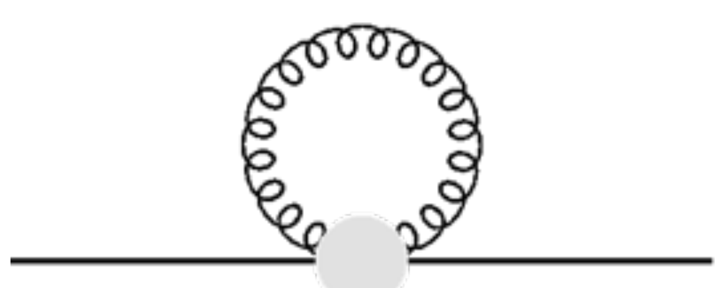
$$U_\mu(x) = \exp\left(i \int_x^{x+\hat{\mu}} dx' A_\mu(x')\right)$$

$$U_\mu(x) \rightarrow U'_\mu(x) = \Omega(x) U_\mu(x) \Omega^{-1}(x+\hat{\mu})$$

$$P_{\mu\nu} = U_\mu(x) U_\nu(x+\hat{\mu}) U^\dagger_\mu(x+\hat{\nu}) U^\dagger_\nu(x)$$

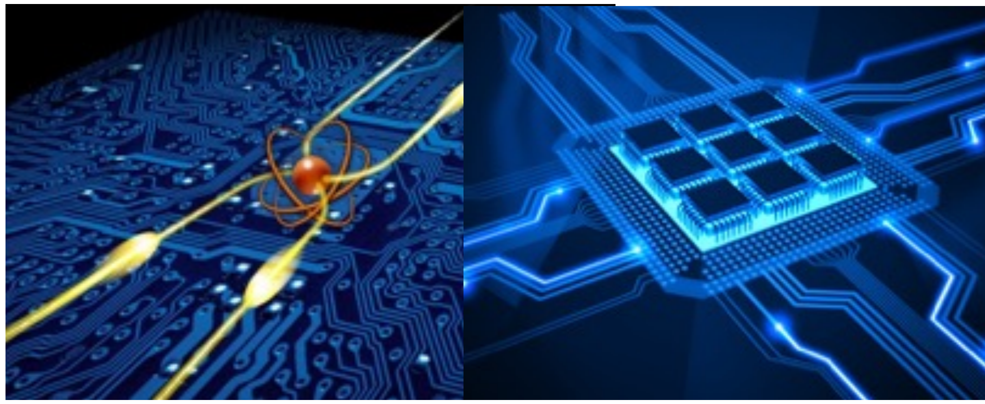


$$\begin{aligned} S_{\text{classical}} &\equiv -\beta \sum_{x,\mu>\nu} \left\{ \frac{5 P_{\mu\nu}}{3} - \frac{R_{\mu\nu} + R_{\nu\mu}}{12} \right\} + \text{const} \\ &= \int d^4x \sum_{\mu,\nu} \tfrac{1}{2} \operatorname{Tr} F^2_{\mu\nu} + \mathcal{O}(a^4). \end{aligned}$$

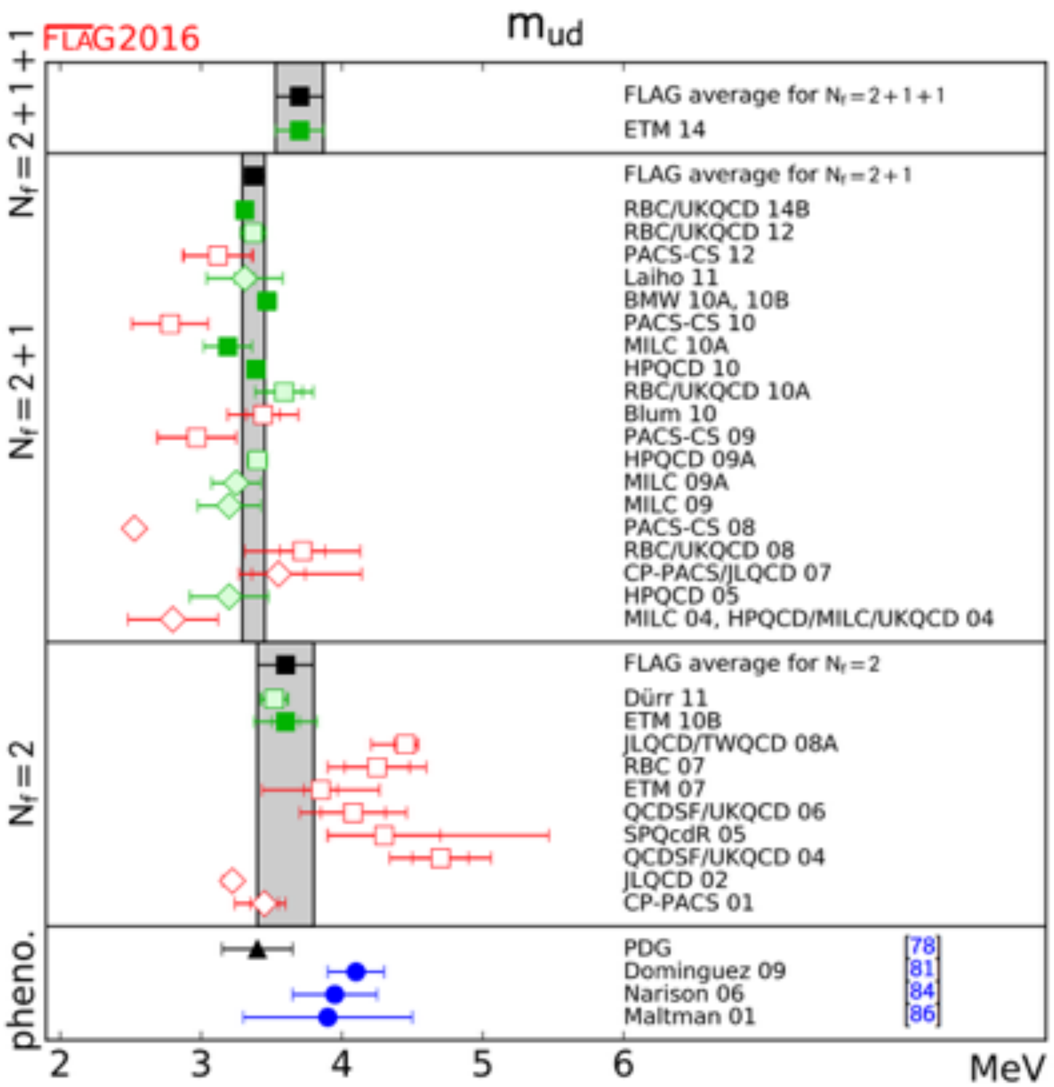


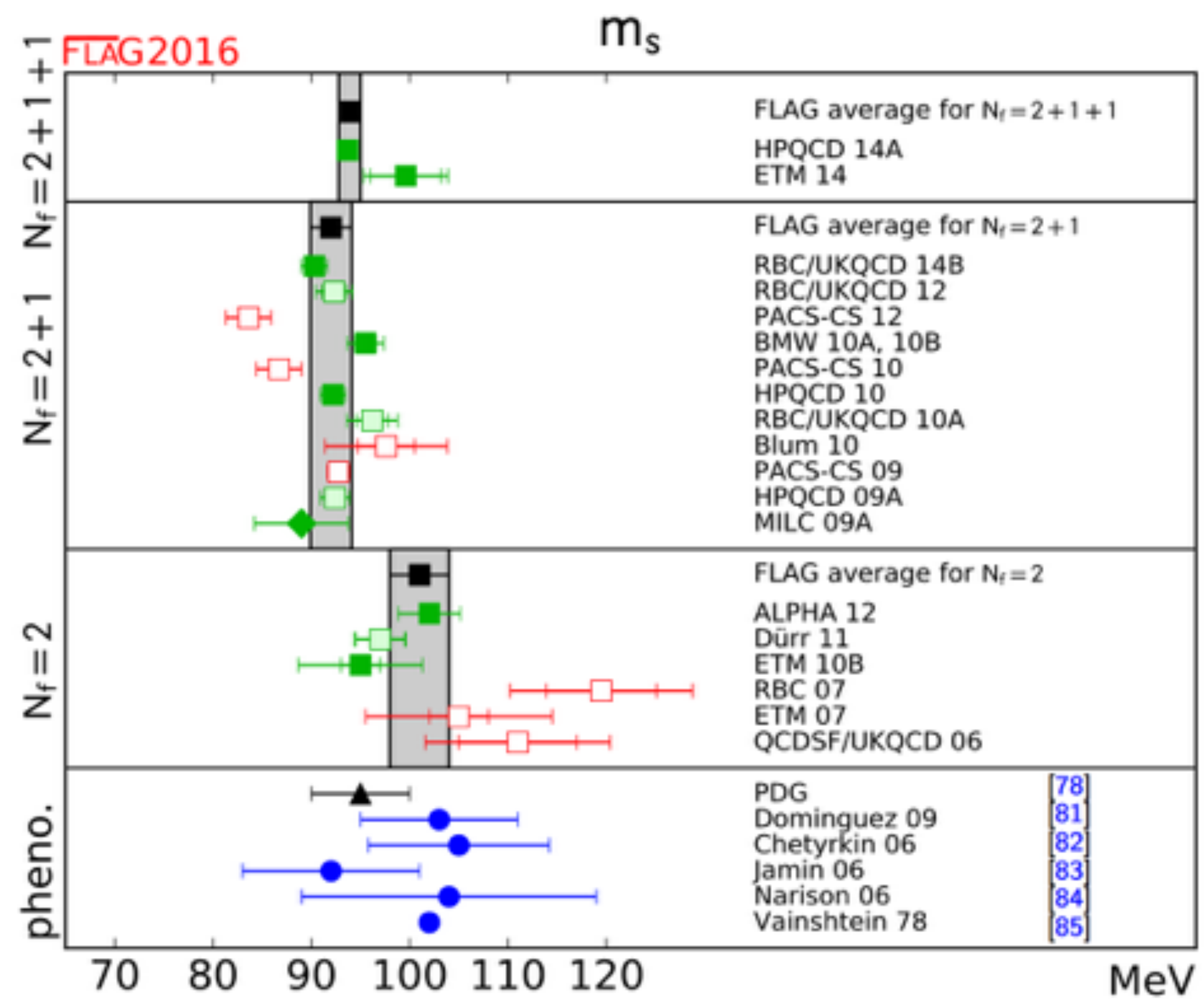
$$S = -\beta \sum_{x,\mu>\nu} \left\{ \frac{5}{3} \frac{P_{\mu\nu}}{u_0^4} - \frac{R_{\mu\nu} + R_{\nu\mu}}{12\, u_0^6} \right\}$$

Quantum gauge action tadpole improved



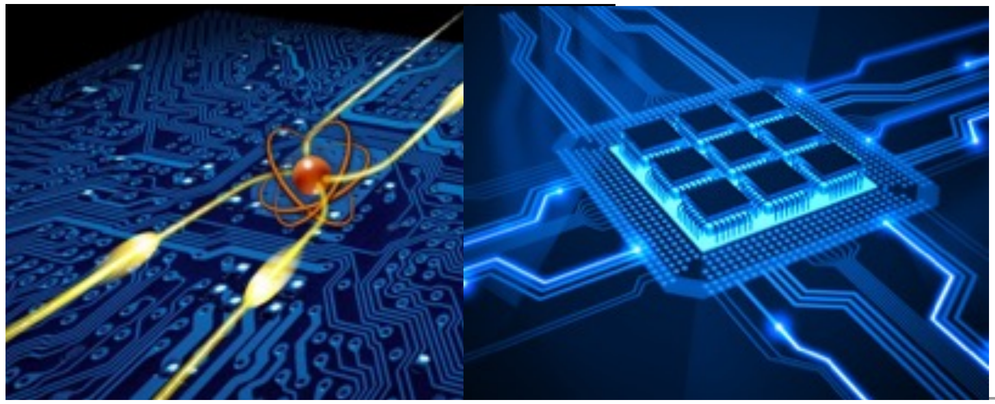
Lattice QCD
The Quark Masses





N_f	m_u	m_d	m_u/m_d
2+1	2.16(9)(7)	4.68(14)(7)	0.46(2)(2)
2	2.40(23)	4.80(23)	0.50(4)

$$\overline{\mathrm{MS}}\ ,\ \mu = 2\ \mathrm{GeV}$$



Lattice QCD
Sketch of Methodology

Start with a selection of quark+gluon sources and sinks ``designed” to have good overlap onto the low-lying hadronic/nuclear states in the volume.

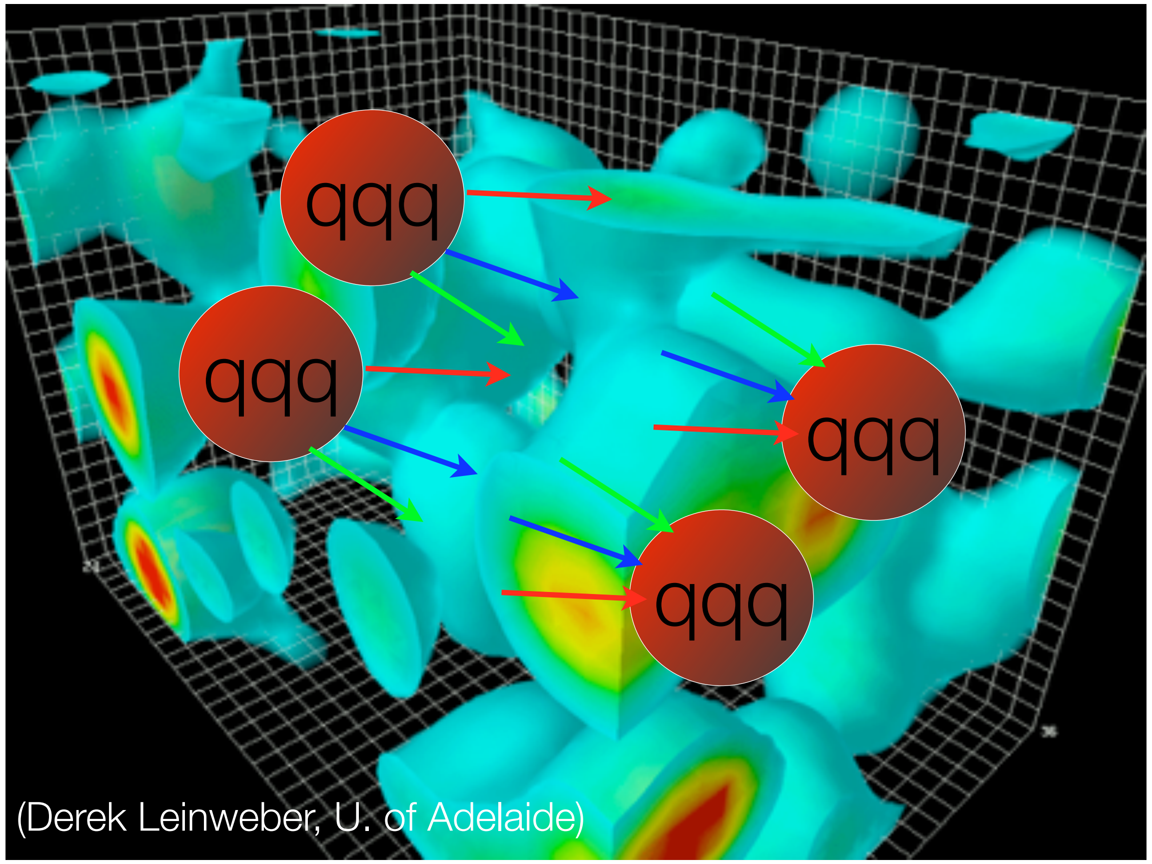
Iteratively (manually) refine to produce ``best estimates” of QCD states.

