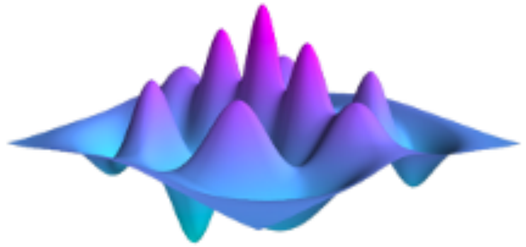
Quantum physics and science with open-source software: QuTiP, the Quantum Toolbox in Python



QuTiP

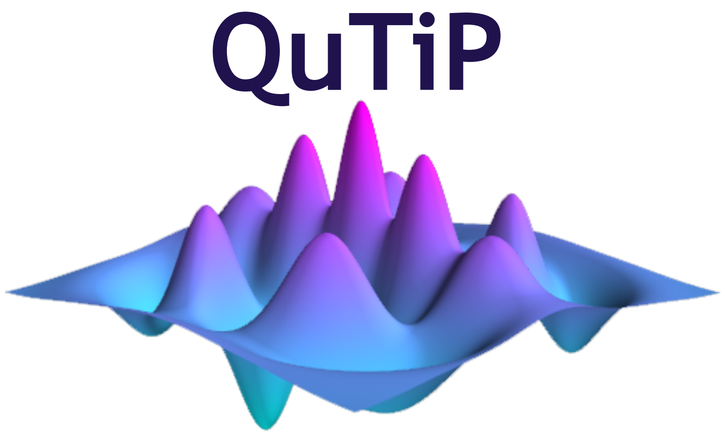
Quantum Toolbox in Python

Nathan Shammah
Theoretical Quantum Physics Lab
Cluster for Pioneering Research
RIKEN, Saitama, Japan

26th June 2019
CM Seminar
ICTP, Trieste

QuTiP: The Quantum *Physics* Simulator

The **Qu**antum **T**oolbox **i**n **P**ython: A toolbox to study the **open** quantum dynamics of realistic systems.



Interactive Lectures @ ICTP, Leonardo Building

Tue 25th June - 11:45am, Seminar Room – Driven-dissipative models in quantum physics
Wed 26th June - 11am, Seminar Room – Quantum Open Source & Introduction to QuTiP
Thur 27th June - 9am, Computer Room – Hands-on session on QuTiP's main features
Mon 1st July - 9am, Computer Room – QuTiP stochastic solvers
Tue 2nd July - 9am, Computer Room – How to Build your Own Scientific Software Library in Python
(Wed 3rd July - 9am, Computer Room – Extra meeting: SISSA/ICTP projects)

Take a snapshot

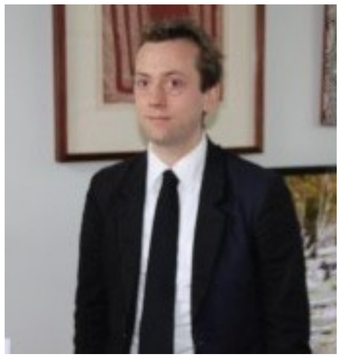
https://github.com/nathanshammah/interactive-notebooks

Acknowledgements and funding

Shahnawaz Ahmed
Chalmers, Sweden
(RIKEN, Japan)

Alex Pitchford
Aberystwyth University
United Kingdom

Eric Giguère
U. de Sherbrooke
Canada



Dr. Neill Lambert
RIKEN, Japan

Prof. Franco Nori
RIKEN, Japan
U. of Michigan (USA)

RIKEN

日本学術振興会
Japan Society for the Promotion of Science

JST Japan Science and Technology Agency

THE ROYAL SOCIETY

JOHN TEMPLETON FOUNDATION

NUMFOCUS
OPEN CODE = BETTER SCIENCE

Google Summer of Code

UNIVERSITÉ DE SHERBROOKE

PRIFYSGOL ABERYSTWYTH UNIVERSITY

@NathanShammah

medium.com/quantum-tech

GitHub: nathanshammah
LinkedIn: Nathan Shammah

quantika.co

Open Source

A new era for open source

Open-Source Basics

Read. Download. Deploy.

Definition: You can **read** the source code (open-source ≠ free).

Examples of open-source: Linux, Android, FireFox, MySQL, LibreOffice, **Python**.

Open-source deployment is **accelerating** many end-industries applications.

Features for Developers

Learn. Debug. Deploy.

You can **learn** by reading the code and become a better developer.

You can edit the source code (licenses apply) and **collaborate** to existing projects.

You can submit **fixes** to bugs, propose improvements.

Open-source for Businesses

Flexible. Valuable. Growing fast.

Source is generally free but companies can charge for additional services.

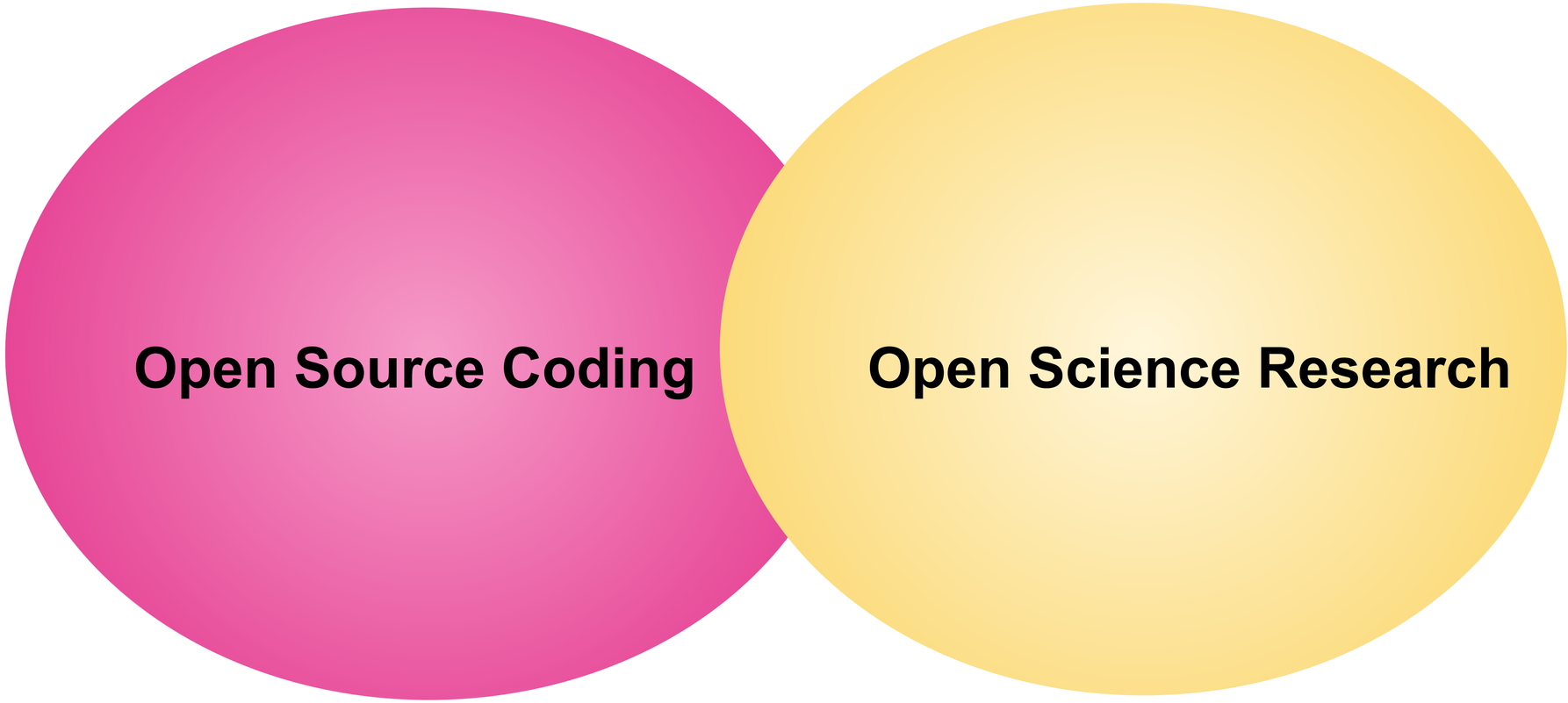
GitHub acquired for $7.5 bln (2018).GitLab: $100 mln in funding (2018).

Red Hat acquired by IBM for $34 bln (2019).

Machine learning (‘AI’) is driving **fast**, pervasive adoption of open-source libraries.

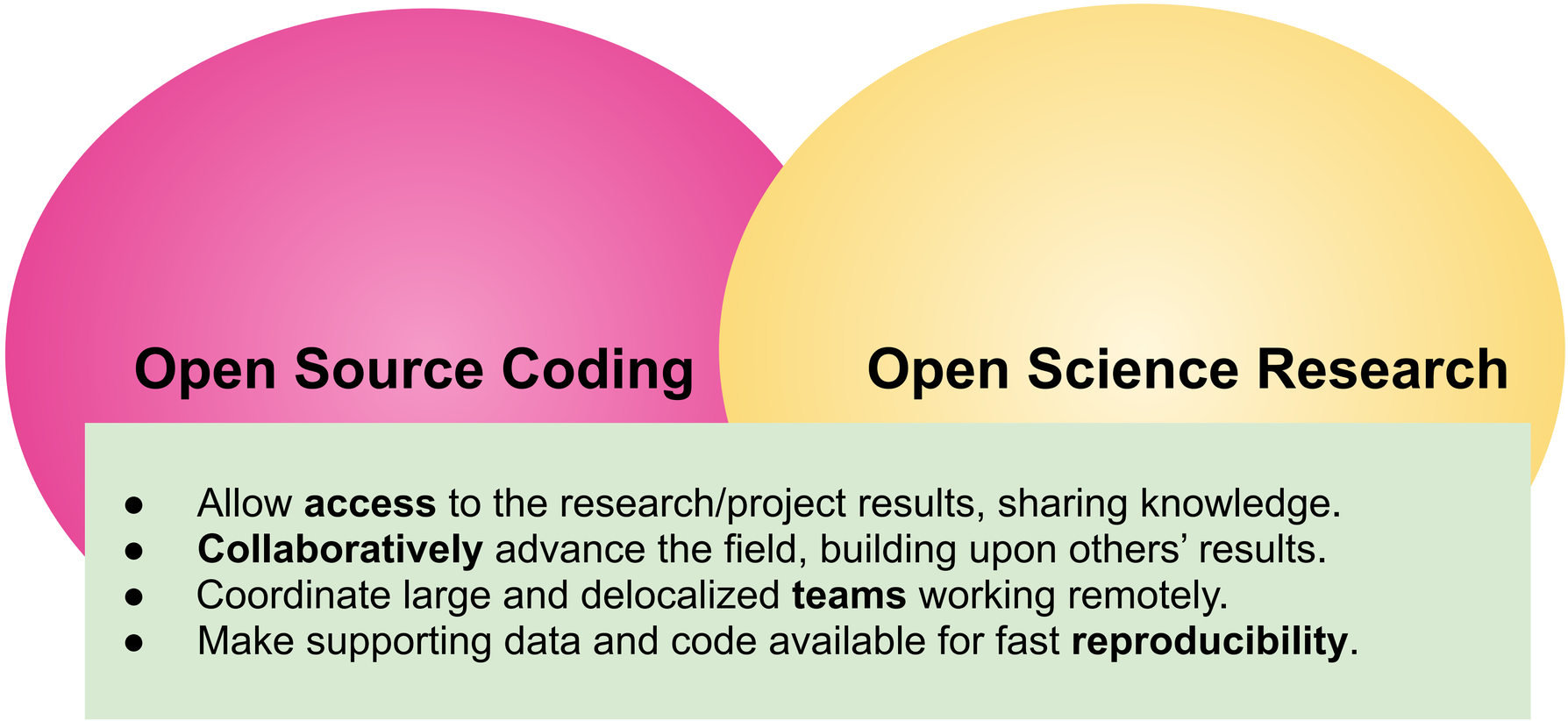
Open source and open science

Aligned vision



Open source and open science

Aligned vision



- Allow **access** to the research/project results, sharing knowledge.
- **Collaboratively** advance the field, building upon others' results.
- Coordinate large and delocalized **teams** working remotely.
- Make supporting data and code available for fast **reproducibility**.

Open Source for Open Science

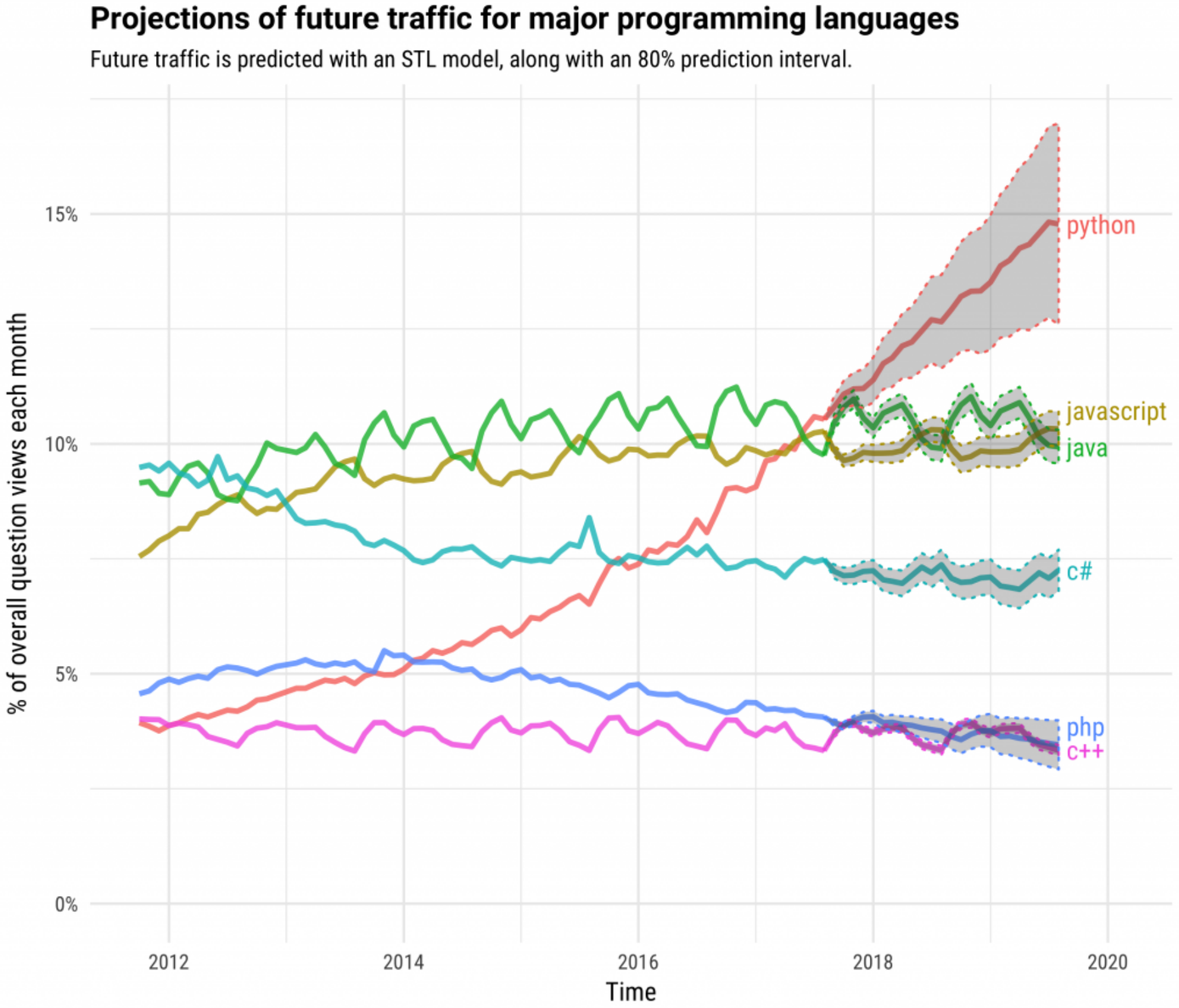
A new movement in research strengthening science

G. Varoquaux: Group leader at INRIA in Paris.
One of the scikit-learn core developers.

From reproducible data to reusable code.

The steady growth of Python

Empowered by a large open-source ecosystem



stackoverflow

Source: David Robinson

Python’s strengths

A community-based programming language

Community

Resources

Tools

Python’s strengths

A new community-based programming language

Community

PyCons
Workshops
Sprints
EuroSciPy

Python’s strengths

A modular architecture for well-maintained libraries

Resources

Libraries
Matplotlib
Scikit-learn
NumPy

Python’s strengths

Interactive Jupyter notebooks run an IDE in your browser

Tools

Notebooks
LaTeX comments
Interactive code
Jupyter

Below we give basic examples on the use of `qutip.piqs`. In the first example the incoherent emission of N driven TLSs is considered. In tl
two-level system ensemble is a subsystem coupled to another subsystem, a bosonic cavity. Similar considerations apply to the coupling to
subsystems (a single qubit, another two-level system ensmble).

