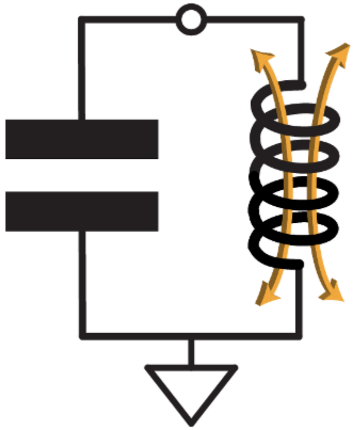
Advancing Quantum Sensing via Quantum Control

Superconducting



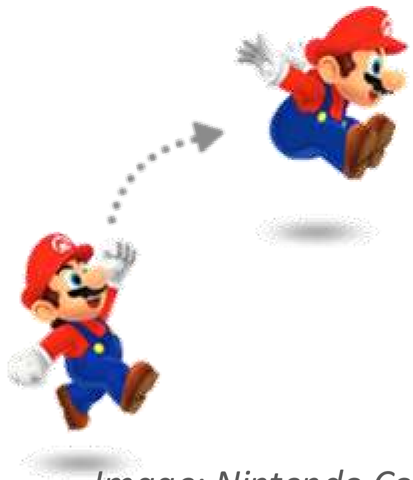


Image: Nintendo Corp.

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Yale University

Presently
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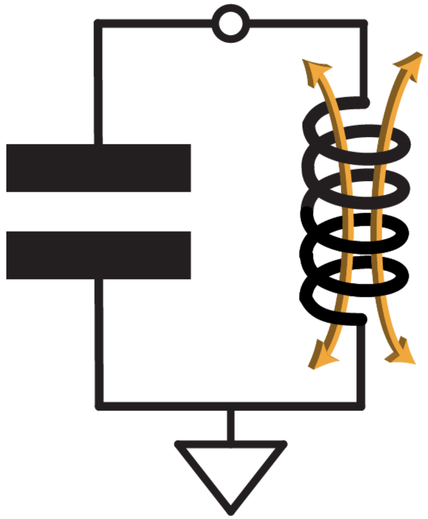
Outline

What is quantum sensing?

Measurements



Circuits

Sensing with circuits: survey

Case study

Sensing photons with nearly 100% efficiency

To catch and reverse a quantum jump mid-flight

What is quantum sensing?

(a discussion)

What is quantum sensing?

"Quantum sensing" describes the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity.

(close to application)

Degen, Reinhard, and Cappellaro, RMP (2017)

a physical quantity is defined by prescribing the operations that are carried out in order to measure it.

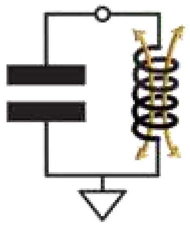
Cook, A.H., Cambridge (1994)

"I know it when I see it."

378 U.S. at 197 (Stewart, J., concurring)

Principal element of sensing: the measurement

Advancing Quantum Sensing via Quantum Control with



Good at measurements

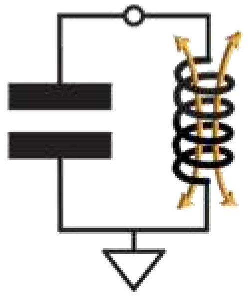
(principal element of sensing)

Good at real-time control

Versatile

Thesis of the talk

Quantum measurements: a primer

with emphasis on sensing for quantum 

continuous

generally dyne detection (diffusive)

time-resolved

near-unit efficiency

resolve the collapse dynamics

A classical measurement example

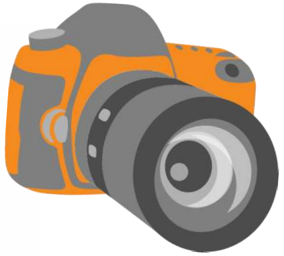
Are there fumes in the oil barrel?

Example based on Wiseman and Milburn (2010)

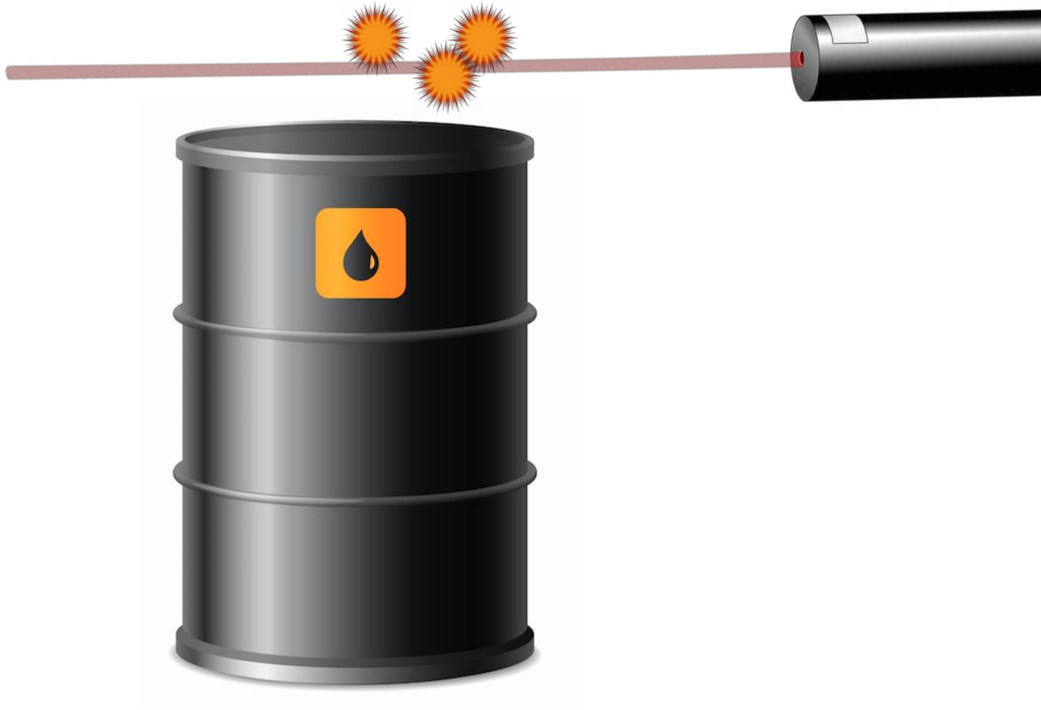
image:freepik.com

Two basic classes of measurements

Demolition



Non-demolition



Caution: Classical measurements can also be disturbing!

e.g., photon absorption

e.g., dispersive cavity

Both accessible in circuits, more on this later

image:freepik.com

Dynamics of interrogating a qubit

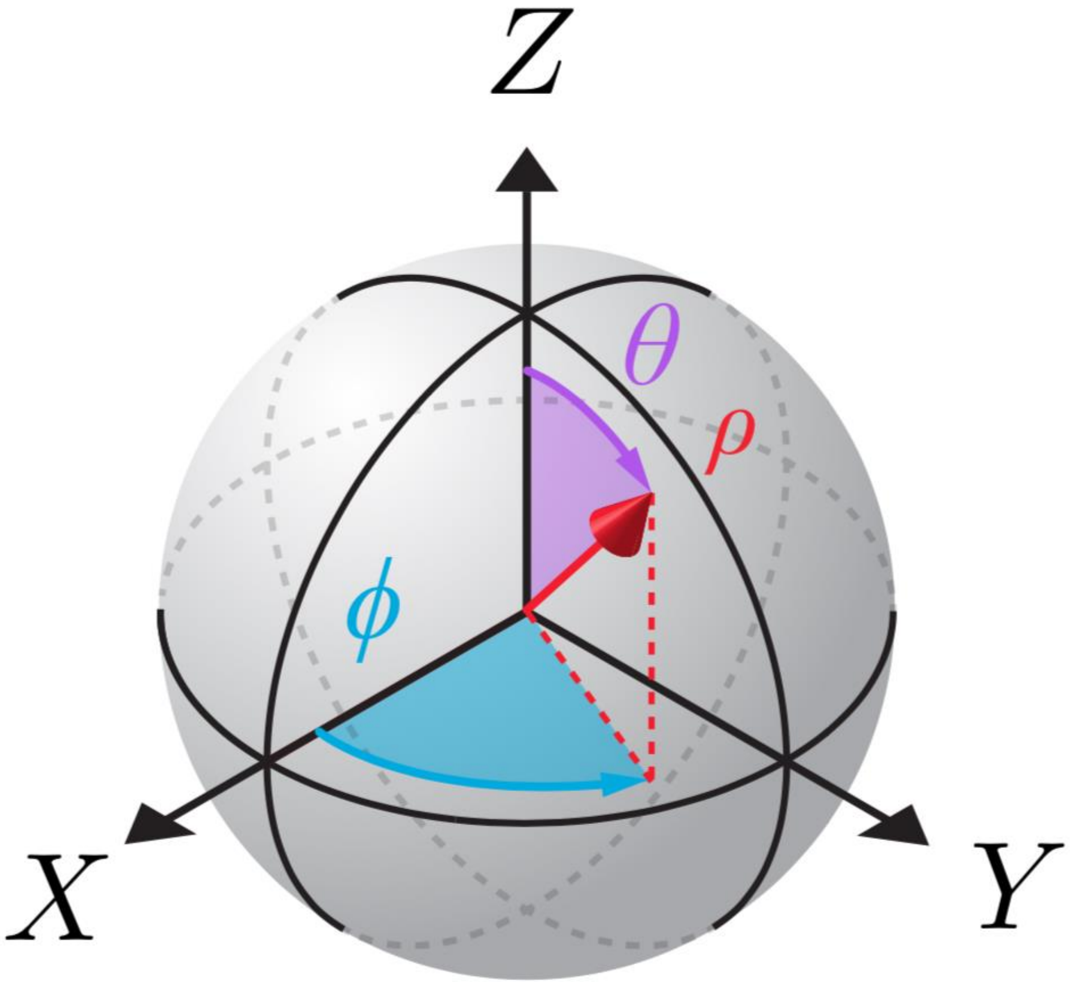
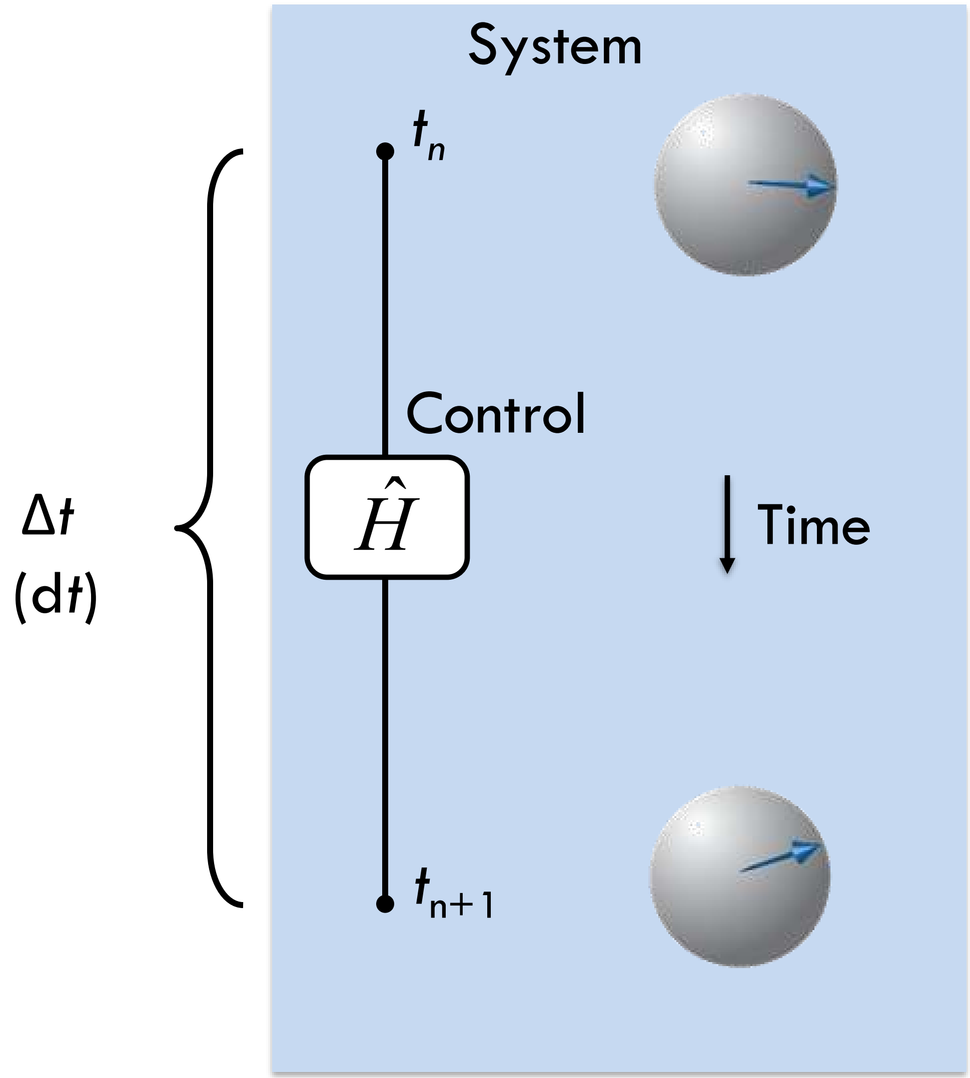
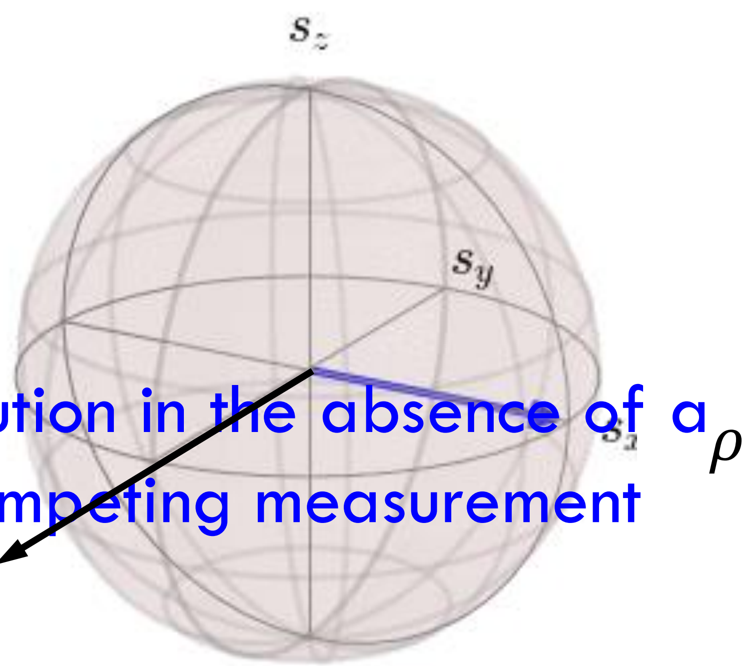


image: Minev, Yale Thesis (2018)

Isolated system



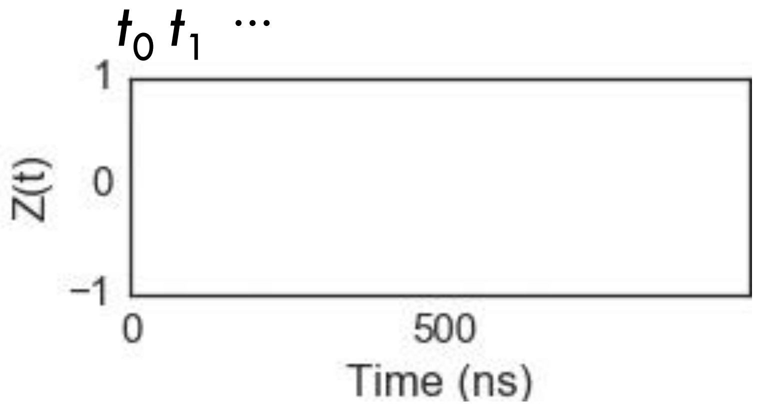
Example: Rabi drive



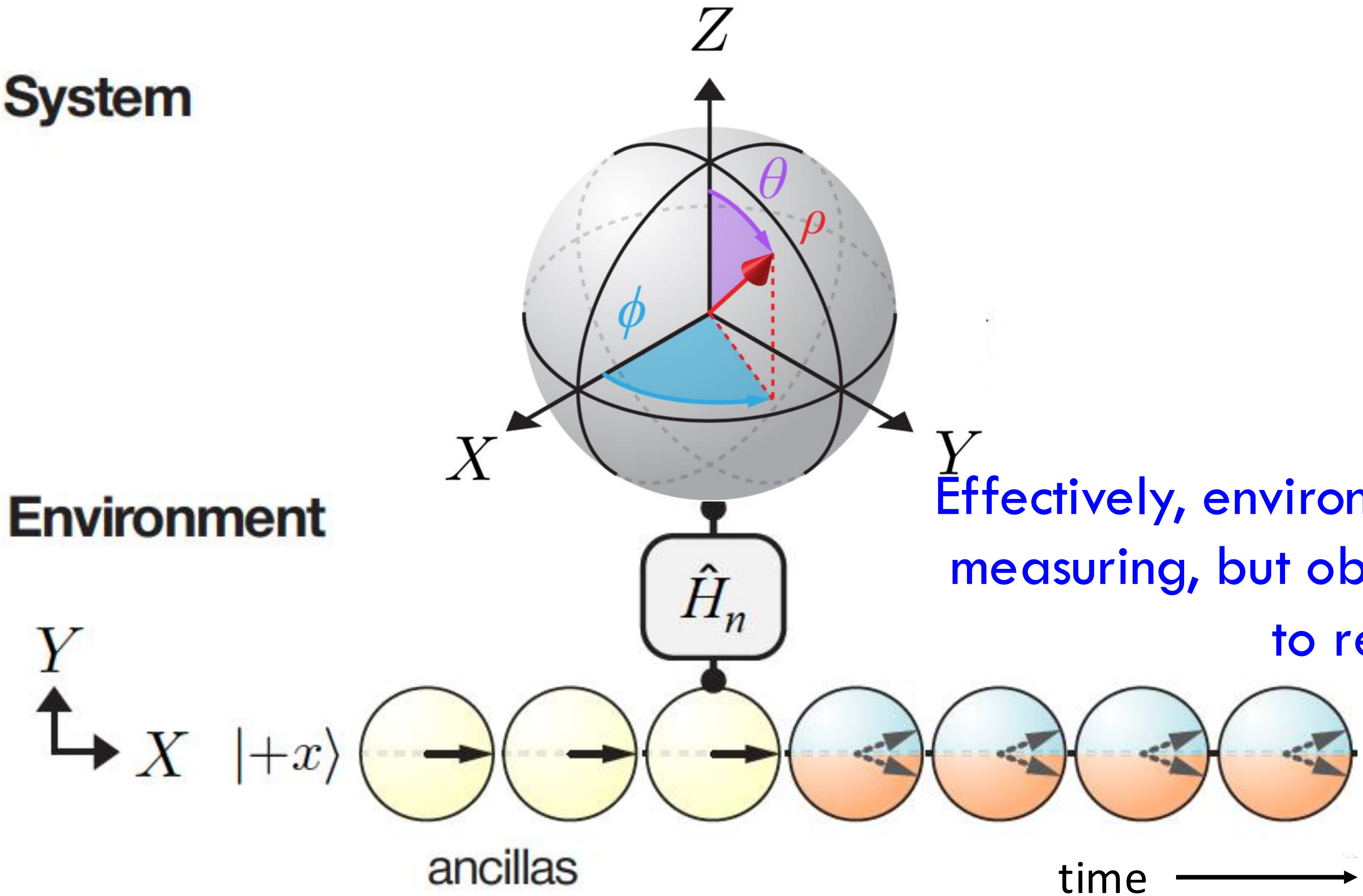
Evolution in the absence of a competing measurement

$$\hat{H} = -\frac{1}{2}\omega_R \hat{\sigma}_Y$$

Bloch component



Open quantum system



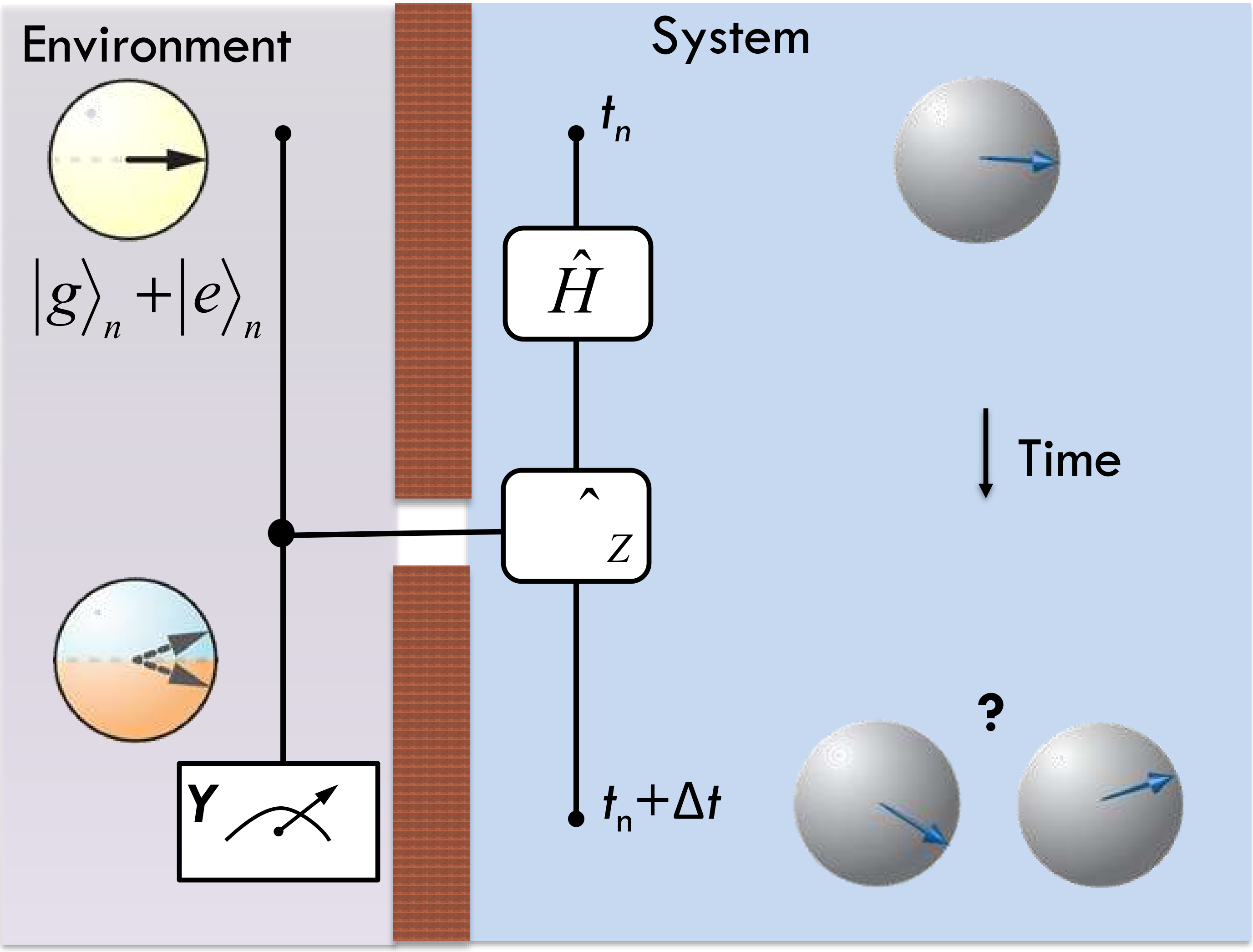
probes

Effectively, environment is continuously measuring, but observer lacks access to record

time →

image: Minev, Yale Thesis (2018)

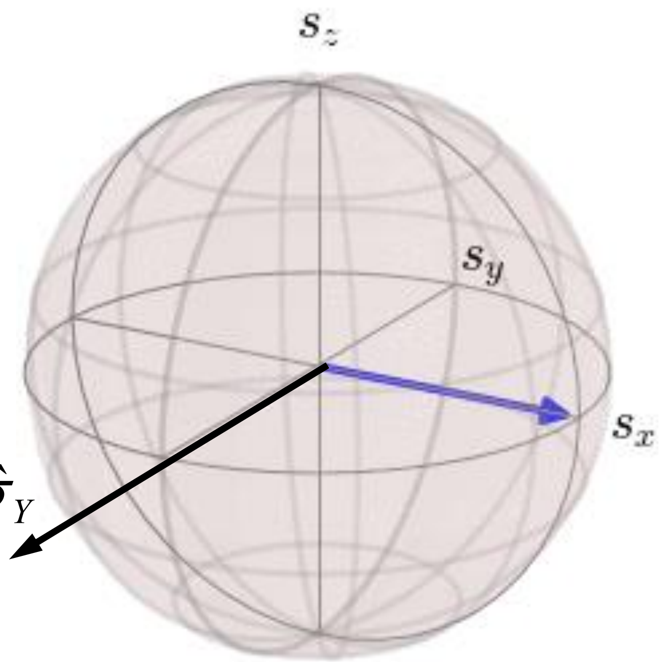
Open system



Example

$\hat{c} = \hat{\sigma}_Z$

$\hat{H} = -\frac{1}{2}\omega_R \hat{\sigma}_Y$



ρ

Model of a monitored quantum system

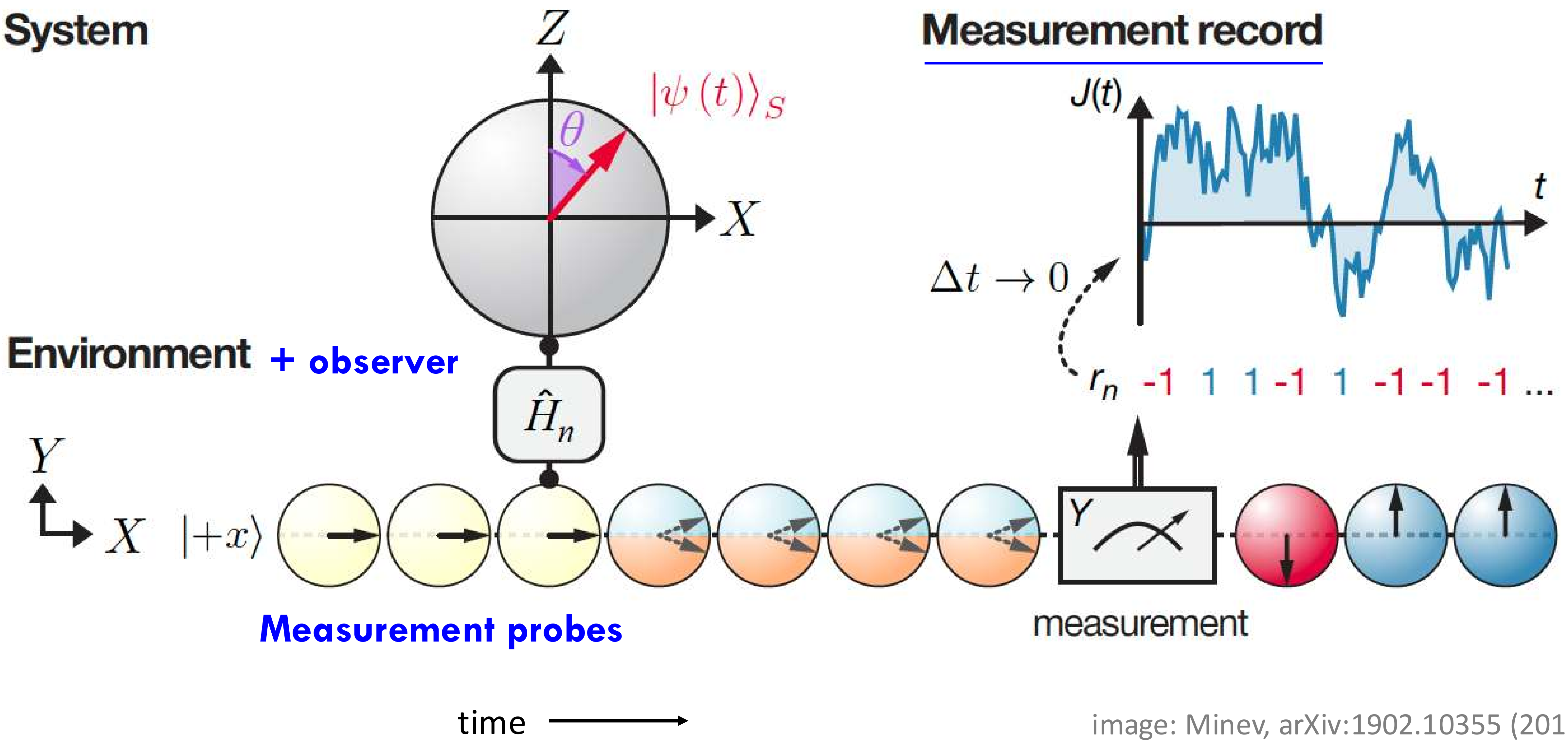
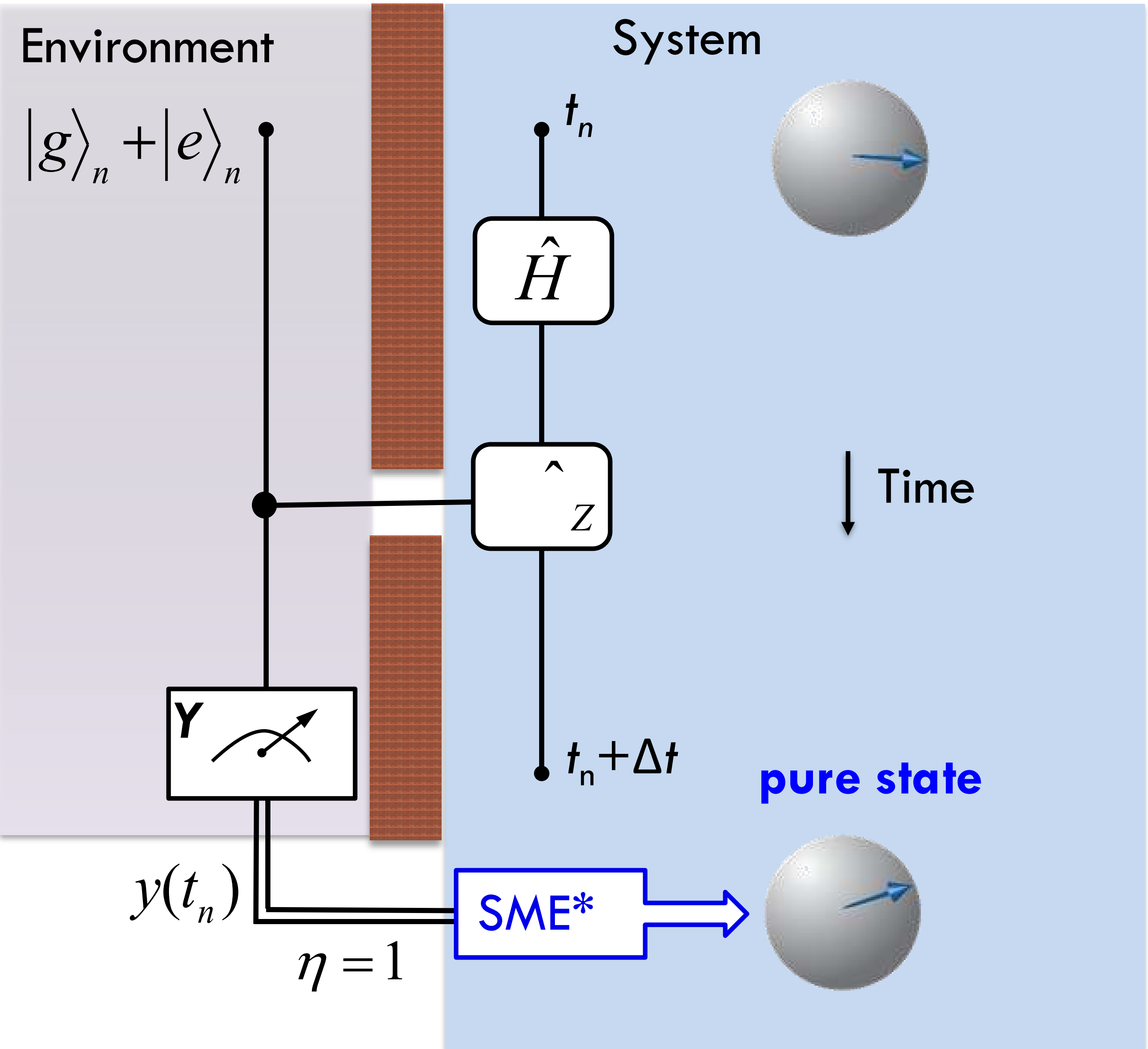


image: Minev, arXiv:1902.10355 (2018)

System + omniscient *observer*

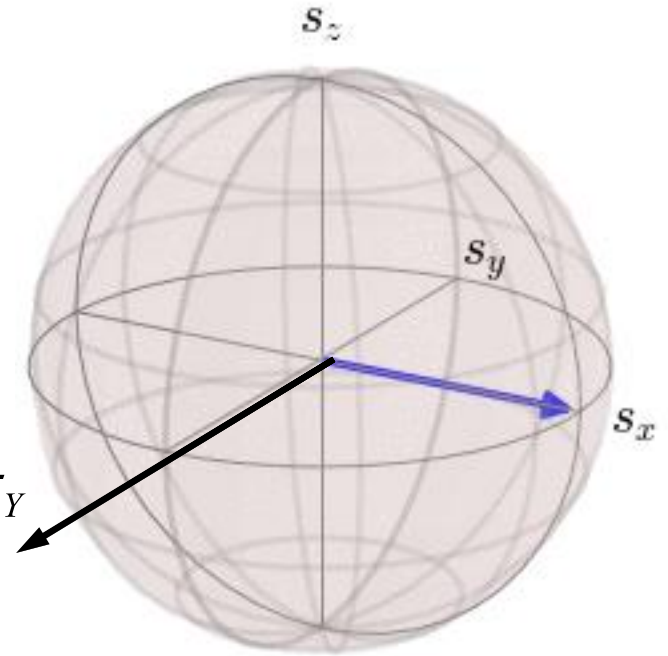


Example

$\hat{c} = \hat{\sigma}_Z$

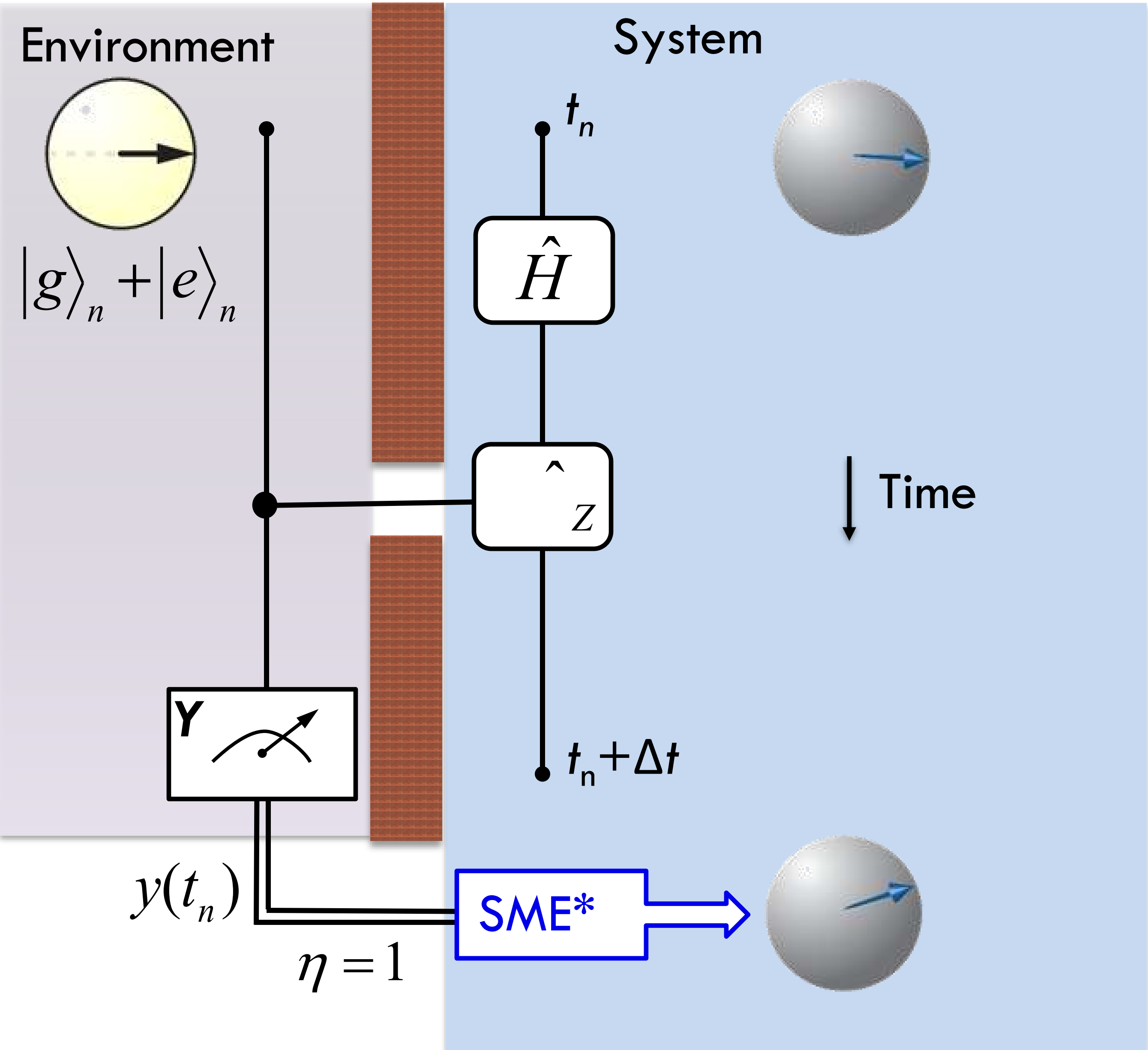
homodyne

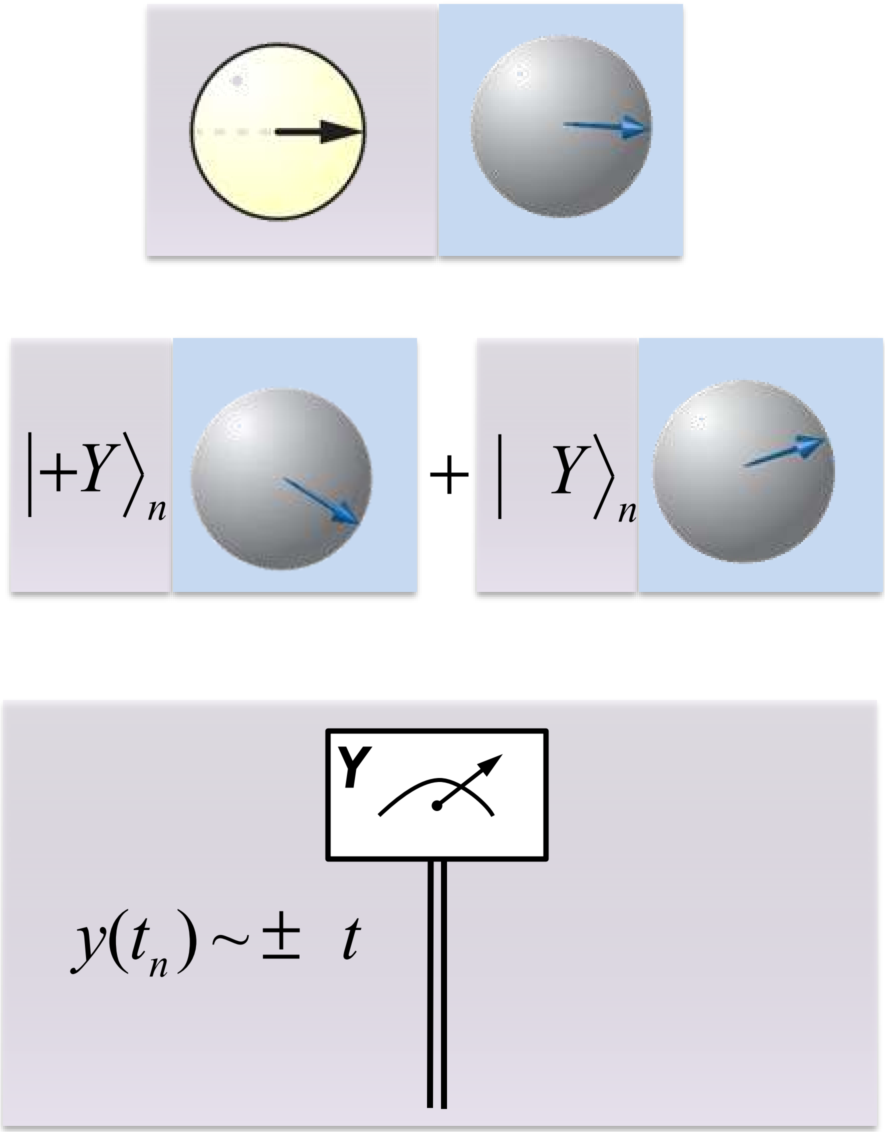
$\hat{H} = -\frac{1}{2}\omega_R \hat{\sigma}_Y$