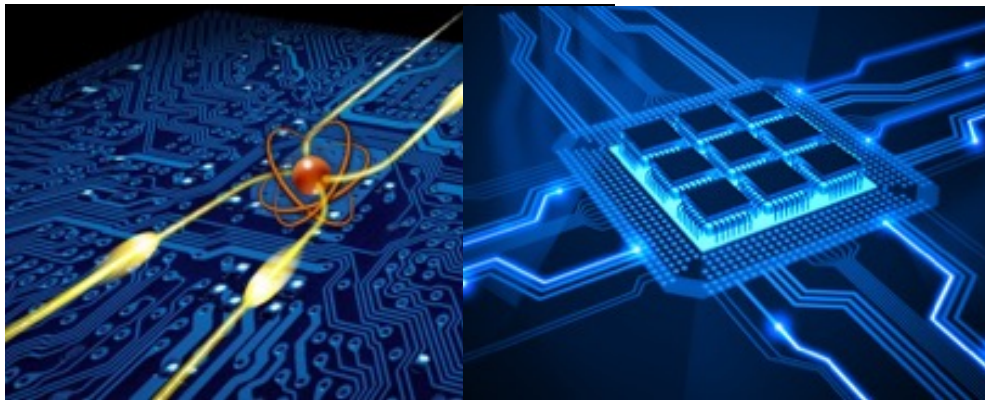
Form correlation functions between all combinations

Diagonalize to find the energy eigenvalues and eigenstates (Variational or other)

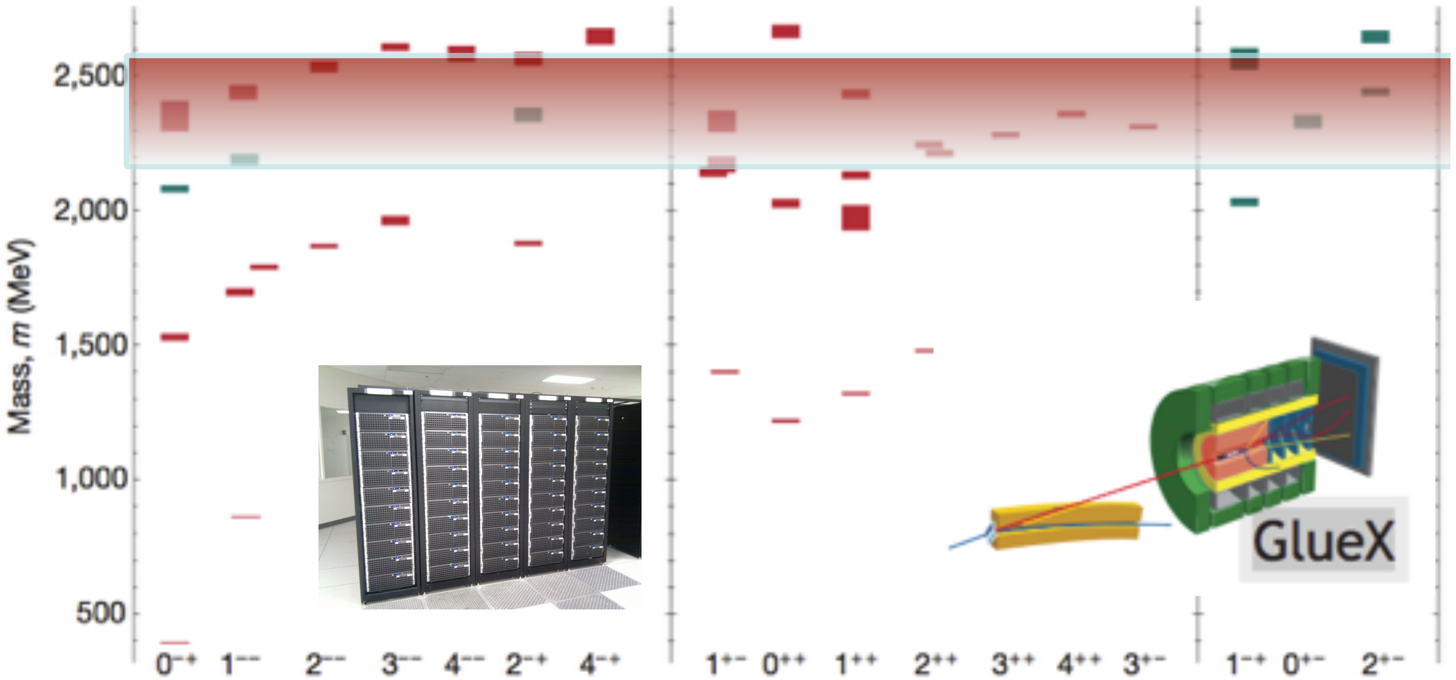
Post-analyze accordingly
- Luscher’s Methods for S-matrix elements,…

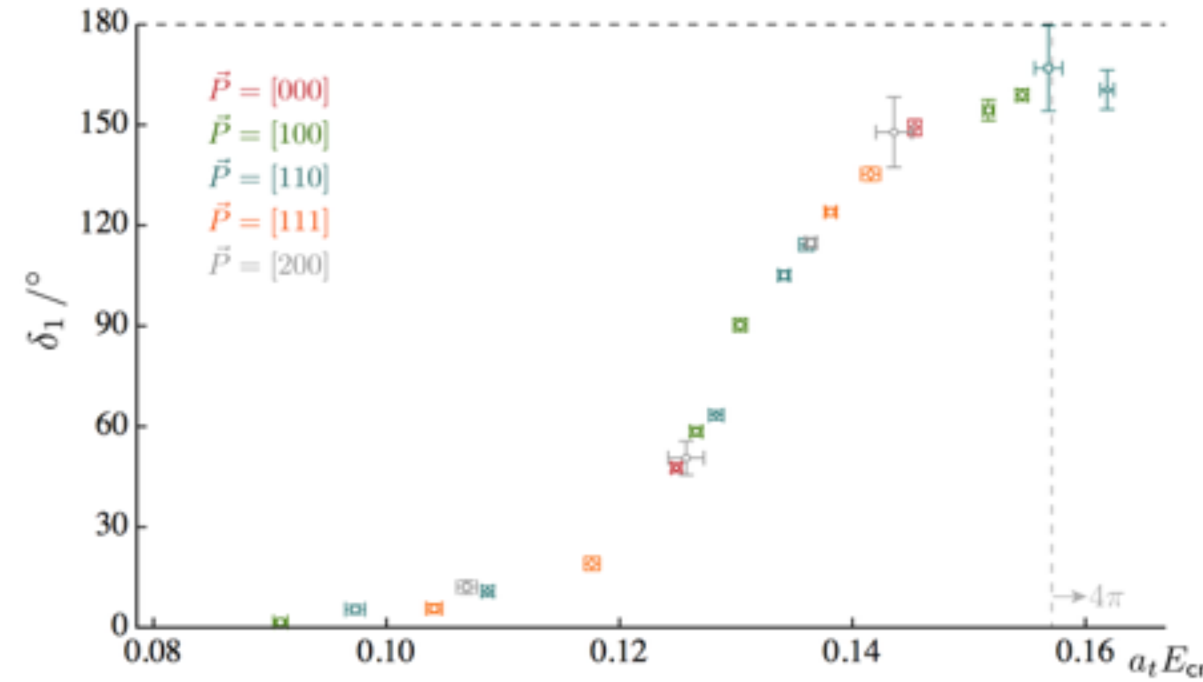
I anticipate this sort of refinement of sources and sinks occur before initializing a QC.



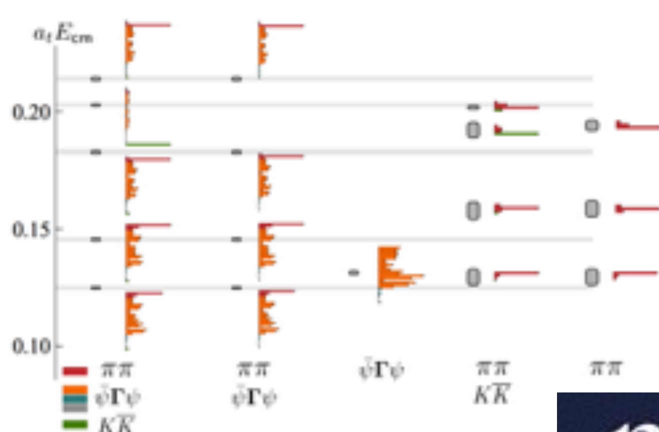


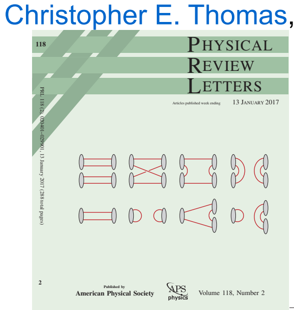
Lattice QCD
Spectroscopy and GlueX



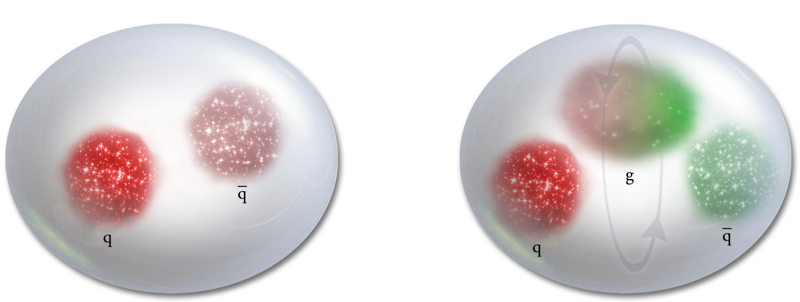


David J. Wilson, Raul A. Briceno, Jozef J. Dudek, Robert G. Edwards, Christopher E. Thomas,
Phys.Rev. D92 (2015) no.9, 094502





Pattern of states suggest gluonic excitations



Conventional Meson

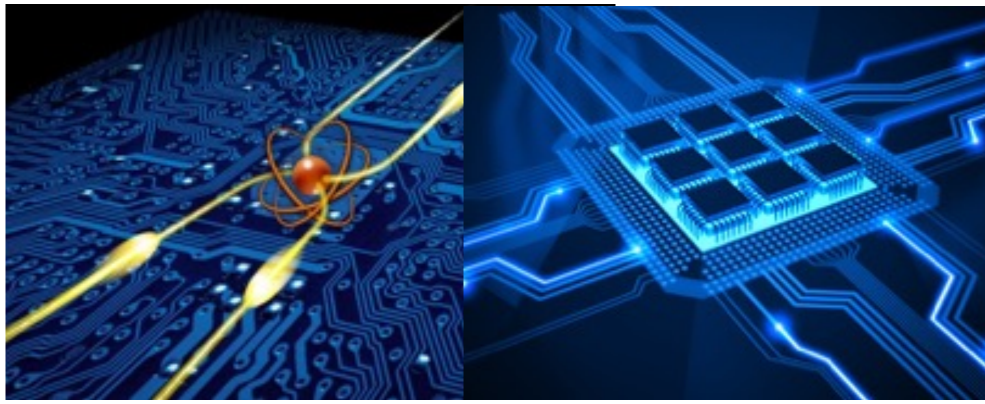
Hybrid Meson

NATURE | REVIEW

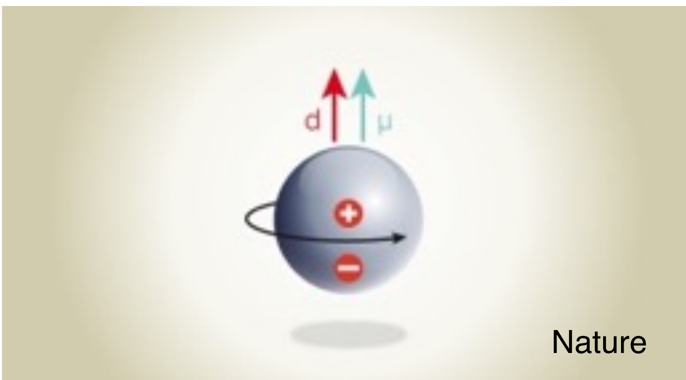
Searching for the rules that govern hadron construction

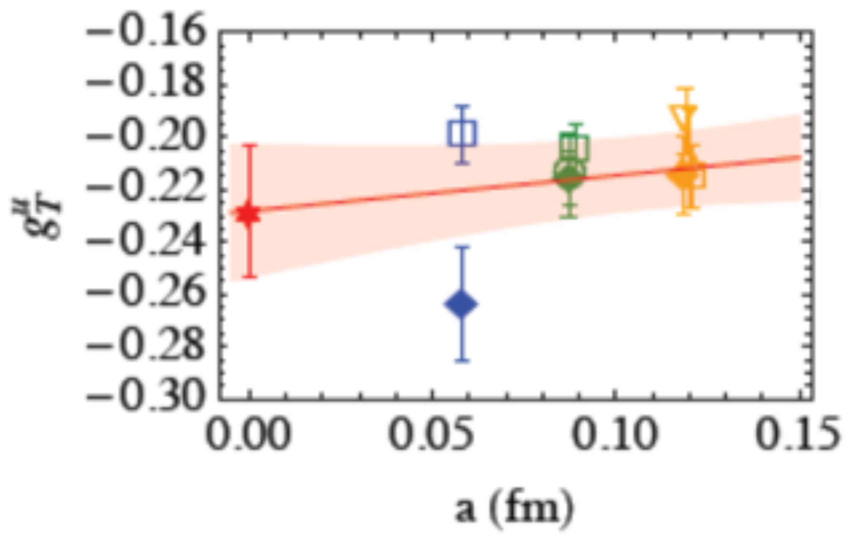
Matthew R. Shepherd, Jozef J. Dudek & Ryan E. Mitchell

Nature **534**, 487–493 (23 June 2016) | doi:10.1038/nature18011



Lattice QCD
Fundamental Symmetries



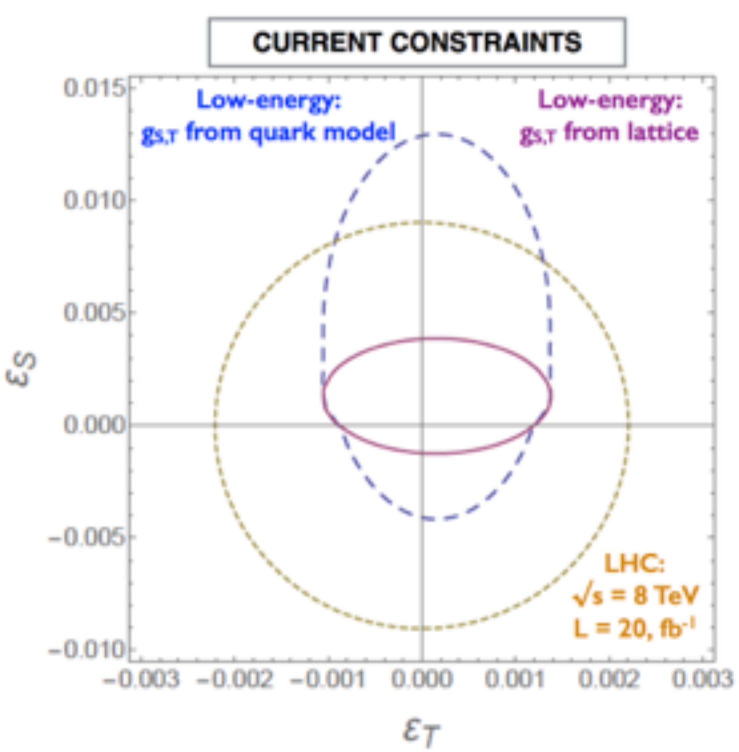


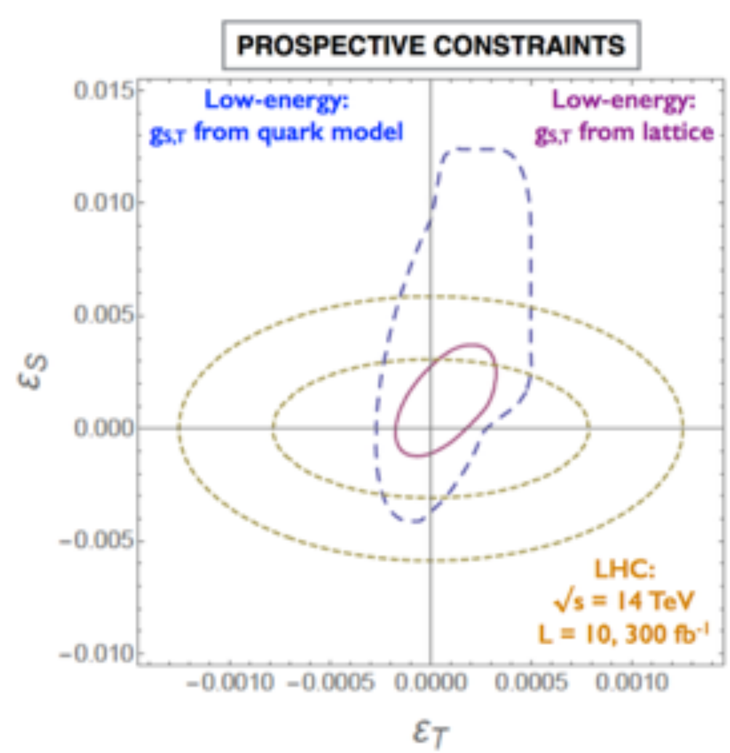
$$\boxed{d_n = d_u\, g_T^{(n,u)} + d_d\, g_T^{(n,d)} + d_s\, g_T^{(n,s)}}$$

