To catch and reverse a quantum jump mid-flight

Nature 570, 200 (2019)
(Thesis: arXiv:1902.10355)

Nintendo Corp.

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Is it possible to get an advance warning signal

that a quantum jump is about to occur?

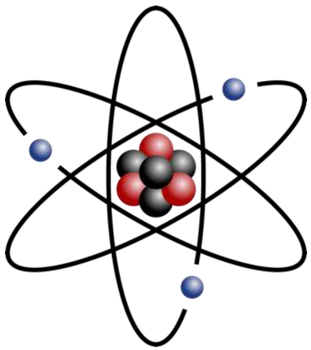
H.J. Carmichael

Outline

Jumps in a quantum system

original observation

quantum trajectory prediction

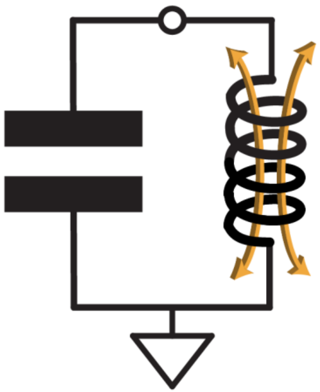


Art: Indoleces

Circuit quantum electrodynamics realization

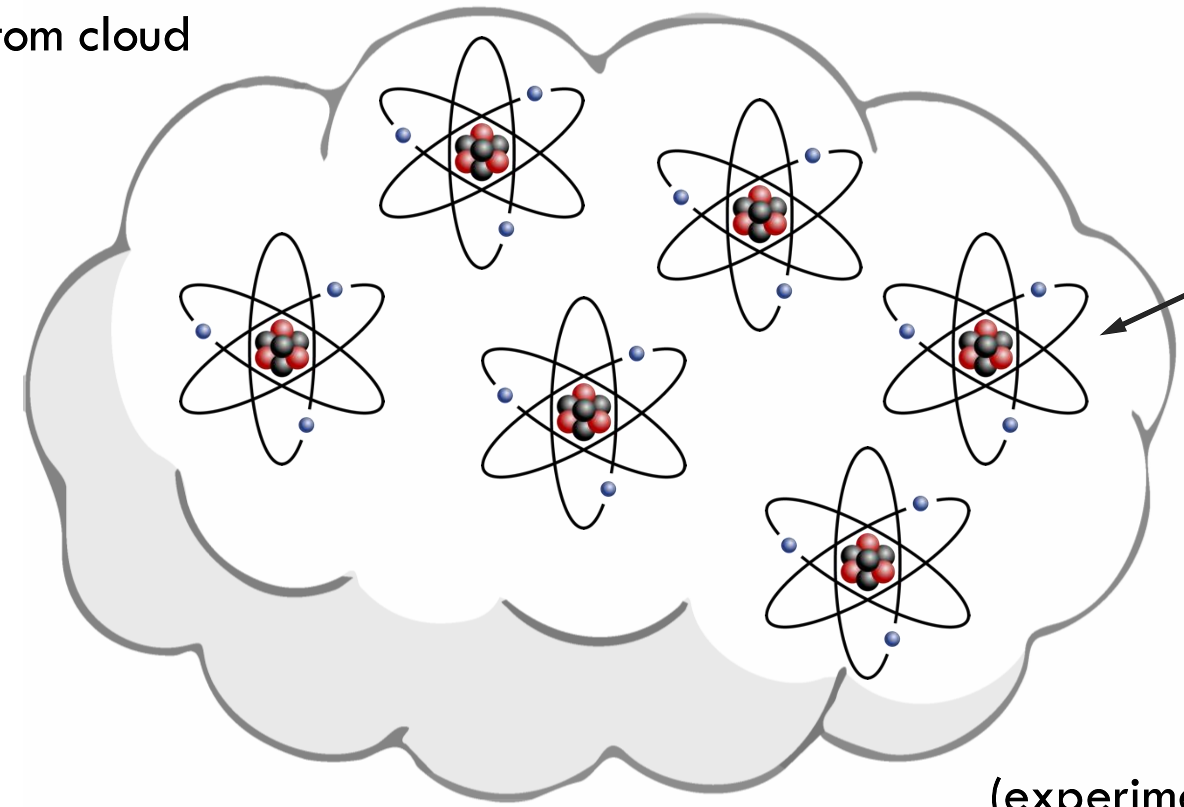
experimental apparatus

results on jump coherence and determinism



Ensemble of quantum systems

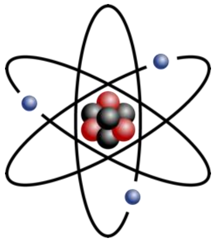
e.g., atom cloud



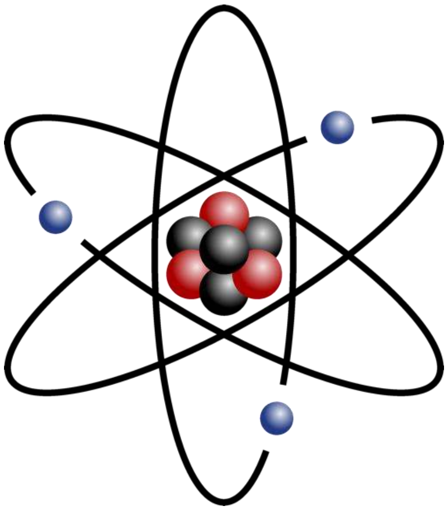
individual atom

(experiments until c. 1980)

Individual quantum system

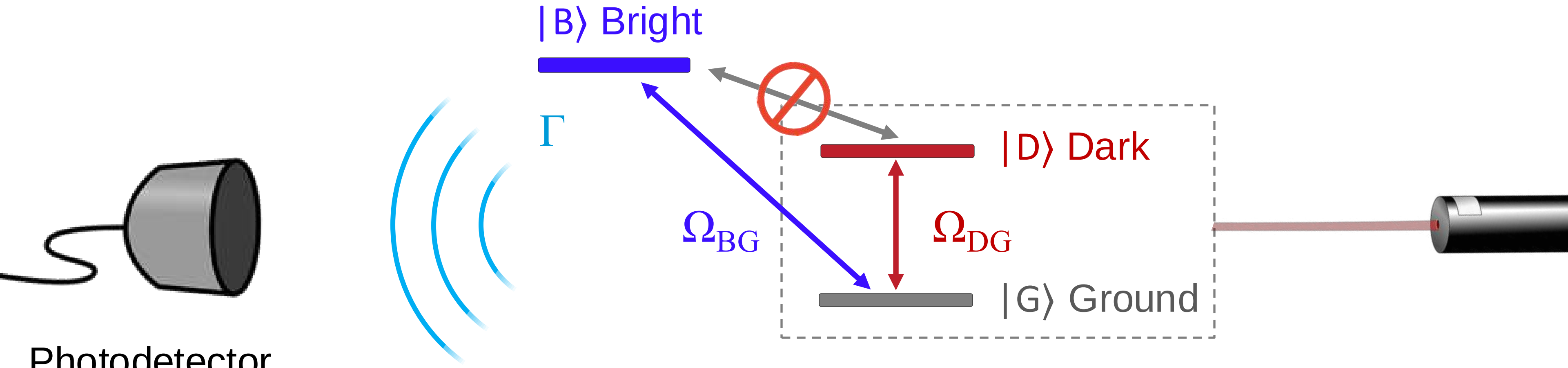


Quantum jumps of an *individual* atom



Bohr (1913)

Observation of jumps in an *individual* atom



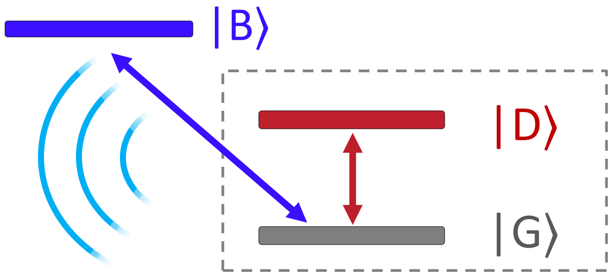
Photodetector

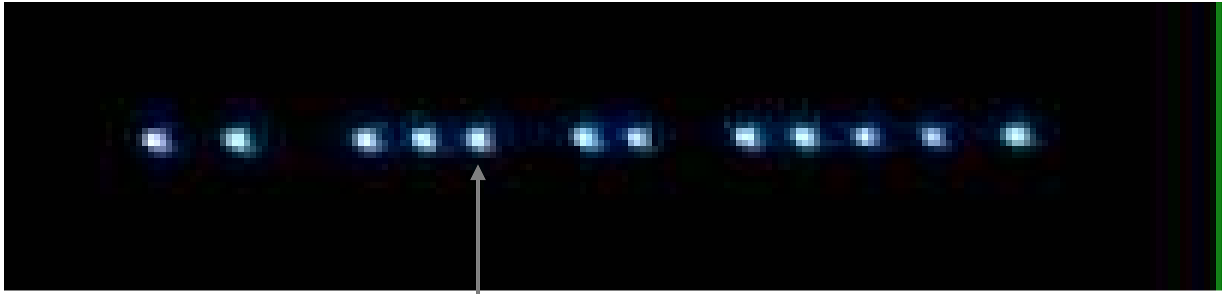
Collection efficiency
$\eta \sim 10^{-3}$

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

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



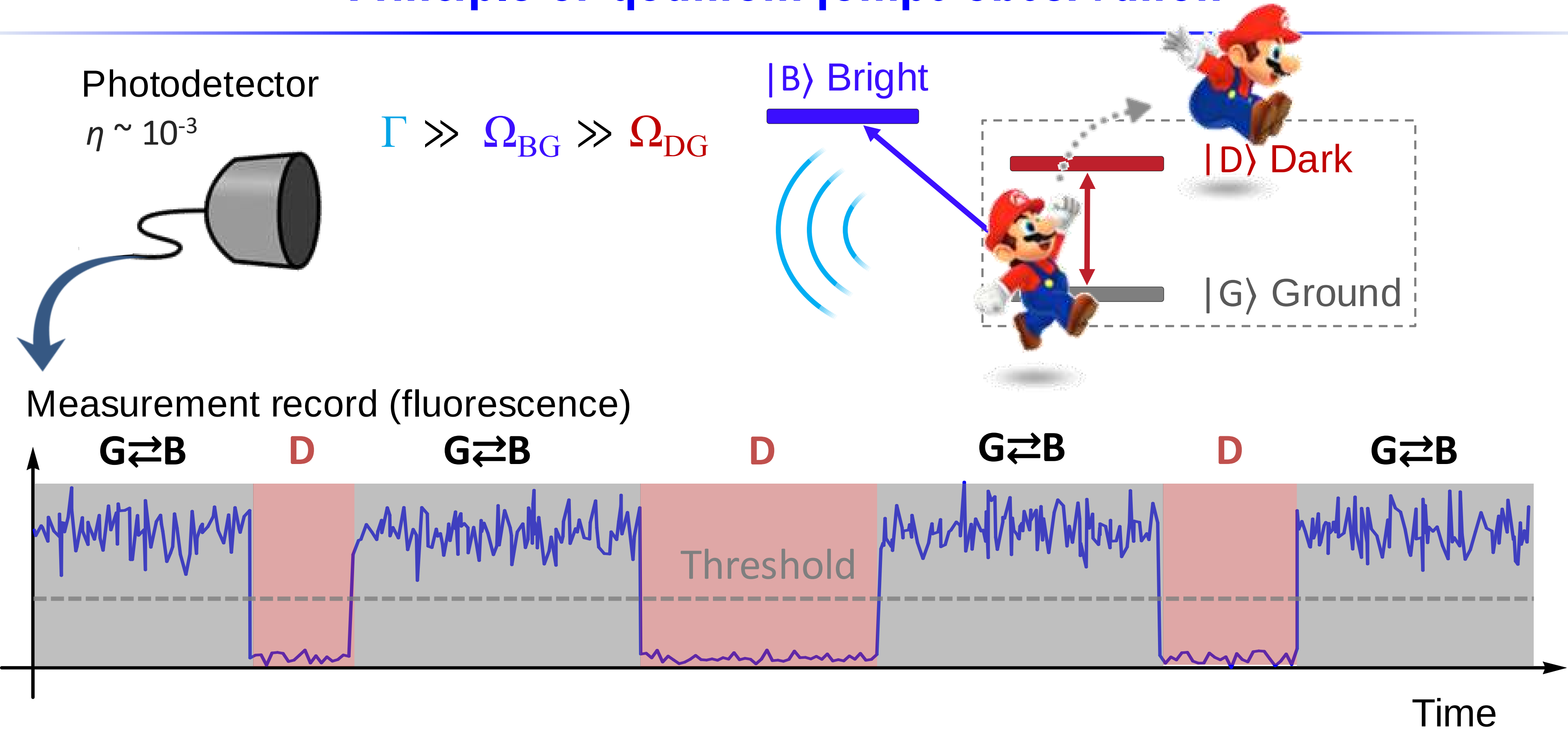


Single Ca^+ ion

(real-time)

Video credit: R. Blatt group, Petar Jurcevic

Principle of quantum jumps observation



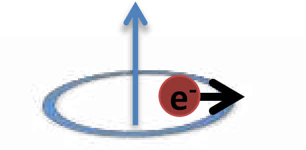
Berquist *et al.*, PRL (1986); Sauter *et al.*, PRL (1986); Nagourney *et al.*, PRL (1986); Cook, P. Scripta (1988)

Observations of quantum jumps since 1986

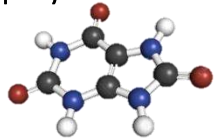
Trapped massive particles

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

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

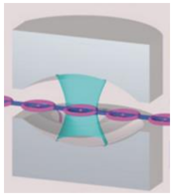


Single *molecule* [5] (1995)
(large polyatomic molecule)

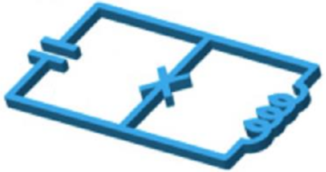


Light quanta

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

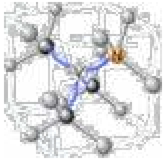


Superconducting qubit
& cavity (*cQED*) [9-11] (2011)

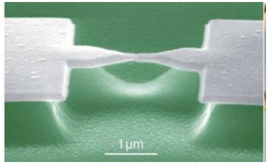


Solid state and mesoscopic

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

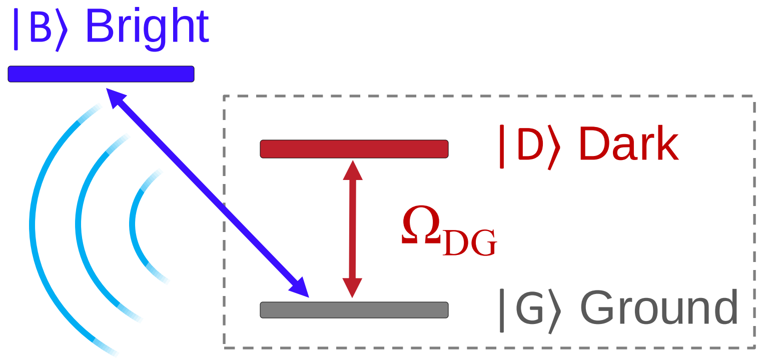
Schrödinger, Brit. J. Philos. Sci. III, 109 (1952)

The case of the fully efficient observer

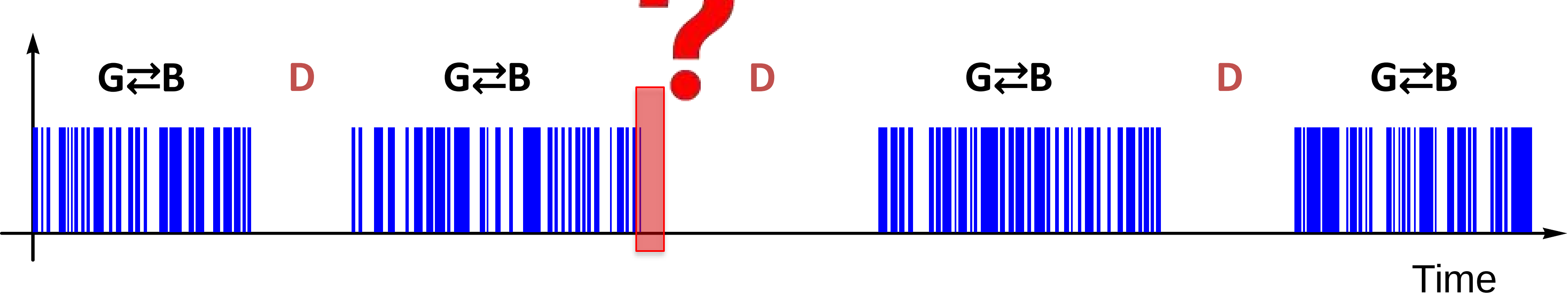
Hypothetical efficiency $\boxed{\eta = 1}$

$$\boxed{BW_{det} \gg \frac{\Omega_{BG}^2}{\Gamma} \gg \Omega_{DG}}$$

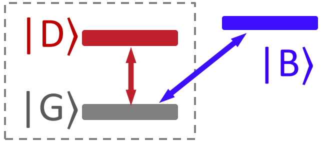
$$\Gamma \gg \Omega_{BG} \gg \Omega_{DG}$$

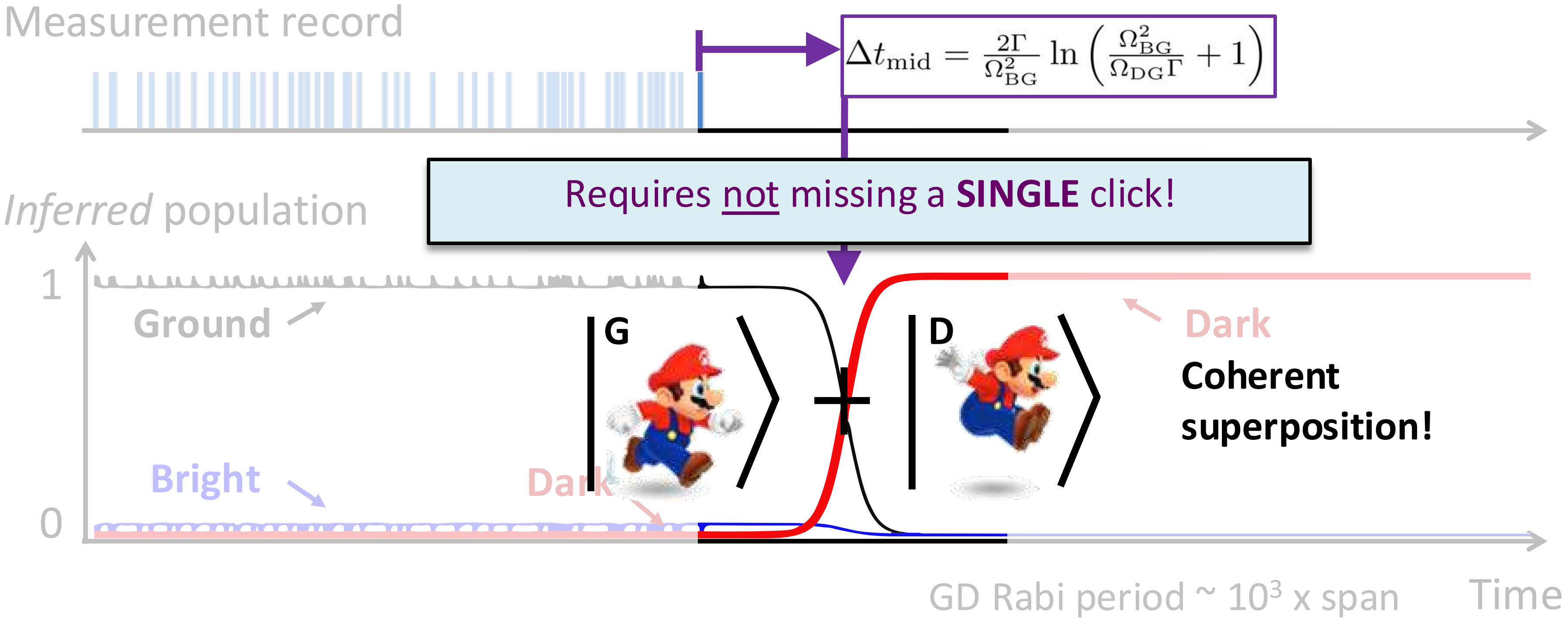


Measurement record (click? Y/N)



No-click trajectory



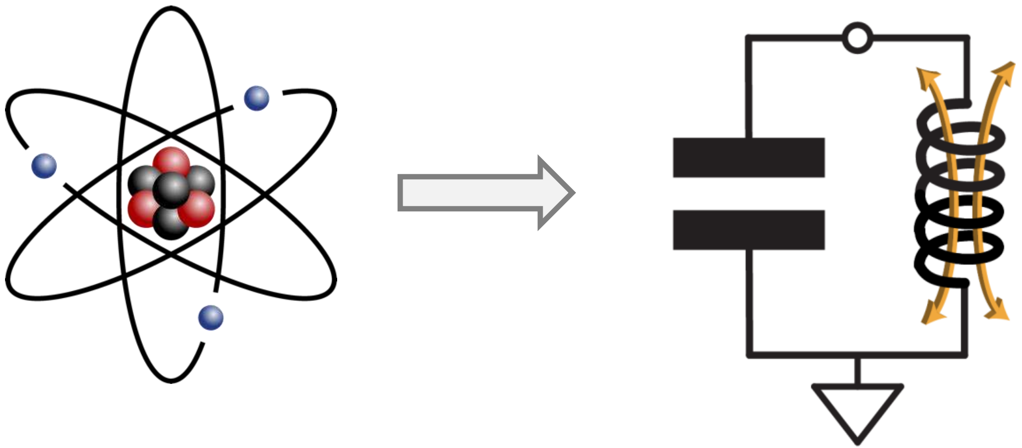


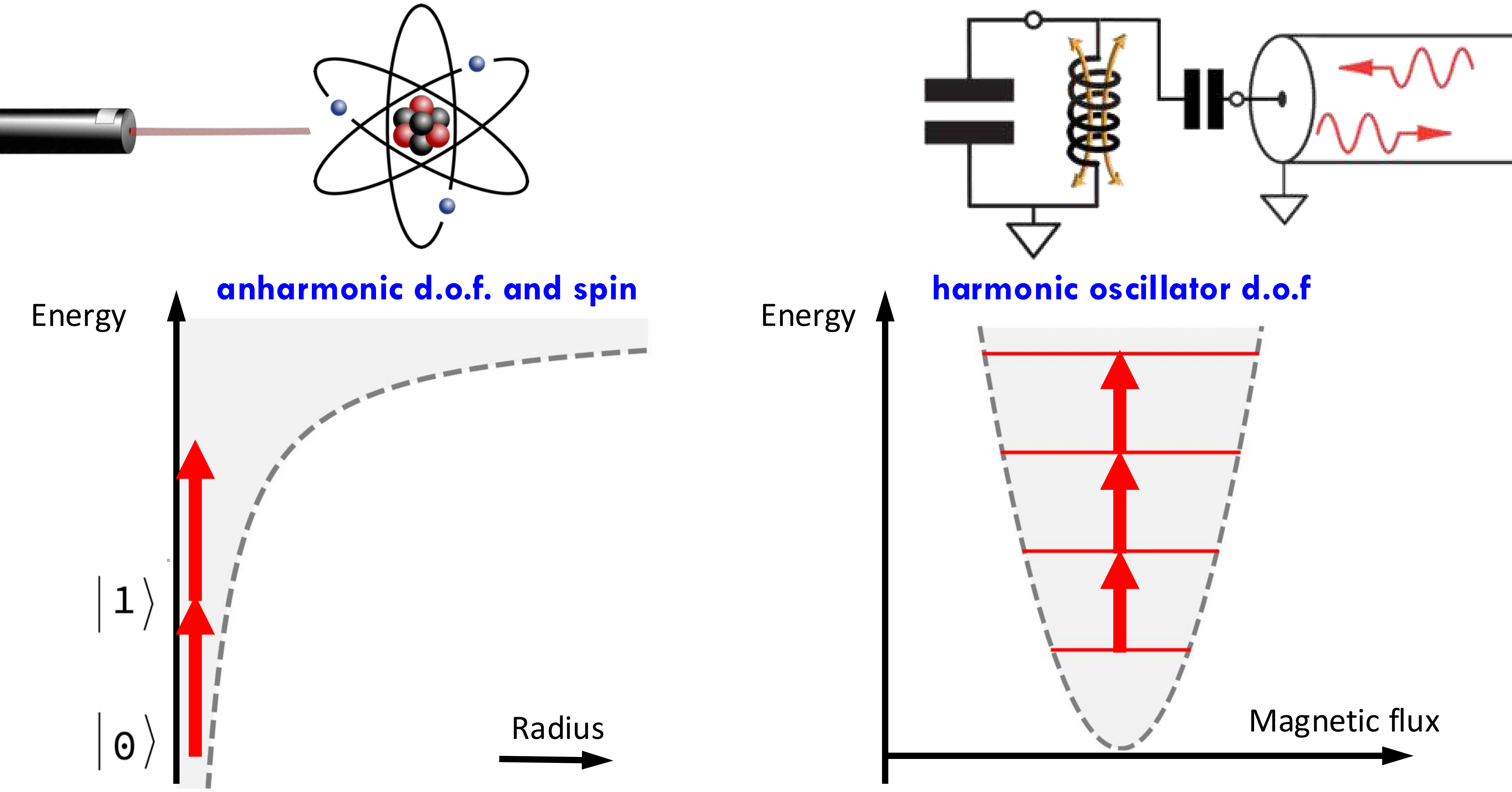
Carmichael, SUSSP71 (2015); Ruskov et al., PRB (2007); Related: Porrati & Putterman, PRA (1987); Mabuchi & Zoller PRL (1996); Plenio & Knight, RMP (1998); Katz et al., Science (2006) & PRL (2008)

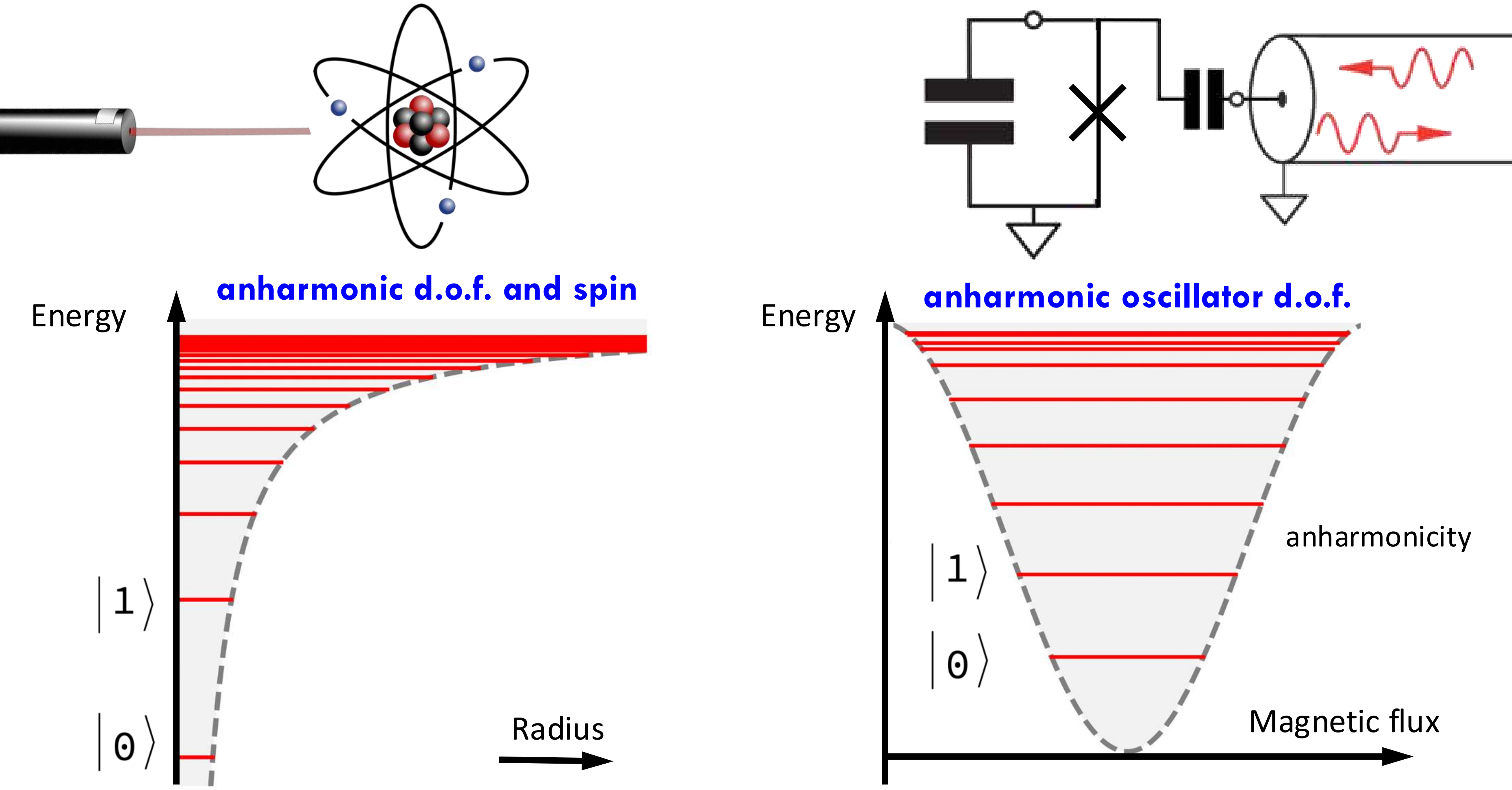
Principle of our cQED experiment

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)
...



