

Future of QI (2011-23)

The Benasque Quantum Information Workshops 2011 – 2023

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2011

Quantum Computation

-) Q. Algorithms
-) "Linear" Optics
-) Robust 2D Topological QC & Memory

Q. Simulation

-) Validation (Error Correction)
-) Prediction: Q. Simulation
✓
Mark: 2 Years C. Simulation
Funding > 1

+5 more...

2013

QUANTUM INFORMATION THEORY

- NPT Bound Entanglement
- Quantum Violation ≥ 0
- Characterization M-part, entanglement + apps

- Q. Discord??

* Univ. Q.C. with Q. Walks

* Unifying Q. Correl. \Leftarrow Discord

* Q.C. with little entang.

- Charact. LOCC + POVM (measurements)

- Role ent. in Q.C.

* Security Dev. indep QKD

- General framework security dev. indep

- Certification Spoo-like separation dev. indep

- Example non-sec. C.C. Channels

- PPT \Rightarrow E. Breaking

NEUTRAL VS NESS FOUNDATIONS OF QUANTUM PHYSICS

* PBR THEOREM

* Activation Q. non-locality

- B.E.S violate B. ineq

- Beyond B. ineq.

- PRINCIPLES FOR Q CORRELATIONS

* Form: Landauer pple + 2nd law

- QUANTUM RELATIVITY

- Firewall in BH.

- ARE LEGGETI-GARG INEQUALITIES USEFUL?

- Decidability in QIT

- NON-LOCALITY IN MANY-BODY PHYSICS

- MULT. PRINCIPLES ENOUGH?

- LIFE AFTER LOOPHOLE-FREE BI?

- TSIRELSON'S PROBLEM

MANY-BODY PHYSICS

* TIME-DEPENDENT VARIATIONAL PRINCIPLE

* CRITICALITY IN OPEN Q SYSTEMS

- EFFICIENT SIMULATION OF Q DYNAMICS

- CLASS. PHASES HIGHER-D

- APPROXS. (TRUNCATION) TN

- THERMALIZATION PHYSICAL SYST.

- NON-EG. INEQUALITIES (QUANTUM)

- SIMULATION TN HET

- TN \Leftrightarrow ADS/CFT

- RELATIONS FUCT - ENTANGLEMENT

- LOW-ENERGY EFFECTIVE THEORIES

- \exists SELF PROTECTING QIM IN $D < 4$

QUANTUM OPTICS & IMPLEMENTATIONS

* GROUND STATE OF NANOMECHANICAL RESONATOR

- What is D-wave doing?

- IMPLEMENTATIONS OF DI STUFF

* DETECTION-LOOPHOLE FREE PHOTONIC EXPERIMENT

- Def. entang. bosons/fermions

- LIMITATIONS OF Q SIMULATION

- BOSON SAMPLING (LIMITATIONS)

* SUPERCONDUCTING QUBITS

* SIMULATION OF HIGH-ENERGY PHYSICS IN OPTICAL LATTICES

- CHEAP QKD

- SATELLITE-BASED Q COMM.

- CERTIFICATION OF Q SIMULATION

- LONG-DISTANCE ENT. BASED QC

- EXP. IMPL. OF PBL-LIKE THEOREMS?

MANY-BODY STATE PREPARATION

Quantum Info

- Universal qc w/ q walk
- Unifying q correlations
- QC w/ little entanglement
- security device-indep QKD

Foundations QP

- PBR Theorem
- activation of q nonlocality
- Q thermo: Landauer's principle & 2nd Laws

Q Optics & Implementations

- ground state nanomech syst
- detection-loophole-free photonic Bell exp
- superconducting qubits
- q sim.: high-energy physics in opt lattices
- q sim.: beating class comp

Many-Body Physics

- complexity of Hamiltonians
- criticality in open systems
- time-dependent variational principle

2013: Open Problems I

Quantum Info

- NPT bound entanglement
- Q violation Ingleton ineq
- m -partite entanglement: characterization & applic
- Q discord ??
- LOCC: characterization
- rôle of entanglement in QC
- device-indep: general framework security; certification of spacelike sep
- non-additivity of EOF/class capacity: examples
- QC more powerful than CC?
- $PPT^2 \Rightarrow$ ent breaking

Foundations QP

- bound ent violate Bell Ineq?
- beyond Bell Ineq
- principles for Q correlations
- relativity & QM in low-energy physics
- QI + relativity
- B.H. info paradox / firewall
- are Leggett-Garg Ineq useful?
- decidability in QIT
- non-locality in many-body phys
- life after loophole-free Bell Exp
- Tsirelson's Problem
- Q chaos & entanglement