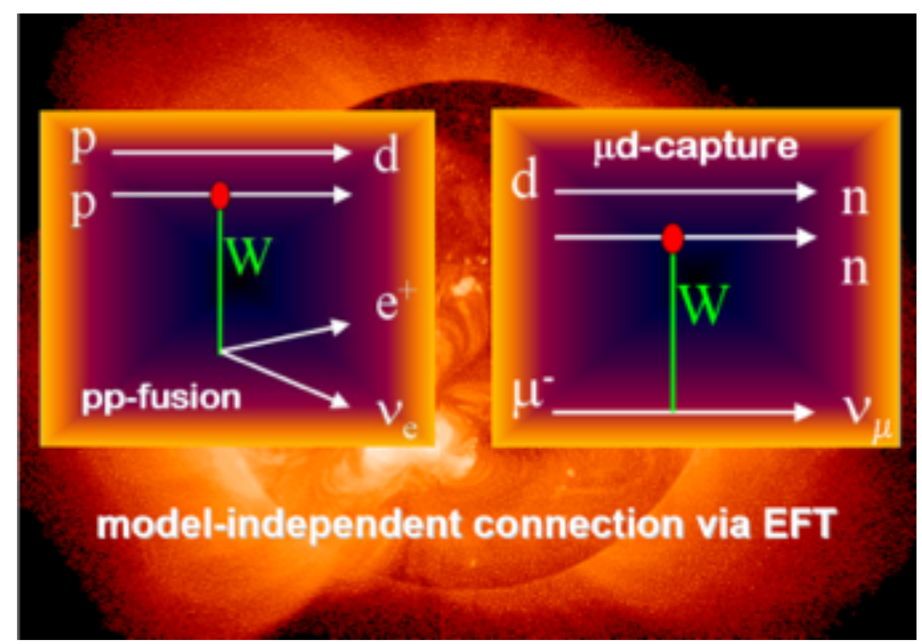
$g_T^{(n,u)} = -0.23(3)$ $\quad$ $g_T^{(n,d)} = 0.77(7)$ $\quad$ $g_T^{(s)} = 0.008(9)$

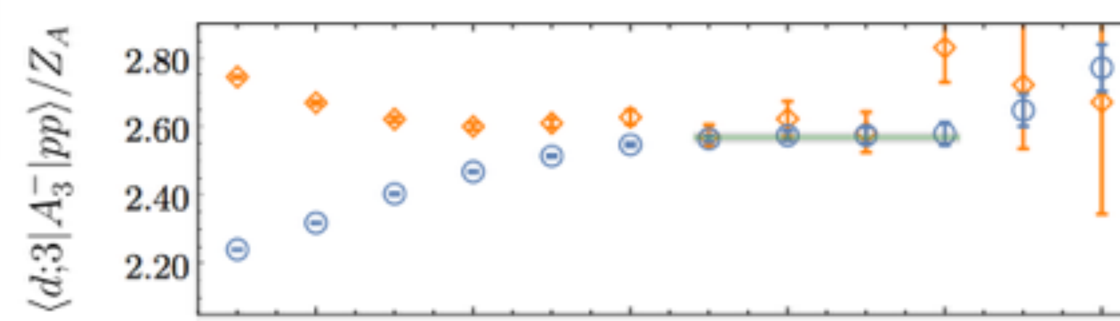
PNDME: Bhattacharya et al PRL 115 (2015) 212002 [1506.04196], PRD 92 (2015) 114026 [1506.06411]

USQCD US Lattice Quantum Chromodynamics

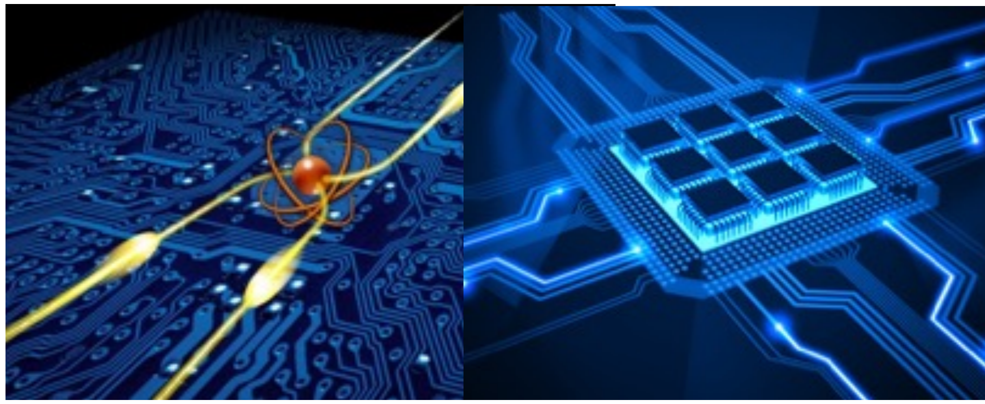




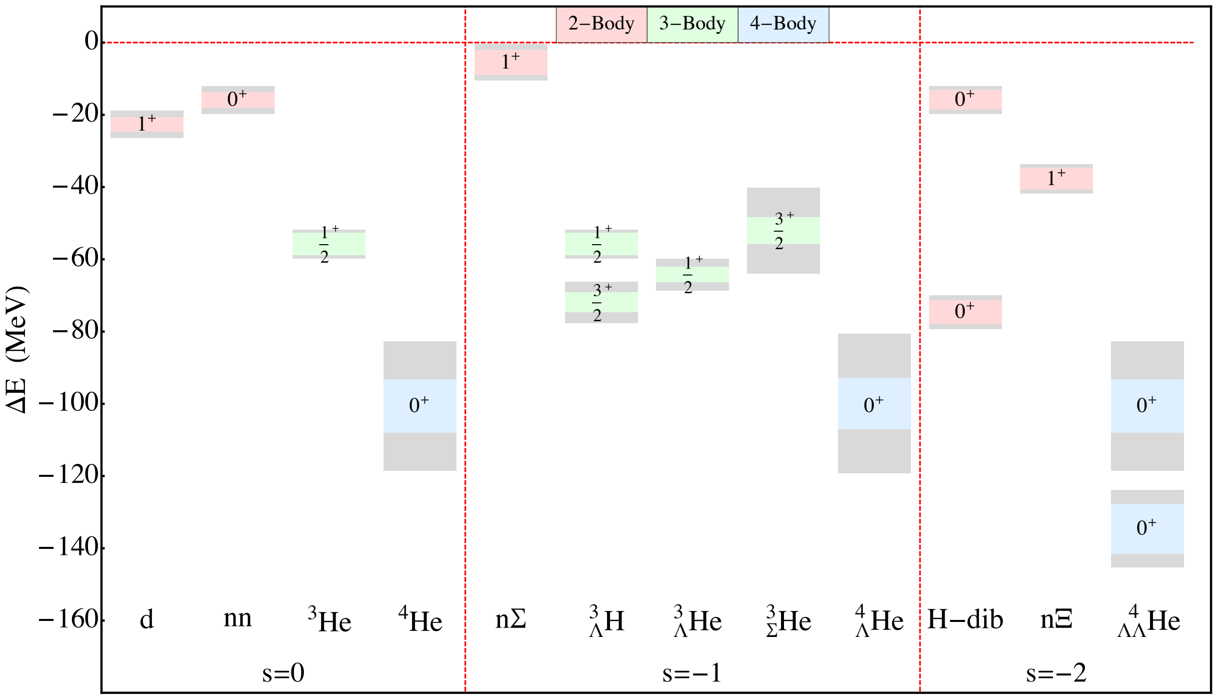


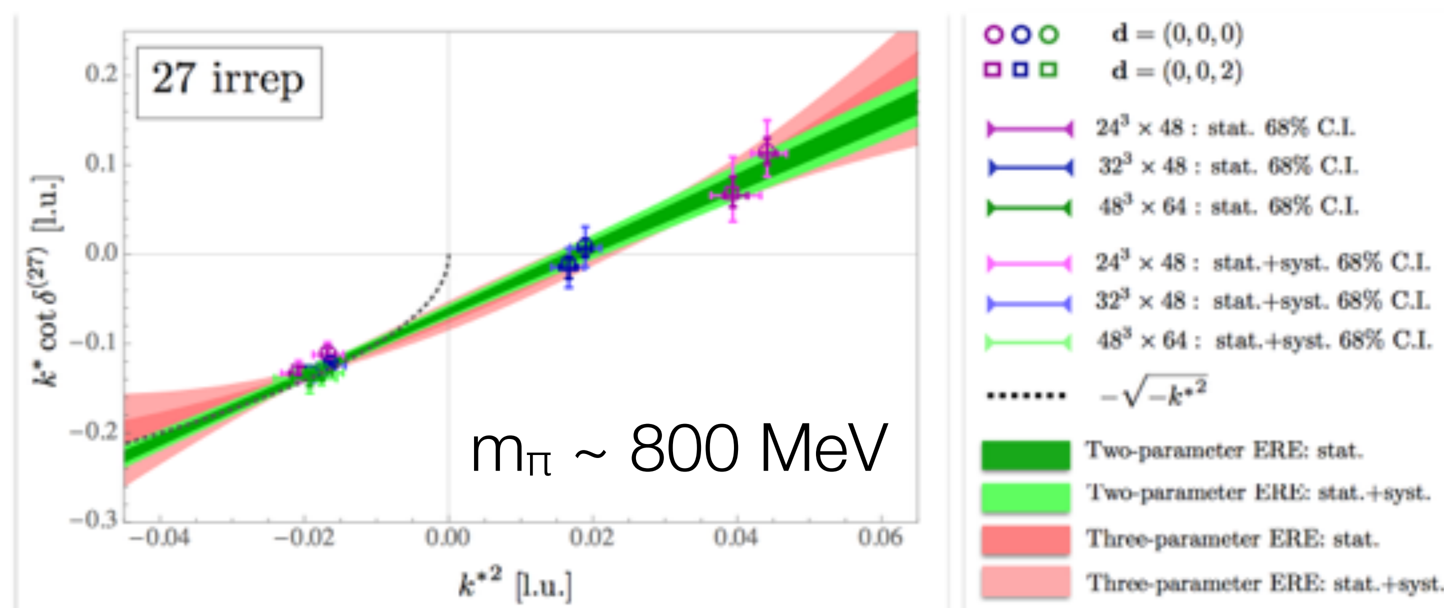


Tanmoy Bhattacharya, Vincenzo Cirigliano, Saul Cohen, Rajan Gupta, Huey-Wen Lin, Boram Yoon
Phys.Rev. D94 (2016) no.5, 054508

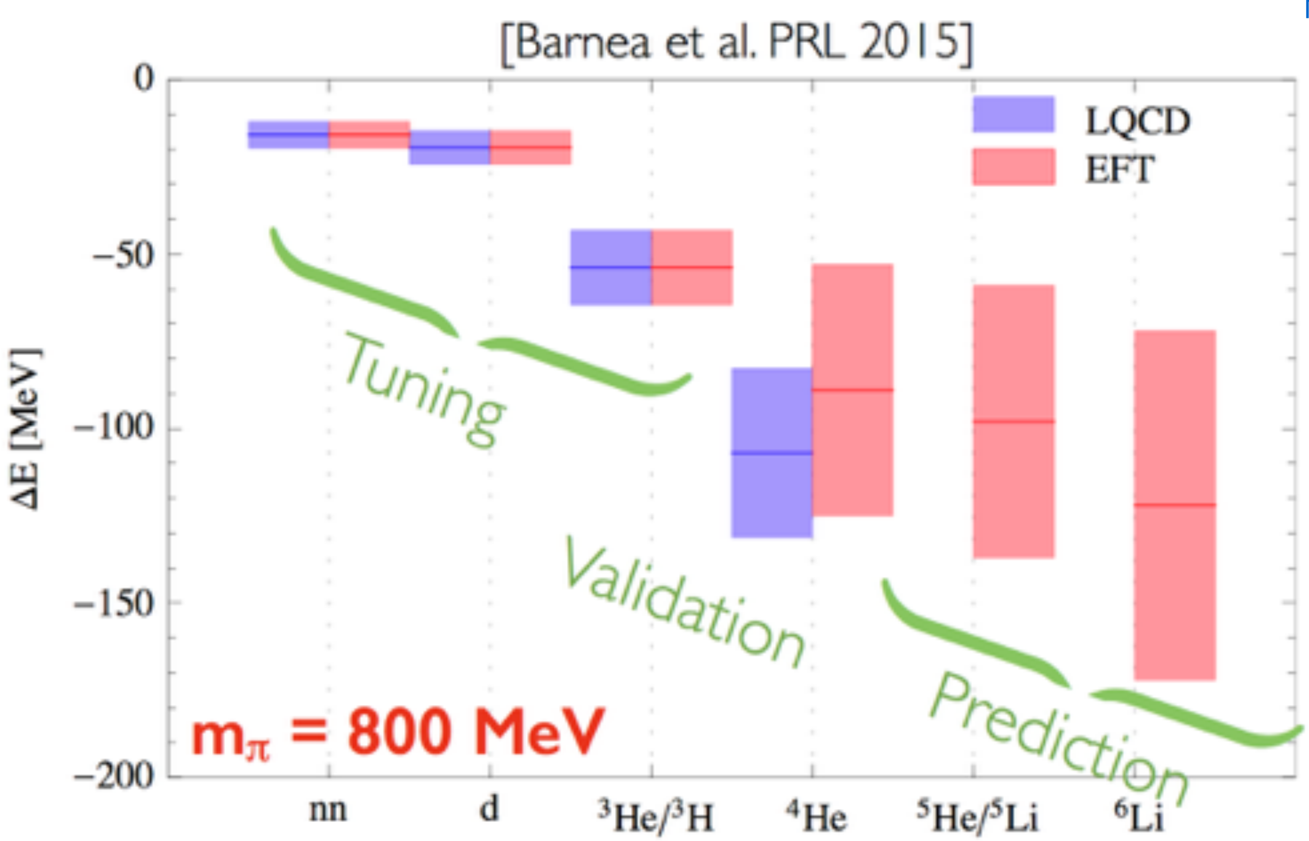


Lattice QCD
QCD to Nuclear Forces: First Steps





Michael L. Wagman, Frank Winter, Emmanuel Chang, Zohreh Davoudi, William Detmold, Kostas Orginos, Martin J. Savage, Phiala E. Shanahan, arXiv:1706.06550

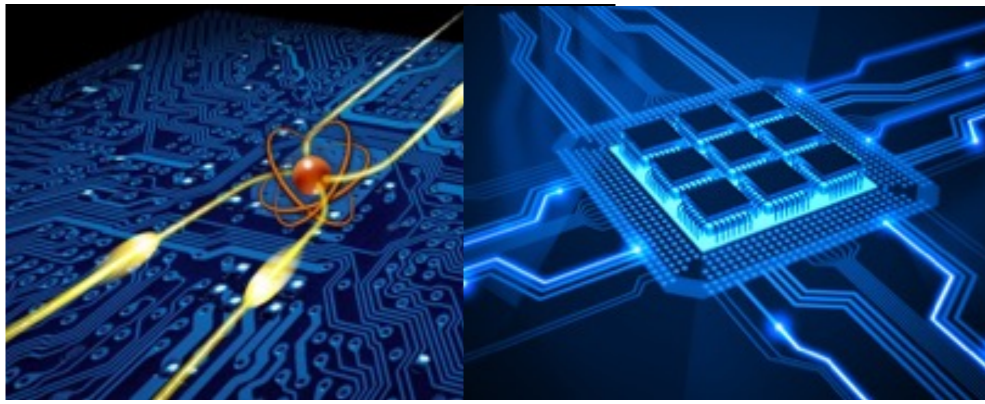


Finite-Volume Energy Eigenvalues

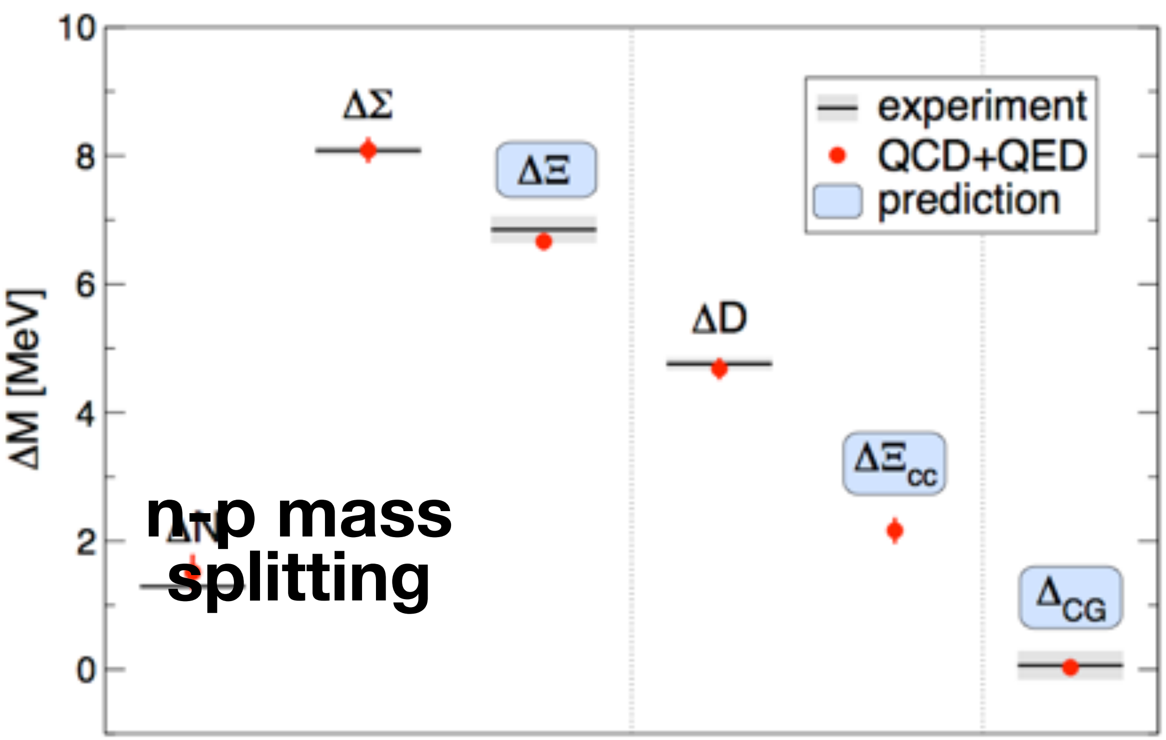
Unnatural systems with approximate SU(6) and SU(16) Spin-Flavor Symmetries