In [1]:
```
import matplotlib.pyplot as plt
import matplotlib as mpl
from matplotlib import cm

from qutip import *
from qutip.piqs import *

import matplotlib.animation as animation
from IPython.display import HTML
from IPython.core.display import Image, display
```

1. N Qubits Dynamics

We study a driven ensemble of N TLSs emitting incoherently,

$$H_{\rm TLS} = \hbar\omega_0 J_z + \hbar\omega_x J_x$$

$$\dot{\rho} = \mathcal{D}_{\rm TLS}(\rho) = -\frac{i}{\hbar}[H_{\rm TLS}, \rho] + \sum_{n=1}^{N} \frac{\gamma_{\rm E}}{2}\mathcal{L}_{J_{-,n}}[\rho]$$

Open Science through Open Source

The tools of open source make your code count

Code & Testing

Documentation

Publication

Tue 2nd July - 9am, Computer Room – “How to Build your Own Scientific Software Library in Python”

Beyond Reproducibility

		DATA	
		Same	**Different**
ANALYSIS	**Same**	Reproducible	Replicable
	Different	Robust	Generalizable

https://dx.doi.org/10.6084/m9.figshare.7140050

Quantum Tech: Quantum computing

Open-source and quantum technologies

NATURE | COMMENT

Commercialize quantum technologies in five years

Masoud Mohseni, Peter Read, Hartmut Neven, Sergio Boixo, Vasil Denchev, Ryan Babbush, Austin Fowler, Vadim Smelyanskiy & John Martinis

03 March 2017

Google

TC

IBM adds new API to quantum computing cloud service

Posted yesterday by Ron Miller (@ron_miller)

nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | Fo

Archive > Volume 549 > Issue 7671 > Comment > Article

NATURE | COMMENT

First quantum computers need smart software

Will Zeng, Blake Johnson, Robert Smith, Nick Rubin, Matt Reagor, Colm Ryan & Chad Rigetti

13 September 2017

Early devices must solve real-world problems, urge Will Zeng and colleagues.

PDF | Rights & Permissions

Subject terms: Quantum physics · Quantum information · Mathematics and computing ·

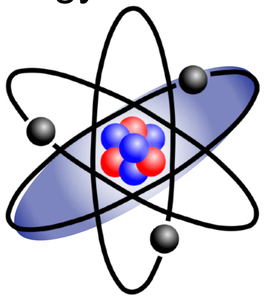
A Recent Review:

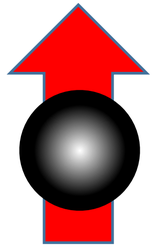
Mark Fingerhuth, Tomáš Babej, and Peter Wittek, *Open source software in quantum computing*, PLoS ONE **13** (12): e0208561 (2019).

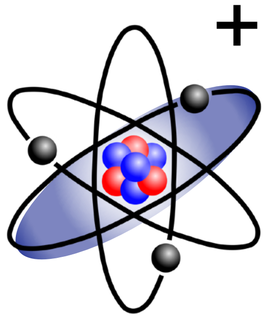
Quantum Tech

Different platforms for qubit technology

1 :

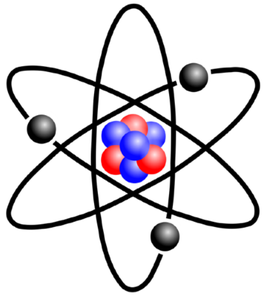


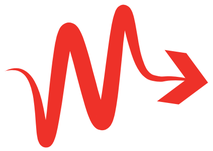


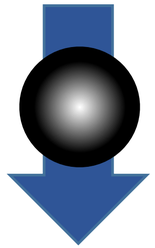


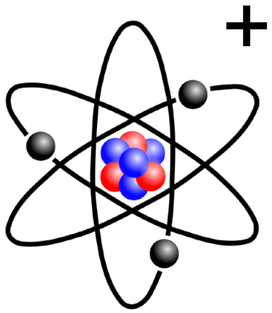
Atoms **Photons** **Spins** **Ions**

0 :

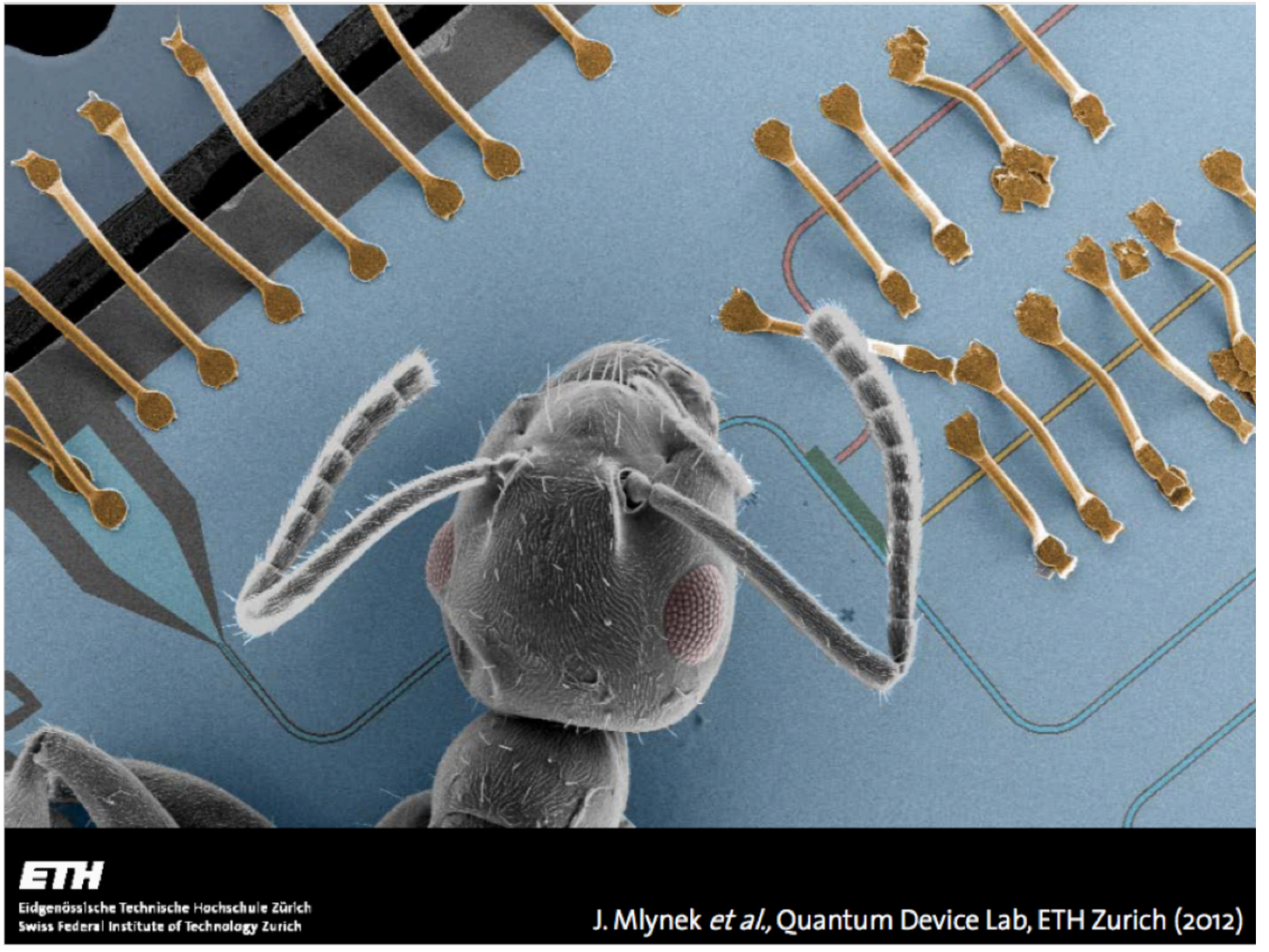






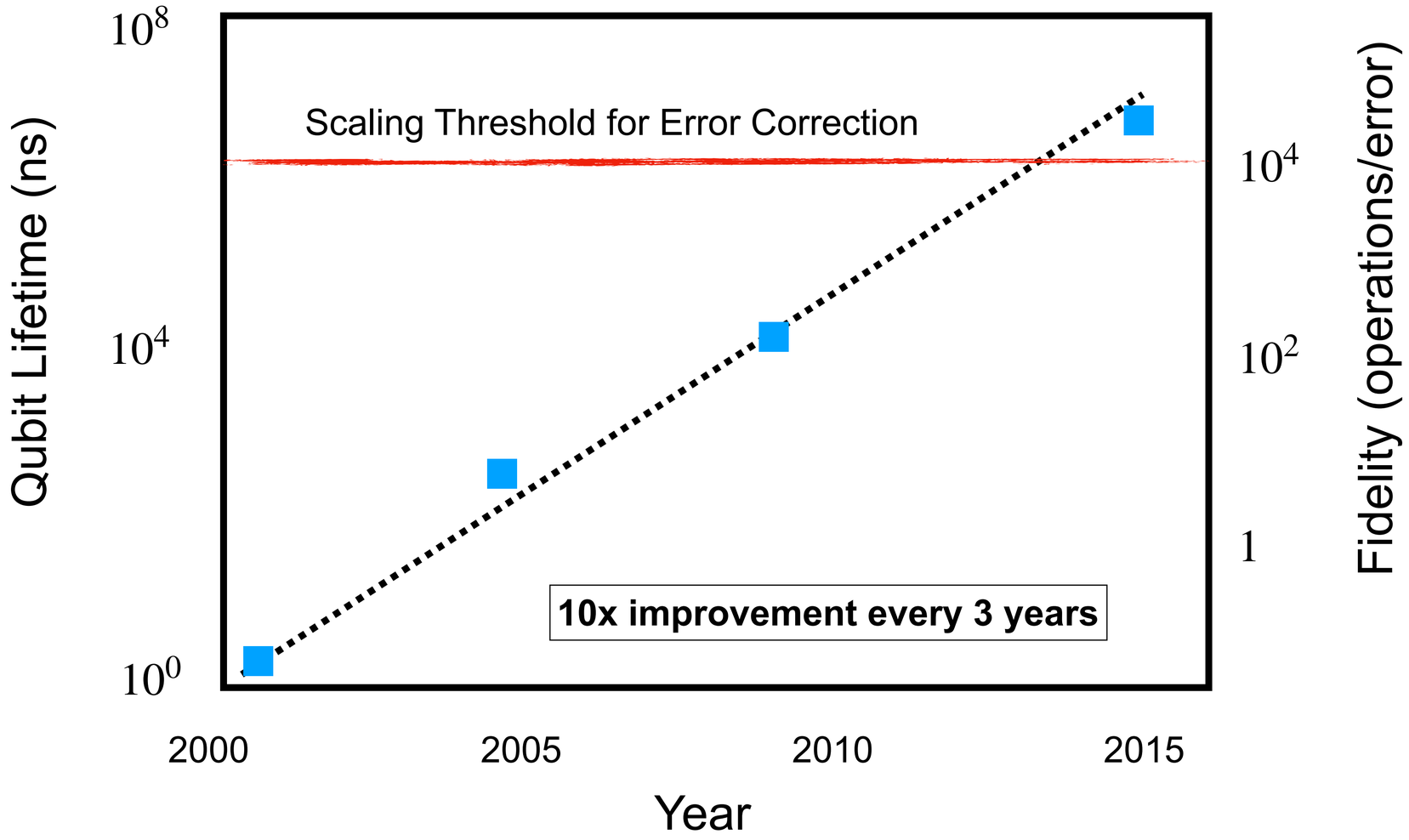


Superconducting circuits



Quantum Tech: Better qubits

Superconducting circuits exponential improvement in preserving quantum coherence



Data: I. Buluta, S. Ashhab, and F. Nori, Natural and artificial atoms for quantum computation, Rep. Prog. Phys. 74, 104401 (2011);
M. H. Devoret and R. J. Schoelkopf, Superconducting Circuits for Quantum Information: An Outlook, Science 339, 1169 (2013)
R. Schoelkopf, 2017, QFML workshop, Cargèse, France.

Quantum Tech: Quantum computing

Different platforms and hardware

		Advantages	Challenges
Gate-based	 Superconducting circuits	15 years of exponential improvement in extending dephasing time (x10 / 3yrs).	Artificial atoms: defects, off-resonances. Wiring leads to qubit cross-talk. Requires cooling @ micro K Temp.
	 Trapped ions	‘Perfect’ qubits due to identical ions. Long coherence time even @ room Temp. Long-range interaction: Full connectivity.	Photonic link/ion shuttling needed to create entanglement between distant modules.
	 Photonics	‘Flying’ qubits for quantum internet. Silicon integrated chips (CMOS industry). Very long coherence time.	Small interaction hampers two-qubit gates. Hard to have identical photons on demand. Requires interface for storing memory.
	 Spins	CMOS and SiMOS integration. Long coherence time. Up to room temperature qubits.	Charge and nuclear spin noise. Weak interaction with controlling fields.
	 Neutral Atoms	Atoms are identical components. Long-range interactions. Recently: two-Rydberg-atom entanglement.	Hard to trap atom and control qubit. Linear optics, low Temp required @ micro K.
Annealing	Superconducting circuits	Encode optimization problems. No error correction required.	Not a universal quantum computer. Unclear implementation of adiabatic QC. Uncertain entanglement role and scalability.

Quantum Tech: Quantum computing

Different platforms and hardware

		Startups	Corporate	Academia (selection)
Gate-based	Superconducting circuits	rigetti, qci, QILIMANJARO	IBM Q, Microsoft, Google, intel, Alibaba.com	UCSB, U Berkley Yale, ETH Zurich RIKEN, NTT Labs
	Trapped ions	IONQ Alpine QT		U Maryland, NIST IQOQI, Oxford
	Photonics	PsiQ (stealth), XANADU		U Bristol, Paris Telecom Equs (Australia)
	Spins	SILICON QUANTUM COMPUTING	intel	QuTech, U Chicago UNSW, RIKEN
	Neutral Atoms	ATOM COMPUTING		Harvard MIT, LMU Munich NIST, U Chicago
Annealing	Superconducting circuits	D-Wave The Quantum Computing Company™		

Quantum Tech: Quantum *and optical* computing

Different platforms and hardware

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	 Photonics	PsiQ (stealth), XANADU		U Bristol, Paris Telecom Equs (Australia)
	 Spins	SILICON QUANTUM COMPUTING	intel	QuTech, U Chicago UNSW, RIKEN
	 Neutral Atoms	ATOM COMPUTING		Harvard MIT, LMU Munich NIST, U Chicago
Annealing	Superconducting circuits	D-Wave The Quantum Computing Company™		
Neuromorphic	Photonics (classical, from quantum photonics community)	LIGHTELLIGENCE, LIGHTMATTER, LightOn, LASOLV		MIT, Stanford RIKEN, JST

Quantum Tech: Quantum Circuit Simulators

Open-Source Quantum Computing

	Language	Library	Quantum Compiler	Features
D-Wave	Python	qbsolv	Not a circuit-based computer	Optimization problems
IBM Q	**Python**	QISKit	20 qubits***	Thousands of experiments from the cloud by online users on the *IBM quantum experience*
Rigetti	**Python**; pyquil	Forest toolkit Grove	19 qubits*** 128 qubits*	Open to research collaborations. Proof-of-concept clustering
Google	**Python**	Cirq (simulation)	49 qubits*** 72-qubit SC chip: Bristlecone*	*Cirq*: an open-source platform for noisy quantum computing
Microsoft	**Python**; Q#	Liquid Quantum Dev Kit	NA	Topological quantum computing with Majorana particles
Alibaba	NA	NA	11-qubit SC chip* unknown architecture	Cloud computing announced

*announced only. *** limited connectivity

Quantum Tech: Quantum Circuit Simulators

Open-Source Quantum Computing

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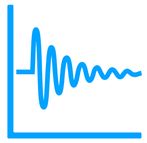
For the first time theorists can run online quantum experiments

*announced only. *** limited connectivity

Open-source cloud quantum labs

Copying Open-Source Quantum Computing

Could academic institutions, physicists replicate this model?

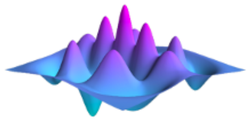
Language	Library		Quantum Experiment	Features
		Actuators Effort $$$ Standards	 	Science acceleration via automation (maybe). Educational value.