Many-Body Physics

- efficient sim of Q Dynamics
- classific phases higher D
- approx TN
- thermalization
- non-equilib inequalities (quantum)
- simulation TN HEP
- TN $\stackrel{?}{\leftrightarrow}$ AdS/CFT
- relation fluctuat \leftrightarrow entang.
- low-energy effective theories
- self-protect. Q Mem. $D < 4$?
- robustness topolog memories

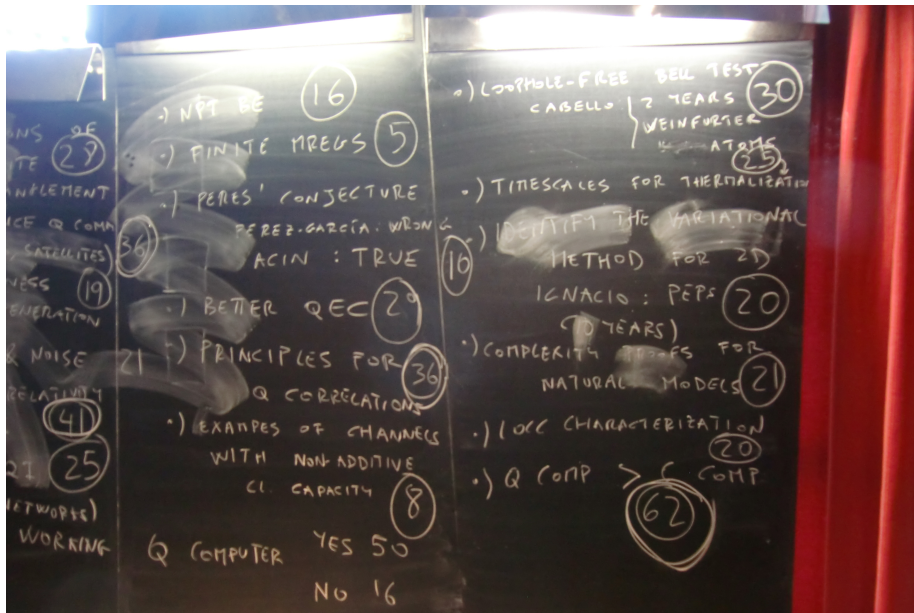
Q Optics & Implementations

- what is D-Wave doing?
- implementations of QI stuff
- Q networks
- cheap QKD
- satellite-based Q Comm
- certification of Q Sim
- long-distance ent-based QC
- exp test of PBR-like theorems
- many-body state prep
- def ent of bosons/fermions
- limitations of Q simulations
- Boson Sampling (limitations)

2013 – Concluding Session

-) NEW Q ALG. (45)
 -) ROBUST TOPOLOGICAL QC & MEMORY (26)
 -) VALIDATION OF Q SIMULATION & D-WAVE? (42)
 -) Q PHENOMENA IN BIOLOGY (15)
 -) APPLICATIONS OF MULTIPARTITE ENTANGLEMENT (27)
 -) ONE-DISTANCE Q COMM (NETWORKS, SATELLITES) (36)
 -) Q RANDOMNESS GENERATION (19)
 -) METROLOGY & NOISE (21)
 -) BLACK-HOLE, RELATIVITY & QI (41)
 -) QCD & QI (TENSOR NETWORKS) (25)
 -) FINITE PERES' REACTION (36)
 -) BETTER Q (21)
 -) PRINCIPLES & EXAMPLES WITH CI.
- I WILL SEE A WORKING Q COMPUTER

2013 – Concluding Session



The Top 10 of Open QIS Challenges 2013

- 1 Q computation more powerful than classical? **(62)**
- 2 New q algorithms **(45)**
- 3 Certification of q simulation **(42)**
- 4 Black Holes, general relativity & q information (black hole information paradox) **(41)**
- 6 Long-distance q communication (networks, satellites) **(36)**
- 6 Principles for q correlations **(36)**
- 7 Loophole-free Bell test (30)
- 8 better QECC (29)
- 9 robust topological QC & QMemory (26)
- 10 timescales for thermalization (25)
- 10 high-energy physics and QI (tensor networks) (25)

2015

2015 Open Problems

OPEN PROBLEMS SESSION

Benasque 2015

Adán Cabello & Géza Giedke

July 8th, 2015

208	INFORMATION/COMPUTATION
30	black holes & holography
30	demonstrate supremacy/speedup of QC
28	better quantum error correcting codes
21	multipartite entanglement
16	QFT and tensor networks
10	macroscopic qubits/QI
10	quantum artificial intelligence (machine learning, etc.)
10	the existence of NPT bound entanglement