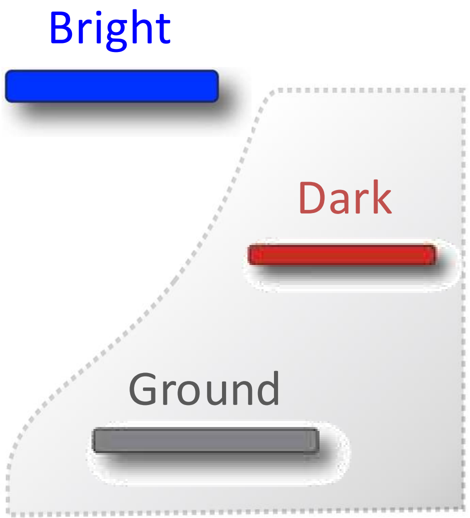

anharmonic d.o.f. and spin
Energy
|1⟩
|0⟩
Radius
harmonic oscillator d.o.f
Energy
Magnetic flux

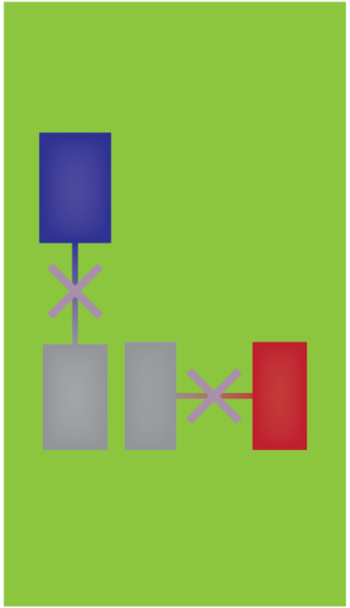


anharmonic d.o.f. and spin
Energy
|1⟩
|0⟩
Radius
anharmonic oscillator d.o.f.
Energy
anharmonicity
|1⟩
|0⟩
Magnetic flux

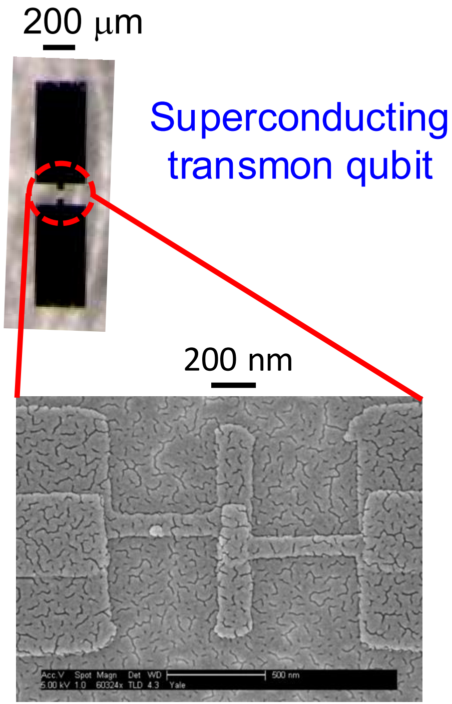
Quantum superconducting circuit architecture

Schematic representation of chip



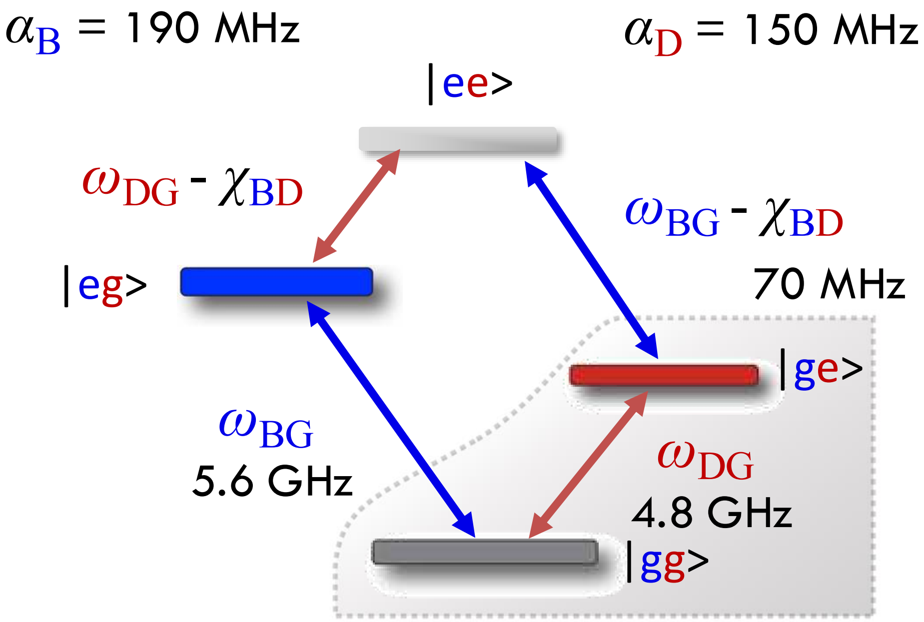


Substrate
(not to scale)

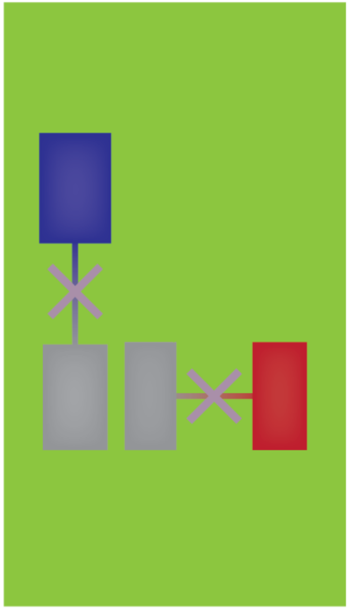


Blais *et al.*, PRA (2004); Paik *et al.*, PRL (2011)

cQED implementation of V-system



Schematic representation of chip

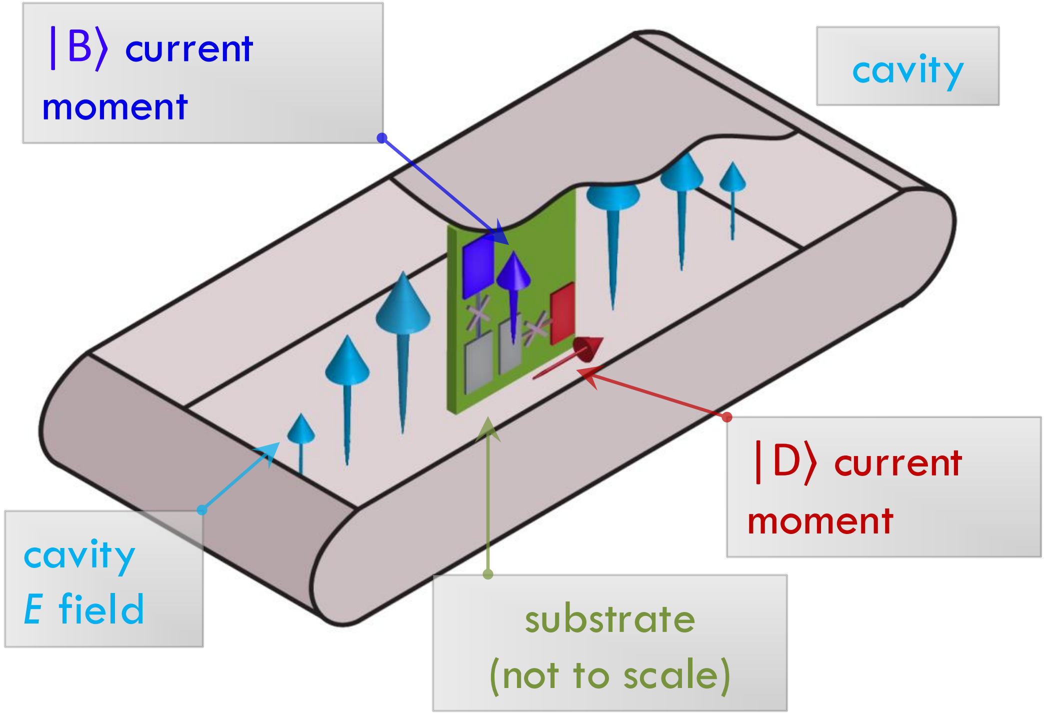


Substrate
(not to scale)

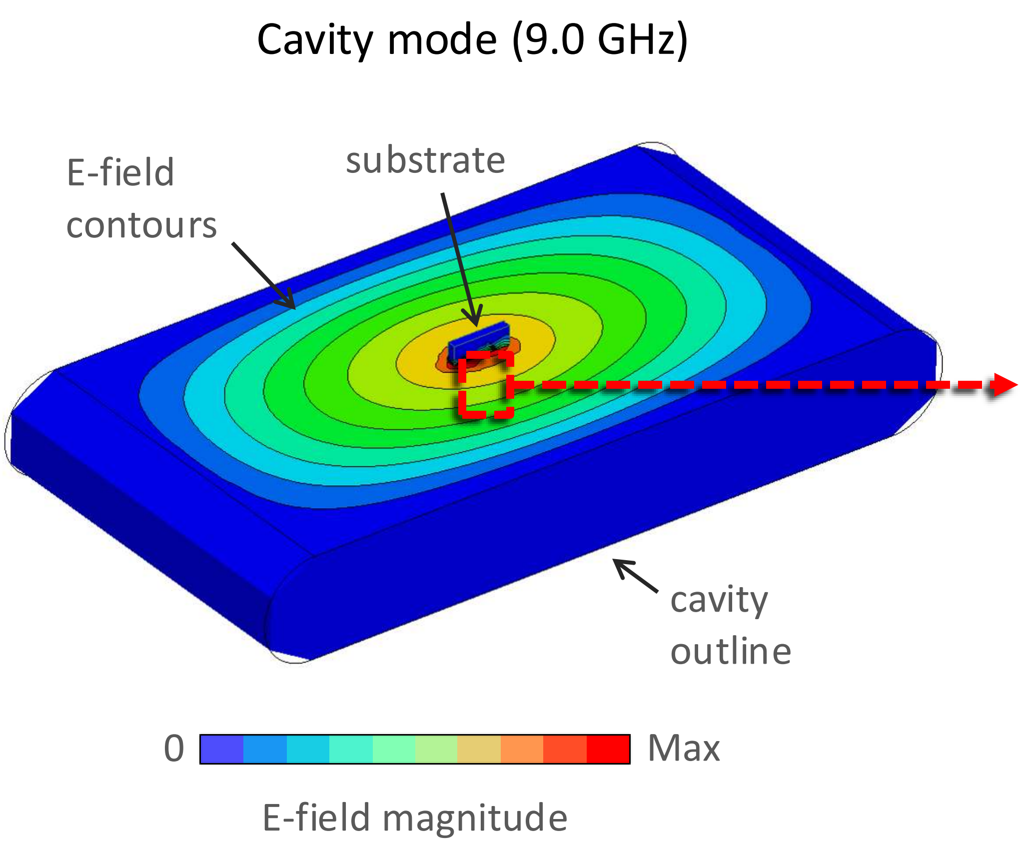
Related work: Gambetta *et al.*, PRL (2011)
Srinivasan *et al.*, PRL (2011) Dumur *et al.*, PRB (2015) Zhang *et al.*, Nature JQI (2017) …
Tanay Roy, … Dr. Rajamani Vijayaraghavan

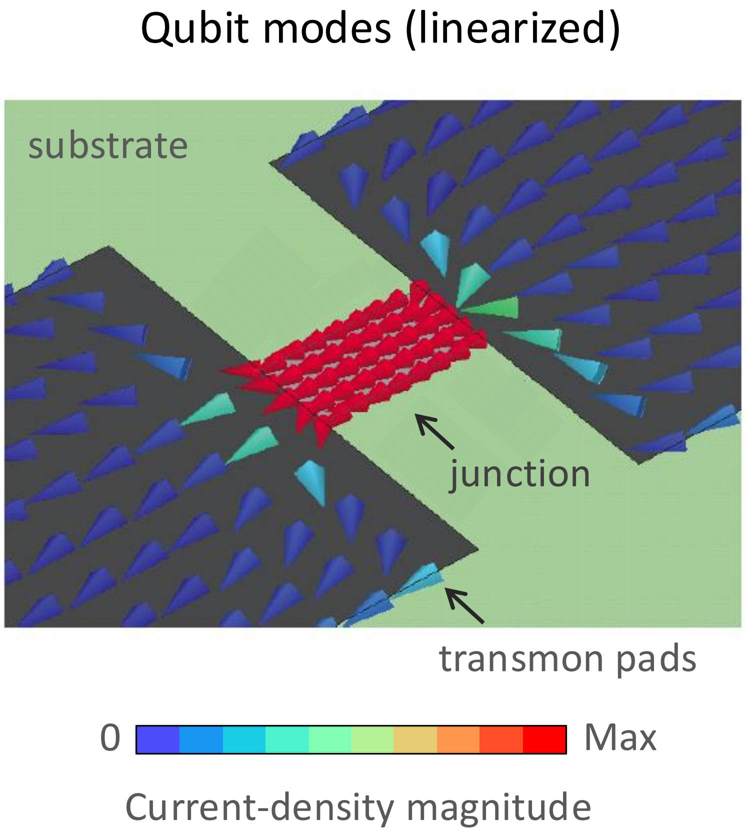
cQED implementation of V-system

Schematic representation of design



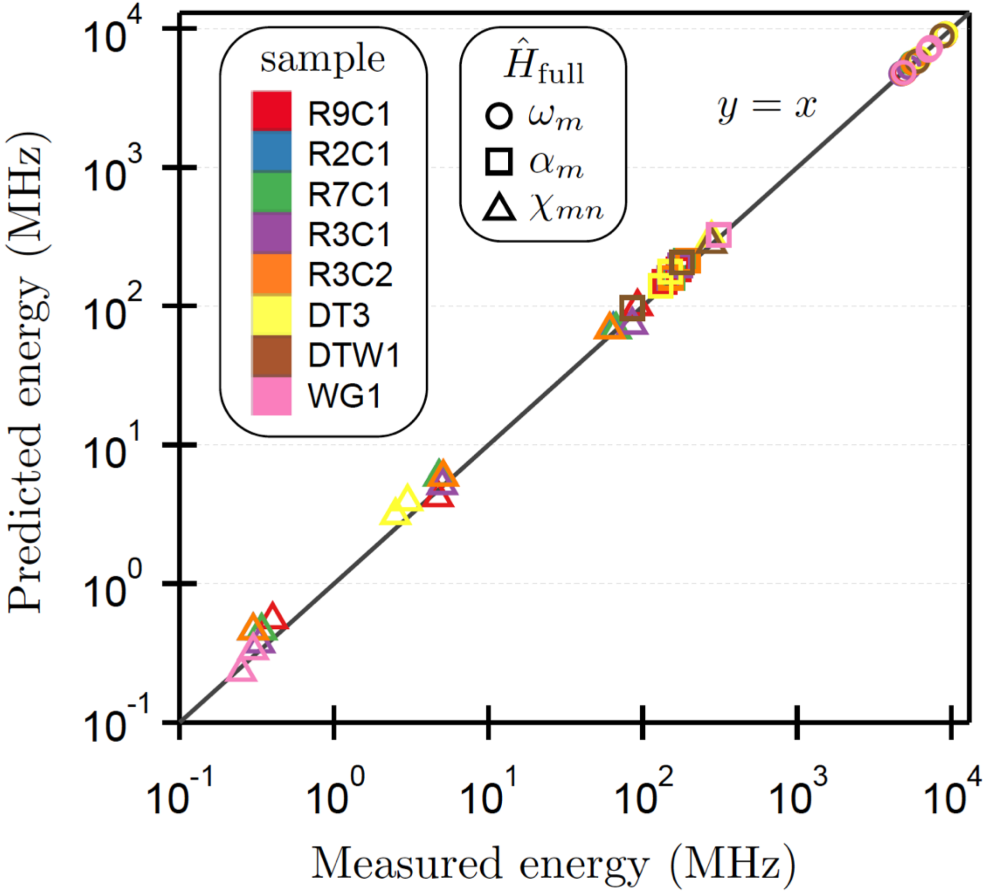
Energy participation ratio (EPR) approach*

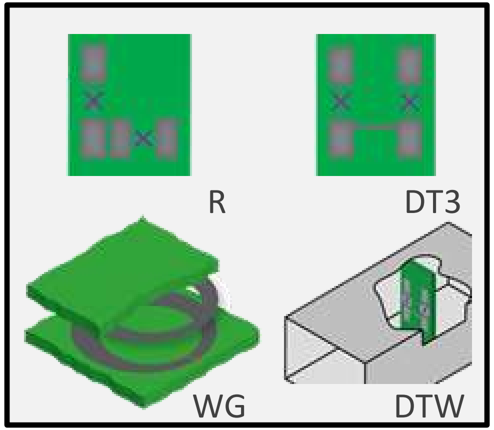




* Minev arXiv:1902.10355 (2019) Related: Nigg *et al.* (2012); Bourassa *et al.* (2012); Solgun & DiVincenzo …

EPR theory vs. experiment: agreement over 5 orders of magnitude

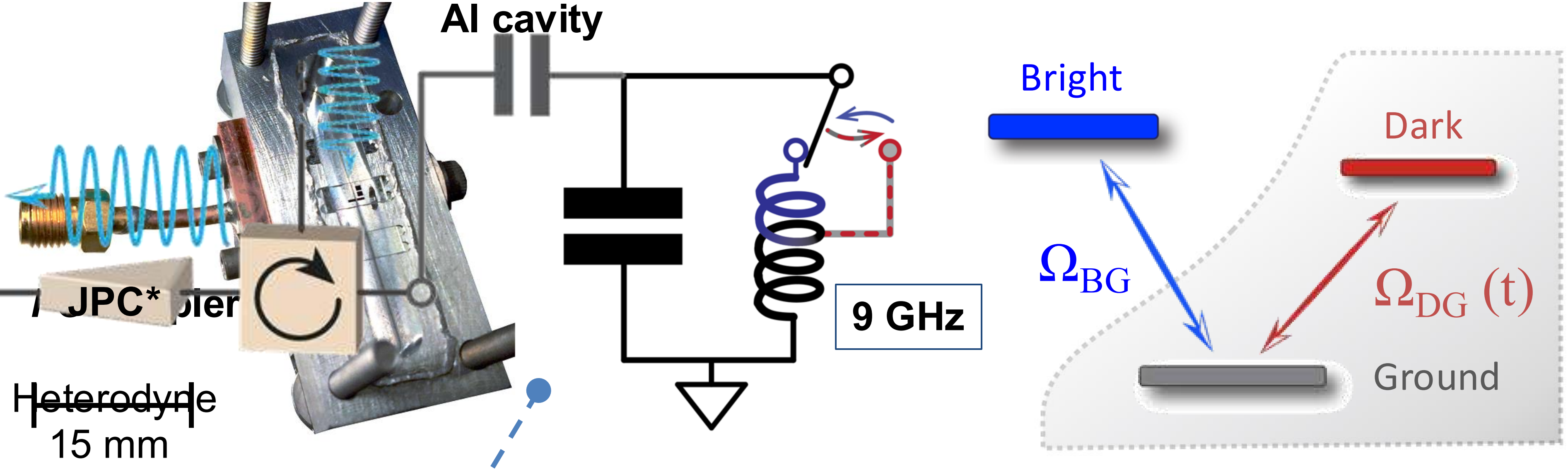


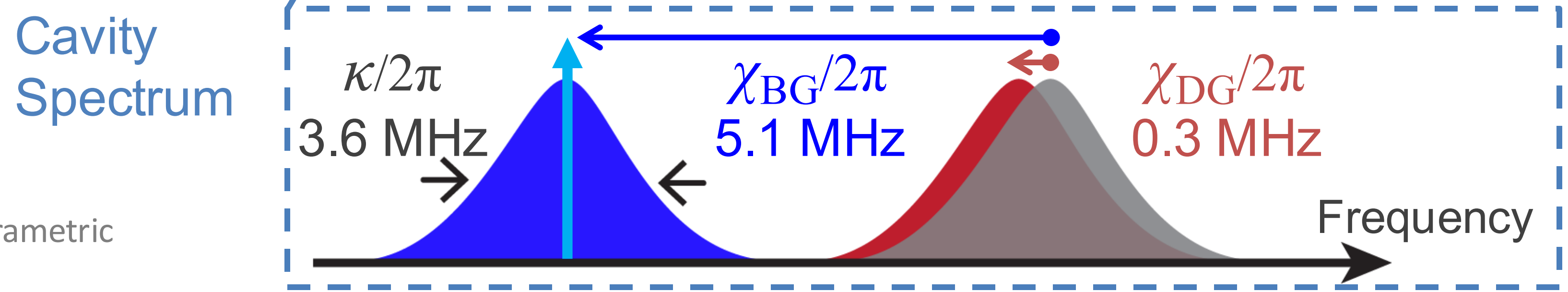


R: Minev *et al.* (2018)
WG: Minev *et al.* (2013, 2016) DT3,
DTW:
Minev *et al.* (2019)

www.github.com/zlatko-minev/pyEPR
* Minev arXiv:1902.10355 (2019)

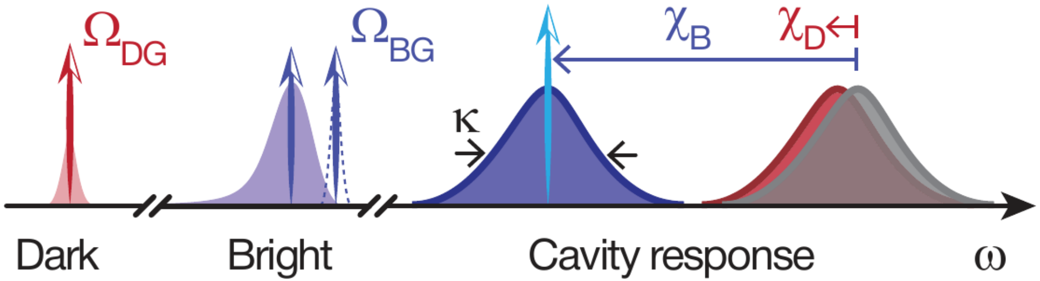
Measuring B / non-B with 90% efficiency

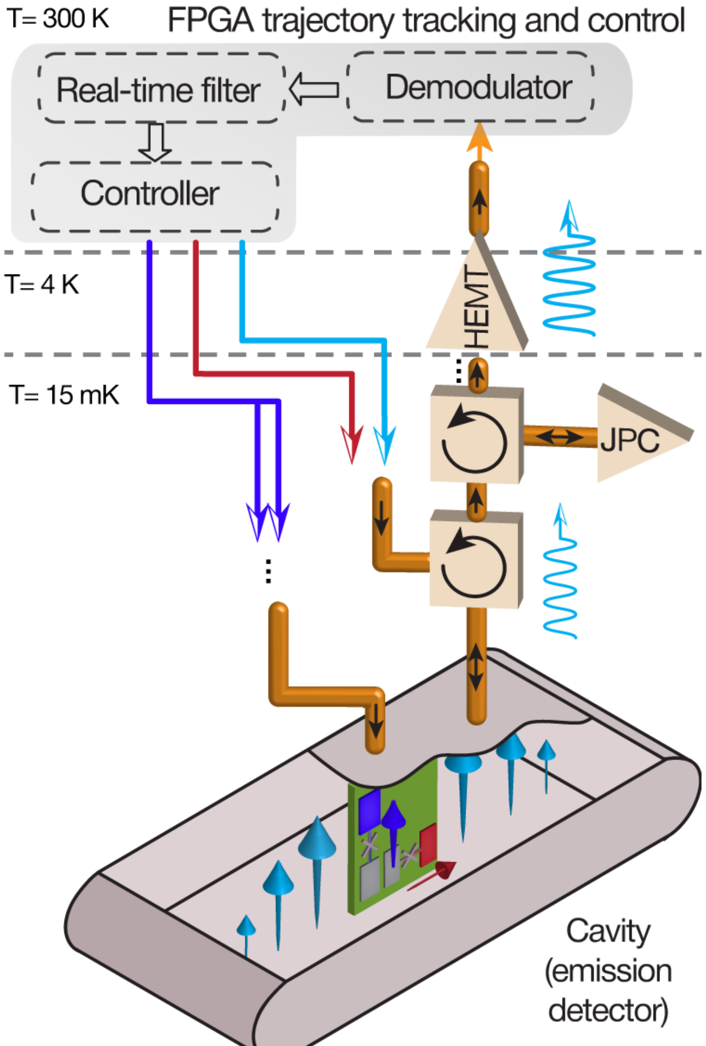




* Josephson parametric converter

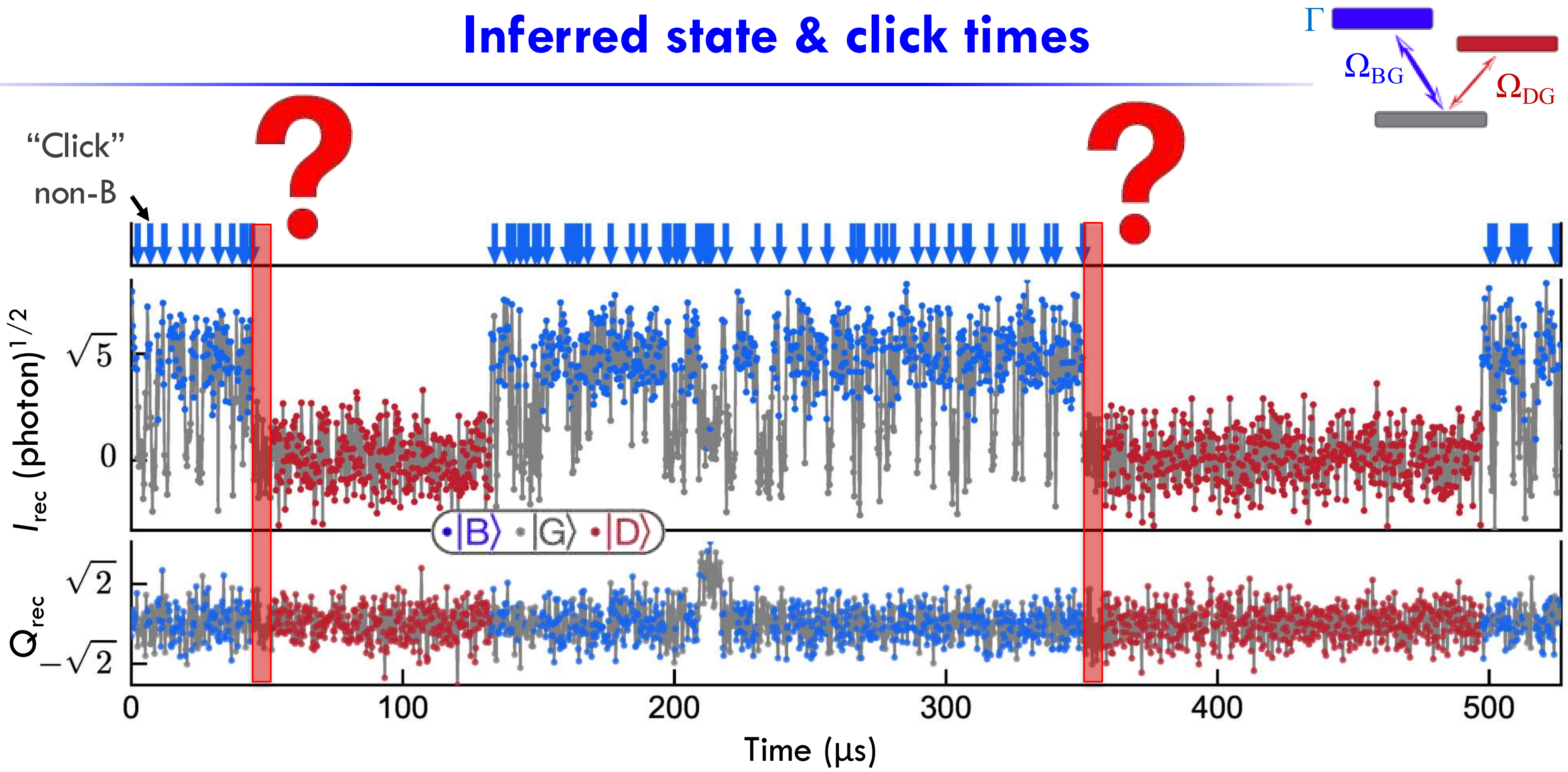
Frequency landscape





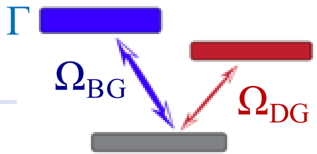
Unconditioned quantum jumps

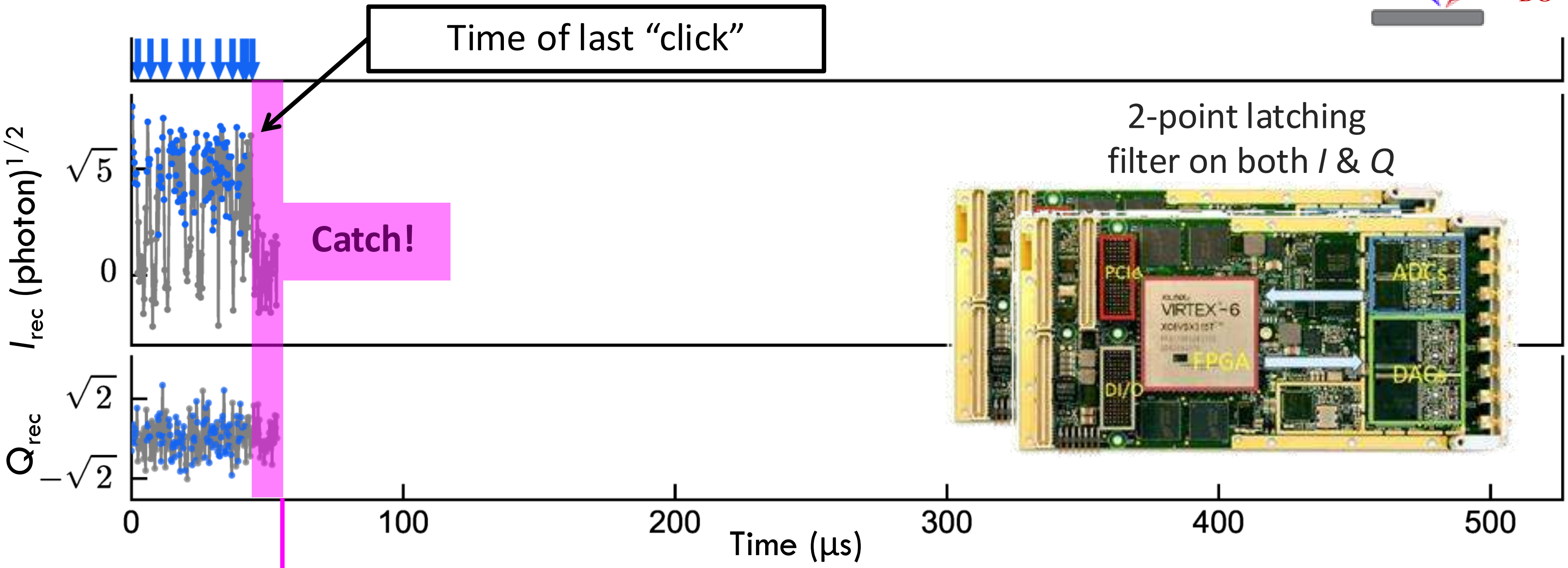
Inferred state & click times



Real-time detection of a quantum jump

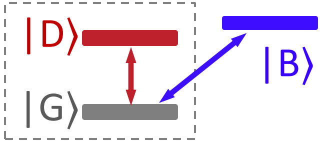
Catch protocol

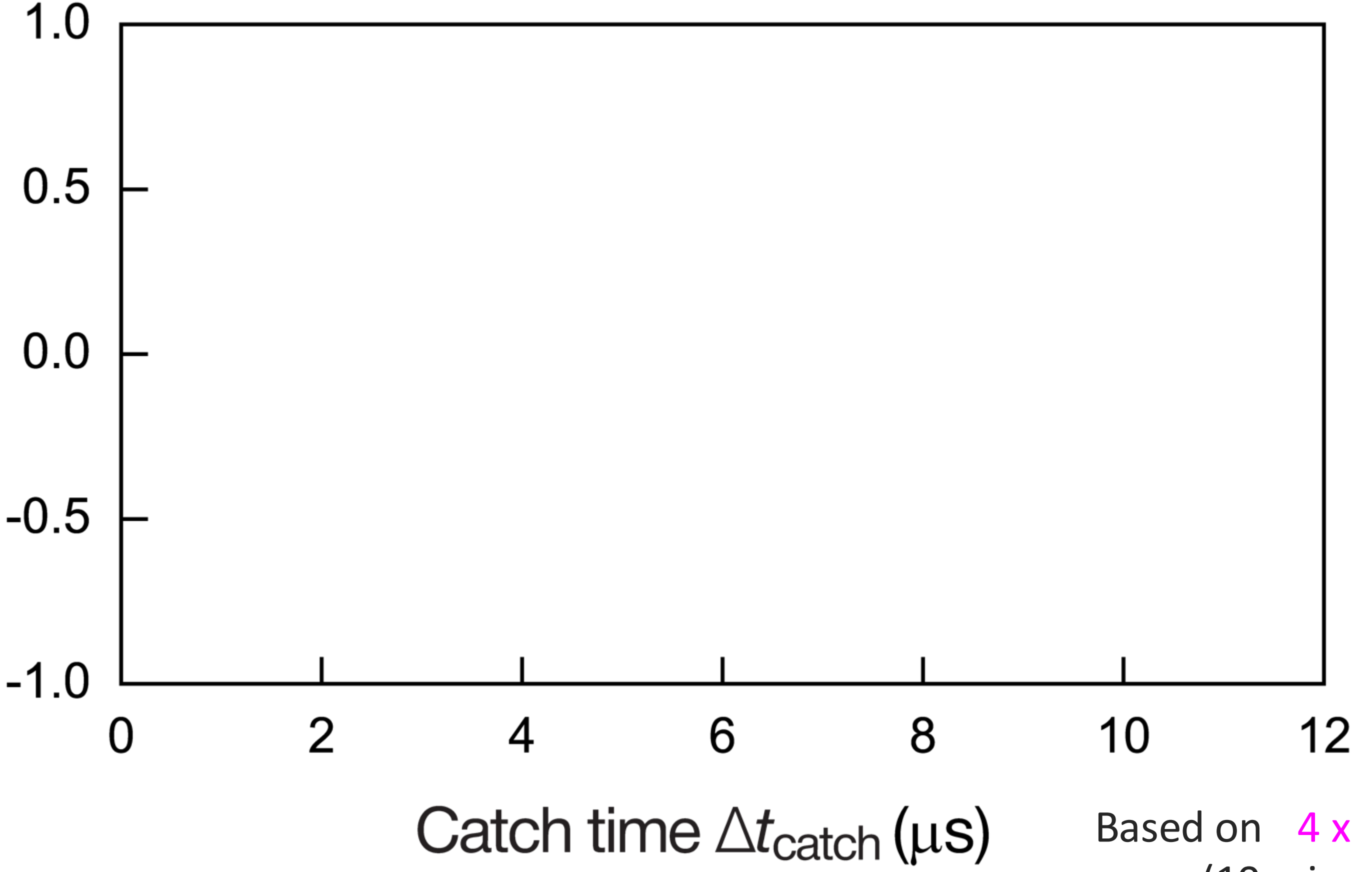




Msmt. rate $\Gamma_m^{-1} \sim 8$ ns	$\ll$	Integration time 2.6×10^2 ns	$\ll$	GB jump timescale 10^3 ns	$\ll$	t_{mid}	$\ll$	GD jump timescale $\sim 10^5$ ns