ρ

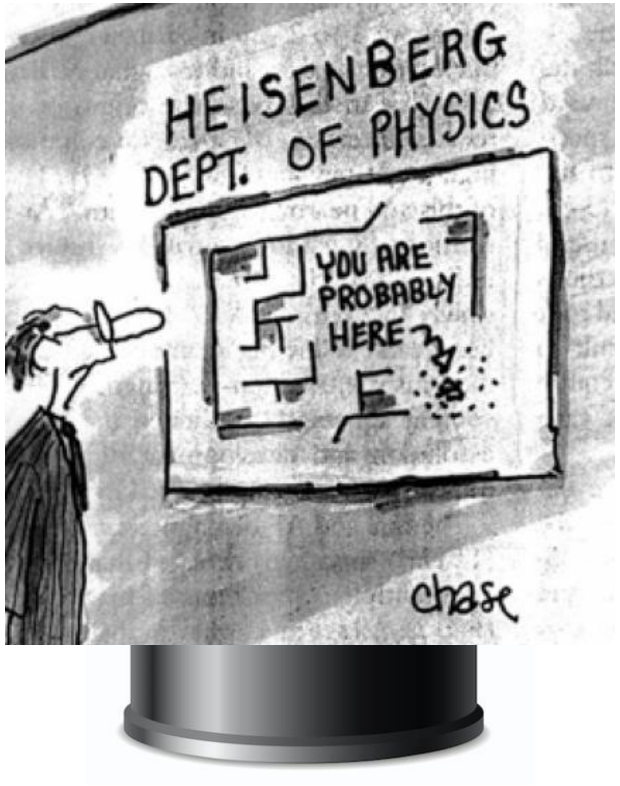
System + omniscient *observer*



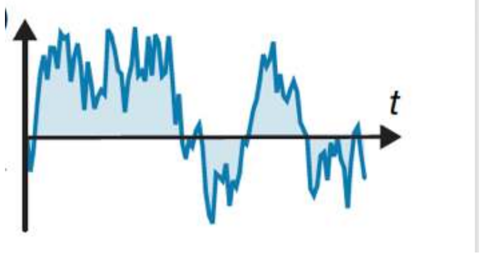


see for instance, Carmichael, *An Open Systems Approach to Quantum Optics* (1993)

Takeaways: Basic character of quantum measurements

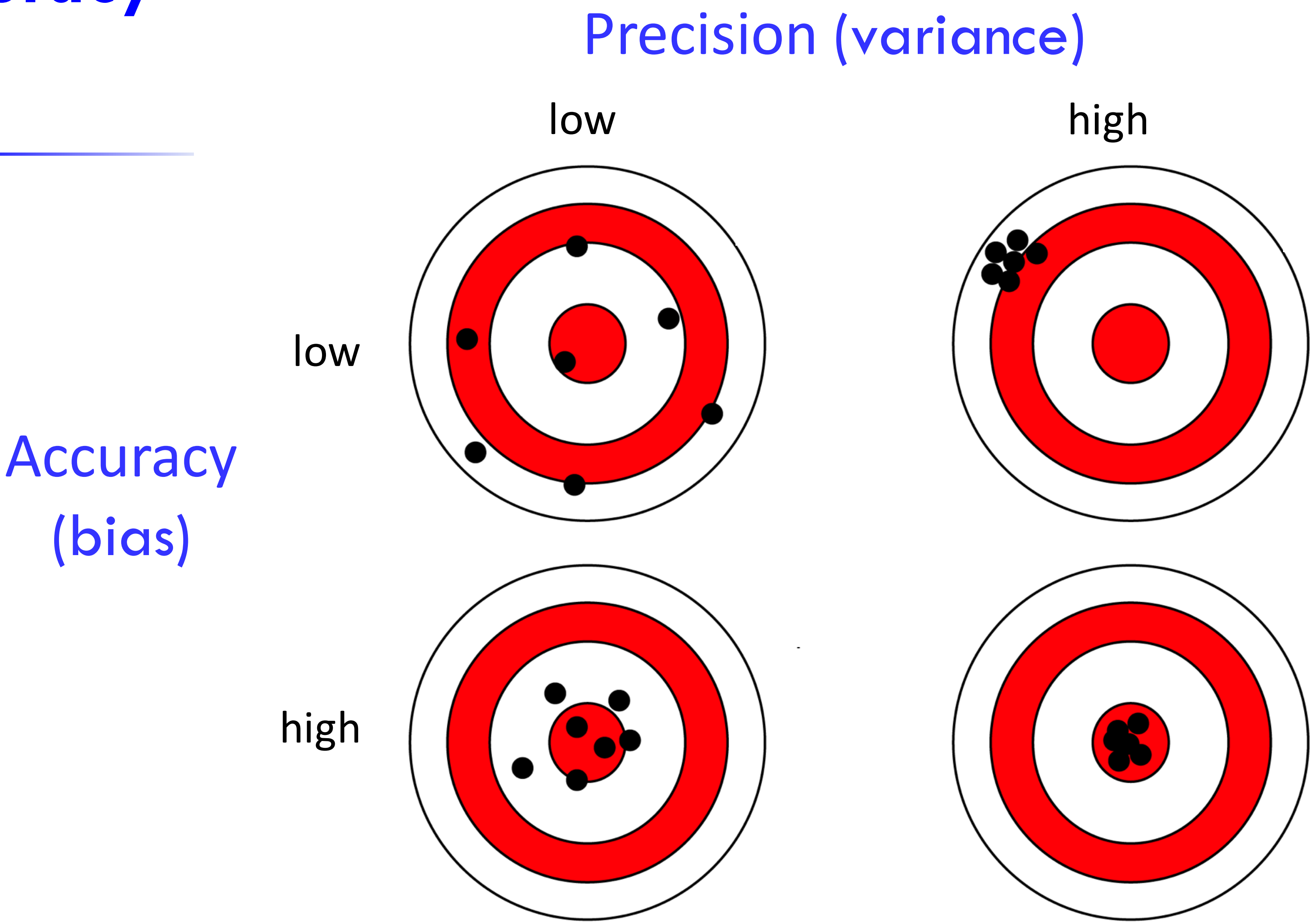


Necessarily *disturb* system (back-action)



- non-commuting
- Heisenberg uncertainty
- fundamental limits to precision, e.g., SQL, …
- no joint probability distribution (over x, p)
  - quasi-probabilities (Wigner functions)
  - no classical Fisher information
- entropy-increasing
- contextuality
- ….

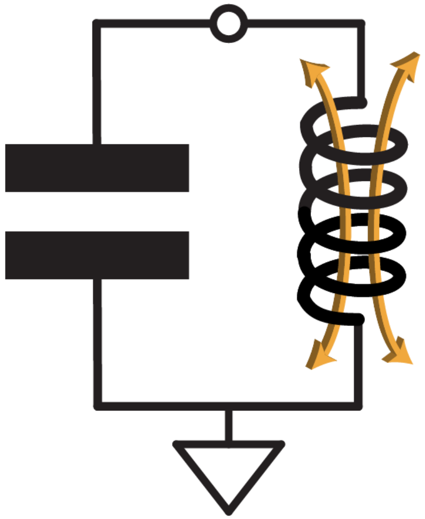
Measurement: accuracy vs. precision

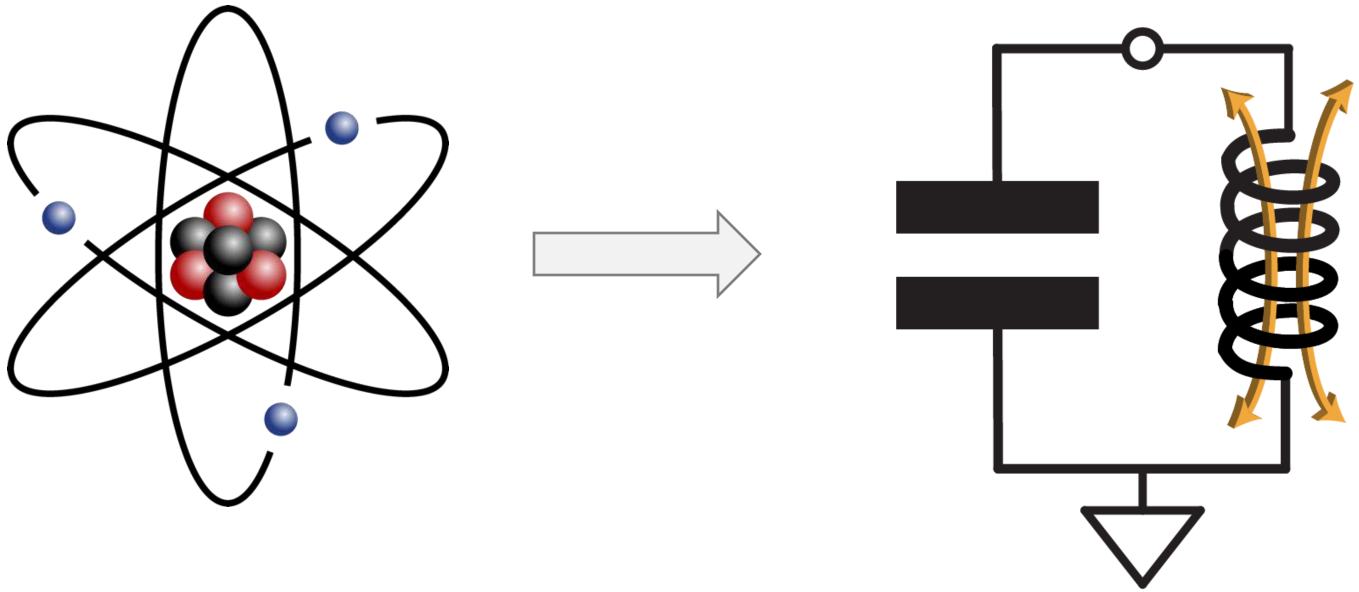


Caution: Within the ISO (5725) framework, there is a slight but important shift in the meaning of these terms

image: antarcticglaciers.com

Superconducting quantum circuits





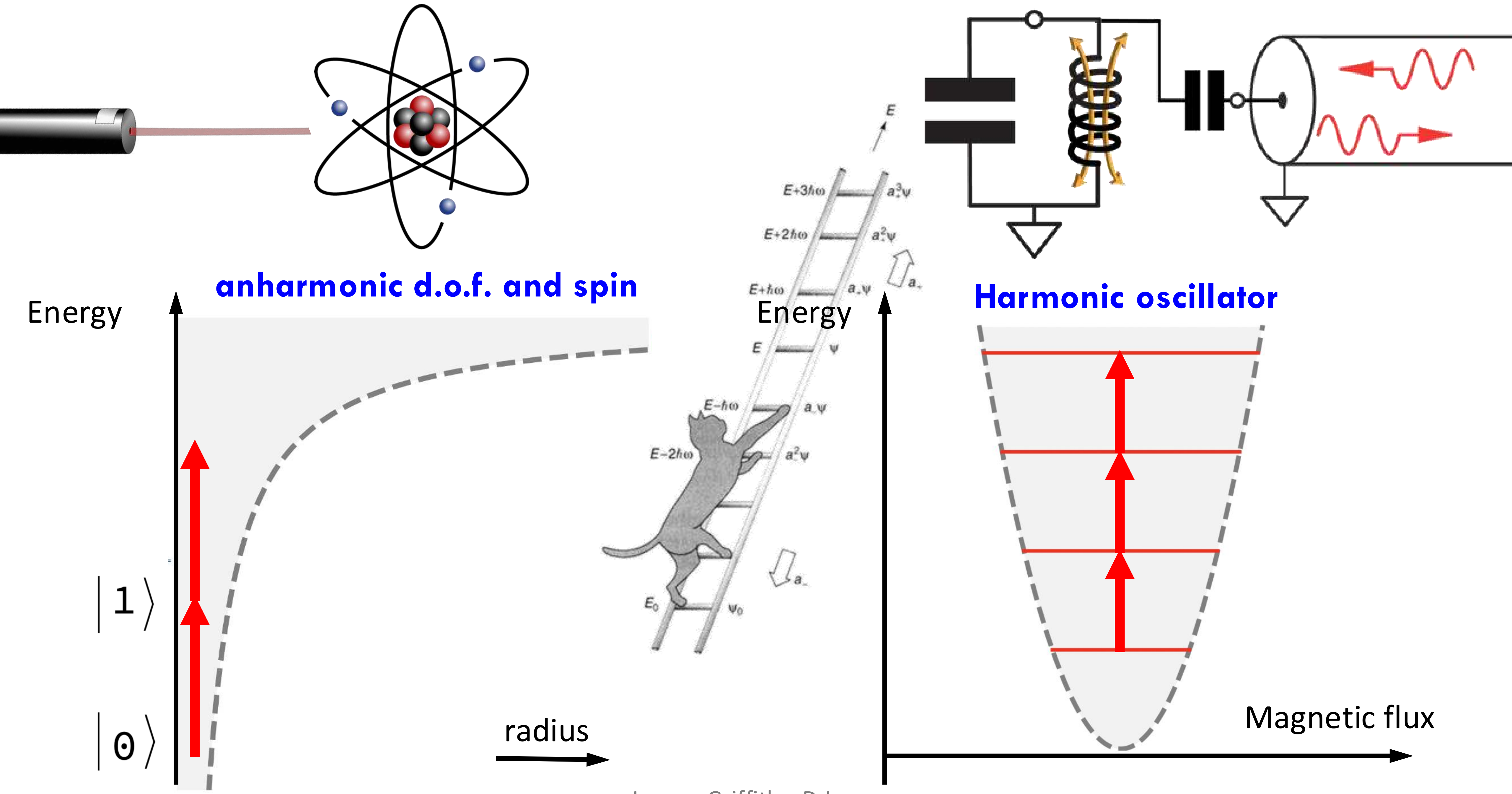
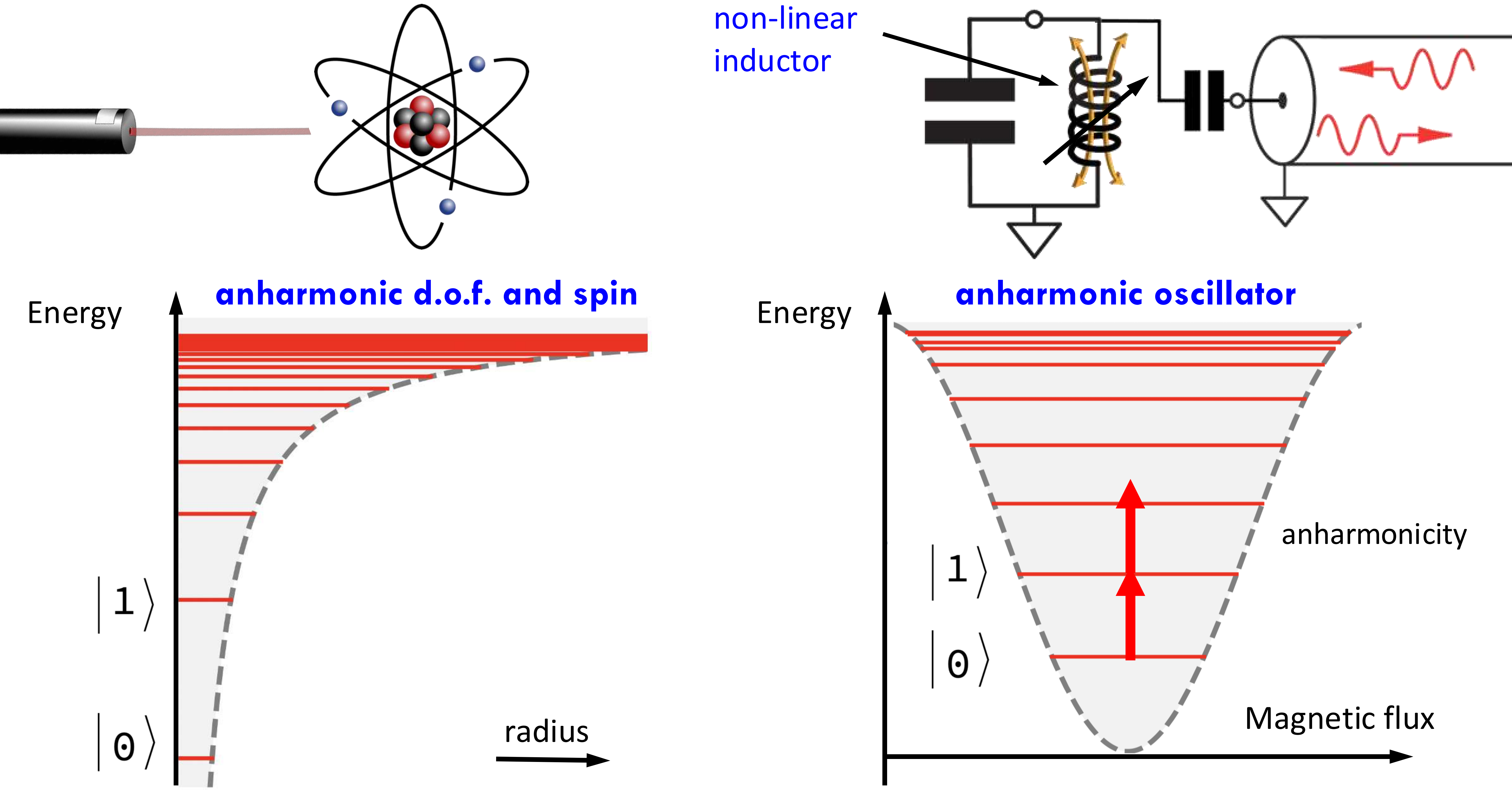
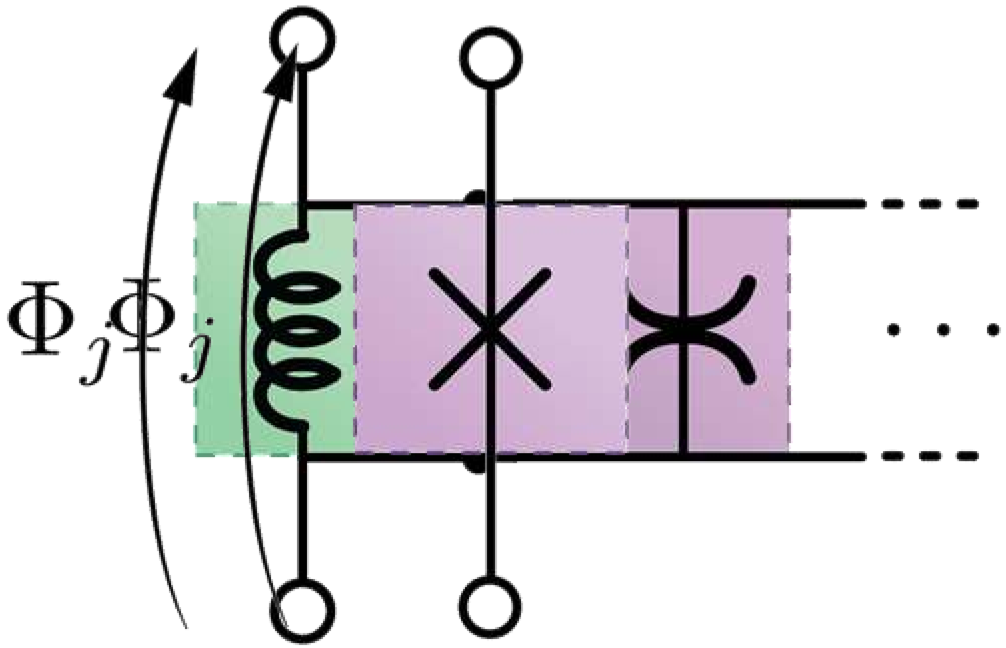


Image: Griffiths, D.J.


non-linear
inductor
anharmonic d.o.f. and spin
Energy
|1⟩
|0⟩
radius
anharmonic oscillator
Energy
anharmonicity
|1⟩
|0⟩
Magnetic flux

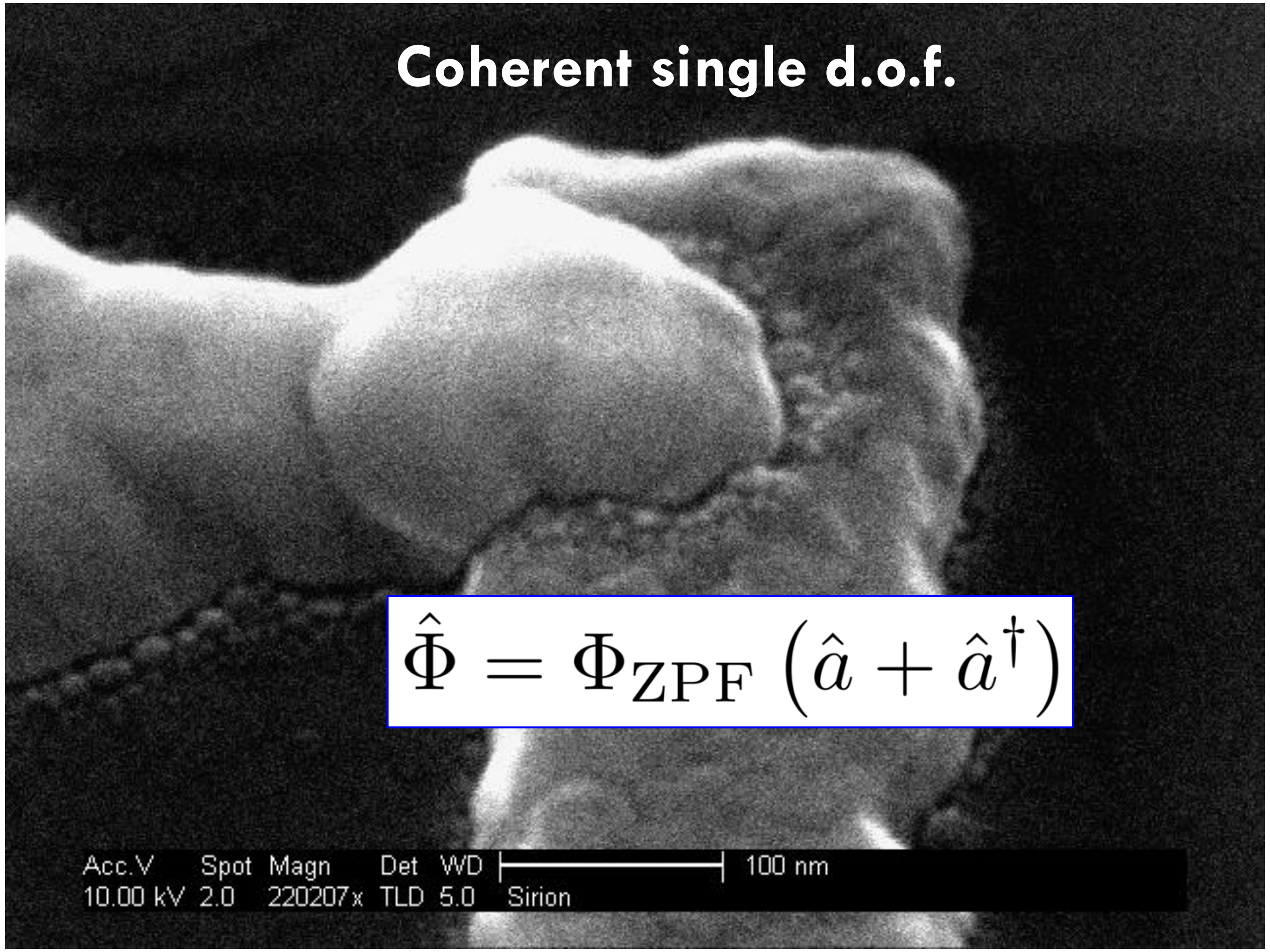
Non-linear element: Josephson tunnel junction



$$\mathcal{E}_j\left(\Phi_j\right) = E_j\left(1 - \cos\left(\Phi_j/\phi_0\right)\right)$$

$$\phi_0 \equiv \hbar/2e \, \Phi_j) + \mathcal{E}_j^{\mathrm{nl}}\left(\Phi_j\right)$$

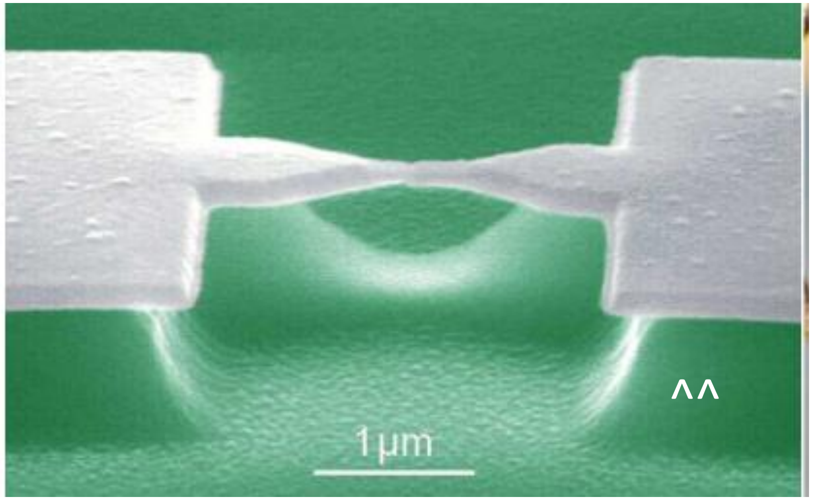
$$= \frac{E_j}{2}\left(\frac{\Phi_j}{\phi_0}\right)^2 - \frac{E_j}{4!}\left(\frac{\Phi_j}{\phi_0}\right)^4 + \mathcal{O}\left(\Phi_j^6\right)$$



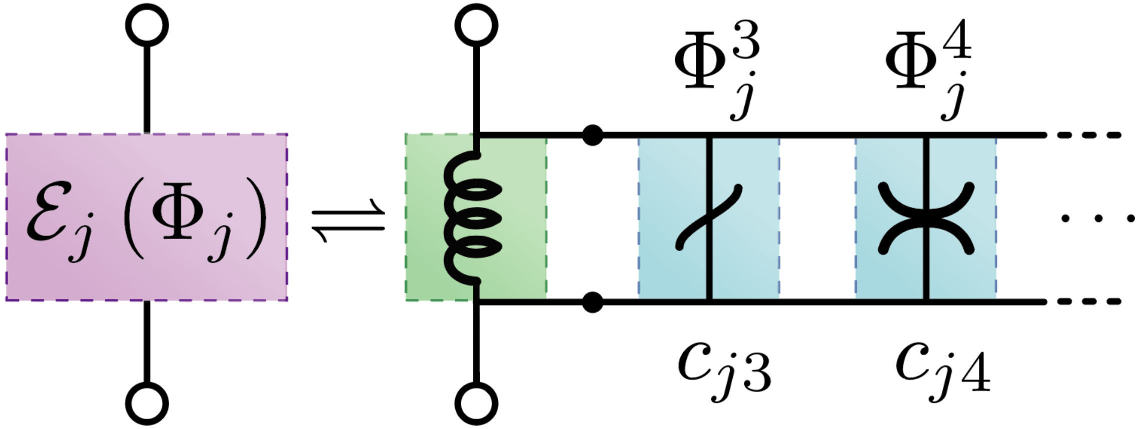
* Minev, Sec. 4.1.1, arXiv:1902.10355

SEM image: L. Frunzio

More general non-linear and hybrid elements



$$\mathcal{E}_j\left(\Phi_j\right) = \mathcal{E}_j^{\text{lin}}\left(\Phi_j\right) + \mathcal{E}_j^{\text{nl}}\left(\Phi_j\right)$$ *



weak-links
nanobridges
kinetic-inductance

atomic point contacts
semiconducting nanowires
2degs
…

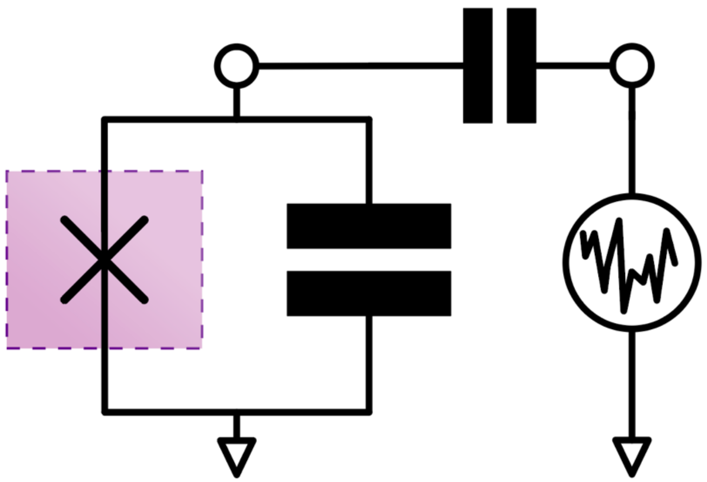
^^ image: Janvier 2015; Vijay 2010, Peltonen 2016; Mooij 2006, Abay 2014, Larsen 2015, DeLange 2015, Casparis 2016; Ho Eom 2012, Vissers 2015; Shim 2014; Shabani 2019; …

* Minev, Sec. 4.1.1, arXiv:1902.10355 and Minev *et al.*, in prep (2019)

Transmon qubit

Circuit

$$\Phi_{\mathrm{ZPF}}/\phi_0 \sim 0.1$$



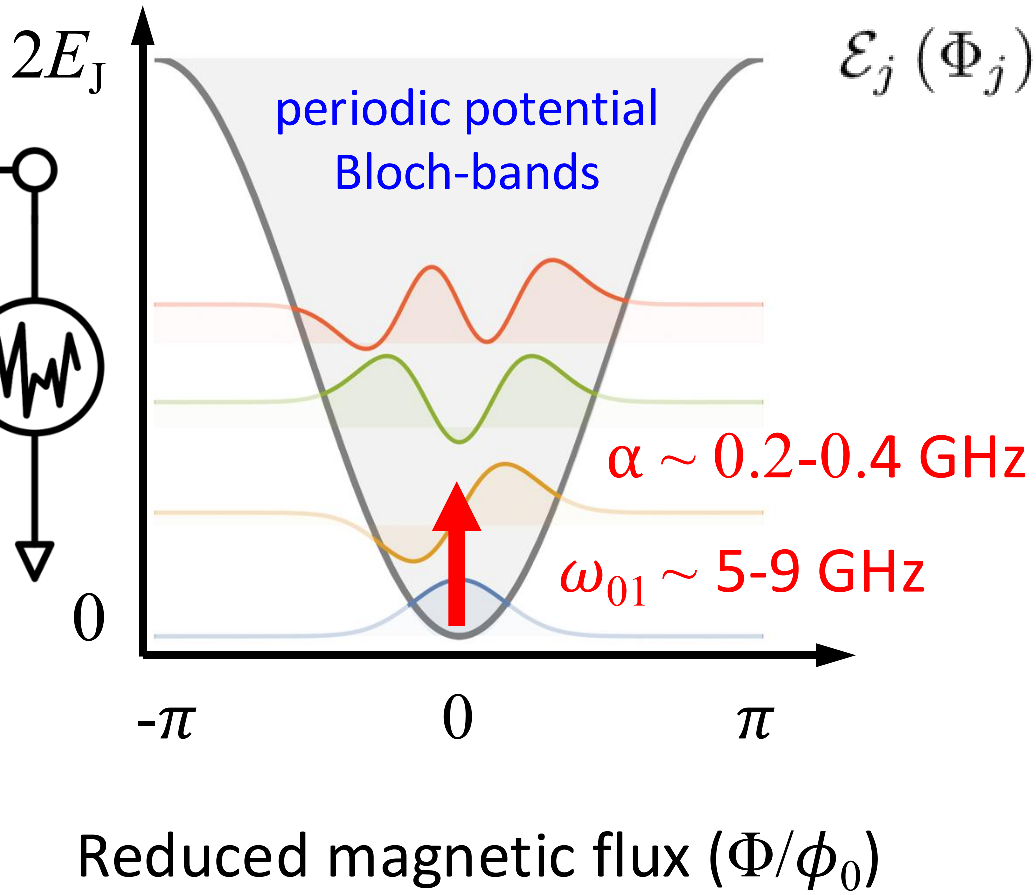
Regime reduces charge sensitivity

Koch *et al.* (2007)

Blais *et al.* (2004)

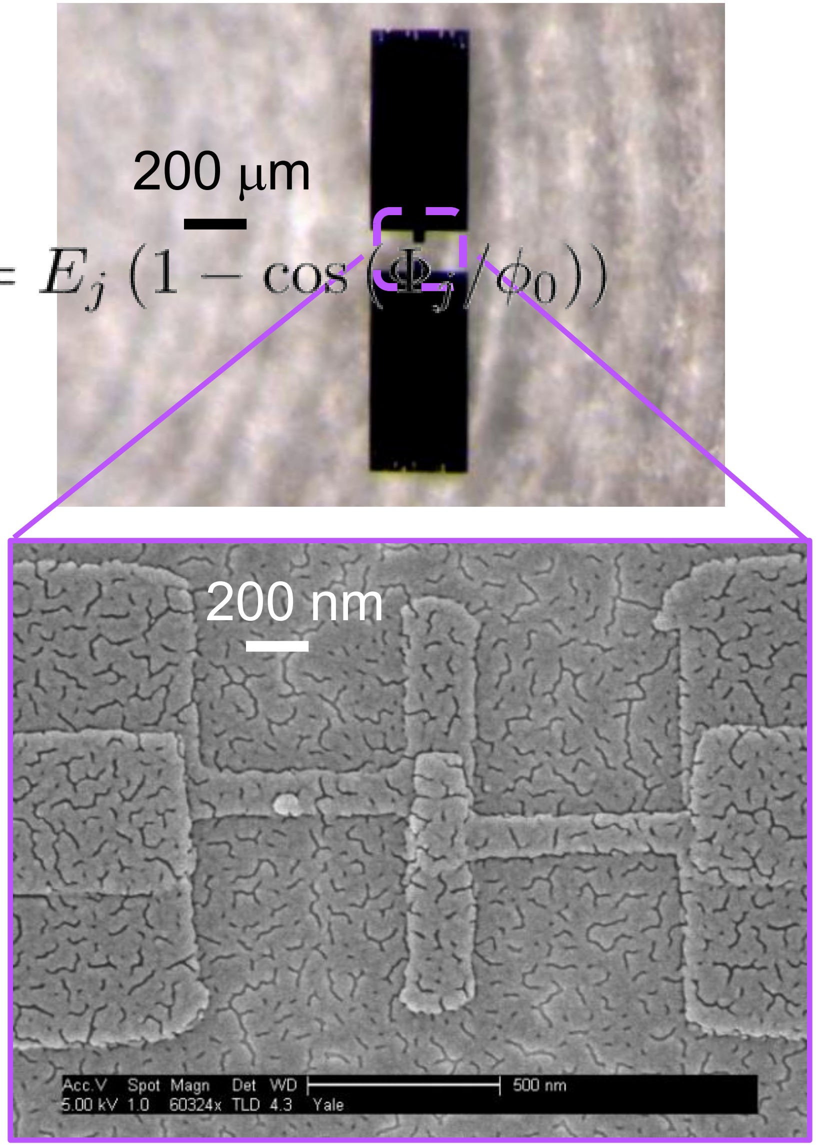
Energy spectrum

$$\hat{H} \approx \omega_0 \hat{a}^\dagger \hat{a} - \frac{\alpha}{2} \hat{a}^{\dagger 2} \hat{a}^2$$



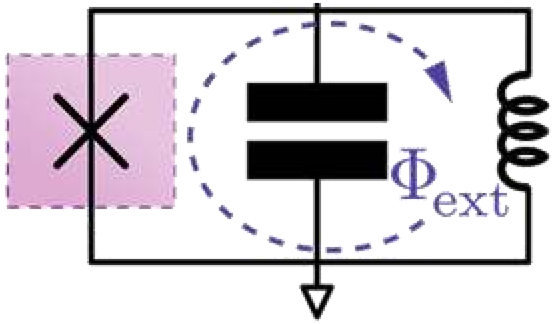
Implementation

$$\mathcal{E}_j\left(\Phi_j\right) = E_j\left(1 - \cos\left(\Phi_j/\phi_0\right)\right)$$

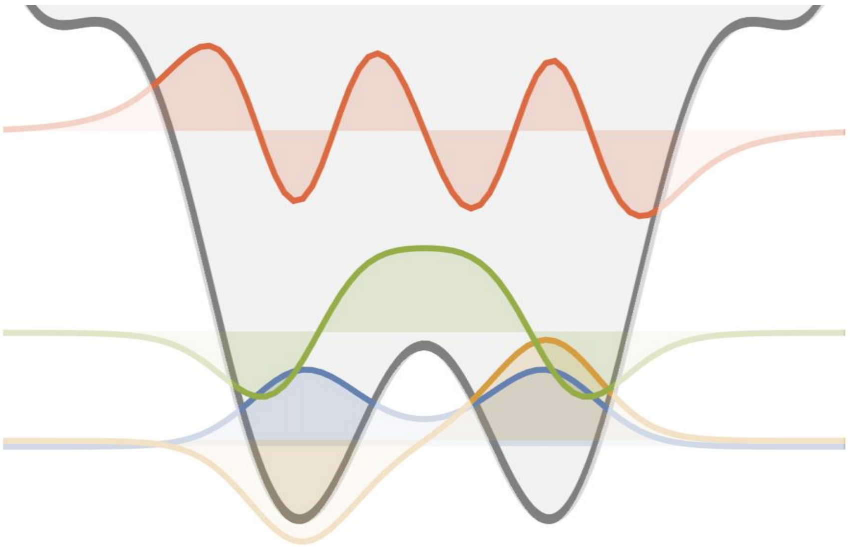


Lego land of qubits: engineer susceptibilities to ext. params.