Open Labs

*announced only. *** limited connectivity

Quantum Tech: Open Source Libraries

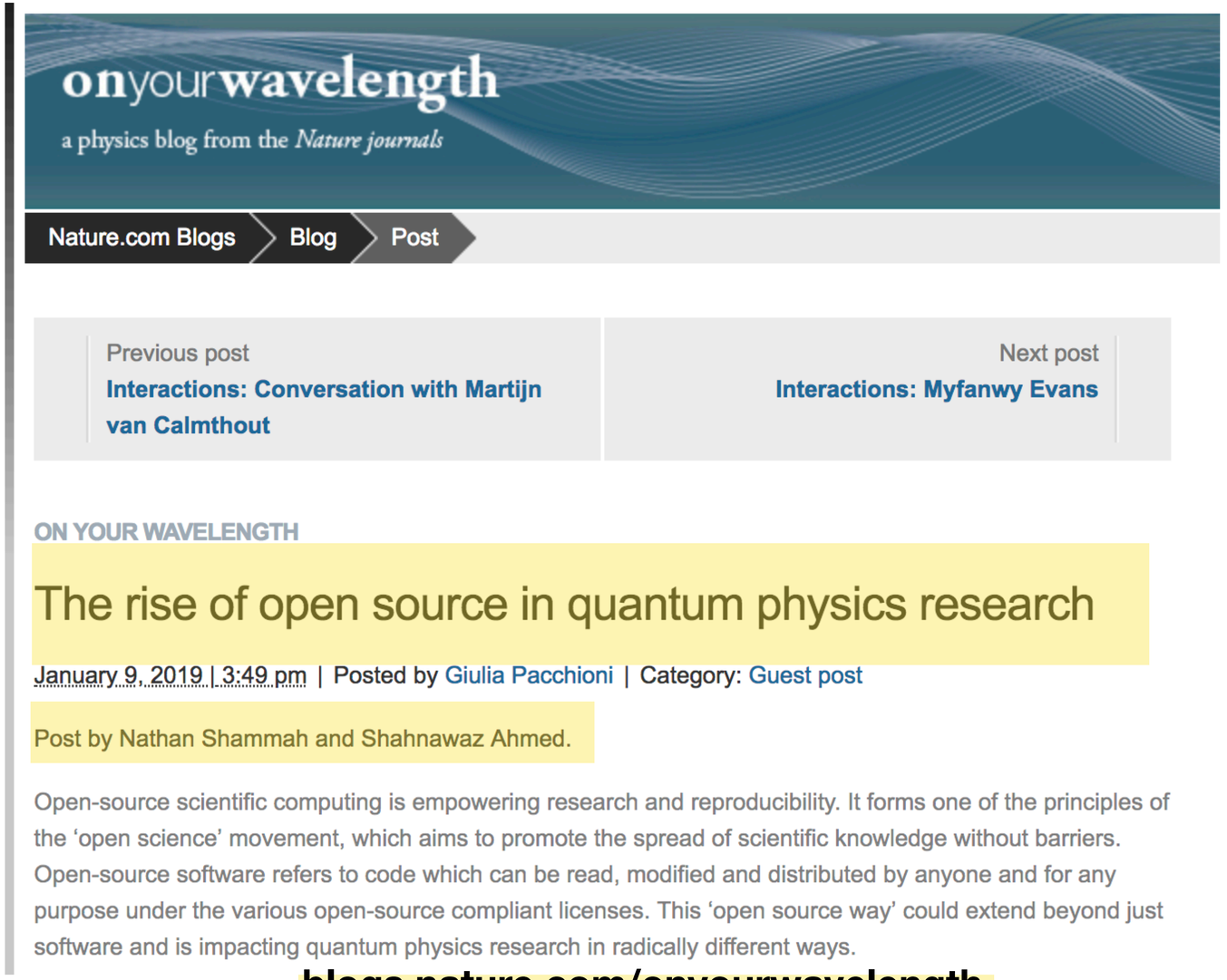
More open-source is empowering broad research in the field

Library	Year	Creators	Institution	Language	Description
 QuTiP Quantum Toolbox in Python	2012	Rob Johannson Paul Nation Franco Nori	RIKEN	**Python**	Simulation of open quantum systems; quantum optics, cavity QED.
 **QNet**	2012	Nikolas Tezak, Michael Goerz Hideo Mabuchi	Stanford	**Python**	Computer algebra package for quantum mechanics and photonic quantum networks
 QuantumOptics.jl	2017	Sebastian Krämer *et al.*	U Innsbruck IQOQI	Julia	Quantum optics and open quantum systems framework inspired by the QO toolbox in Matlab and QuTiP
ProjectQ	2016	Damian S. Steiger Thomas Häner Matthias Troyer	ETH Zurich	**Python**	Hardware-agnostic framework with compiler and simulator with emulation capabilities.
 OpenFermion	2017	Ryan Babbush *et al.*	Google (unofficial)	**Python**	Fermionic potential calculations for quantum chemistry
 **NetKet**	2018	Giuseppe Carleo	The Simons Foundation	C++ **Python**	Studying many-body quantum systems with artificial neural networks and ML techniques.
STRAWBERRY FIELDS	2018	Nathan Killoran *et al.*	Xanadu Inc	**Python**	Photonic quantum computing with continuous-variable optical circuits

Checkout more open-source projects at https://qosf.github.io

The rise of open source in quantum physics research

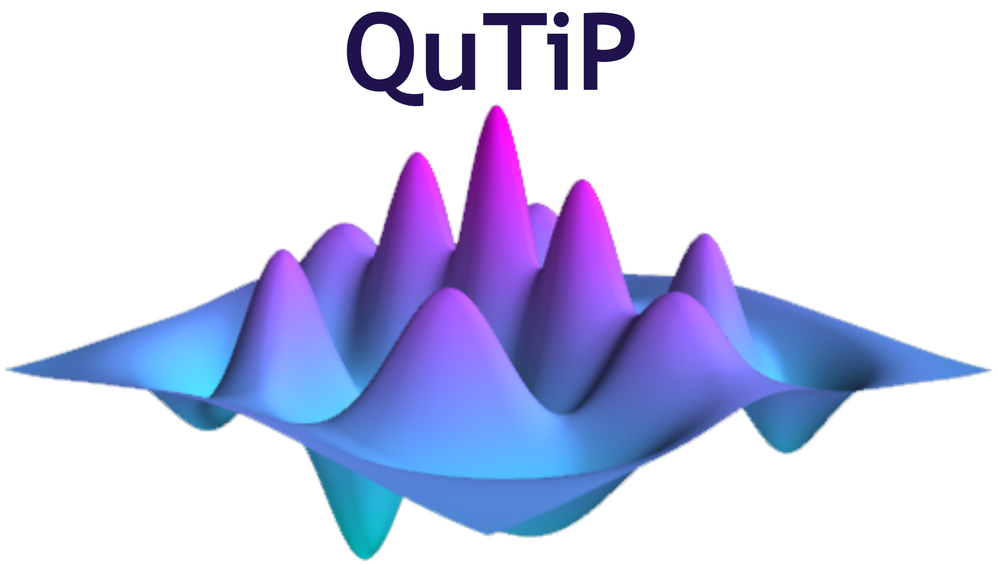
Nathan Shammah and Shahnawaz Ahmed



blogs.nature.com/onyourwavelength

QuTiP: The Quantum *Physics* Simulator

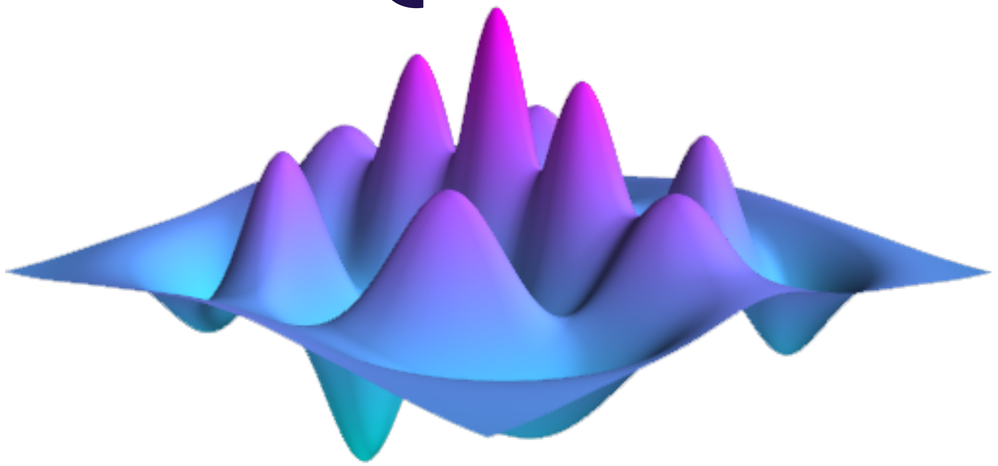
The **Qu**antum **T**oolbox **i**n **P**ython



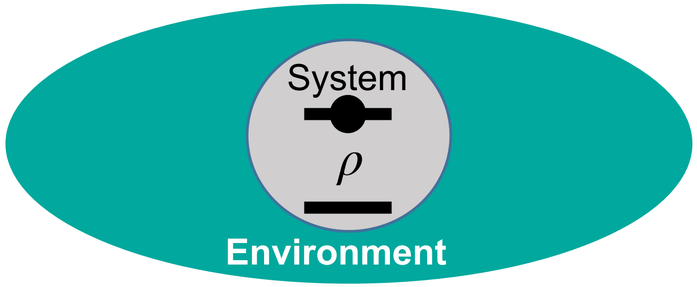
QuTiP: The Quantum *Physics* Simulator

The **Qu**antum **T**oolbox **i**n **P**ython

QuTiP



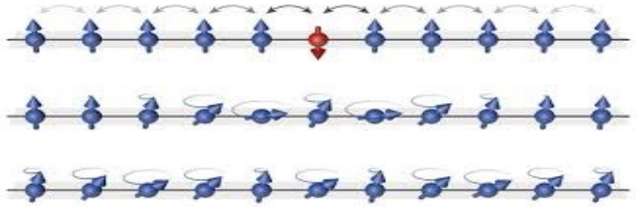
A toolbox to study the **open** quantum dynamics of realistic systems.



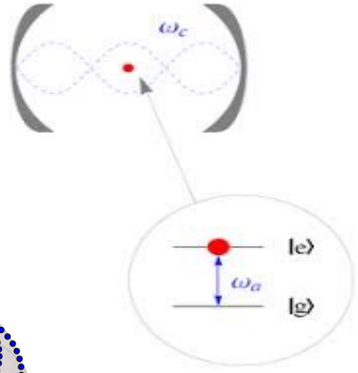
QuTiP: The Quantum *Physics* Simulator

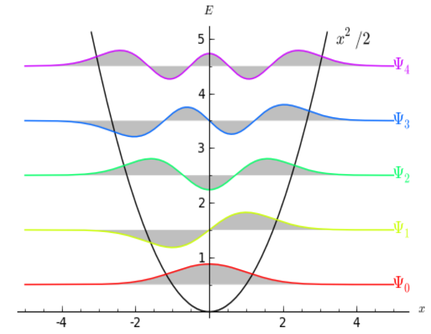
The **Qu**antum **T**oolbox **i**n **P**ython

Spin Lattices

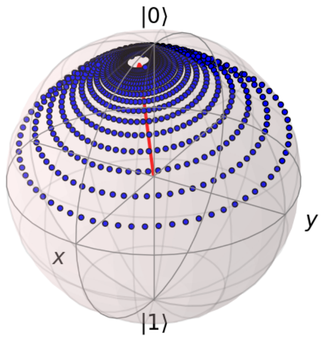


Cavity QED



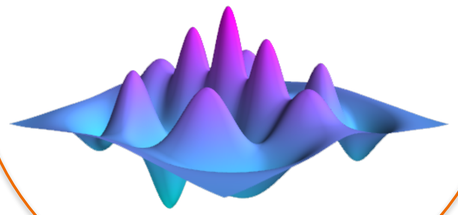


Condensed Matter

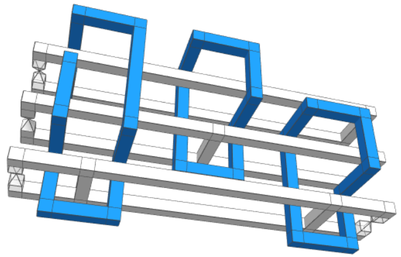


Quantum Optics

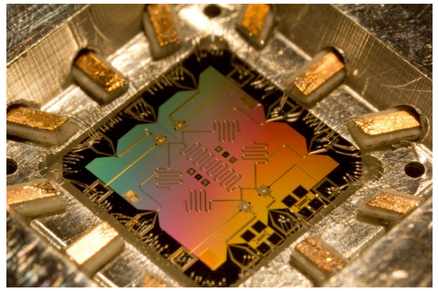
QuTiP



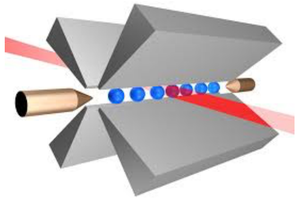
qutip.org



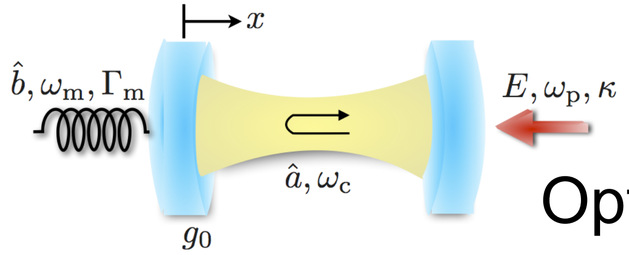
Quantum Error Correction



Superconducting Circuits



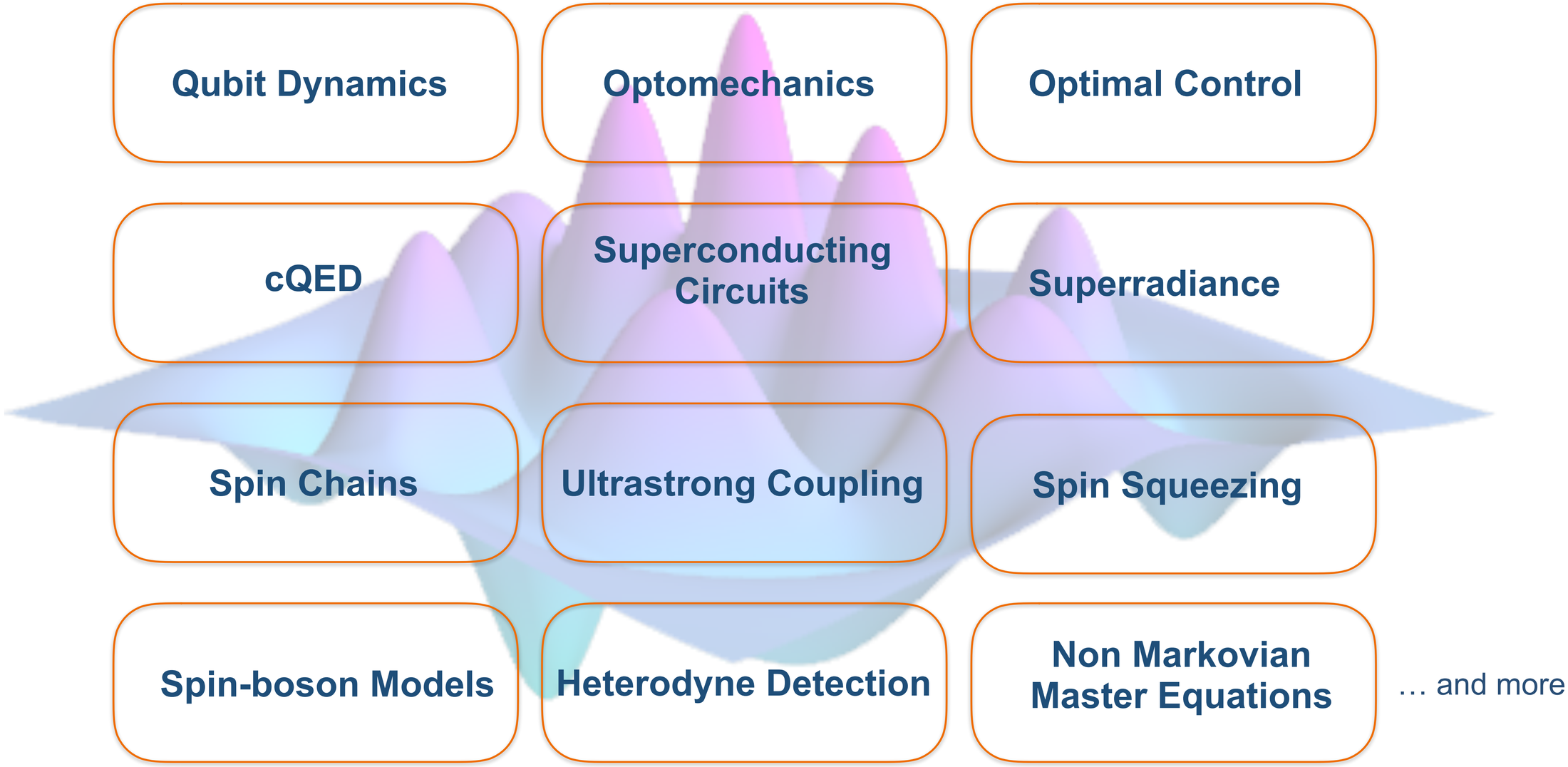
Ion Traps



Optomechanics

QuTiP: What research enables

The **Qu**antum **T**oolbox **i**n **P**ython



QuTiP: Features at a glance

The **Qu**antum **T**oolbox **i**n **P**ython

Built with Python

Python's **straightforward syntax.** Ideal toolbox for research or the classroom.