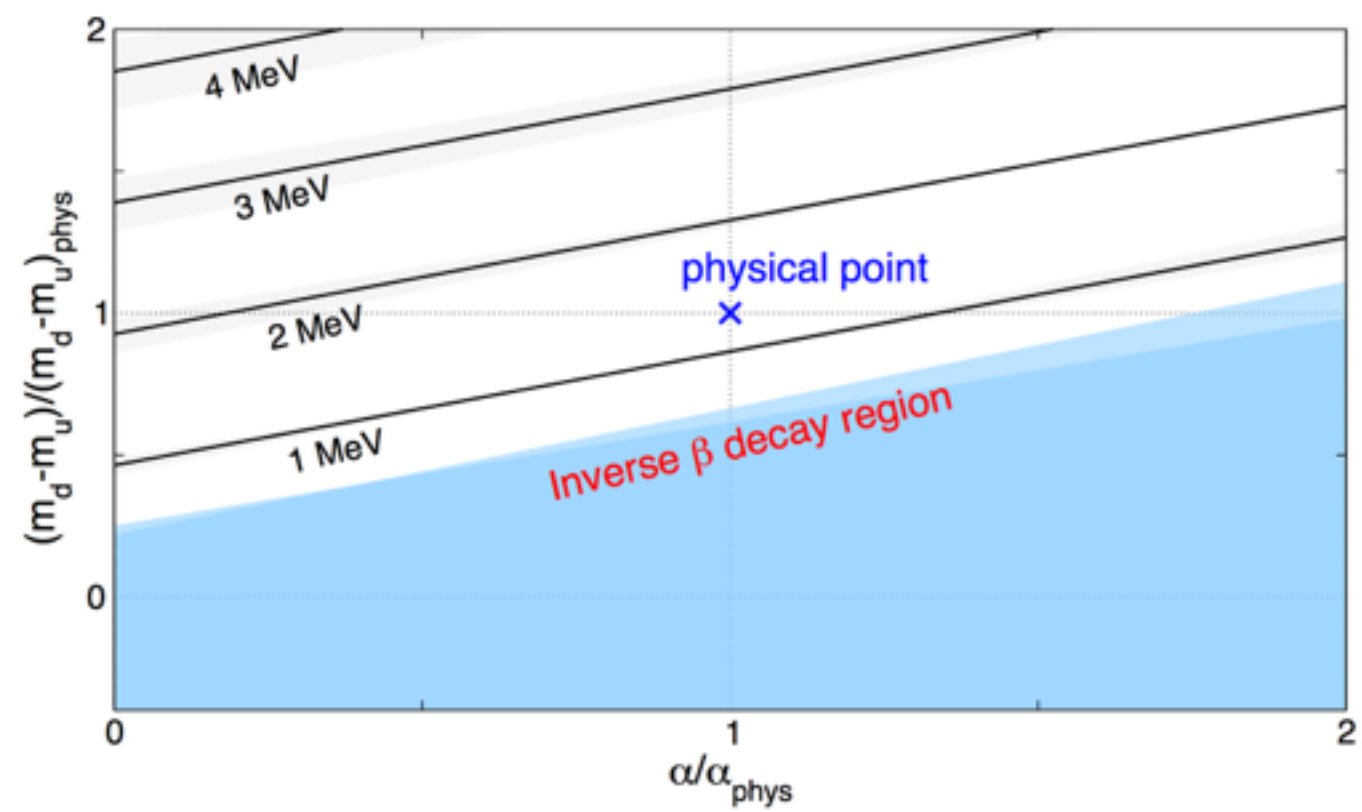
^{16}O appears to be unbound - limits of Periodic Table

Must calculate over a range of quark masses to refine nuclear forces



Lattice QCD Mass-Splittings





BMW collab

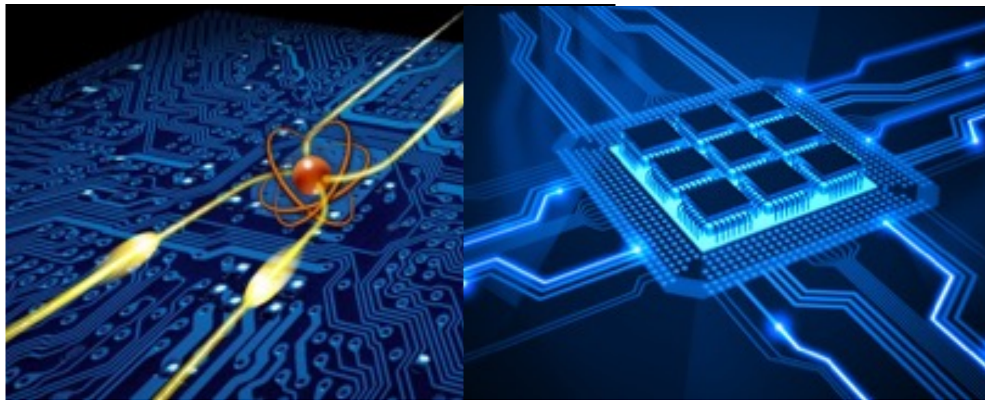
USQCD

e.g., Proton Structure Deliverables

- Quantities with currently quantifiable uncertainties and goals

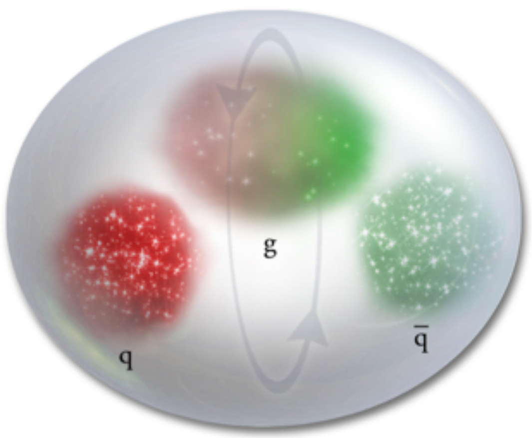
Quantity	Current uncertainty	Uncertainty Goal	Impact/Target
g_A	5%	3%→1%	Benchmark of LQCD; Neutrino-nucleus X-secs V_{ud} given high enough precision
L_u, L_d	~20%	5%	Understanding the spin of the proton
g_S, g_T	20%, 7%	10%, 3%	Ultracold neutron experimental searches for BSM interactions in neutron decay
$a_{\pi\pi}^{(I=2)}$	1%	✓	More precise than experiment/phenomenology
$\langle N \vert \bar{s}s \vert N \rangle$	25%	10%	Input for dark matter direct detection experiments; mu2e conversion
$\langle x \rangle$	~15%	5%	Aim for ab initio input to PDFs (USQCD goal)
$\langle r^2 \rangle_p$	~10%	2%	Impact proton radius puzzle
L_1, L_{1A}	20%	5%	pp fusion; next generation neutrino detectors

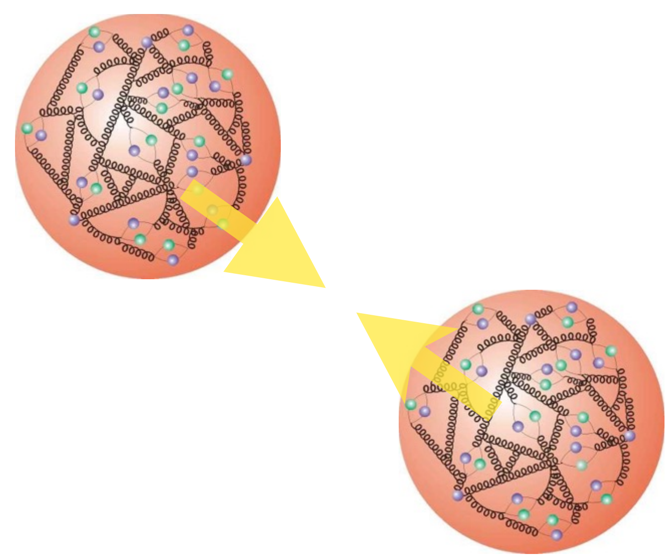
- Most goals achievable achievable in 2021 timeframe



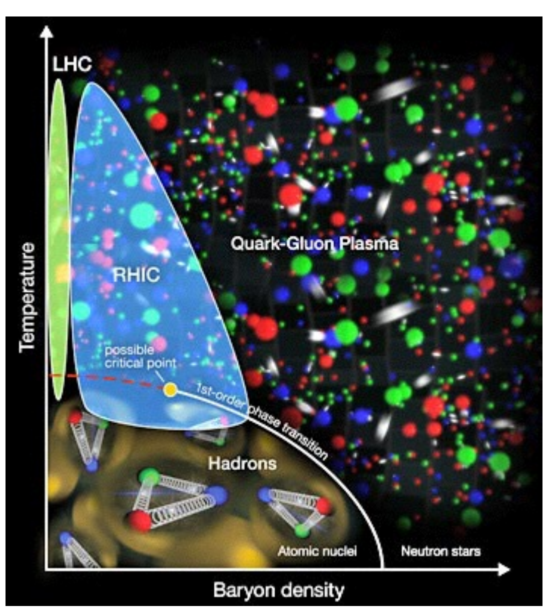
Systems to Explore Quantum Computing Potential

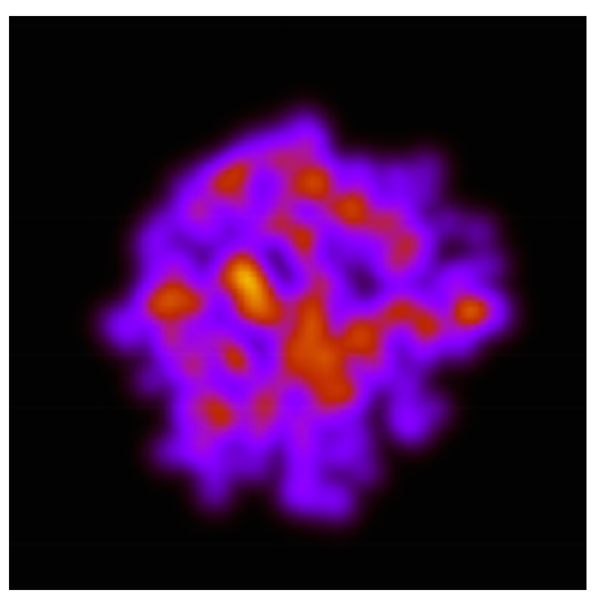
S-matrix elements, equilibrium properties, definite quantum numbers, e.g., 2 neutrons and 1 proton

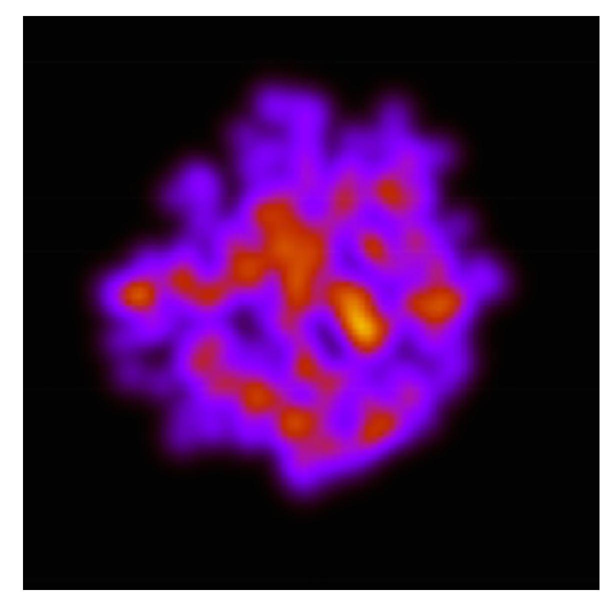


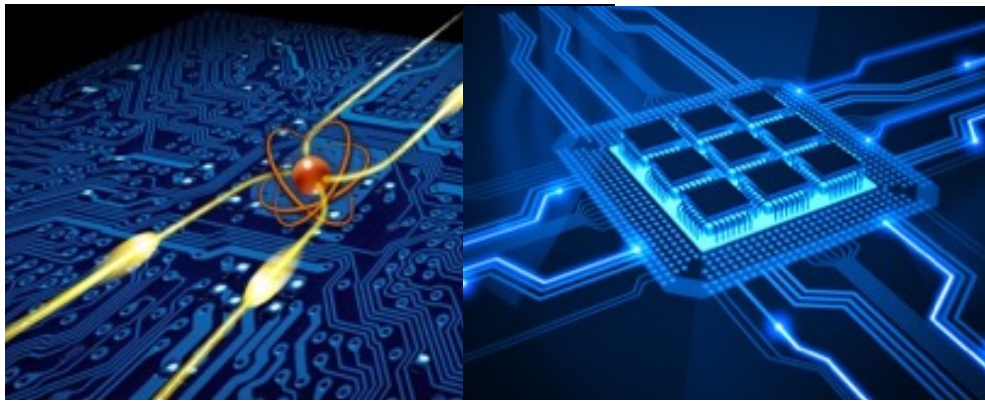


Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution





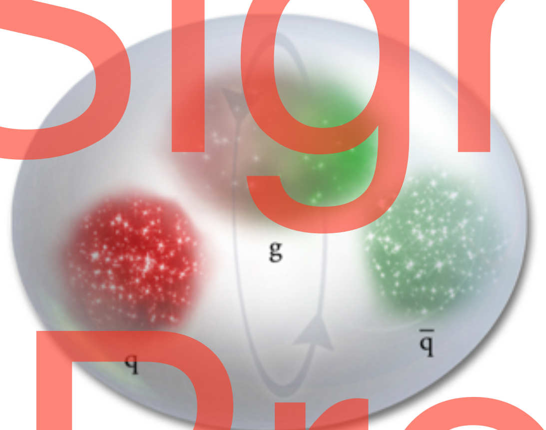


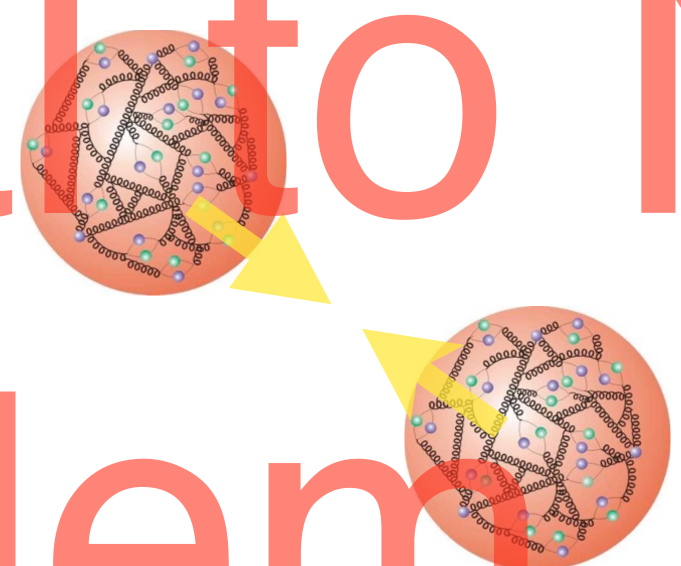


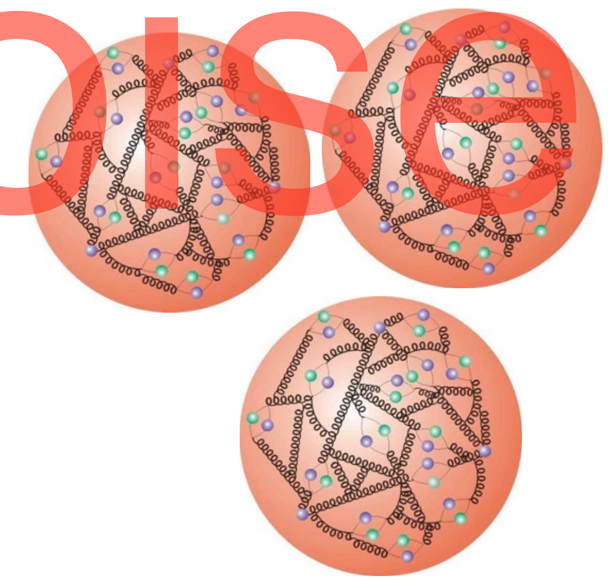
Systems to Explore Quantum Computing Potential