Fluxonium

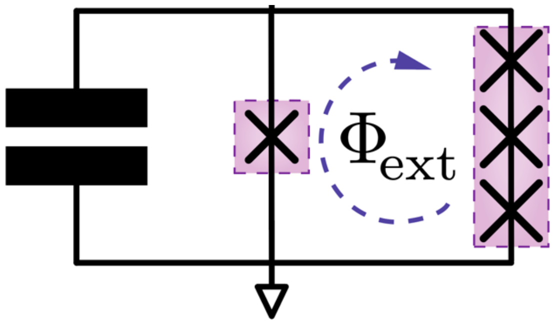


Energy vs. flux (at sweet spot)

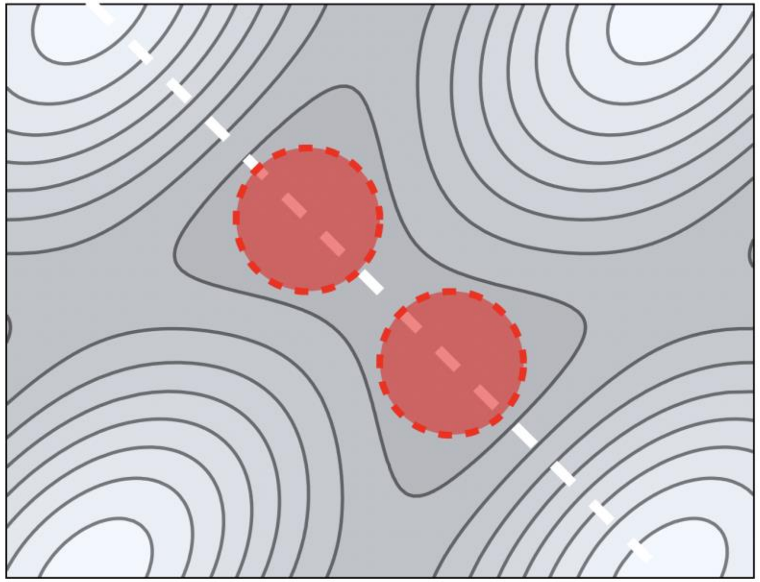


Manucharyan *et al*. (2009), Earnest *et al*. (2018), Lin *et al*. (2018), …

(C-shunted) flux qubit



2D potential (flux degeneracy)



Orlando *et al*. (1999), Mooij *et al*. (1999), You (2006), Stern *et al*. (2014), Yan *et al*. (2016), …

Many more

Quantronium

Phase qubit

Zero-pi qubit

Sin 2 phi qubit

Inductively-shunted transmon

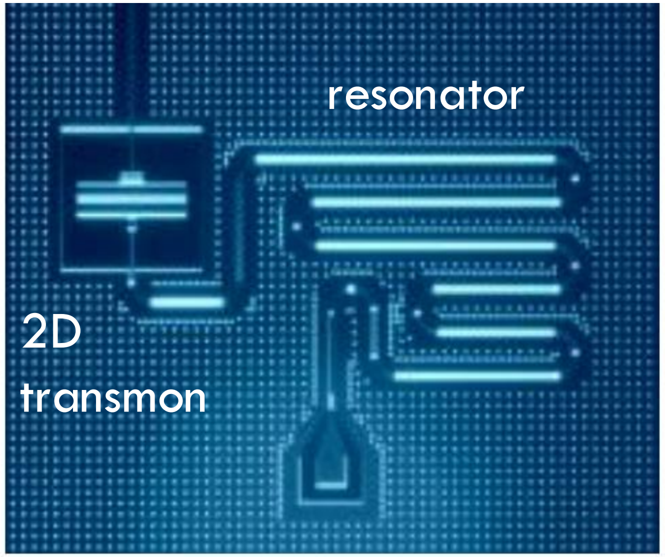
…

Versatile

images: Minev, in prep (2019)

Hardware architectures

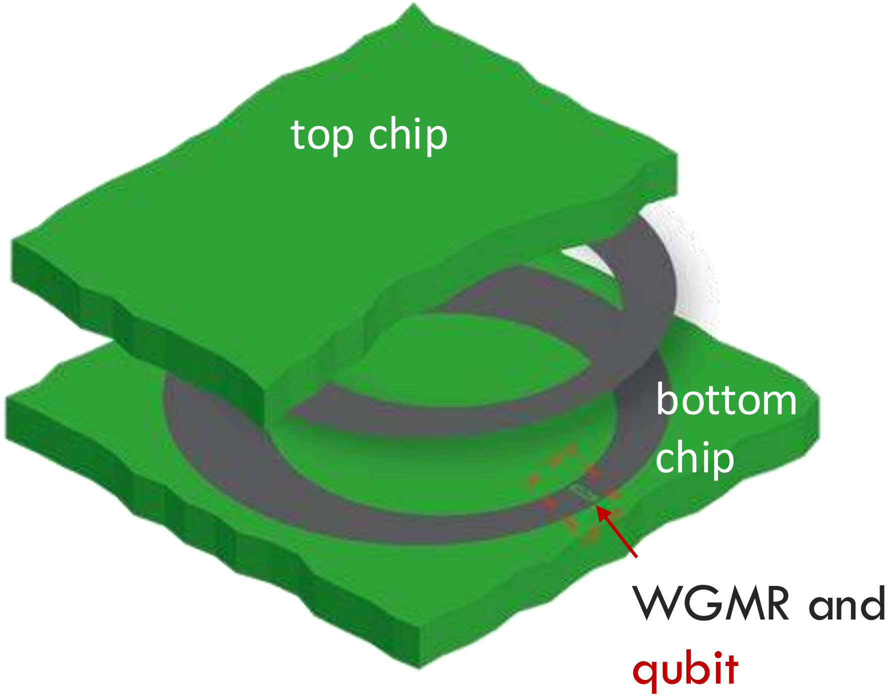
Planar (2D)



Blais *et al.* (2004), Wallraff *et al.* (2004), Barends *et al.* (2014), Yan *et al.* (2014), …

Image: Gambetta, Chow, and Steffen (2017)

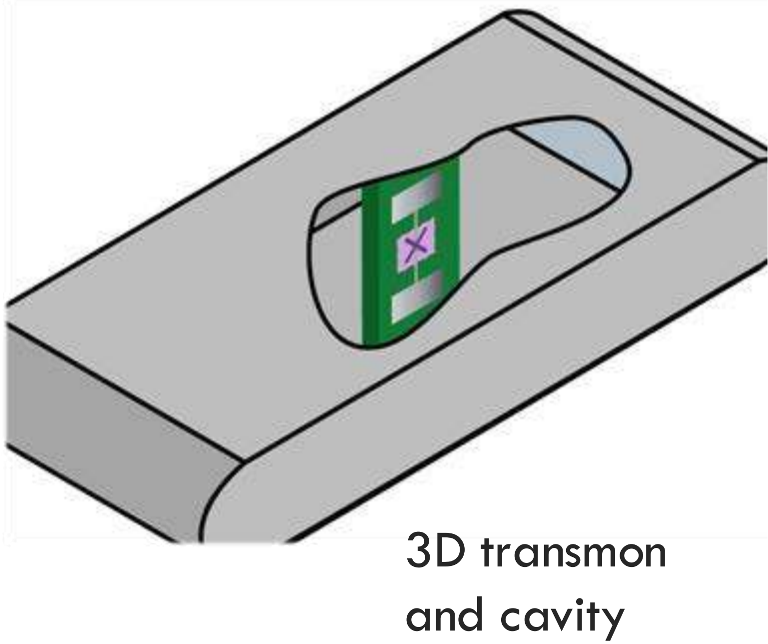
Multilayer planar (2.5D)



Minev *et al.* (2013, 2016), Brecht *et al.* (2016), Rosenberg *et al.* (2017), Yan *et al.* (2014), …

Image: Minev *et al.* (2016)

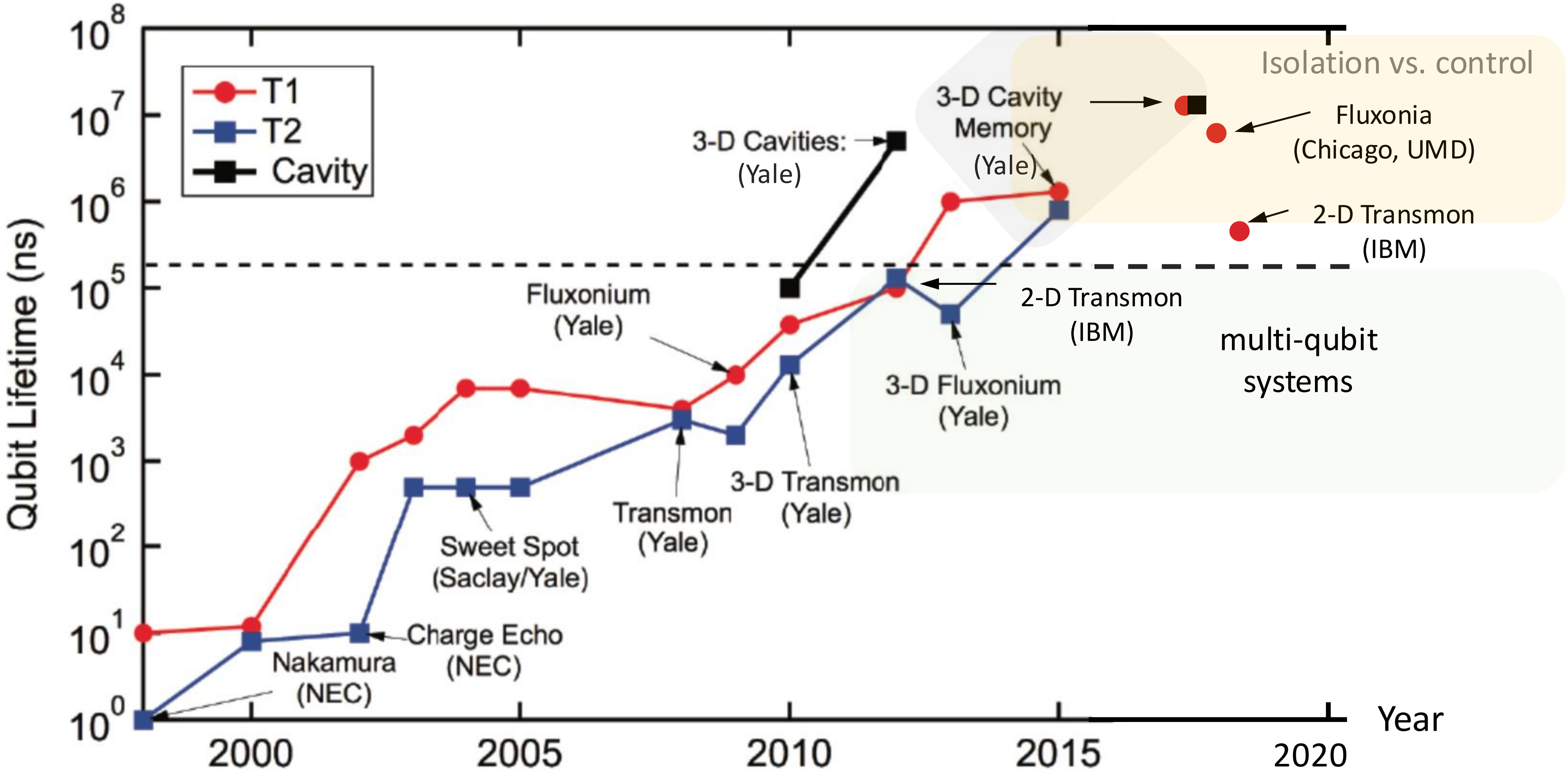
Three-dimensional (3D)



Paik *et al.* (2011), Reagor (2016) …

Image: Minev *et al.* (2019)

Coherence in superconducting circuits



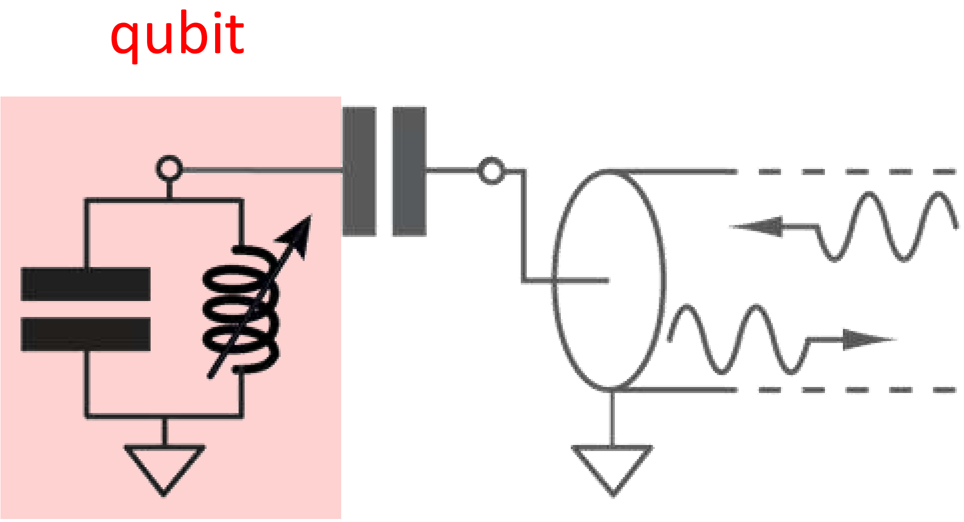
Schoelkopf's law: coherence 10x every 3 yrs. Note, for single system.

Image reproduced Reagor (2015), an update of Devoret and Schoelkopf (2013), and updated (2019)

How to measure?

Qubit measurement with circuits

Direct monitoring

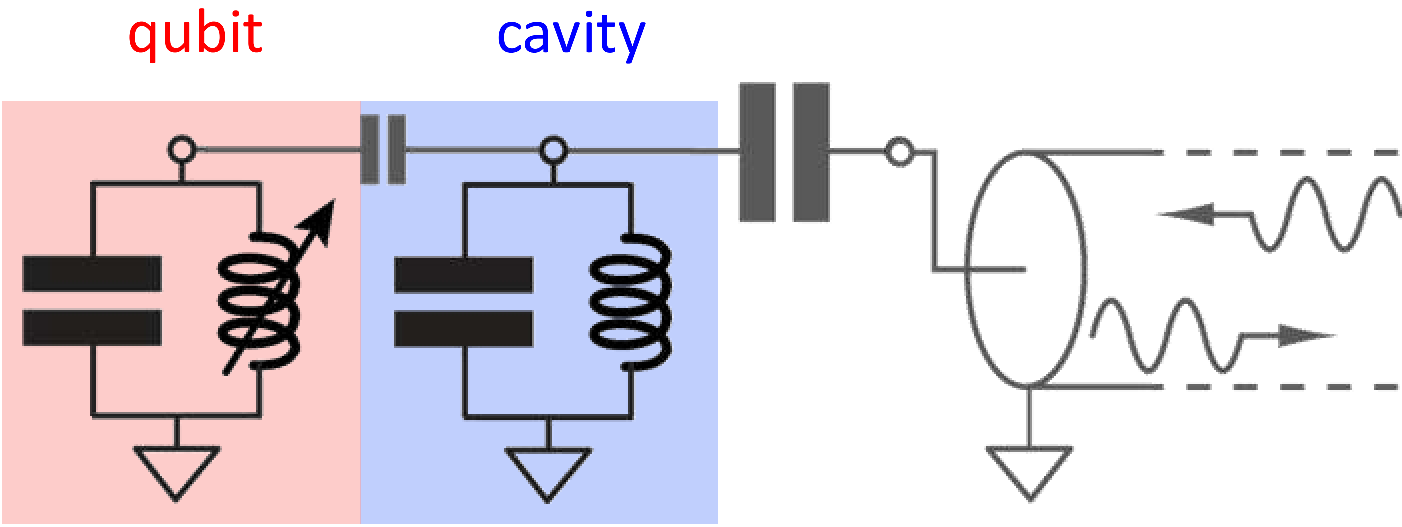


 Demolition

 Spontaneous emission

Clarke & Wilhelm, Nature (2008)

cQED dispersive



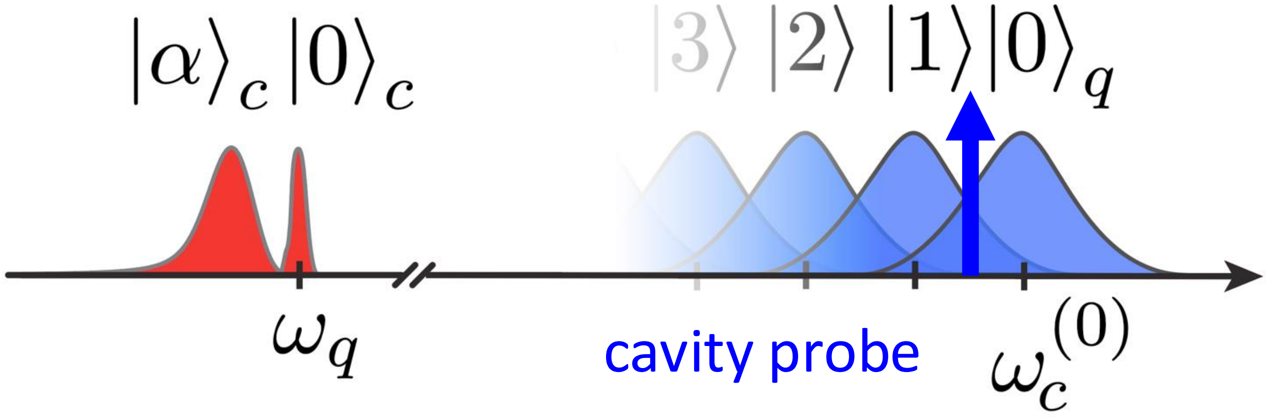
 Quantum non-demolition* (QND)

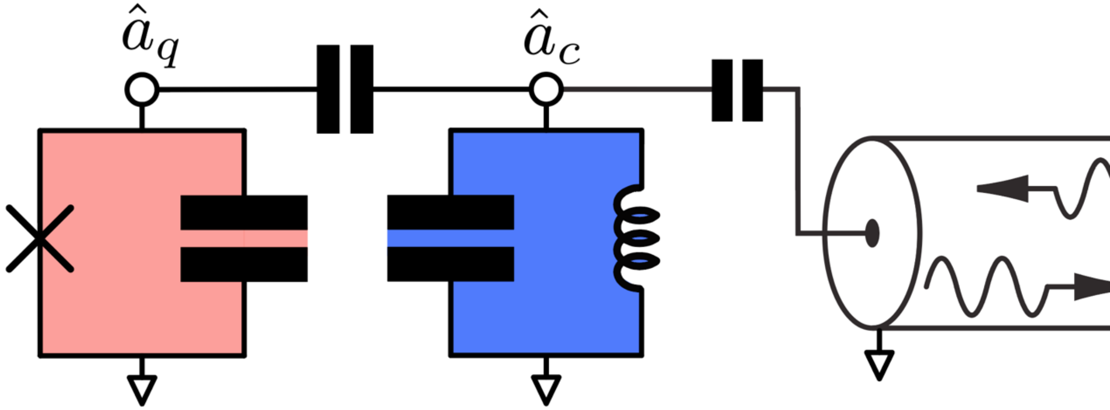
 Inhibited spontaneous emission

Blais *et al.*, PRA (2004)

cQED dispersive readout: measuring Z

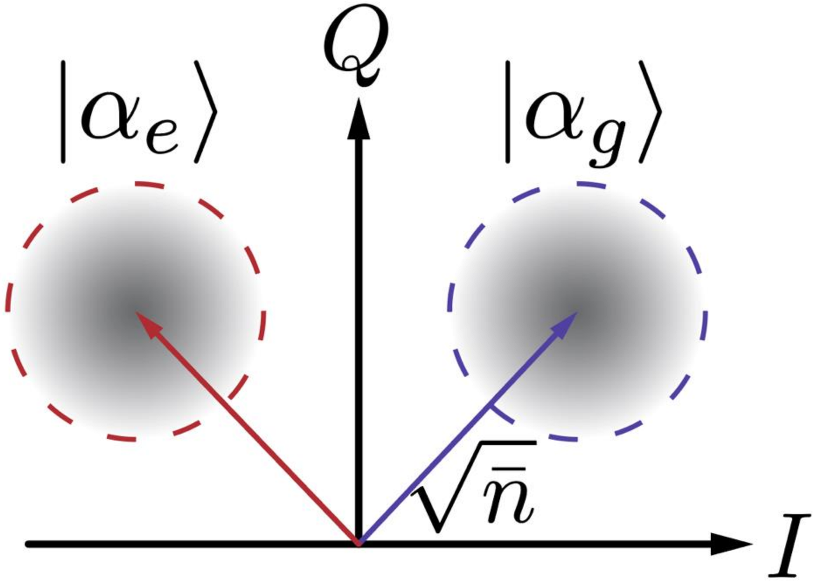
Response spectrum





qubit

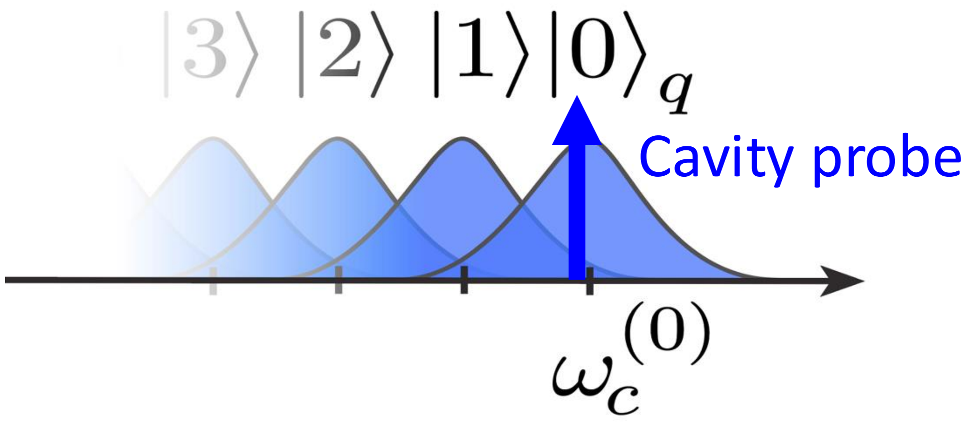
cavity
(msrmt. apparatus)

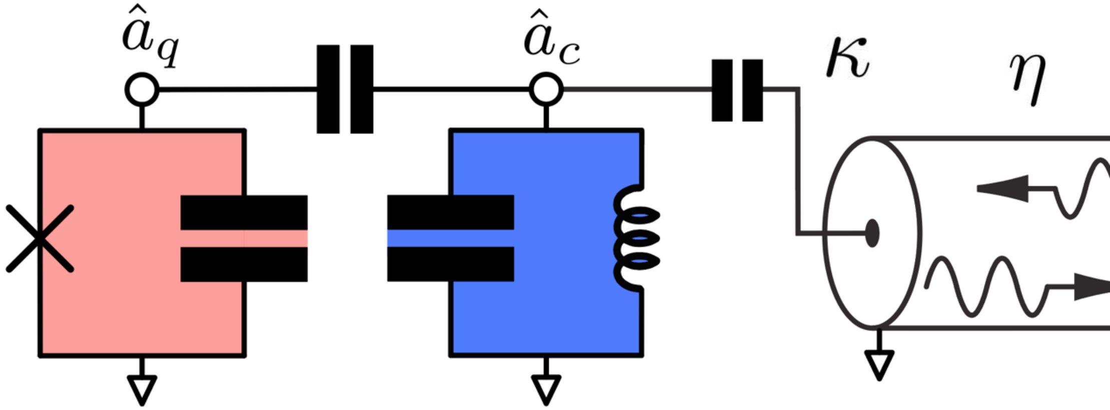


$$\hat{H}_{\text{int}} = \hbar\chi \hat{a}_q^\dagger \hat{a}_q \hat{a}_c^\dagger \hat{a}_c$$

Pointer states of measurement apparatus (cavity) correspongin to the qubit in the ground (*g*) and excited (*e*) states

cQED dispersive readout: measuring Z





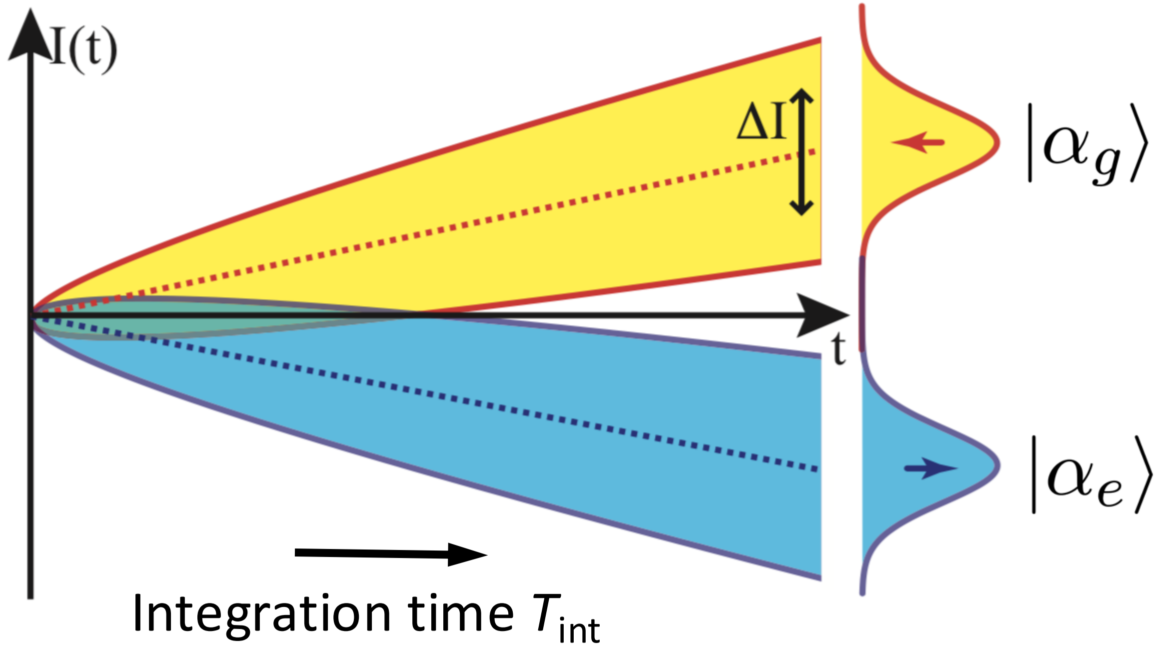


image: Clerk *et al.* (2010)

$$\mathrm{SNR} = \frac{1}{2}\eta\kappa T_{\mathrm{int}}\,|\alpha_e - \alpha_g|^2$$

distinguishability

$$\eta_{\mathrm{disc}} = \frac{1}{2}\,\mathrm{erfc}\left[-\sqrt{\frac{\mathrm{SNR}}{2}}\right]$$

efficient, fast measurements

Tradeoff: sensitivity vs. noise-susceptibility

Purcell effect

T_1

$$T_1^{\text{Purcell}} = \frac{C_q}{\text{Re}[Y(\omega_{\text{q}})]}$$

Esteve *et al.*, PRB (1986)
Neeley *et al.*, PRB (2008)
Reed, Thesis (2013)
…

Photon-shot-noise dephasing

T

$$\Gamma_{\text{th}} = \frac{4\chi^2 n_{\text{th}}^{\text{eff}}}{\kappa_{\text{tot}}}(n_{\text{th}}^{\text{eff}} + 1) \quad \text{large } \kappa_{\text{tot}}/\chi$$

Gambetta *et al.*, PRA (2006)
Schuster, Thesis (2007)
Rigetti *et al.*, PRB (2012)
…

T1 vs. $\overline{n}$

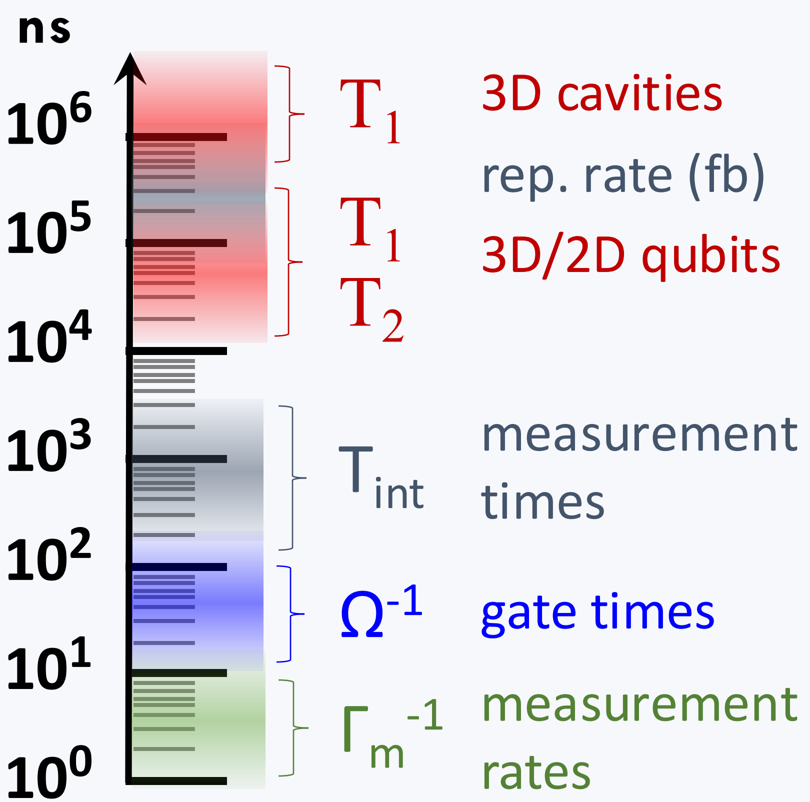
readout, QND

?

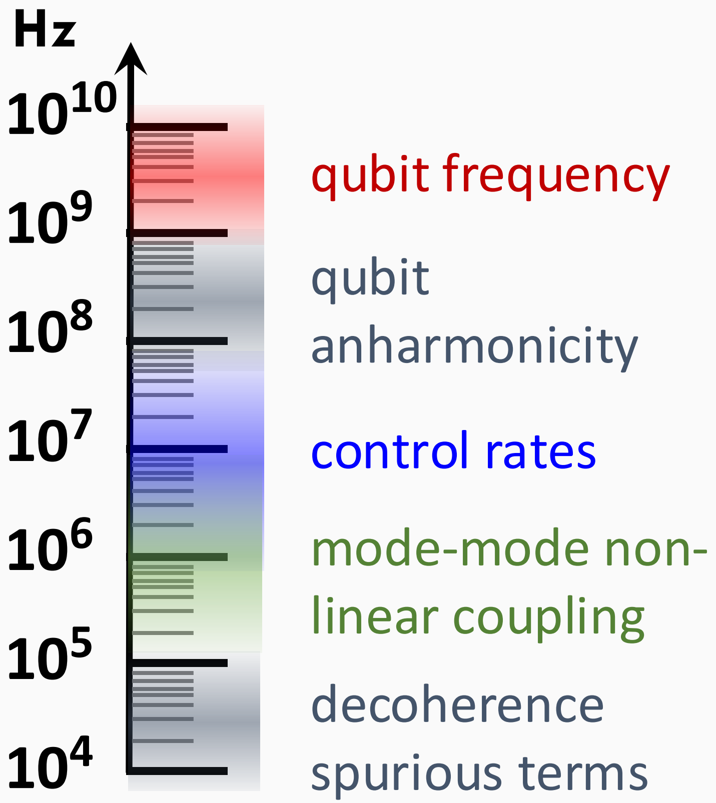
Boissonneault *et al.*, PRA (2009)
Slichter *et al.*, PRL (2012)
Shantanu, MLS (2015)
Sank *et al.*, PRL (2016)
…

High separation of timescale b/w noise and control

System timescales

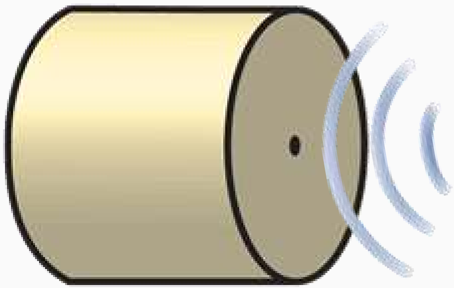


Frequency bands



High efficiency detection

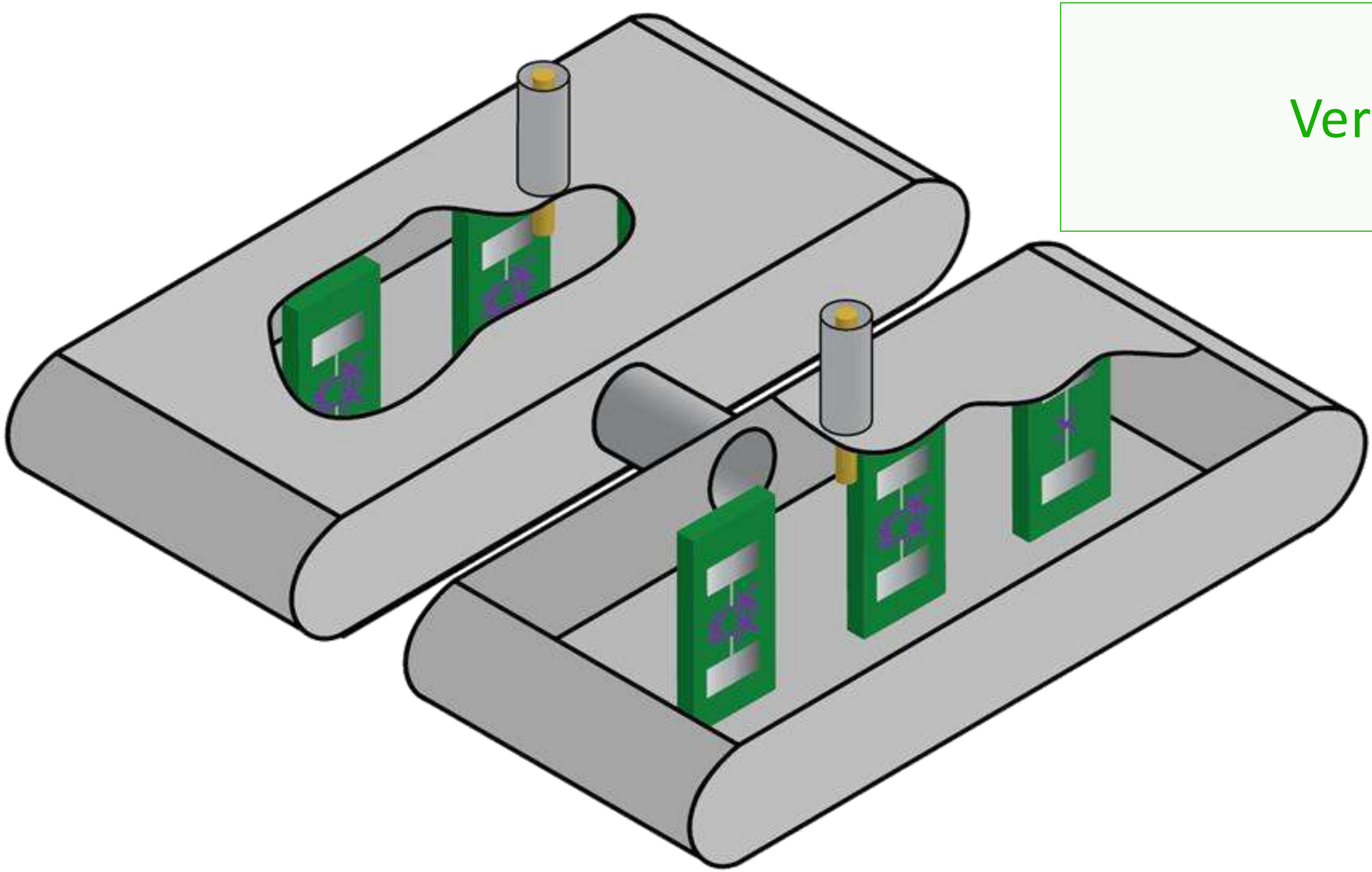
$\eta \sim 0.1\text{-}0.5$



(using quantum-limited amplifiers)

How to design circuits with versatility and precision?