176	FOUNDATIONS
28	principles for quantum correlations
26	incorporating time into the foundations of QT
19	quantum mechanics and relativity at low energies
17	experiment to rule out realist interpretation
15	role of causality
13	quantum thermo: work and heat?
12	are all states useful?
11	protocols using QT + relativity

178	MANY-BODY PHYSICS
32	better numerical algorithms for simulation
24	Quantum PCP conjecture
19	understanding the interplay of equilibration/transport/localization
18	entanglement detection
18	variational methods/tensor networks for field theories/continuous models in ∞ -2D
14	uses for many-body phases
13	classifying topological phases in D=2 or higher
12	timescales of equilibration (also thermalization)

170	IMPLEMENTATIONS
25	experimental demonstration of a protocol enhanced by quantum error correction
25	a 2D topological (e.g. surface) code
24	a quantum computer
23	long-distance quantum teleportation
23	q. chemistry simulation
22	gravity tested in the lab
20	quantum repeaters
8	more efficient process tomography

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2017

Open problems

QI

- Physical multipartite entanglement
- Coherence theory and entanglement
- QI and gravity (ECC)
- Black holes / Holography
- Quantum learning theory
- Supremacy
- New killer applications of QC
- Resources for delegated QC
- AQ approach to nonlinear channels
- Q Speedup before QEC?
- Existence of NPT bound entanglement
- No. of qubits issues

2017

Foundations

- The role of causality
- New reconstructions based on interpretations
- Q thermodynamics
- Networks vs Bell nonlocality
- Certification of randomness and quantum in temporal correlations
- QT - exotic space-time connection
- Feeling sensitive collapse brackets
- Why probabilities

Many body

- More applications of tensor networks
- Many body localization
- Applications of tensor networks to
 - The renormalization group
 - QFT
 - Quantum learning
 - Classical "
- Quantum FCP conjecture
- Efficient algorithms
 - Gapless
- Open Q systems Non-Markovian effects

Implementations

- Useful metrology
- Understanding Fermi-Hubbard models
- Q thermo machines - to use
 - with
 - Q supremacy without universality
 - Certifying
- Q certification
- DI QKD
- Q nanophotonics for QI
- IFTQC really possible?
 - Is adiabatic " " " "
- * 'Politically correct words' (e.g. Supremacy)
- Make a surface code
- * Supporting new journals

QI

- physical multipartite entanglement
- coherence theory and entanglement
- QI and gravity (ECC)
- Black Holes / holography
- (supreme) quantum machine learning
- new killer applications for QC
- resources for delegated QC
- q approach to nonlinear channels
- q speedup before QECC?
- NPT bound entanglement?

Foundations

- role of causality
- new reconstructions based on interpretations
- q thermodynamics
- network vs Bell nonlocality
- certification of randomness and quantumness in temporal correlations
- QT–exotic space-times connection
- falsifying sensitive collapse models
- why probabilities?

Many-body

- more applications tensor networks
- many-body localization
- applications of TN to: RNG, QFT, q learning, c learning
- quantum PCP conjecture
- efficient algorithms for gapless systems
- open q systems w non-Markovian effects

Implementations

- useful q metrology
- understanding Fermi-Hubbard model
- q thermo machines to use
- certifying q supremacy without (or with) universality
- q certification
- device-independent QKD
- q nanophotonics for QIP
- is FTQC really possible?
- is adiabatic QC really possible?
- make a surface code

Bets over the years

- NPT bound entanglement? 2011 Ruskai: No
- general composable security proof for DI-QKD 2011 Winter: yes; Acín: 2 yrs
- Peres' Conjecture? 2011 Perez-García: False ✓
Vertesi and Brunner 2014
- optimal states for 1-mode Gaussian channels? 2011
García-Patrón: vacuum (✓)
- loophole-free Bell test
2011 Kleinmann: > 2y ✓ 2013 Cabello: 2y, Weinfurter (✓)
2015: Hensen et al; Giustina et al; Shalm et al
- D-wave QC? 2011 Cirac: No (2y) ✓
- q repeater better than direct transmission 2011 Brask Bohr: 3y
- q sim better than c sim Lewenstein: 2y; Cirac: > 1y
- **the** variational method? 2013 Cirac: PEPS (10y)
- business interest in QC will increase 2015 Latorre: yes (2y) ✓