Custom algorithms

Maximize performance, e.g., sparse matrices.

Fast

Multiprocessing libraries, OPENMP, SSE3 processor extensions, and Intel MKL.

Built-in solvers

Dynamical simulations and steady-state analysis.

C++ performance

C++ behind the scenes using Cython (**compiled code**).

Experimental Data

Construct a function from a data set, **interpolating functions**.

Ad-hoc visualization tools

A host of **built-in visualization routines**, from Bloch spheres to Wigner maps.

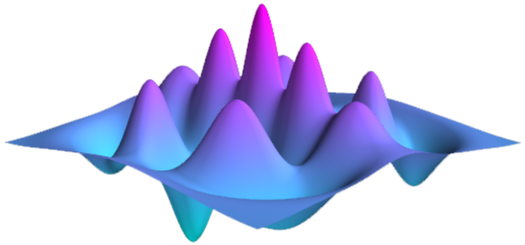
Independent testing

Large collection of **built-in test scripts** independently run by Travis CI.

User friendly

Wide **documentation** and a multitude of **tutorials** with Jupyter notebooks.

QuTiP: The Quantum Toolbox in Python



About QuTiP

QuTiP is a free and open source library for efficient simulation of a wide variety of quantum systems.

<u>Field-specific</u> intuitive framework

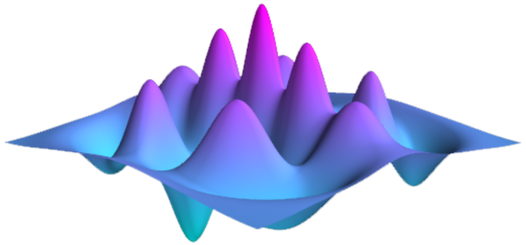
The mathematics of quantum mechanics

- Complex number matrices
- Non-commutative algebras
- Operators and superoperators
- Intuitive Python classes: `QObj`

`Results`

More info at <u>http://qutip.org/</u>

QuTiP: The Quantum Toolbox in Python



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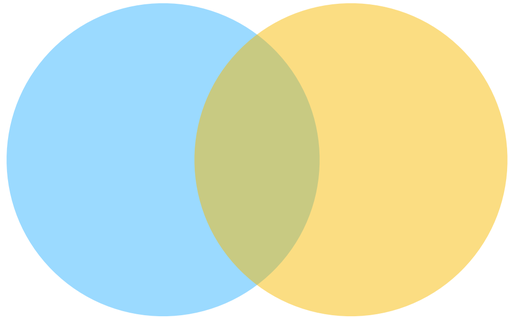

<u>Advanced</u> mathematical techniques

- **Noisy Dynamics**: Master equation solvers
- Correlation functions (quantum regression formula)
- **Modularity**: Permutational invariant quantum solver
  Hierarchical equations of motion
  Waveguide photon scattering
  Topological quantum circuits

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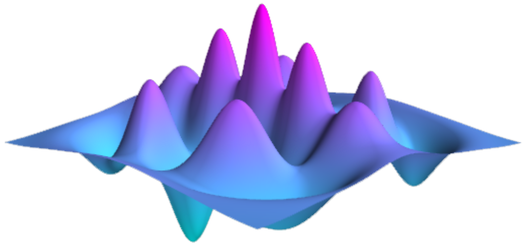

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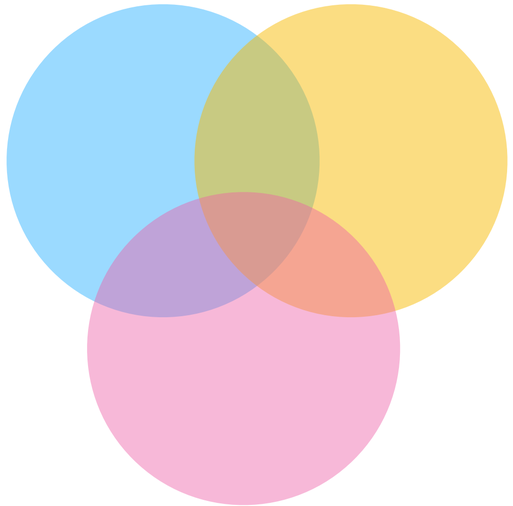

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- **Noisy Dynamics**: Master equation solvers
- Correlation functions (quantum regression formula)
- **Modularity**: Permutational invariant quantum solver
  Hierarchical equations of motion
  Waveguide photon scattering
  Topological quantum circuits

<u>Efficient</u> numerical calculations

- *Fast complex-complex matrix-vector multiplication* with SSE3 intrinsics.
- **Multiprocessing**: Enhanced parallel performance with OPENMP

- **Sparse Matrices**: Fast CSR (Compressed Sparse Row) matrix class.
- *Up to 100x improvement:* in CSR adjoint & transpose
  in Hermitian verification, Krönecker product
  in partial trace calculation

More info at <u>http://qutip.org/</u>

QuTiP: The project at a glance

The **Qu**antum **T**oolbox **i**n **P**ython

Project Impact

QuTiP
Quantum Toolbox in Python

>**600** citations (Google Scholar)

downloads 79k total (conda forge)

More info at http://qutip.org/

Authors

Comp. Phys. Comm. 183, 1760–1772 (2012); ibid. 184, 1234 (2013).

Code

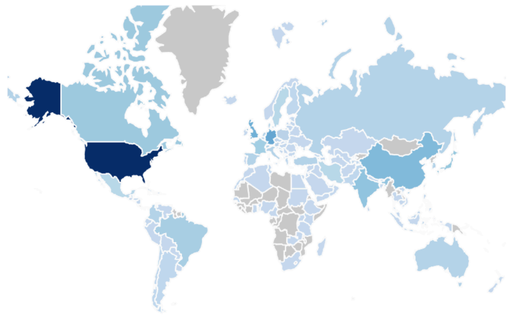
Robert J. Johansson
Rakuten Inc.

Paul D. Nation
IBM Q

Franco Nori
RIKEN / U. Michigan

Users

Distribution of 25k website visitors (2016)



Timeline:

Inspired by the Quantum Toolbox in MatLAB.

- 2011-2012: **QuTiP** 1.0
- Aug 2015: 100 citations
- Aug 2016: 200 citations
- Jan 2017: QuTiP 4.0
- July 2018: QuTiP 4.3

Lead Developers

Alex Pitchford
Aberystwyth University

Éric Giguère
U. Sherbrooke

Arne Grimsmo
Universite de Sherbrooke

Chris Grenade
University of Sydney

Contributing Developers

- Neill Lambert (RIKEN)
- Denis Vasilyev (Leibniz)
- Kevin Fischer (Stanford)
- Jonathan Zoller (Ulm University)
- Ben Criger (RWTH Aachen)
- …
- Louis Tessler (RIKEN)
- Shahnawaz Ahmed (Chalmers)
- Nathan Shammah (RIKEN)

- **GitHub**: 44 contributors, 4k commits

License: BSD

(Berkeley Software Distribution)
Style: PEP8 compliant

Libraries used:

- Scipy
- NumPy
- Cython
- Matplotlib
- SymPy

- Jupyter notebooks
- Online documentation
- Independent testing

QuTiP: A wide range of applications

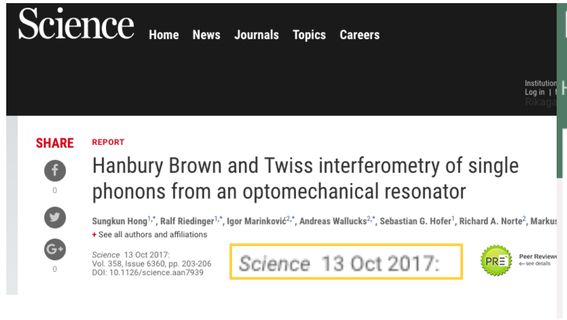
The **Qu**antum **T**oolbox **i**n **P**ython

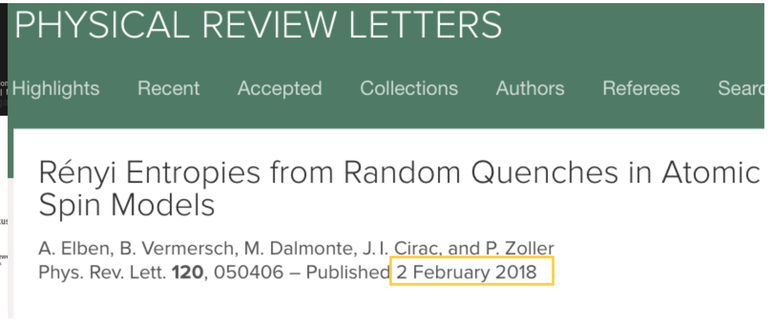
Research

>600 citations

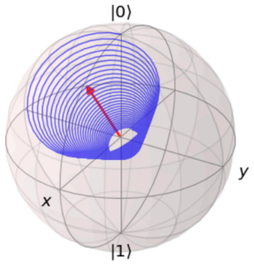
July 2018

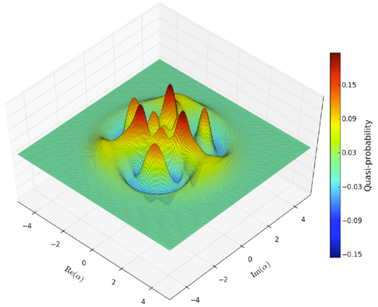
Feb 2019

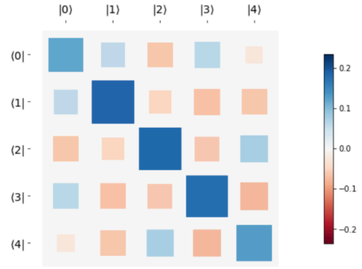


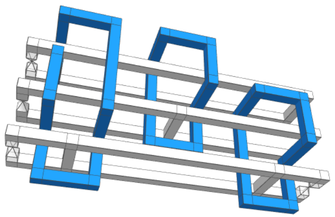


Education









Industry

Google
NORTHROP GRUMMAN
Microsoft
amazon.com
IBM
Alibaba.com
intel
Honeywell
NASA
IONQ
rigetti

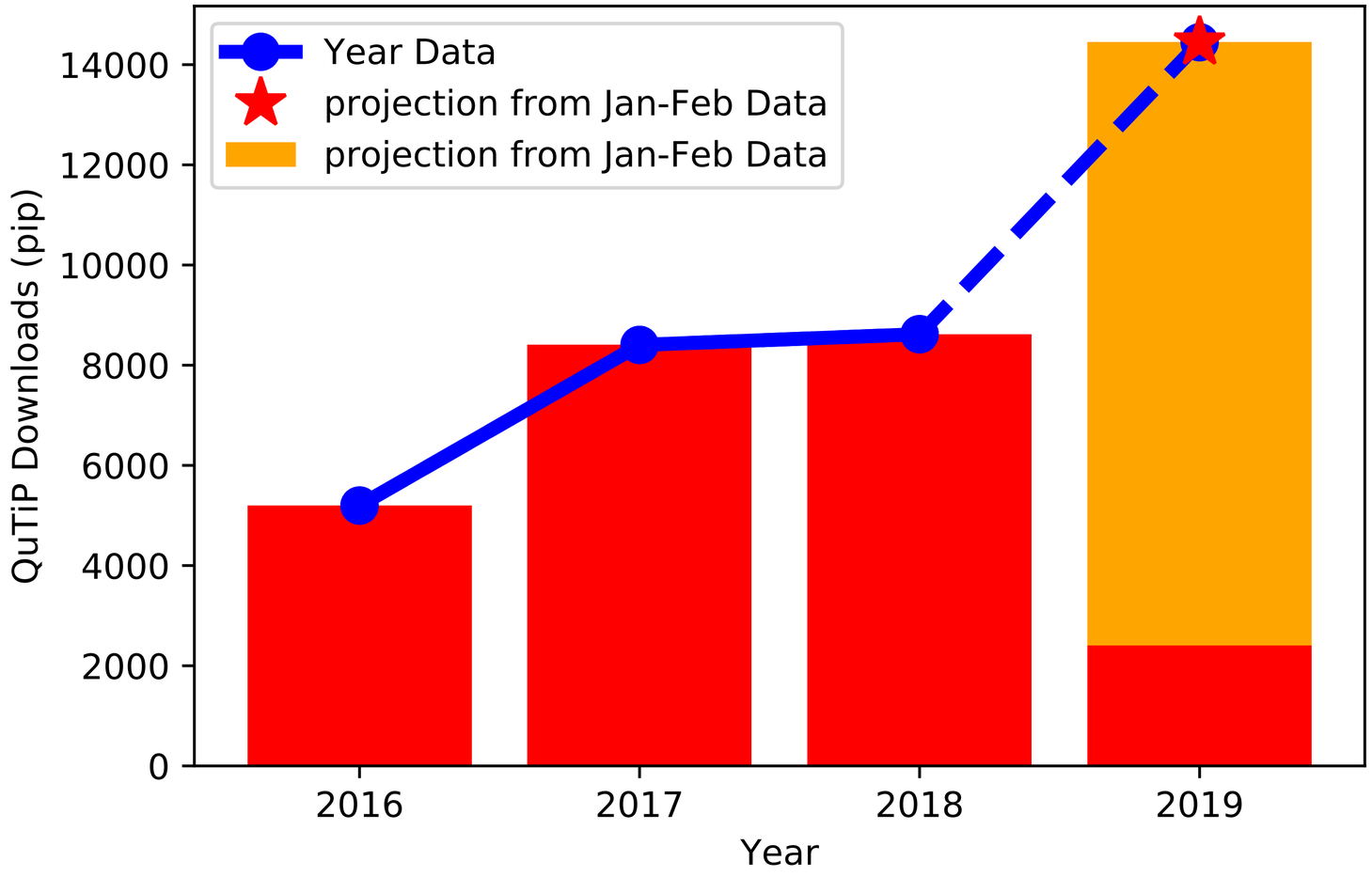
QuTiP inside

QuTiP: Some Statistics

The **Qu**antum **T**oolbox **i**n **P**ython

Data obtained using: https://github.com/ofek/pypinfo

(**pip install qutip**)