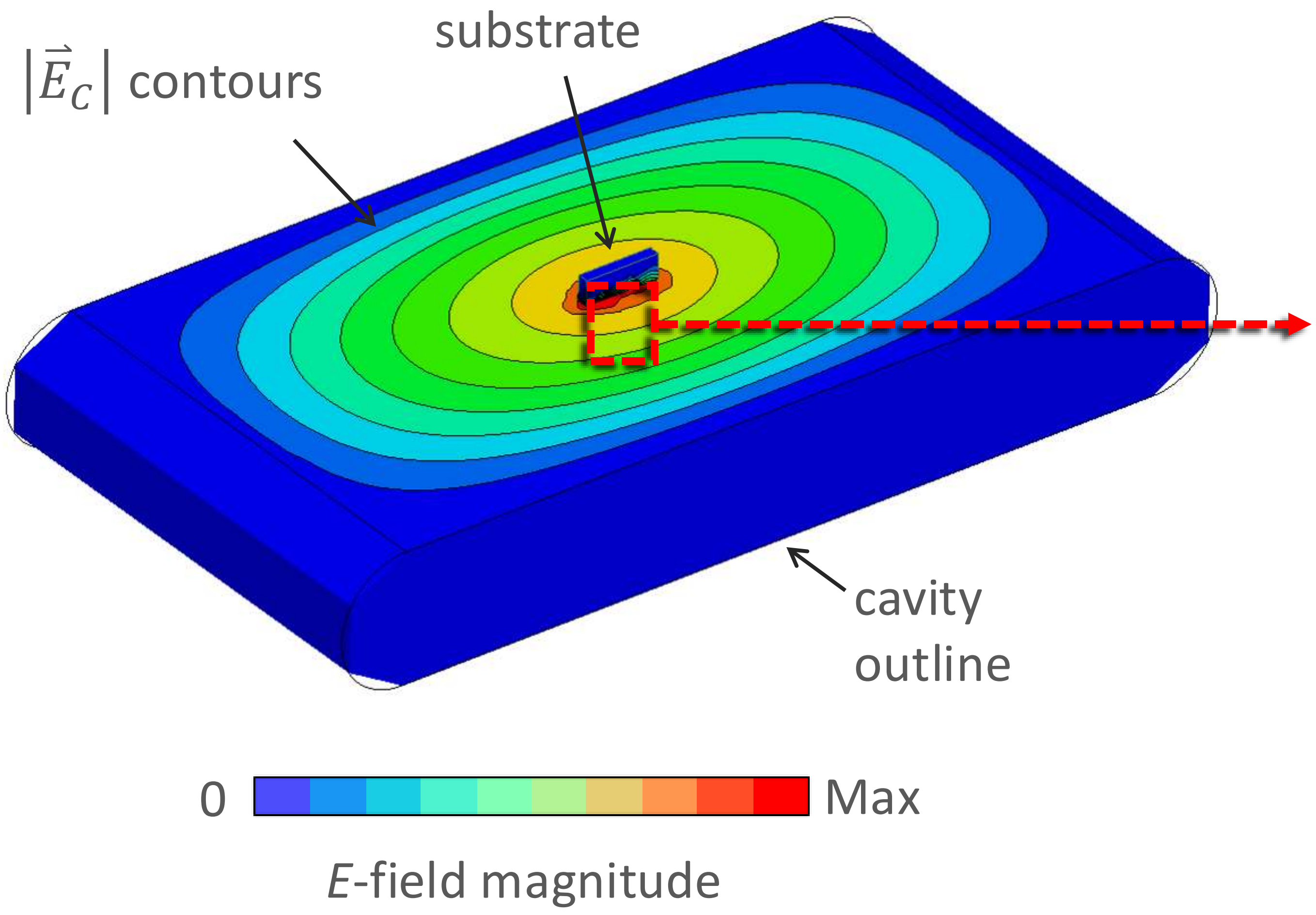
Minev, arXiv:1902.10355 (2018), Minev *et al.* in prep. (2019)



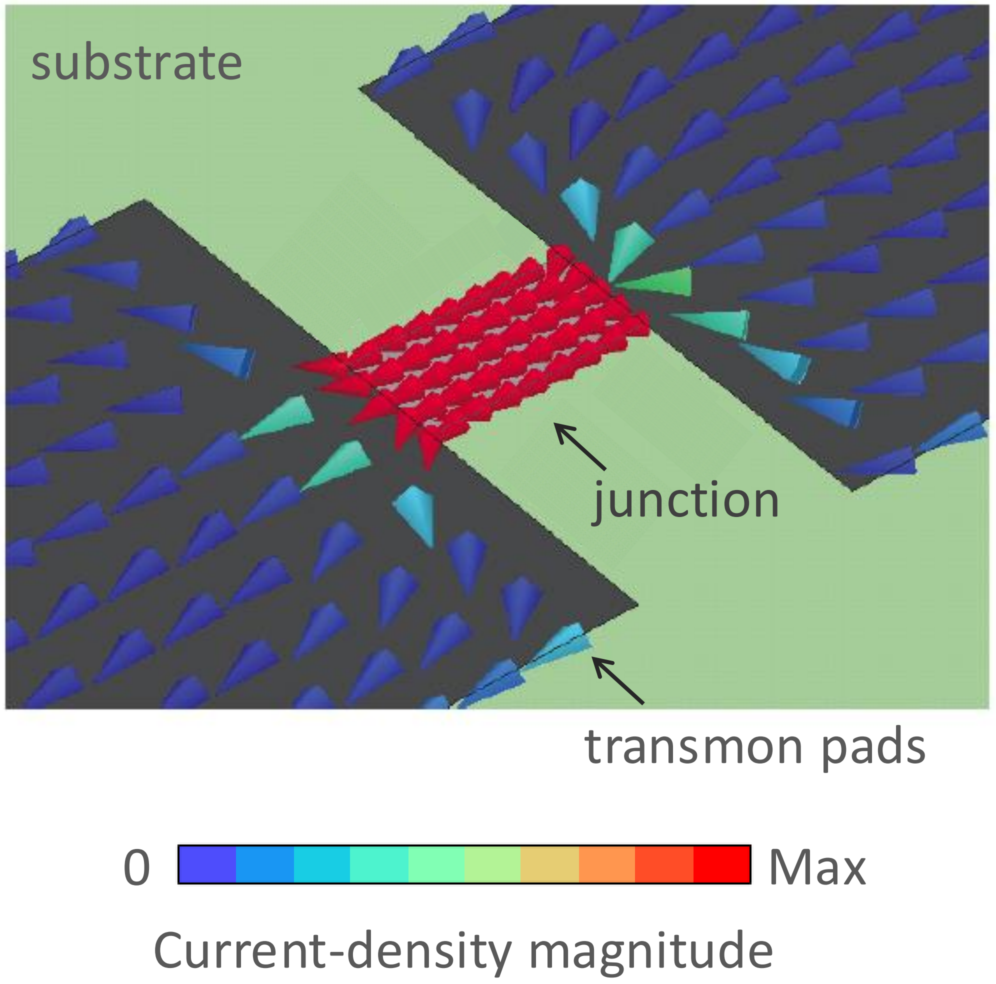
Versatile

$\mathcal{H}_{\mathrm{lin}}$ eigen modes

Cavity mode (7.0 GHz)



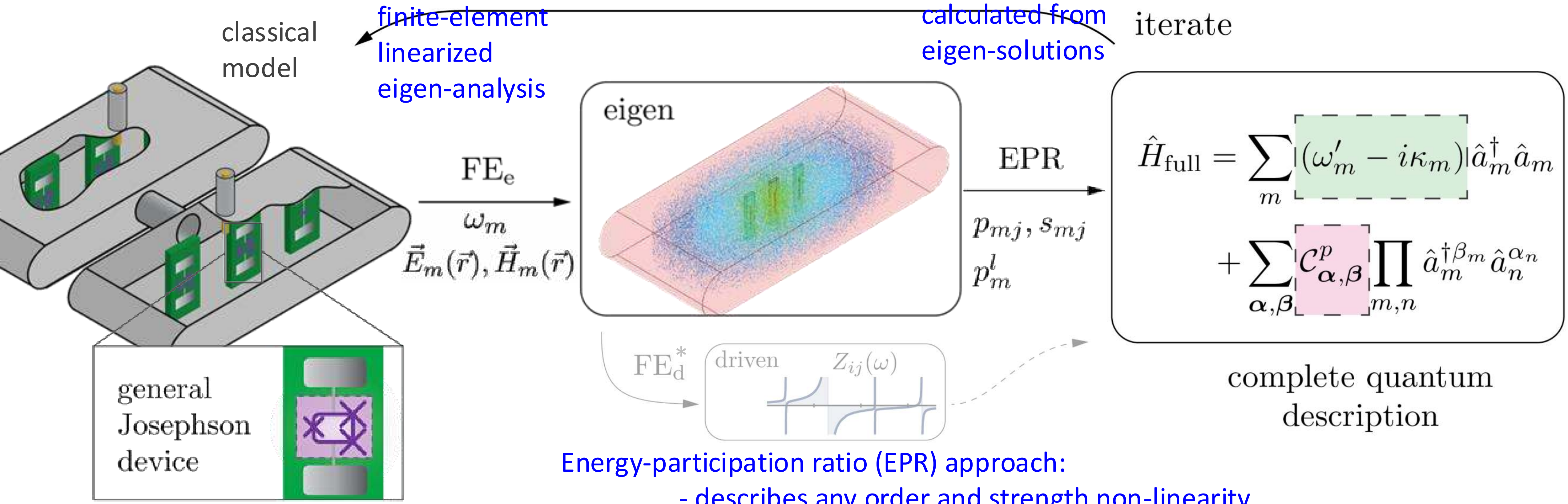
Qubit mode (linearized, 5 GHz)



* Minev *et al.*, in prep. (2019)   Impedances: Nigg *et al.*, PRL (2012); Bourassa *et al.* (2012); Solgun *et al.* (2014, 2015, 2017) …

Overview of energy participation approach

Minev, Ch. 4, arXiv:1902.10355 (2018), Minev *et al.* in prep. (2019)



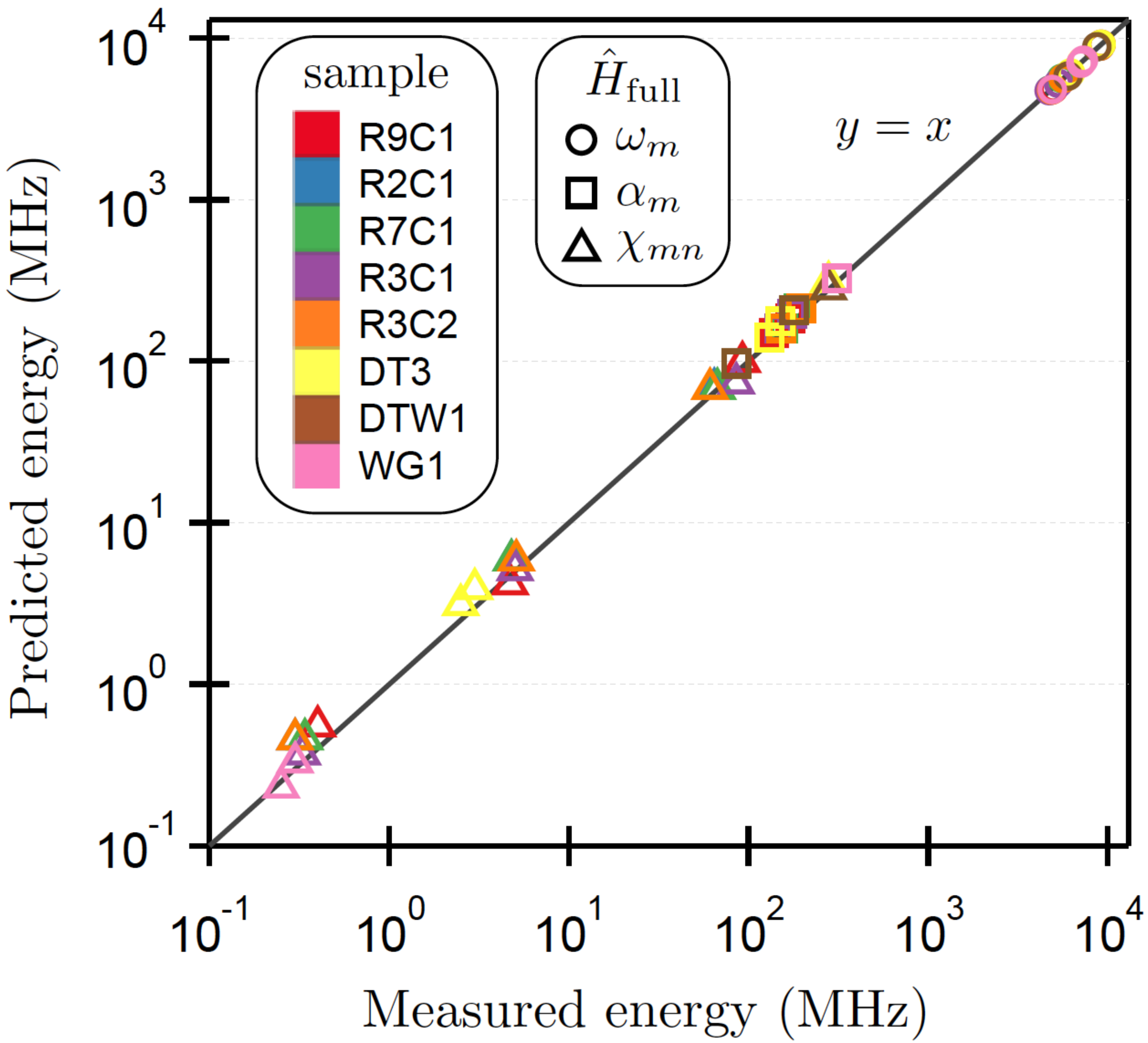
Energy-participation ratio (EPR) approach:

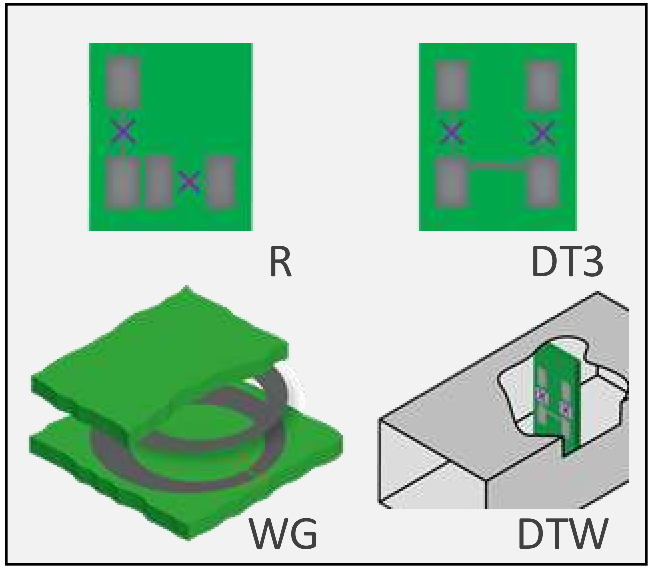
- describes any order and strength non-linearity
- describes arbitrary (composite) non-linear inductive devices
- first-principle derivation
- zero approximations (aside from truncation of modes)
- fully automated in python (github.com/zlatko-minev)

Practical limits: Fock and mode basis truncation due to computing power

* Nigg, Paik, *et al.*, PRL (2012),
Bourassa *et al.* (2012),
Solgun *et al.* (2014, 2015, 2017), …

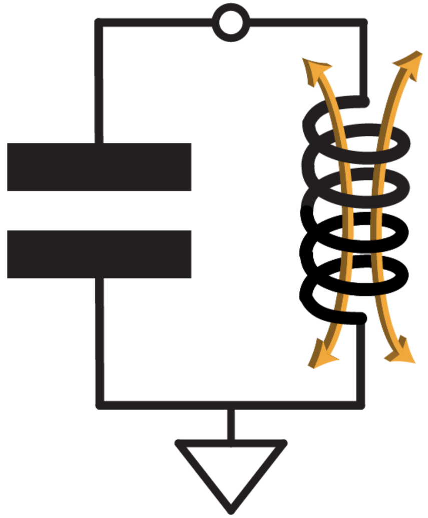
Theory vs. experiment: agreement over 5 orders of magnitude





R: Minev *et al.* (2018)
WG: Minev *et al.* (2013, 2016)
DT3, DTW: Minev *et al.* (2019)

Quantum sensing with superconducting quantum circuits

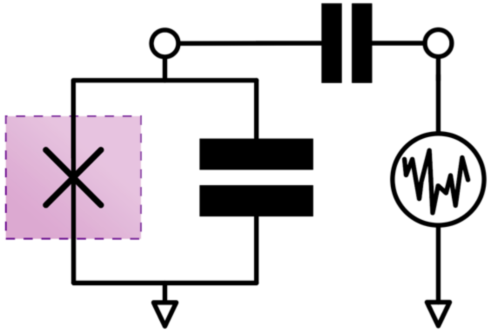


(an incomplete) survey

Sensing with circuits: survey

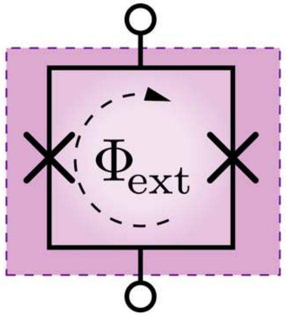
Charge

transmon

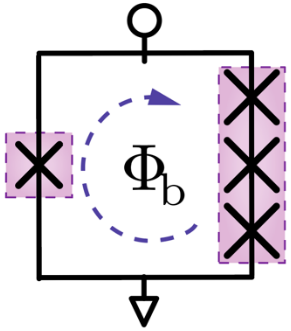


Flux

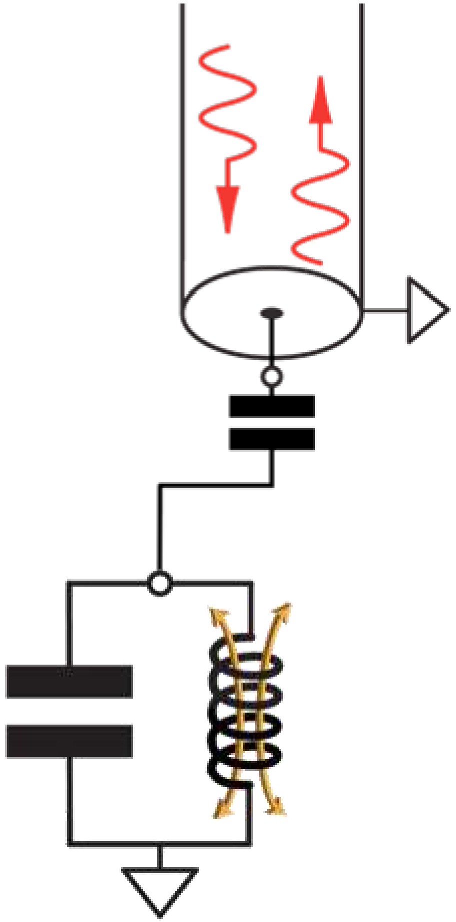
SQUID



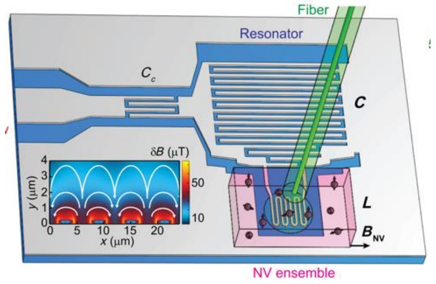
flux qubit

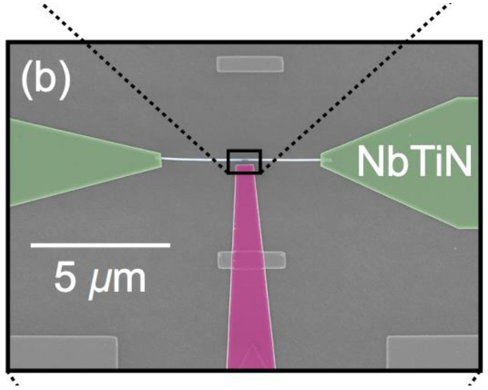


Frequency/ adaptive

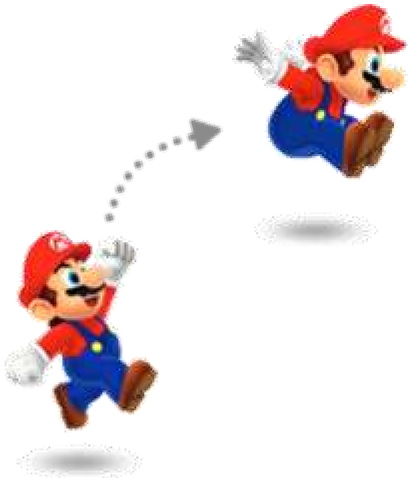


Hybrid





Photons/ feedback



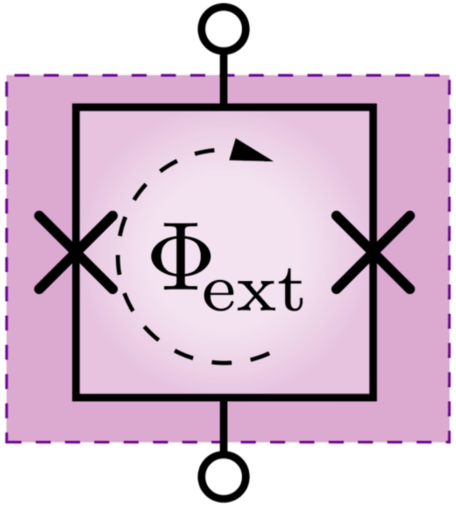
SQUID magnetometer

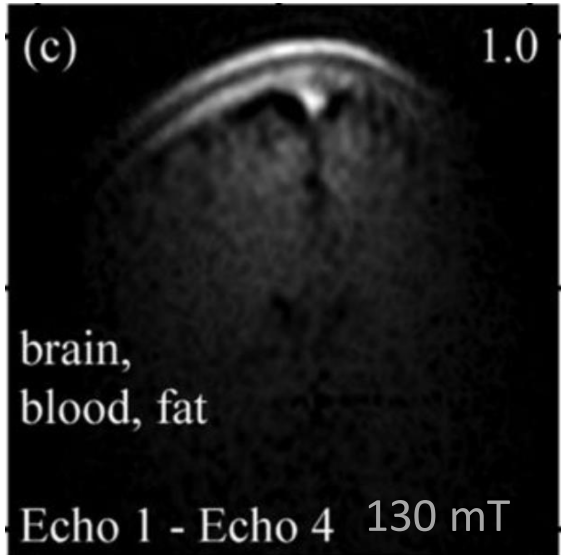
Sensor characteristics

responds to: magnetic field
frequency: dc-GHz

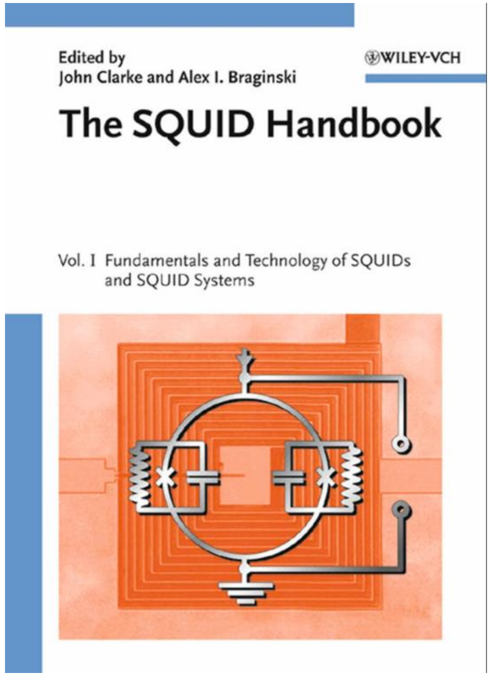
min field: ~ aT
max sensitivity: 0.01-10 aT/√Hz
size: can be submicron

status: commercial





*

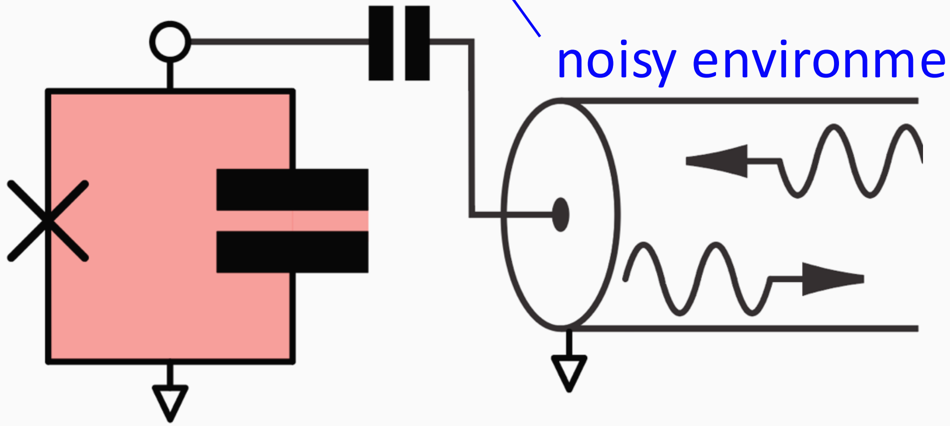


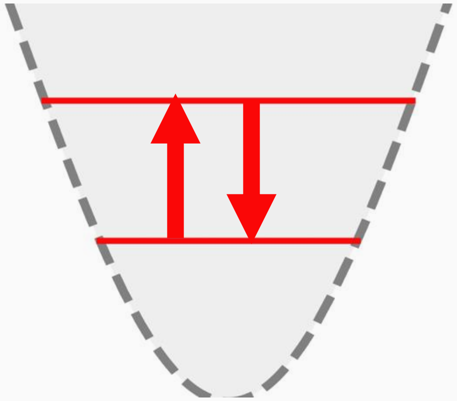
* image: Inglis (2013)
Jaklevic *et al.* (1965); Clarke and Braginski (2004); Fagaly (2006)

Qubit as a spectrometer (relaxometry, thermometry, etc.)

interaction $\hat{V} = A\hat{F}\hat{\sigma}_x$

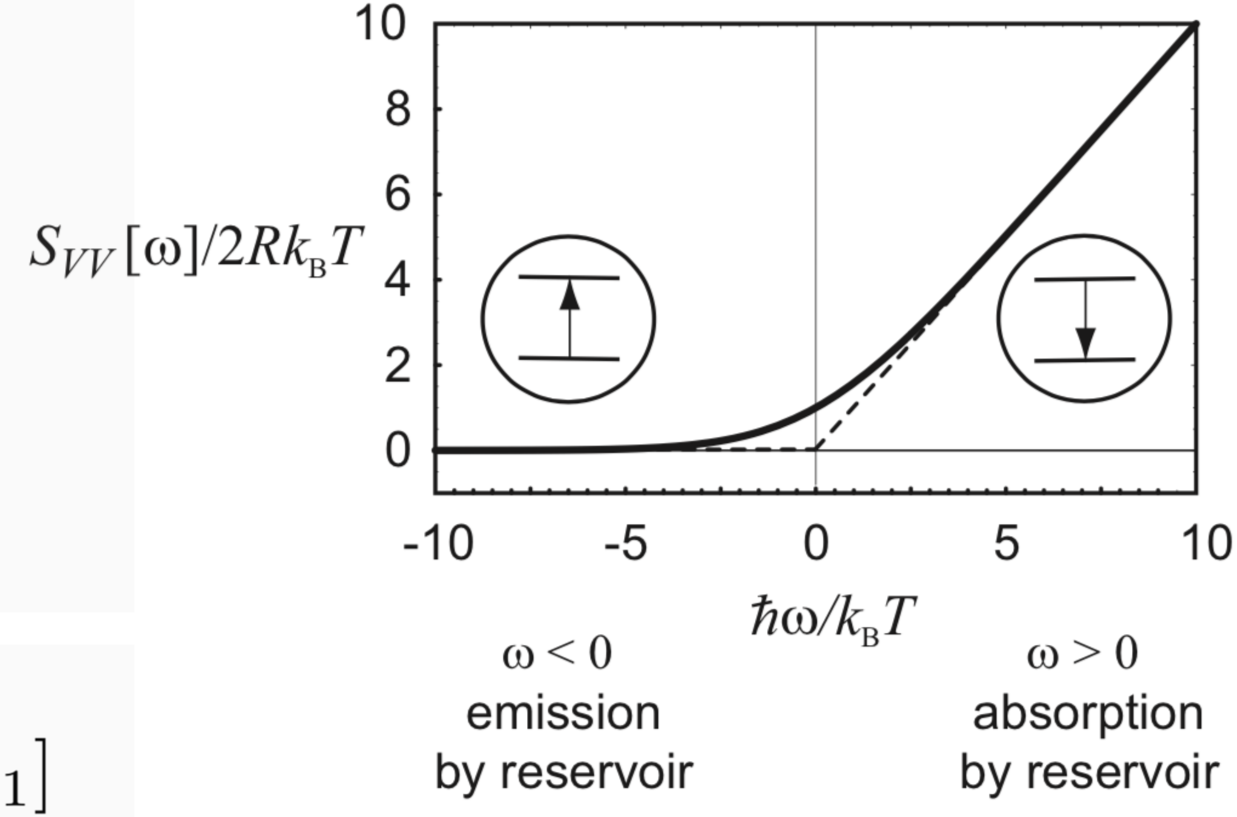
noisy environment





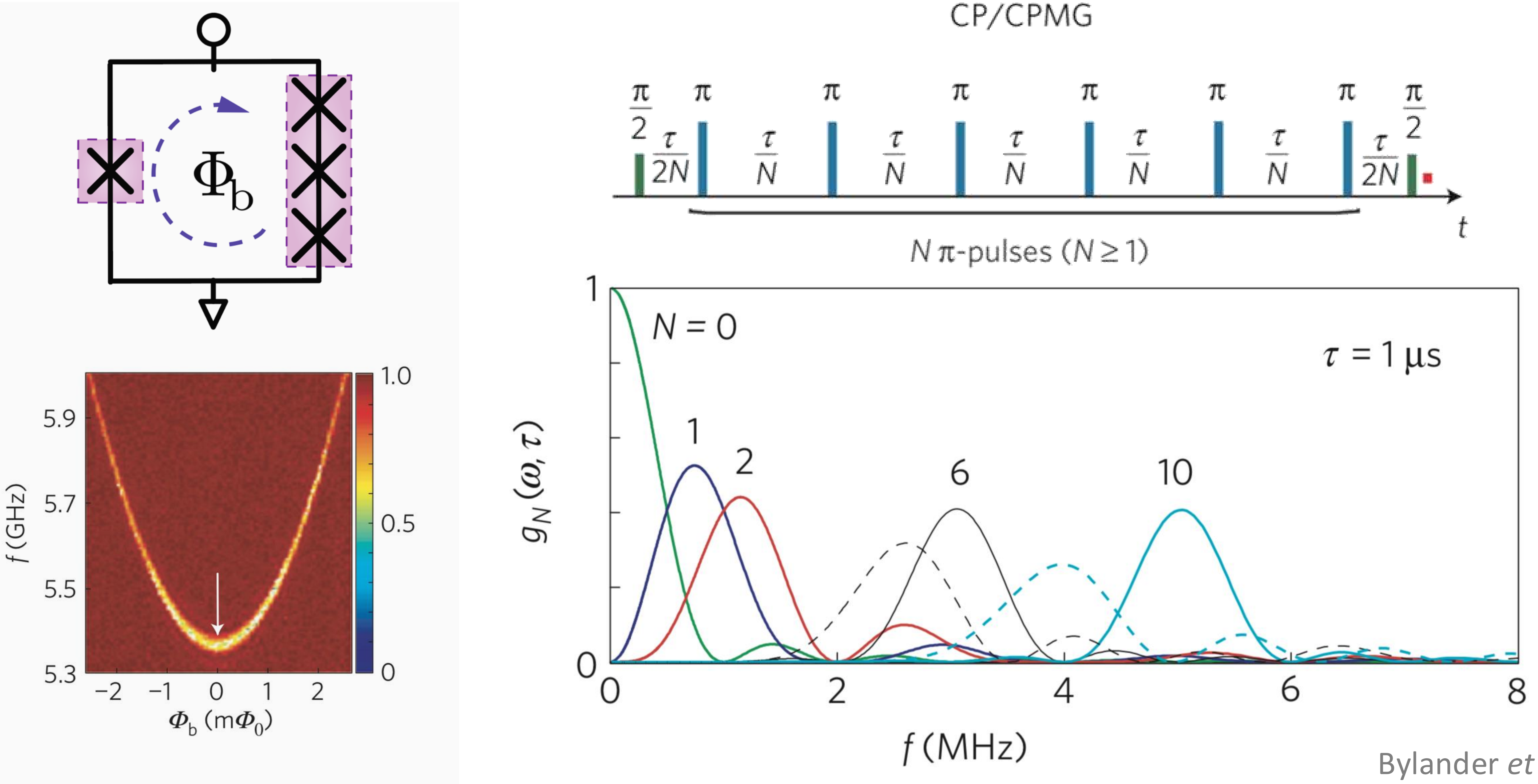
$$\Gamma_{\uparrow} = \frac{A^2}{\hbar^2} S_{FF}[-\omega_{01}]$$

$$\Gamma_{\downarrow} = \frac{A^2}{\hbar^2} S_{FF}[+\omega_{01}].$$



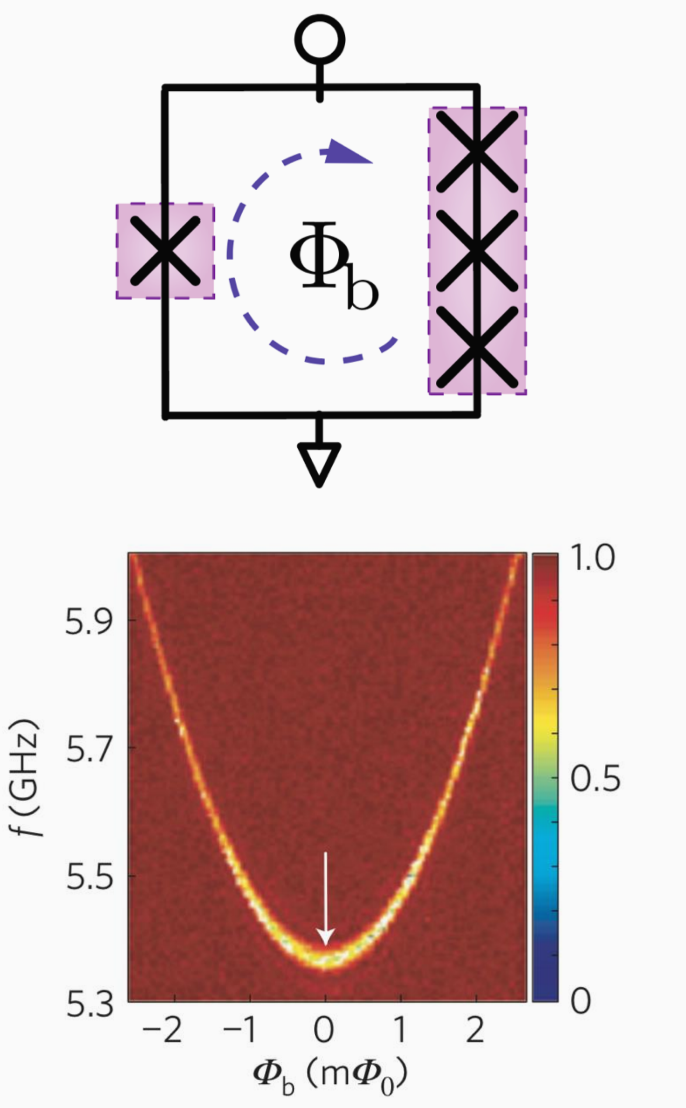
Clerk *et al.*, RMP, (2010)