Voted predictions

- a universal quantum computer within our lifetimes?
in 2013: **YES: 50**; NO: 16 in 2015: **YES: 60**; NO: 11; ABS: 5.
- predictions 2017 (for 2019):
 - quantum computers with X qubits and 10^3 gates:
(A) > 100 qubits (3; 4%) (B) **50 – 100 (37; 58%)** (C) < 50 (24; 38%)
 - device-independent QKD:
(A) $< 1\text{km}$ (3; 6%) (B) **1 – 10km (35; 71%)** (C) $> 10\text{k}$ (11, 23%)
 - reliable phase diagram Hubbard model:
(A) Yes (9; 29%) (B) **NO (22; 71%)**
 - q metrology: commercial device using
(A) **only entanglement (24; 61%)** (B) entanglement and (Q?)EC (2; 5%) (C) none (13, 33%)

2019

recent advances – major open problems – bets/predictions

The 2019 Quantum Information Workshop

Recent advances 2017-2019

Quantum information

- * Prog of DI QKD (Roten et al)
- * Q separation in constant depth circuit (Bravyi et al Science)
- * Classical verification of Q computation (Mahadev)
- * Simulation of Boson Sampling

Social impact

- * Higher

Foundations

↳ * Wigner's friends (Leifer)

- * Sloppy and loose Bell correlations are not class
- * Emergence of algebra (Muller)
- * Redundancy in Q protocols (Muller, Masser)

Many body

- * Progress in Fermi-Hubbard
- * Conclusions from few particles
- * Progress in Gutzwiller

Experimental

- * Many-body localization in 2D (Bloch)
- * Quantum crystal in an optical lattice
- * Bigger Q processors
- * Rydberg atoms
- * Satellite (Muller)

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Open Problems 2019

Quantum information

- * Verification benchmarks
- * Machine learning techniques
- * MPT bound entanglement
- * Can a Q computer break some post-quantum cryptos?
- * Are the resources to break post-quantum cryptos?
- * Q Supremacy proof
- * Problems useful for Q machine learning
- * Multiparticle entanglement
- * Less overhead QEC

Foundations

- * Unified framework for temporal and spatial Q correlations
- * Principles for Q correlations
- * Why Q correlations for Bell scenarios aren't closed?
- * Indefinite causal order

Experimental

- * Room temperature superconductors?
- * Simulations of Q gravity
- * Q gravity effects
- * Proof of Q Supremacy
- * Commercial devices for metrology and sensing
- * DI QKD

* European Quantum

Many body

- * Topological
- * Other applications
- * Function
- * Tensor networks and QFT
- * Proof of many body local P
- * Out of equilibrium dynamics
- * Foundations of QFT
- * Tensor network investigations
- * Experiments-theory connections

Bosonics and related

- * Large investments
- * Chemical
- * Ethics
- * Q bubble?
- * Atomic clocks
- * Open access publishing

The 2019 Quantum Information Workshop



Quantum Information

- Proof of DI QKD ([Arnon-Friedman et al., '16](#))
- Q separation constant-depth circuit ([Bravyi, Gosset, Koenig '18](#))
- Classical verification of QC ([Mahadev, 2018](#))
- Simulation of Boson sampling

Quantum foundations

- Wigner's friend ([Frauchinger & Renner](#))
- Bell correlations ([Slofstra 2017...](#))
- Emergence object. reality ([Müller](#))
- Redundancy in Q postulates ([Masanes, Galley, Müller 2018](#))

Many-body

- Fermi Hubbard (Corboz et al.)
- Constructions from free fermions
- Frustrated q spin models not tractable by Q Monte Carlo

Implementations

- Many-body localization in 2d (Bloch)
- Quasicrystals in optical lattices (Bloch?)
- Tweezer technology (Lukin)
- Scaling up to 50 qubits (ions, atoms, and sc qubits)
- Satellite (Micius)

Quantum information

- verification & benchmarks of QC
- quantum machine learning
- NPT bound entanglement?
- Can QC break post-q crypto?
- Resources to break position-based crypto
- Q supremacy proof
- Problems useful for QML
- Multipartite entanglement
- QEC: Higher-threshold error correcting codes with less overhead

Many-body

- TNs and QFT
- Proof of MBL phase
- Out-of-equilibrium dynamics
- Foundations of QFT
- TN investigations of strong correlations
- Experiment theory corrections
- Classification of topological phases in 3D
- Applications of TNs outside QMB physics
- Finite temperature results

Foundations

- Unified Framework for temporal and spatial Q correlations
- Principles (and bounds) for Q correlations
- Why are Q correlations for bell scenarios not closed?
- Indefinite causal order

Business & Societal

- large investments (financial, chemical,...)
- ethics?
- q bubble? and consequences?
- open access publishing

Implementations/Experiment

- Room-temp SC
- QSim of Q gravity
- detection of Q Gravity effects
- Proof of Q supremacy
- Commercial devices for metrology and sensing
- DI QKD

Will it be shown within 2 years that...?