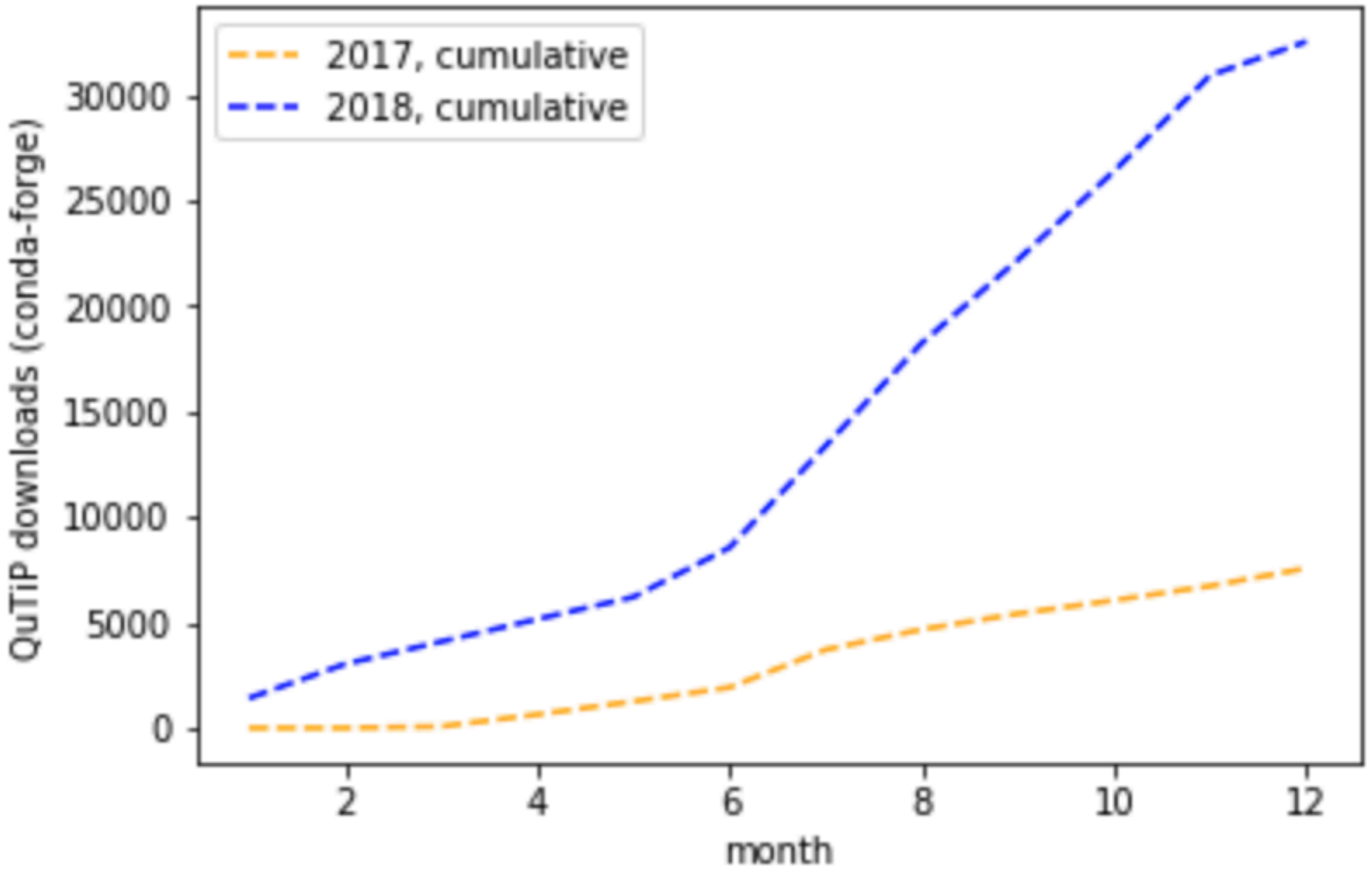


QuTiP: Some Statistics

The **Qu**antum **T**oolbox **i**n **P**ython

conda install qutip

July 2018	downloads 43k
Feb 2019	downloads 79k total
Apr 2019	downloads 112k total
Jun 2019	downloads 130k total

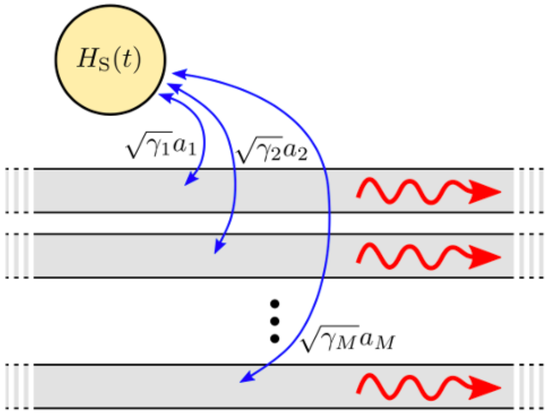


QuTiP recent additions (2018-2019)

qutip.scattering

Model nonlinear photon scattering
in multiple waveguides

How photons scatter into the waveguide
when the system is driven
with some excitation field

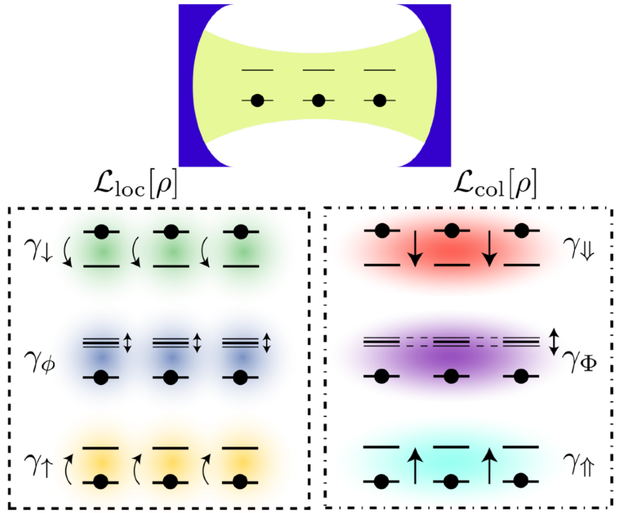


K.A. Fischer, *et.al.* (2017), arXiv: 1710.02875

Code: Ben Bartlett. Github: bencbartlett

qutip.piqs

Efficiently model local dissipation
Collective dissipation
vs. Local dissipation
vs. Coherent coupling

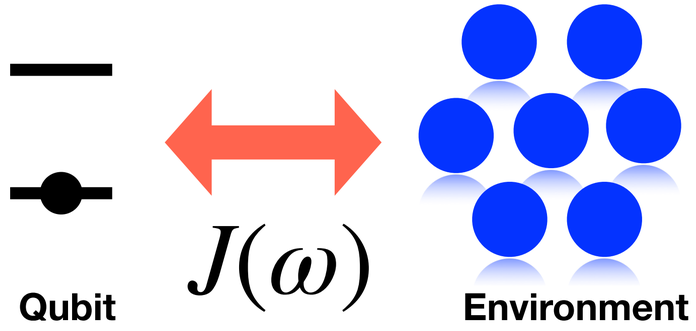


N. Shammah *et al.*, Phys Rev A **98**, 063815 (2018)

Code: Nathan Shammah and Shahnawaz Ahmed

qutip.nonmarkov

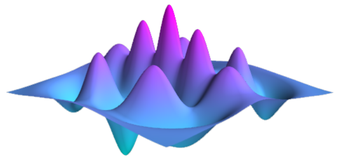
The environment has a memory
Non-Markovian dynamics
Hierarchical Equations of Motion
(HEOM).



A. Fruchtman, *et al.*, Sci. Rep. **6**, 28204 (2016)
N. Lambert *et al.*i arXiv: 1903.05892

Code: Shahnawaz Ahmed and Neill Lambert

QuTiP ongoing expansion [WIP]



qutip.nisq

Model noise in quantum information processing (QIP)

QuTiP's QIP module represents ideal quantum circuits.

Student: Boxi Li (ETH Zurich)

Objectives:
- Go beyond gates as instantaneous unitary transformation
- Noise model for realistic devices
- Noise model for dissipative dynamics

First results:
- Added Mølmer-Sørensen gate
- Allowed user-defined gates
- Added optical pulses for gate shaping

Code: Boxi Li. Github: BoxiLi
Mentors: Alex Pitchford,
Neill Lambert,
Shahnawaz Ahmed,
Nathan Shammah

Google Summer of Code

https://gsoc2019-boxili.blogspot.com

qutip.lattice

Model lattices in QuTiP

A qutip.lattice module implementing Hamiltonians for paradigmatic 1D lattice models.

Student: Saumya Biswas (U. Oregon)

Objectives:
Single particle picture,
- SSH model (topological properties)

Spin chains and bosonic lattices
- Bose-Hubbard model

Complement existing libraries:
- QuSpin
- pythontb

Code: Saumya Biswas
Mentors: Clemens Gneiting,
Eric Giguere,
Shahnawaz Ahmed,
Nathan Shammah

Google Summer of Code

https://latticemodelfunctions.blogspot.com

qutip.tiqs

Translational invariant Lindblad dynamics

Driven-dissipative systems
Liouvillian spectrum

Idea
Exploit the symmetries of the dynamics
Spin chains and bosonic lattices
Liouvillian spectrum

$$\dot{\rho} = \mathscr{L}\rho$$

$$[\mathscr{L}, S] = 0$$

F. Minganti, *et.al.* Phys. Rev. A 98, 042118 (2018)

Code: Fabrizio Minganti. Github: fminga

QuTiP: A Growing Ecosystem

What's going on

- 2018: Joined NumFOCUS, foundation for scientific code (NumPy)

- 2019: Participating to Google Summer of Code 2019:

Student Applications opened March 26th. Closed April 9th. 3 students working on summer projects.

https://github.com/qutip/qutip/wiki//Google-Summer-of-Code-2019

2019: Applied to 1st Google Season of Docs 2019: Technical writers projects for documentation.

- 2018-2019: Reaching out to the sci-dev community.

EuroScipy 2018
July 2018
Trento, Italy

PyData 2018
November 2018
Warsaw, Poland

FOSDEM'19 (Quantum Computing)
February 2, 2019,
Brussels, Belgium

EuroScipy 2019
September 2019
Bilbao, Spain

1st QuTiP developers workshop
February 19-21, 2019
RIKEN, Wako, Japan

- 2018-2019: A growing QuTiP ecosystem of satellite libraries:

`piqs`
QuTiP library
Now a qutip module

`krotov`
QuTiP-based quantum optimal control library

`matsubara`
A qutip plugin for non-Markovian dynamics

`qupulse`
QuTiP-integrated hardware control

QuTiP ecosystem:
Like AstroPy,
but for Quantum

QuTiP: Some Statistics

The **Qu**antum **T**oolbox **i**n **P**ython

The recent feature by GitHub "**Used by**" allows to draw **connection graphs** on the quantum open source ecosystem:

- IBM’s qiskit is used by 122 other libraries.

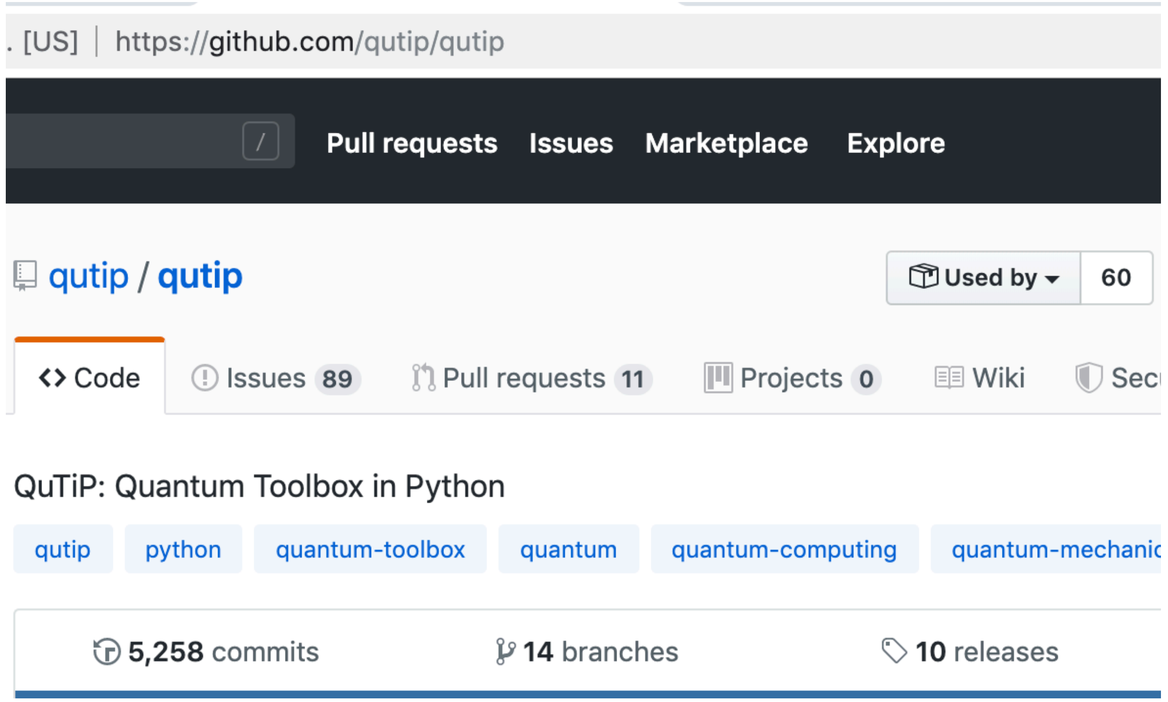
- **qutip by 60**.

- Rigetti’s pyquil 53 (grove 8).

- ProjectQ 29.

- Google’s OpenFermion 22.

- Dwave’s ocean-sdk 14.



This data shows how QuTiP helps engineer an ecosystem of other libraries.

QuTiP: A tool to explore quantum mechanics

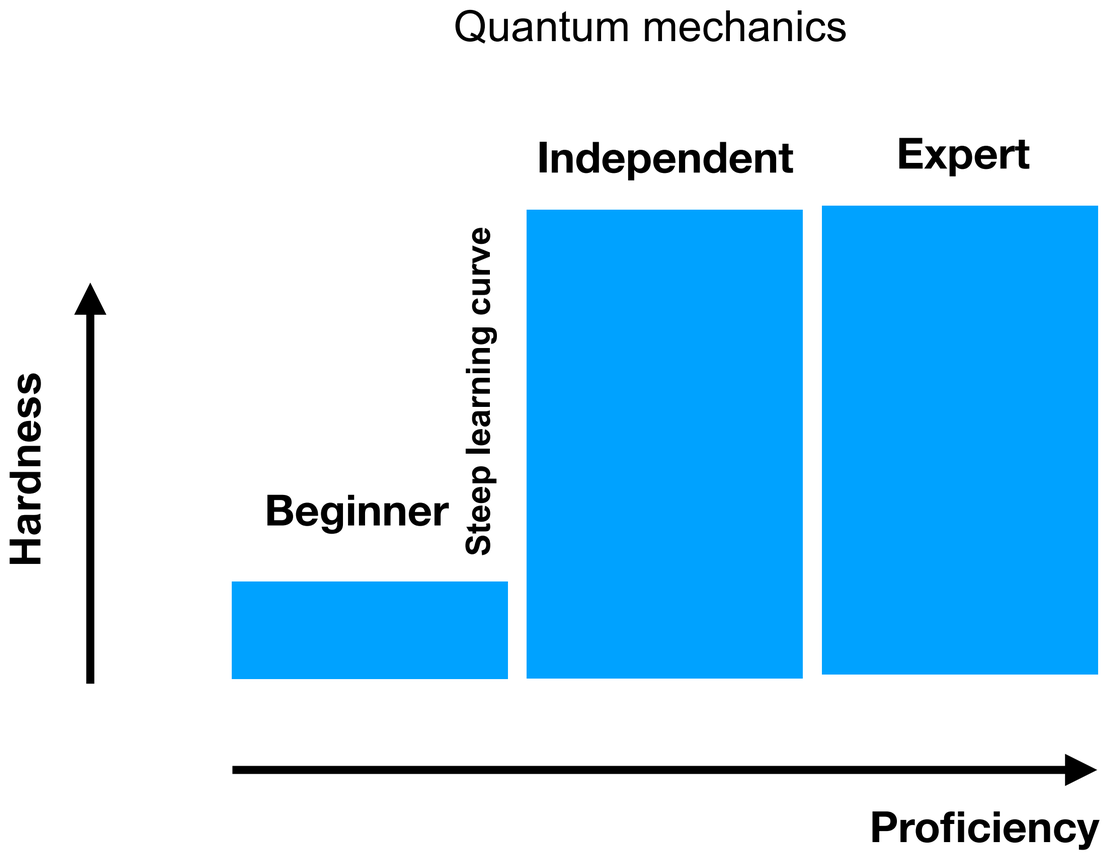
The **Qu**antum **T**oolbox **i**n **P**ython

	Academic Research	**Corporate**
Profile	Academic Researchers	Data Scientists
Drive	Personal interests	CTO>R&D>Analyst
Focus	Physicists care about a *problem*.	Analysts care about a *solution*.
Desired Support	Tweak functions	Simplify complexity
Interest	Vertical depth	Cross-platform compatibility

