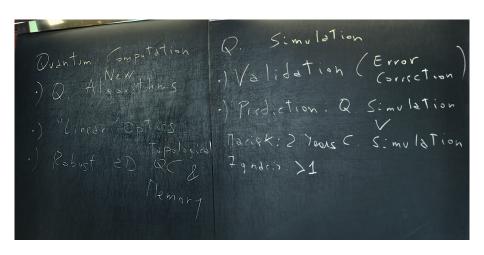
# Future of QI

# The Benasque Quantum Information Workshops 2011 – 2019

compiled by Adán Cabello and Géza Giedke

July 2019

July 2019



+5 more...

FOUNDATIONS OF QUANTUM PHYSICS QUANTUM INFORMATION THEORY \* PBR THEOREM UPT BOUND ENTANGERENT \* Activation Q. non-locality -Buantum volteIngleton ≥0 - B.E.S violate B. ineg - Characknization M-garl, entanglement - Beyond B. Irug. + appe PRINCIPLIS FOR Q CORRELATIONS - O. Discord ?? \* Unv. O.c. with Q walks ermi: Landouer pple + 2 mlaw \* Unitying Q Grield Discord R QTI IN LOW. ENERGY \* O.C. with little entang. - Firewall in BH. - Charact LOCC + POVM (Measurement) ARE LEGGETI - GARG - Rôle ent. in O.C. INEQUALITIES USEFUE? \* Security Devicindep akt - Decidability in QIT - Geneal framework security devinty - Mary LUCALITY IN MANY BODY PRYSIES - Certification space-like separation devined - MULT PRINCIPLES ENDUCH? - Example non-god C.C. Channot \_ LIFE AFTER LOOPHOLE-FREE BI! - PPTZ => E. Breaking MSYBERG Z'HOZJSAIZT -

MANY-BOPY PHYSICS - What is D-wave doing \* Title- DEPENDENT, MERTIPHAL - I TIPLETIENT ATIONS OF DI PRINCIPLE \* DETECTION LOOPHOLE FREE STUFF

PHOTONIC EXPERIMENT X (FITICACITY IN OPEN & STETES - EFFICIENT SIAVIATION OF Q DYNAMICS - Def. entang, bosous/fermons - CLASS PHASES HIGHER-D - Approxs (truncation) TN - LIMITATIONS OF Q SIMULATION -Thermalitation physical Syst - Boson sampling (Limitations) - Non-eg, inequalities (Quantum) \* SUPERCONDICTING QUEITS \* STANGATION OF HIGH-ENEERS - Simulation TV HET PHYSICS IN OPTICAL LATTICES - TN ( AAS/CFT CHEAP QKD - SATELLITE-BASED & COTIT - Pelatims fluct-entanglement - CEPTIFICATION OF Q SITTUENT - LUW-ENIRON EFFECTIVE THEOPIES - LONG: DISTANCE ENT BASED &C - EXP MPL OF IBE-LINE THEODERS - 11 3 Seel protecting QIM in D<4 N-17 1/2 FIFE BEAGAPATION

# 2013: Achievements in the last few years

#### **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 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<sup>2</sup> ⇒ ent breaking

- Foundations QPbound 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

# 2013: Open Problems II

# Many-Body Physics efficient sim of Q Dynamics

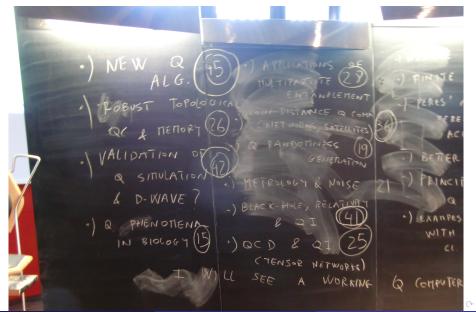
- classific phases higher D
- approx TN
- thermalization
- non-equilib inequalities (quantum)
- simulation TN HEP
- TN <sup>?</sup>

   AdS/CFT
- relation fluctuat ↔ entang.
- low-energy effective theories
- self-protect. Q Mem. D < 4?</li>
- robustness topolog memories

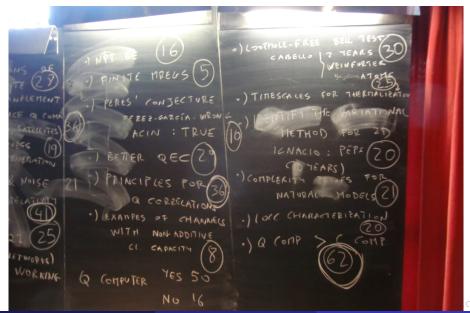
# **Q Optics & Implementations** what is D-Wave doing?

- 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



# 2013 - Concluding Session



# The Top 10 of Open QIS Challenges 2013

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

# 2015 Open Problems

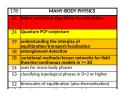
#### OPEN PROBLEMS SESSION

# 208 INFORMATION/COMPUTATION 30 black holes is holography 30 demonstrate supremacy/speedup of QC 30 better quantum error correcting codes 31 multipartite entanglement 41 QFT and tensor networks 410 macroscopic quibits/91 410 quantum artifical intelligence (machine learning, etc.) 411 the existence of NPT bound entanglement

#### Benasque 2015

176	FOUNDATIONS
28	principles for quantum correlations
26	encorporating 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

#### Adán Cabello & Géza Giedke



#### July 8th, 2015

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

# 2015 Open Problems

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

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4.0	

# 2015 Open Problems

470	1 441 D/ B B B / B I D/0100
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 equlibration (also thermalization)
40	

170	IMPLEMENTATIONS
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Many body

AEllicent algorithms Gapless

# Implementations

ucedul a metadogy Underslanding Fermi-Hubbard models Qthermo machines-lo use a supremacy without universality Q ranophotonics or QI ISTTQC really Possible? Its adiobatical "" 11

# 2017 Open Problems I

## 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 sensitve collapse models
- why probabilities?

# 2017 Open Problems I

# 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<sup>3</sup> gates:

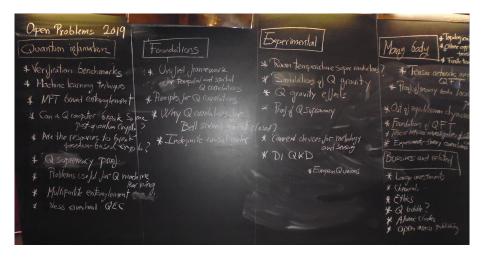
```
(A) > 100 qubits (3; 4%) (B) 50 - 100 (37; 58%) (C) < 50 (24; 46%)
```

- device-independent QKD:
- (A) < 1 km (3; 6%) (B) 1 10 km (35; 71%) (C) > 10 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







# 2019: Recent Advances

### **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)

# 2019: Open problems I

## **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

# 2019: Open problems II

#### **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

# 2019 Voted Predictions

# 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 (> 1Mbit/s)YES: 8; NO: 23
- QECC-corrected (& improved) qubit: YES: 30; NO: 8

- q supremacy YES: 20; NO: 23
- reliable algorithm for simulating dynamics (≥ 1d):

YES: 8; NO: 21

- major qtech investment (≥ 100MEUR) 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