- QC is better than CC
YES: 9; **No: 30**
- q supremacy proof without depth restrictions
YES: 9; NO: 7
- Slofstra “problem” is not a problem: YES: Adán, Alex, Barbara; NO: David, Pepe
- usable DI-QKD (> 1 Mbit/s)
YES: 8; **NO: 23**
- QECC-corrected (& improved) qubit: **YES: 30**; NO: 8
- q supremacy
YES: 20; **NO: 23**
- reliable algorithm for simulating dynamics (≥ 1 d):
YES: 8; **NO: 21**
- major qtech investment (≥ 100 MEUR) by *European* company? **YES: 28**; NO: 7
- will investment hurt the way we do science? **YES: 26**; NO: 17

A fault-tolerant scalable QC within your lifetime? **YES: 40**; NO: 12

2023

recent advances – major open problems – (bets/predictions)

The 2023 Quantum Information Workshop

Q INFO

-) $HIP^* = RE$, TSIKELSON PROBLEM
-) DEQUANTIZATION
-) NOISE AND CLASSICAL SIMULATION AHARONOV ET AL.
-) QUANTUM LDPC CODES
-) SHADOW TOMOGRAPHY
-) GRAND UNIFICATION
-) GROWTH OF CIRCUIT COMPL.

Q FOUNDATIONS

-) SIMULATION OF ENTANGLEMENT
-) Q REFERENCE FRAMES
-) REAL & COMPLEX (Th) (Exp)
-) QUANTUM CAUSAL MODELS
-) CERTIFICATION OF INDEFINITE CAUSAL ORDER
-) PROOFS OF QUANTUMNESS
-) ENTROPY ACCUMULATION THEOREMS
-) RECOVERABILITY AND RELATIVE ENTROPY
-) XITE STATES

ADVANCES 2019-2023

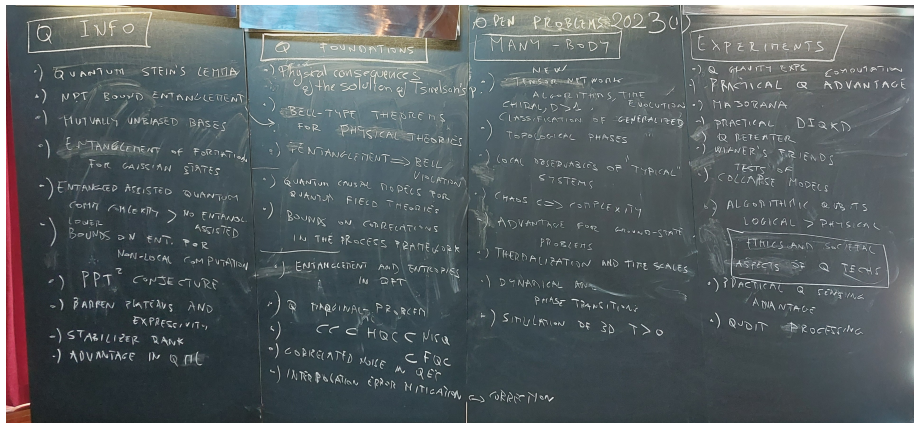
MANY-BODY

-) UNDERSTANDING HUBBARD MODEL
-) NO LOW-ENERGY ANSHU ET AL. TRIVIAL STATES
-) SLOW THERMALIZATION MBL, SCARS
-) TV SIMULATION 3D INTERING
-) DUAL UNITARIES

EXPERIMENTS

-) APPROX. OF-PRINCIPLE EXP DIARD
-) Q "ADVANTAGE" EXPS.
-) LOGICAL > PHYSICAL
-) SPIN LIQUIDS IN RIBBER ATOMS
-) ERROR MITIGATION
-) SINGLE ION CLUSTER STATE GENERATION

The 2023 Quantum Information Workshop



Quantum Information

- MIP* = RE; Tsirelson prob [Ji et al.]
- dequantization, noise and classical simulation (Aharonov et al.)
- classical and quantum LDPC codes [Panteleev and Kalachev]
- shadow tomography [Huang et al.]
- q singular value decomposition / grand unification of q algorithms [Gilyén et al.]
- growth of circuit complexity [Haferkamp et al.]
- proofs of quantumness [e.g., Brakerski et al.]
- entropy accumulation theorems [e.g., Metger et al.]
- recoverability & rel entropy in v Neumann algebras/QET [Faulkner et

Quantum foundations

- simulation of entanglement [Renner et al.]
- q reference frames [Giacomini et al.] (2017)
- “real and complex” [Renou et al.]
- q causal models [Barrett et al.]
- certification of indefinite causal order [van der Lugt et al.]