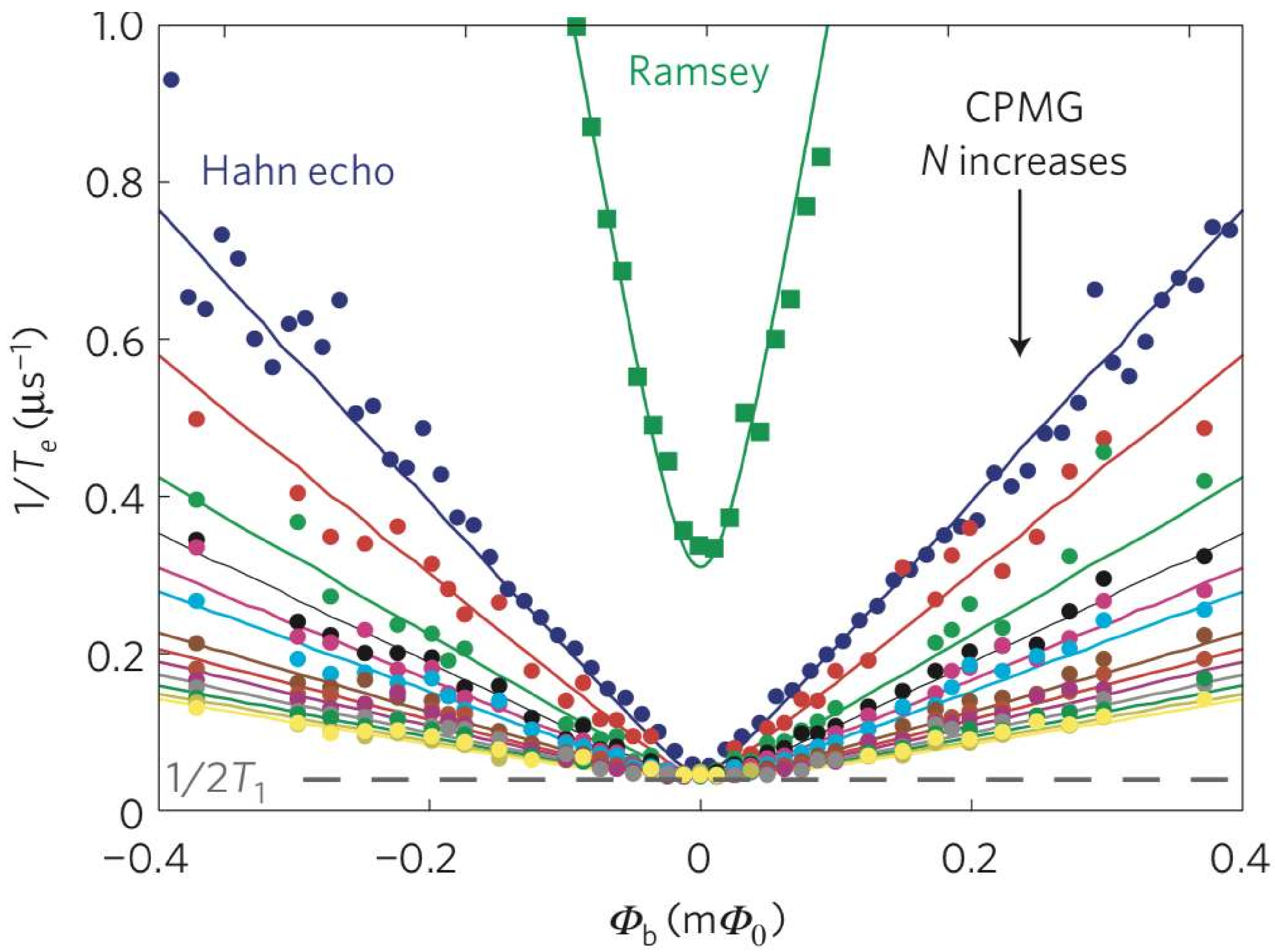
Flux noise sensing with flux qubits (T_2 relaxometry)



Bylander *et al.* (2011)

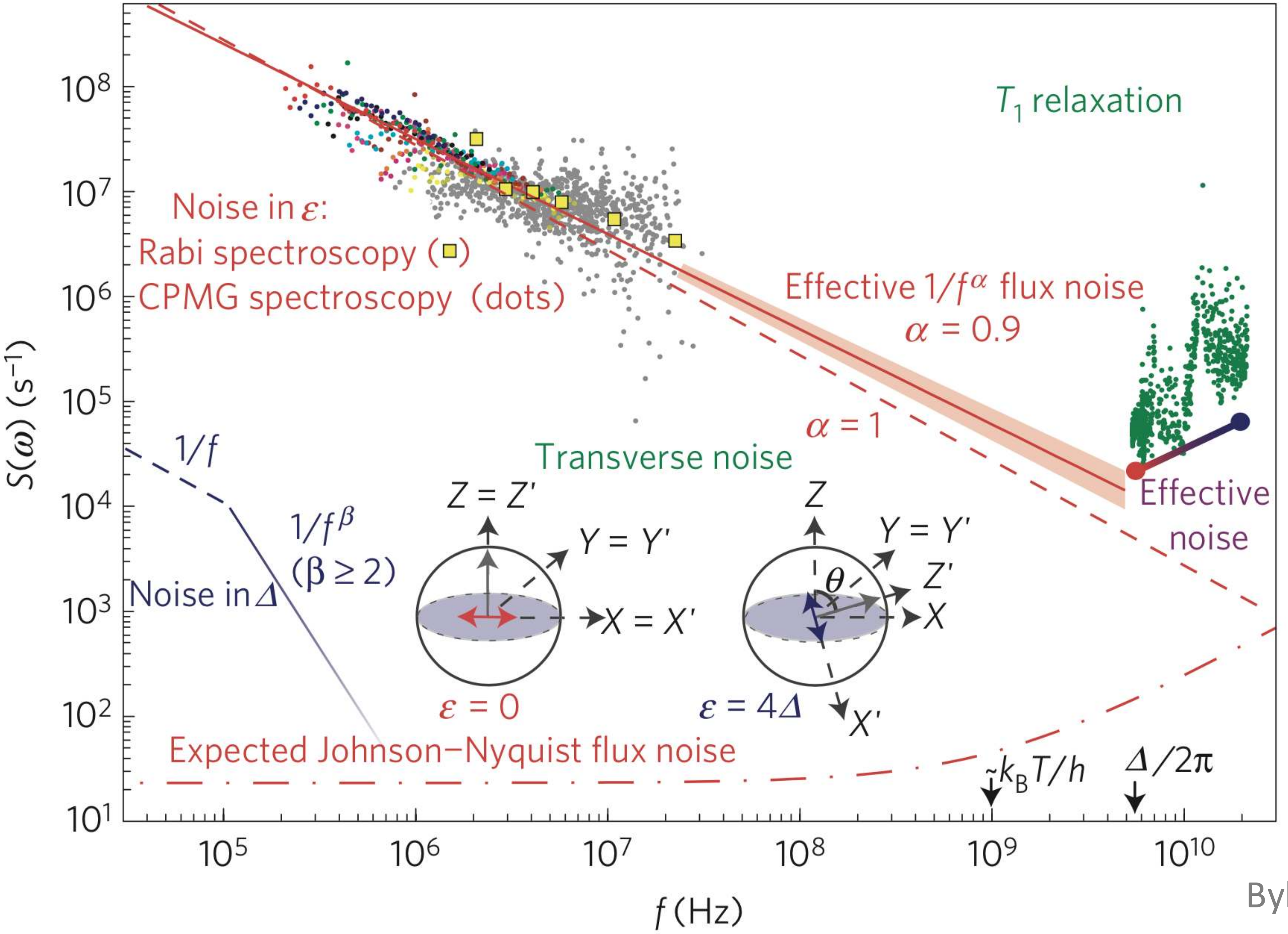
Flux noise sensing with flux qubits (T_2 relaxometry)





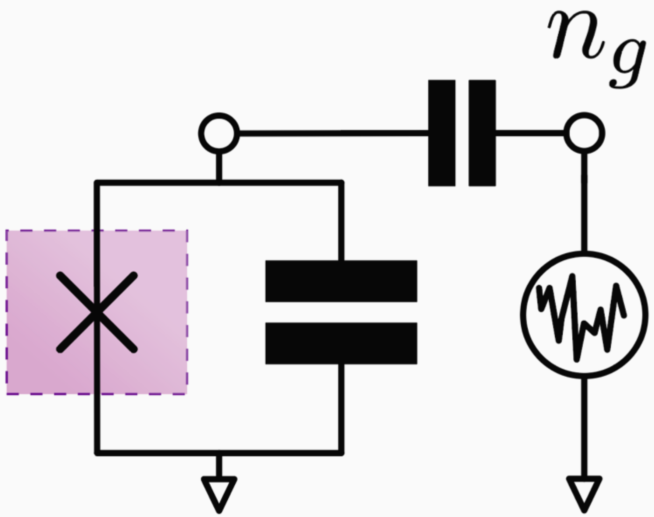
Bylander *et al.* (2011)

Flux noise sensing with flux qubits (T_1,T_2 relaxometry)

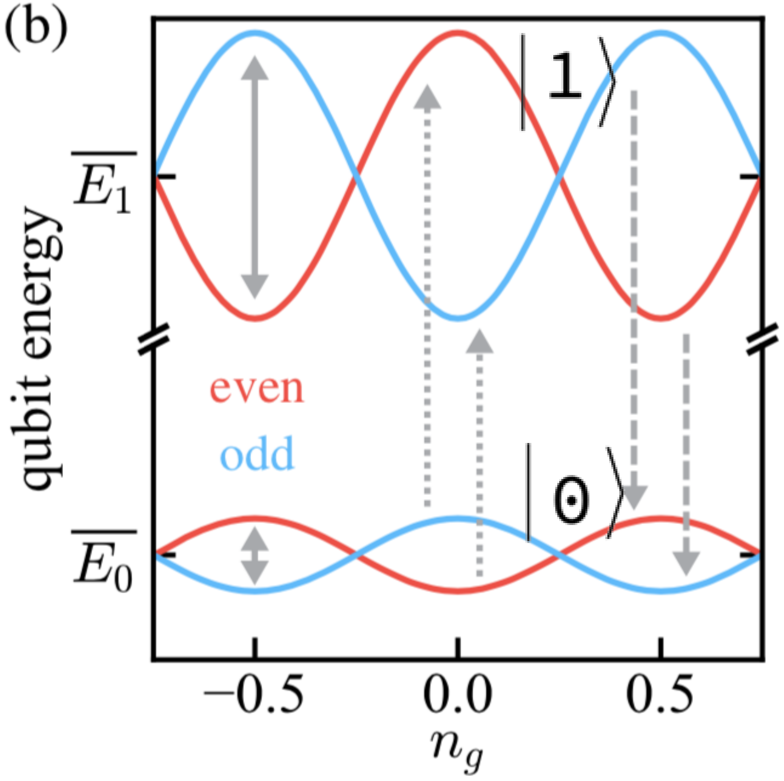


Bylander *et al.* (2011)

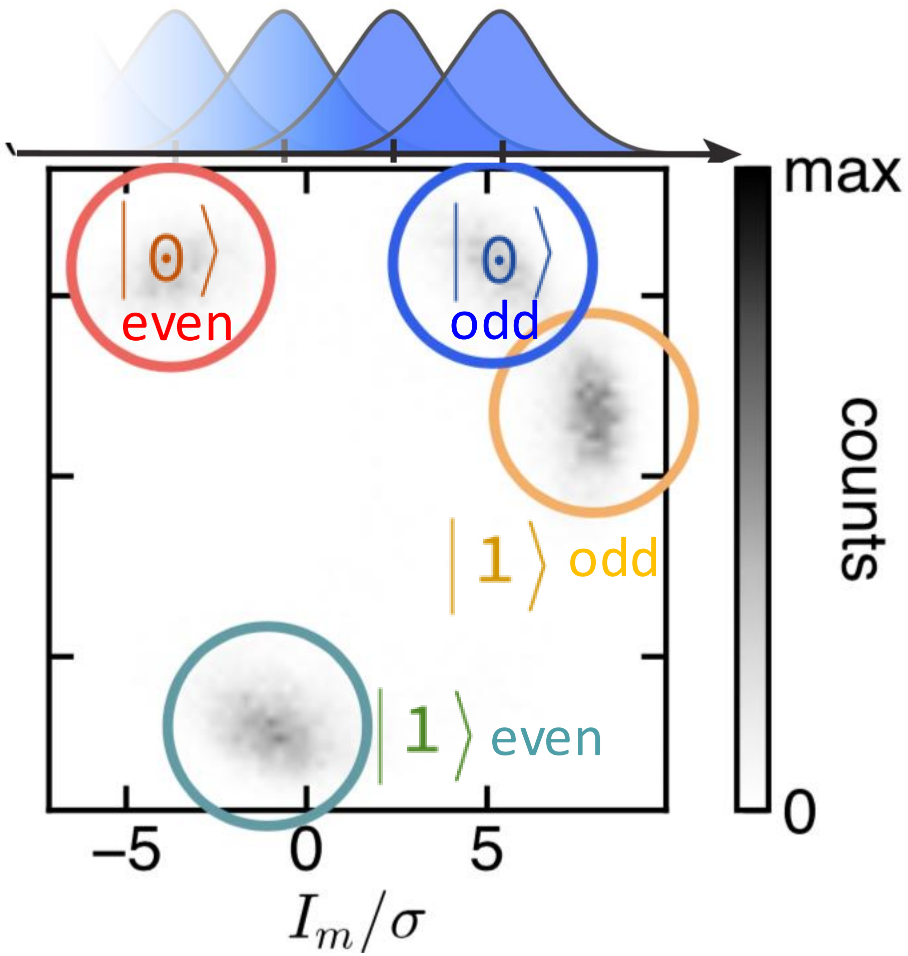
Charge sensing with OCS transmon



Energy susceptibility



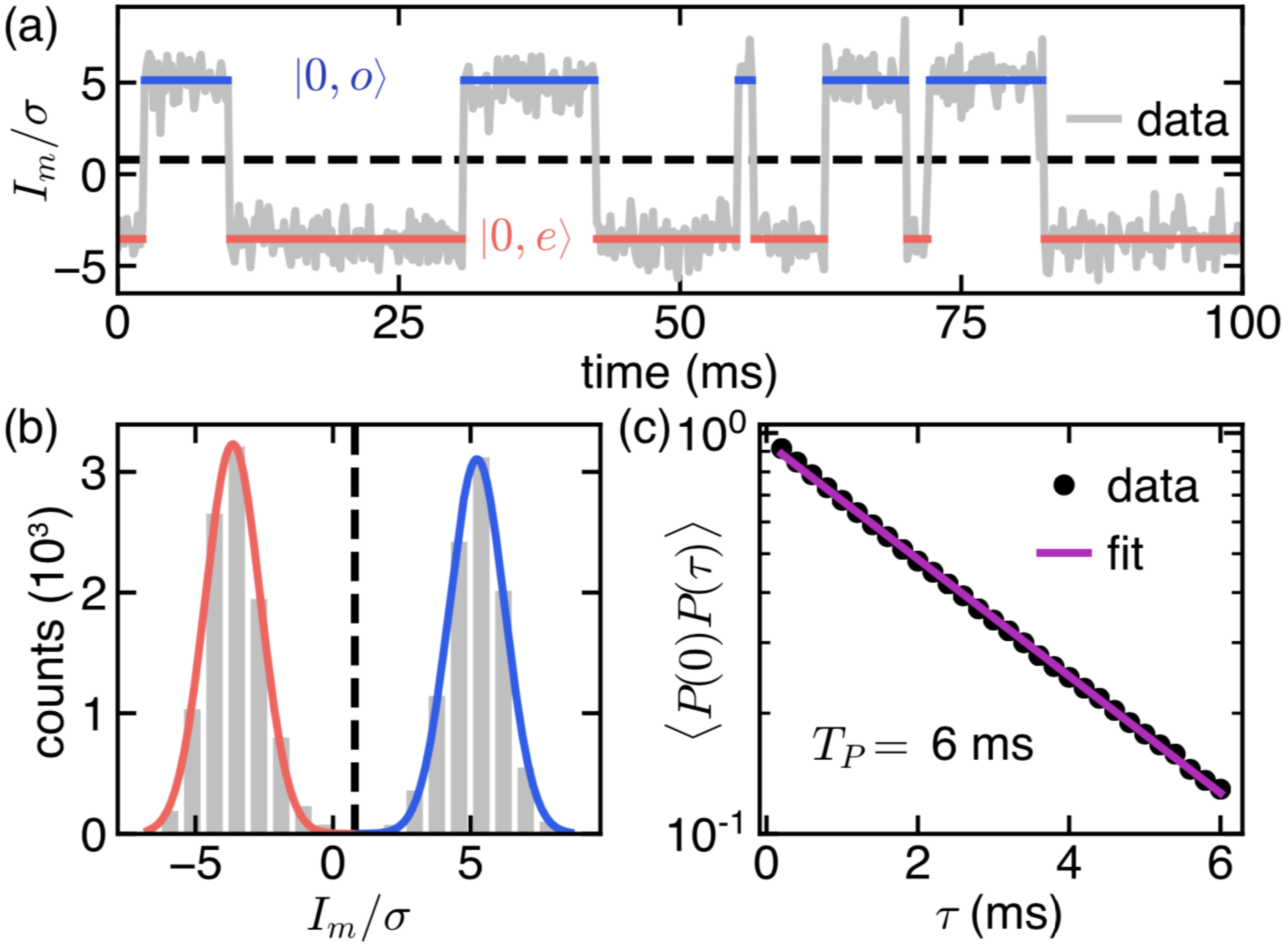
Cavity response



Riste, *et al.* (2013), Serniak, *et al.* (2018), Serniak, *et al.* (2019)

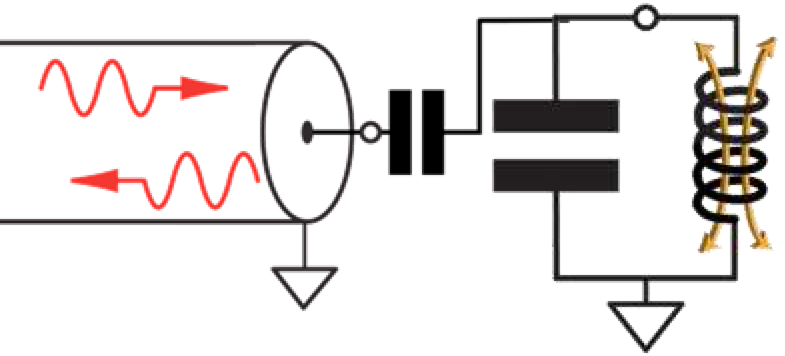
Charge sensing with OCS transmon

Quantum jumps of quasiparticle parity in real-time

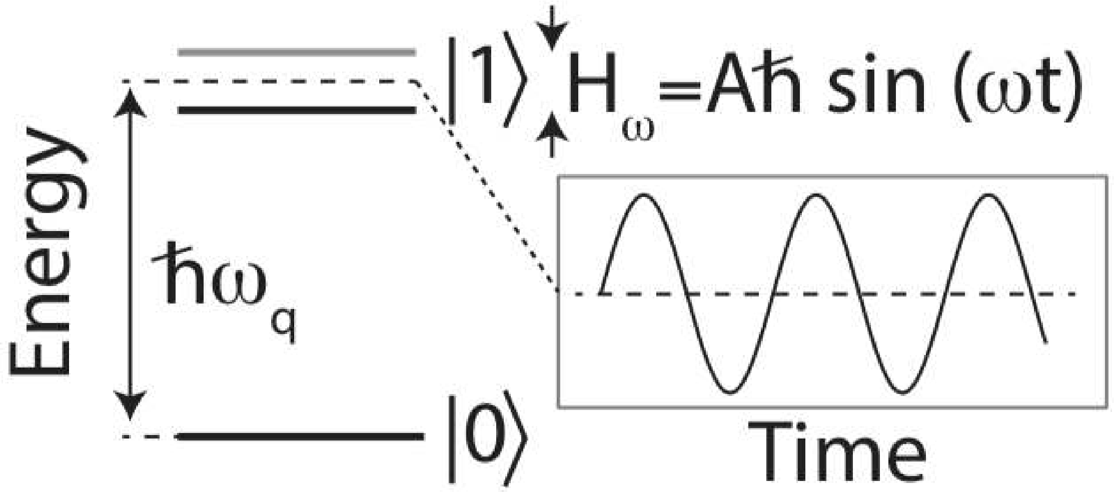


Serniak *et al.* (2019)

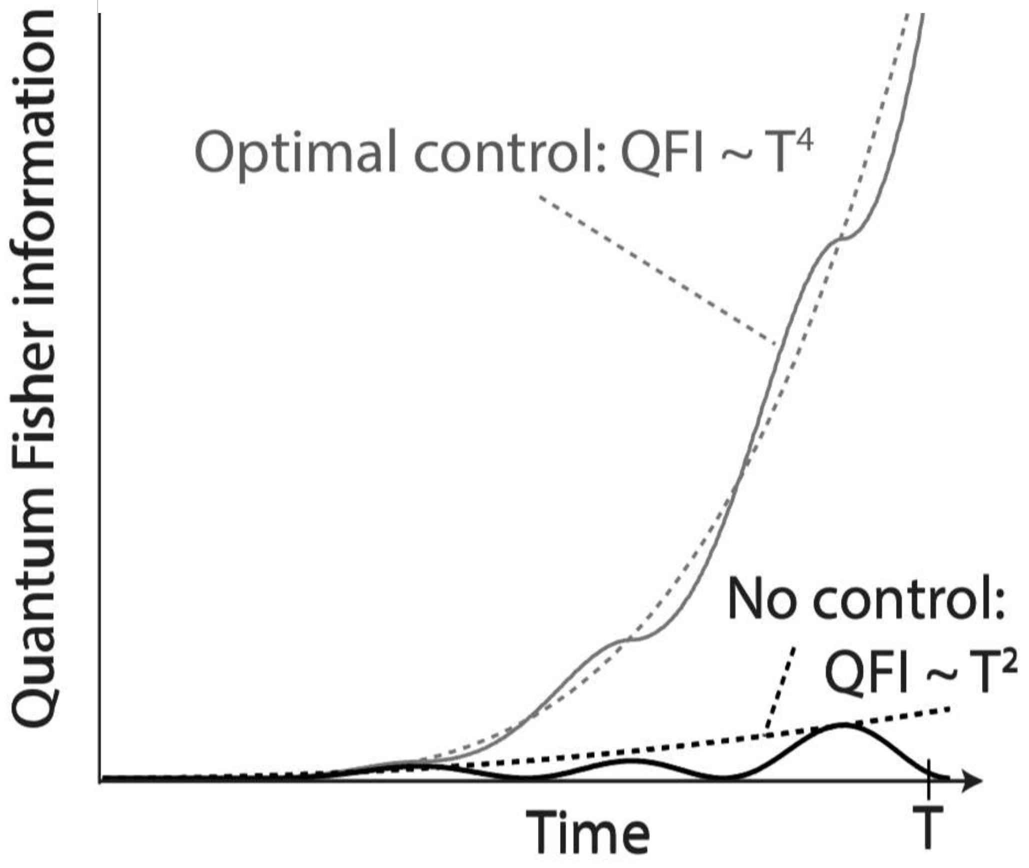
Adaptive sensing: frequency estimation



Goal: Estimate drive freq.



Improved the QFI by factor of 740.
First observation of this T^4 scaling.
Absolute fundamental limit.



Naghiloo, et al., Murch group (2018)

Hybrid systems and sensors

NV / spins

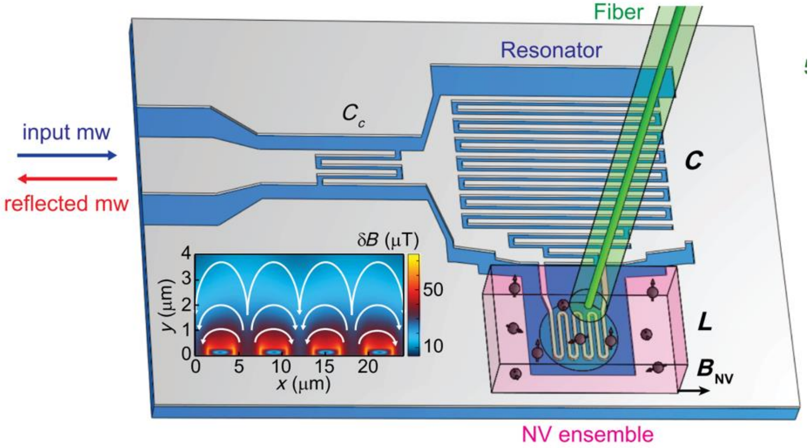


image: Grezes (2014), see also Bienfait (2015)

Quantum magnonics

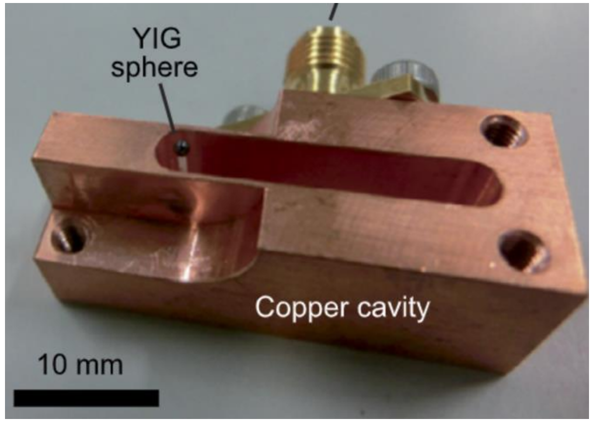


image: Tabuchi (2016)

Squeezed-vacuum bath

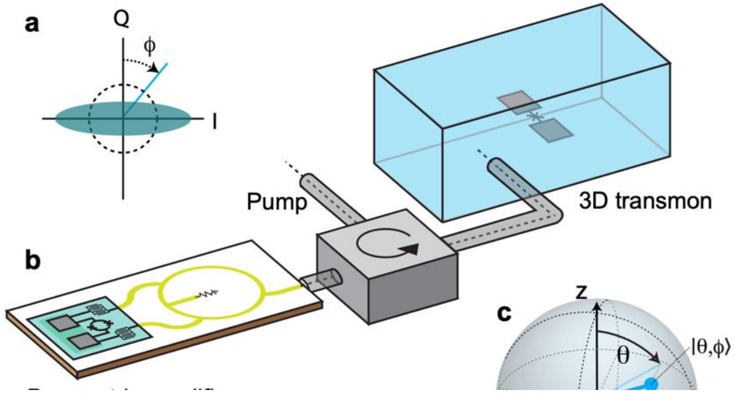


image: Murch (2018)

ABS (break jj)

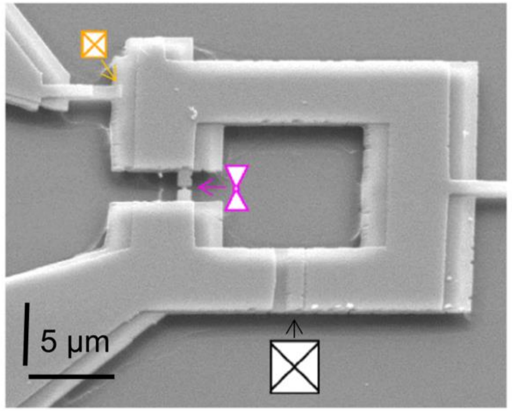


image: Bretheau (2013)

Semiconductor nanowire

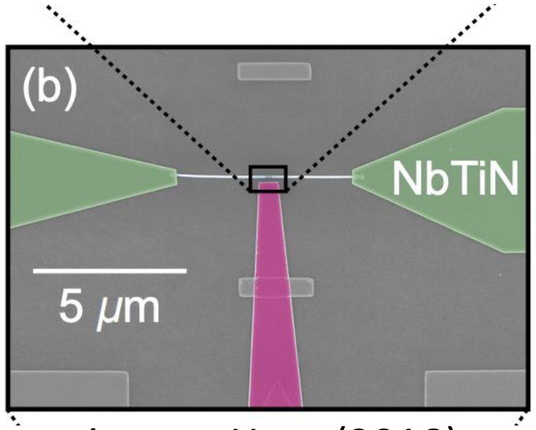


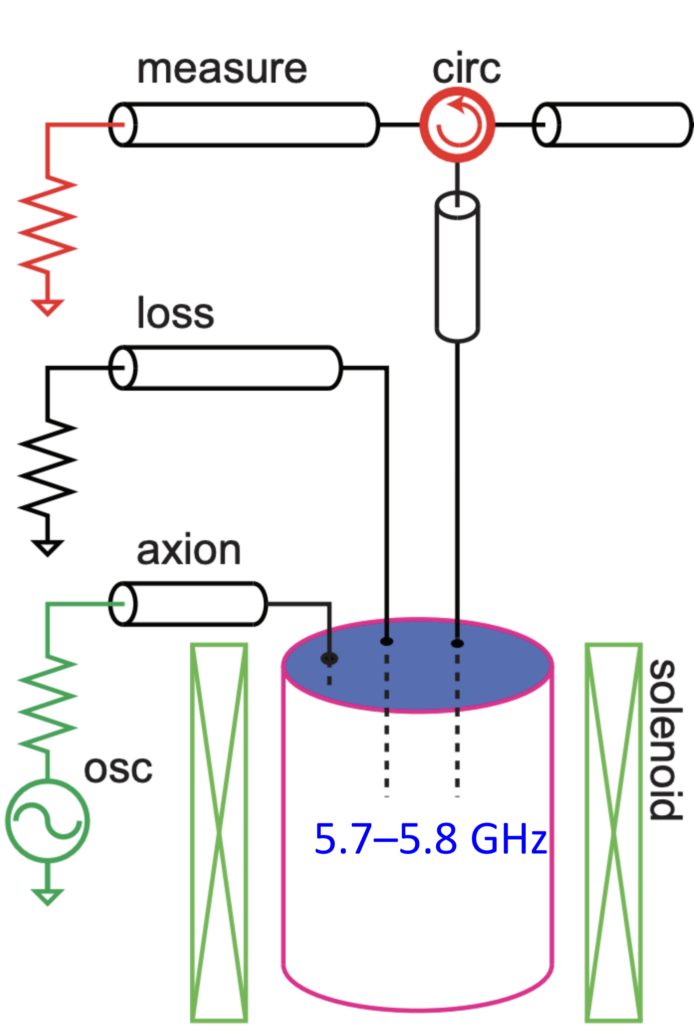
image: Hays (2018)

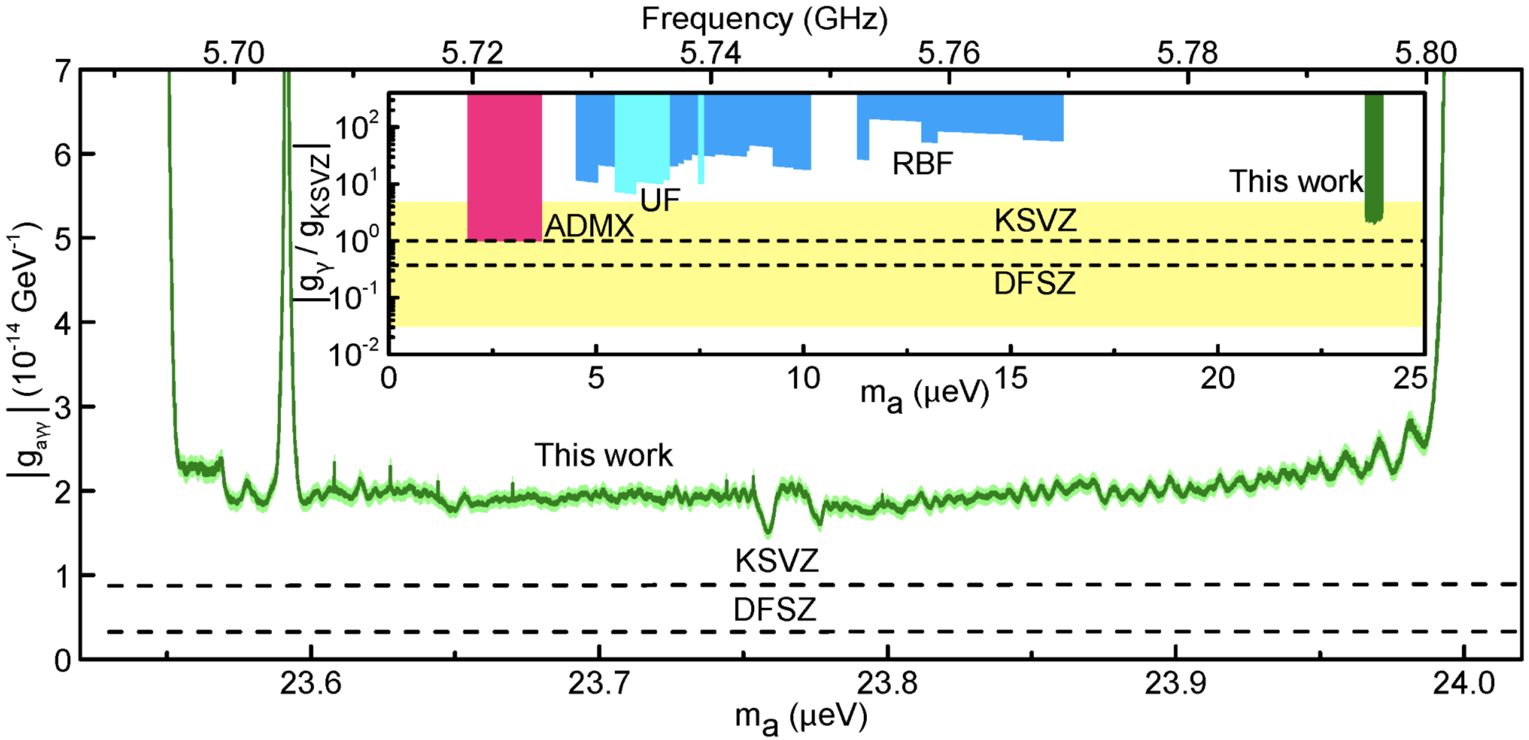
and many more

…

Axion search: detecting photos

a microwave cavity search for cold dark matter (CDM) axions with masses above 20 μeV



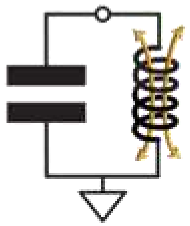


Zheng et al. (2016), Brubaker et al. (2017)

Detecting photos

Case study

Advancing Quantum Sensing via Quantum Control with



Good at measurements

Demonstrate highest efficiency to
measure single atomic de-excitation
$\eta \approx 1$

Good at real-time control

Demonstrate ns-latency feedback
and conditional measurements

Versatile

Demonstrate an atom experiment, not natural to circuits, that
cannot be done with real atoms

To catch and reverse a quantum jump mid-flight

Nature 570, 200 (2019)

Thesis: arXiv:1902.10355

Nintendo Corp.