S-matrix elements, equilibrium properties, definite quantum numbers, i.e. 2 neutrons and 1 proton

Signal to Noise Problem

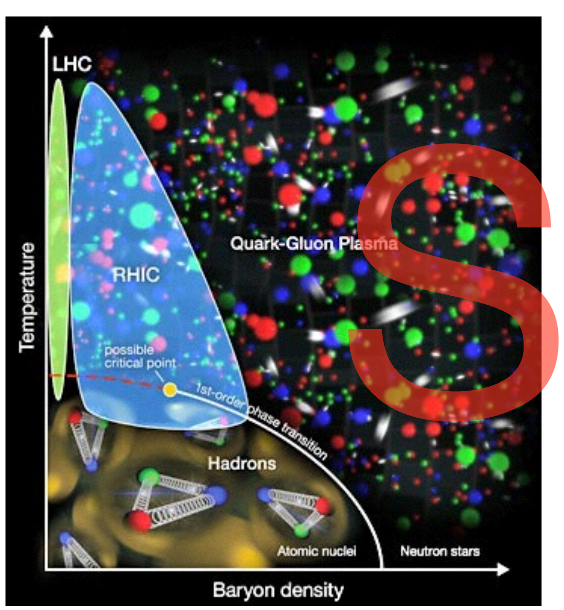


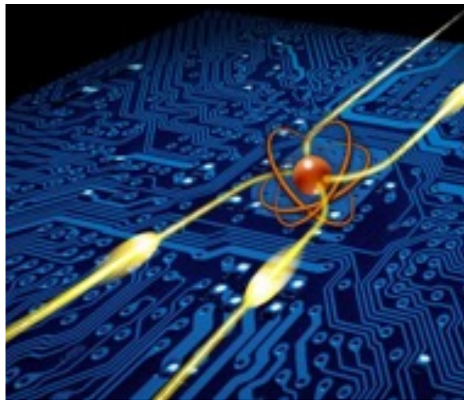


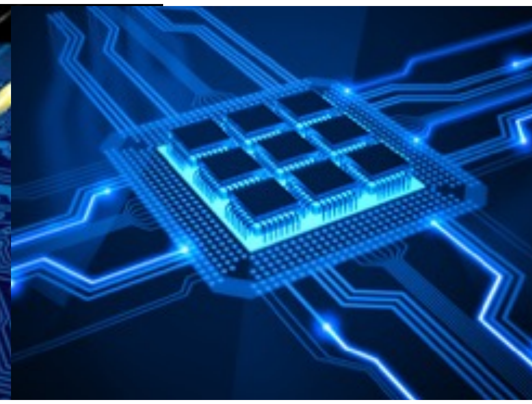


Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution

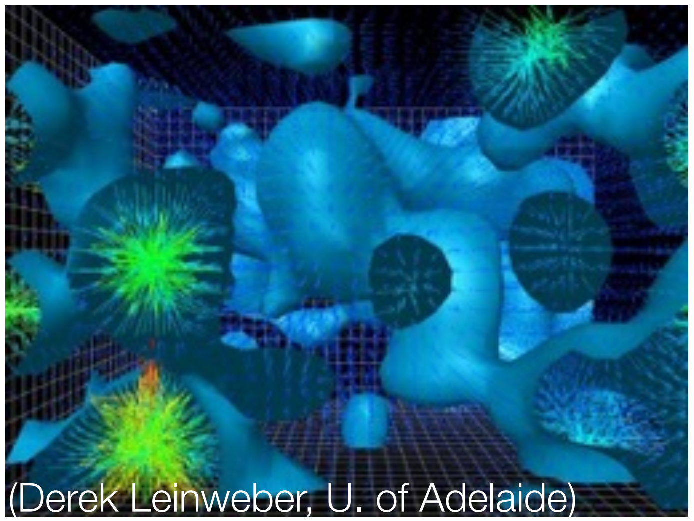
Sign Problem

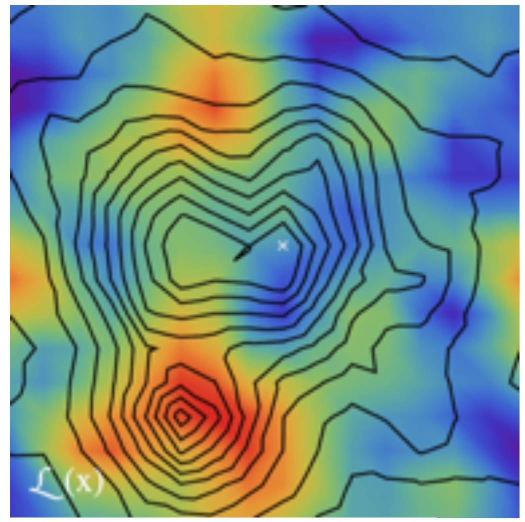


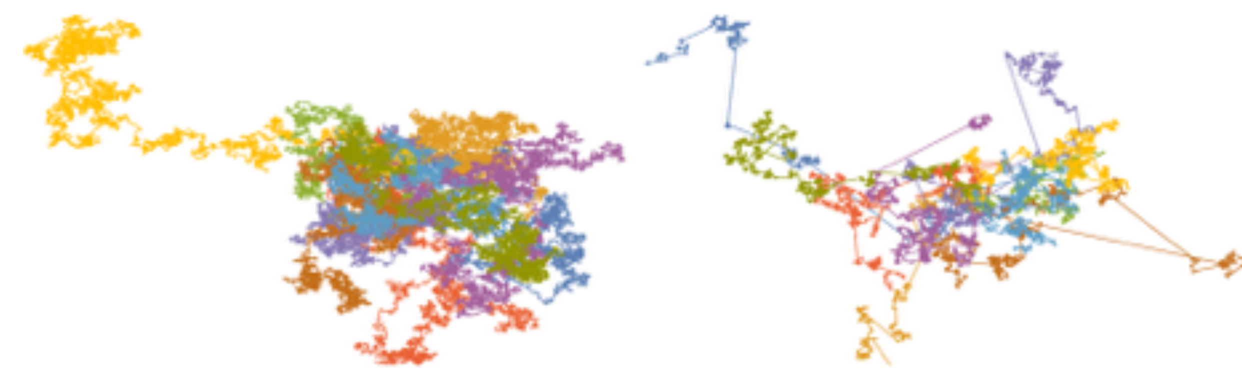




Systems to Explore Quantum Computing Potential One Baryon and More

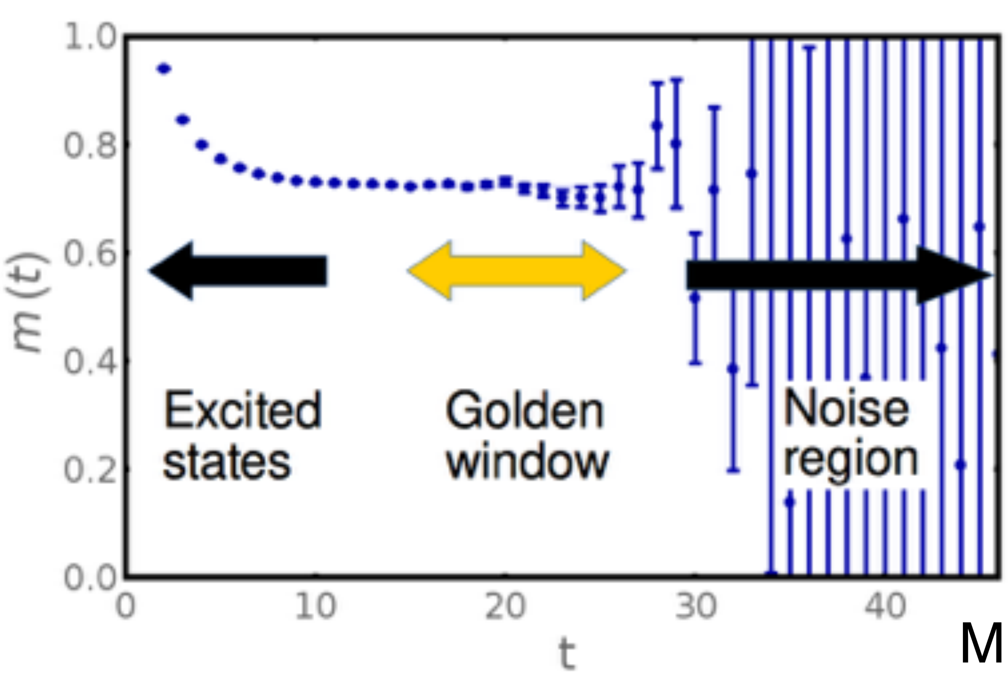


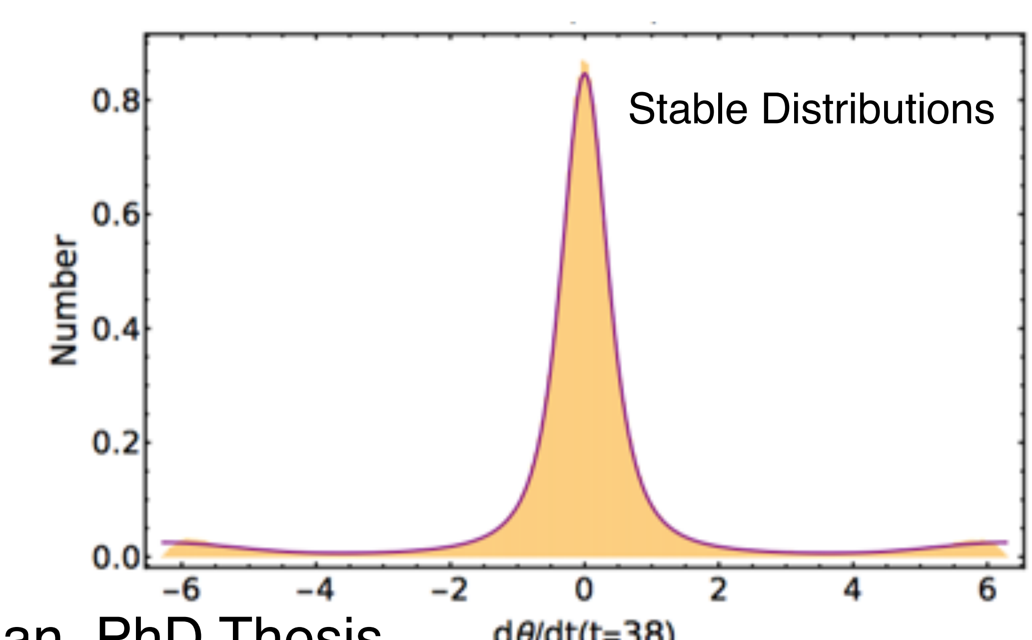




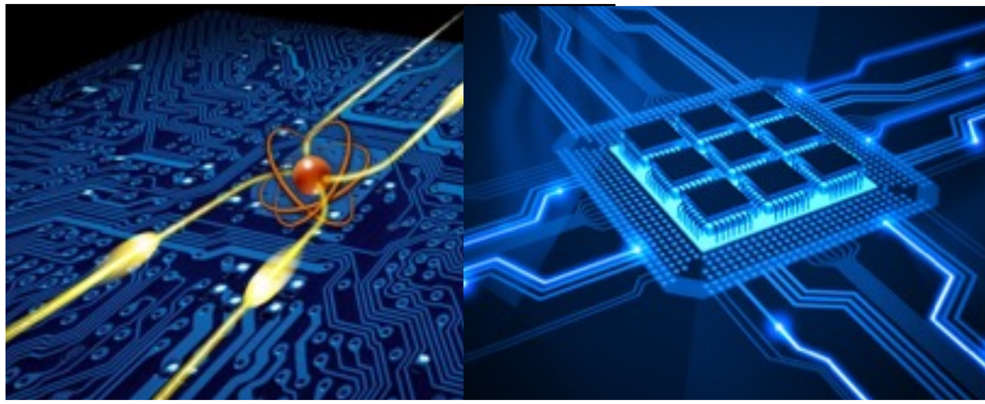
$$C(t) = e^{R(t)+i\theta(t)} \rightarrow \frac{1}{N}\sum_{U_i} e^{R(t;U_i)+i\theta(t;U_i)}$$

$$\langle C(t)\rangle \approx \left\langle e^{R(t)}\right\rangle \left\langle e^{i\theta(t)}\right\rangle \sim \left(e^{-\frac{3}{2}m_\pi t}\right)\left(e^{-\left(m_N-\frac{3}{2}m_\pi\right)t}\right)$$



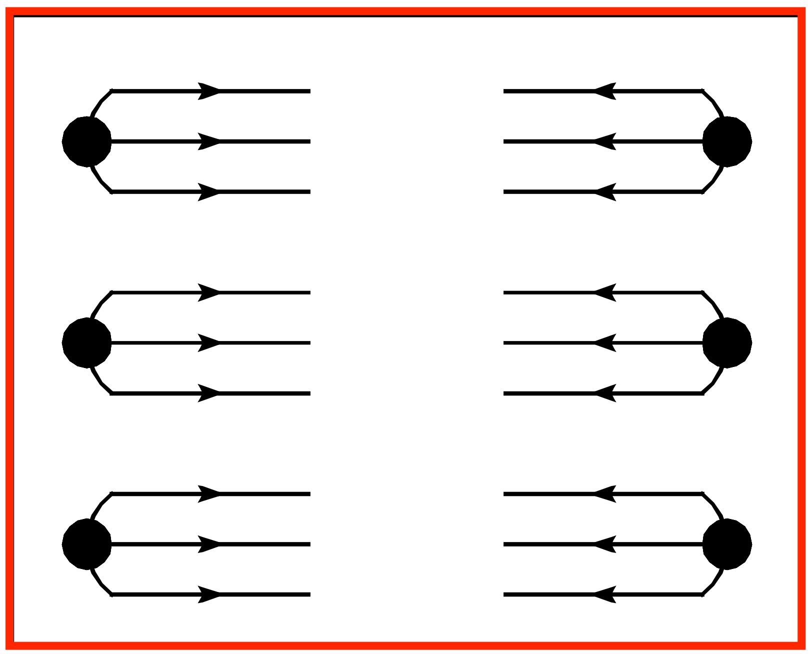


Michael Wagman, PhD Thesis



Systems to Explore Quantum Computing Potential Combinatorics and Antisymmetry

Large number of quark contractions



Proton : $N^{\text{cont}} = 2$

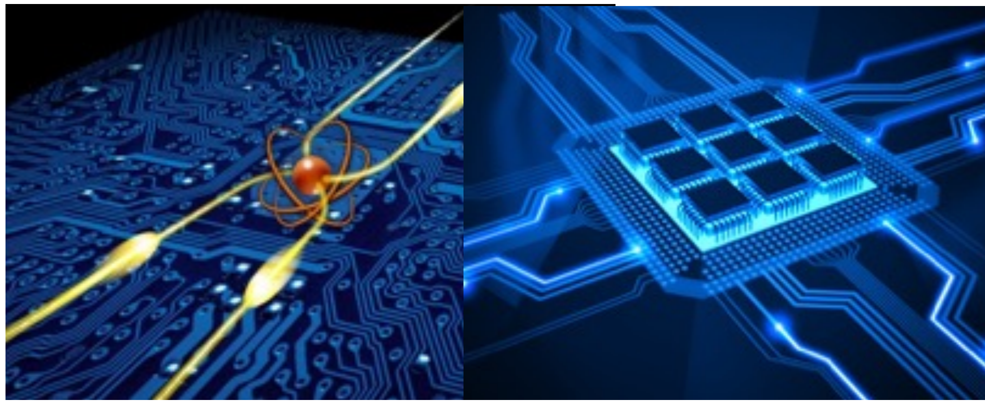
^{235}U : $N^{\text{cont}} = 10^{1494}$

$$N_{\text{cont.}} = u!d!s! \quad (\text{Naive})$$
$$= (A+Z)!(2A-Z)!s!$$

Symmetries provide significant reduction

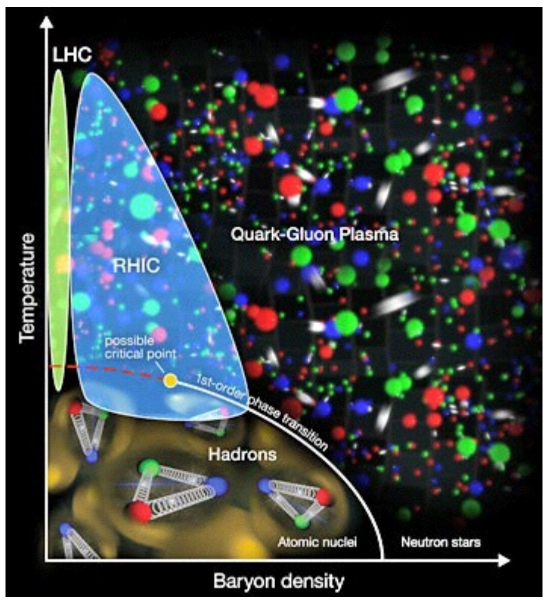
$$^{3}\text{He} \;:\; 2880 \rightarrow 93$$