Many-body

- understanding the Hubbard model [Review by Qin et al.]
- no low-energy trivial states [Anshu et al.]
- slow thermalization, many-body scars (review), many-body localization
- tensor-network simulations of 3d materials
- dual unitaries [Bertini et al.]

Experiments

- proof-of-principle DI-QKD [Nadlinger et al. and Zhang et al.]
- q “advantage” experiments [Arute et al.]
- logical qubit better than physical [Ryan-Anderson et al.]
- max-cut and spin-liquids in Rydberg atoms [Ebadi et al., Semeghini et al.]
- error mitigation [Review by Cai et al.]
- single-atom cluster-state generation [Thomas et al.]

Most popular advances 2019-23 acc. to SciRate I

- 287 **MIP*=RE**, Ji *et al.*, [arXiv:2001.04383](#) (✓)
- 197 **Exponential quantum speedup in simulating coupled classical oscillators**, Babbush *et al.*, [arXiv:2303.13012](#)
- 183 **NLTS Hamiltonians from good quantum codes**, Anshu *et al.*, [arXiv:2206.13228](#) (✓)
- 179 **Information-theoretic bounds on quantum advantage in machine learning**, Huang *et al.*, [arXiv:2101.02464](#)
- 171 **The Complexity of NISQ**, Chen *et al.*, [arXiv:2210.07234](#)
- 162 **Predicting Many Properties of a Quantum System from Very Few Measurements**, Huang *et al.*, [arXiv:2002.08953](#) (✓)
- 162 **A polynomial-time classical algorithm for noisy random circuit sampling**, Aharonov *et al.*, [arXiv:2211.03999](#) (✓)
- 156 **Fault-Tolerant Operation of a Quantum Error-Correction Code**, Egan *et al.*, [arXiv:2009.11482](#)

Most popular advances 2019-23 acc. to SciRate II

- 150 Provably efficient machine learning for quantum many-body problems, Huang *et al.*, [arXiv:2106.12627](#)
- 148 Linear growth of quantum circuit complexity, Haferkamp *et al.*, [arXiv:/2106.05305](#) (✓)
- 146 The Quantum Fourier Transform Has Small Entanglement, Chen *et al.*, [arXiv:2210.08468](#)
- 146 Building a fault-tolerant quantum computer using concatenated cat codes, Chamberland *et al.*, [arXiv:2012.04108](#)
- 143 Quantum advantage in learning from experiments, Huang *et al.*, [arXiv:2112.00778](#)
- 142 Efficient tensor network simulation of IBM's kicked Ising experiment, Tindall *et al.*, [arXiv:2306.14887](#)
- 142 Efficient classical simulation of random shallow 2D quantum circuits, Napp *et al.*, [arXiv:2001.00021](#)

- 137 Exponentially tighter bounds on limitations of quantum error mitigation, Quek *et al.*, [arXiv:2210.11505](https://arxiv.org/abs/2210.11505)
 - 137 The Power of Adiabatic Quantum Computation with No Sign Problem, Hastings, [arXiv:2005.03791](https://arxiv.org/abs/2005.03791)
 - 137 Dissipative ground state preparation and the Dissipative Quantum Eigensolver, Cubitt, [arXiv:2303.11962](https://arxiv.org/abs/2303.11962)
- (list leaves out review articles...)

Quantum information

- q Stein's lemma
- NPT bound entanglement
- mutually unbiased bases
- EoF for Gaussian states
- ent-assisted q comm complexity
- lower bounds on ent for non-local computation
- PPT² conjecture
- barren plateaus and expressivity
- stabilizer rank
- advantage in QML
- CC[?]hQC[?]CNISQC[?]FQC
- corr noise in QEC
- interpolation error mitigation — error correction

Many-body

- new tensor-network algorithms, time-ev, chiral PEPS ($d>1$)
- classific of gen. topolog. phases
- local observables of “typical” systems
- chaos \Leftrightarrow complexity
- advantage for ground-state problems?
- thermalization and time scales; ETH
- dynamical and complexity phase transitions
- simulations of 3d, $T > 0$ systems