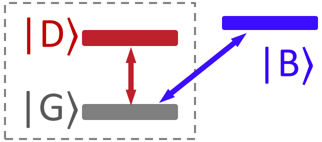
Catching the quantum jump mid-flight

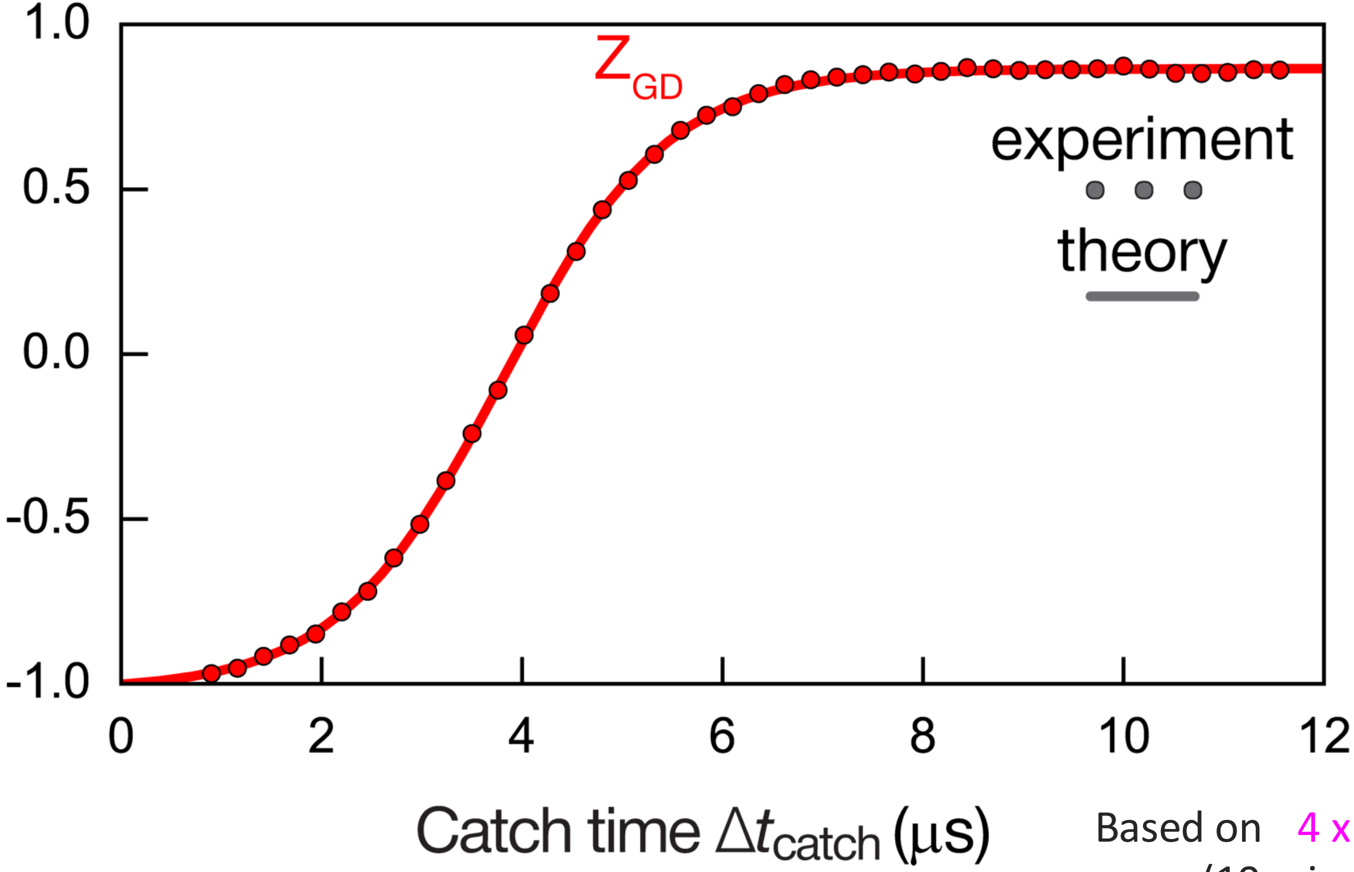




Based on 4 x 10^6 catch events
(10 min. tracking time)

Catching the quantum jump mid-flight





Based on 4 x 10^6 catch events
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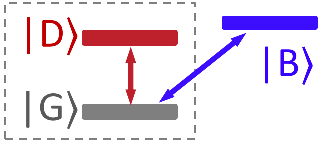
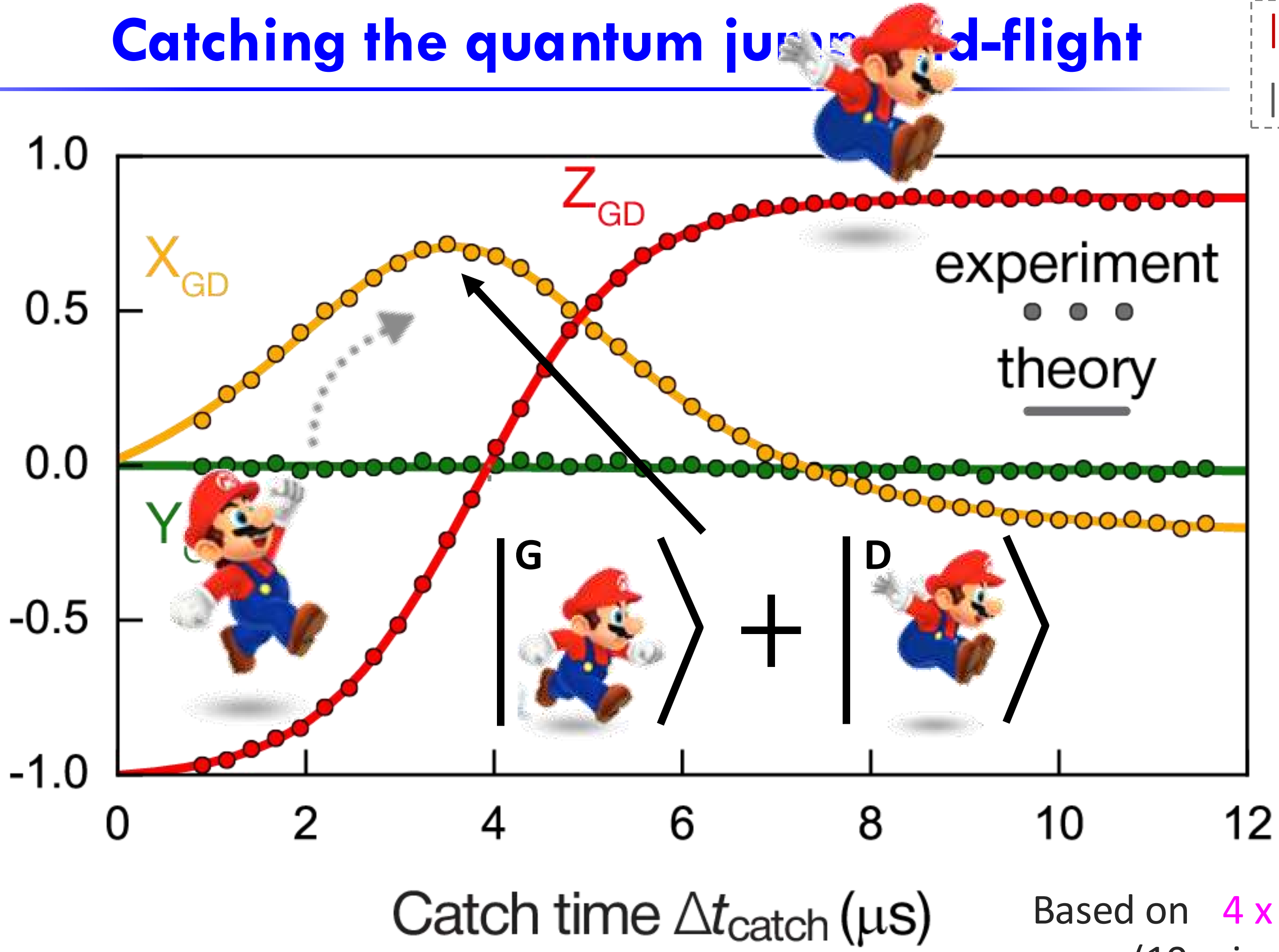
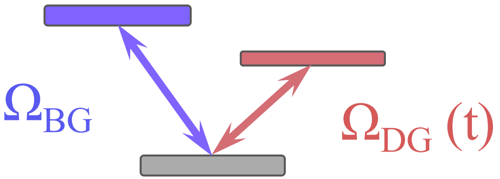
Catching the quantum jump mid-flight

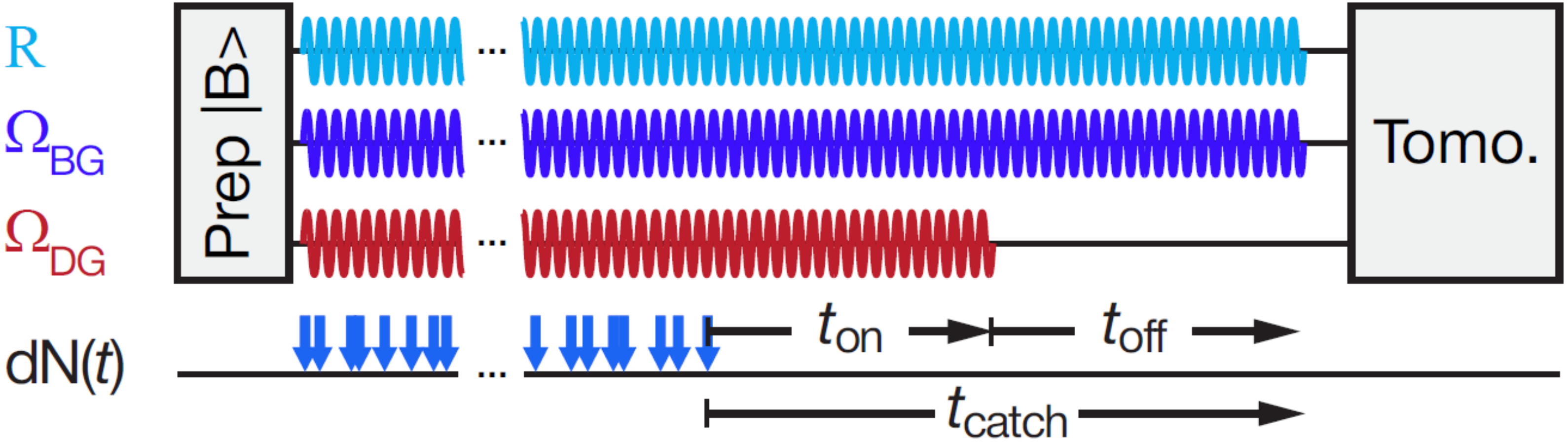




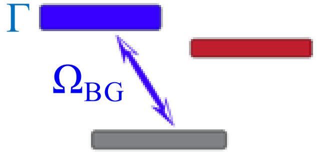
Based on 4×10^6 catch events
(10 min. tracking time)

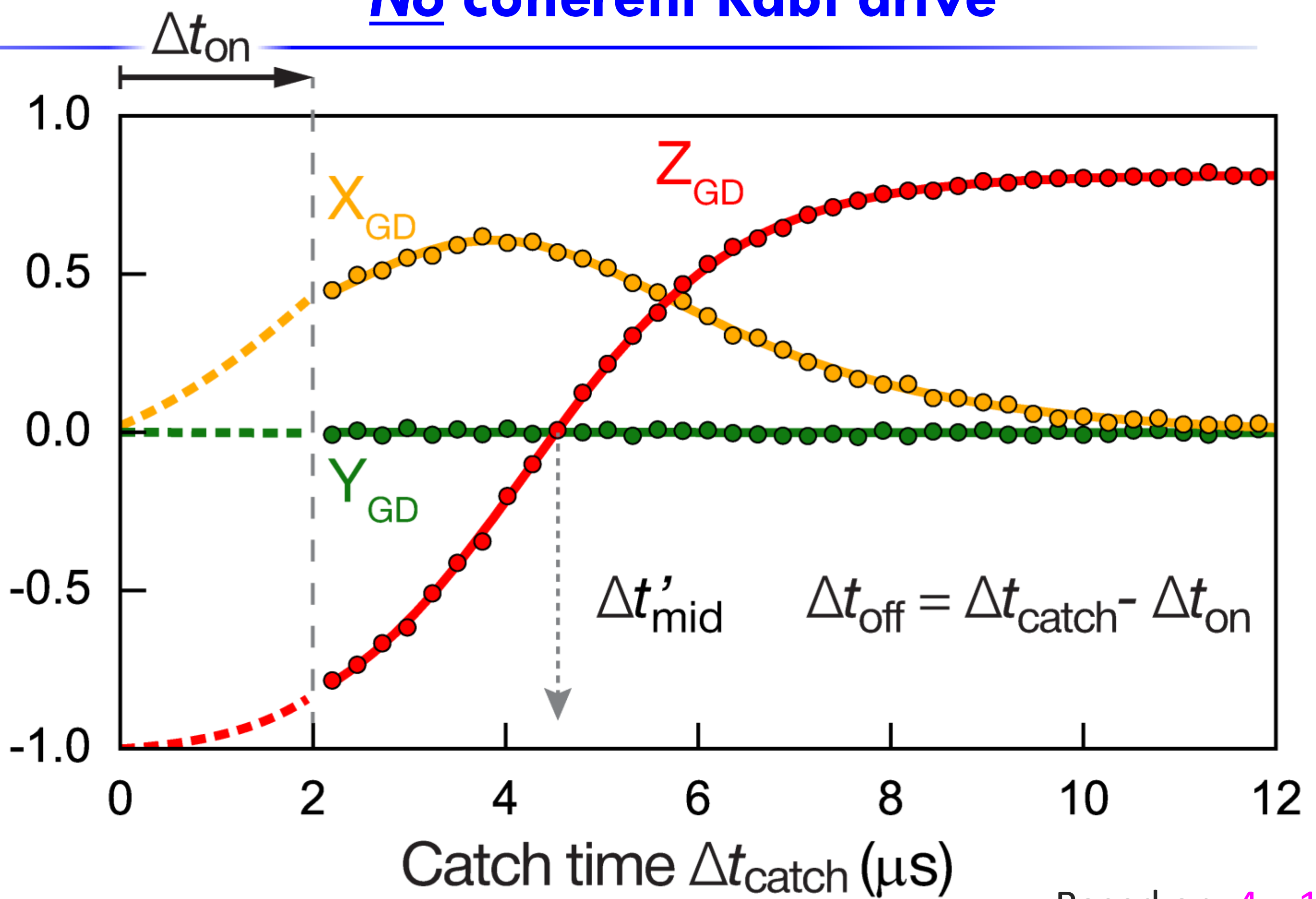


Catch in *absence* of Dark drive



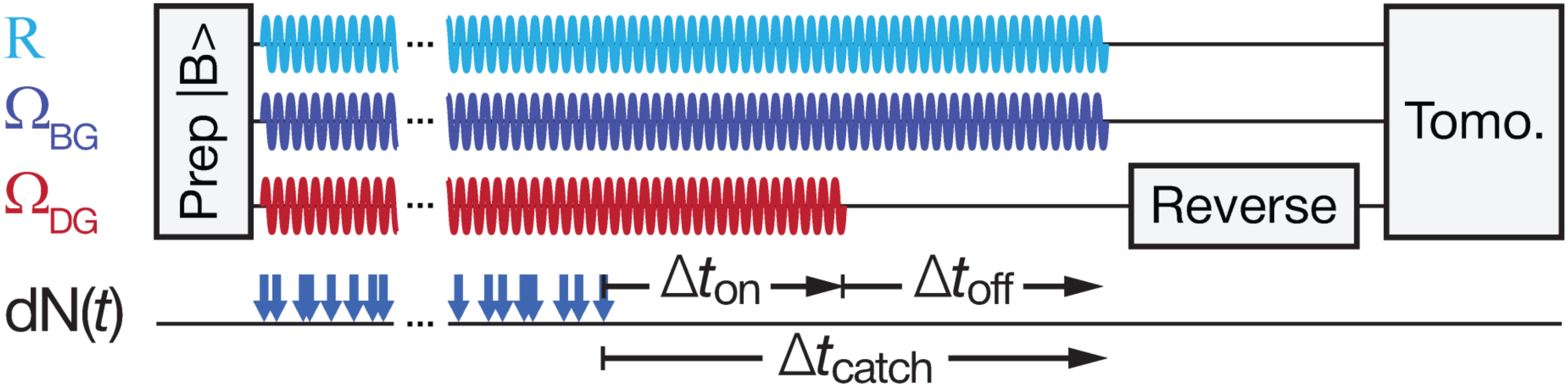
No coherent Rabi drive





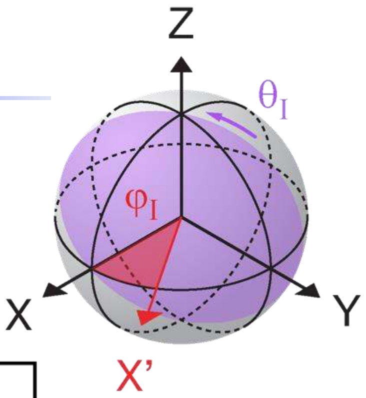
Based on 4×10^6 catch events

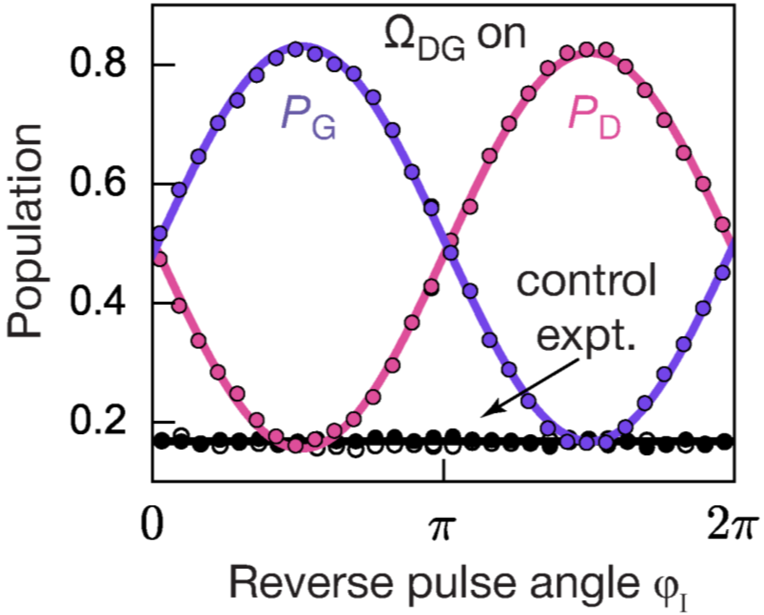
Reversing the quantum jump mid-flight

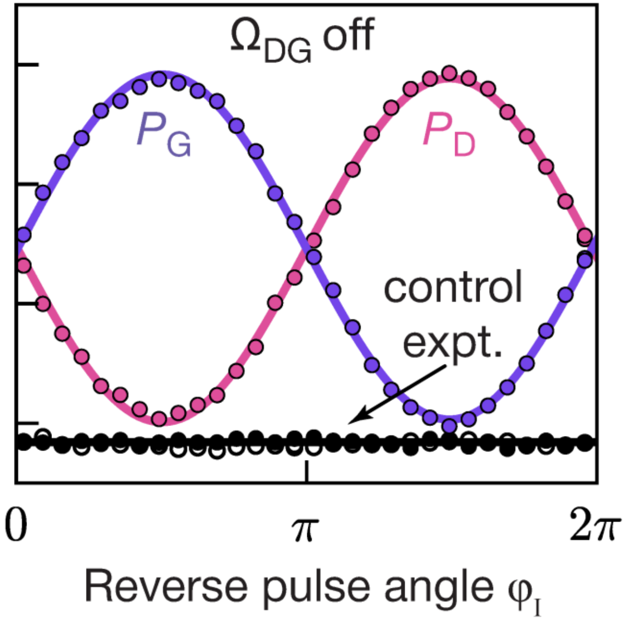


Experimental reversal of jump

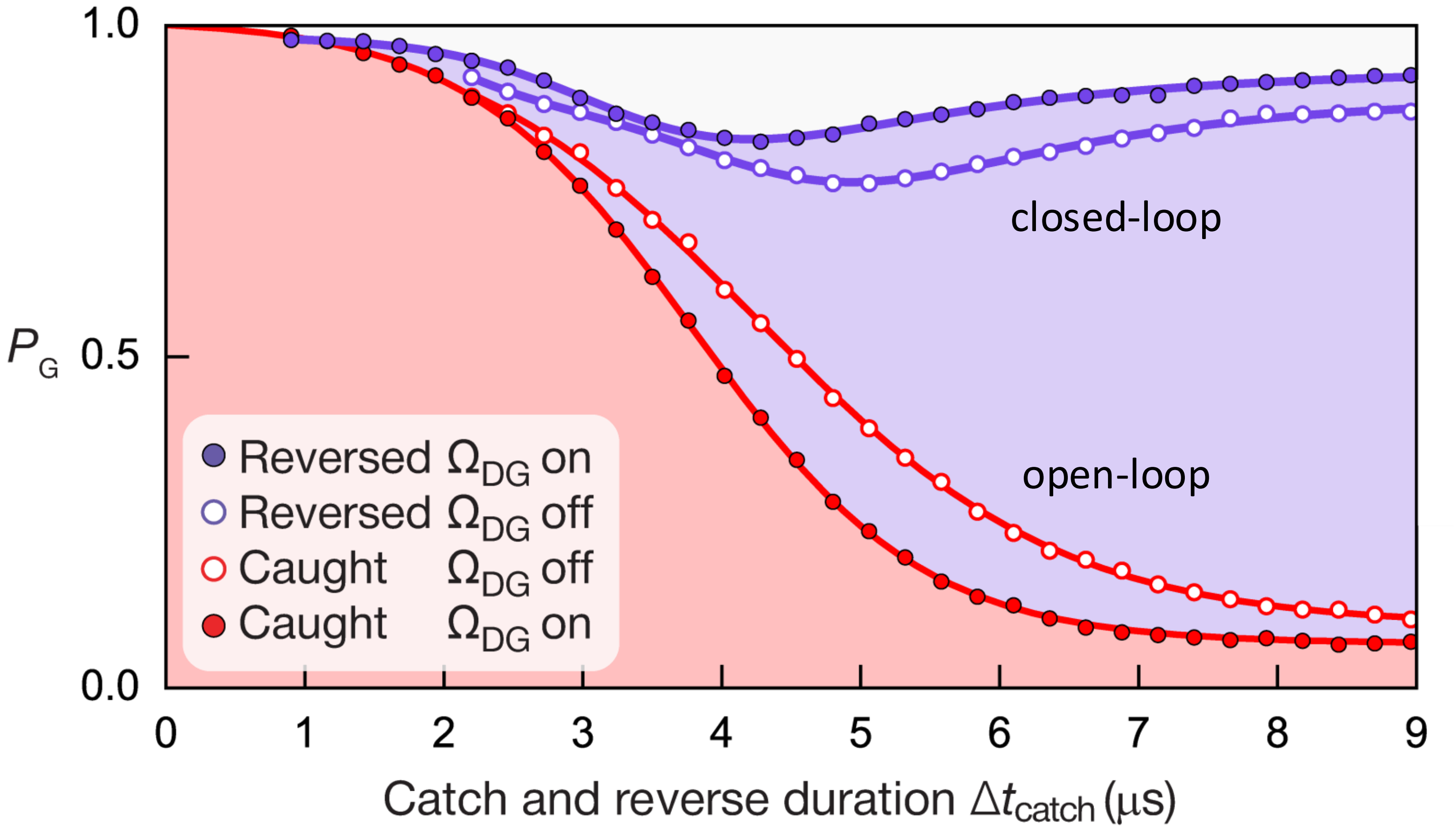
No click until Δt_{mid} = advance warning of individual jump





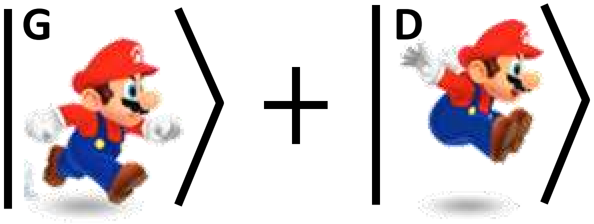


Catching and reversing the quantum jump mid-flight



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

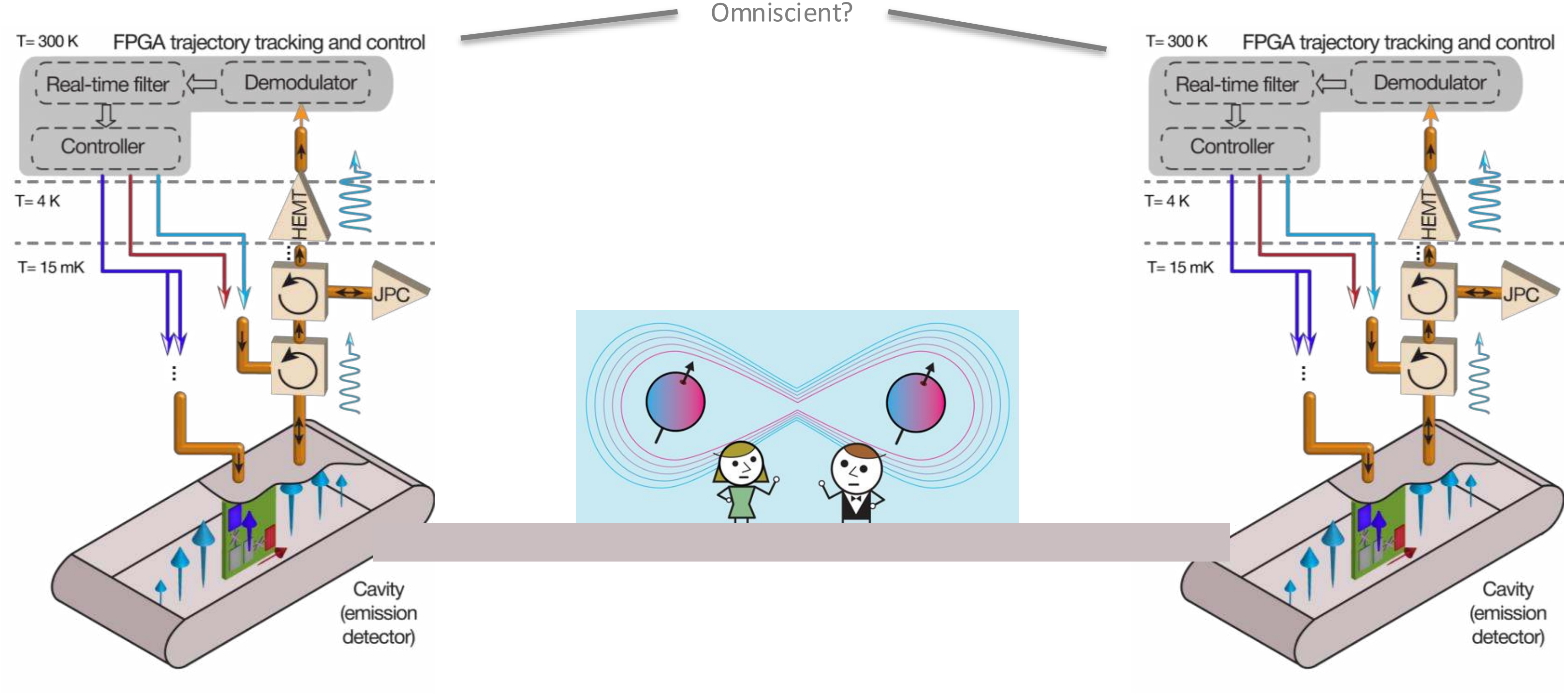
Nature 570, 200 (2019)   Minev, Ph.D. Thesis (2018)

Continuous syndrome measurement for autonomous quantum error correction

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

Next experiment idea for non-local / Wigner / Bell

Next experiment idea for non-local / Wigner / Bell



For original discussion see Minev arXiv:1902.10355; Middle cartoon: MARK MONTGOMERY