Both ‘tracks’ require a basic understanding of quantum mechanics

QuTiP: A tool to explore quantum mechanics

The **Qu**antum **T**oolbox **i**n **P**ython



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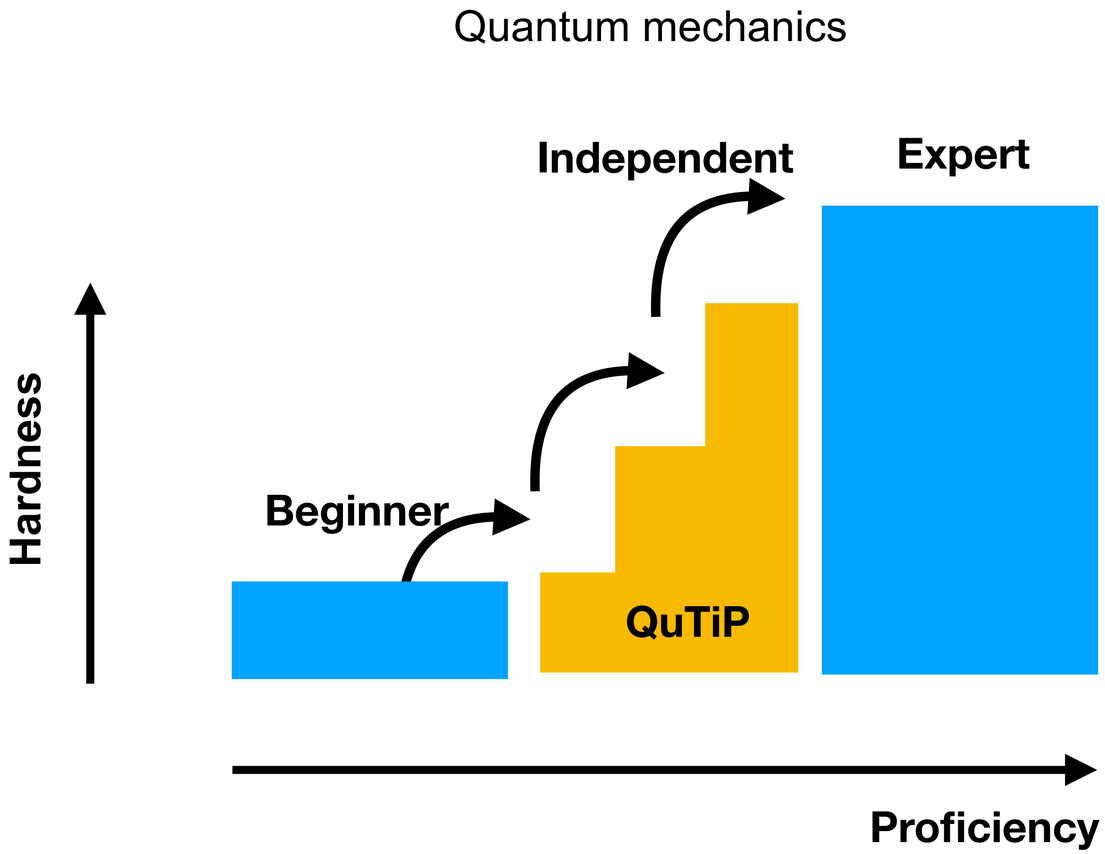

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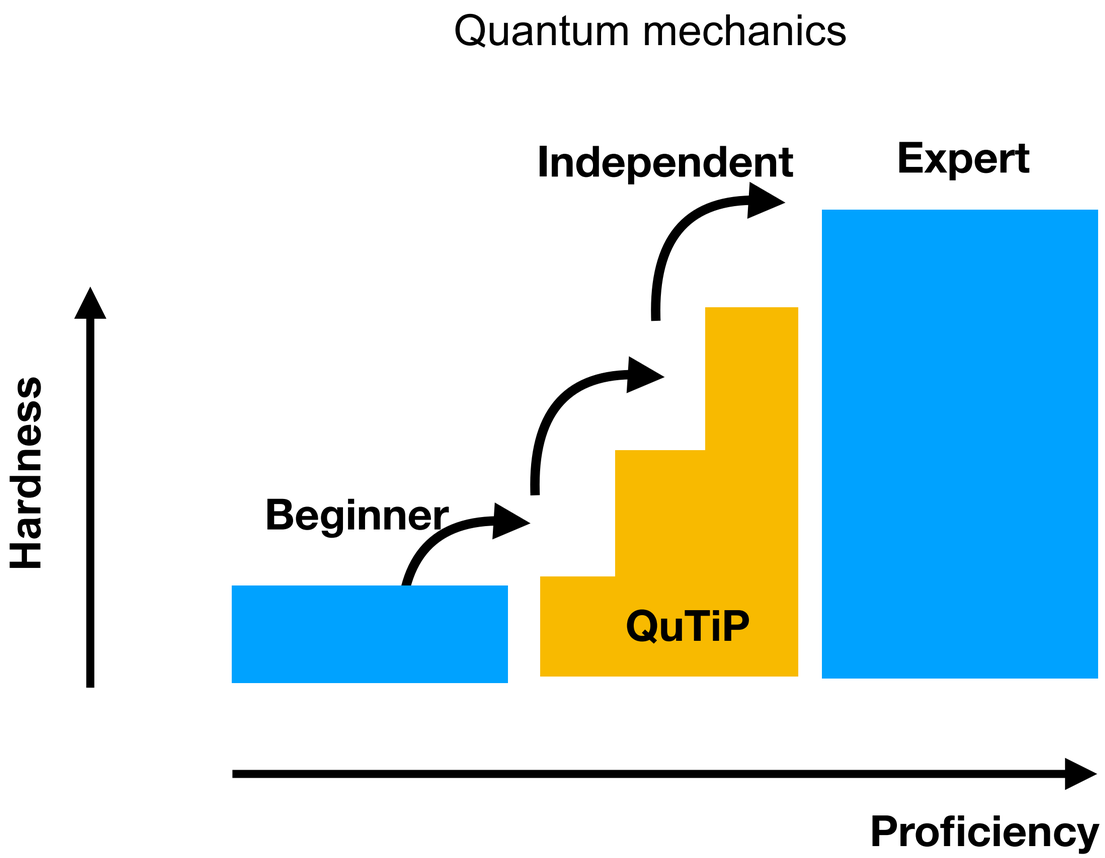


Tutorials at qutip.org/tutorials

Python Introduction

- Quick introduction to Python
- Overview of NumPy Arrays
- Brief Introduction to Matplotlib

For a more in depth discussion see: Lectures on scientific computing with Python.

Basics

- Introduction to QuTiP
- Exponential series
- Groundstates: Jaynes-Cumming model in the ultrastrong coupling regime
- Superoperators, Pauli Basis and Channel Contraction

Visualization

- Visualization demos
- Energy-level diagrams
- Bloch-sphere animation
- Bloch Sphere with Colorbar
- Wigner functions
- Pseudo-probability functions
- Process tomography
- Qubism visualizations

Quantum information processing

- Quantum gates and circuits
- Toffoli gate to CNOT
- Spin Chain Qubit model

Time evolution

- Master equation solver: Qubit dynamics
- Master equation solver: Vacuum Rabi oscillations
- Master equation solver: Spin chain
- Monte-Carlo solver: Trilinear oscillators
- Monte-Carlo solver: Birth and Death of Photons in a Cavity
- Bloch-Redfield master equation solver
- Time-dependent Bloch-Redfield Quantum Dot
- Floquet formalism
- Quasi-steadystate of time-dependent (periodic) systems
- Time-dependent master equation: Landau-Zener transitions
- Time-dependent master equation: Landau-Zener-Stuckelberg inteferometry
- Stochastic master equation: Heterodyne detection
- Stochastic master equation: Inefficient detection
- Stochastic master equation: Jaynes-Cumming model with photocurrent detection
- Stochastic master equation: Feedback control
- Steady state solvers: Optomechanical system
- Homodyned Jaynes-Cummings Emission

Optimal control

- Overview
- Hadamard
- QFT
- Lindbladian
- Symplectic
- QFT (CRAB)
- state to state (CRAB)
- CNOT
- iSWAP
- Single-qubit rotation
- Toffoli gate

- **Over 60** Jupyter notebook tutorials
- **Over 20** quantum mechanics lectures

QuTiP: A wide range of applications

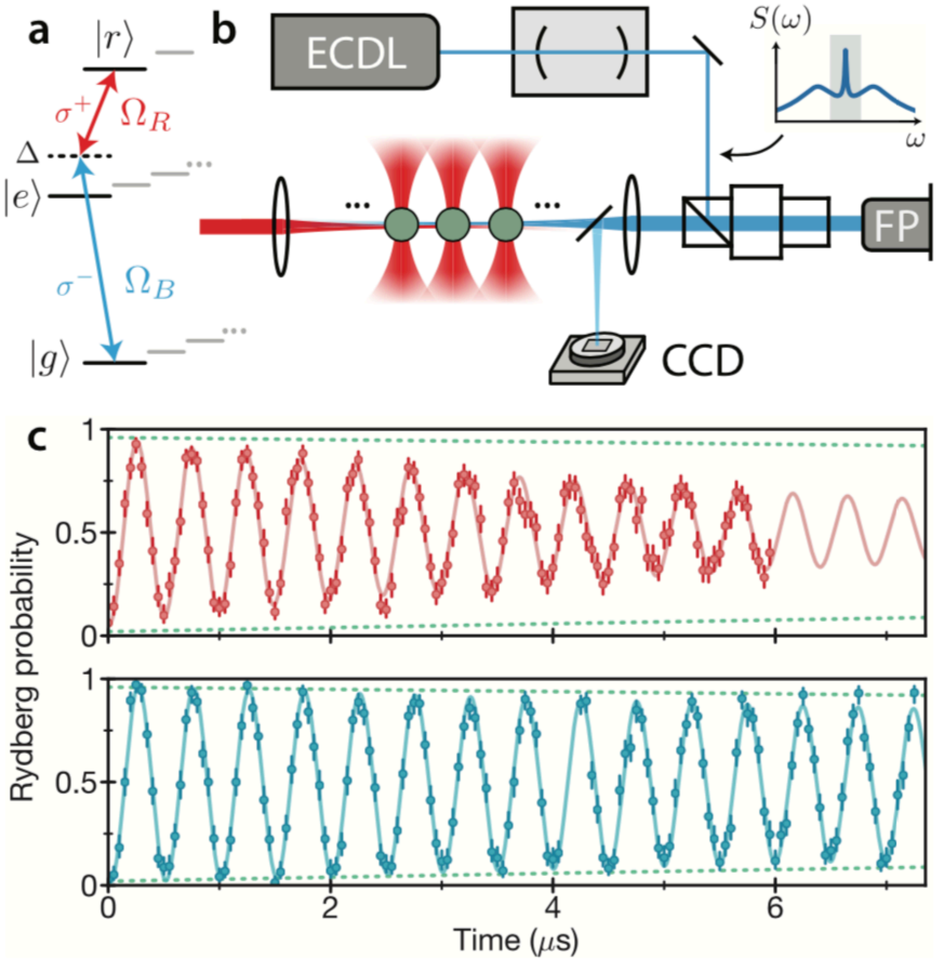
The **Qu**antum **T**oolbox **i**n **P**ython

Experimental Research

arXiv:1806.04682v1 [quant-ph] 12 Jun 2018

High-fidelity control and entanglement of Rydberg atom qubits

H. Levine, […] and M.D. Lukin



Numerical model for single atoms

The numerical model is implemented using the Python package QuTiP [2].

It includes the following three effects:

1. A static but random Doppler shift in each iteration of the experiment […].

2. Off-resonant scattering from the intermediate state |r⟩. […].
   This process is modeled by Lindblad operators.

3. Finite lifetime of the Rydberg state |r⟩.

QuTiP: A wide range of applications

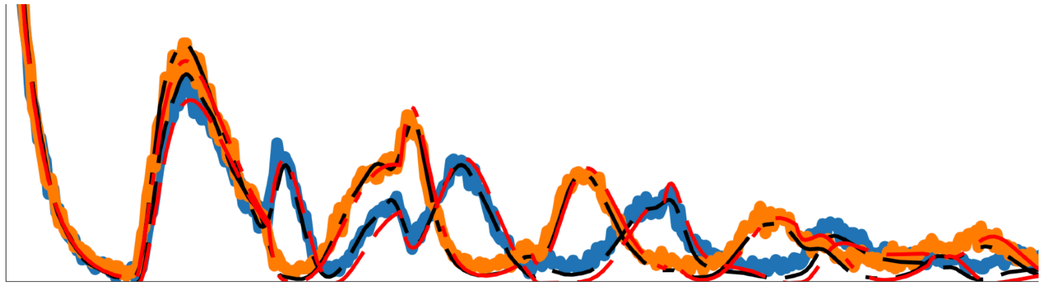
The **Qu**antum **T**oolbox **i**n **P**ython

Experimental Research

arXiv:1903.05672 [quant-ph] 13 Mar 2019

Phonon-mediated quantum state transfer and remote qubit entanglement

A. Bienfait, […] and A.N. Cleland, Science **10**, 1126 (2019)



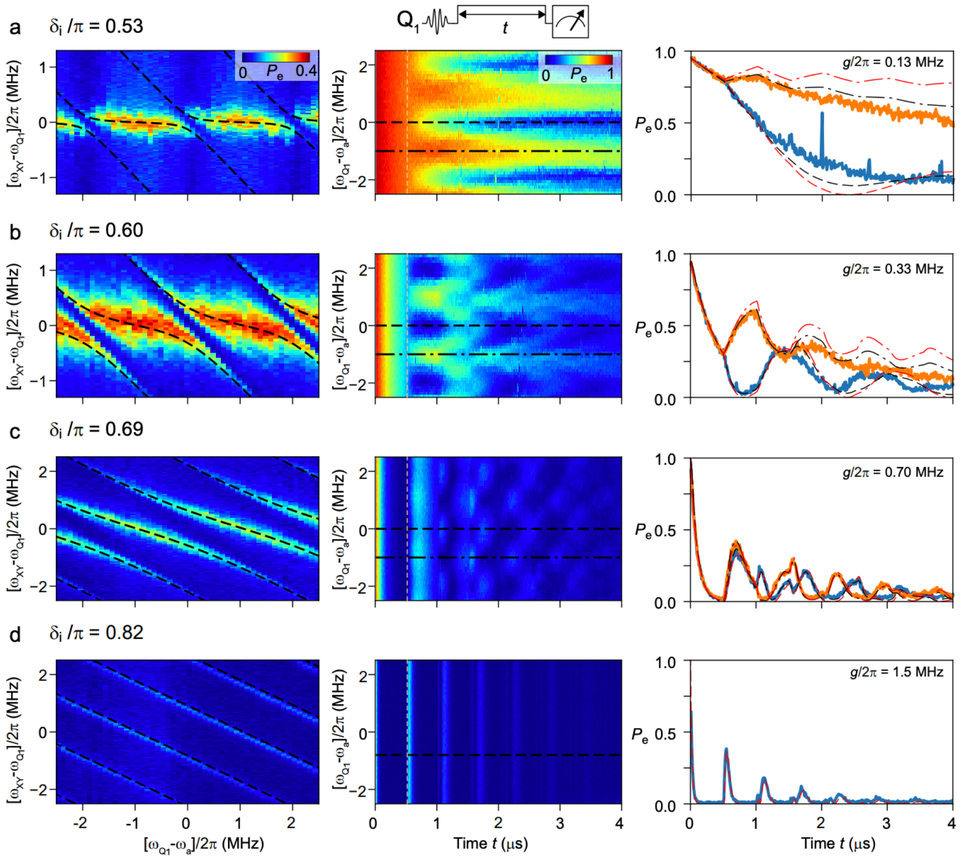
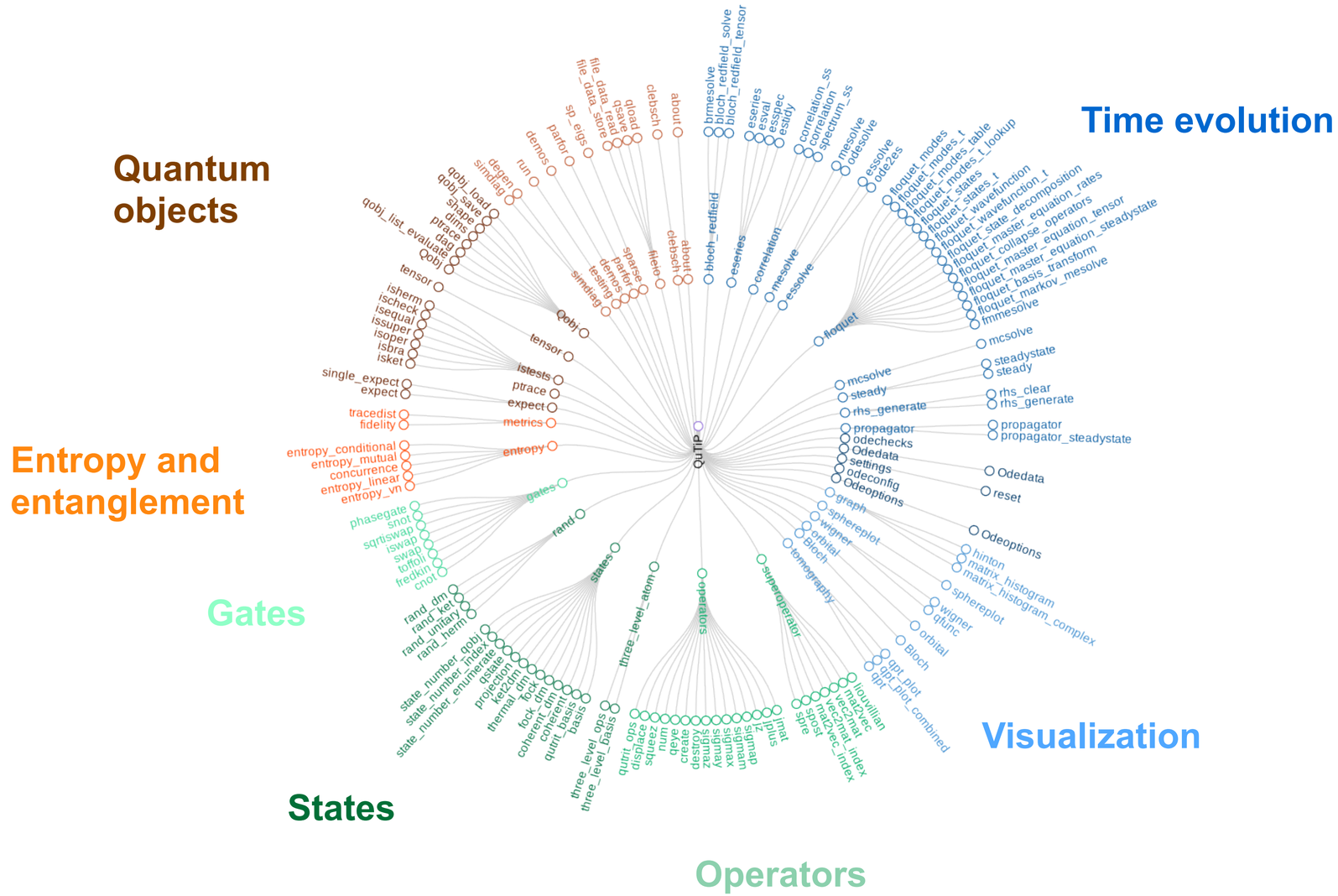