Zlatko Minev*

Department of Applied Physics, Yale University

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R.J. Schoelkopf M. Mirrahimi[‡] H.J. Carmichael[+] **M.H. Devoret**

* Present: IBM Research [+] U. Auckland, New Zealand [‡] INRIA Paris, France

Yale Institute for Nanoscience and Quantum Engineering

Is it possible to sense if there is an

advance warning signal

that a quantum jump is about to occur?

measurements	versatility	real-time control

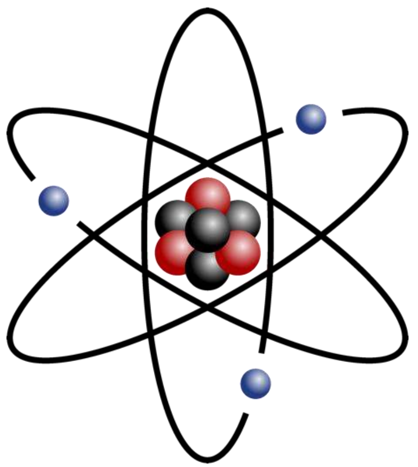
H.J. Carmichael

Outline

Jumps in a quantum system

original observation

quantum trajectory prediction

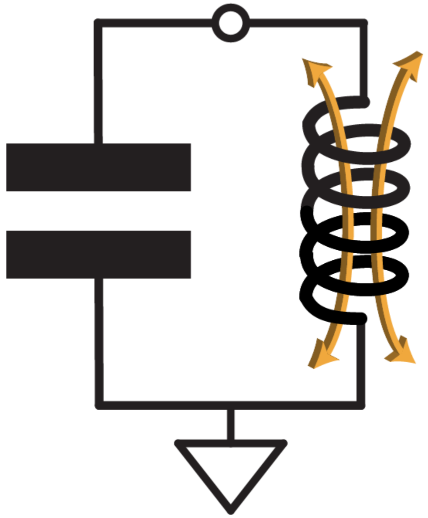


Art: Indoleces

Circuit quantum electrodynamics realization

experimental apparatus

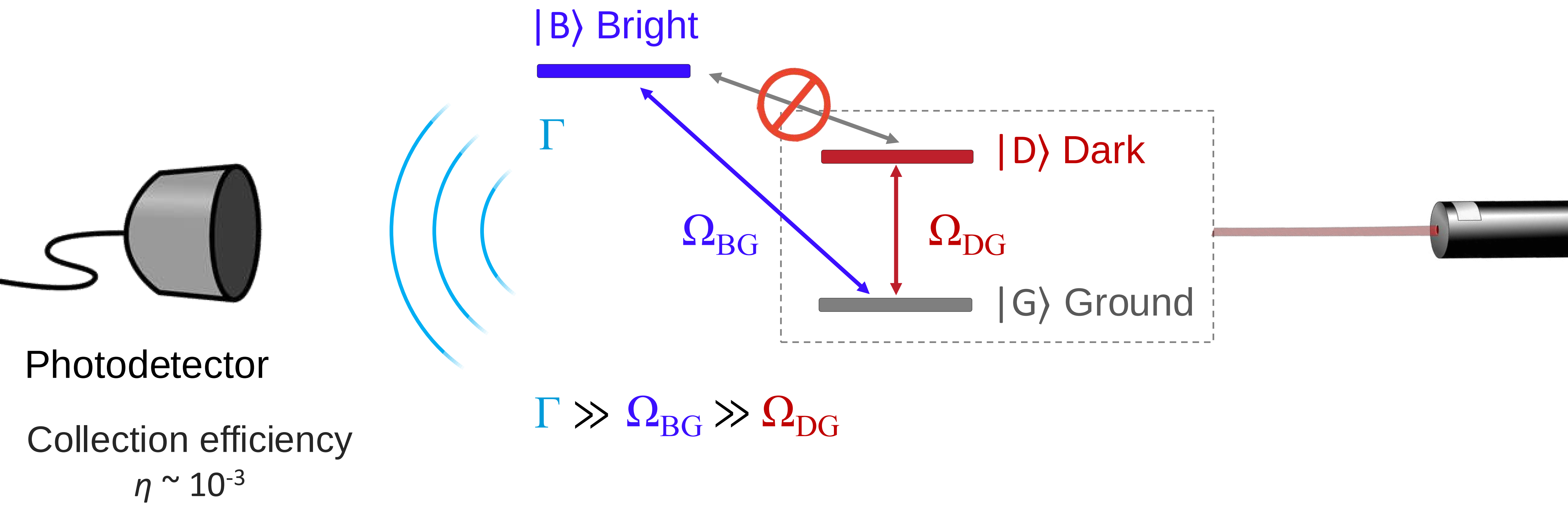
results on jump coherence and determinism



Quantum jumps of an *individual* atom

Bohr (1913)

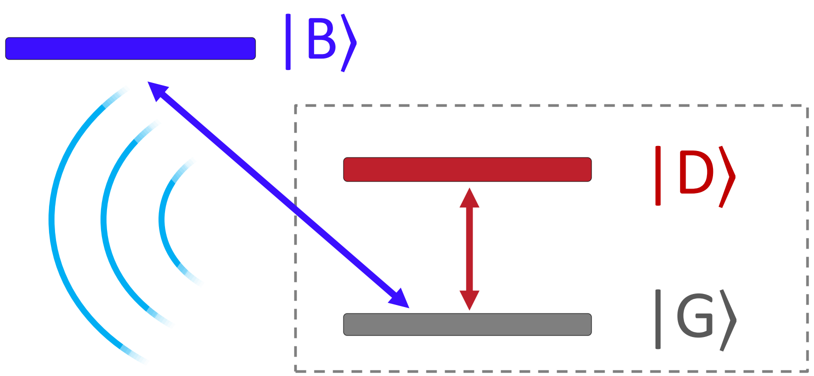
Observation of jumps in an *individual* atom

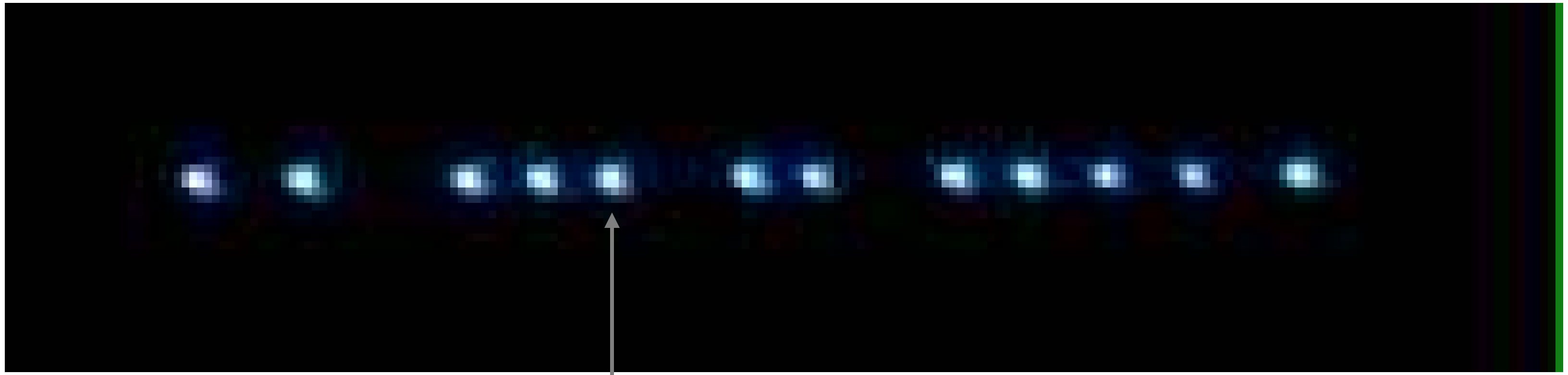


$\Gamma \gg \Omega_{BG} \gg \Omega_{DG}$

Exp: Berquist *et al.*, PRL (1986); Sauter *et al.*, PRL (1986); Nagourney *et al.*, PRL (1986)
Thy: Cook & Kimble, PRL (1985); Cohen-Tannoudji & Dalibard, EPL (1986), …

Quantum jumps of *individual* ions



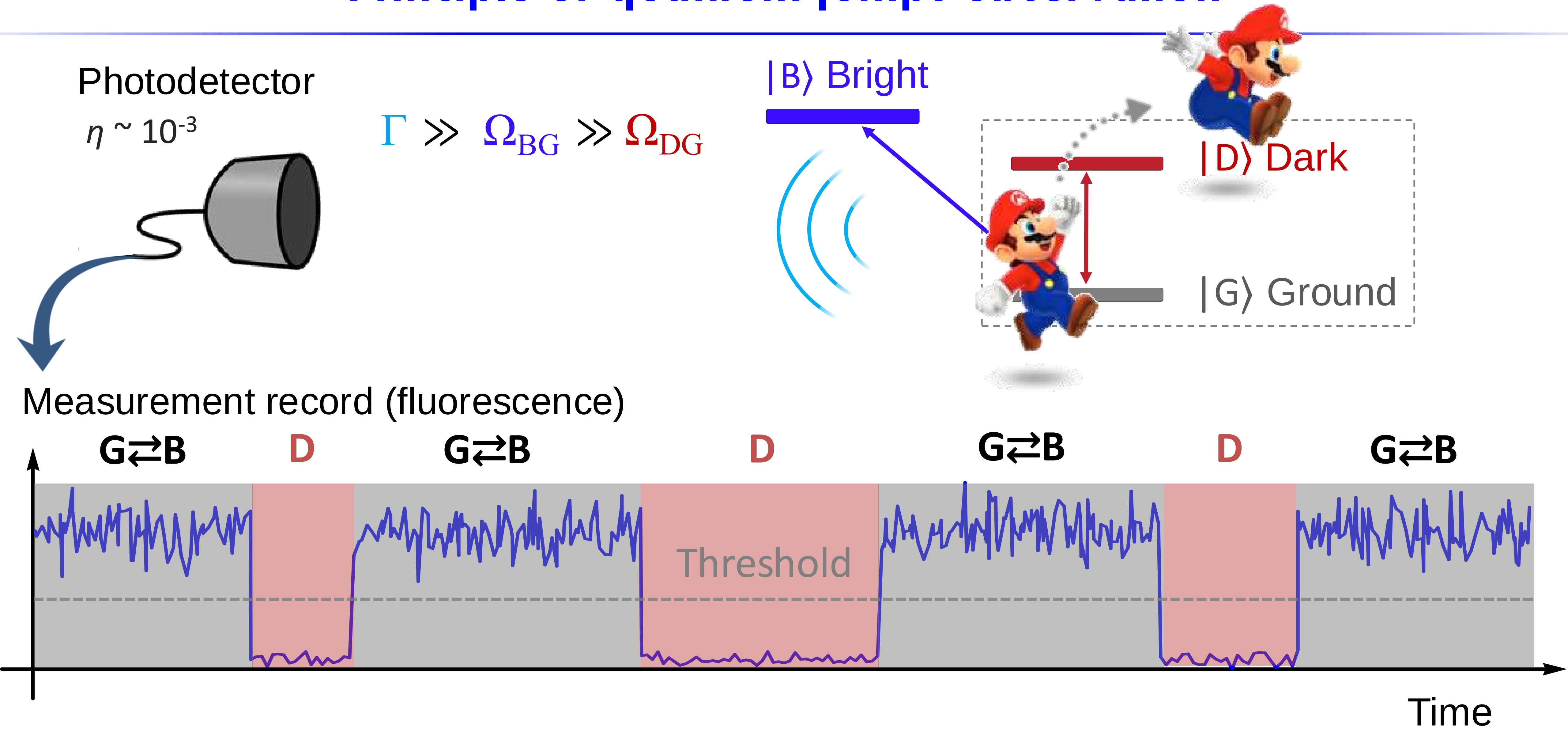


Single Ca^+ ion

(real-time)

Video credit: R. Blatt group, Petar Jurcevic

Principle of quantum jumps observation



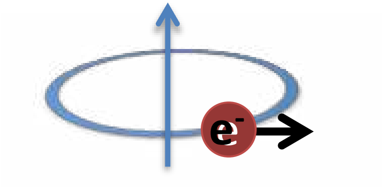
Berquist *et al.*, PRL (1986); Sauter *et al.*, PRL (1986); Nagourney *et al.*, PRL (1986); Cook, P. Scripta (1988)

Observations of quantum jumps since 1986

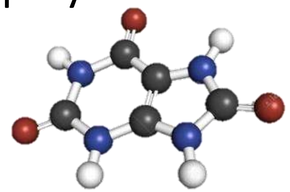
Trapped massive particles

Single *ion* [1-3] (1986)

Single *electron* [4] (1992)
($1e^-$ cyclotron oscillator)

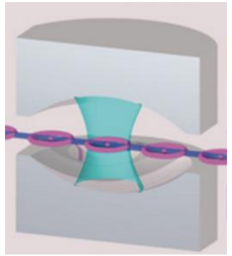


Single *molecule* [5] (1995)
(large polyatomic molecule)

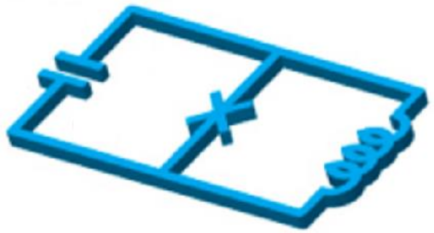


Light quanta

Microwave cavity
(*CQED*) [6] (2007)

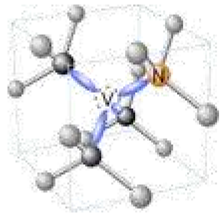


Superconducting qubit
& cavity (*cQED*) [9-11] (2011)

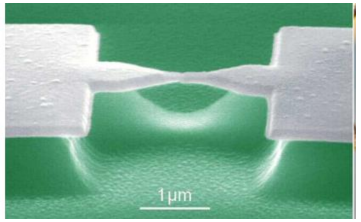


Solid state and mesoscopic

Nitrogen–vacancy center
in diamond [7,8] (2010)



Atomic-point contact
(Andreev states) [12] (2015)



And others!

[1] PRL 56, 2797 (1986)
[2] PRL 57, 1696 (1986)
[3] PRL 57, 1699 (1986)
[4] PRL 83, 1287 (1999)
[5] Nature 373, 132 (1995)
[6] Nature 446, 297 (2007)
[7] Science 329, 542 (2010)
[8] Nature 477, 574 (2011)
[9] PRL 106, 110502 (2011)
[10] Science 339, 178 (2013)
[11] Nature 511, 444 (2014)
[12] Science 349, 1199 (2015)

"If all this damned *quantum jumping* were really to stay,

I should be *sorry* I ever got involved with quantum theory."

- E. Schrödinger

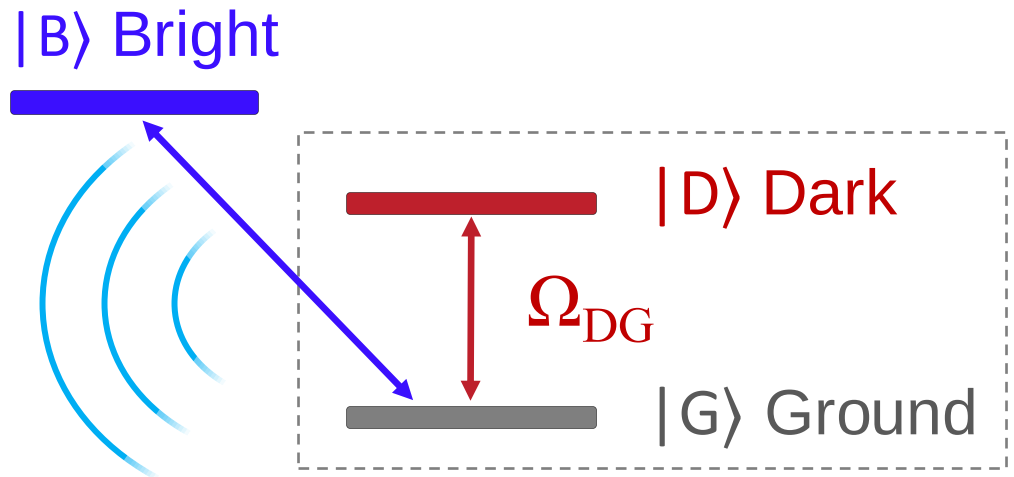
Schrödinger, Brit. J. Philos. Sci. III, 109 (1952)

The case of the fully efficient observer

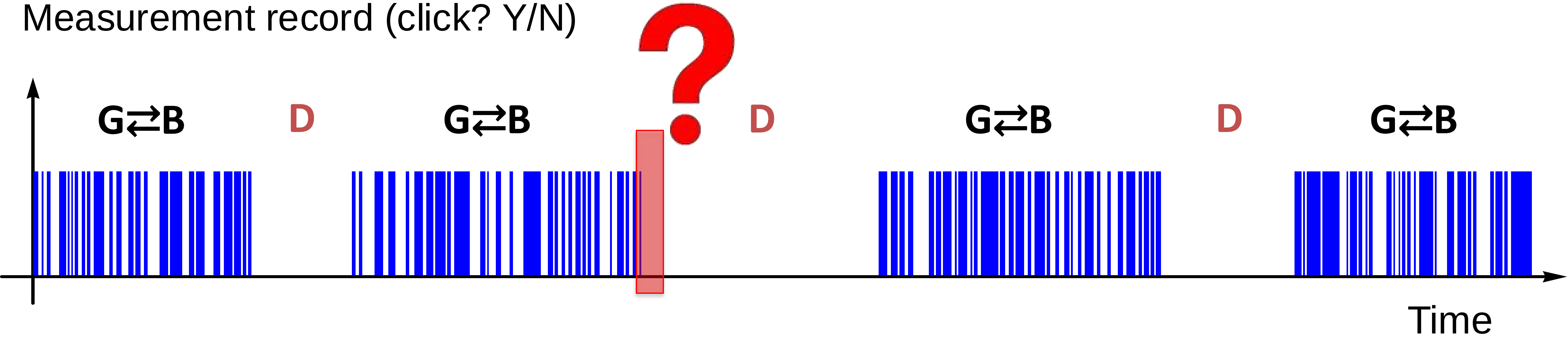
Hypothetical efficiency $\boxed{\eta = 1}$

$$\boxed{\mathrm{BW}_{\mathrm{det}} \gg \frac{\Omega_{BG}^2}{\Gamma} \gg \Omega_{DG}}$$

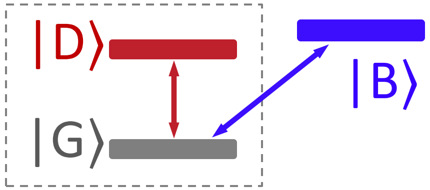
$$\Gamma \gg \Omega_{BG} \gg \Omega_{DG}$$

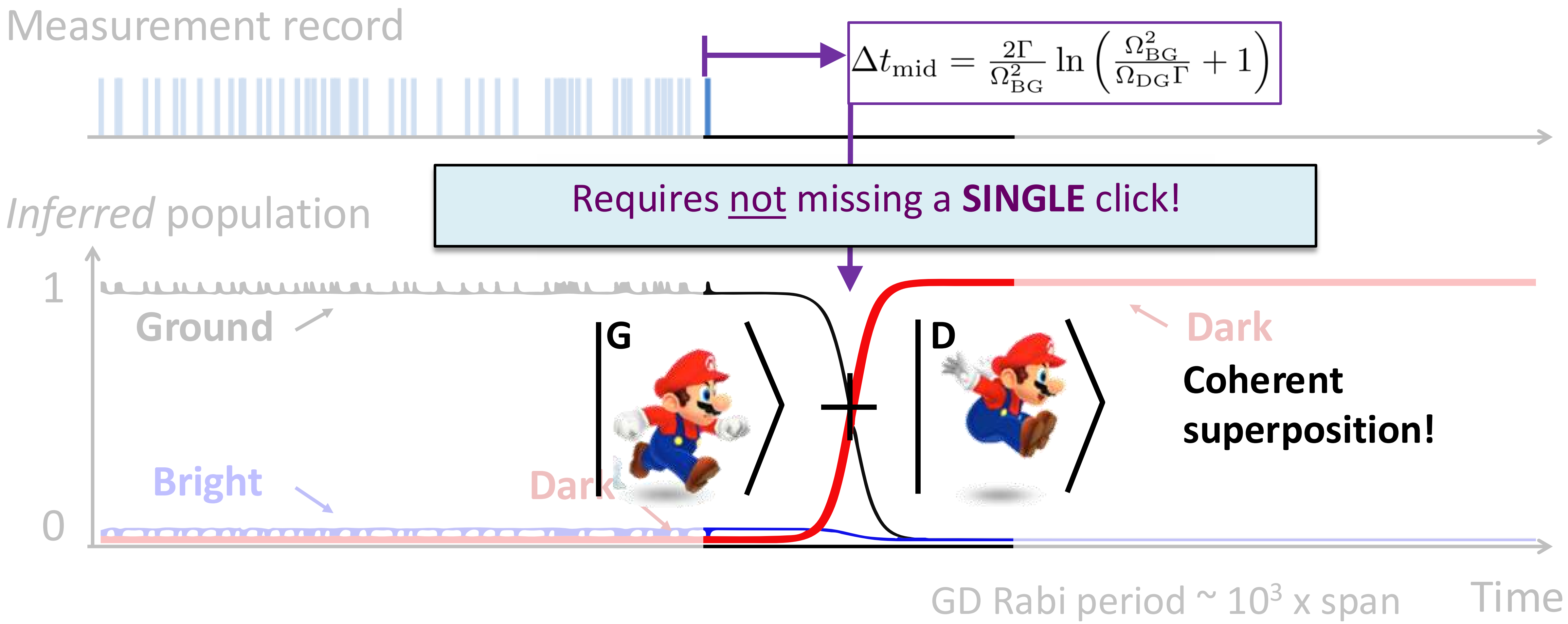


Measurement record (click? Y/N)



No-click trajectory



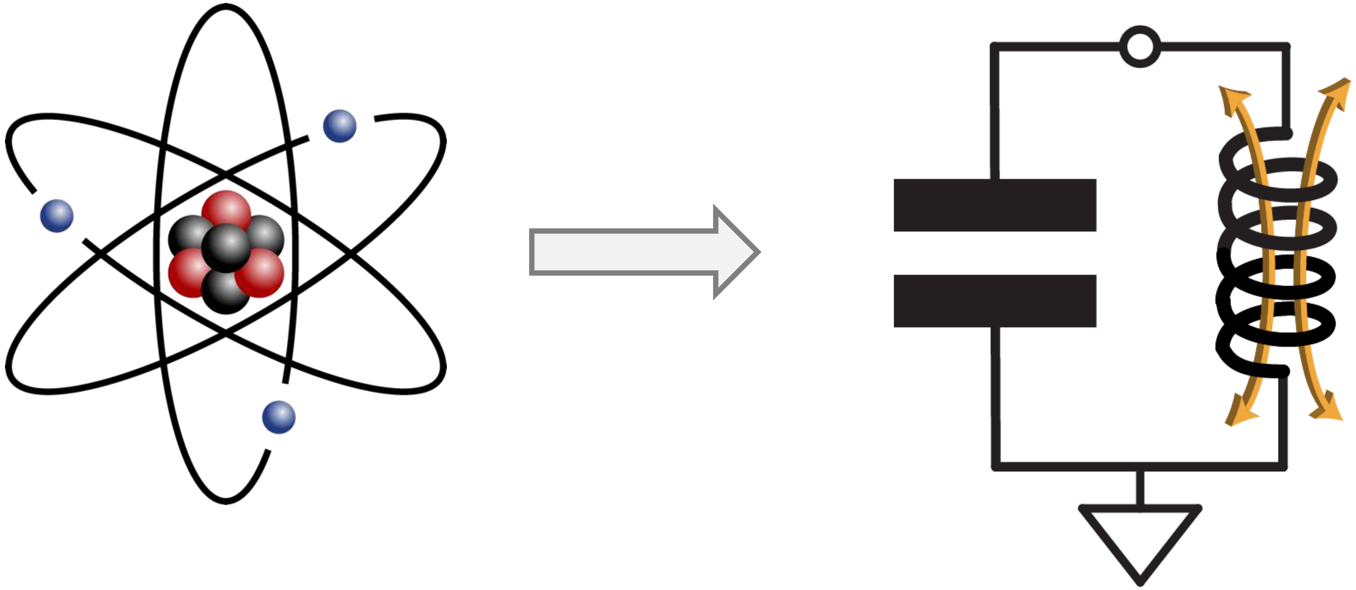


Carmichael, SUSSP71 (2015); Ruskov et al., PRB (2007); Related: Porrati & Putterman, PRA (1987); Mabuchi & **Zoller** PRL (1996); Plenio & Knight, RMP (1998); Katz et al., Science (2006) & PRL (2008)

Principle of our cQED experiment

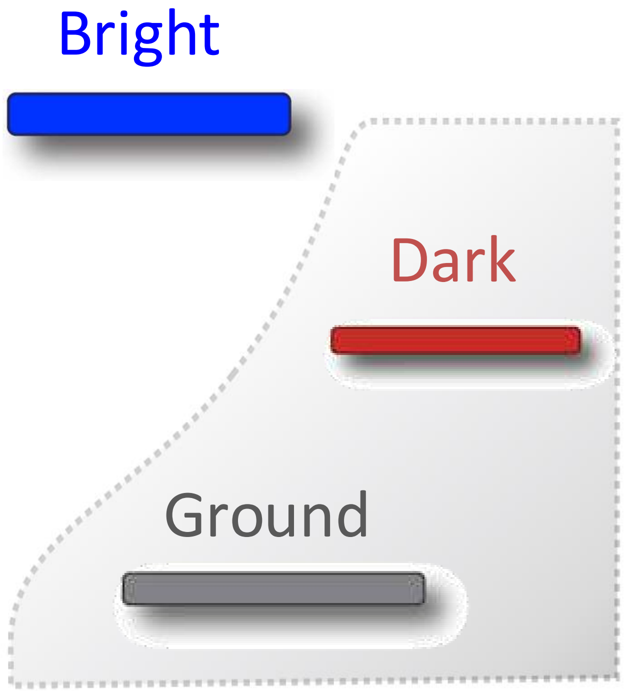
Related quantum circuit experiments on trajectories of 2-level atoms:

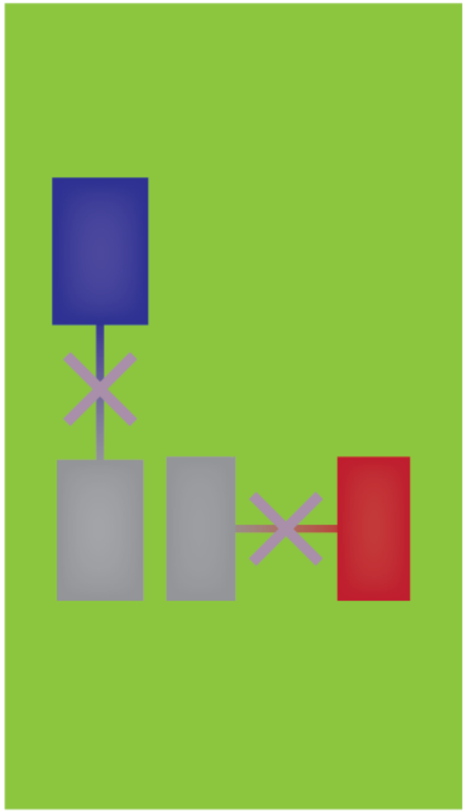
Hacohen-Gourgy *et al.*, PRL (2018)
Cottet *et al.*, PNAS (2017)
Hacohen-Gourgy *et al.*, Nature (2016)
Slichter *et al.*, NJP (2016)
Naghiloo *et al.*, Nat. Comm. (2016)
Campagne-Ibarcq *et al.*, PRL (2016)
Weber *et al.*, Nature (2014)
de Lange *et al.*, PRL (2014)
Murch *et al.*, Nature (2013)
Campagne-Ibarcq *et al.*, PRX (2013)
Katz *et al.*, PRL (2008)
Katz *et al.*, Science (2006)
…



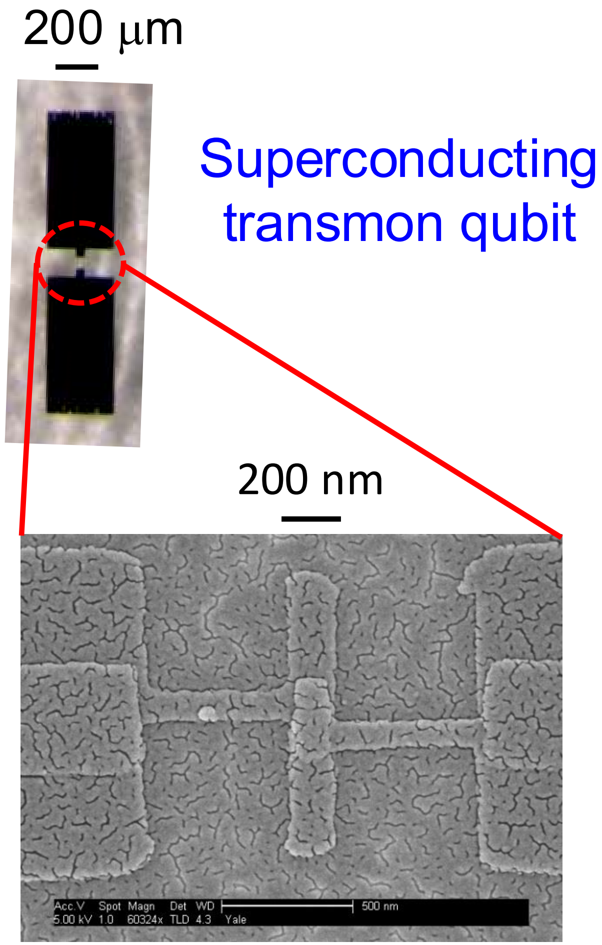
Quantum superconducting circuit architecture

Schematic representation of chip



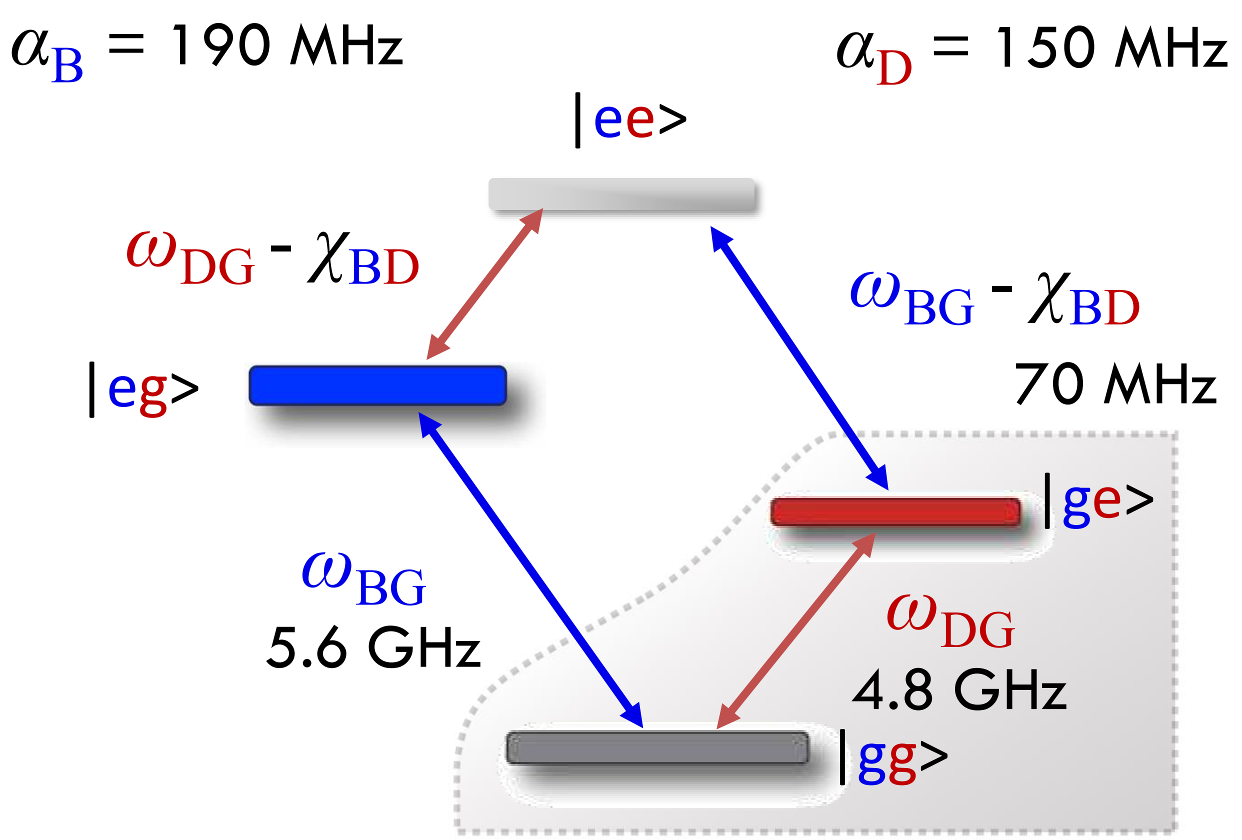


Substrate
(not to scale)

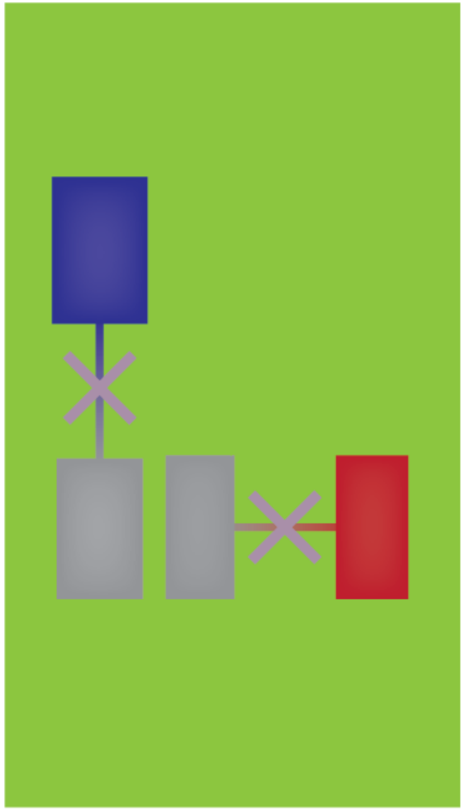


Blais *et al.*, PRA (2004); Paik *et al.*, PRL (2011)

cQED implementation of V-system



Schematic representation of chip

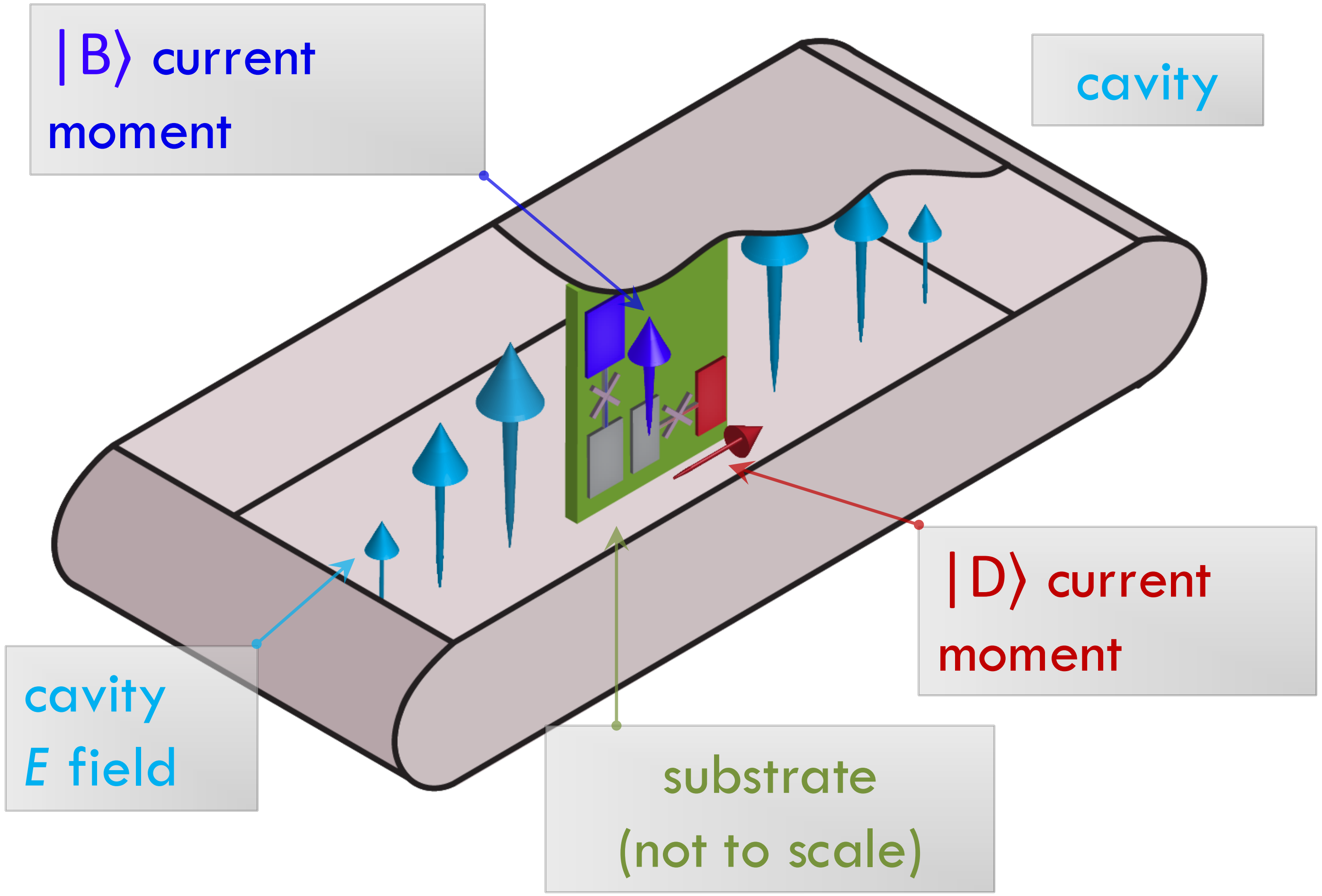


Substrate
(not to scale)

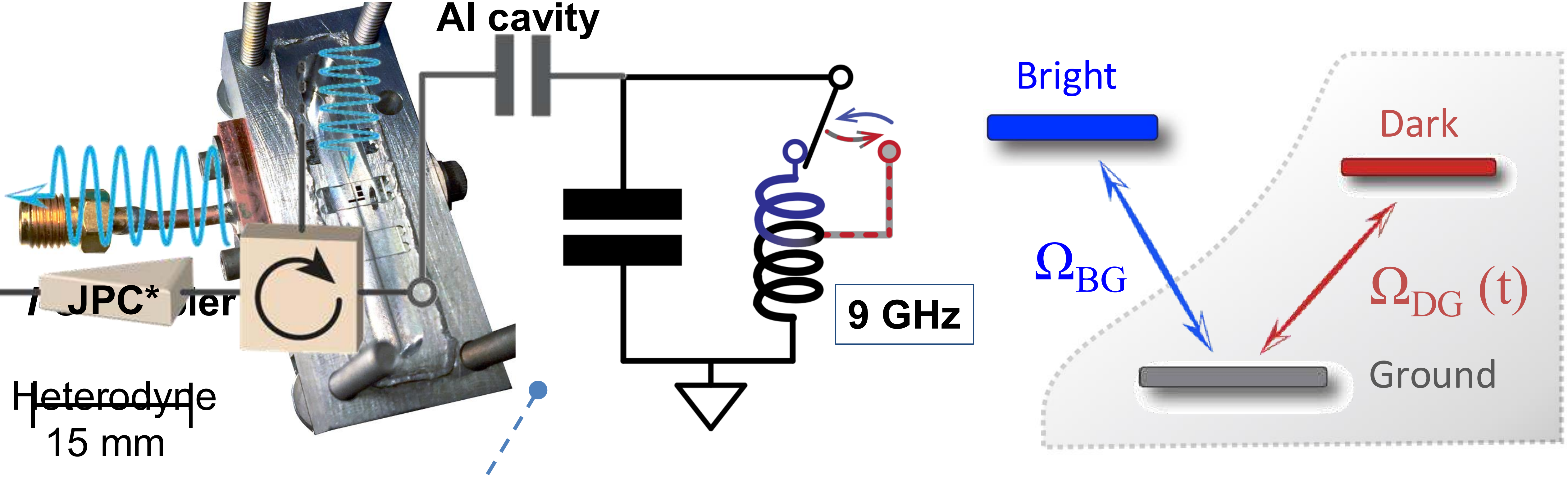
Related work: Gambetta *et al.*, PRL (2011)
Srinivasan *et al.*, PRL (2011) Dumur *et al.*, PRB (2015) Zhang *et al.*, Nature JQI (2017) …