Open Labs

Est. 2012

Yale-Jefferson Award

Open Labs

Science outreach and career pathways

Yale University

University of Pennsylvania

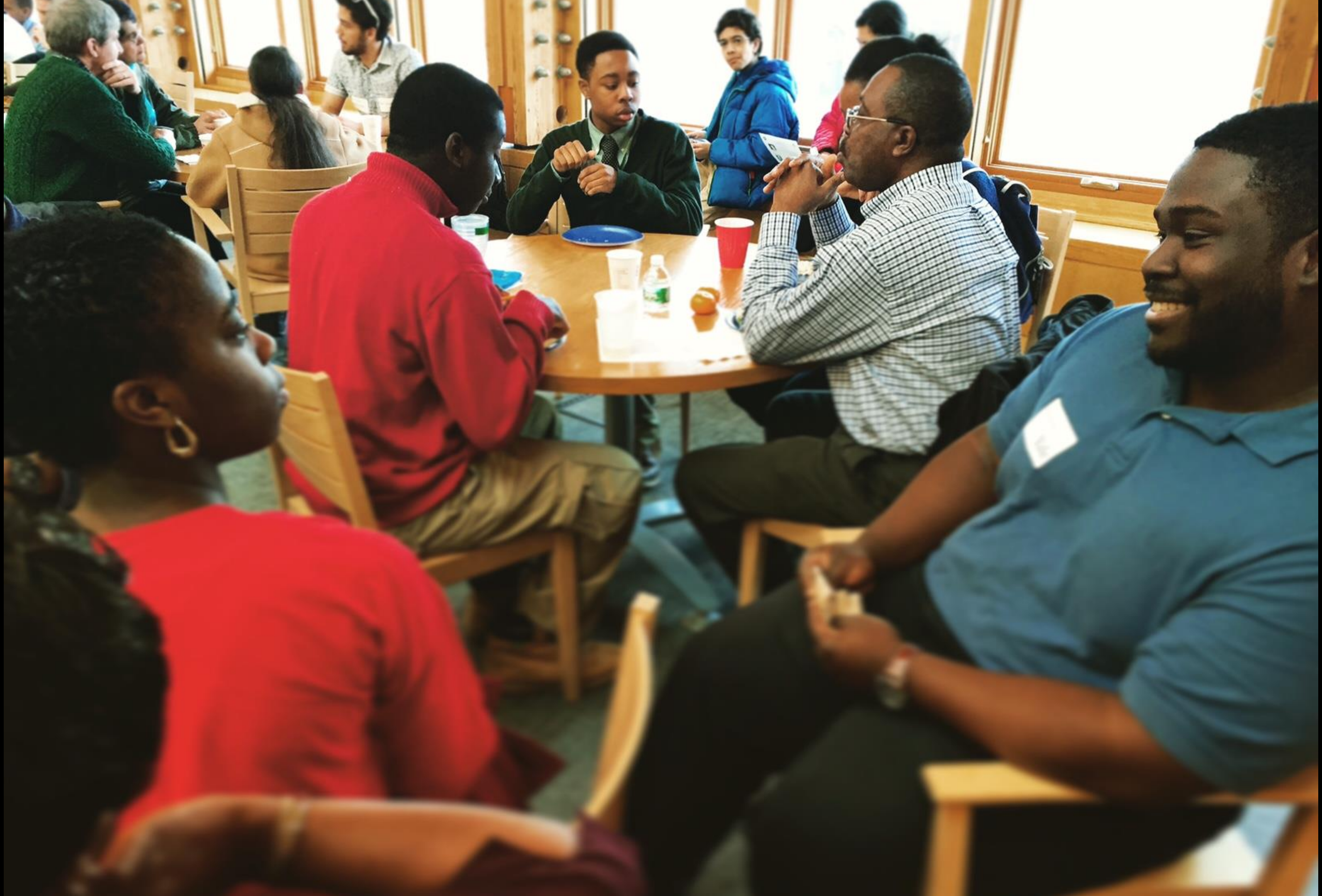
Princeton University

Columbia University

Harvard University

...

theOpenLabs.org

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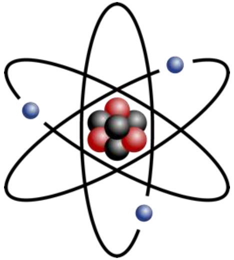
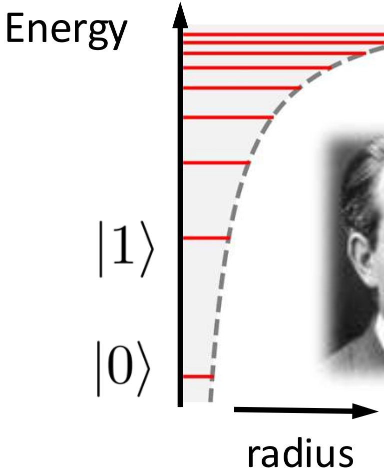
EXTRA SLIDES

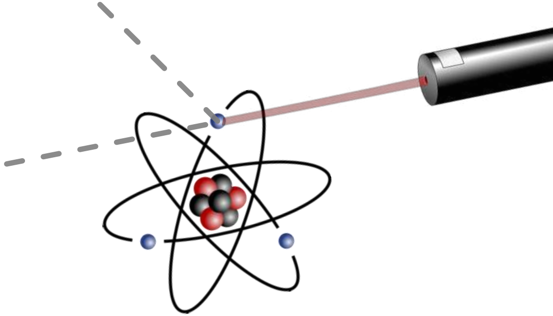
Quantum physics





discrete

random



$|0\rangle$ or $|1\rangle$??

images: atom:indoleces column: vectorpocket

nature
International journal of science

Letter | Published: 03 June 2019

To catch and reverse a quantum jump mid-flight

Z. K. Minev, S. O. Mundhada, S. Shankar, P. Reinhold, R. Gutiérrez-Jáuregui, R. J. Schoelkopf, M. Mirrahimi, H. J. Carmichael & M. H. Devoret

Nature **570**, 200–204 (2019) | Download Citation

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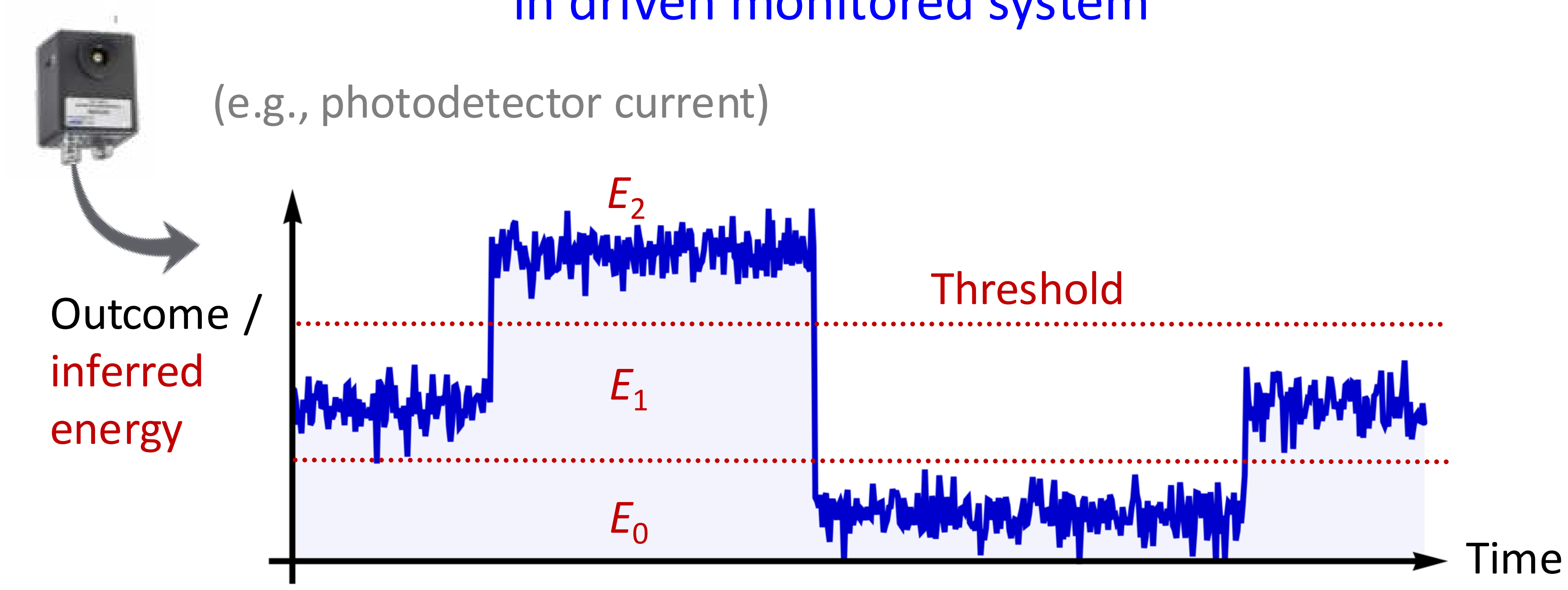
Operational definition of quantum jumps in driven monitored system



Measurement record is *continuous*: a time series of outcomes

(threshold is essential to declare when jump has occurred)

Cook, Phys. Scripta T21, 49 (1988)

What is deterministic/predictable and what is not?

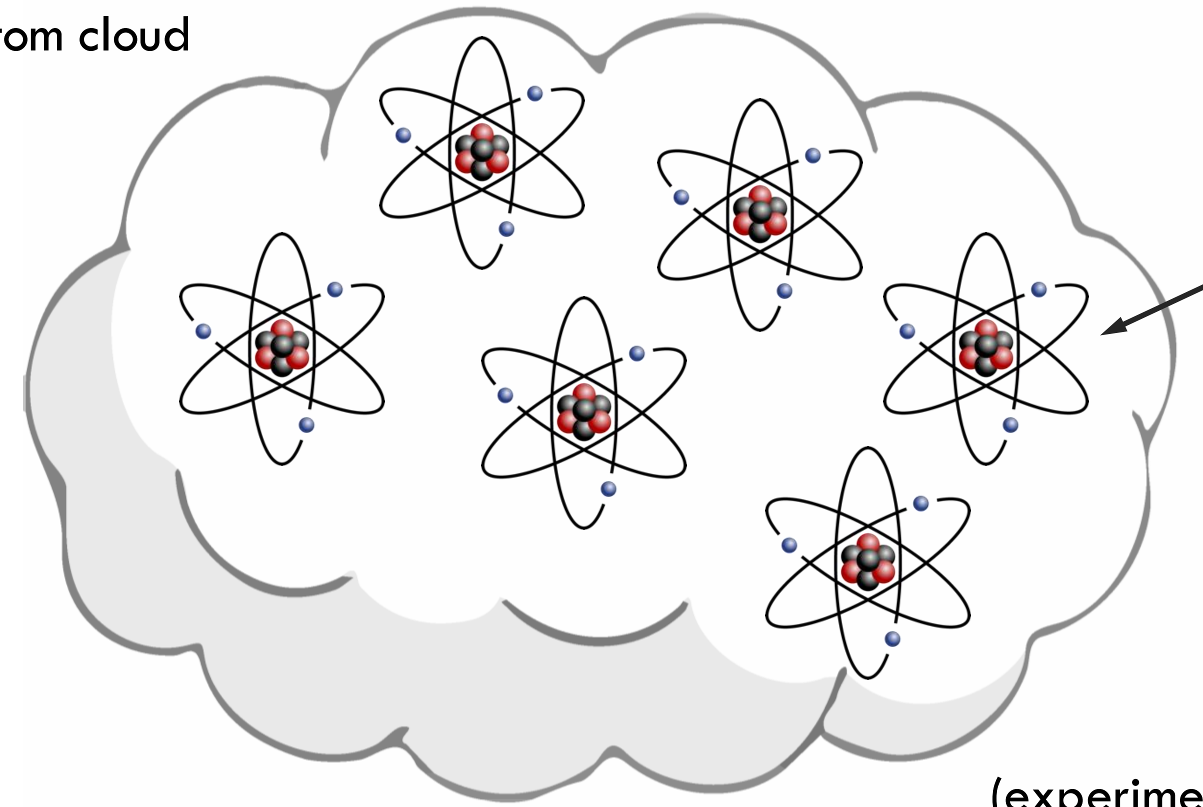
1. The onset of an individual jump evolution is not predictable; although it is knowable from the null-event readout signal.

2. The individual jump evolution is deterministic (predictable if known to have started) for as long as it continues; it follows exactly the same path in every occurrence.

3. Whether an individual jump evolution completes (continues all the way to state |D>) is not predictable, which is why the passage quoted from our paper references the COMPLETED quantum jump. Although not predictable, noncompletion of a jump is knowable from the readout signal.

Ensemble of quantum systems

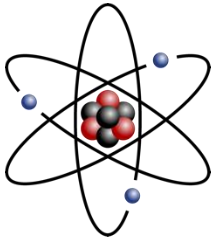
e.g., atom cloud



individual atom

(experiments until c. 1980)

Individual quantum system

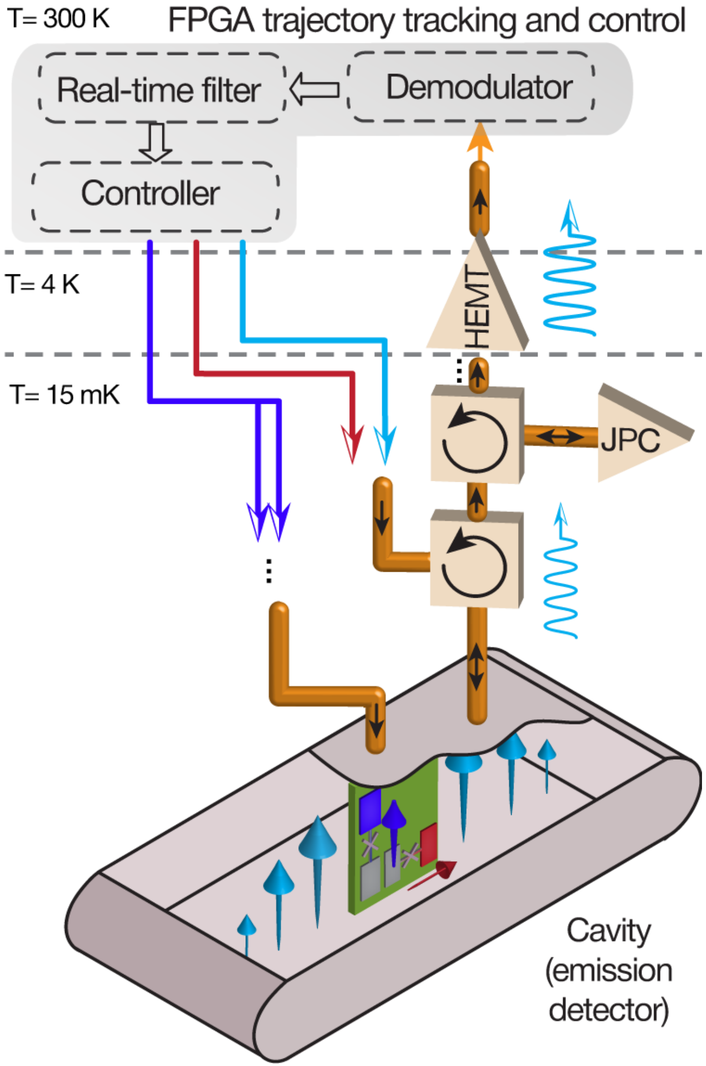


Can there be, despite the indeterminism of quantum physics,

a possibility to know

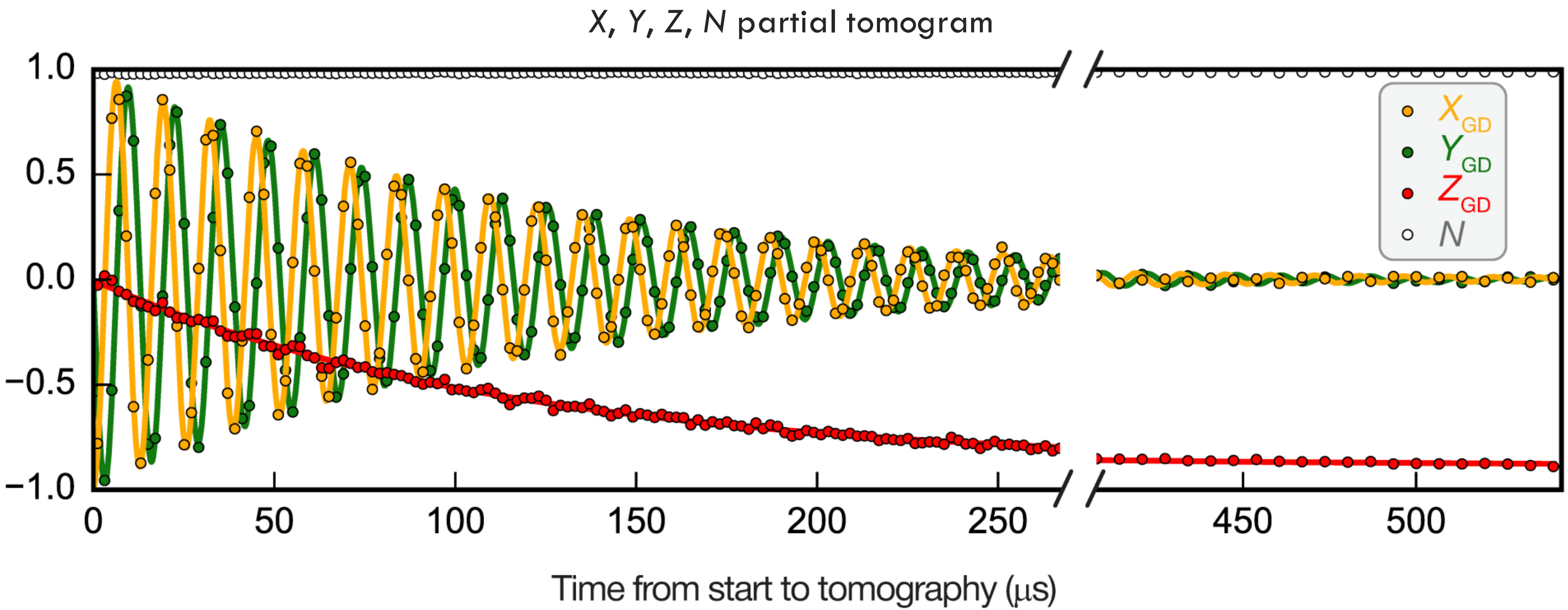
if a quantum jump is about to occur or not?

Schematic of the experiment



Control experiments

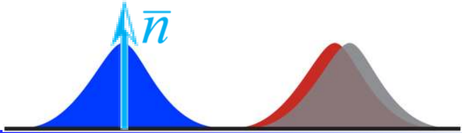
Coherences: free evolution

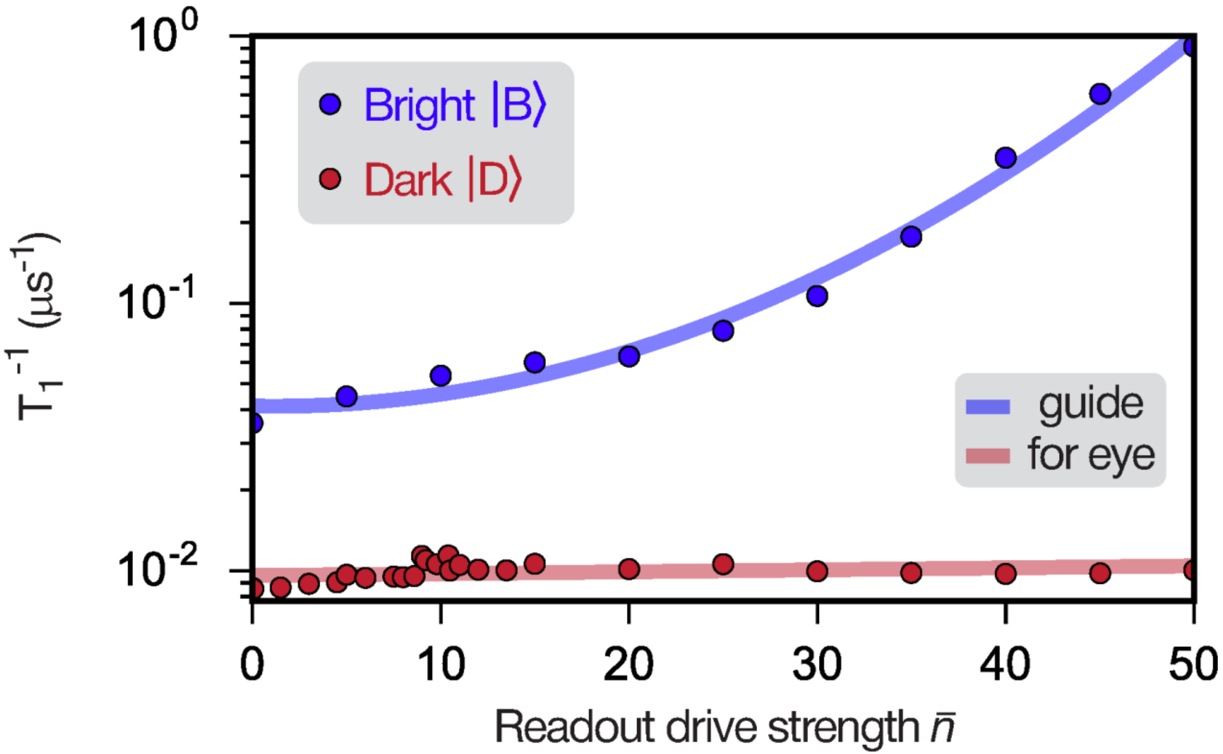


T_1^{DG} ($\overline{n}$ = 0) = 116 ± 5 µs
T_{2R}^{DG} ($\overline{n}$ = 0) = 120 ± 5 µs

* Detuned generator

T_1 vs. readout strength

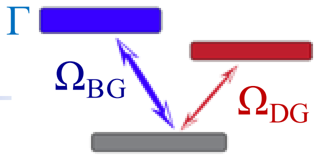


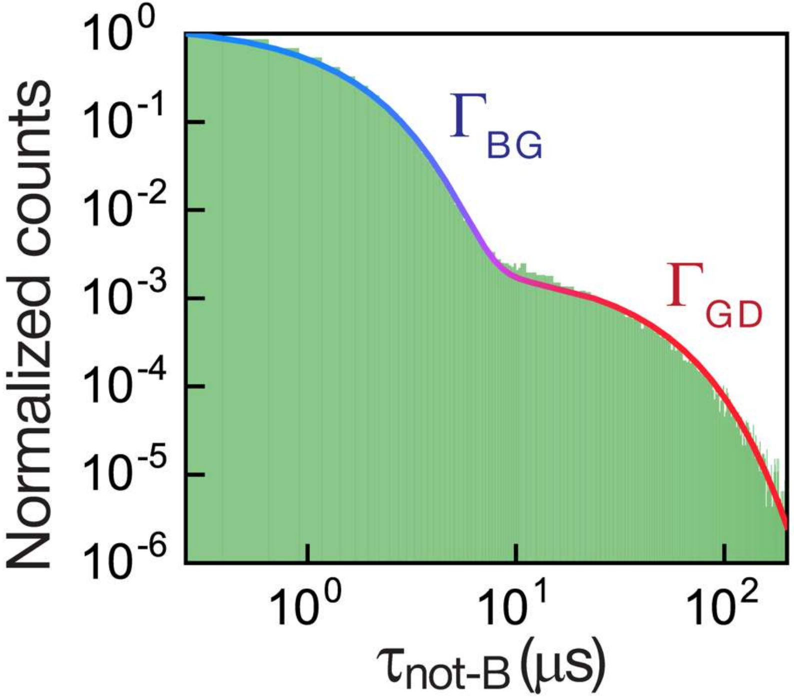


Boissonneault *et al.*, PRA (2009) Slichter *et al.*, PRL (2012) Sank *et al.*, PRL (2016) …

Unconditioned quantum jumps

Unconditioned quantum jumps

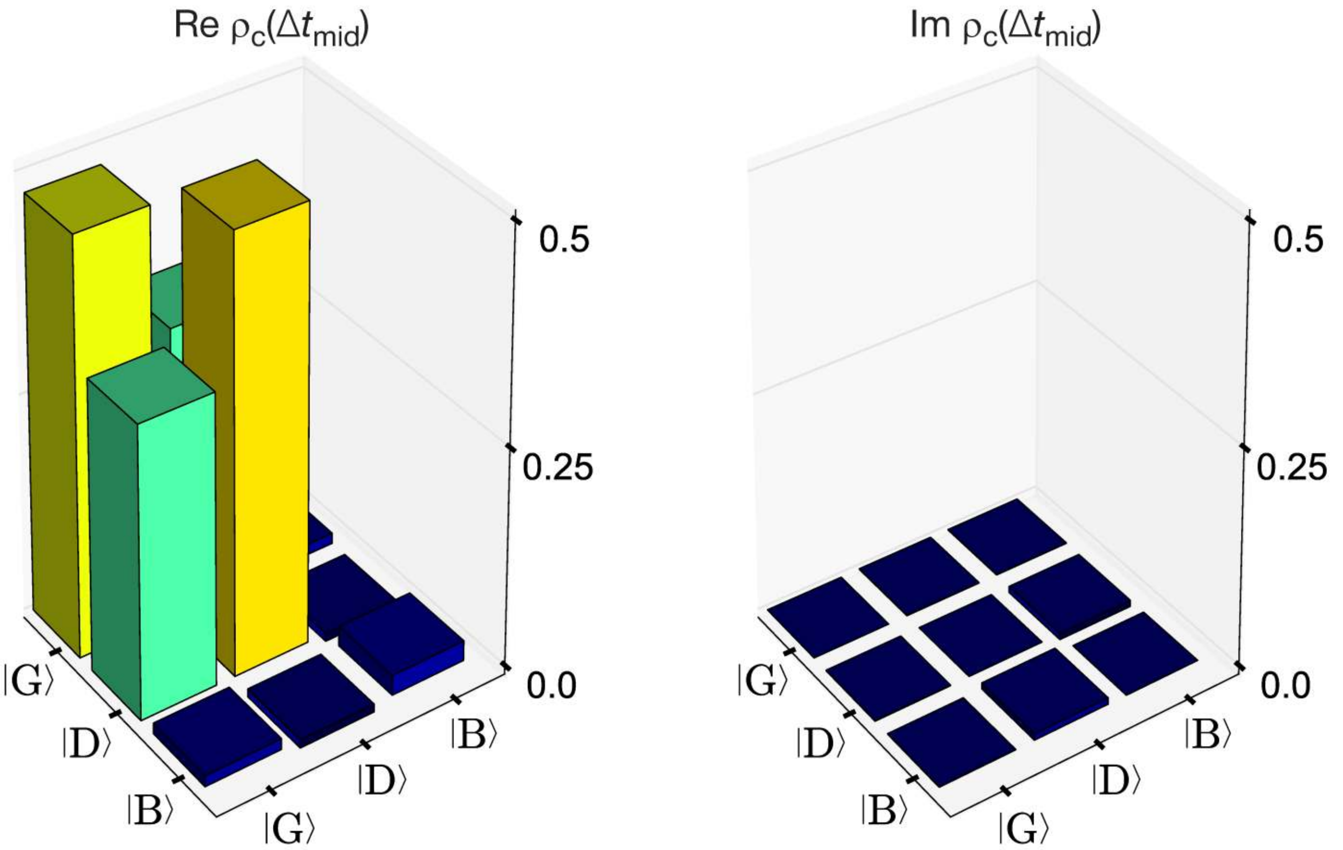




* Note the *log-log* scale

Jumps in a qubit: Slichter *et al.*, New J. Phys. (2016)

Mid-flight tomogram



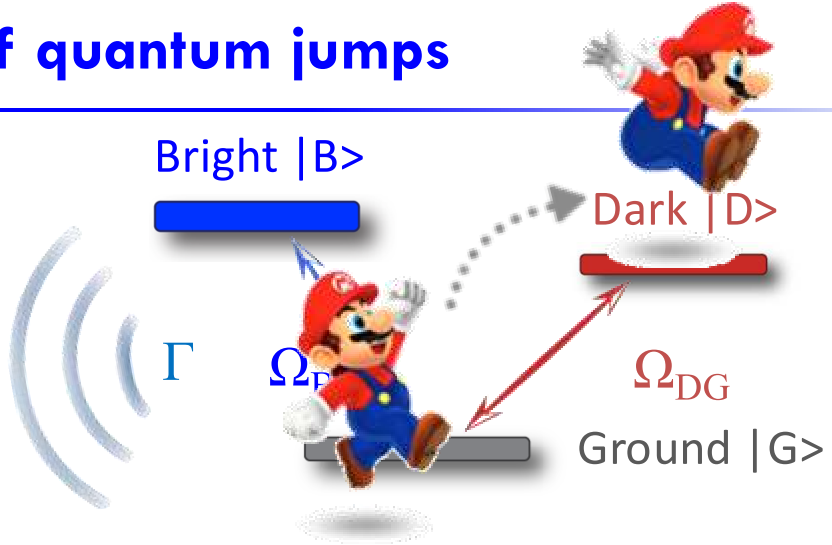
Based on 4×10^6 catch events

Original observation of quantum jumps

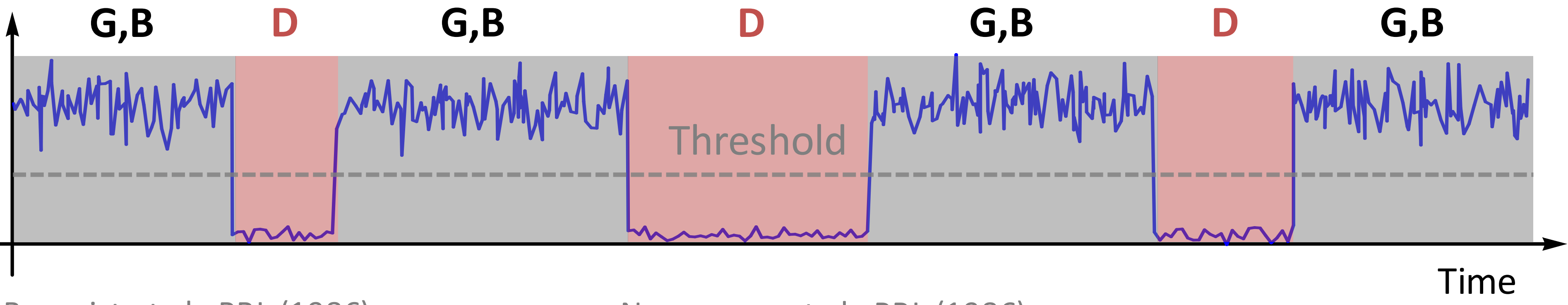
Photodetector

Collection efficiency η ~ 10^{-3}

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



Measurement record (fluorescence)



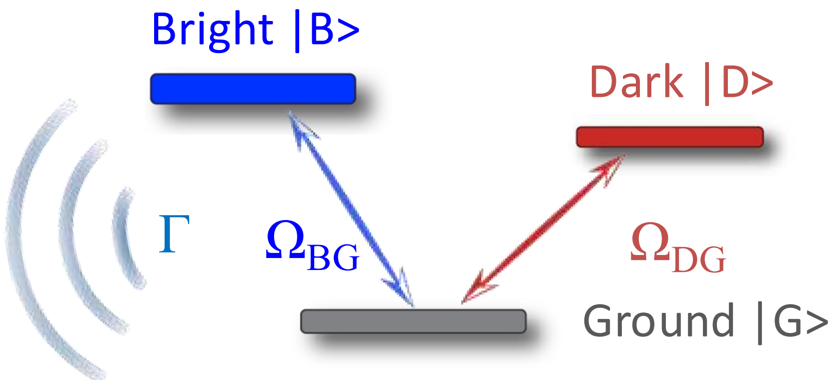
Berquist et al., PRL (1986)
Sauter et al., PRL (1986)

Nagourney et al., PRL (1986)
Cook, *What are quantum jumps?* Phys. Scripta (1988)