Foundations

- physical consequences of solution of Tsirelson's problem
- Bell-type theorems for physical(?) theories
- entanglement \Rightarrow Bell violation?
- q causal models for QFT
- bounds on correlations in process framework
- entanglement and entropies in QFT
- q marginal problem

Business & Societal

- ethics of q tech

Experiment

- practical q advantage
- practical DI-QKD
- q repeater
- Wigner's friends
- tests of collapse models
- practical q sensing advantage
- qudit processing
- Majoranas
- q gravity experiments

Open Problems Session (3rd week) I

Proof Q, advantage (76)

New Q. Adv. (77)

Q. adv. in ML (11)

Relevant problems limited Q.c (65)

Q. Advantage

Error corrected Q.c (86)

Develop annealing (3)

Physically reasonable def. F.T. (1)

Q. SIM & M, B

Reasonable relevant H (47)

Q. Sim. chemistry/material (54)

Complexity classification (52)

Optimal fermi \rightarrow qubit (5)

Explaining HTC-supercond (39)

Design materials (46)

Transition $Q \rightarrow C$ (2)

Q. Heuristic alg. & tools (39)

Hybrid Q-c (19)

Q, I, T.

Q. Stein's lemma (15)

Q. Separability (19)

Mutually unbiased L (22)

Security multi-server homomorph. encryption (3)

Q. COMM

Noisy Q. Comm. (51)

Multi-plex protocols (3)

Q. Networks protocols (16)

Daylight/free space Q. channel (9)

Converting qubits $Comp \rightarrow Comm$ (22)

Integrity device-mid. Q-c (9)

Practical Q. advantage (15)

Q. M.S.

Connecting sensors & Q. (27)

Optimal Q. states (19)

Clocks (better), gravimetric (32)

OTHER

Q. bio & neural sci (17)

Exp: Q. Autonomous Mach (3)

Connecting to society (45)

Ethics/regulations (31)

Deal Q. Bubble (73)

Biomedical apps

Resistance plan

Energy costs (22)

Q. Inspirability (26)

Q. Found

Mac. superp. (Exp) (30)

Basic principles & M. (46)

Quantum nature gravity (Exp) (23)

Q. Causal inference (5)

Are fundamental limits (17)

Macro superp

Ent - non-locality (42)

Implications Birelson (5)

Foundations Q. adv. (30)

Quantum Computing

- proof of q advantage
- new q algorithms
- relevant problems for limited QC
- error corrected QC
- develop annealing
- q advantage in machine learning
- physically reasonable def of fault-tolerance
- q heuristic algorithms and tools
- hybrid classical-q computing

QIT

- q Stein's lemma
- q separability
- mutually unbiased bases
- security of multi-server homomorphic encryption

Quantum Measurement/Sensing

- connecting sensors & QC
- optimal q states
- better clocks, gravimeters

Quantum Simulation & many-body

- reasonable relevant Hamiltonians
- q sim of chemistry/materials
- complexity classification
- optimal mapping fermions \rightarrow qubits
- explaining high- T_c supercond
- design materials
- transition q \rightarrow c

Quantum Communication

- noisy q comm
- multiplex protocols
- q network protocols
- daylight/free-space q channel
- converting comp to comm qubits
- inter-city device-independent QKD
- practical q advantage

Quantum Foundations

- macro superpositions (exp)
- basic principles for QM
- q nature of gravity (exp)
- q causal inference
- fundamental limits to macro superpos?
- entanglement \leftrightarrow non-locality
- implication of sol to Tsirelson's problem
- foundation of q advantage

Other

- q autonomous machines (exp)
- connecting to society
- ethics/regulations
- deal w/ q bubble
- energy costs
- q inspiration
- q bio & neuro science

Quantum Computing

- error corrected QC (86)
- new q algorithms (77)
- proof of q advantage (76)
- relevant problems for limited QC (65)
- q heuristic algorithms and tools (39)
- hybrid c-q computing (19)
- q advantage in machine learning (11)
- physically reasonable def of fault-tolerance (9)
- develop annealing (3)

QIT

- mutually unbiased bases (22)
- q separability (19)
- q Stein's lemma (15)
- security of multi-server homomorphic encryption (3)

Quantum Measurement/Sensing

- better clocks, gravimeters (32)
- connecting sensors & QC (27)
- optimal q states (19)

Quantum Simulation & many-body

- q sim of chemistry/materials (54)
- complexity classification (52)
- reasonable relevant Hamiltonians (47)
- design materials (46)
- explaining high- T_c supercond (39)
- transition q \rightarrow c (22)
- optimal mapping fermions \rightarrow qubits (5)