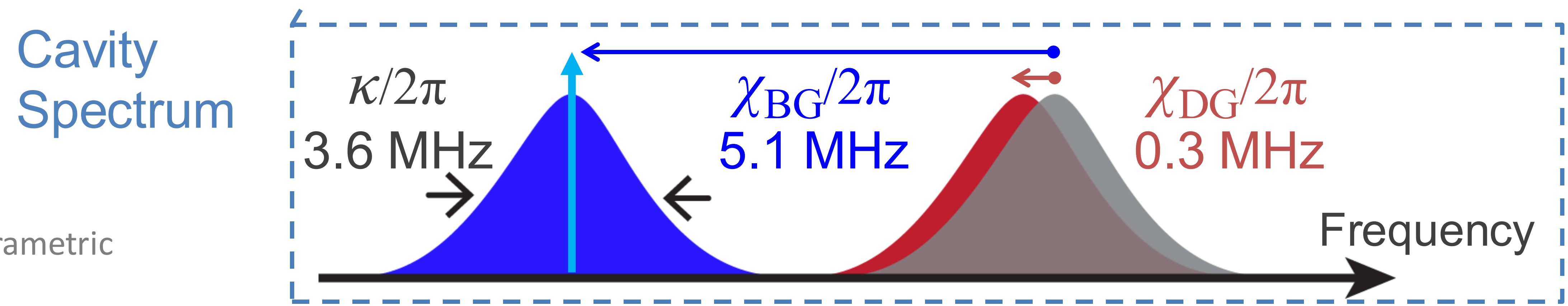
cQED implementation of V-system

Schematic representation of design



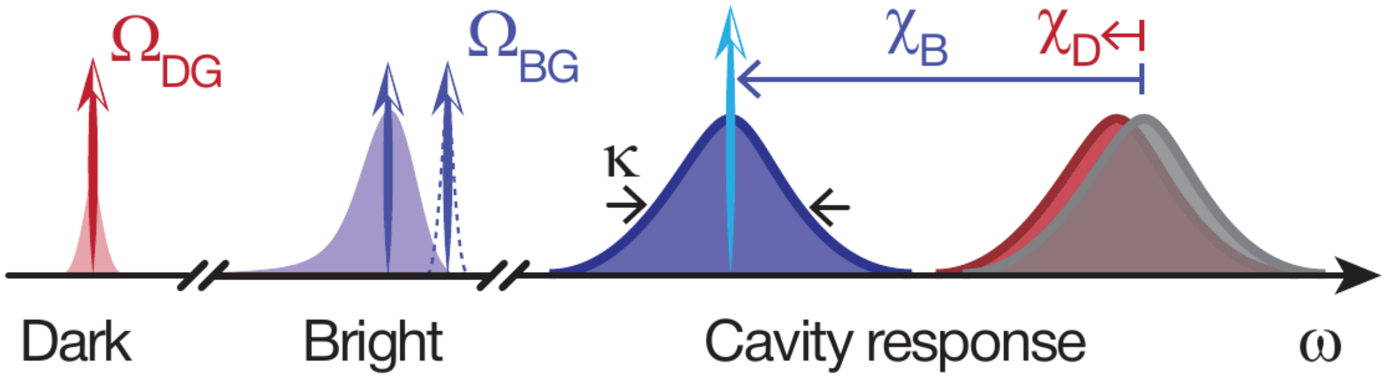
Measuring B / non-B with 90% efficiency

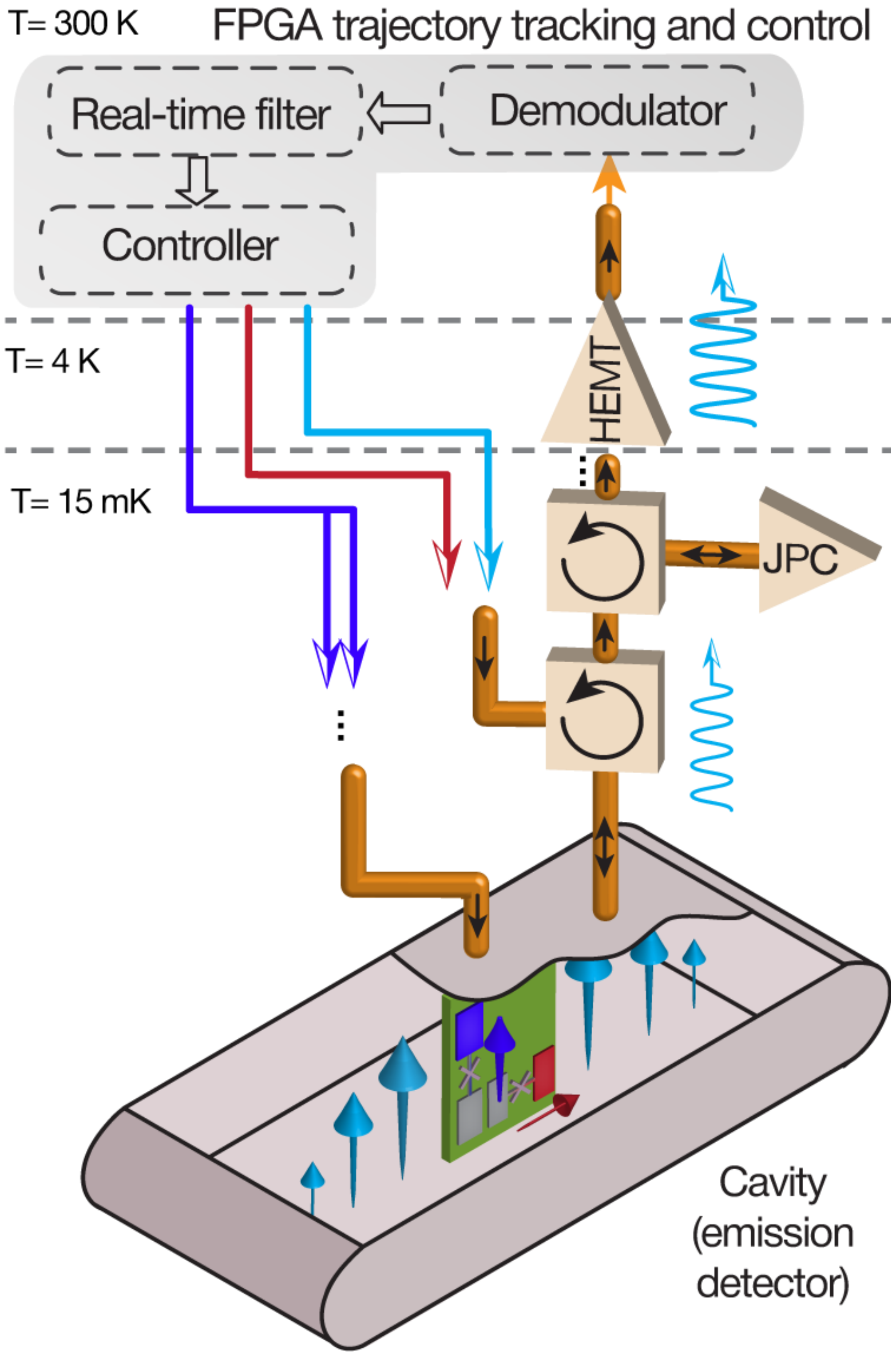




* Josephson parametric converter

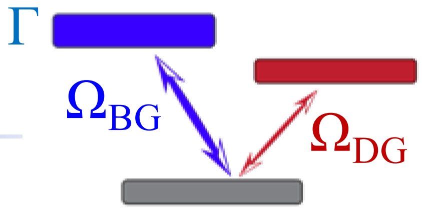
Frequency landscape

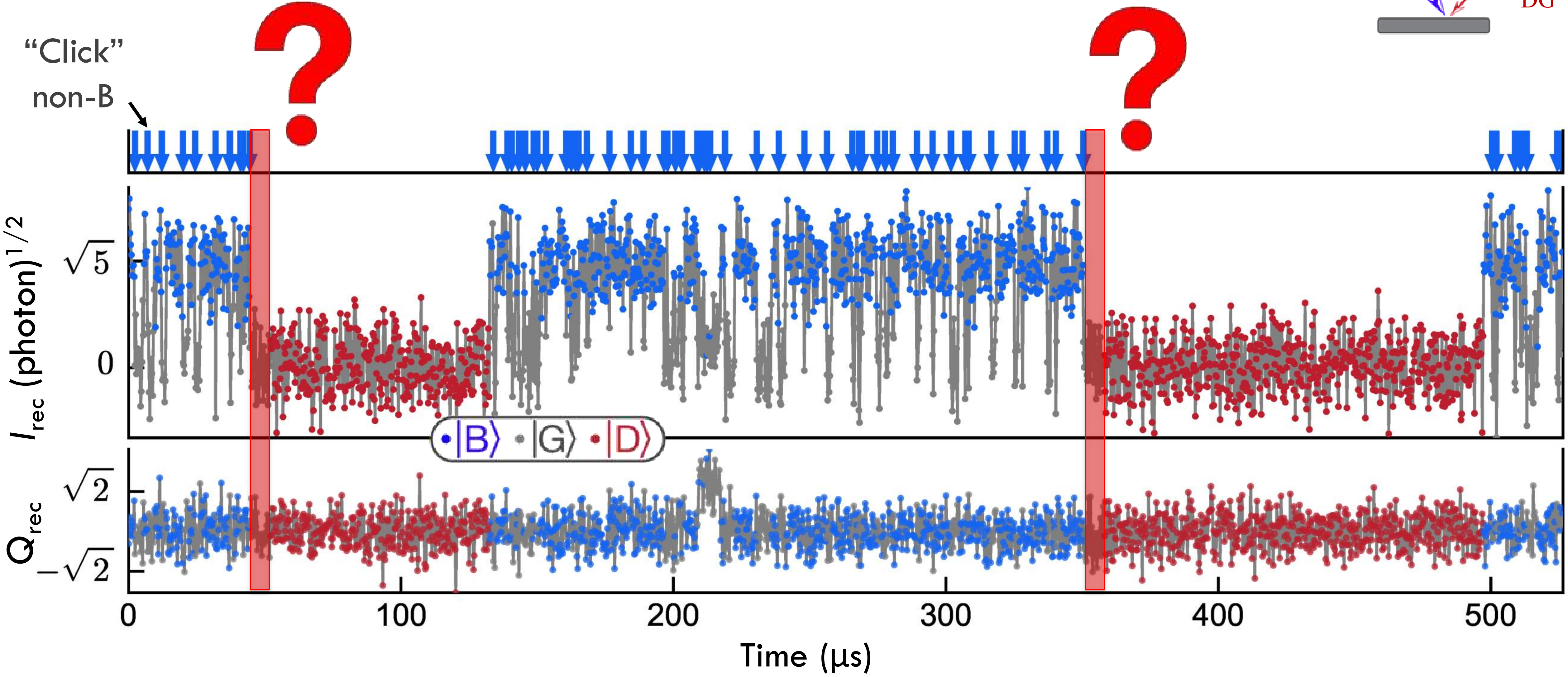




Unconditioned quantum jumps

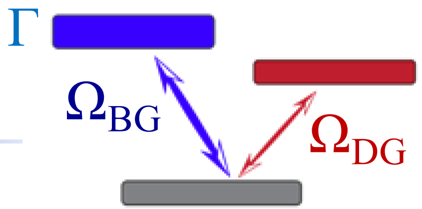
Inferred state & click times

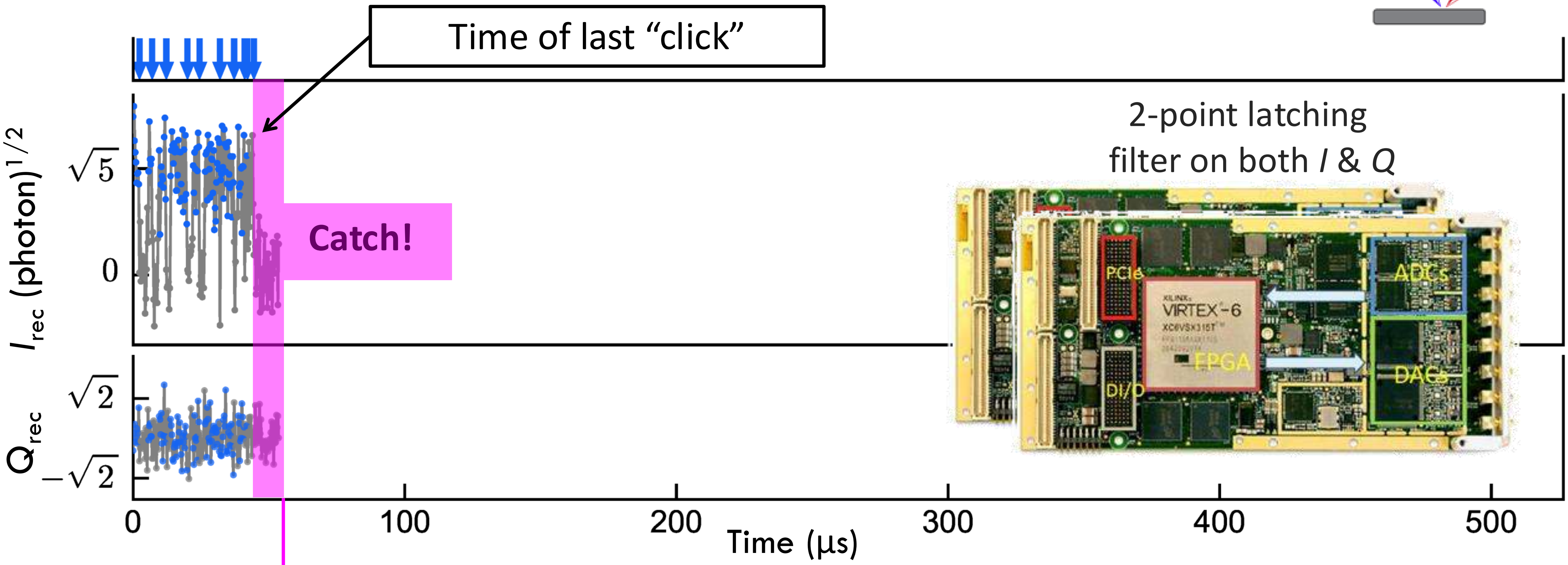




Real-time detection of a quantum jump

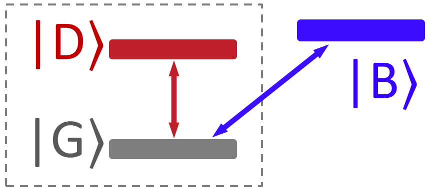
Catch protocol

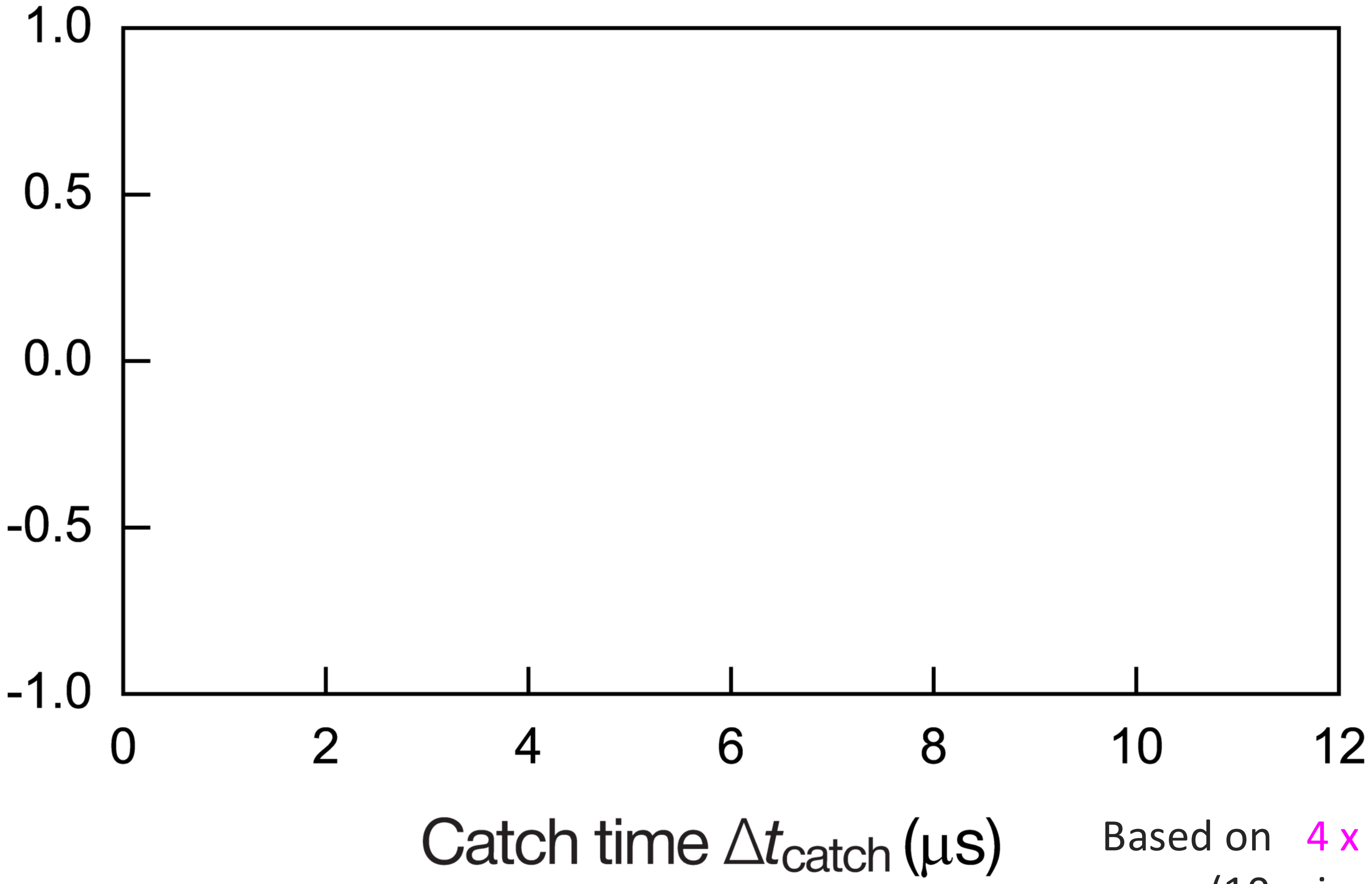




Msmt. rate Γ_m^{-1} ~ 8 ns	≪	Integration time 2.6 x 10^2 ns	≪	GB jump timescale 10^3 ns	≪	t_{mid}	≪	GD jump timescale ~ 10^5 ns

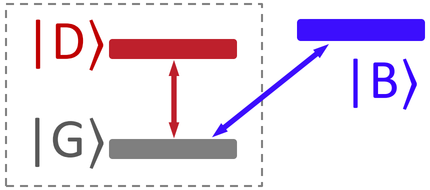
Catching the quantum jump mid-flight

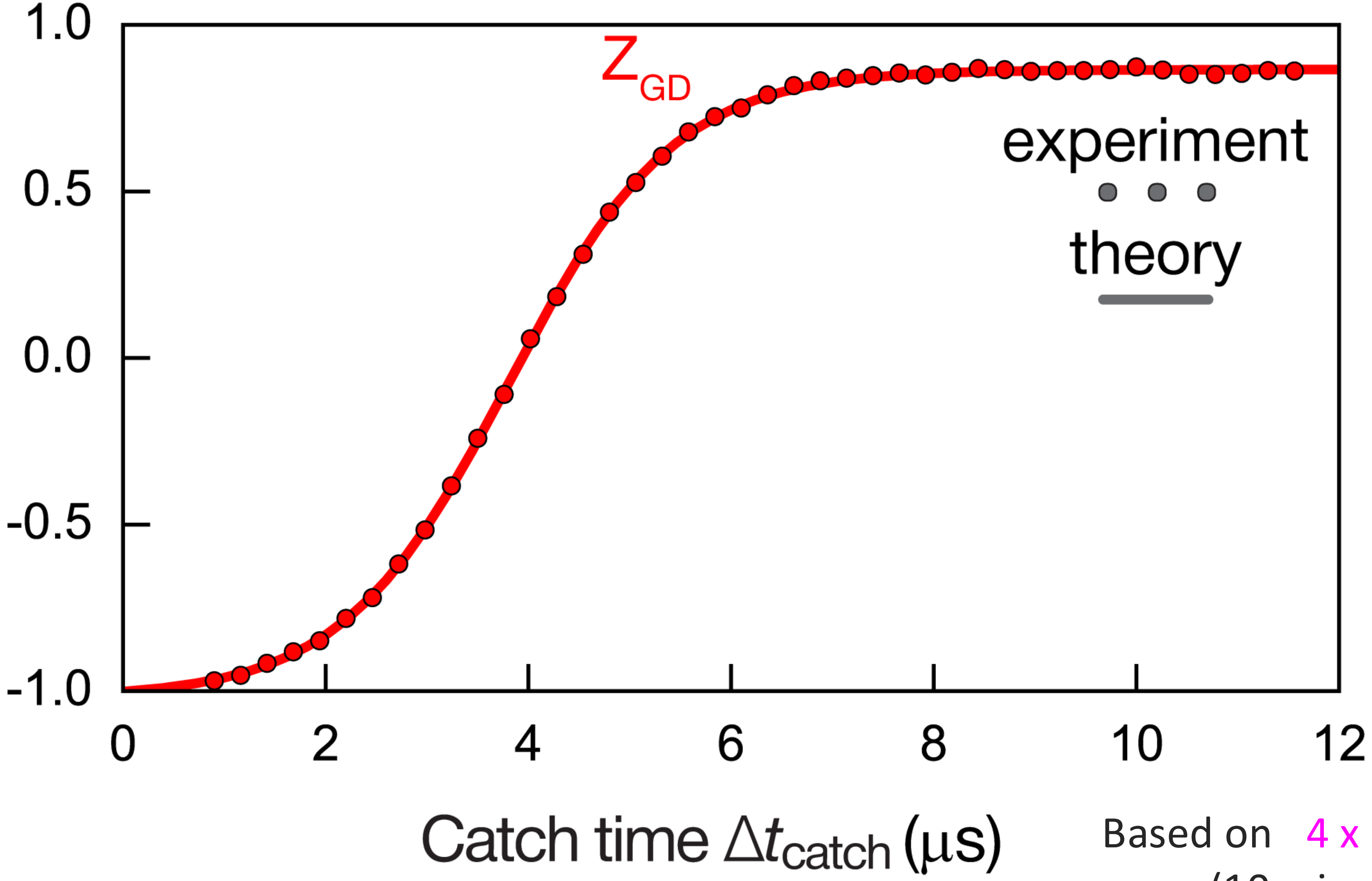




Based on 4 x 10^6 catch events
(10 min. tracking time)

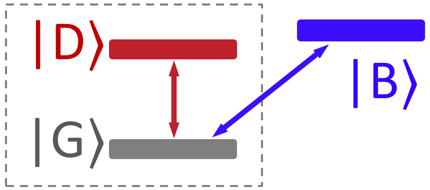
Catching the quantum jump mid-flight

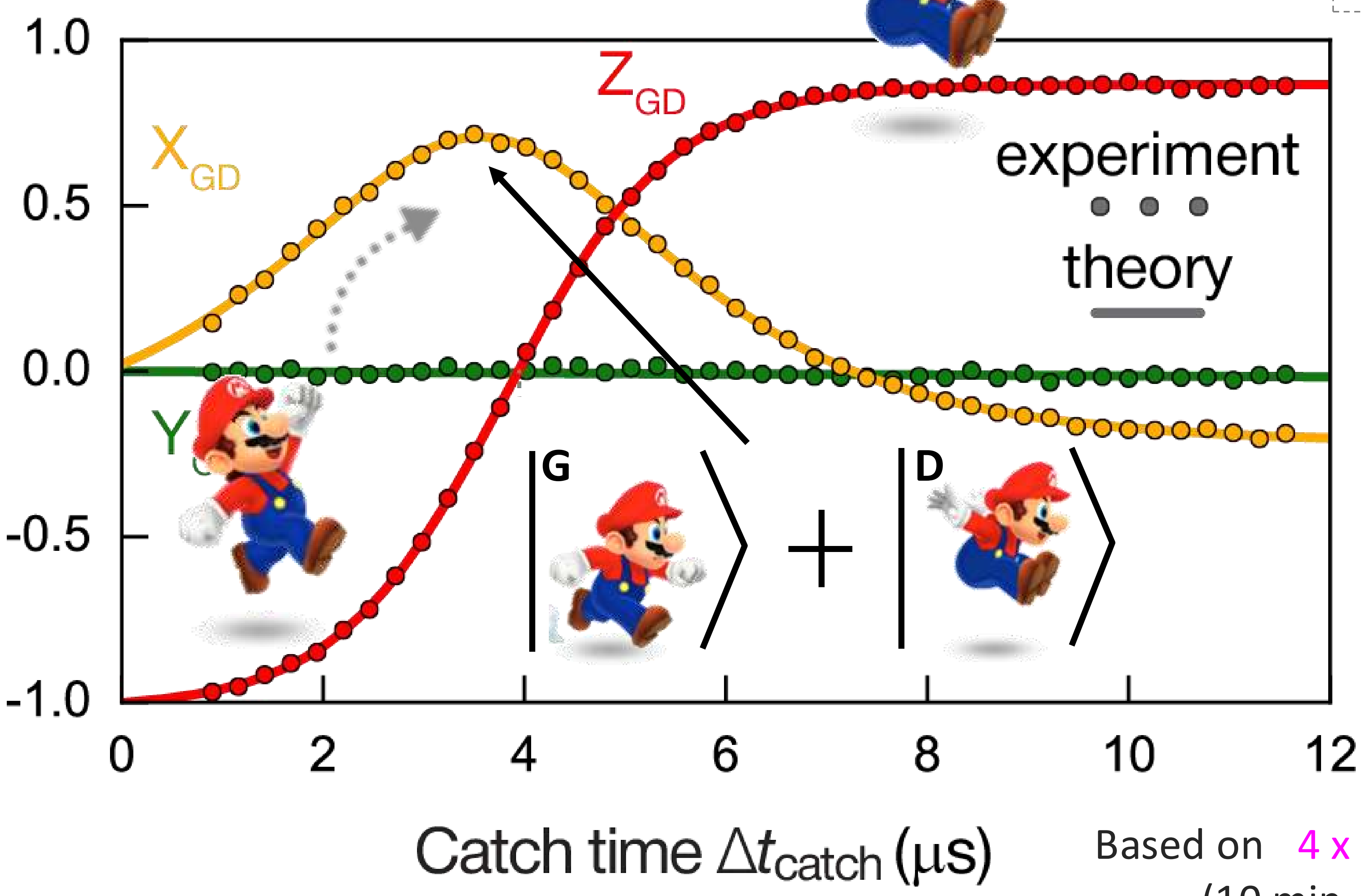




Based on 4 x 10^6 catch events
(10 min. tracking time)

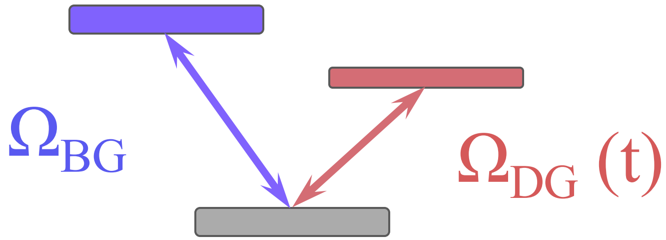
Catching the quantum jump mid-flight

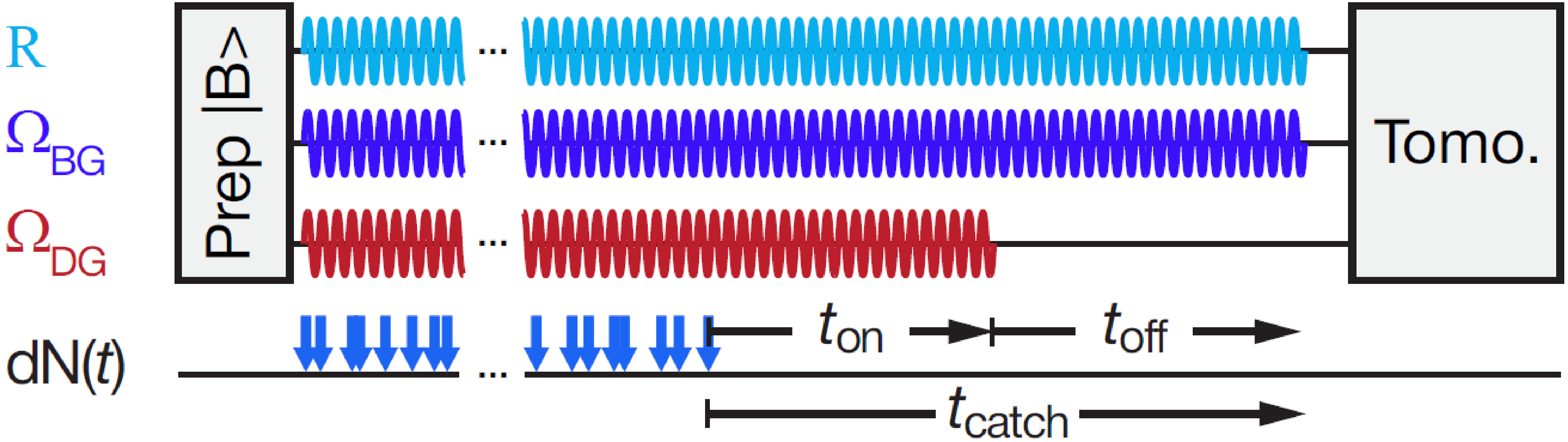




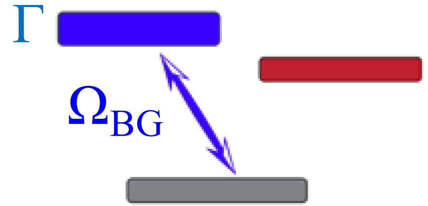
Based on 4×10^6 catch events
(10 min. tracking time)