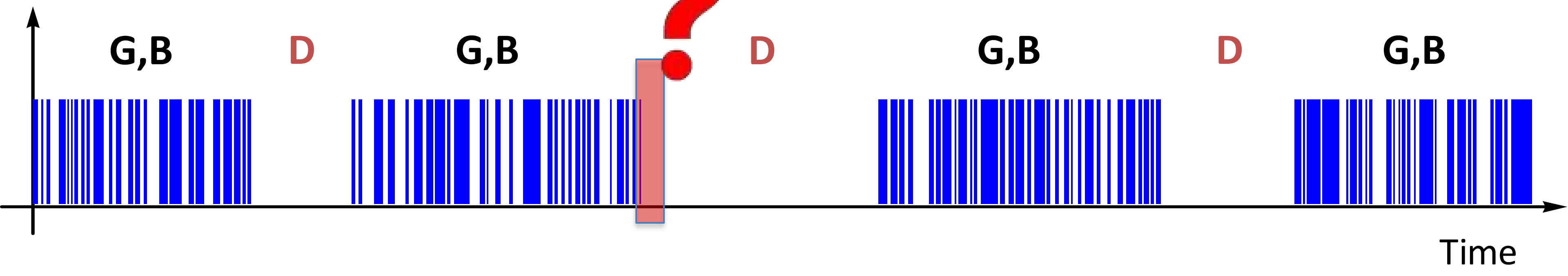
Omniscient observer

Hypothetical efficiency $\eta = 1$

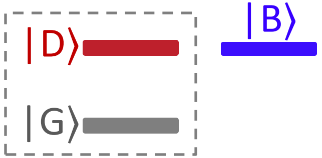
$$BW_{det} \gg \frac{\Omega_{BG}^2}{\Gamma} \qquad \Gamma \gg \Omega_{BG} \gg \Omega_{DG}$$

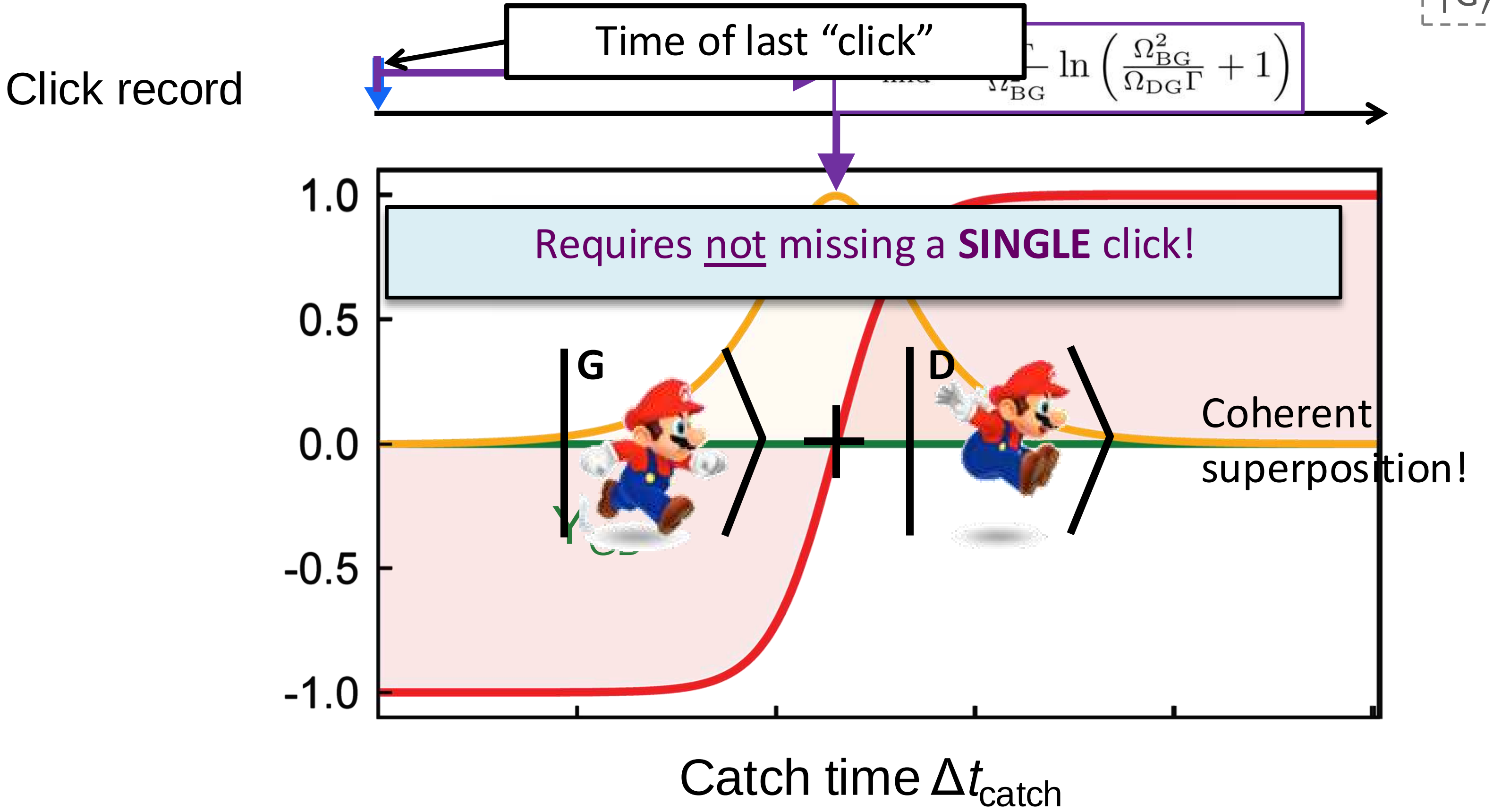


Measurement record (click? Y/N)



Quantum jump from |G⟩ to |D⟩: prediction

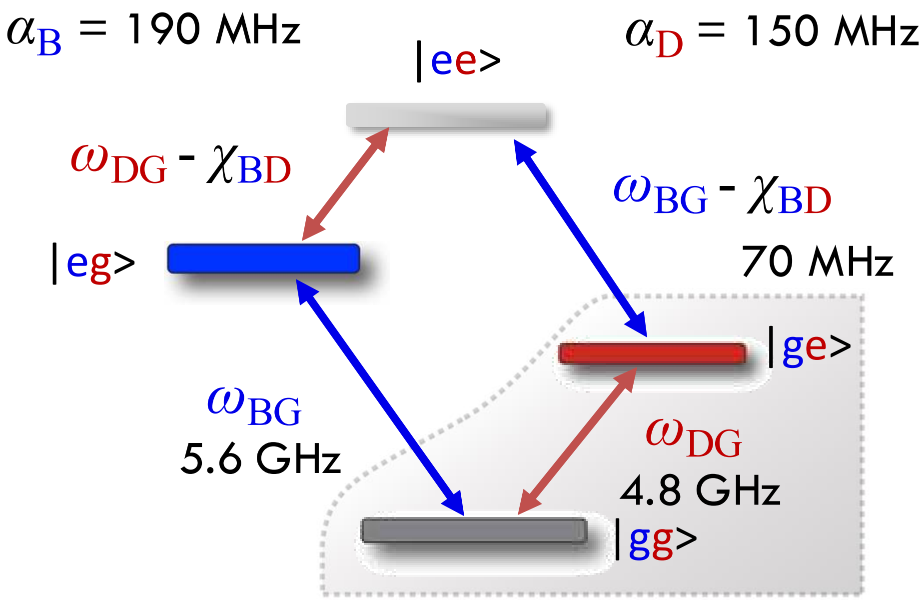




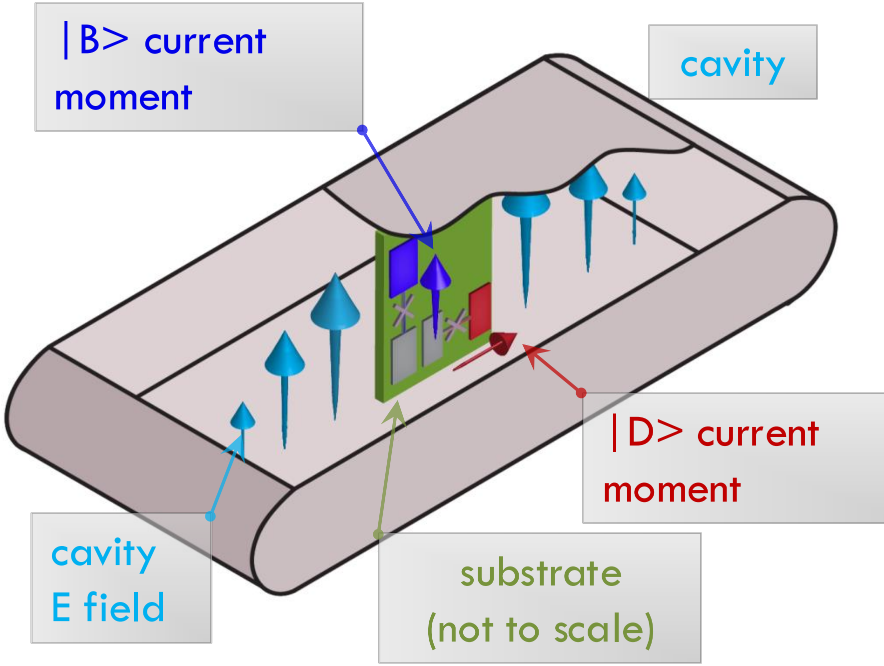
Carmichael, SUSSP71 2015

cQED implementation of V-system

$$\hat{H} = \omega_{DG}\hat{\sigma}_Z \otimes \hat{I} + \omega_{BG}\hat{I} \otimes \hat{\sigma}_Z - \chi_{BD}\hat{\sigma}_Z \otimes \hat{\sigma}_Z$$

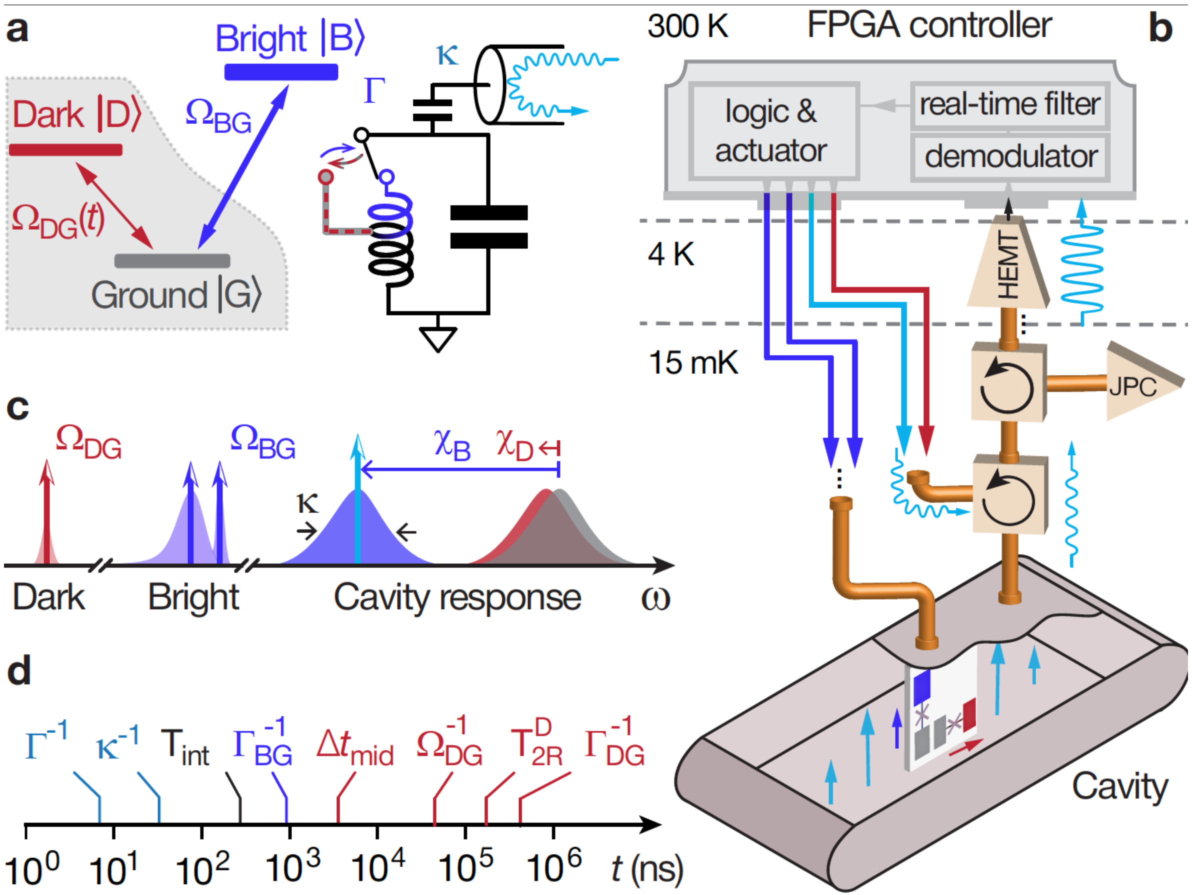


Schematic representation of design



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

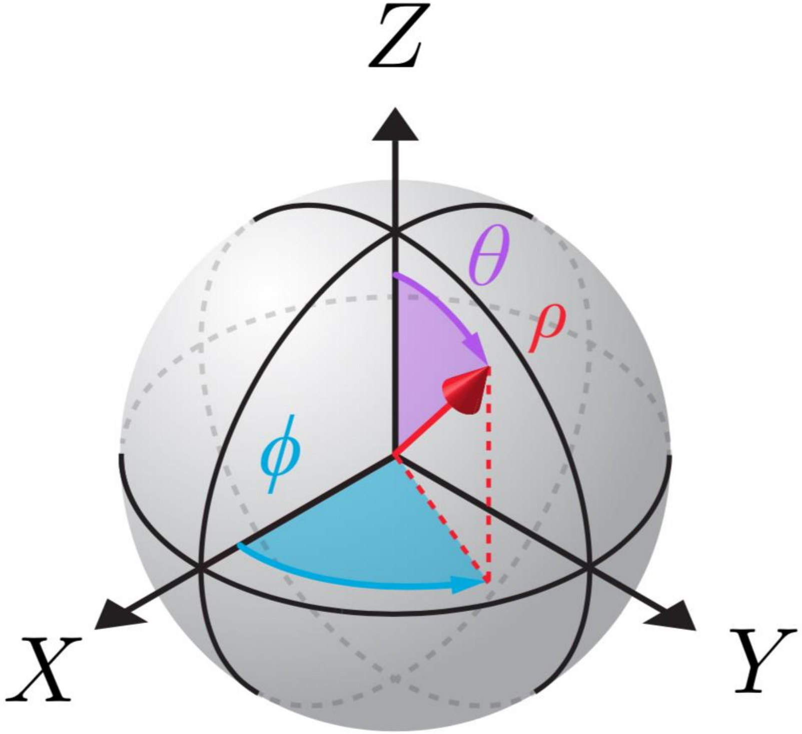
Setup of the experiment



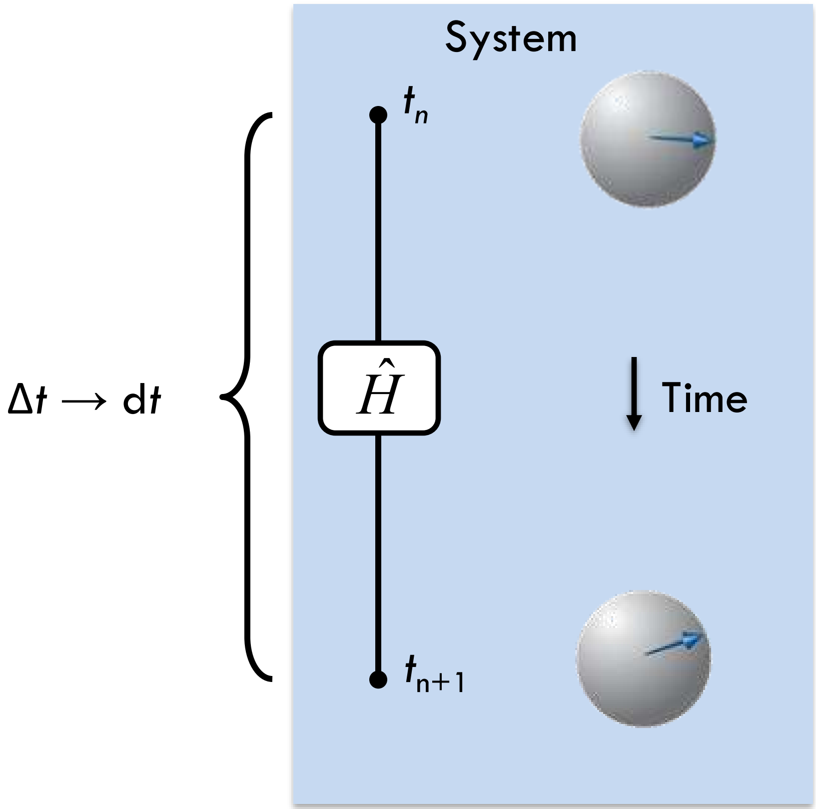
A primer on trajectory theory

Qubit evolution: finite-difference model

(theoretical-minimum example)

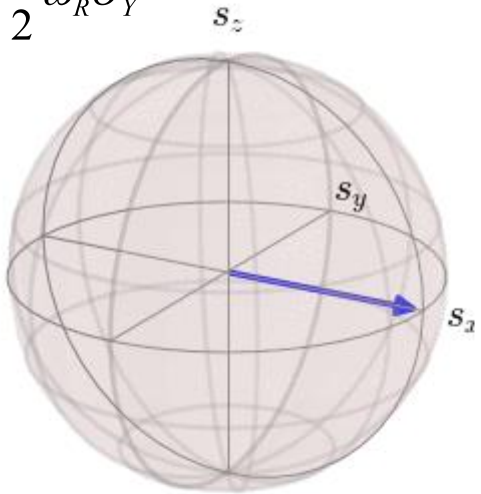


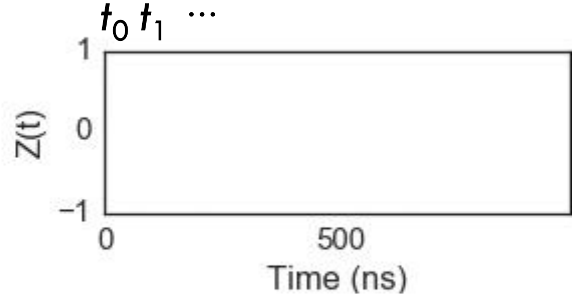
Isolated system



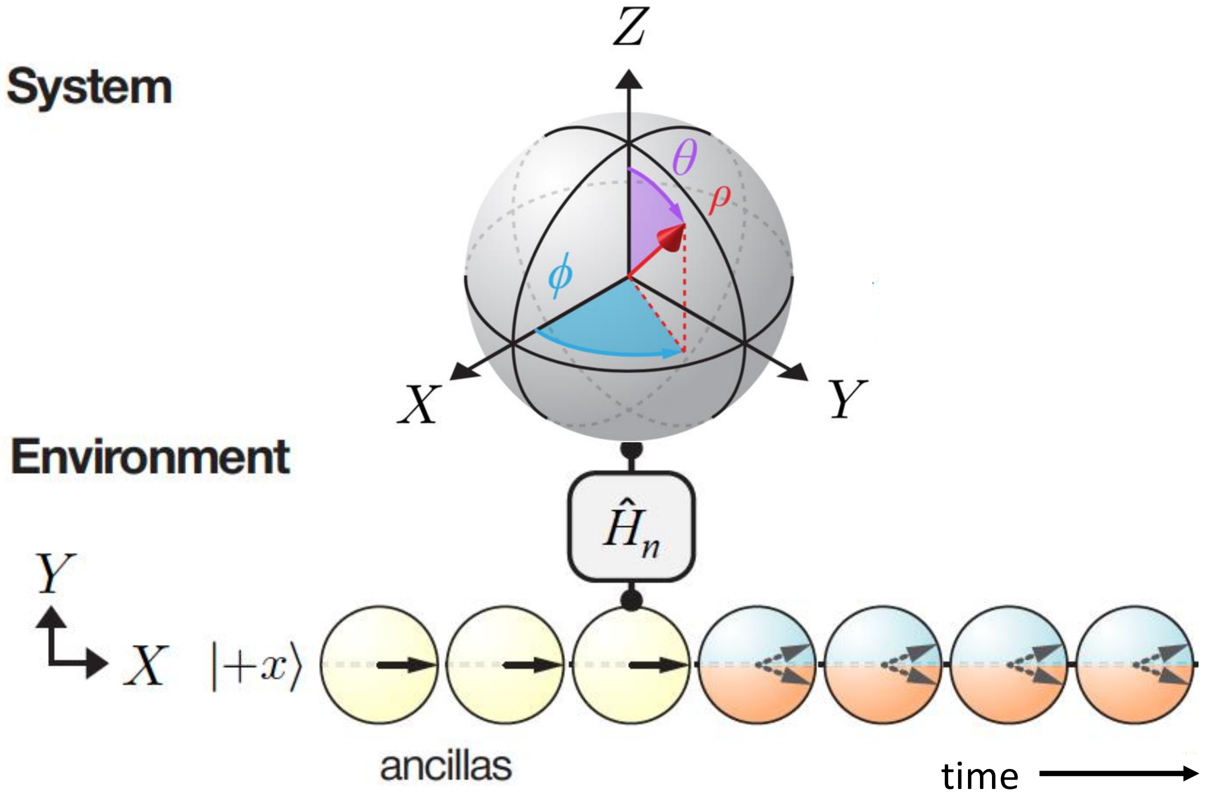
Example

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

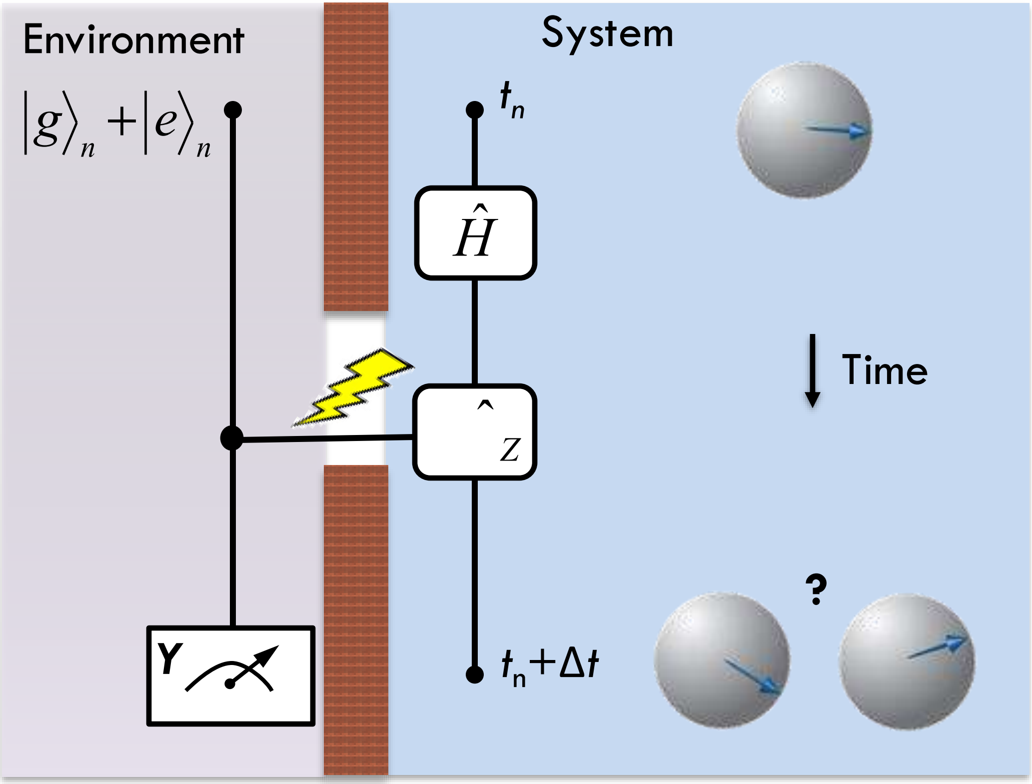




Model of an open quantum system

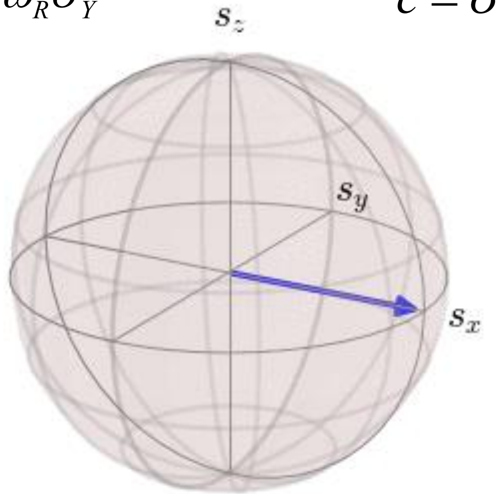


Open system

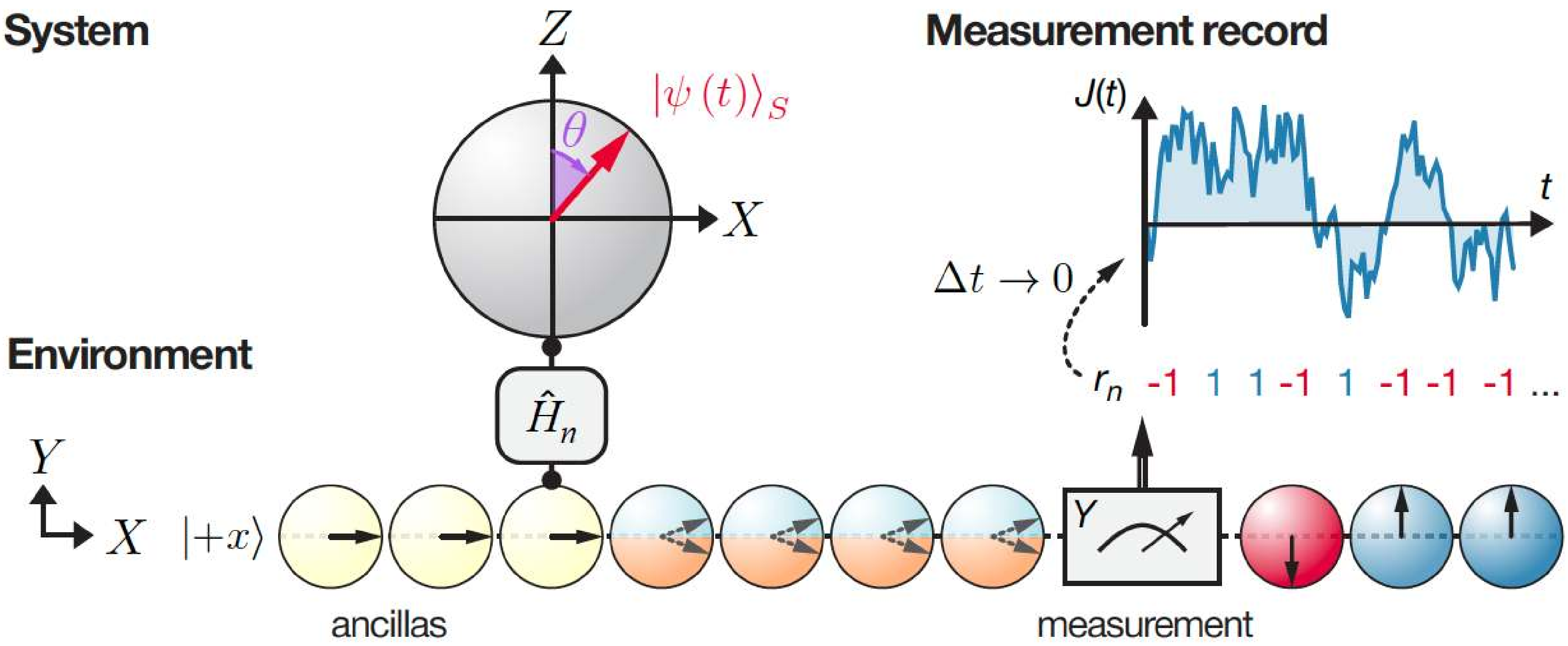


Example

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

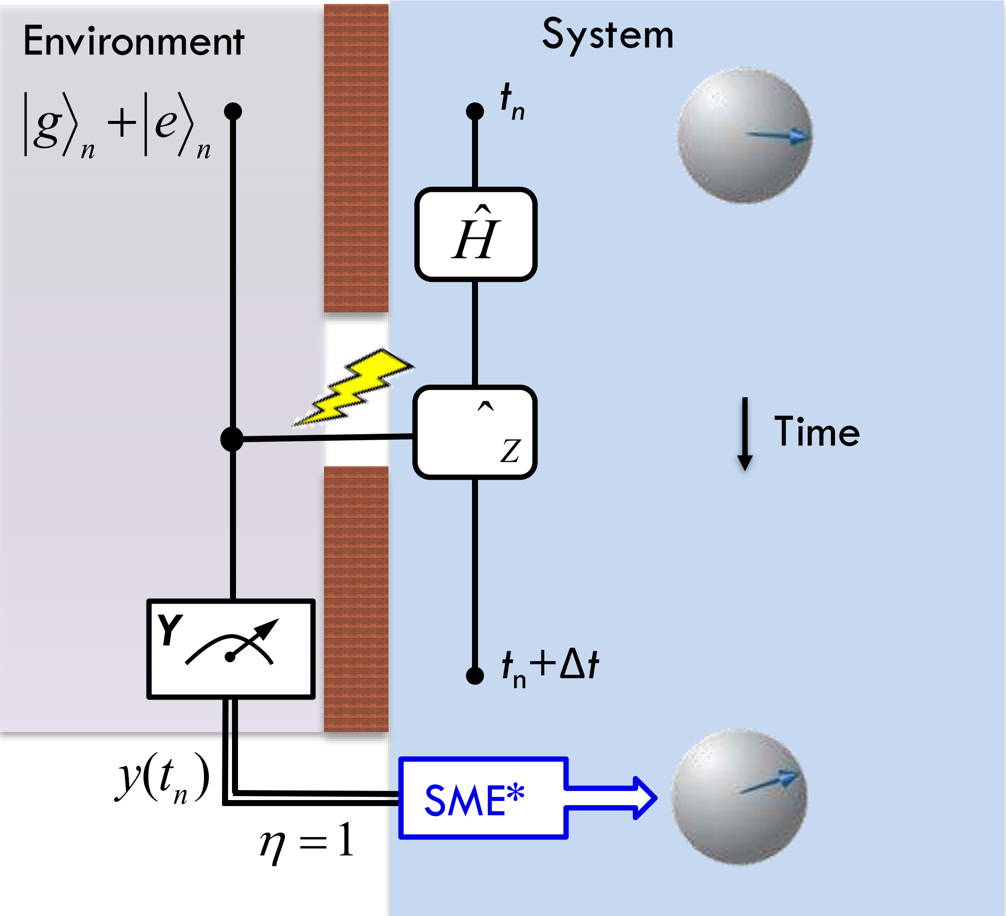


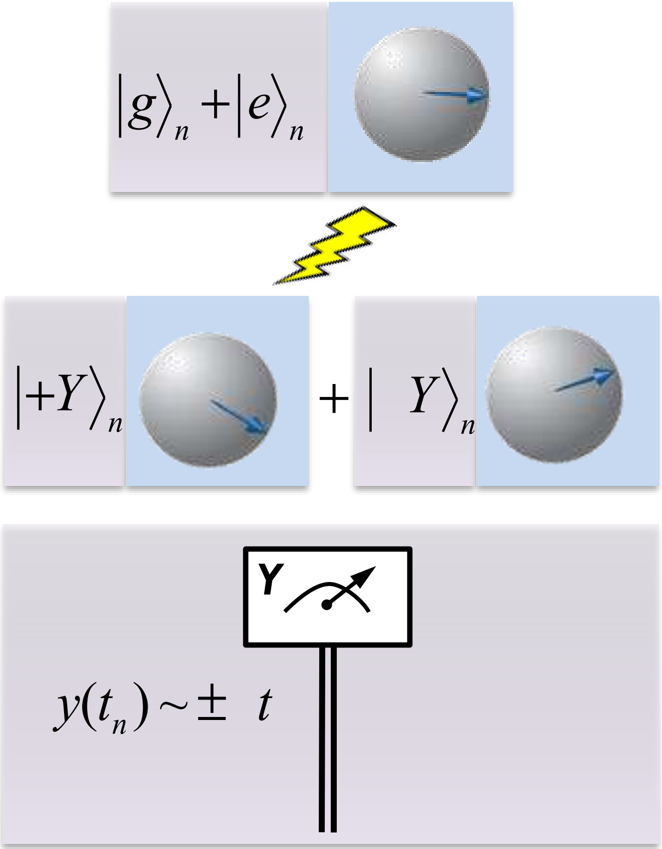
Model of a monitored quantum system



time

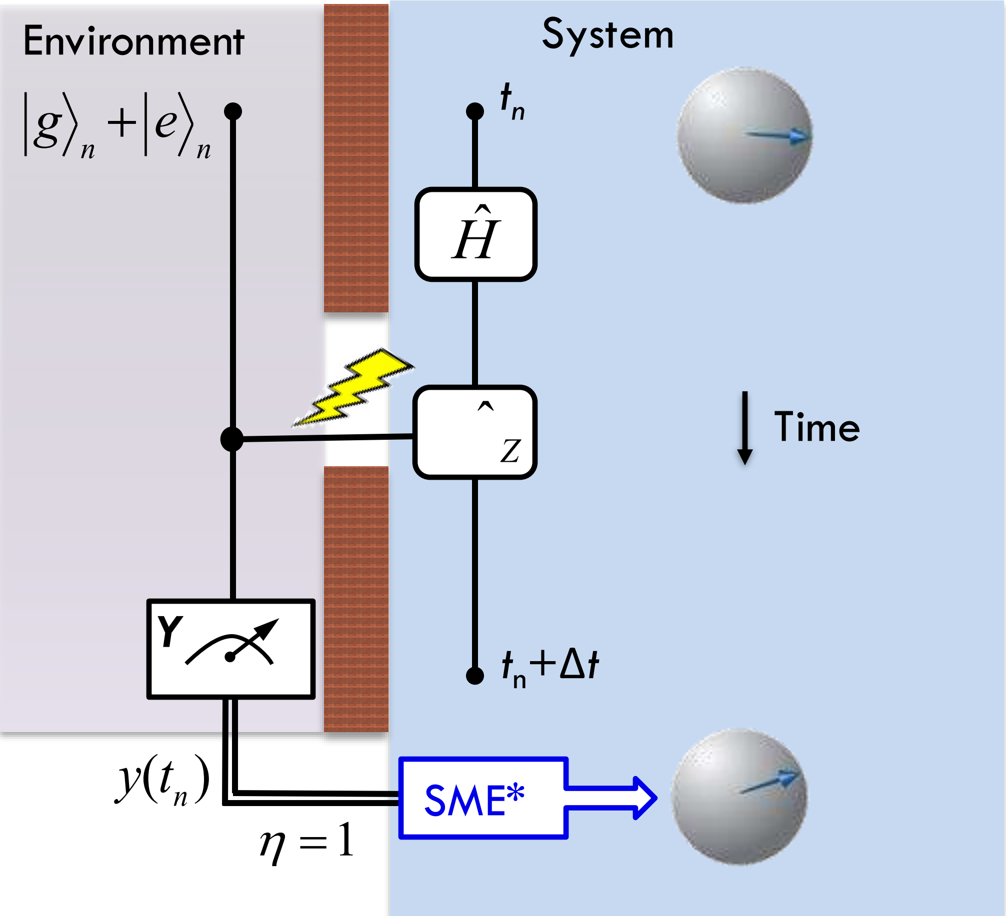
System + omniscient *observer*





* Carmichael, H. *An Open Systems Approach to Quantum Optics* (Springer-Verlag, 1993)