Figure S3. (a-d) *Left*: Qubit 1 spectroscopy near the SAW Fabry-Pérot mode $\omega_a/2\pi = 3.9542$ GHz for different coupling biases corresponding to the coupling strengths indicated on each of the right panels. *Center*: Corresponding energy decay rate measurements in the same frequency range. *Right*: Line cuts through the data in the central panels at $\omega_q = \omega_a$ (blue curves) and $\omega_q = \omega_a - \omega_{\mathrm{FSR}}/2$ (orange curves). Black dashed lines are QuTiP simulations as described in the text, red dashed lines are from Eq. S2. We did not perform a QuTiP simulation for d, as it requires the inclusion of more than 20 oscillators, which is very computationally intensive.

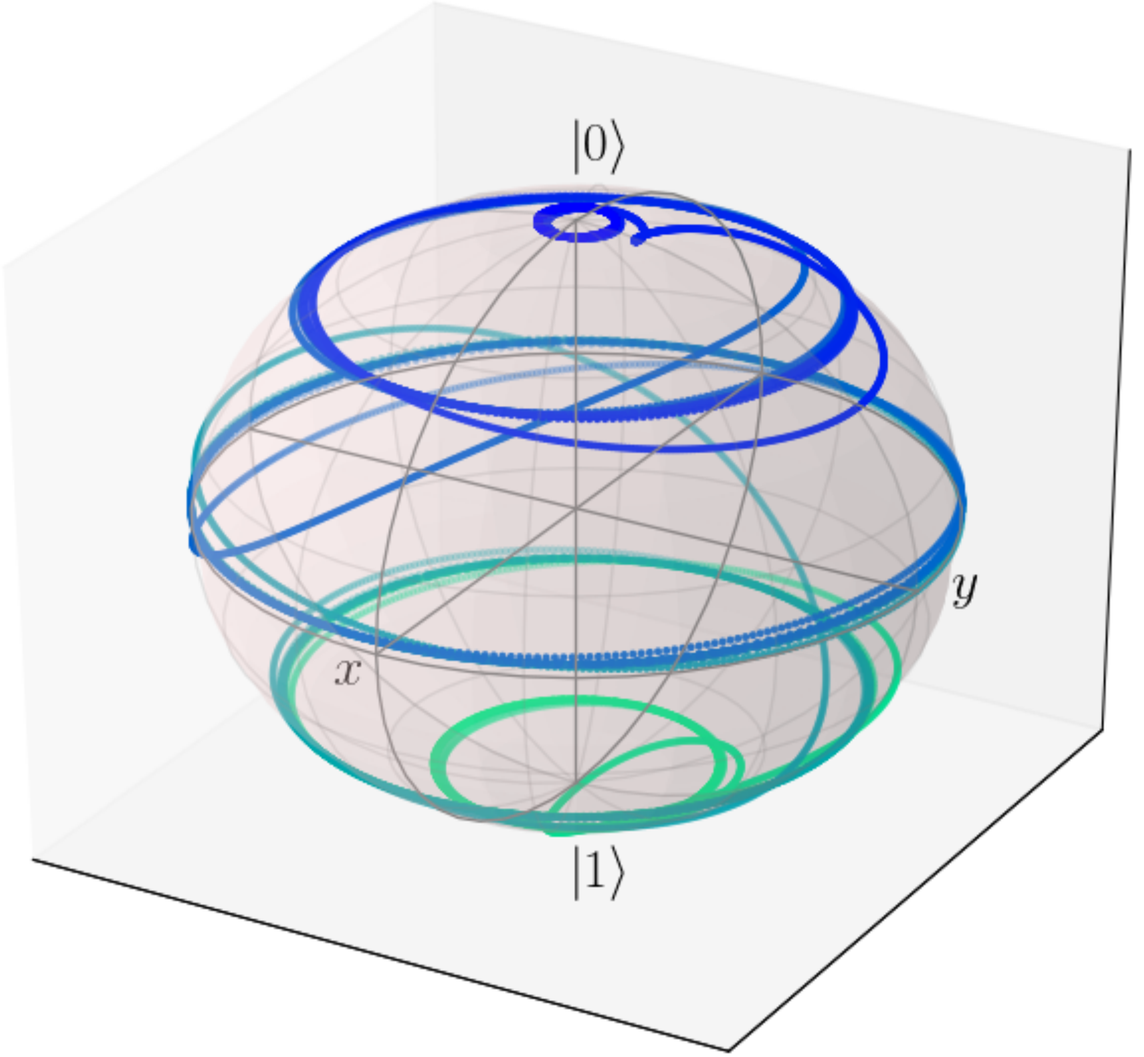
QuTiP: Map of code

The **Qu**antum **T**oolbox **i**n **P**ython



QuTiP: Ad-hoc visualization tools

The **Qu**antum **T**oolbox **i**n **P**ython



QuTiP: Ad-hoc visualization tools

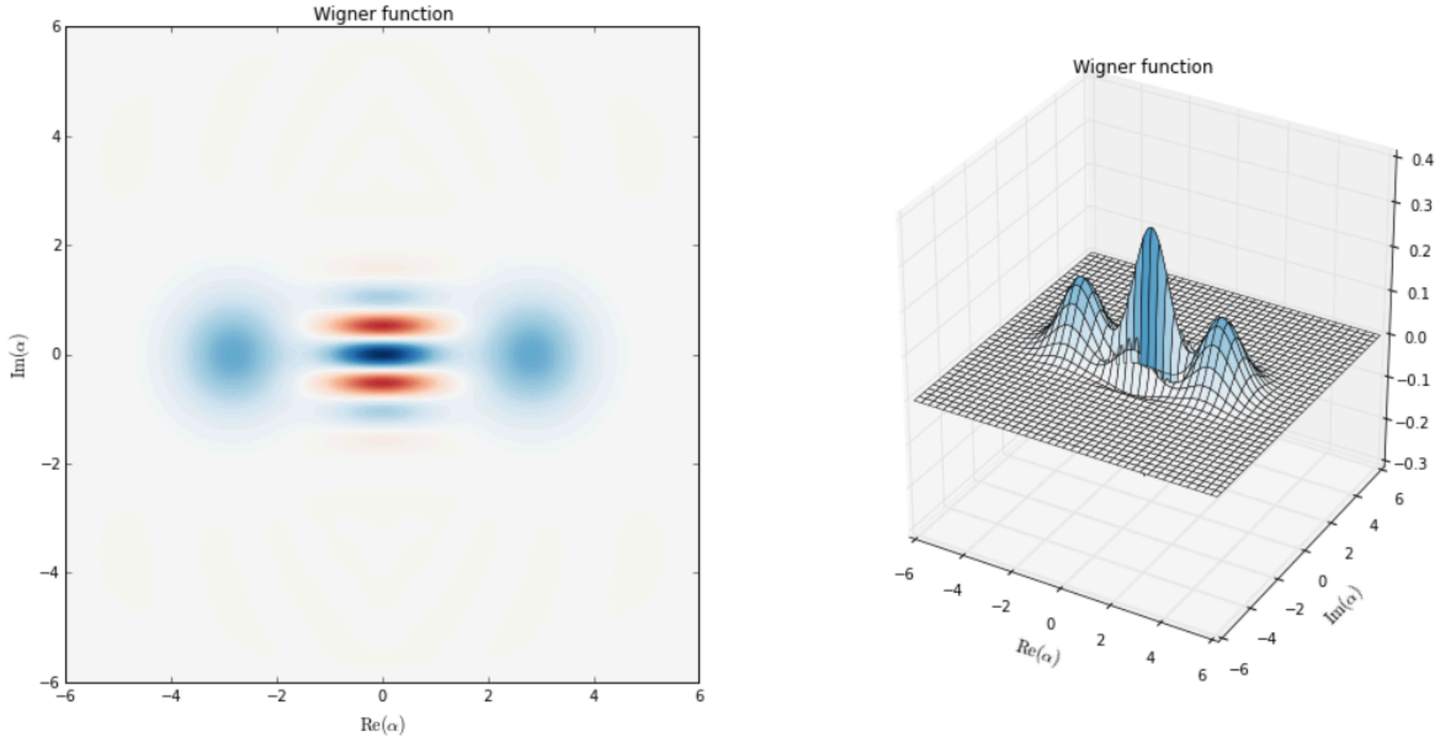
The **Qu**antum **T**oolbox **i**n **P**ython

Superposition of coherent states

qutip.org/tutorials

In [9]:
```
psi = (coherent(N, -2.0) + coherent(N, 2.0)) / np.sqrt(2)
plot_wigner_2d_3d(psi)
```

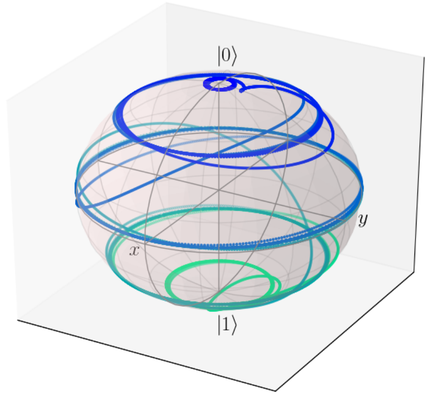
Out[9]:



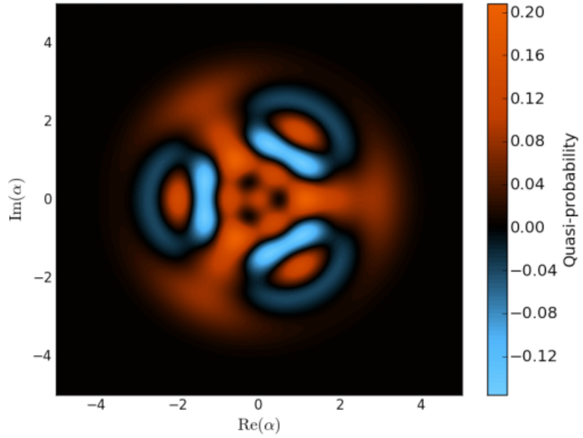
QuTiP: Ad-hoc visualization tools

The **Qu**antum **T**oolbox **i**n **P**ython

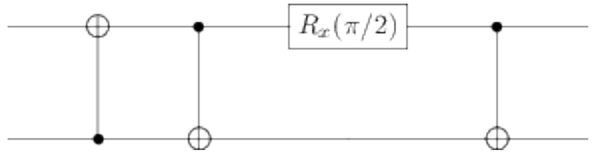
Bloch Sphere



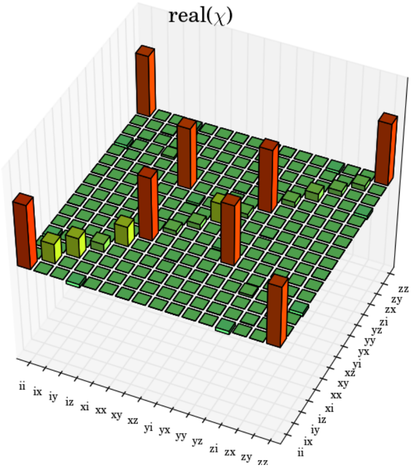
Wigner Function



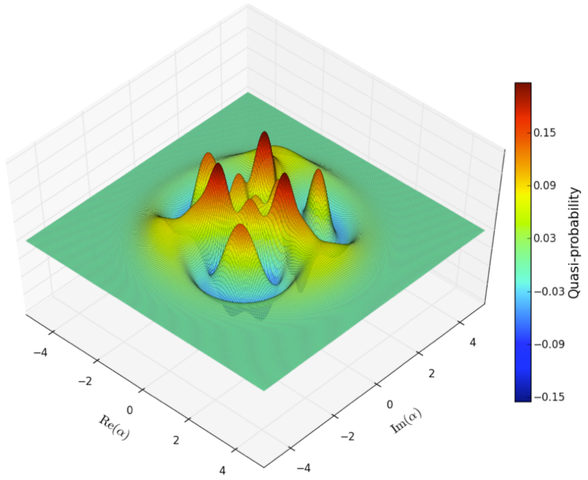
Quantum Circuits



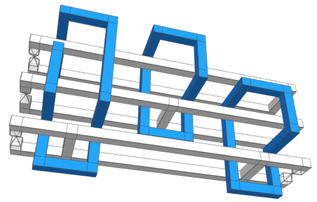
State Tomography



3D Wigner Function



Surface Code Topological Circuits*



*open pull request

QuTiP: The building blocks: states, operators and gates

The **Qu**antum **T**oolbox **i**n **P**ython

$$H = \frac{\sigma_z}{2}$$

$$a, a^\dagger$$

$$|\psi\rangle = \frac{1}{\sqrt{(2)}}\left(|0\rangle + |1\rangle\right)$$

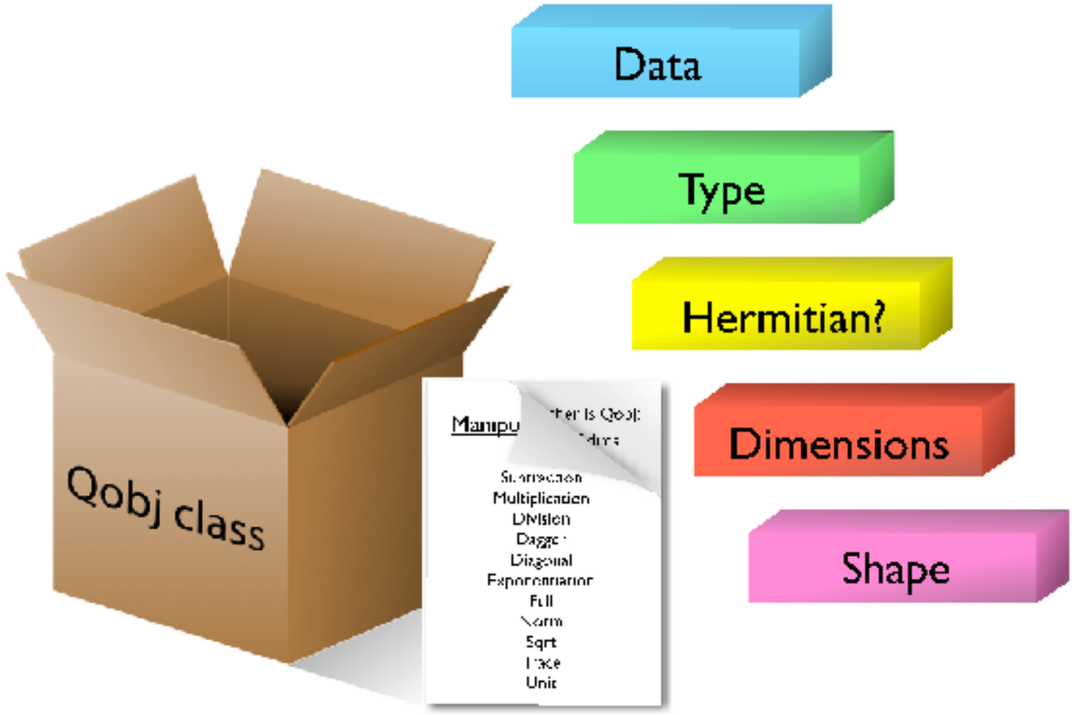
$$\sigma_z \otimes \sigma_x$$

$$\rho$$

```
>> from qutip import *
>> H = sigmaz()/2


>> a = destroy(2)


>> psi1 = basis(2, 0)
>> psi2 = basis(2, 1)
>> psi = (psi1 + psi2)/1.414

>> tensor(rho1, rho2)
>> tensor(sigmaz(), sigmax())

>> rho = ket2dm(psi)
>> op = vector_to_operator(rho)
```