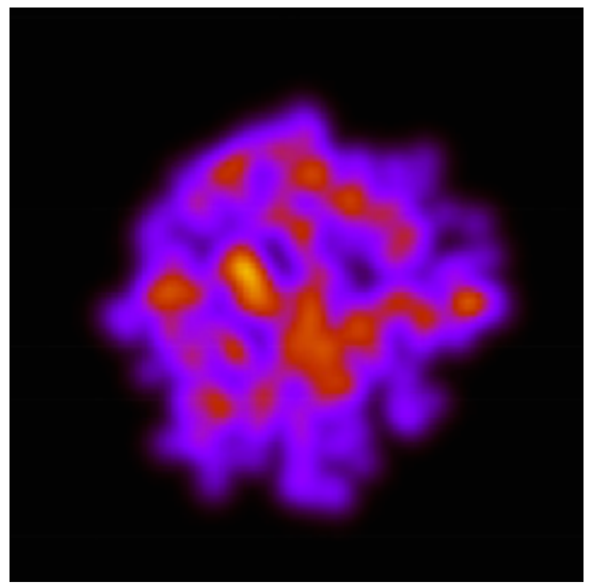
Recursion Relations are crucial

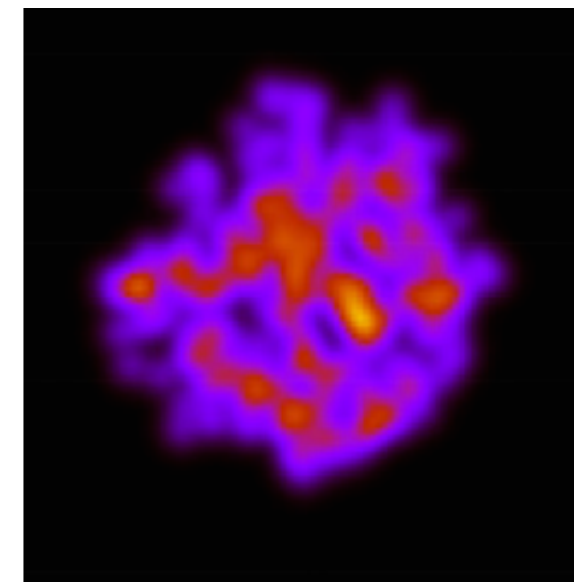


Systems to Explore Quantum Computing Potential Finite Density, Chemical Potentials

Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution

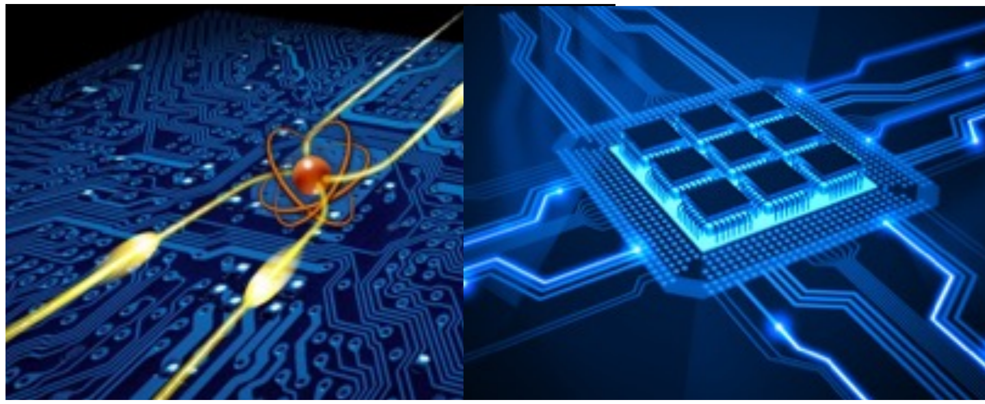






$$\langle \hat{\theta} \rangle \sim \int \mathcal{D}\mathcal{U}_\mu \; \hat{\theta}[\mathcal{U}_\mu] \; \det[\kappa[\mathcal{U}_\mu]] \; e^{-S_{YM}}$$

Complex for non-zero chemical potential



Systems to Explore Quantum Computing Potential Finite Density, Chemical Potentials

Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution

Taylor expansion in μ/T (methodology)

$$\boxed{\frac{p(\vec{\mu},T)}{T^4} = \sum_{i,j,k=0}^{\infty} \frac{1}{i!j!k!} \chi_{i,j,k}^{BQS}(T) \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k}$$

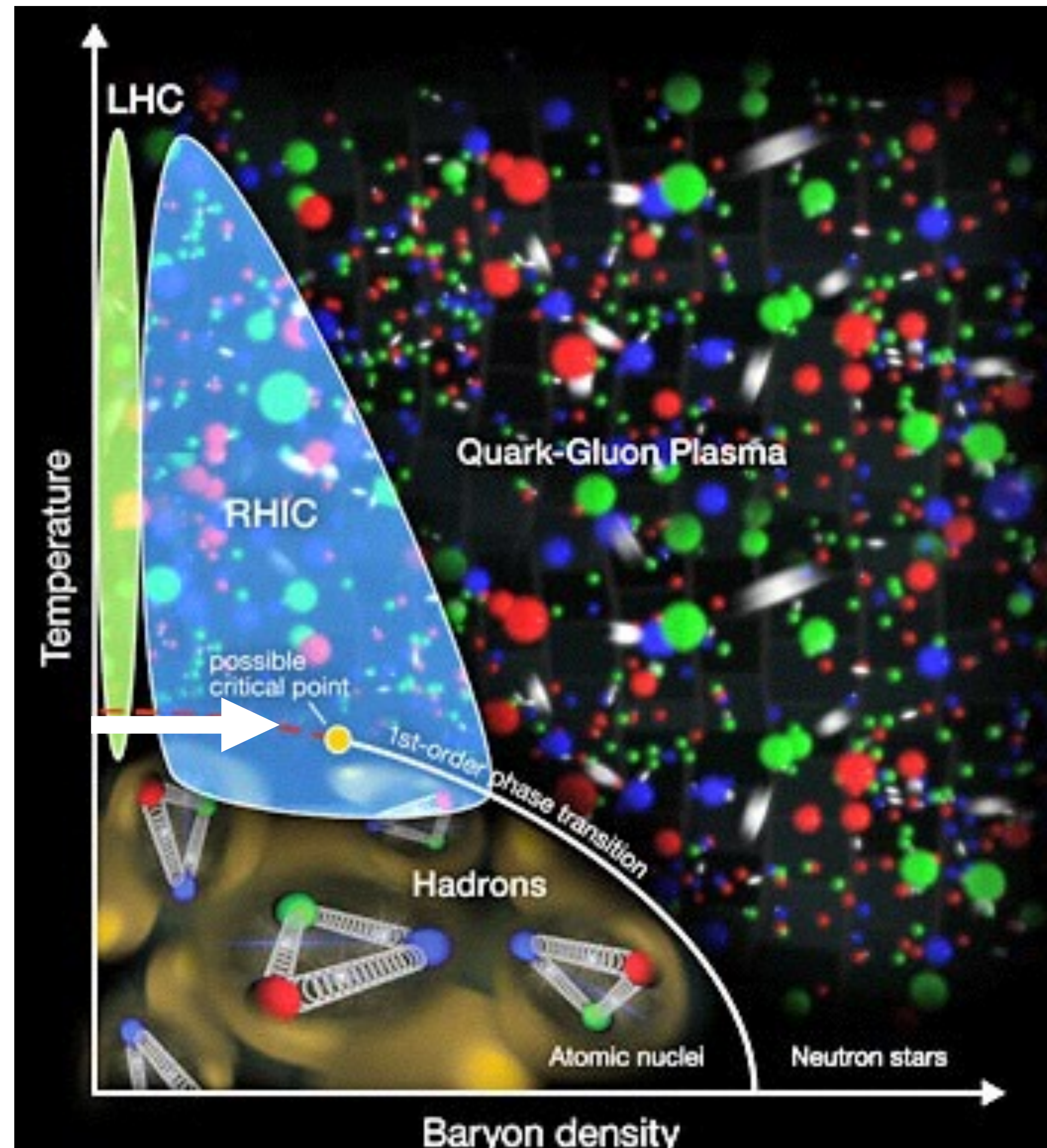
with $\chi_{i,j,k}^{BQS}(T) = \frac{1}{VT^3} \left.\frac{\partial^{i+j+k} \ln Z(\vec{\mu},T)}{\partial\hat{\mu}_B^i \partial\hat{\mu}_Q^j \partial\hat{\mu}_S^k}\right|_{\vec{\mu}=0}$ and $\hat{\mu} = \mu/T$

Example:

$$\frac{\partial^2 \ln Z}{\partial\mu^2} = \langle \mathrm{Tr}\left[M^{-1}M''\right]\rangle - \langle \mathrm{Tr}\left[M^{-1}M'M^{-1}M'\right]\rangle + \left\langle \mathrm{Tr}\left[M^{-1}M'\right]^2\right\rangle$$

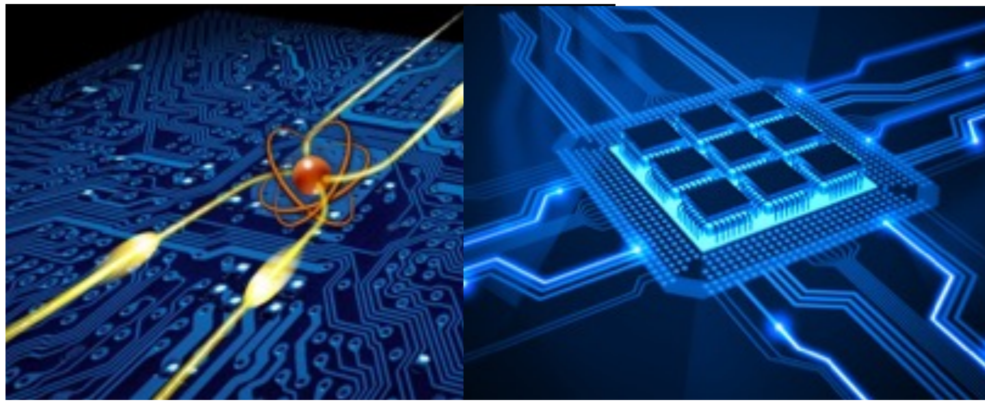
$$\simeq \left\langle n^2(x) \bigcirc \right\rangle - \left\langle n(x) \bigcirc n(y) \right\rangle + \left\langle n(x) \bigcirc \bigcirc n(y) \right\rangle$$

C. Schmidt, SIGN 2017, INT-17-64W, Seattle, WA, USA 6



USQCD

In production - large resource requirements - limits are visible



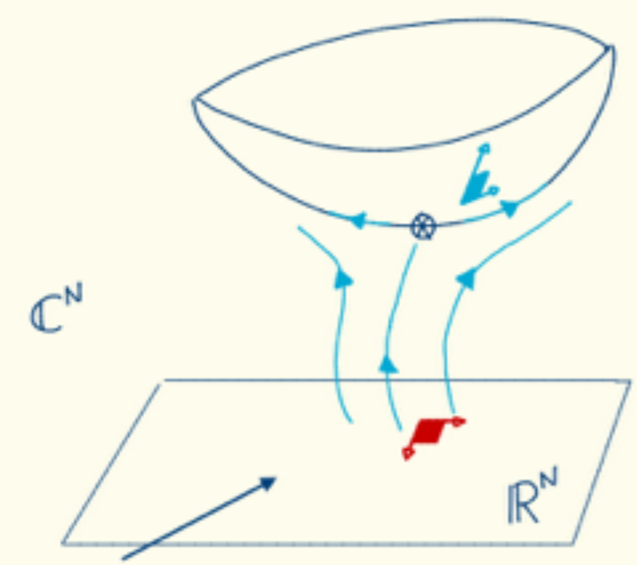
Systems to Explore
Quantum Computing Potential
Formal Developments

Time evolution of system with baryon number, isospin, electric charge, strangeness, …..
Currents, viscosity, non-equilibrium dynamics - real-time evolution

Field redefinitions that eliminate or reduce the phase

- Lefschetz Thimbles

How to find good deformations ?

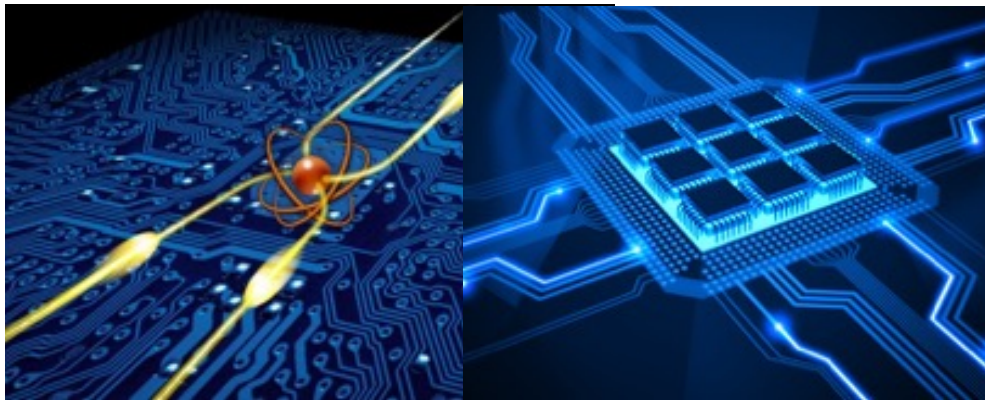


real fields $\tilde{\phi}$ parametrize the flowed R^{N}:

$$S_{eff}[\tilde{\phi}] = S[\phi(\tilde{\phi})] - \log J[\tilde{\phi}]$$

Not yet in large-scale production for QCD
- formal algorithm developments

Bedaque, Warrington, … , Sign 2017, INT



Quantum Field Theory
A couple of theory papers that jump out

Simulating lattice gauge theories on a quantum computer

Tim Byrnes*
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan

Yoshihisa Yamamoto
E. L. Ginzton Laboratory, Stanford University, Stanford, CA 94305 and
National Institute of Informatics, 2-1-2 Hitotsubashi, Chiyoda-ku, Tokyo 101-8430, Japan
(Dated: February 1, 2008)

We examine the problem of simulating lattice gauge theories on a universal quantum computer. The basic strategy of our approach is to transcribe lattice gauge theories in the Hamiltonian formulation into a Hamiltonian involving only Pauli spin operators such that the simulation can be performed on a quantum computer using only one and two qubit manipulations. We examine three models, the U(1), SU(2), and SU(3) lattice gauge theories which are transcribed into a spin Hamiltonian up to a cutoff in the Hilbert space of the gauge fields on the lattice. The number of qubits required for storing a particular state is found to have a linear dependence with the total number of lattice sites. The number of qubit operations required for performing the time evolution corresponding to the Hamiltonian is found to be between a linear to quadratic function of the number of lattice sites, depending on the arrangement of qubits in the quantum computer. We remark that our results may also be easily generalized to higher SU(N) gauge theories.

Phys.Rev. A73 (2006) 022328

Quantum Computation of Scattering in Scalar Quantum Field Theories

Stephen P. Jordan,[†§] Keith S. M. Lee,[‡§] and John Preskill [§ *]

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[‡] *University of Pittsburgh, Pittsburgh, PA 15260*

[§] *California Institute of Technology, Pasadena, CA 91125*

Abstract

Quantum field theory provides the framework for the most fundamental physical theories to be confirmed experimentally, and has enabled predictions of unprecedented precision. However, calculations of physical observables often require great computational complexity and can generally be performed only when the interaction strength is weak. A full understanding of the foundations and rich consequences of quantum field theory remains an outstanding challenge. We develop a quantum algorithm to compute relativistic scattering amplitudes in massive ϕ^4 theory in spacetime of four and fewer dimensions. The algorithm runs in a time that is polynomial in the number of particles, their energy, and the desired precision, and applies at both weak and strong coupling. Thus, it offers exponential speedup over existing classical methods at high precision or strong coupling.