System + omniscient *observer*

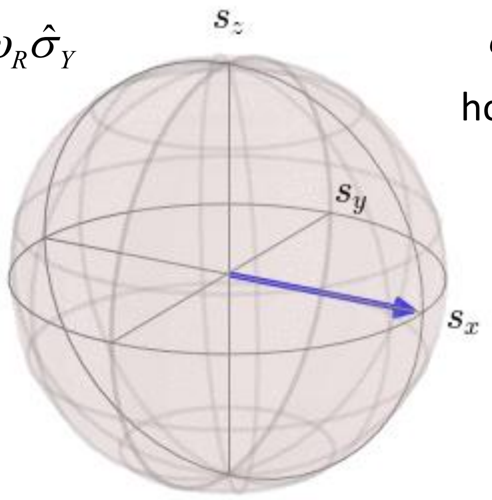


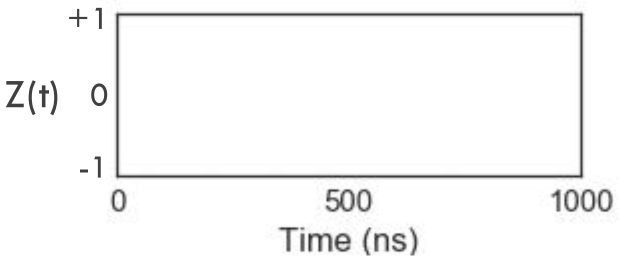
Example

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

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

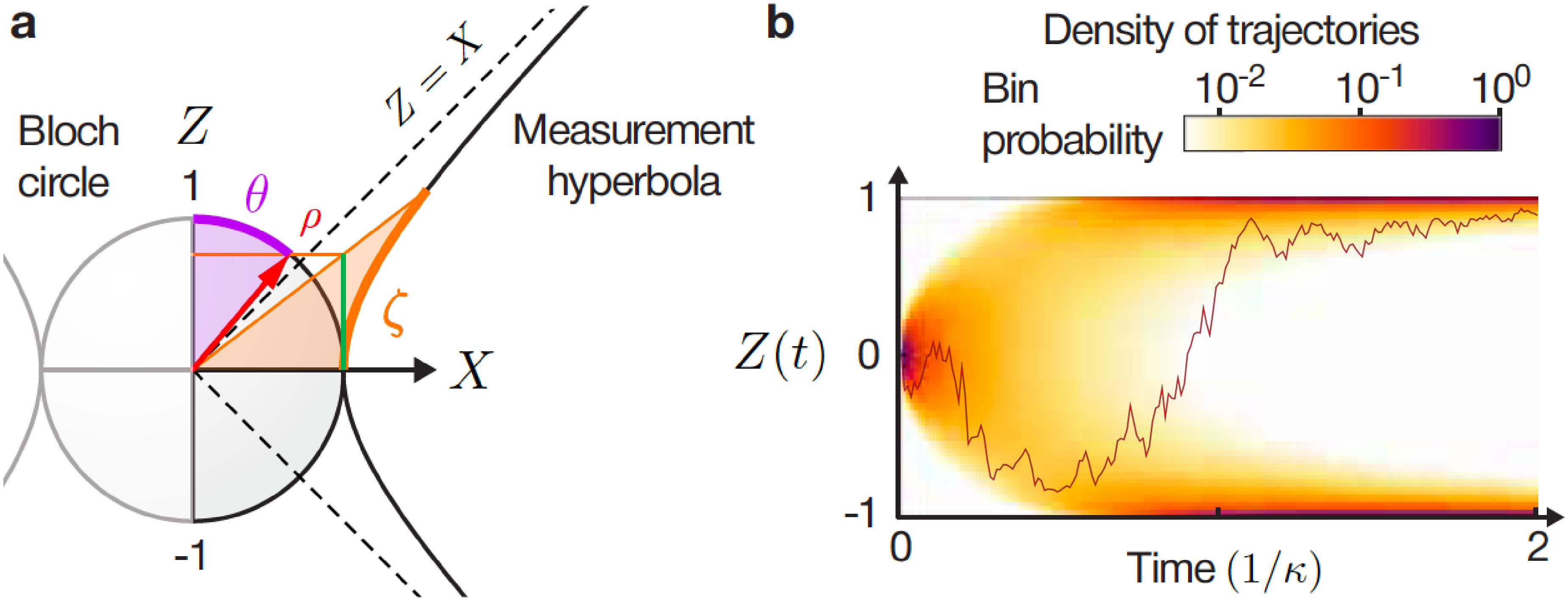
homodyne





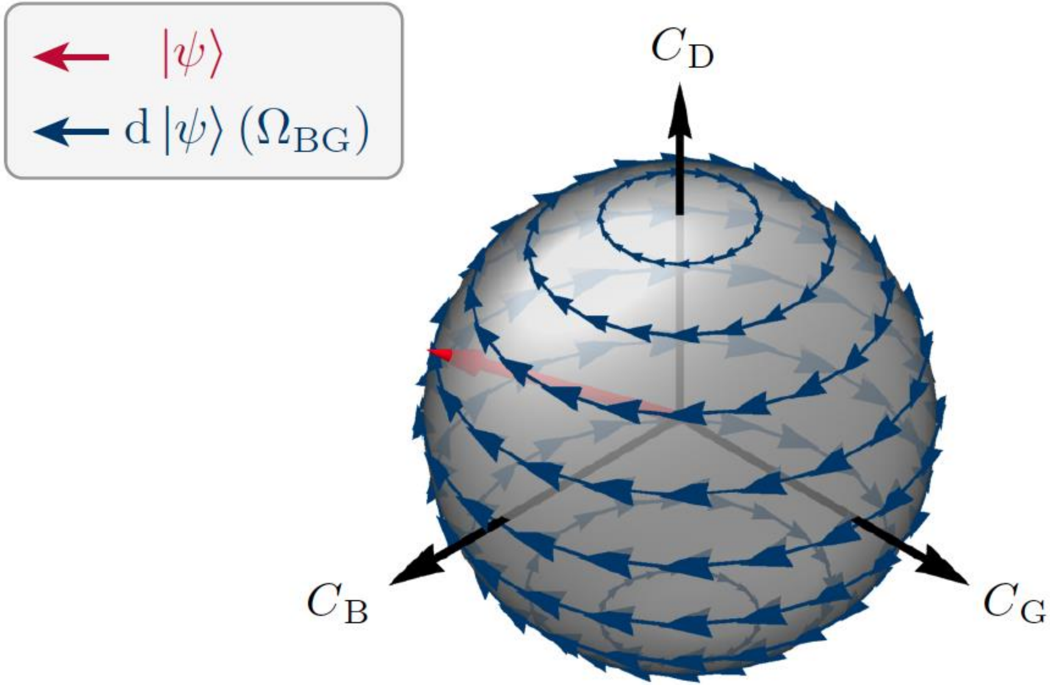
* Carmichael, H. *An Open Systems Approach to Quantum Optics* (Springer-Verlag, 1993)

Continuous quantum measurement

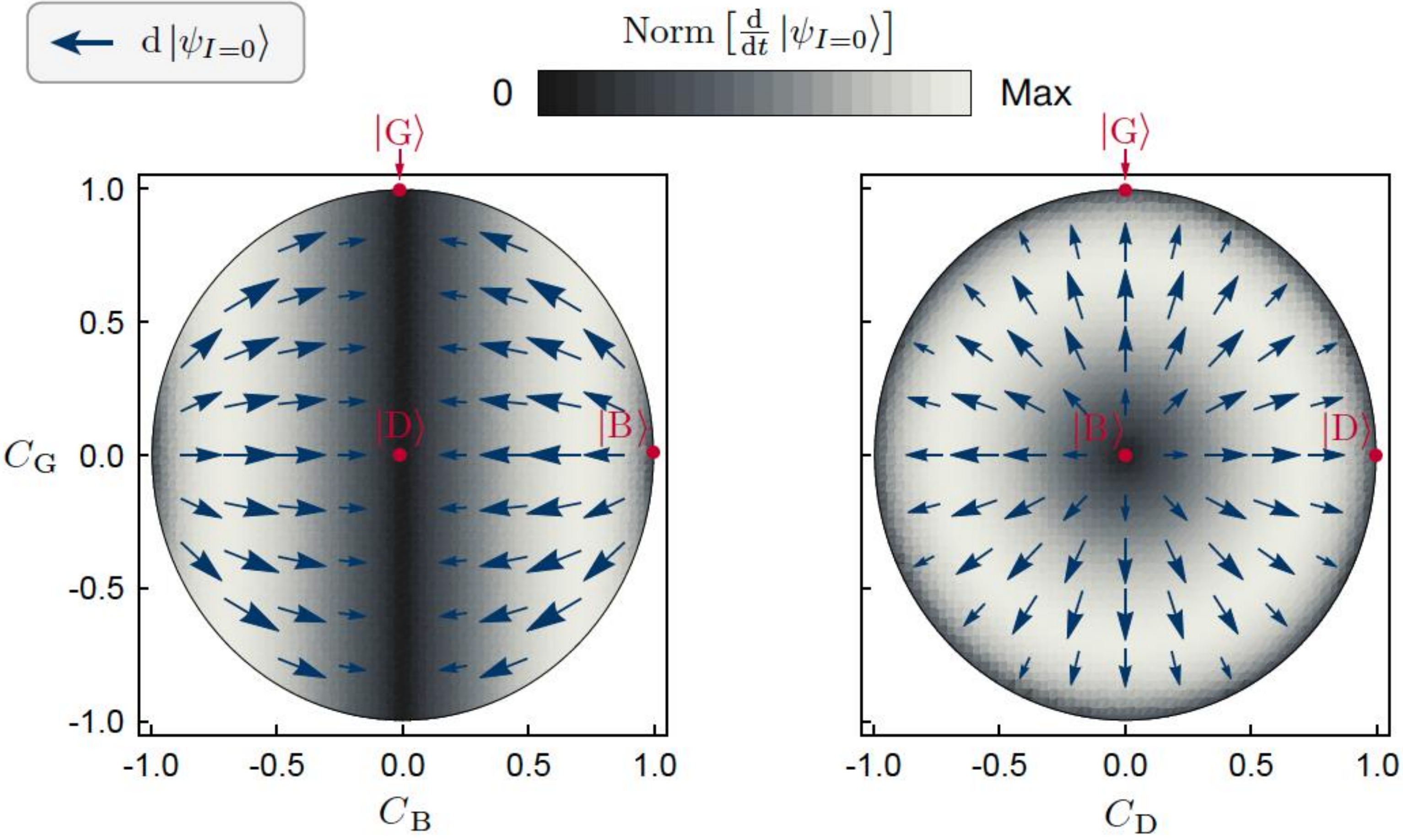


Geometrical representation

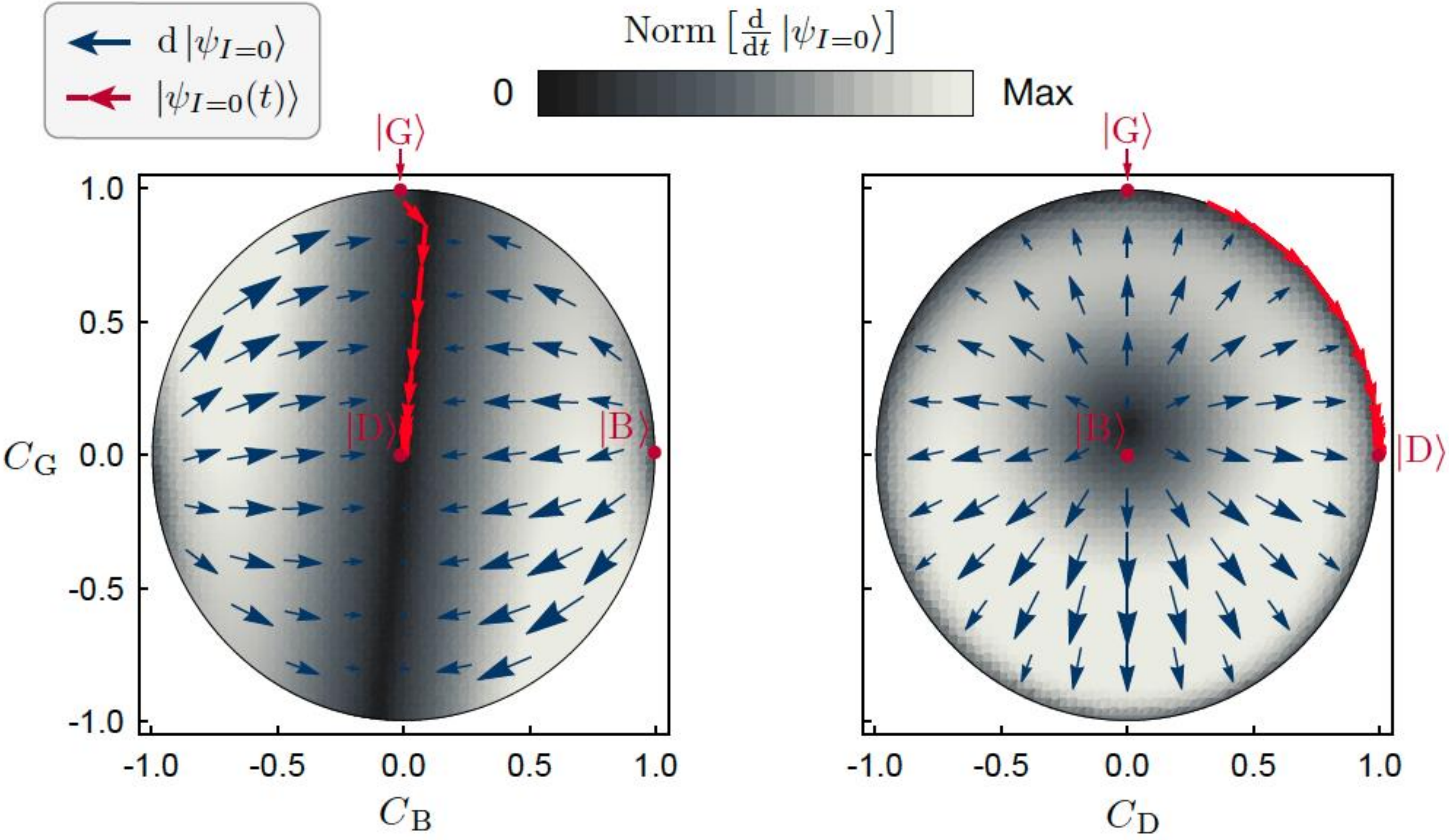
$$|\psi\rangle = C_{\mathrm{B}}\,|\mathrm{B}\rangle + C_{\mathrm{G}}\,|\mathrm{G}\rangle + C_{\mathrm{D}}\,|\mathrm{D}\rangle$$



Geometrical representation: B/not-B

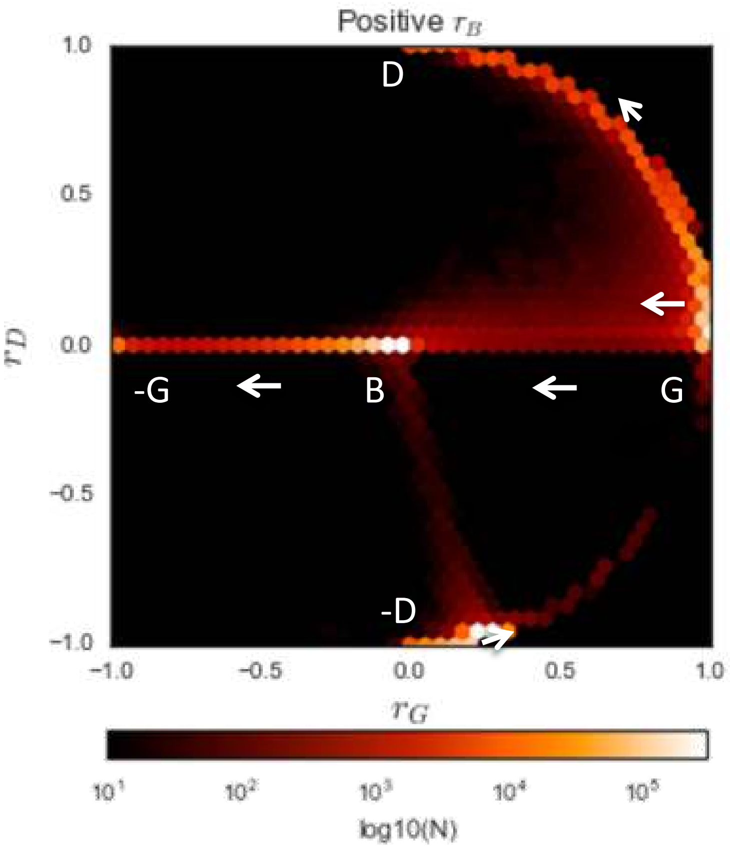


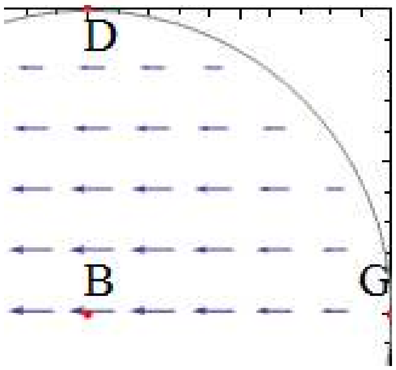
Geometrical representation: B/not-B and Ω_{BG}



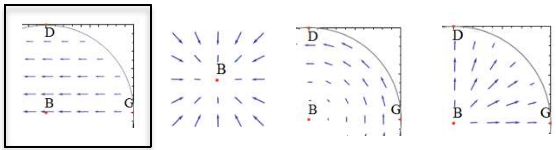
Forces of wind: controller vs. observer

Hilbert space



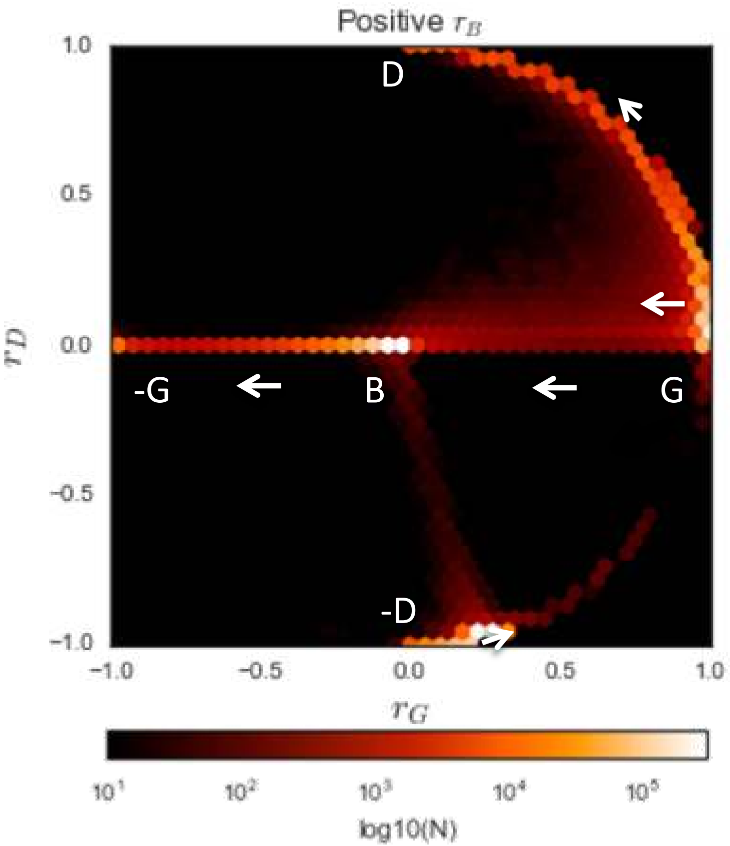


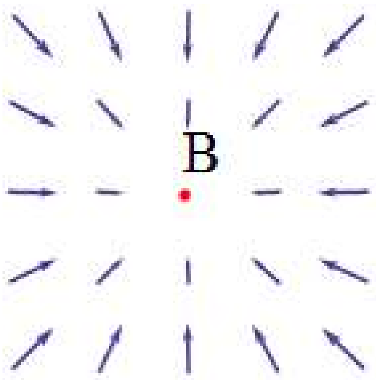
Ω_B



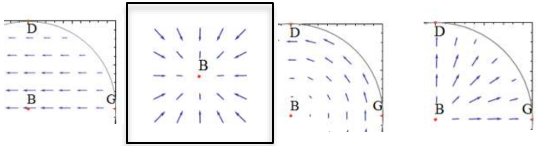
$\Gamma_m^{-1} = 0.02 \quad 2\pi\ \Omega_B^{-1} = 1.5 \quad 2\pi\ \Omega_D^{-1} = 60 \ (\mu s)$

Forces of wind: controller vs. observer



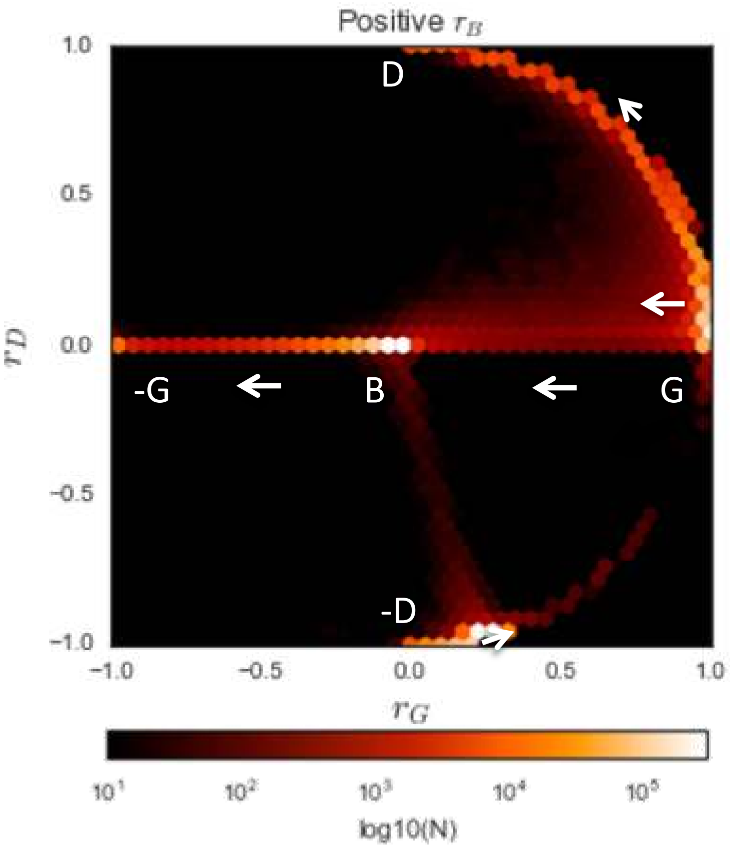


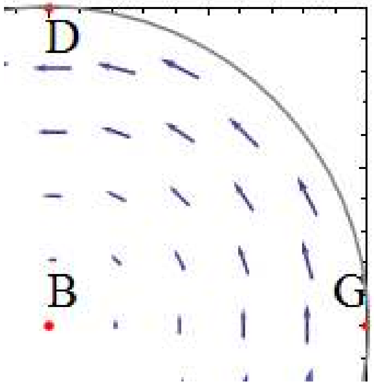
Γ_m : dy ~B

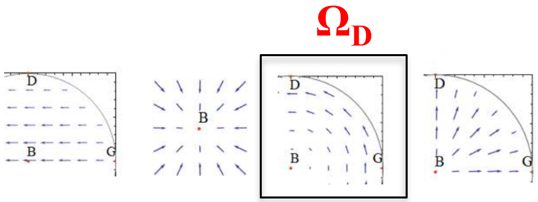


$\Gamma_m^{-1} = 0.02 \quad 2\pi\ \Omega_B^{-1} = 1.5 \quad 2\pi\ \Omega_D^{-1} = 60$ (μs)

Forces of wind: controller vs. observer

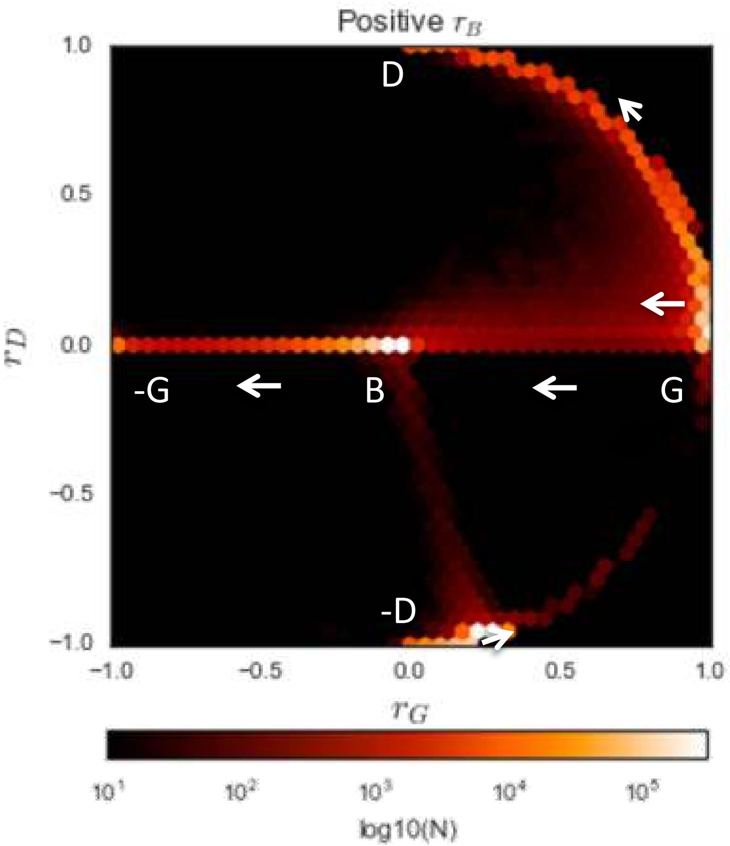


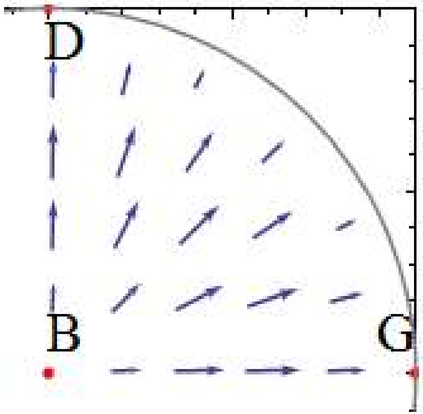




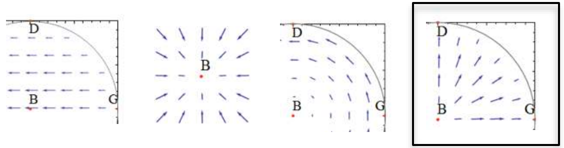
$\Gamma_m^{-1} = 0.02 \quad 2\pi\,\Omega_B^{-1} = 1.5 \quad 2\pi\,\Omega_D^{-1} = 60$ (μs)

Forces of wind: controller vs. observer



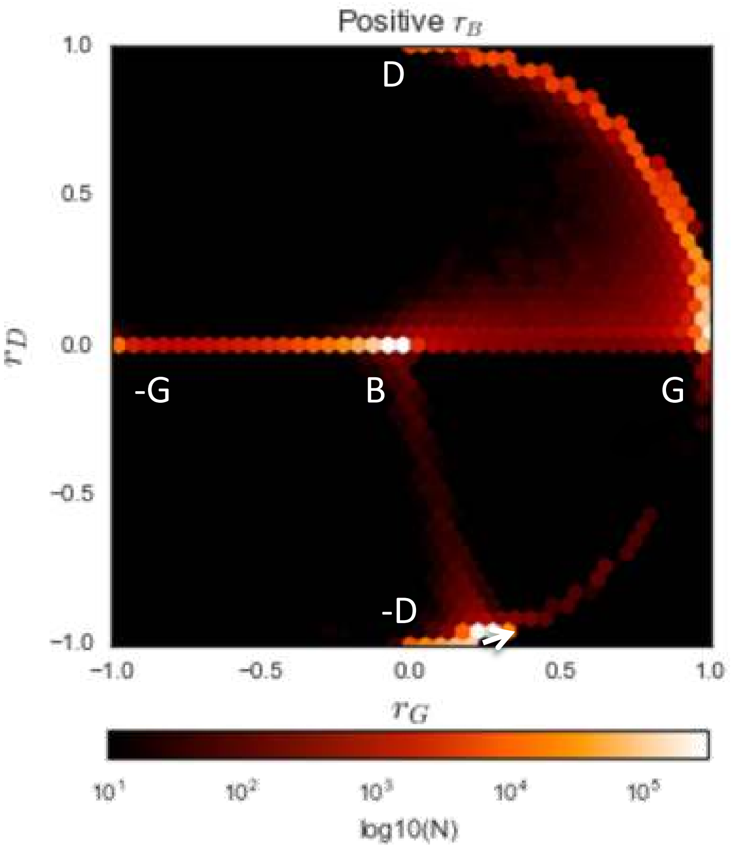


Γ_m : dy ~ not B



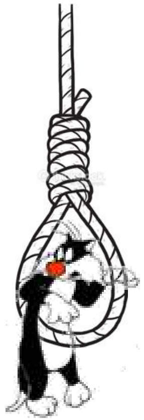
$\Gamma_m^{-1} = 0.02 \quad 2\pi\,\Omega_B^{-1} = 1.5 \quad 2\pi\,\Omega_D^{-1} = 60 \;\; (\mu s)$

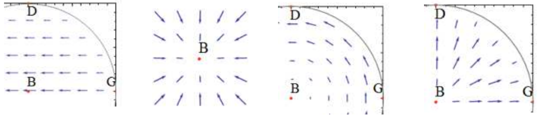
Forces of wind: controller vs. observer



⇧measurement

=> ⇧PREDICTABLE dynamics!