QuTiP: The `Qobj` class

The **Qu**antum **T**oolbox **i**n **P**ython



J. R. Johansson, P. D. Nation, and F. Nori, Comp. Phys. Comm. **183**, 1760–1772 (2012)
QuTiP: An open-source Python framework for the dynamics of open quantum systems

QuTiP: The `Qobj` class

The **Qu**antum **T**oolbox **i**n **P**ython

- State and operators are declared as **`Qobj`**

- **Generate states** and operators

- Algebra (bosonic)

$$AB - BA \neq 0$$

$$\mathscr{E}(\rho) = A\rho B^{\dagger} \longrightarrow \mathscr{D} = B^{*} \otimes A$$

$$\dot{\boldsymbol{\rho}} = \mathscr{D}\boldsymbol{\rho}$$

```
>> q = Qobj([1], [0])
Quantum object: dims = [[2], [1]],
shape = (2, 1), type = ket
```

$$\begin{pmatrix} 1.0 \\ 0.0 \end{pmatrix}$$

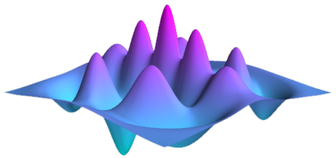
```
>> d = destroy(2)
Quantum object: dims = [[2], [2]],
shape = (2, 2), type = oper,
isherm = False
```

$$\begin{pmatrix} 0.0 & 1.0 \\ 0.0 & 0.0 \end{pmatrix}$$

```
>> q.dag()
Quantum object: dims = [[1], [2]],
shape = (1, 2), type = bra
```

$$\begin{pmatrix} 1.0 & 0.0 \end{pmatrix}$$

QuTiP: Numerical Solvers



The **Qu**antum **T**oolbox **i**n **P**ython

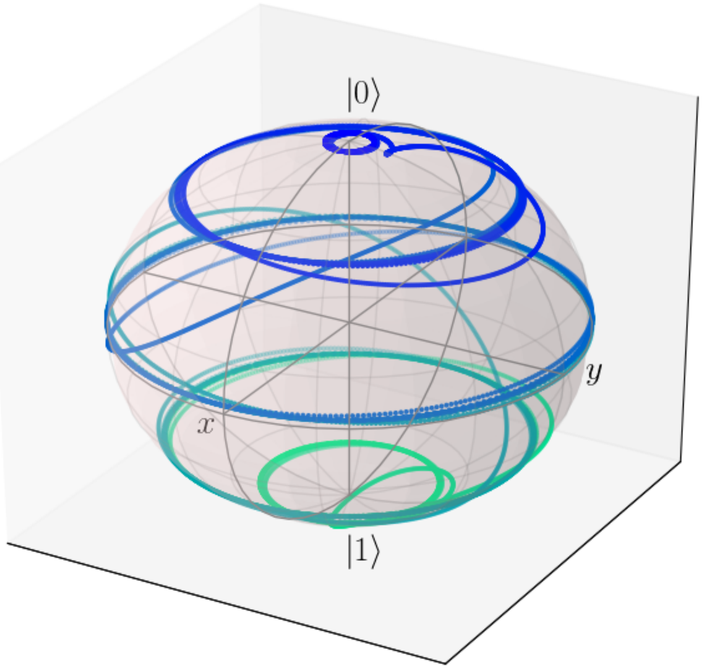
The **`Result`** class stores the expectation values of the operators passed to the solver.

Simple Example: A driven, damped single mode cavity.

```
result_ref = mesolve(H, rho0, times, c_ops, e_ops)
plot_expectation_values(result_ref, y_labels = "E[a'a], …,)
```

Solvers:

- **`mesolve`**: Lindblad master equations
- **`mcsolve`**: Monte-Carlo trajectory
- **`mesolve`**: Floquet
- **`bloch_redfield:`** Bloch-Redfield
- **`sesolve`, `ssesolve`,`smesolve`**: Stochastic solvers



Solving a many-qubit dynamics

Closed vs. Open dynamics

Schrödinger Equation

$$i\hbar\frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

Master Equation

$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \textbf{Noise}$$

	Schrödinger Equation	Lindblad Master Equation
Probability	Conserved	Conserved
Evolution	Unitary, $H = H^\dagger$	Non-Unitary
Time reversal	Preserved	Broken
Features	Closed system	**Open system**: noise and dissipation
Scaling with N qubits	2^N	

Solving a many-qubit dynamics

Exponential scaling even with Lindblad dynamics

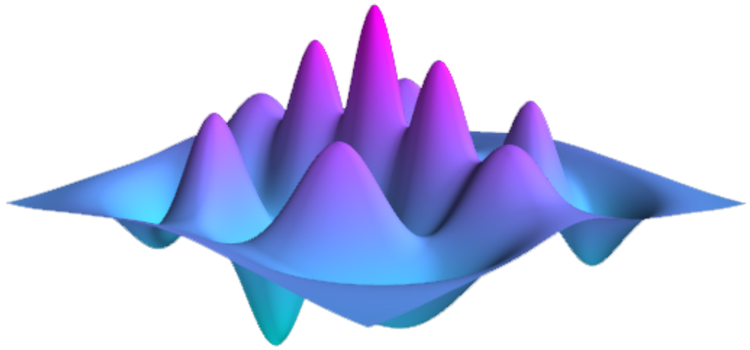
$$i\hbar\frac{d}{dt}\rho = [H,\rho] + \gamma\sum_{i}^{N}\left(L_i\rho L_i^\dagger - \frac{1}{2}L_i^\dagger L_i\rho - \frac{1}{2}\rho L_i^\dagger L_i\right)$$

	Von Neumann Equation	Lindblad Master Equation
Probability	Conserved	Conserved
Evolution	Unitary, $H = H^\dagger$	Non-Unitary
Features	Closed system	**Open system**: noise and dissipation
Scaling with N qubits	2^N	4^N

QuTiP: Outlook

The **Qu**antum **T**oolbox **i**n **P**ython

QuTiP



An Excellent Toolbox

A Growing Community of Users

A Growing Community of Developers

Projects with NumFOCUS & Google Summer of Code

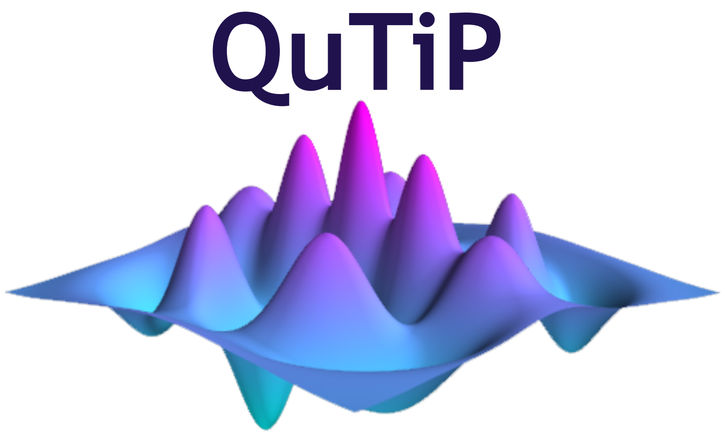
NUMFOCUS

OPEN CODE = BETTER SCIENCE

Google Summer of Code

QuTiP: The Quantum *Physics* Simulator

The **Qu**antum **T**oolbox **i**n **P**ython: A toolbox to study the **open** quantum dynamics of realistic systems.



Interactive Lectures @ ICTP, Leonardo Building

Tue 25th June - 11:45am, Seminar Room – Driven-dissipative models in quantum physics
Wed 26th June - 11am, Seminar Room – Quantum Open Source & Introduction to QuTiP
Thur 27th June - 9am, Computer Room – Hands-on session on QuTiP's main features
Mon 1st July - 9am, Computer Room – QuTiP stochastic solvers
Tue 2nd July - 9am, Computer Room – How to Build your Own Scientific Software Library in Python
(Wed 3rd July - 9am, Computer Room – Extra meeting: SISSA/ICTP projects)

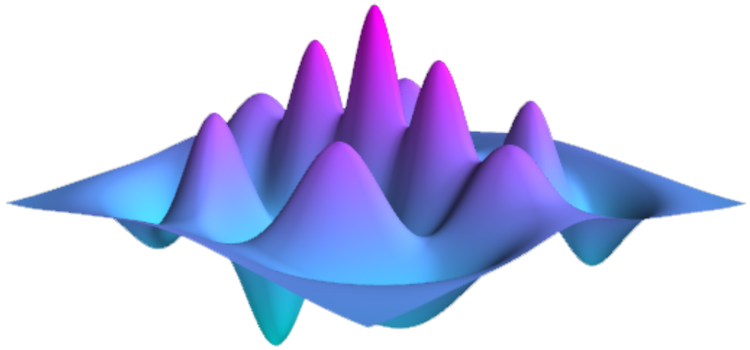
Take a snapshot

https://github.com/nathanshammah/interactive-notebooks

QuTiP: Interactive Notebooks

The **Qu**antum **T**oolbox **i**n **P**ython

QuTiP



You can find an interactive notebook at

https://github.com/nathanshammah/

Repository: **interactive-notebooks**

You can run the notebook live at

https://mybinder.org/v2/gh/nathanshammah/interactive-notebooks/binder

Take a snapshot

Quantum Tech Newsletter

Nathan Shammah
Quantum researcher at RIKEN
Jun 25 · 6 min read

medium.com/quantum-tech

Nathan's Quantum Tech Newsletter: №11

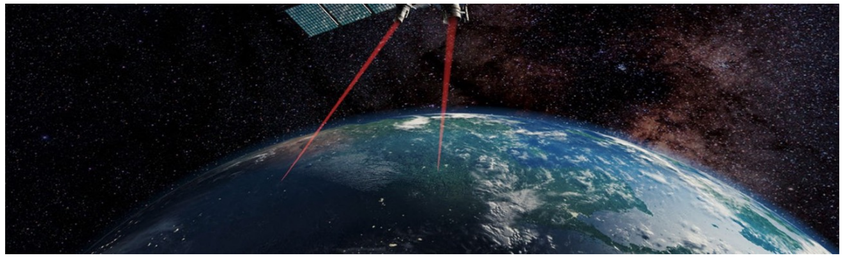
Sign up: eepurl.com/c10FJz

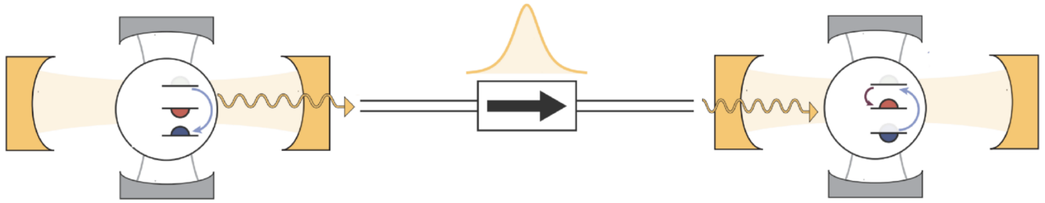
Research Highlights
- Breakthroughs
- Reviews
- Divulgation

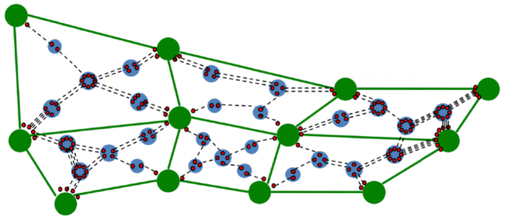
Tech News
- Startup creation, funding rounds
- Corporate Involvement
- Institutional Schemes

Bonus Links
- Videos
- Long-read popular articles

Focus
- Space Quantum Communication
- Quantum Machine Learning
- Open-Source Quantum Tech
- Quantum Games







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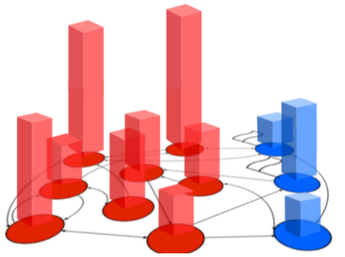
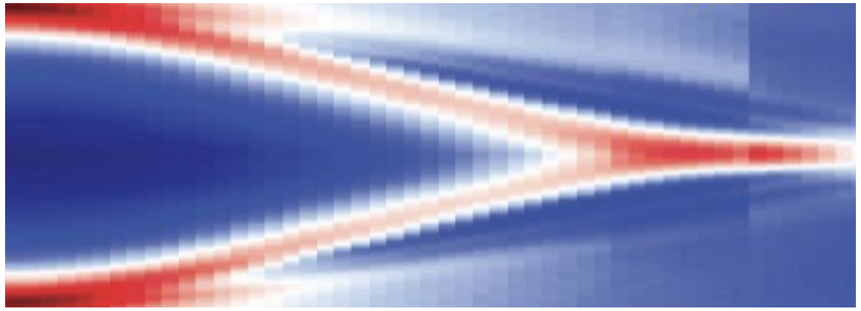


Nathan's Quantum Tech Newsletter: №11



Research Highlights
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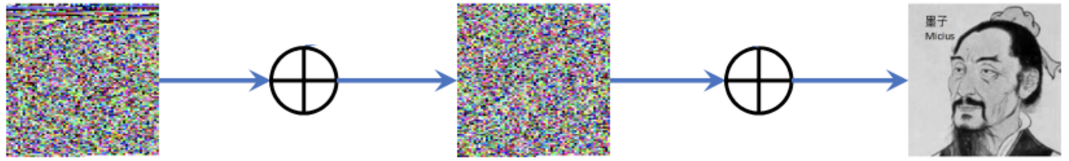

Tech News
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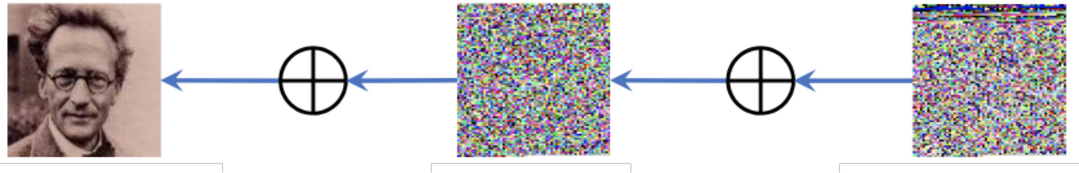

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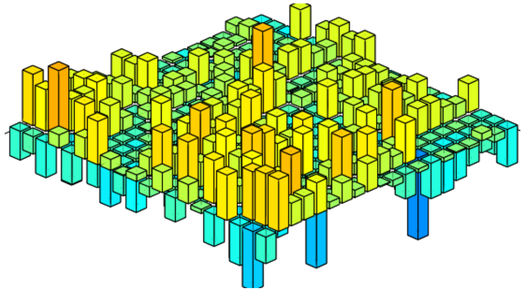

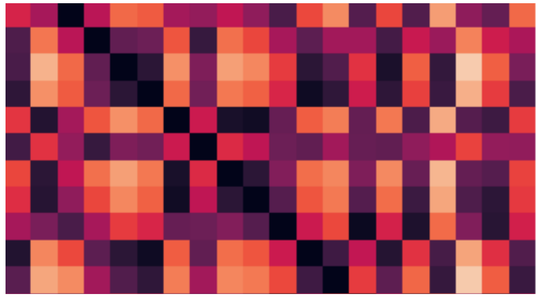

Thank you

 @NathanShammah

GitHub: nathanshammah
LinkedIn: Nathan Shammah