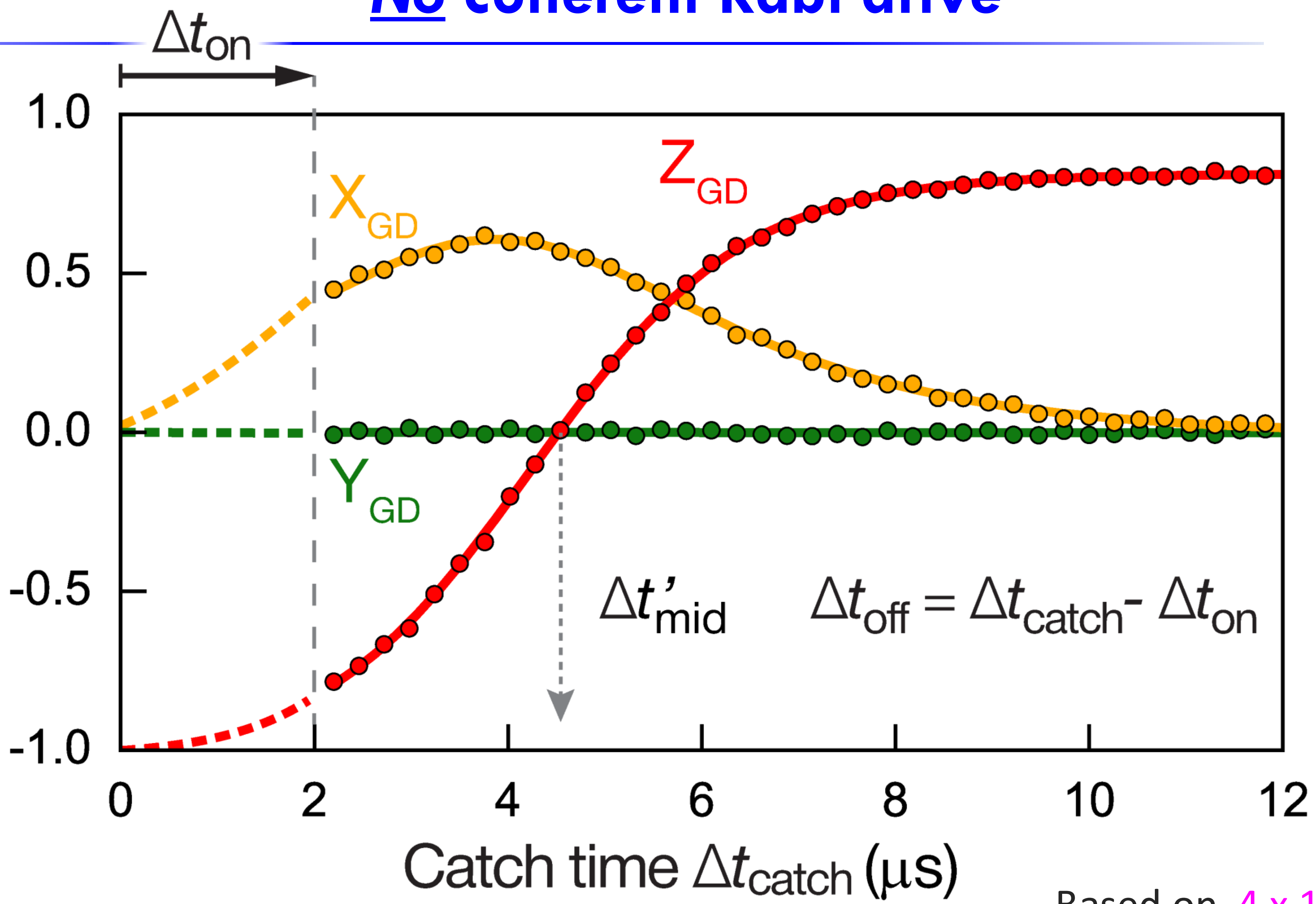
Catch in *absence* of Dark drive





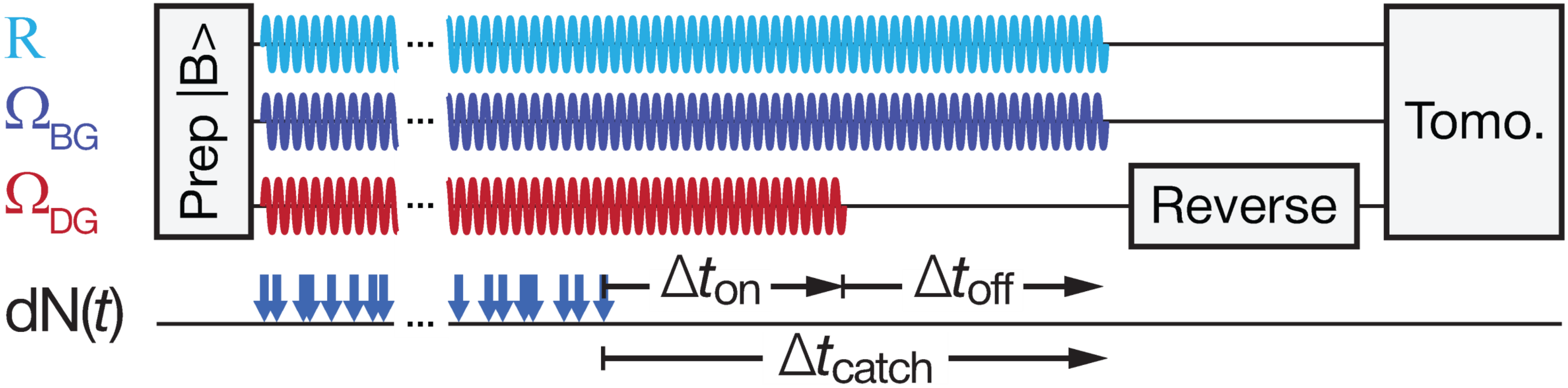
$\underline{No}$ coherent Rabi drive



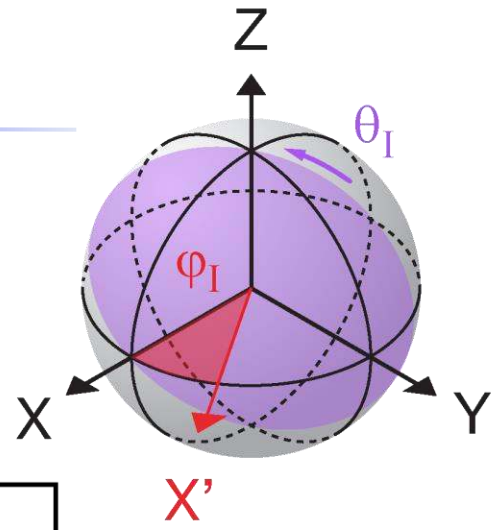


Based on 4×10^6 catch events

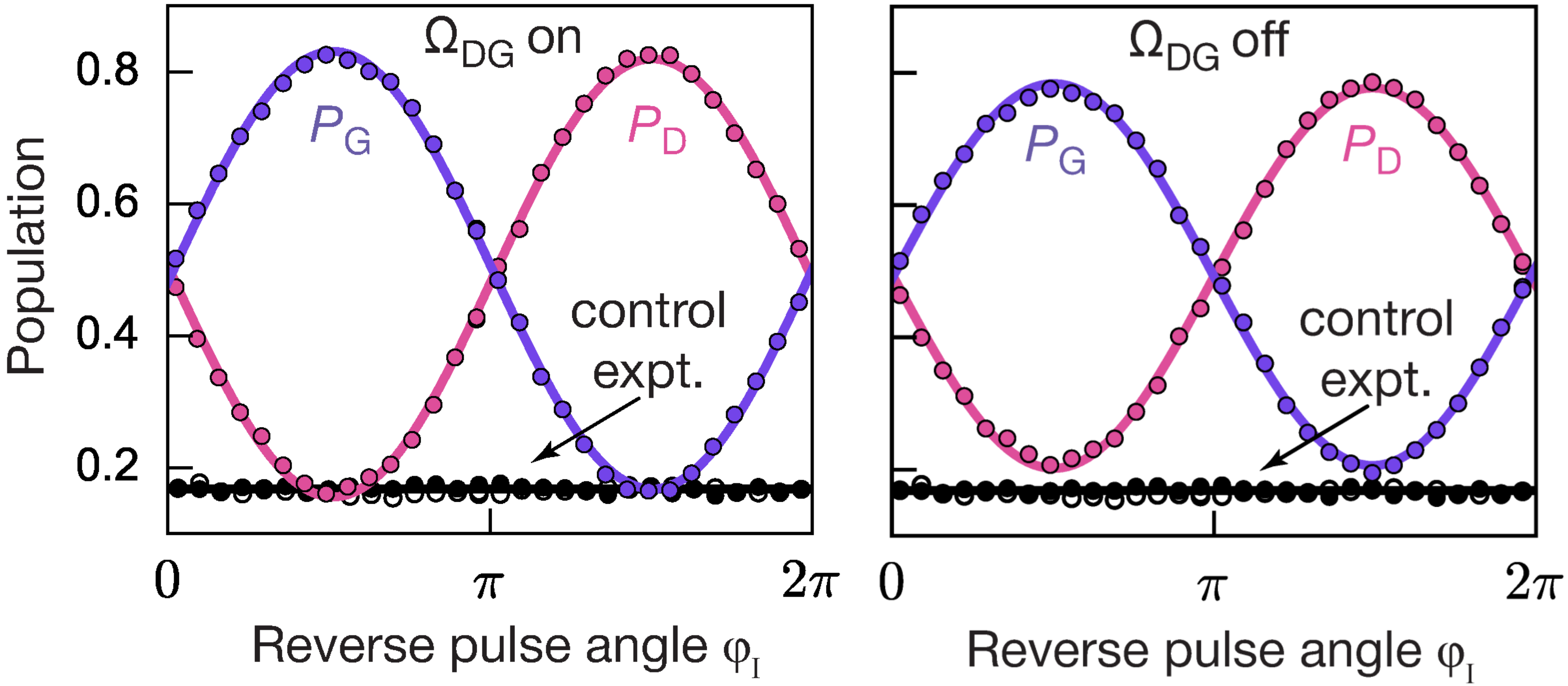
Reversing the quantum jump mid-flight



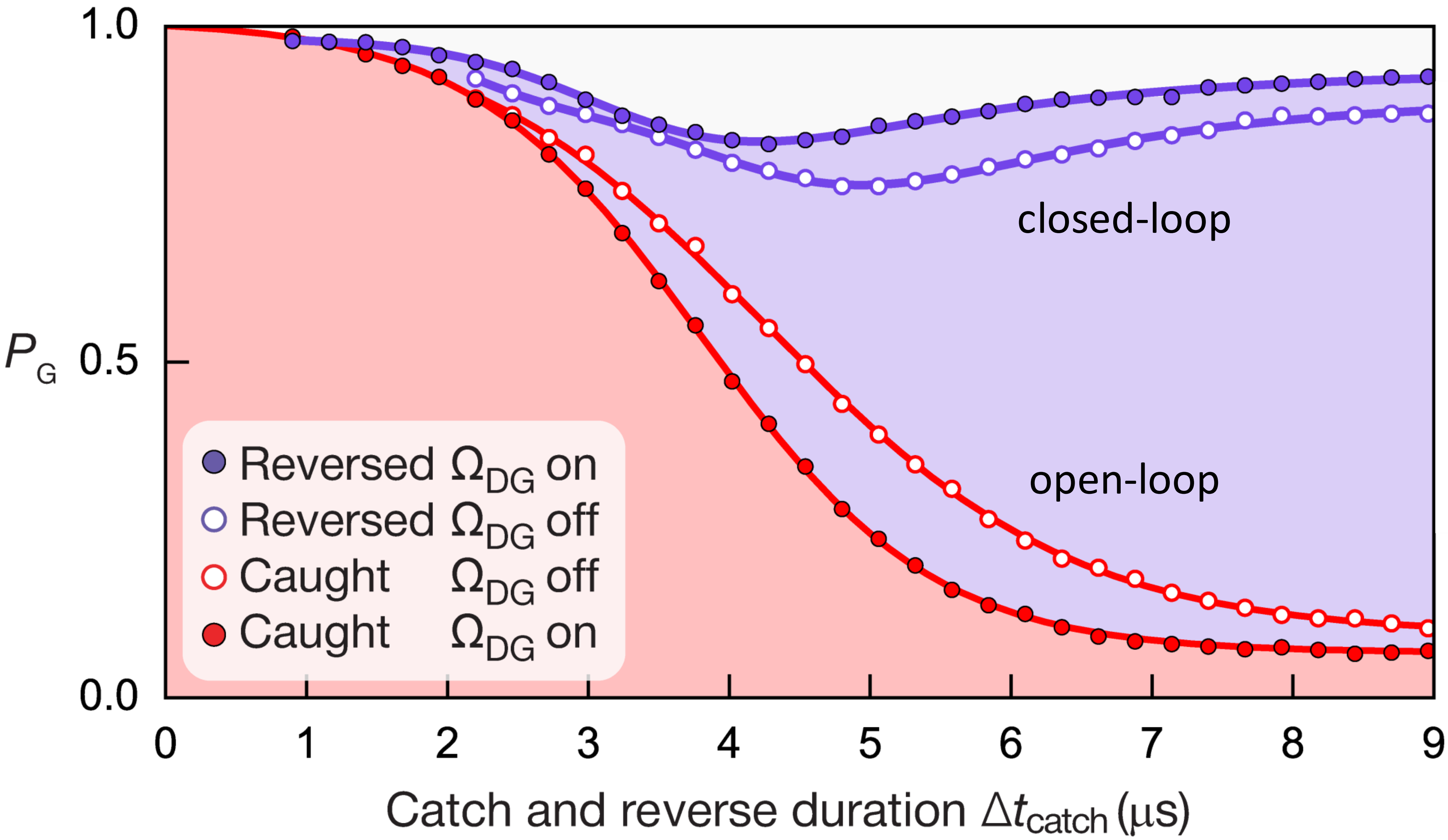
Experimental reversal of jump



No click until Δt_{mid} = advance warning of individual jump

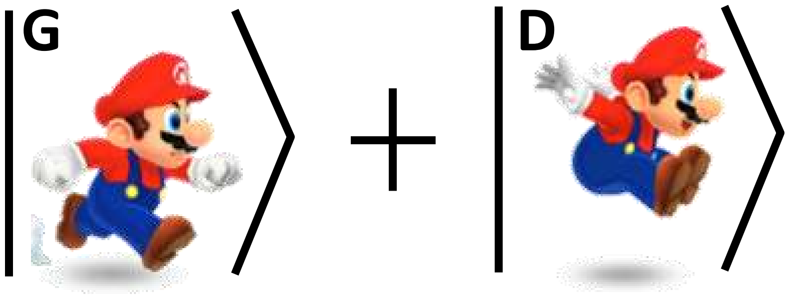


Catching and reversing the quantum jump mid-flight



Conclusions & Future directions

Observed jump “internal coherence” using fast electronics and feed-forward control



Caught individual jumps in mid-flight and reversed them

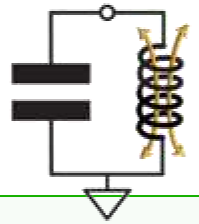
Quantum trajectory efficiently explains details of exp. results

Nature 570, 200 (2019)   Minev, Ph.D. Thesis (2018)

Continuous syndrome measurement for autonomous quantum error correction

Follow ups: arXiv:1808.00726, arXiv:1810.03225, ...

Advancing Quantum Sensing via Quantum Control with



Good at measurements

Time-resolved, quantum-limited measurements
- near-unit quantum efficiency η
- engineer measurements on-demand: X, Y, Z, …
- engineer bath: squeezed vacuum, interaction, …

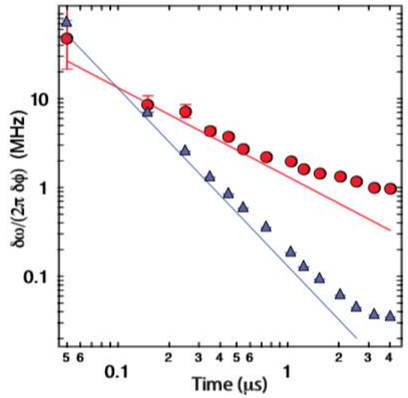
Good at real-time control

Versatile

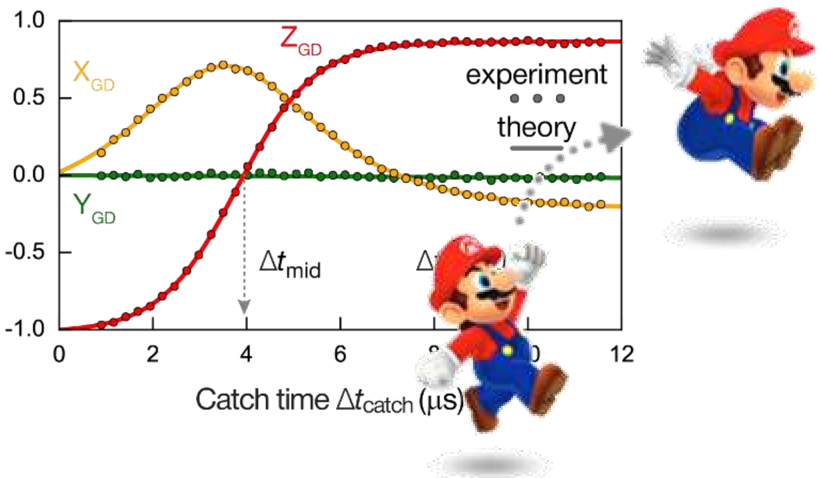
Nanosecond-latency control
- feedforward, feedback
- adaptive, engineerable

Off-the-shelf stability and precision of control

1st observation of fundamental T^4
improved quantum fisher x740



90% quantum detection efficiency



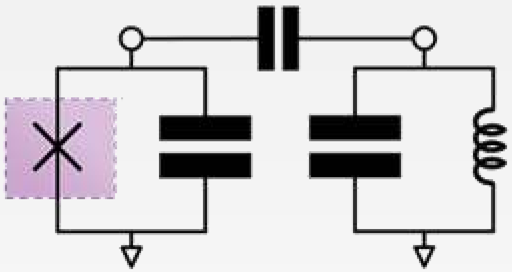
EXTRA SLIDES

JUMPS

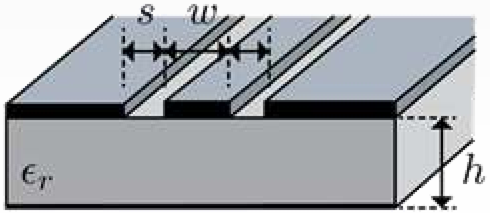
EPR

Circuit quantization

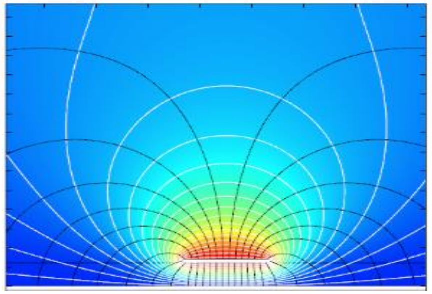
Lumped-element approximation



analytical



FE/boundary



Full Maxwell equations

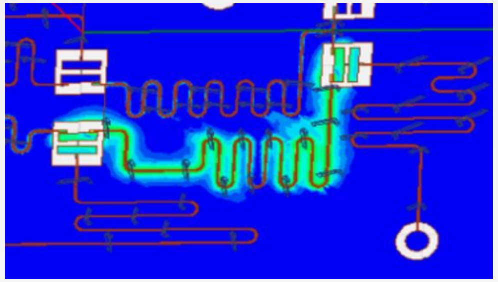
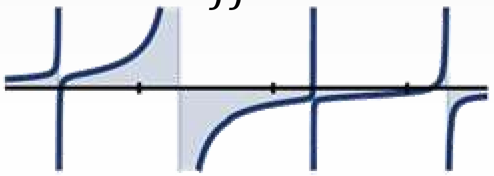


Image: Brahm *et al.*, QST (2018)

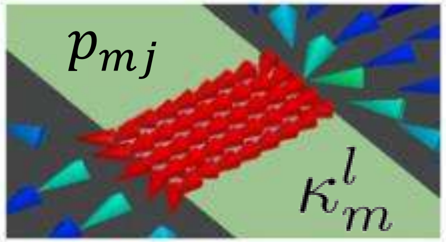
impedance*

$Z_{jj'}(\omega)$



eigen and driven

energy†



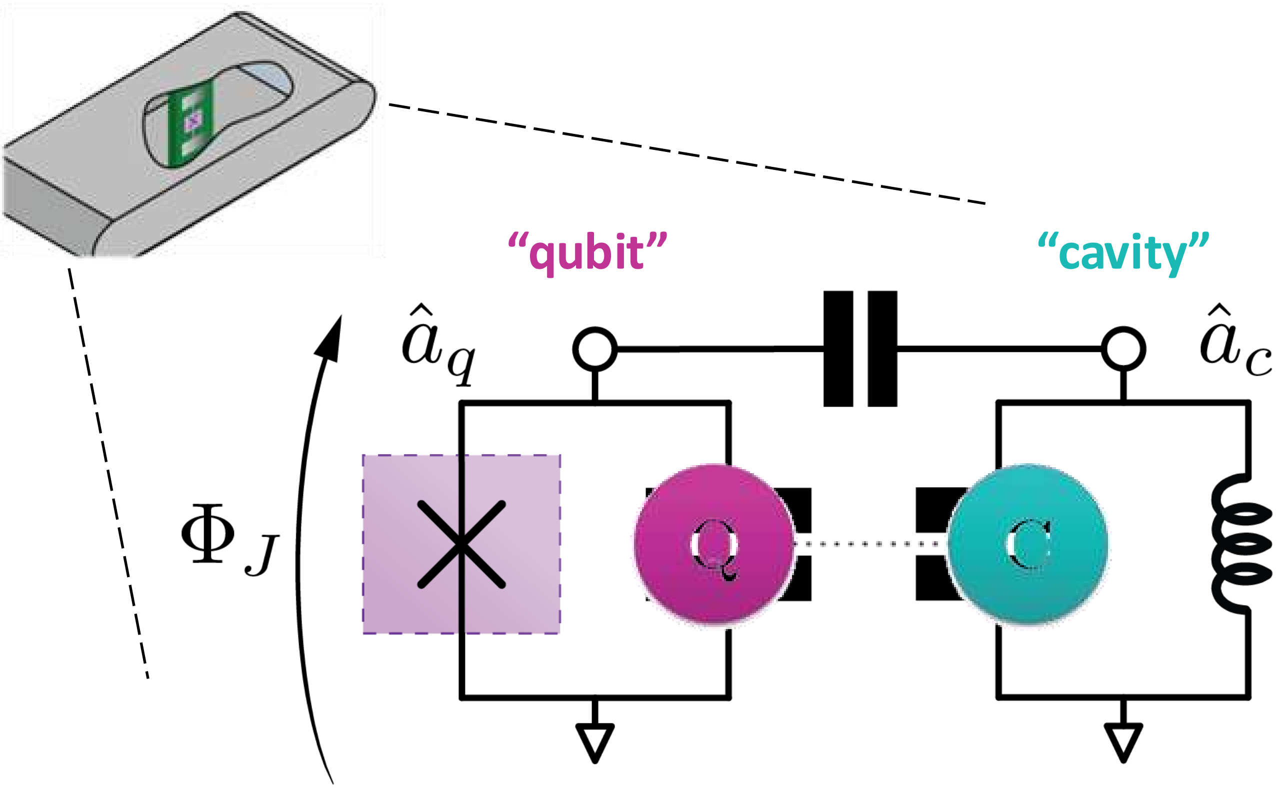
eigen

Captures more information, complexity, accuracy

* Nigg, Paik, *et al.* (2012); Bourassa *et al.* (2012); Solgun *et al.* (2014, 2015, 2017) …

† Minev *et al.*, arXiv:1902.10355, in prep. (2019)

Explanation of quantization



(only conceptual picture)

$$\hbar\omega_c \hat{a}_c^\dagger \hat{a}_c + \hbar\omega_q \hat{a}_q^\dagger \hat{a}_q$$

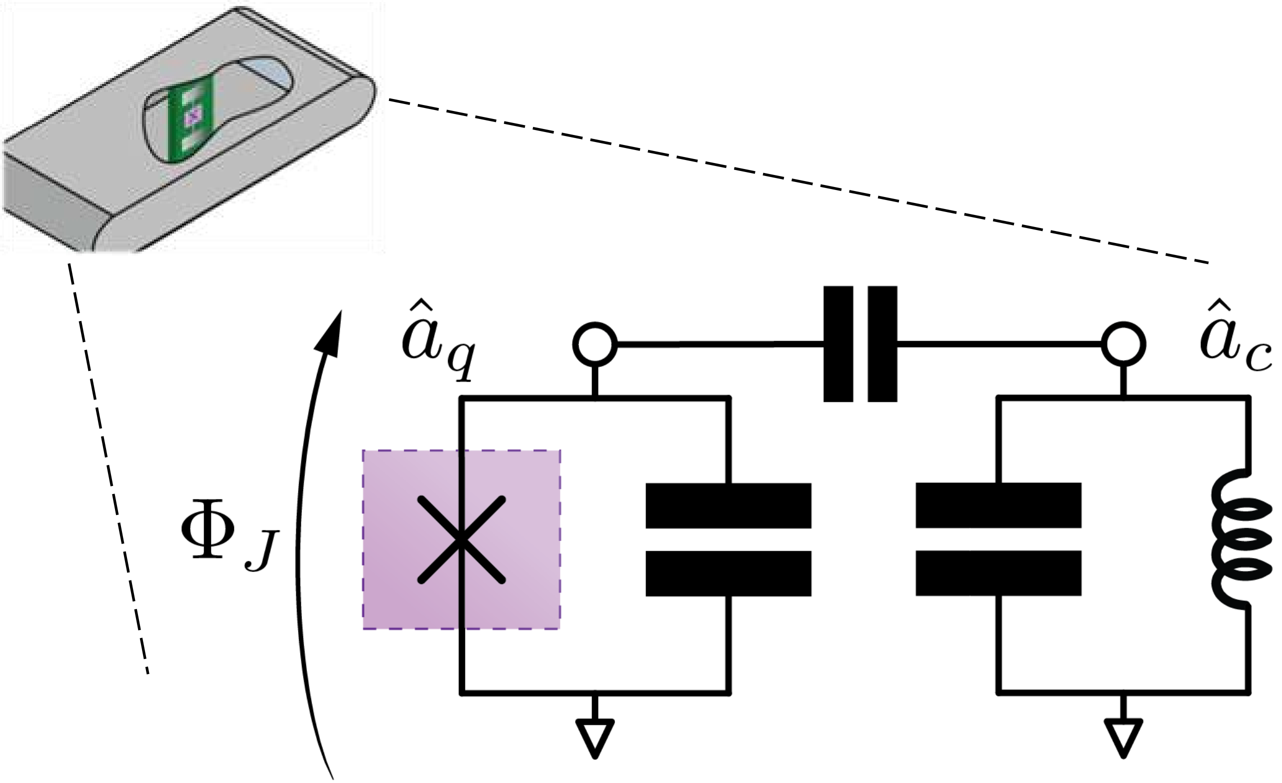
$$\hat{H}_{\text{full}} = \boxed{\hat{H}_{\text{lin}}} + \boxed{\hat{H}_{\text{nl}}}$$

$$-E_J \left(\cos\left(\hat{\phi}_J\right) + \hat{\phi}_J^2/2 \right)$$

$$\hat{\phi}_J = \phi_c^{\text{ZPF}} (\hat{a}_c^\dagger + \hat{a}_c) + \phi_q^{\text{ZPF}} (\hat{a}_q^\dagger + \hat{a}_q)$$

second quantization in eigen basis of linearized circuit

Energy-participation ratio (EPR) and the quantum bridge



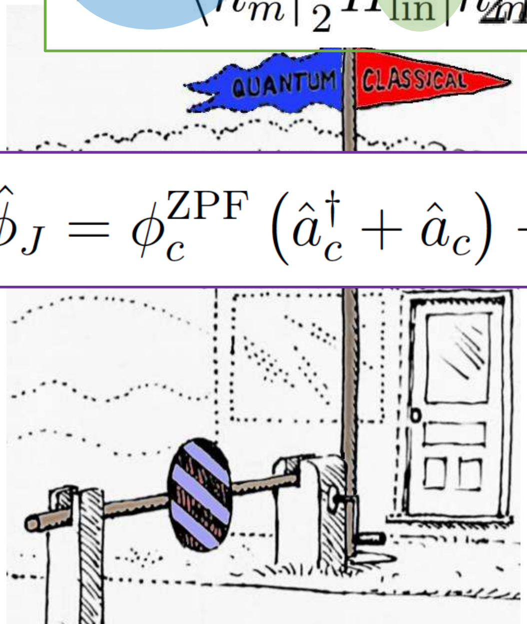
What fraction of the energy of a mode *m* is stored in the junction?

$$p_m = \frac{\text{Energy stored in junction}}{\text{Inductive energy stored in mode } m}$$

$$p_m = \frac{\langle n_m | :\frac{1}{2} E_J \hat{\phi}_J^2: | n_m \rangle}{\langle n_m | \frac{1}{2} \hat{H}_{\mathrm{lin}} | n_m \rangle}$$

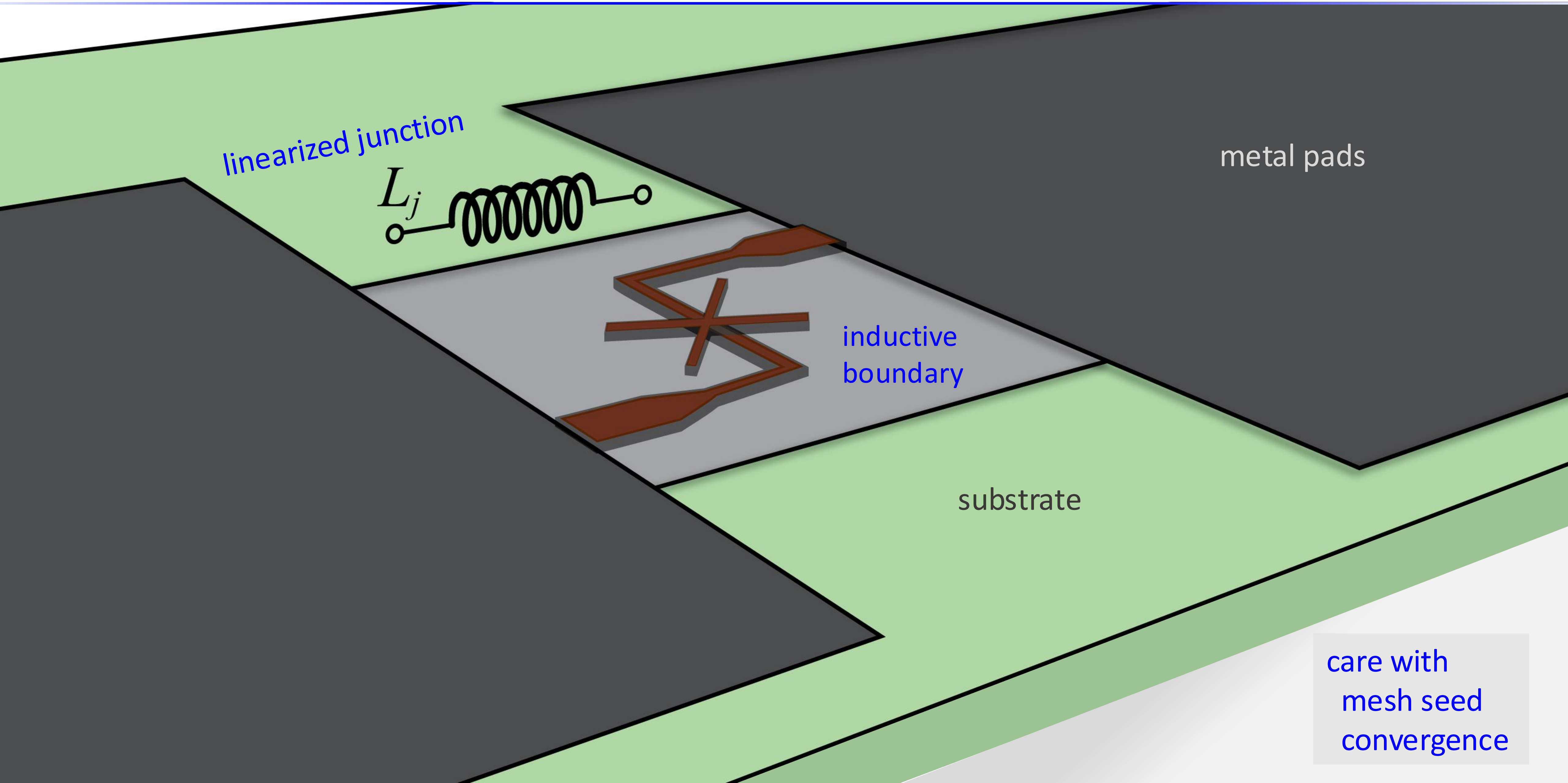
$$\left(\phi_m^{\mathrm{ZPF}}\right)^2 = p_m \frac{\hbar \omega_m}{2 E_J}$$

$$\hat{\phi}_J = \phi_c^{\mathrm{ZPF}} \left(\hat{a}_c^\dagger + \hat{a}_c \right) + \phi_q^{\mathrm{ZPF}} \left(\hat{a}_q^\dagger + \hat{a}_q \right)$$



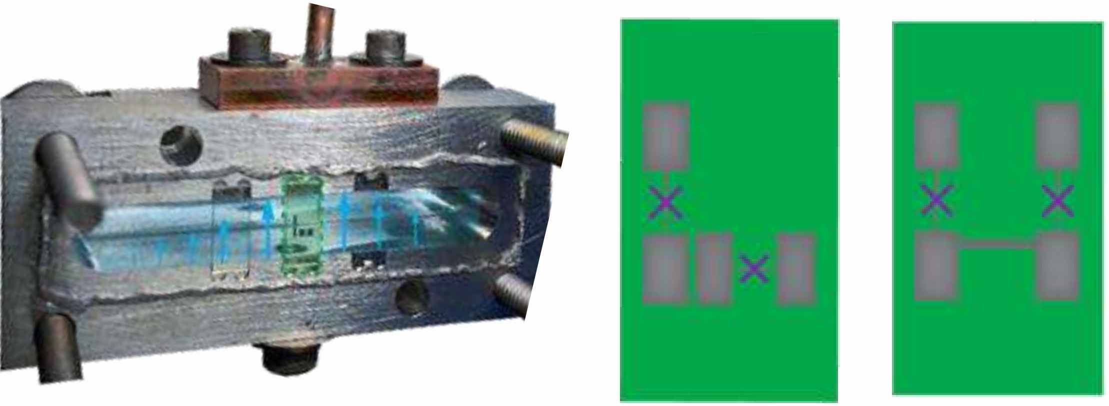
Drawing:
Zurek, Physics Today (1991)

Finite-element model of linearized Junction

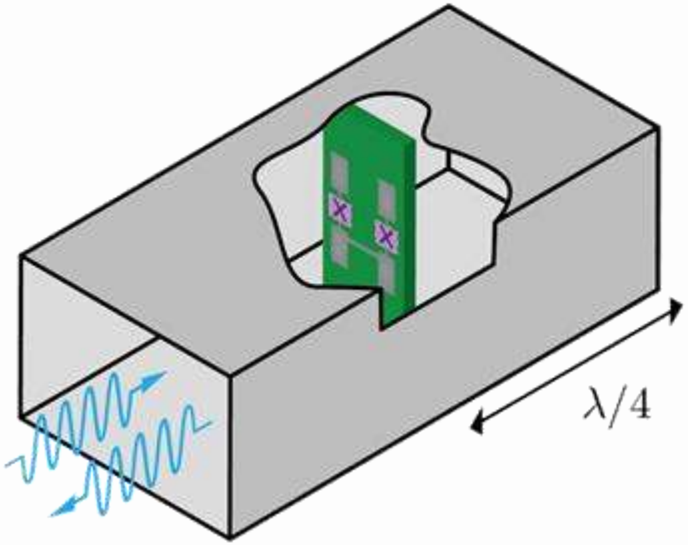


Measured architectures and devices

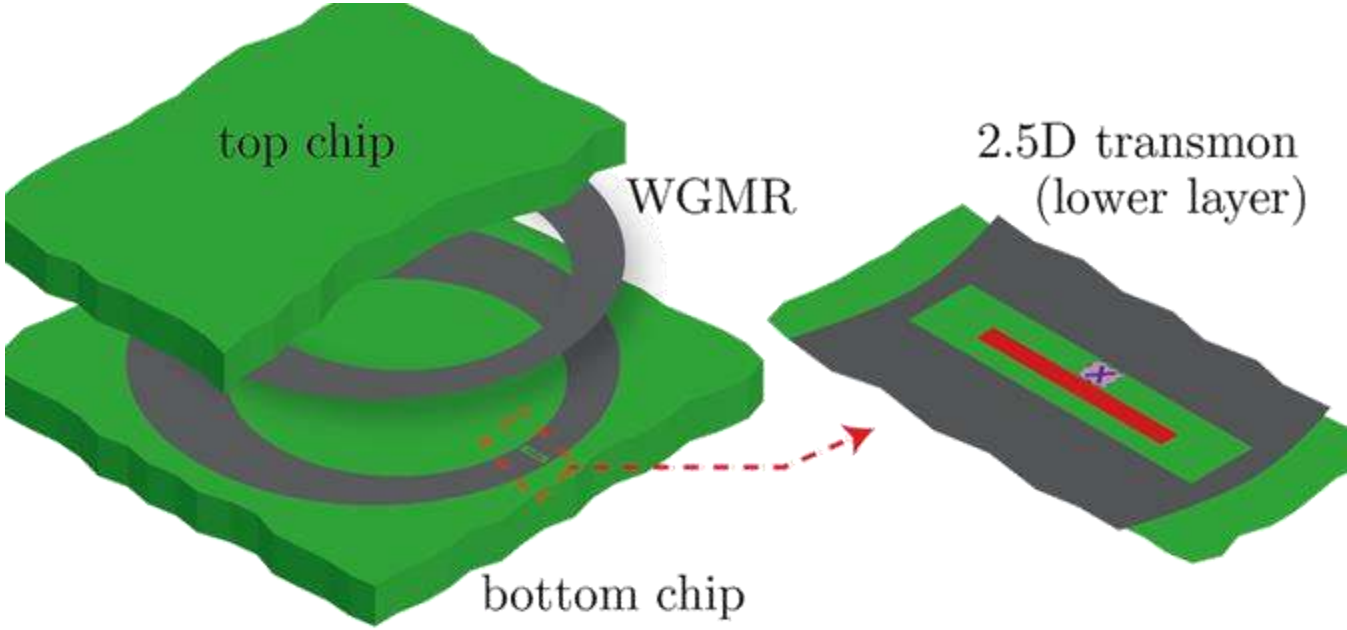
Three-dimensional (3D) *



Waveguide



Multilayer (2.5D) cQED



Minev *et al.*, APL (2013)
Minev *et al.*, WO/2016/138395 (2015)
Minev *et al.*, Phys. Rev. App. (2016)

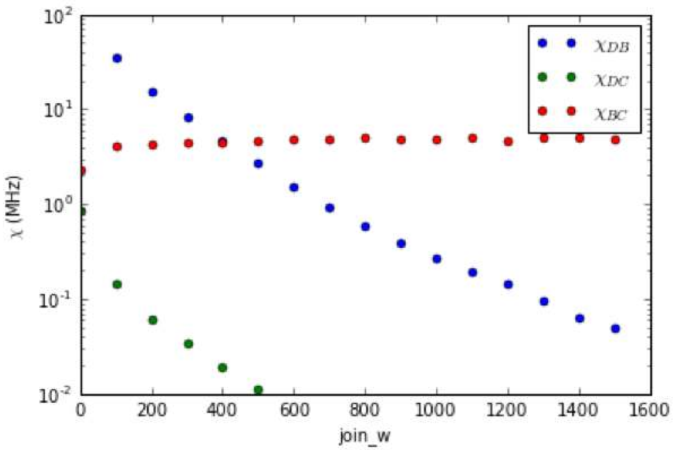
* Minev *et al.*, arXiv:1803.00545 (2018); Related: Gambetta *et al.*, PRL (2011), Srinivasan *et al.*, PRL (2011), Dumur *et al.*, PRB (2015), Zhang *et al.*, Nature JQI (2017) …

How to use the EPR approach

- Fully automated
  - control of HFSS
  - calculations
- Full numerical treatment
- Convergence checks

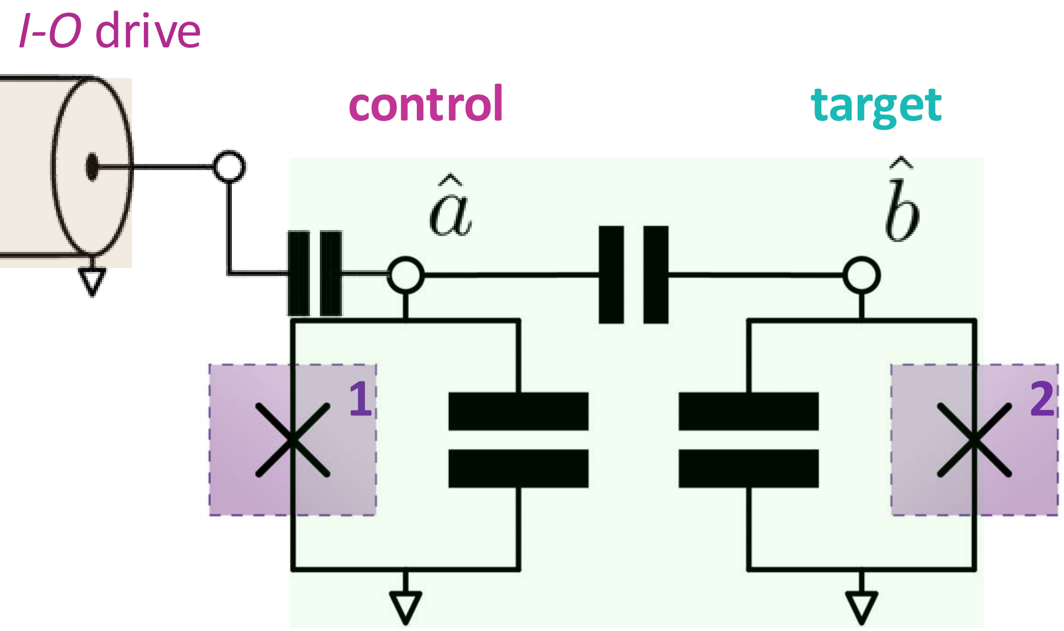
See my open source project on github

Used at Yale, ENS Paris, IBM, Berkeley, Saclay, and others




```python
from pyEPR import *

# 1.  Project and design. Open link to HFSS controls.
project_info = Project_Info('c:/sims',
                            project_name = 'two_qubit_one_cavity',
                            design_name  = 'Alice_Bob'
                            )

# 2a. Junctions. Specify junctions in HFSS model
project_info.junctions['jAlice'] = {'Lj_variable':'LJAlice', 'rect':'qubitA
project_info.junctions['jBob']   = {'Lj_variable':'LJBob',   'rect':'qubitB

# 2b. Dissipative elements.
project_info.dissipative.dielectrics_bulk    = ['si_substrate']
project_info.dissipative.dielectric_surfaces = ['interface']

# 3.  Run analysis
epr_hfss = pyEPR_HFSS(project_info)
epr_hfss.do_EPR_analysis()

# 4.  Hamiltonian analysis
epr      = pyEPR_Analysis(epr_hfss.data_filename)#
epr.analyze_all_variations(cos_trunc = 8, fock_trunc = 7)
epr.plot_Hresults()
```

Cross-resonance (CR) entangling gate



$$\hat{H} = \omega_a \hat{a}^\dagger \hat{a} + \omega_a \hat{b}^\dagger \hat{b} \qquad \text{Eigen modes}$$

$$- \sum_{j=1}^{2} \frac{E_j}{4!} \left(\phi_{aj} \left(\hat{a} + \hat{a}^\dagger \right) + \phi_{bj} \left(\hat{b} + \hat{b}^\dagger \right) \right)^4 + \ldots \qquad \text{Non-linear}$$

$$- i\epsilon_a(t) \left(\hat{a}^\dagger - \hat{a} \right) - i\epsilon_b(t) \left(\hat{b}^\dagger - \hat{b} \right) . \qquad \text{Drives}$$

$$-\frac{E_j}{4!} \phi_a^3 \phi_b \left[\left(\frac{1}{2} \hat{a}^\dagger \hat{a} - \frac{1}{2} \right) \left(\xi \hat{b} + \xi^* \hat{b}^\dagger \right) \right]$$

$$\hat{H}_{CR} = \omega_{zx} \hat{\sigma}_z \hat{\sigma}_x$$

$$\omega_{zx} \approx \sqrt{p_{b1}} \times \frac{1}{2} \ \text{GHz}$$

Participation matrix

$$\begin{pmatrix} p_{a1} & p_{a2} \\ p_{b1} & p_{b2} \end{pmatrix} \approx \begin{pmatrix} 0.92 & 2 \times 10^{-4} \\ 2 \times 10^{-4} & 0.92 \end{pmatrix}$$

dispersive regime; χ_{qc} small