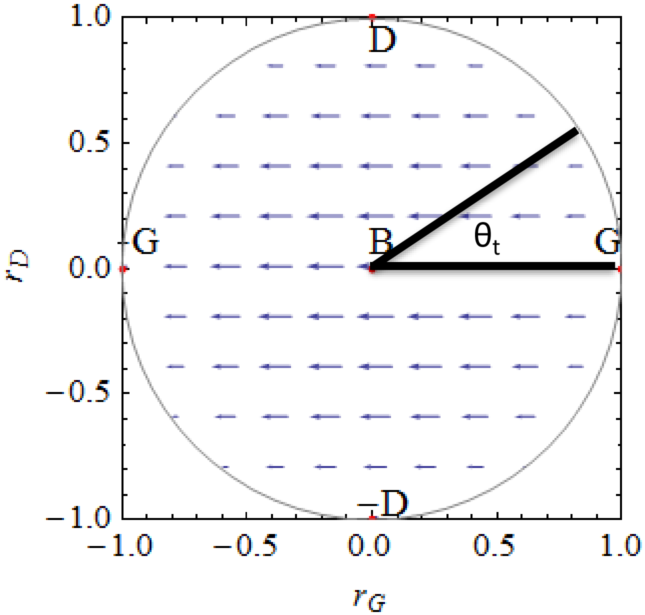


$\Gamma_m^{-1} = 0.02 \quad 2\pi\ \Omega_B^{-1} = 1.5 \quad 2\pi\ \Omega_D^{-1} = 60\ \ (\mu s)$

$\mathbb{R}$-qutrit: sphere representation

Representation

$$|\psi(t)\rangle = \begin{pmatrix} r_b(t) \\ r_g(t) \\ r_d(t) \end{pmatrix} = \begin{pmatrix} \sin(\theta_t)\sin(\phi_t) \\ \sin(\theta_t)\cos(\phi_t) \\ \cos(\theta_t) \end{pmatrix}$$



Evolution under conditioned linear SSE

$$\left|\tilde{\psi}(t+dt)\right\rangle = e^{-\frac{1}{2}\hat{M}^\dagger \hat{M} dt} e^{-i\hat{H}dt} \left|\tilde{\psi}(t)\right\rangle$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\phi(t) = \frac{\Omega}{2} - \frac{1}{4}\Gamma \sin(2\phi(t))$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\theta(t) = -\frac{1}{4}\Gamma \sin^2(\phi(t)) \sin(2\theta(t))$$

$$P_D(t) = \cos^2(\theta(t))$$

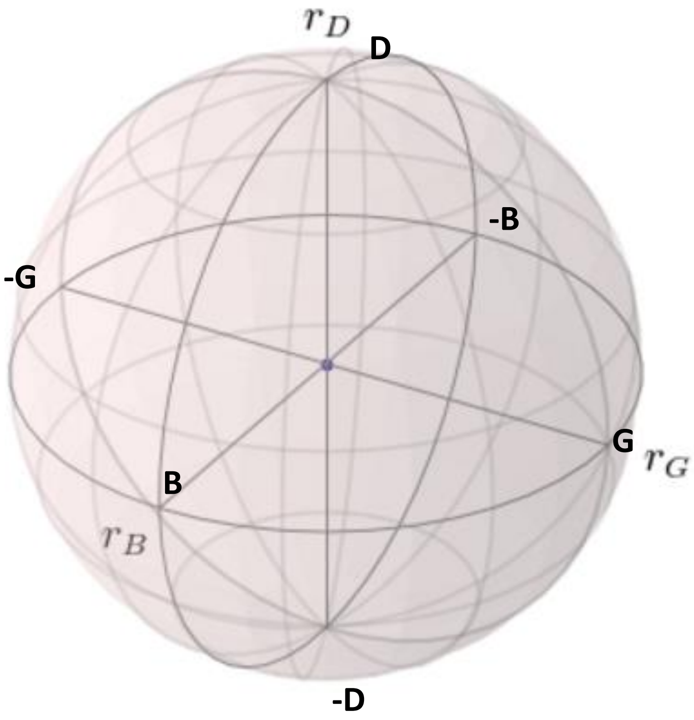
$$= \boxed{\frac{1}{2}\left(1 + \tanh\left[\frac{\Omega^2}{2\Gamma}t + t_0\right]\right)}$$

$\mathbb{R}$-qutrit: sphere representation

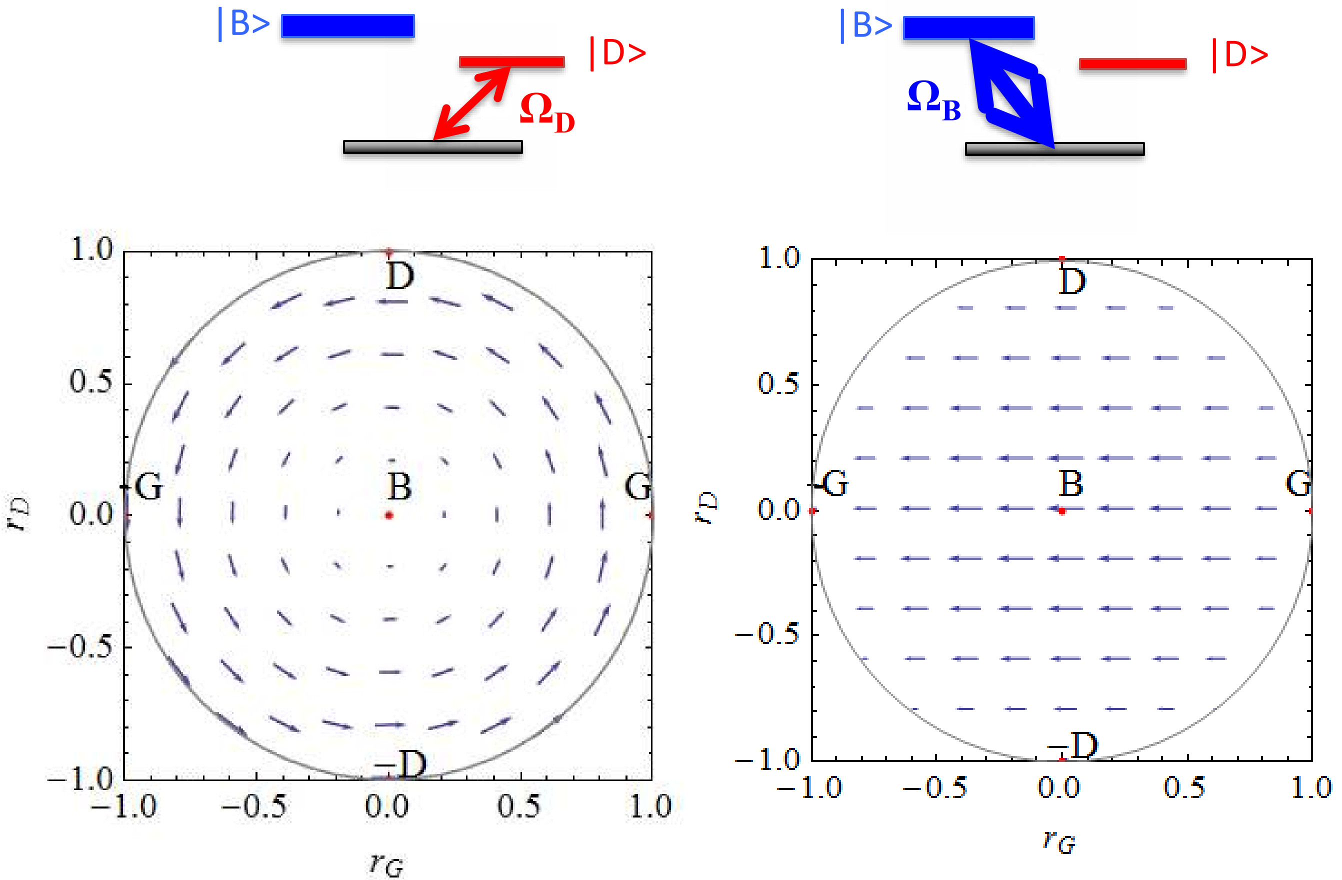
$$|\psi(t)\rangle = r_G\,|G\rangle + r_B\,|B\rangle + r_D\,|D\rangle$$

$$r_G^2 + r_B^2 + r_D^2 = 1$$

H ~ so(3)
U ~ SO(3)

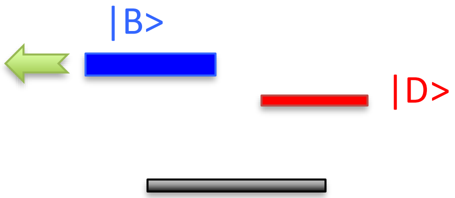


dρ: Deterministic drives



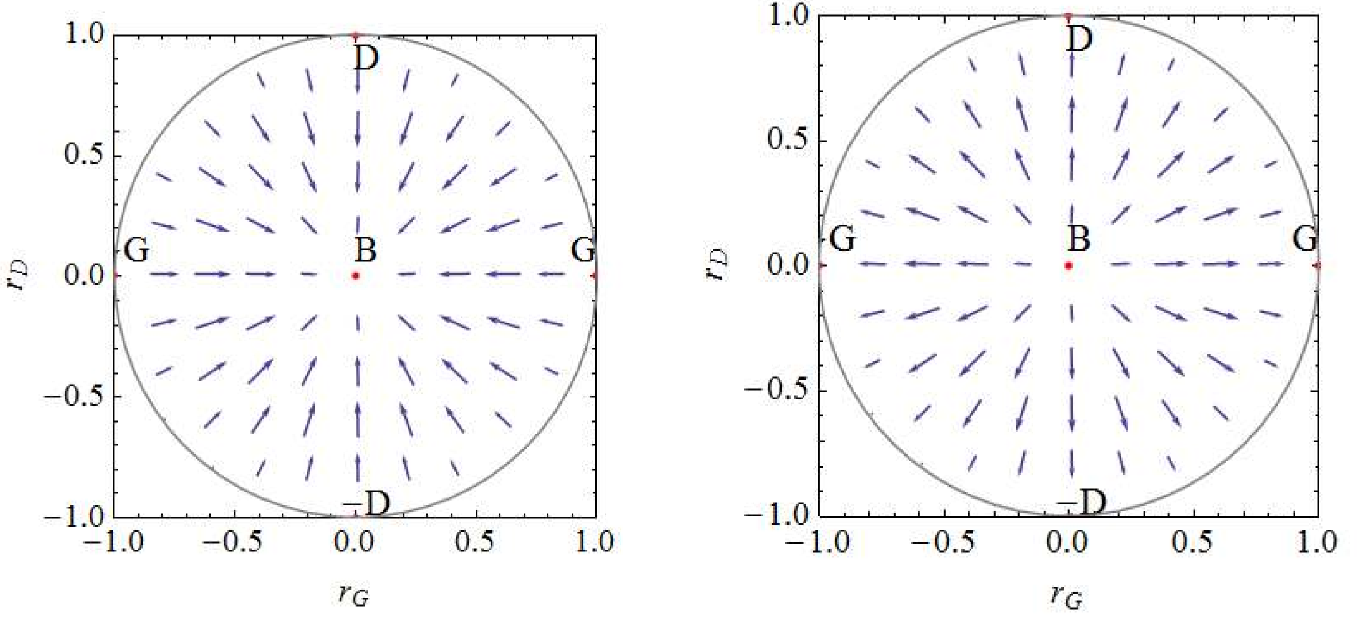
dρ: Measurement – stochastic field

$J_m = \Gamma_m^{\,1/2}|B\rangle\langle B|$

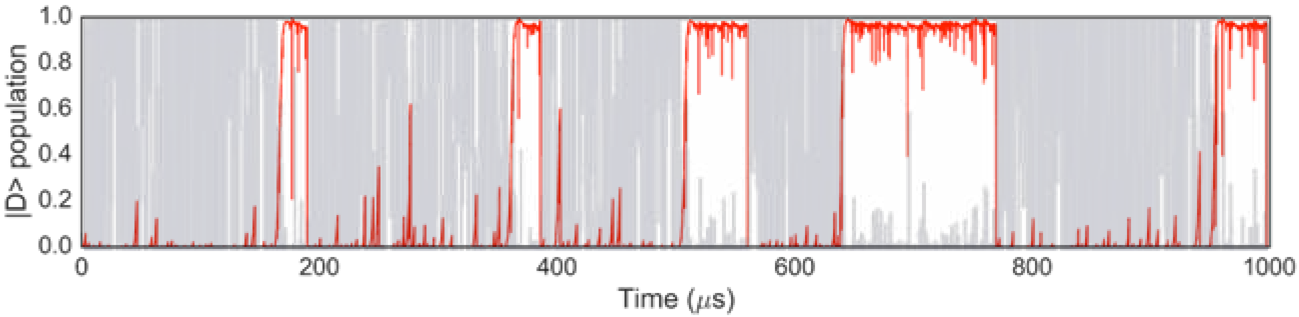


dy ~ B

dy ~ not B

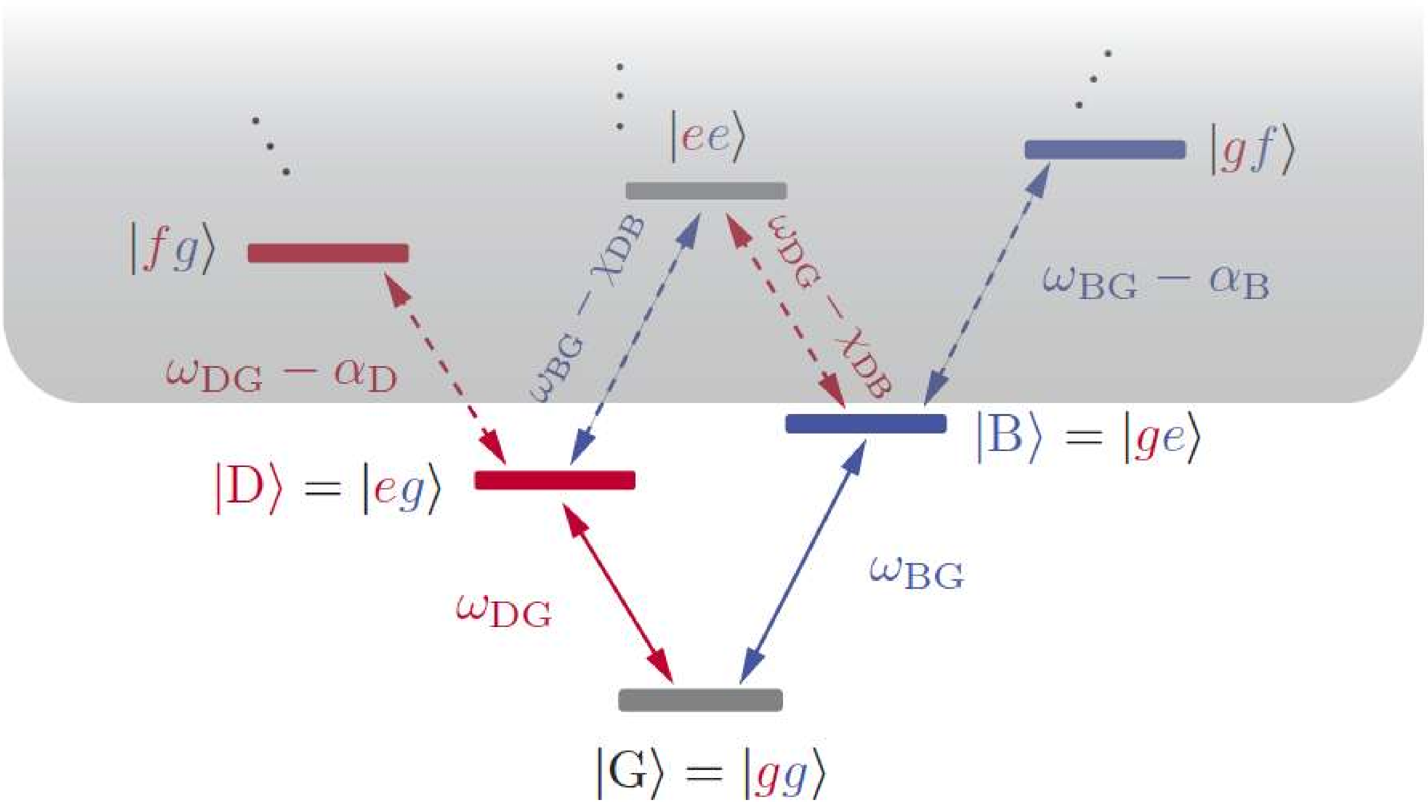


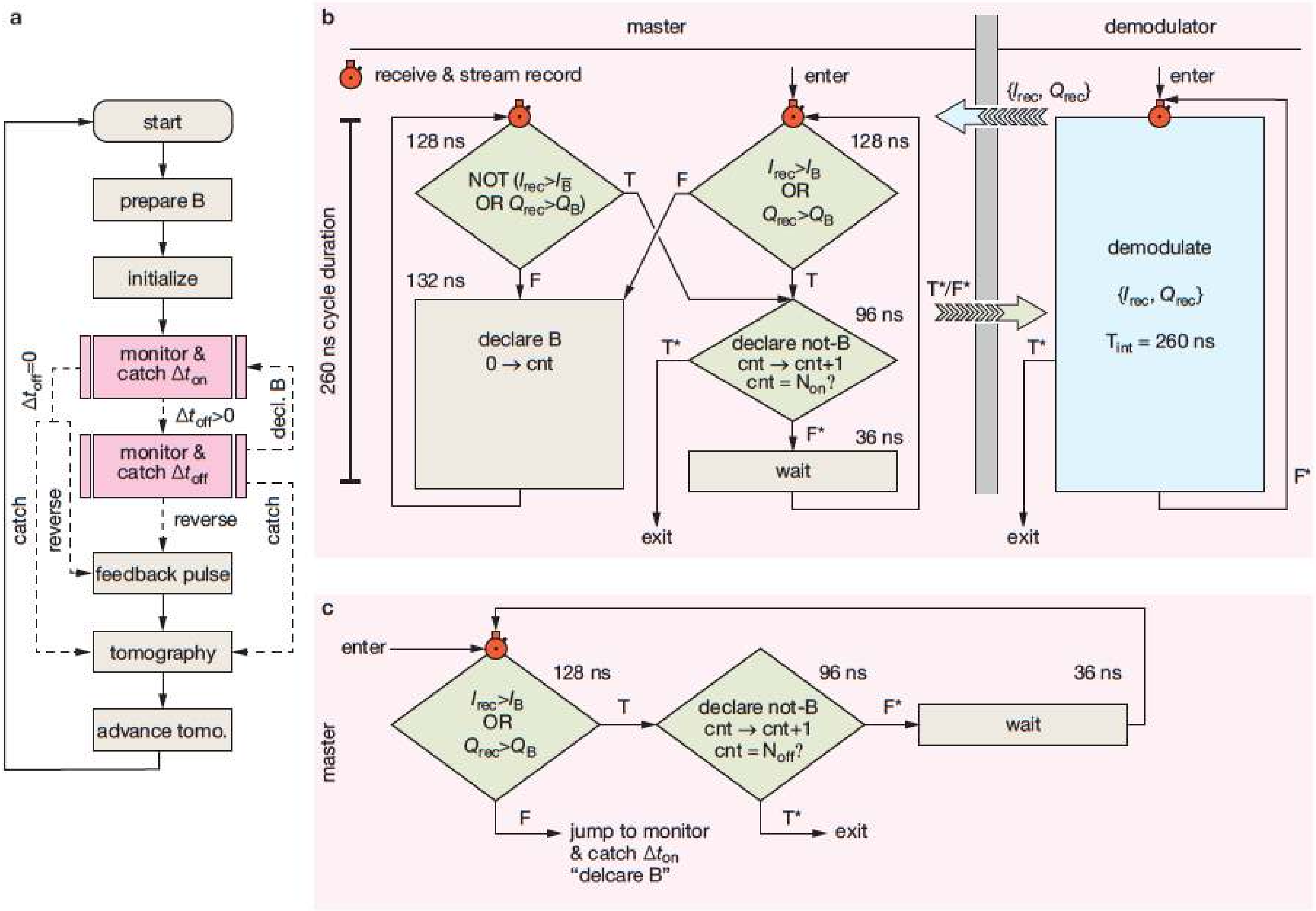
Histogram of dynamics



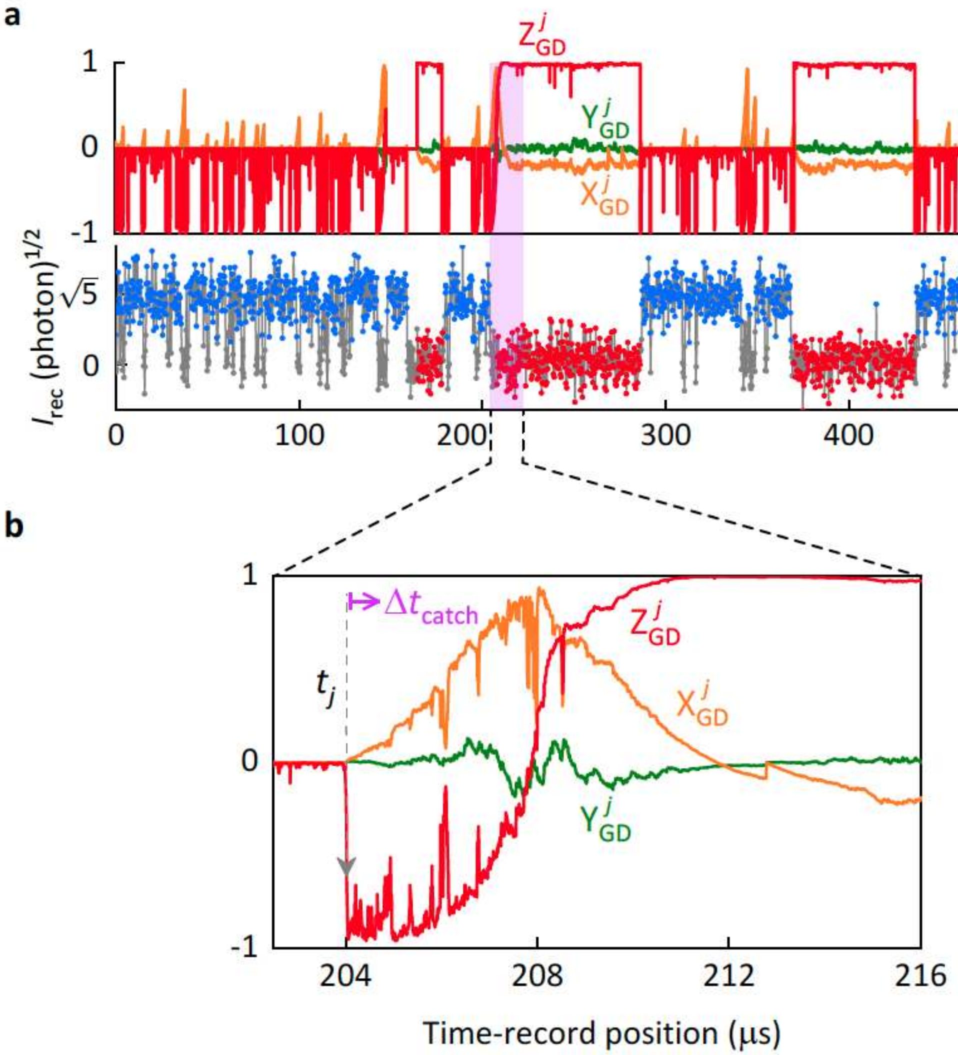
$\Gamma_m^{-1} = 0.02\ \mu s \quad 2\pi\ \Omega_B^{-1} = 1\ \mu s \quad 2\pi\ \Omega_D^{-1} = 60\ \mu s$

Energy-level diagram

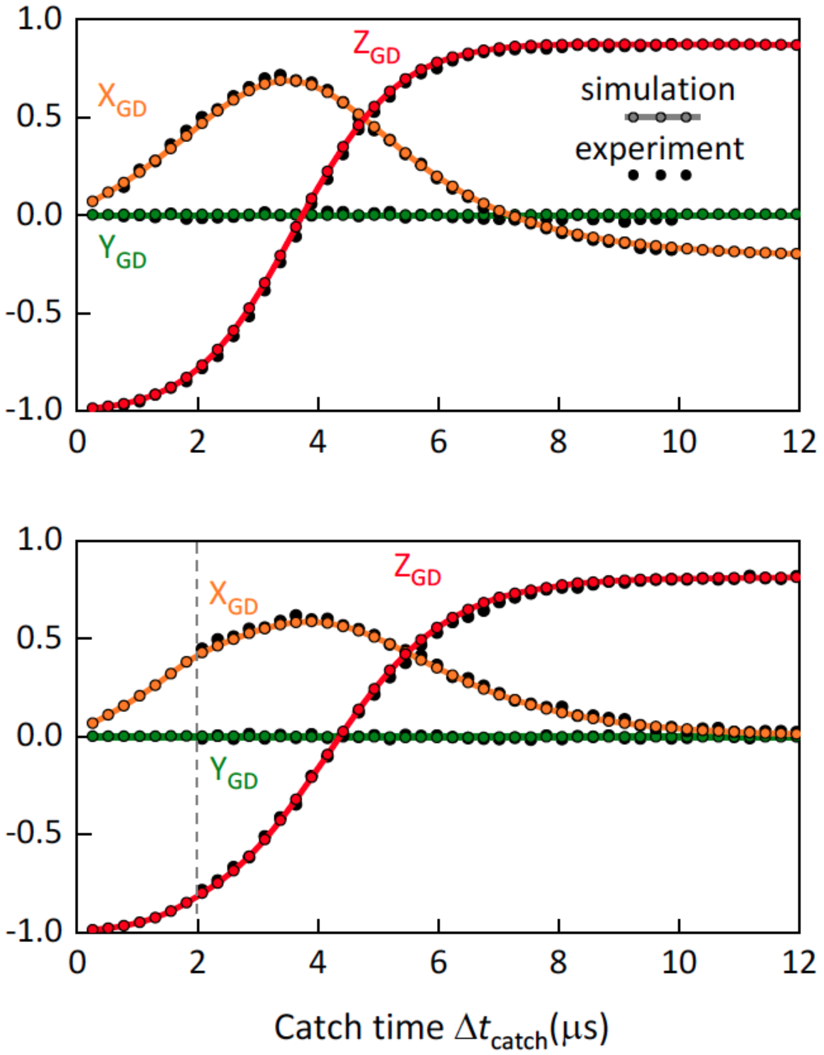




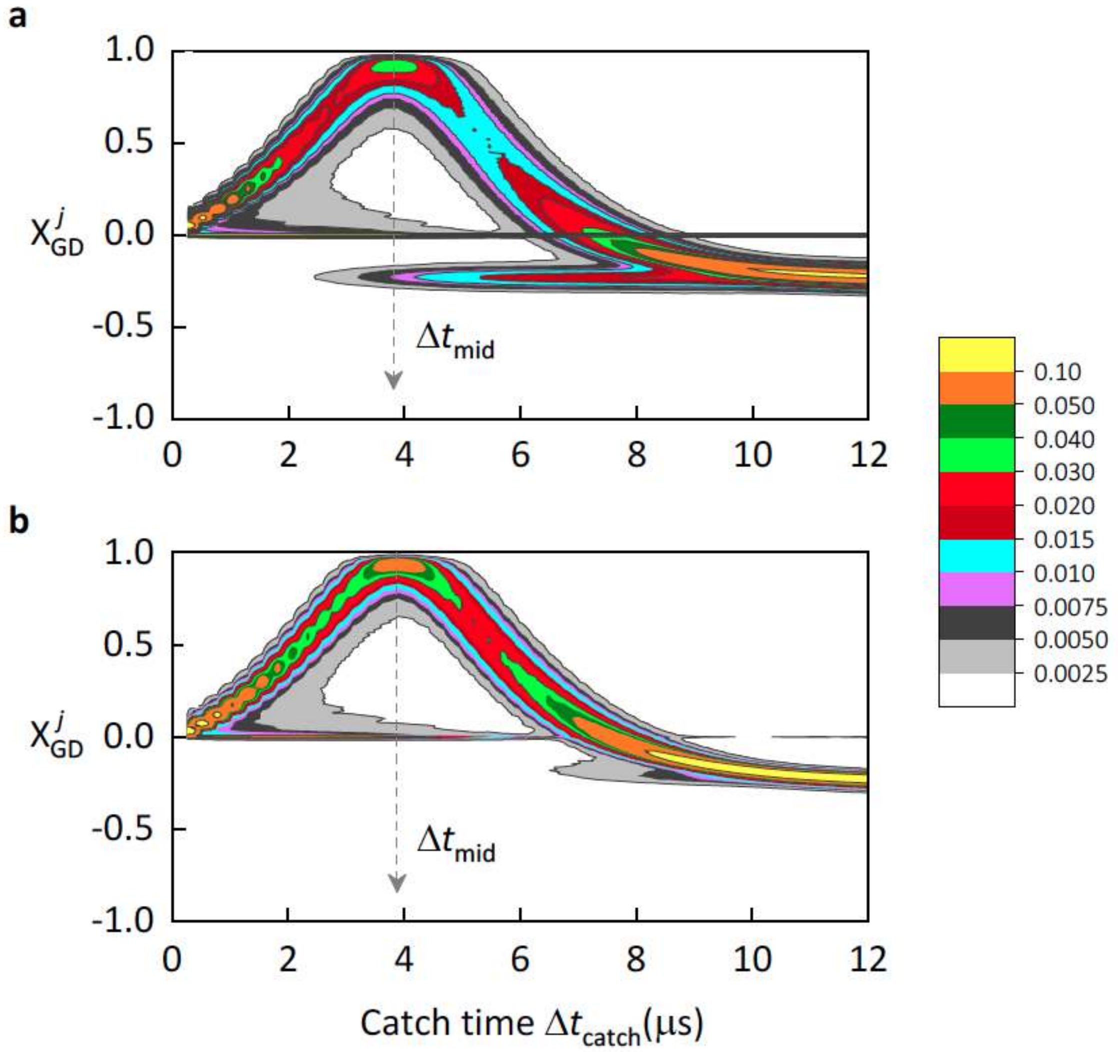
a
start
prepare B
initialize
monitor & catch Δt_{on}
Δt_{off}=0
decl. B
Δt_{off}>0
monitor & catch Δt_{off}
catch
reverse
reverse
catch
feedback pulse
tomography
advance tomo.
b
master
demodulator
receive & stream record
enter
enter
$\{I_{rec}, Q_{rec}\}$
260 ns cycle duration
128 ns
NOT (I_{rec}>$I_{\bar{B}}$ OR Q_{rec}>Q_B)
T
F
I_{rec}>I_B OR Q_{rec}>Q_B
128 ns
132 ns
F
T
declare B
0 → cnt
96 ns
T*
declare not-B
cnt → cnt+1
cnt = N_{on}?
F*
36 ns
wait
exit
T*/F*
demodulate
$\{I_{rec}, Q_{rec}\}$
T_{int} = 260 ns
T*
F*
exit
c
master
enter
128 ns
I_{rec}>I_B OR Q_{rec}>Q_B
T
96 ns
declare not-B
cnt → cnt+1
cnt = N_{off}?
F*
36 ns
wait
F
jump to monitor & catch Δt_{on} "delcare B"
T*
exit