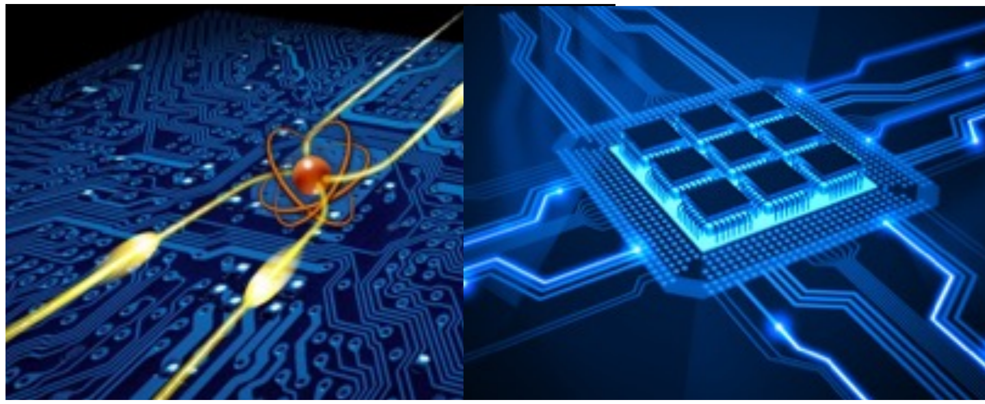
Quantum Information and Computation 14, 1014-1080 (2014)

Detailed formalism for 3+1 Hamiltonian Gauge Theory

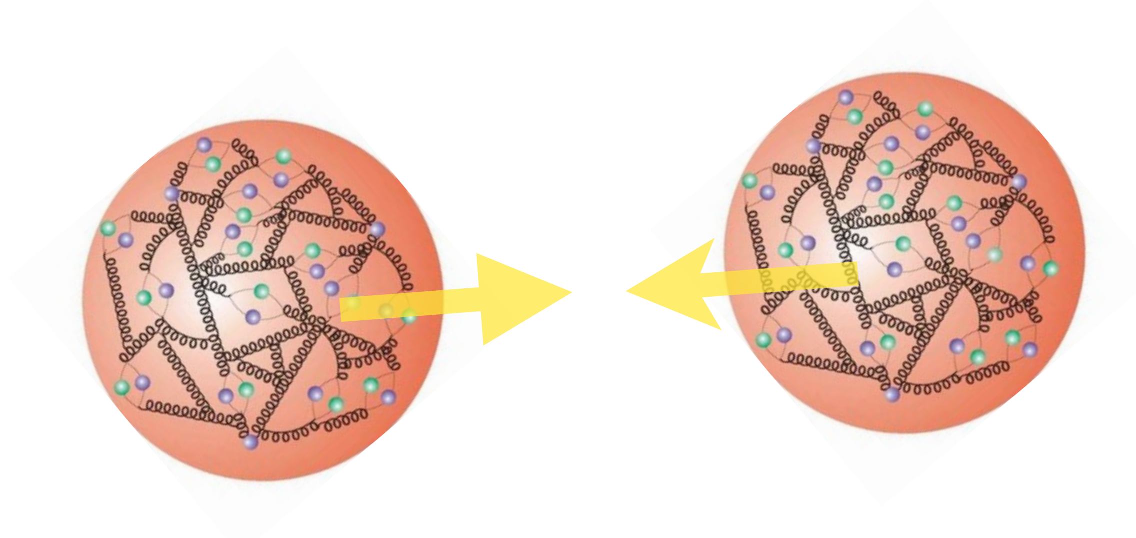
Discretrized spatial volume - no quarks

10^4 spatial lattice sites would require 10^5 * D qubits ,
D=size of register defining value of the field

Scalar Field Theory - Hamiltonian is nice



Quantum Chromodynamics
Asymptotic States

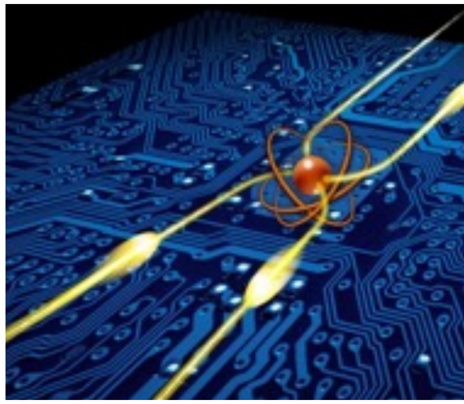


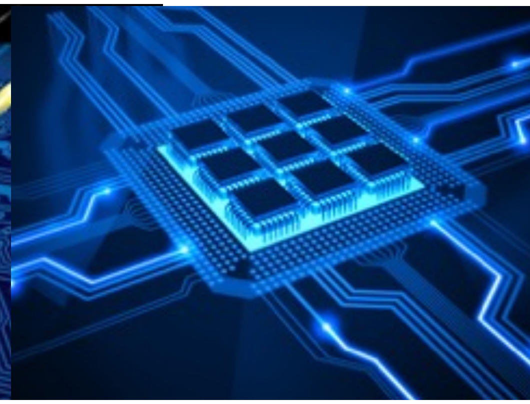
Asymptotic states of QCD are nonperturbative states of quarks and gluons, and the strong vacuum itself is condensate of quarks and gluons that breaks (approximate) global symmetries of QCD.

Hamiltonian or not or both?
Parallel Integrator ?

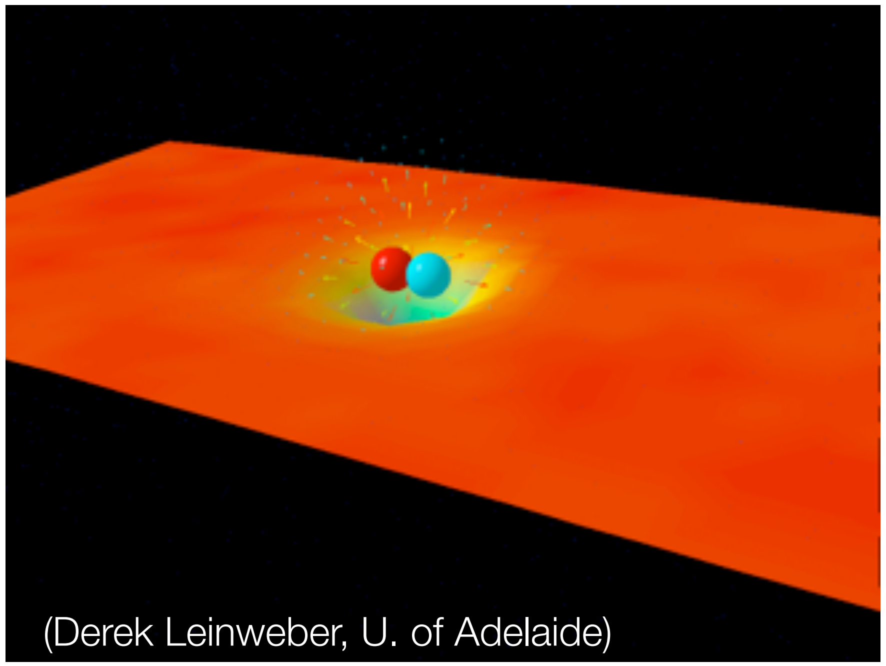
Maybe start with recovering energy-eigenvalues, and S-matrix elements ala Luscher - classical computing provides optimal spatial sources/sinks ?

Initialization of QC registers - what is the mapping of the problem?





QCD Hamiltonian on a Spatial Lattice



(Derek Leinweber, U. of Adelaide)

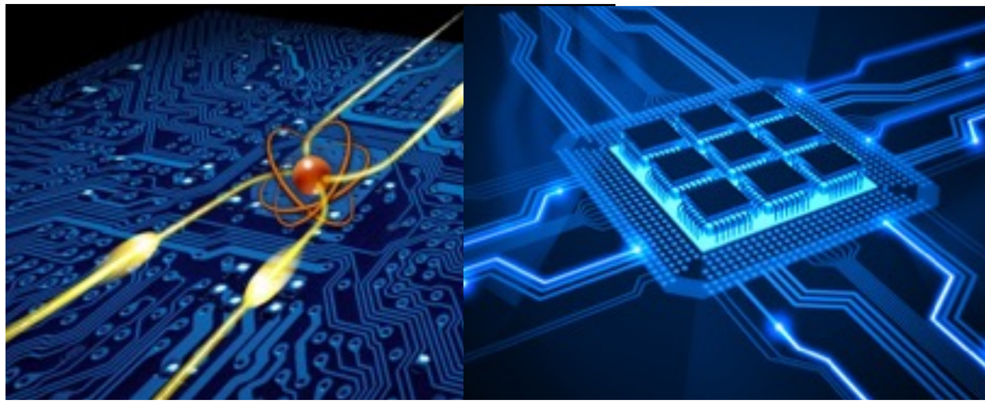
One way to tackle this, might not be the only or best way

$$\boldsymbol{H}_{\mathrm{SU(3)}} = \sum_{r,\mu}\sum_{\alpha=1}^{8}\left(\boldsymbol{E}^{\alpha}(r,\mu)\right)^2 - x \sum_{p\in\{\mathrm{plaquettes}\}}\left(\boldsymbol{Z}(p)+\boldsymbol{Z}^{\dagger}(p)\right)$$

$$\hat{H}_W = \frac{1}{2}\sum_{\mathbf{x}}[\hat{\psi}^{\dagger}_{\mathbf{x}}, \gamma^0\Big(-i\not{D}^s_W + m\Big)\hat{\psi}_{\mathbf{x}}].$$

$$-i\not{D}^s_W\hat{\psi}_{\mathbf{x}} = \frac{1}{2}\sum_{n,i} C_n\Big[\Big(-i\gamma^i - n r_w\Big)U_{\mathbf{x},+n\mathbf{i}}\hat{\psi}_{\mathbf{x}+n\mathbf{i}} + 2nr_w\hat{\psi}_{\mathbf{x}} - \Big(-i\gamma^i + nr_w\Big)U_{\mathbf{x},-n\mathbf{i}}\hat{\psi}_{\mathbf{x}-n\mathbf{i}}\Big]$$

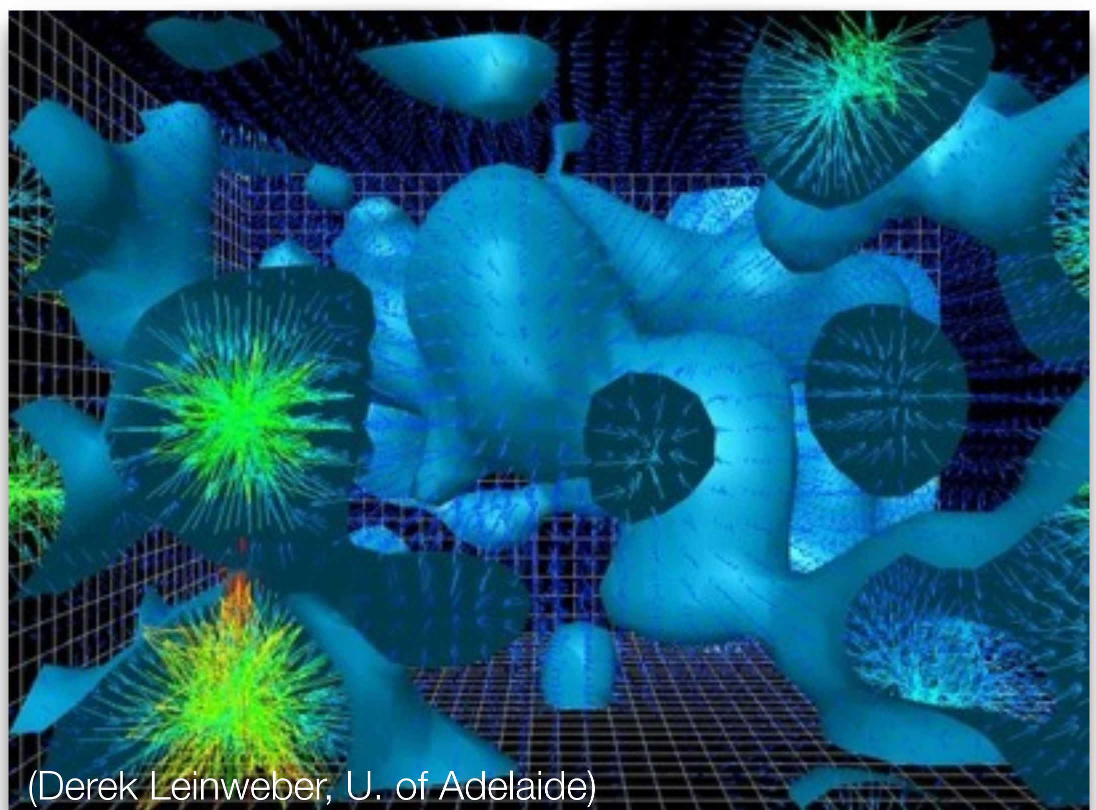
+improvements in discretization (clover, etc)
+ or actions with good chiral symmetry



What is the Quenched QCD Vacuum : E^a |0>=0 ?

Random fields at each point in spacetime is far from ground state.
- generally all 0++ states will be populated with some amplitude

| random > = a |0> + b |(GG)> + c | (GG)(GG)> + ….


(Derek Leinweber, U. of Adelaide)

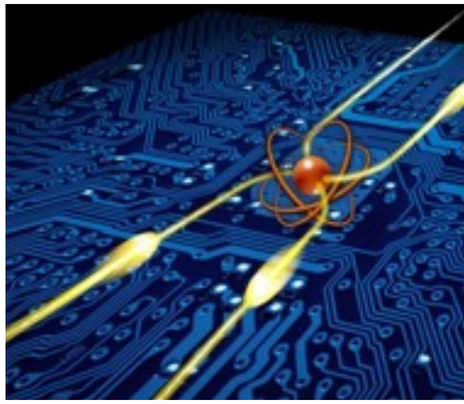
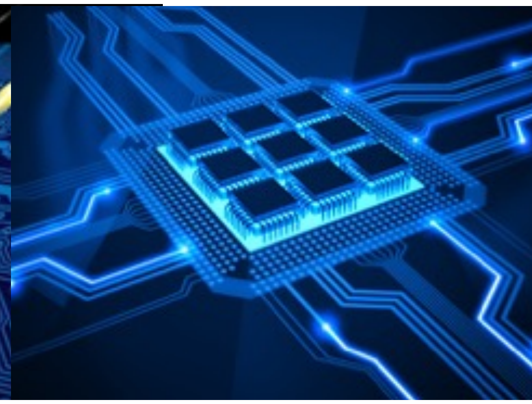
1 vacuum configuration

Probability $e^{-S_{YM}}$

| random > needs to be ``cooled'' to |0>
- repeated ``cuts'' after Quantum Fourier Transform ?

In Lattice QCD, first 1000 steps of HMC thermalize

Euclidean-space Lattice QCD will likely be required to provide initialization of vacuum. How to do this ?

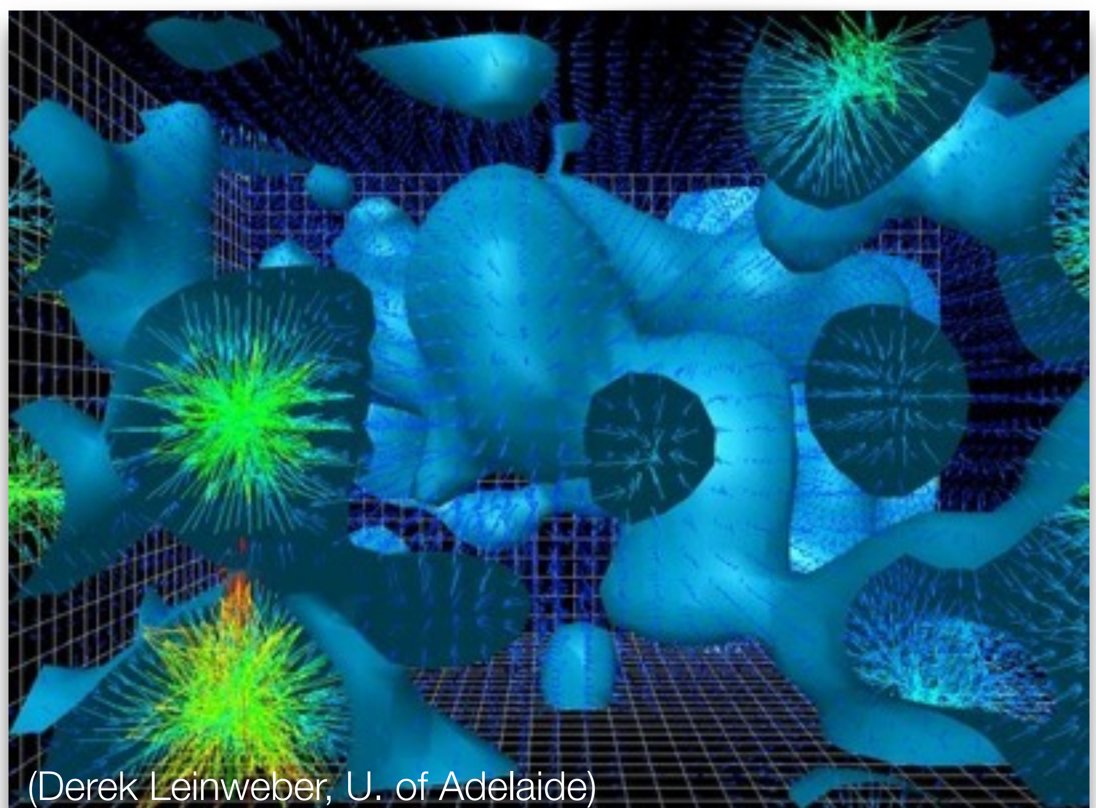



What is the Full QCD Vacuum : $E^a |0\rangle = 0$?