Quantum Communication

- noisy q comm (51)
- converting comp to comm qubits (26)
- q network protocols (16)
- practical q advantage (16)
- inter-city device-independent QKD (9)
- multiplex protocols (8)
- daylight/free-space q channel (8)

Quantum Foundations

- q nature of gravity (exp) **(73)**
- basic principles for QM **(46)**
- entanglement \leftrightarrow non-locality **(42)**
- macro superpositions (exp) (30)
- foundation of q advantage (30)
- fundamental limits to macro superpos? (18)
- implication of sol to Tsirelson's problem (15)
- q causal inference (5)

Other

- deal w/ q bubble **(73)**
- connecting to society **(45)**
- ethics/regulations (31)
- q inspiration (26)
- energy costs (22)
- q bio & neuro science (17)
- q autonomous machines (exp) (3)

IQOQI-List of Open Problems in Quantum Information

OPEN QUANTUM PROBLEMS

IQOQI Vienna

<https://oqp.iqoqi.oeaw.ac.at/open-quantum-problems>

Open Quantum Problems

1	All the Bell Inequalities	R.F. Werner	1999/10/25	2010	Quantum foundations
2	Undistillability implies ppt?	D. Bruß	2000/03/02	2006/08/16	Entanglement theory
5	Maximally entangled mixed states	K. Audenaert	2001/11/08	-	Entanglement theory
8	Qubit formula for Relative Entropy of Entanglement	J. Eisert	2003/06/20	-	Entanglement theory
12	Bell Inequalities for long range vacuum correlations	R. Verch	2002/01/22	-	Quantum foundations
13	Mutually unbiased bases	B.-G. Englert	2003/01/31	2004/01/07	Quantum communication
14	Tough error models	E. Knill	2003/01/31	-	Quantum computation
15	Separability from spectrum	E. Knill	2003/01/31	2013/09/08	Entanglement theory
16	Complexity of product preparations	E. Knill	2003/01/31	-	Quantum computation
20	Reversible entanglement manipulation	M. Plenio	2005/02/08	2023/01/23	Entanglement theory
23	SIC POVMs and Zauner's Conjecture	D. Gross	2005/02/17	-	Quantum communication
24	Secret key from all entangled states	P. Horodecki	2005/03/15	-	Quantum communication
25	Lockable entanglement measures	P. Horodecki	2005/03/15	-	Entanglement theory
26	Bell inequalities holding for all quantum states	R. Gill	2010/04/19	-	Quantum foundations
27	The power of CGLMP inequalities	R. Gill	2006/02/28	-	Quantum foundations
29	Entanglement of formation for Gaussian states	O. Krüger	2005/04/20	-	Entanglement theory
31	Individual measurement strategies on geometrically uniform states	J. Bae	2005/10/06	-	Quantum communication
32	Bell inequalities: many questions, a few answers	N. Gisin	2007/02/02	2016/12/01	Quantum foundations
34	The geometry of quantum nonlocality	W. Slofstra and M. Navascués	2017/04/26	-	Quantum foundations
35	Existence of absolutely maximally entangled pure states	F. Huber	2017/05/19	-	Quantum computation
36	Composition of decoherence functionals	M. Navascués	2017/05/19	-	Quantum foundations
37	Stronger submultiplicativity for the diamond norm	D. Reeb	2017/05/19	-	Quantum communication
38	The PPT-squared conjecture	M. Christandl	2017/05/19	-	Quantum communication
39	Steering bound for qubits and POVMs	R. F. Werner	2017/05/19	-	Entanglement Theory
40	Refinement of the Bessis-Moussa-Villani conjecture	D. Hägele	2017/05/19	-	Many-Body Quantum Information Theory
41	All rank inequalities for reduced states of quadripartite quantum states	M. Huber, N. Linden and A. Winter	2017/05/20	-	Entanglement theory
42	Reversible dynamics on composite systems	B. Dakic and M. Müller	2017/05/20	-	Quantum foundations
43	Are all extensively causal processes purifiable?	M. Araújo and C. Brukner	2017/05/22	-	Quantum foundations
44	Complexity of the separability problem	Henry Yuen	16/01/2023	-	Quantum complexity theory
45	Single-prover interactive proofs for quantum computations	Henry Yuen	16/01/2023	-	Quantum complexity theory
46	Thermodynamic implementation of Gibbs-Preserving Maps	Philippe Faist	16/01/2023	-	Quantum thermodynamics
47	Is there bound information?	Matthias Christandl	20/04/2023	-	Quantum cryptography