Random fields at each point in spacetime is far from ground state.

- generally all 0++ states will be populated with some amplitude

| random > = a |0> + b |(pi pi)> + c | (pi pi pi pi) > + …. + d | (GG) > + ….

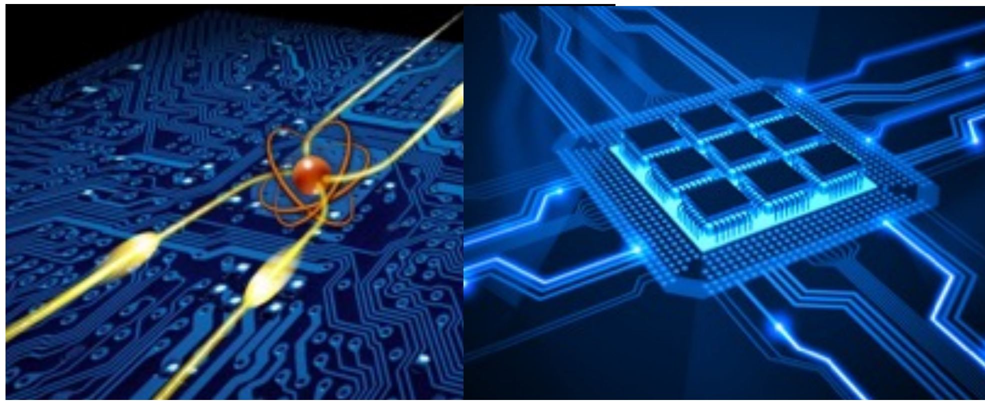

(Derek Leinweber, U. of Adelaide)

1 vacuum configuration

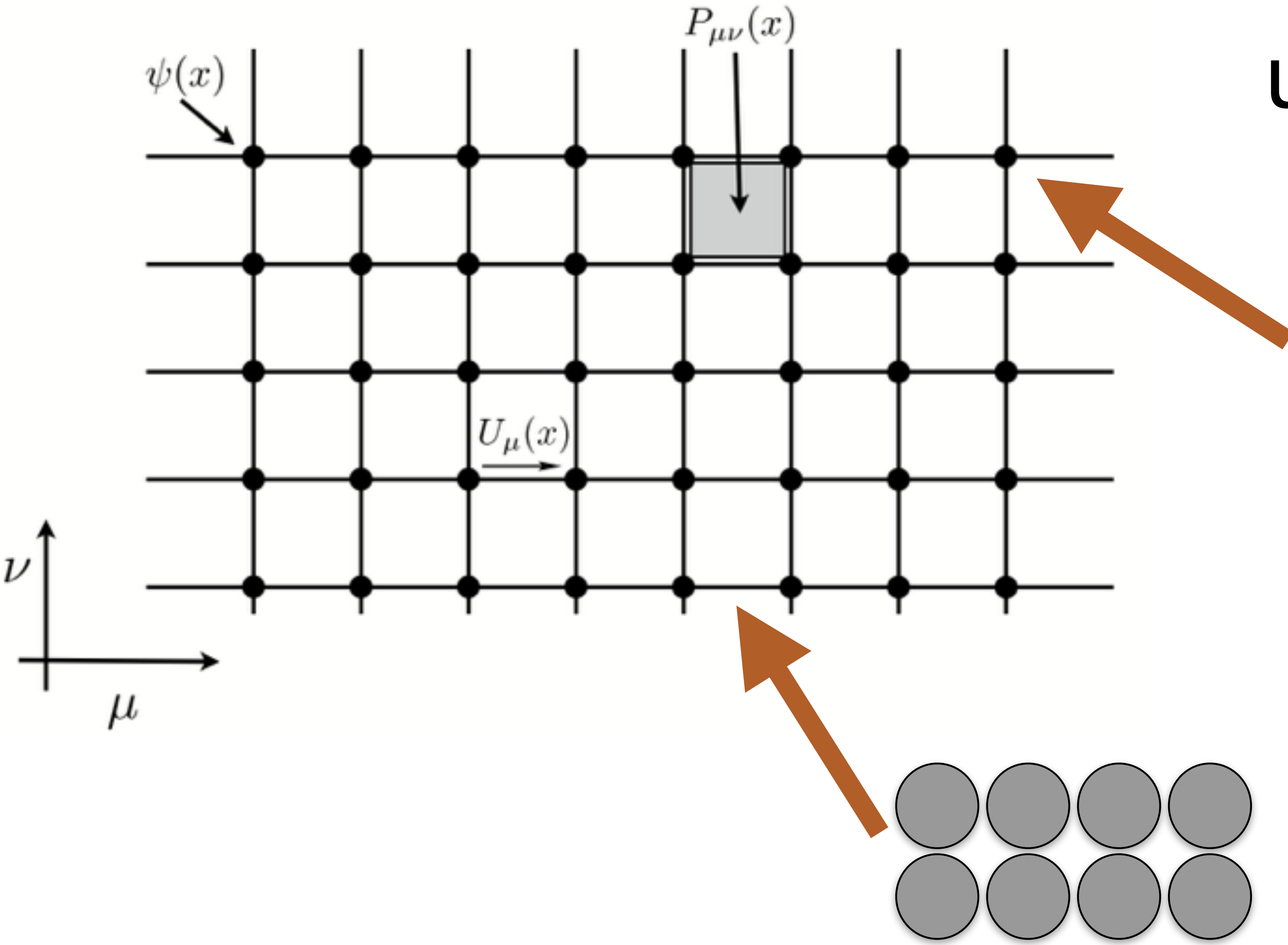
Probability $e^{-S_{QCD}}$

| random > needs to be ``cooled'' to |0>
- repeated ``cuts'' after Quantum Fourier Transform ?

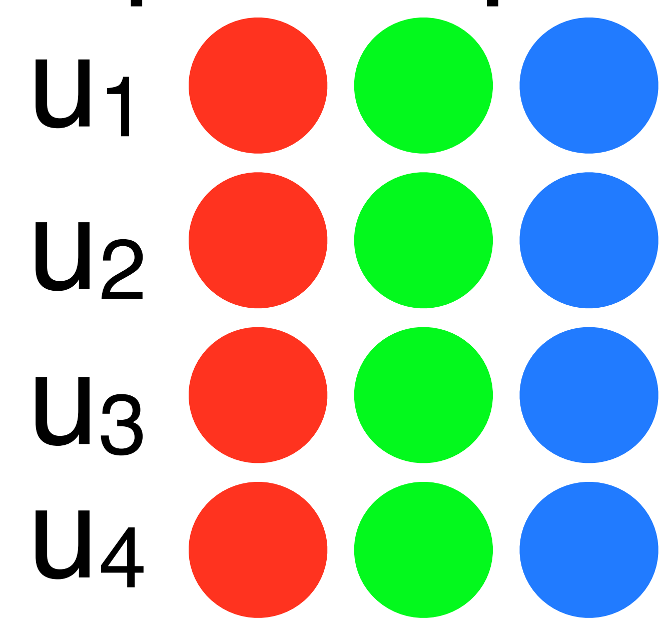
Euclidean-space Lattice QCD will likely be required to provide initialization of vacuum. How to do this ?



QC for Hamiltonian QCD
Naive Estimates of System Register



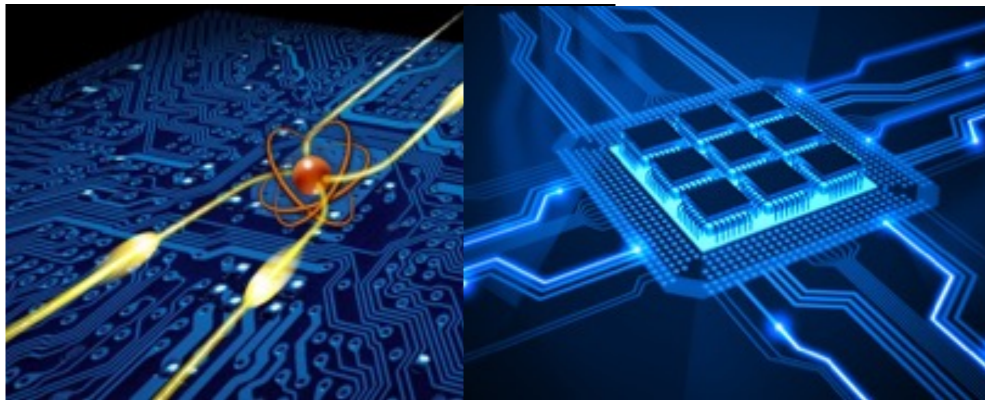
up-quark qubits



+ d,s,c

12 * nf

Gluon Fields:
for each direction (8 real numbers) * (resolution of value of each field)



QC for Hamiltonian QCD
Naive Estimates of System Register

Each site has a register of qubits, scales with spatial volume

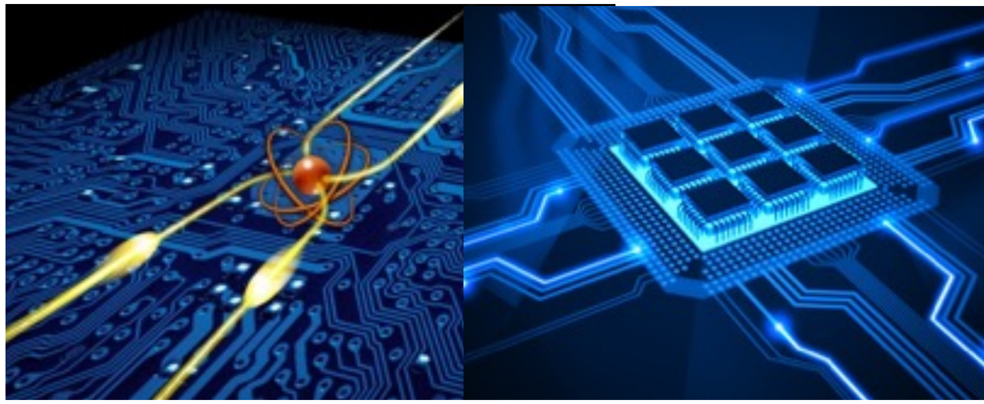
e.g., fully-dynamical QCD
u,d,s quarks
Number of Qubits $= 36\ L^3 + 24\ L^3\ n_{res}$

$L=10$ and $n_{res}=6$
Number of Qubits $= 180\ L^3 = 180K$

c/w: Quenched QCD
$L=10$ and $n_{res}=6$
Number of Qubits $= 24\ L^3\ n_{res} = 144K$

c/w: Scalar-field Theory:
$L=10$ and $n_{res}=6$
Number of Qubits $= L^3\ n_{res} = 6K$

Lattice spacing and volume extrapolations remain



Some (quasi-random) thoughts

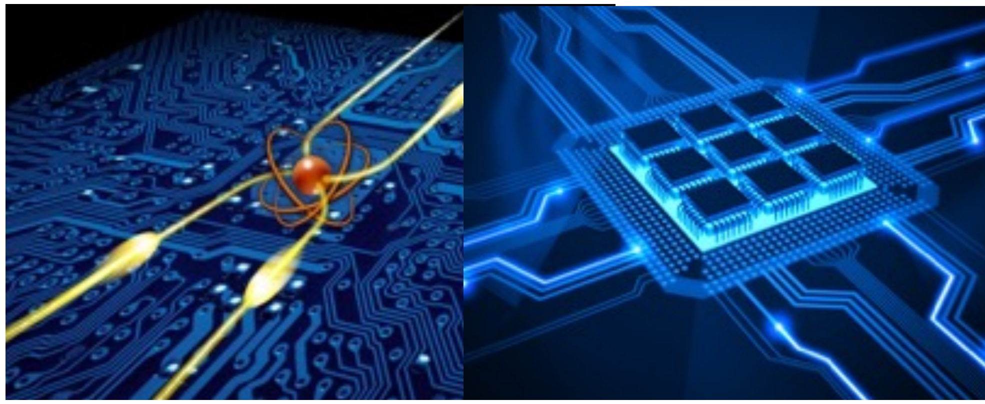
1+1 dim Schwinger model simulated by integrating out gauge fields to leave a spin-model with non-local interactions, (Martinez et al (2016), and others)
- caught my attention!

In LQCD with QED : Gauss's law violated by PBCs in LQCD calculations with QED, introduces non-locality, but it is OK as only the zero-mode is removed !

At present, co-design seems essential - developing algorithms for present and near-term QC hardware, as opposed to ``fantasy/wishful thinking'' QC hardware.

Resource requirement estimates (qubits, gates, oracles) need to be for the integrated application - i.e. what will it actually take to complete the physics objective.

Physics understanding/techniques and algorithms in NP and HEP may be of benefit to more general QC objectives



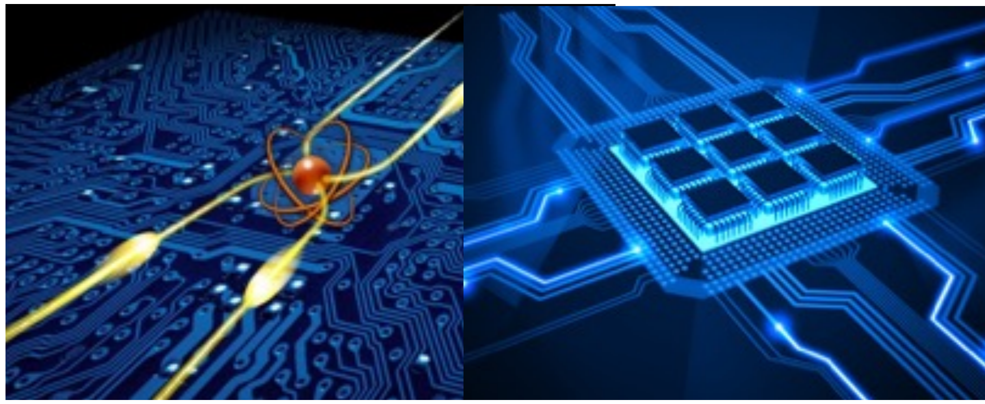
The Role of Quantum Computing for QCD in NP (circa 2017 !)

Classical computing is on track to provide sufficient precision for many experimentally important quantities in HEP and NP in the Exascale.

Finite density systems (including modest size nuclei) require exponentially challenging calculations that may be better suited to QCs in the longer-term.

Anticipate that Exascale classical systems will be required to ``precondition''/ map problem onto qubit registers of QC and then read from qubit registers - BUT currently little is known how to use a QC for QCD

QCs may be first used to accelerate parts of classical Lattice QCD calculations.



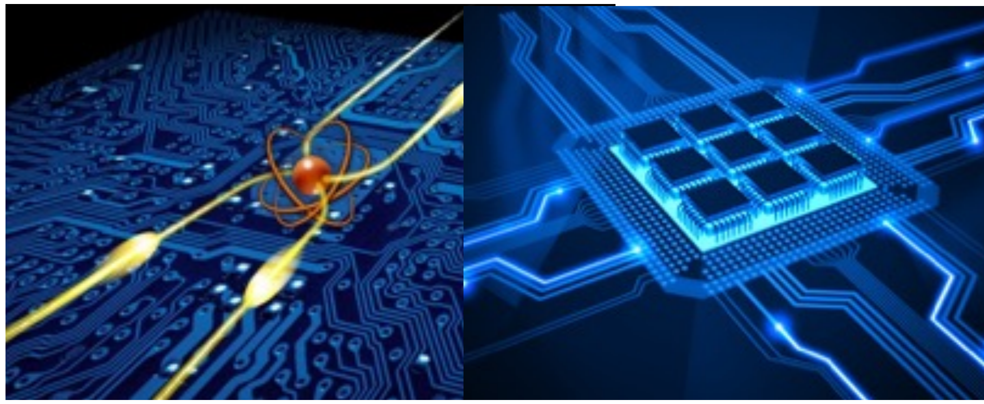
Summary

The next decade will be looked back upon as an important period in QCD in both HEP and NP because of High Performance Computing - possibly accelerated by Quantum Computers.

We speculate that Quantum Computing will be significant in studies of finite-density systems and may be central in achieving important objectives in Nuclear Physics, but significant R+D is required in this area.

The pyramid of classical HPC resources in the exascale is (and will remain) essential.

- QC Algorithms are required for QCD to address
  - systems of nucleons
  - finite density, chemical potentials
  - Hamiltonian evolution
  - Implementing low-energy effective field theories - renormalization group techniques, truncated Hilbert space techniques
- Collaborations with QC/QI experts to accomplish the science objectives
- Co-design important



Summary

``Standing up” QCD on QCs important for NP and HEP.

The most naive implementation appears costly - but this is just the beginning …

FIN