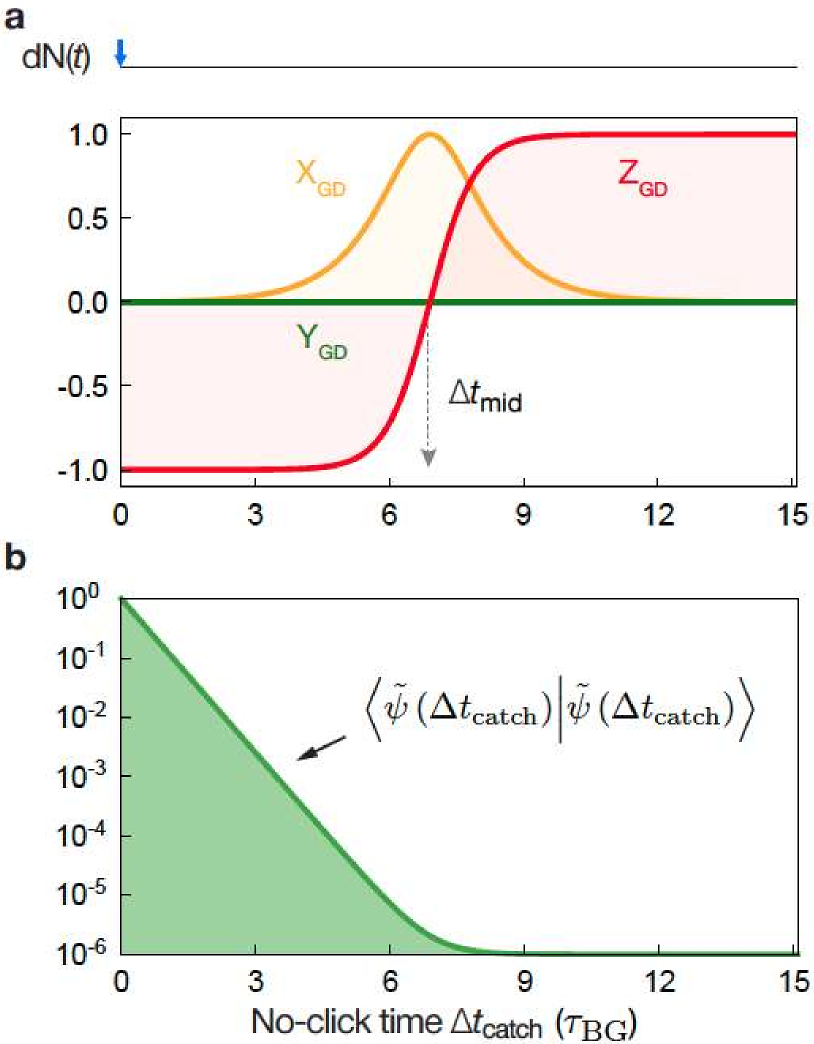
a
Z_{GD}^{j}
Y_{GD}^{j}
X_{GD}^{j}
1
0
-1
I_{rec} (photon)$^{1/2}$
$\sqrt{5}$
0
0
100
200
300
400
500
b
Δt_{catch}
t_j
Z_{GD}^{j}
X_{GD}^{j}
Y_{GD}^{j}
1
0
-1
204
208
212
216
Time-record position (μs)



1.0
0.5
0.0
-0.5
-1.0
0
2
4
6
8
10
12
Z_{GD}
X_{GD}
Y_{GD}
simulation
experiment
1.0
0.5
0.0
-0.5
-1.0
0
2
4
6
8
10
12
Z_{GD}
X_{GD}
Y_{GD}
Catch time Δt_{catch}(μs)



a
b
X_{GD}^{j}
1.0
0.5
0.0
-0.5
-1.0
0
2
4
6
8
10
12
Δt_{mid}
Catch time Δt_{catch}(μs)
0.10
0.050
0.040
0.030
0.020
0.015
0.010
0.0075
0.0050
0.0025

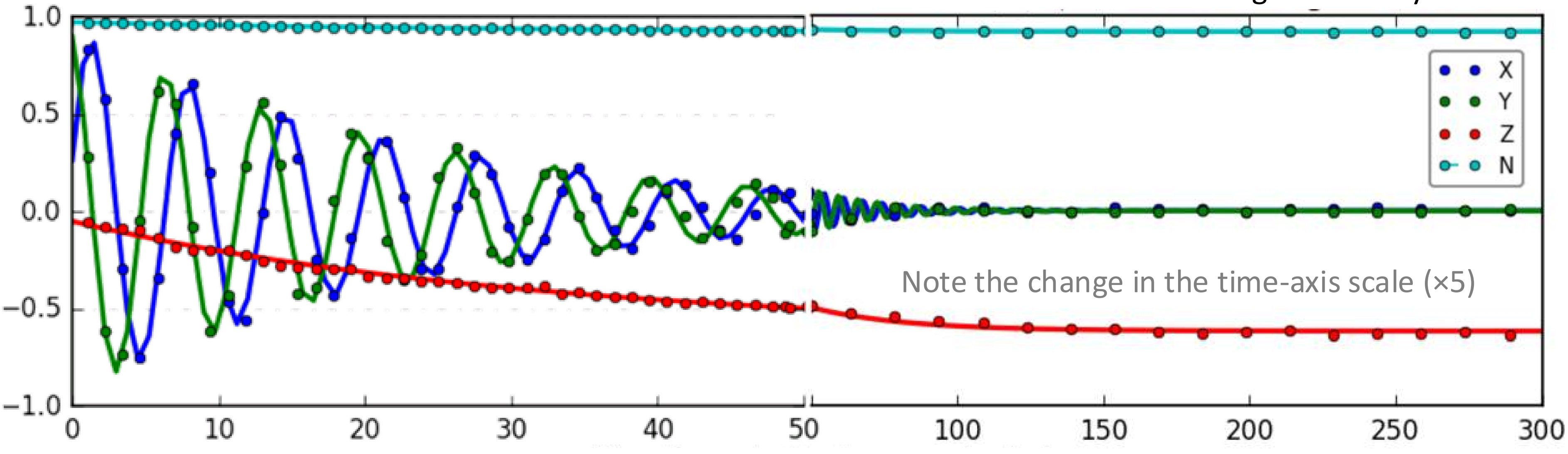


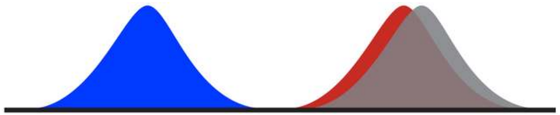
a
dN(t)
1.0
0.5
0.0
-0.5
-1.0
X_{GD}
Z_{GD}
Y_{GD}
Δt_{mid}
0
3
6
9
12
15
b
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\left\langle \tilde{\psi}\left(\Delta t_{\rm catch}\right) \middle| \tilde{\psi}\left(\Delta t_{\rm catch}\right) \right\rangle$
0
3
6
9
12
15
No-click time Δt_{catch} ($\tau_{\rm BG}$)

Coherences: free evolution

X, Y, Z, N partial tomogram

* Detuned generator by 150 KHz



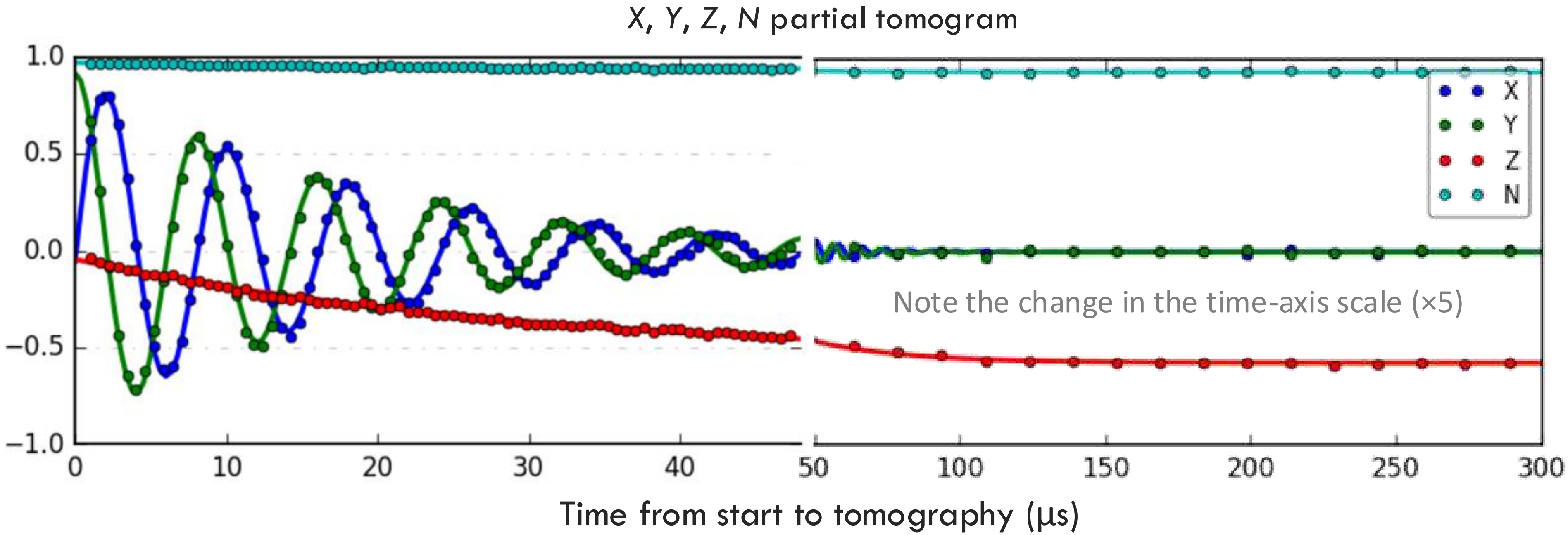


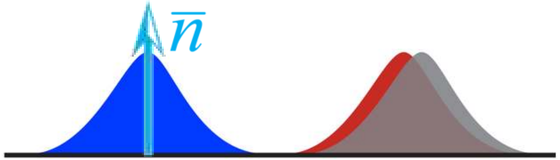
T_2^{GD} ($\bar{n}$ = 0) = 23 ± 2 μs
Δ_{det} ($\bar{n}$ = 0) = 2π × 150 ± 5 KHz

T_1^{DG} ($\bar{n}$ = 0) = 32 ± 1 μs

* different thermal cycle from T_1 vs n-bar measurement

Coherences: $\bar{n} = 7$ photon drive



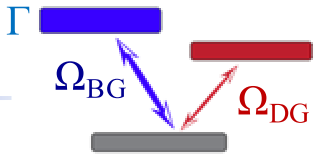


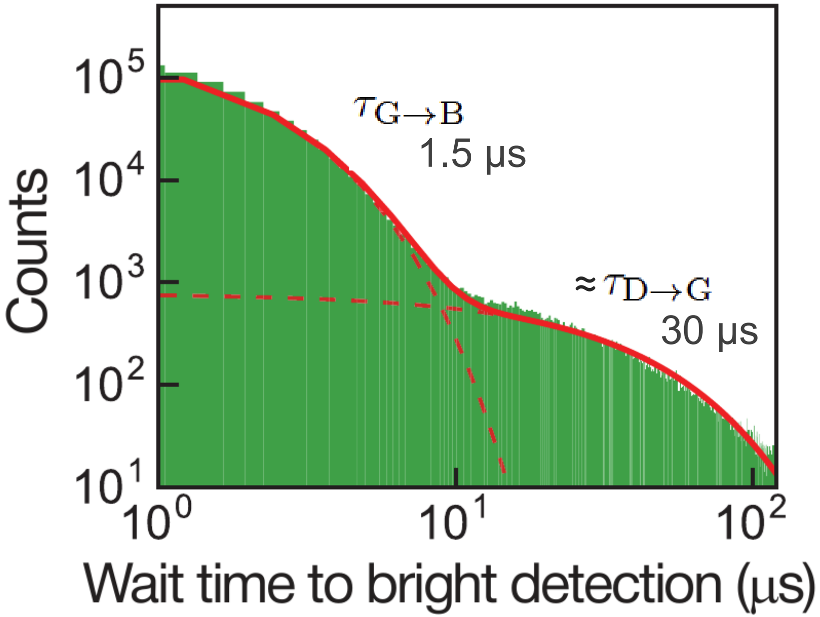
T_2^{GD} ($\bar{n}$ = 7) = 21 ± 2 μs
Δ_{AC} ($\bar{n}$ = 7) = 2π × 125 ± 5 KHz

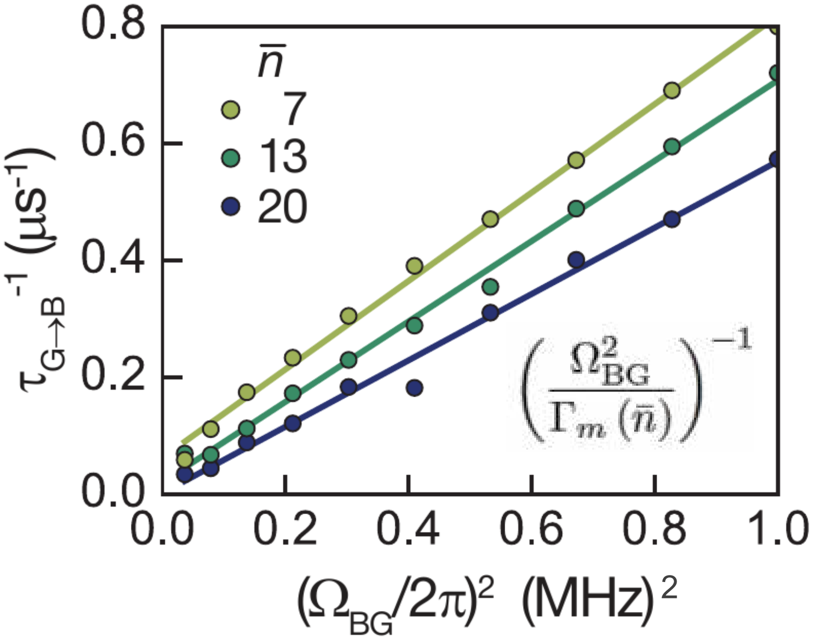
T_1^{DG} ($\bar{n}$ = 7) = 32 ± 1 μs

* different thermal cycle from T_1 vs n-bar measurement

Unconditioned quantum jumps







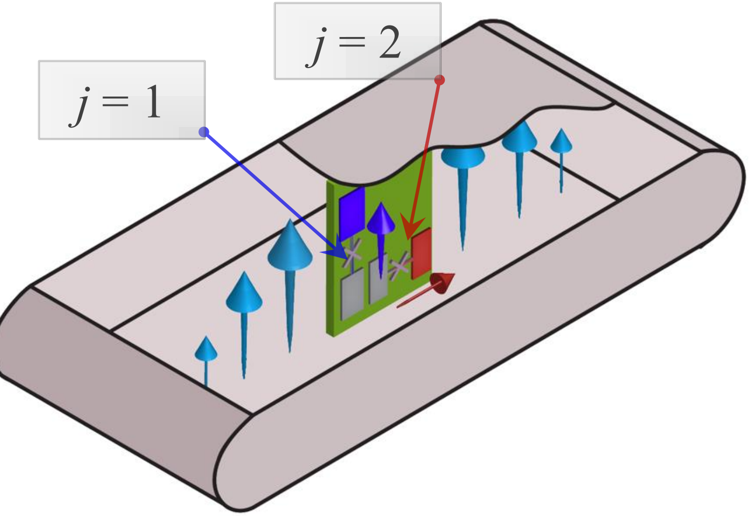
* Note the *log-log* scale

Jumps in a qubit: Slichter *et al.*, New J. Phys. (2016)

Dispersive shift

χ_{BB} χ_{DD}

χ_{BD} χ_{BC} χ_{DC}



Schematic of design

total number of junctions
2

constrained

subject to design

$$\chi_{mn} = \sum_{j=1}^{J} \boxed{\frac{\hbar^2 \omega_m \omega_n}{4E_j}} \boxed{p_{mj} p_{nj}}$$

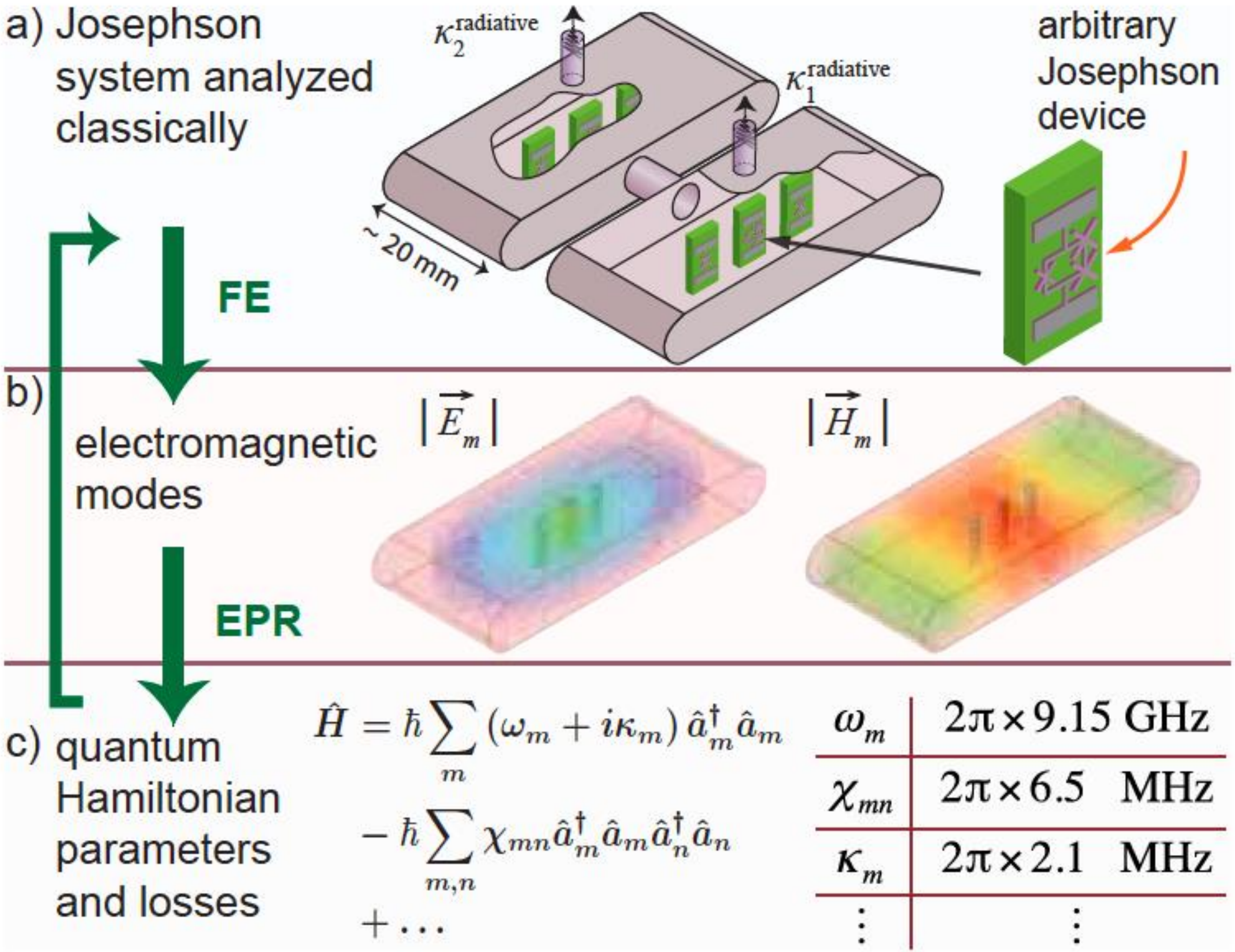
mode label {D,B,C}

junction label {1, 2}

Josephson energy of junction *j*

overlap of energy participation

Nigg *et al.*, PRL (2012) Minev *et al.*, in prep. (2017)


a) Josephson system analyzed classically
$\kappa_2^{\mathrm{radiative}}$
$\kappa_1^{\mathrm{radiative}}$
arbitrary Josephson device
~ 20 mm
FE
b) electromagnetic modes
$|\vec{E}_m|$
$|\vec{H}_m|$
EPR
c) quantum Hamiltonian parameters and losses
$$\hat{H} = \hbar \sum_m (\omega_m + i\kappa_m)\,\hat{a}_m^\dagger \hat{a}_m - \hbar \sum_{m,n} \chi_{mn} \hat{a}_m^\dagger \hat{a}_m \hat{a}_n^\dagger \hat{a}_n + \cdots$$
ω_m | $2\pi \times 9.15$ GHz
χ_{mn} | $2\pi \times 6.5$ MHz
κ_m | $2\pi \times 2.1$ MHz
⋮ | ⋮

Dispersive readout

Issues

Issue	Expression	References
Purcell effect T_1	$T_1^{\mathrm{Purcell}} = \dfrac{C_q}{\mathrm{Re}[Y(\omega_q)]}$	Esteve *et al.*, PRB (1986) Neeley *et al.*, PRB (2008) Reed, Thesis (2013) …
Photon-shot-noise dephasing T	$\Gamma_{\mathrm{th}} = \dfrac{4\chi^2 n_{\mathrm{th}}^{\mathrm{eff}}}{\kappa_{\mathrm{tot}}}(n_{\mathrm{th}}^{\mathrm{eff}}+1)$ large $\kappa_{\mathrm{tot}}/\chi$	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) …

Dispersive readout

Issues

Purcell effect

T_1

Photon-shot-noise dephasing

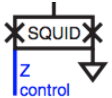
T

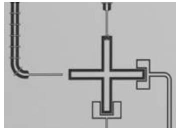
T1 vs. $\bar{n}$

readout’ QND

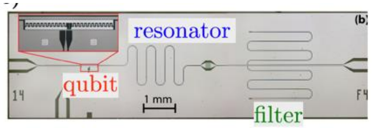
Strategies

Tunable coupler

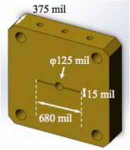




Purcell filter



Thermal attenuator



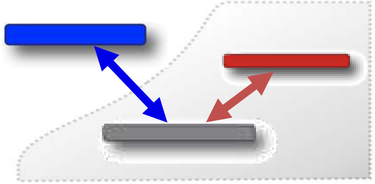
Zhixin

Not dispersive

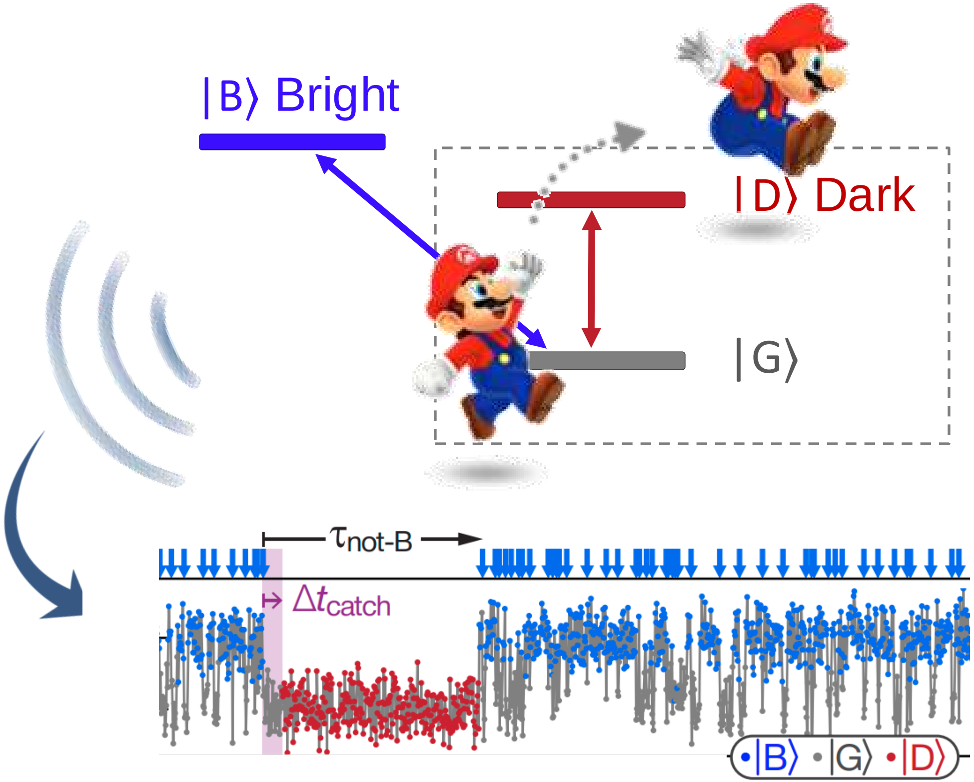
$g_Z \boldsymbol{\sigma}_Z (\mathbf{b} + \mathbf{b}^\dagger)$

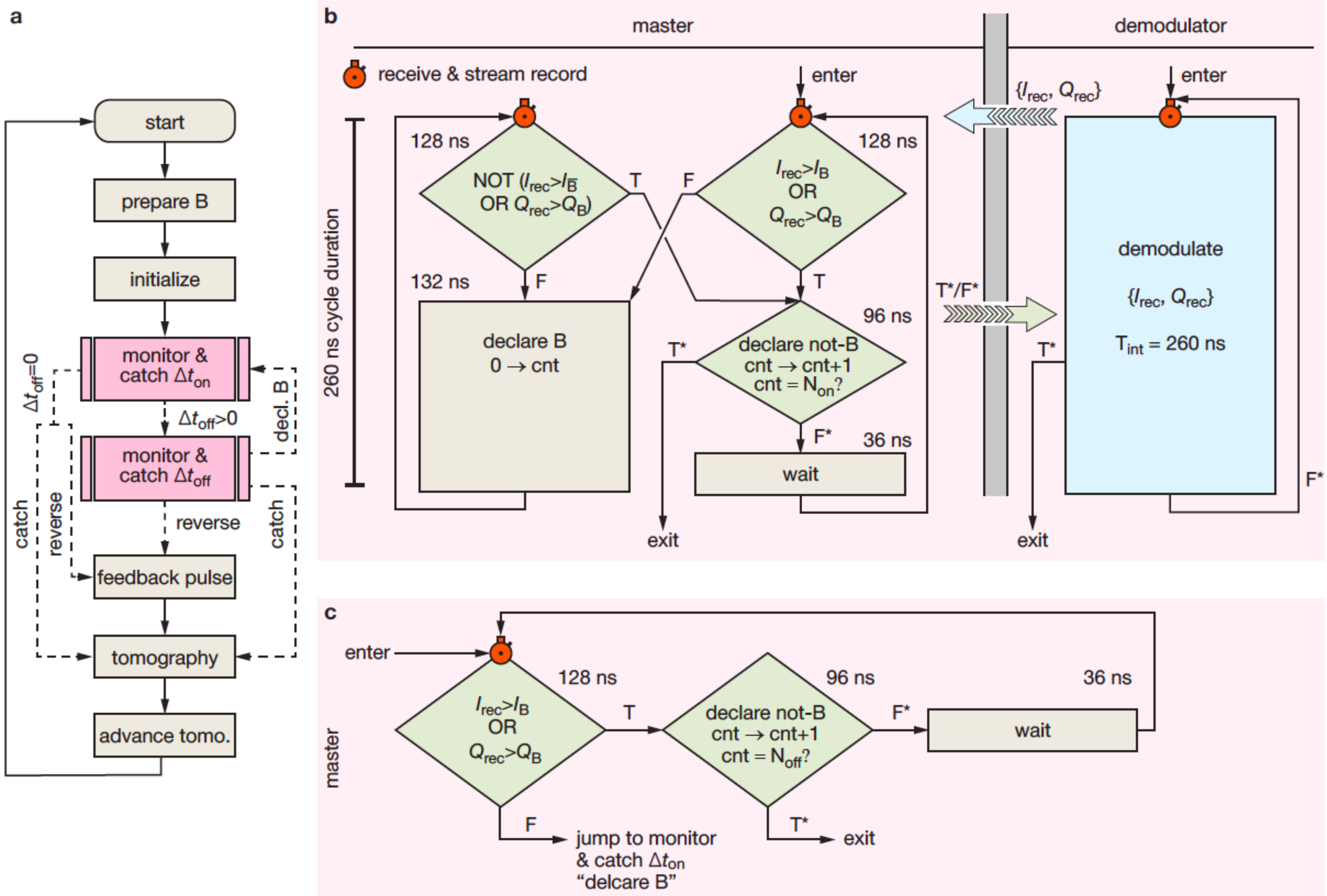
Steven

Protected qubit



Reversing a quantum jump mid-flight





a
start
prepare B
initialize
monitor & catch Δt_on
Δt_off>0
monitor & catch Δt_off
reverse
feedback pulse
tomography
advance tomo.
Δt_off=0
catch
reverse
decl. B
catch
b
master
demodulator
receive & stream record
enter
128 ns
NOT (I_rec>I_B OR Q_rec>Q_B)
T
F
I_rec>I_B OR Q_rec>Q_B
128 ns
132 ns
F
T
declare B
0 → cnt
96 ns
declare not-B
cnt → cnt+1
cnt = N_on?
T*
F*
36 ns
wait
exit
260 ns cycle duration
{I_rec, Q_rec}
T*/F*
enter
demodulate
{I_rec, Q_rec}
T_int = 260 ns
T*
F*
exit
c
master
enter
128 ns
I_rec>I_B OR Q_rec>Q_B
T
96 ns
declare not-B
cnt → cnt+1
cnt = N_off?
F*
36 ns
wait
F
jump to monitor & catch Δt_on "delcare B"
T*
exit

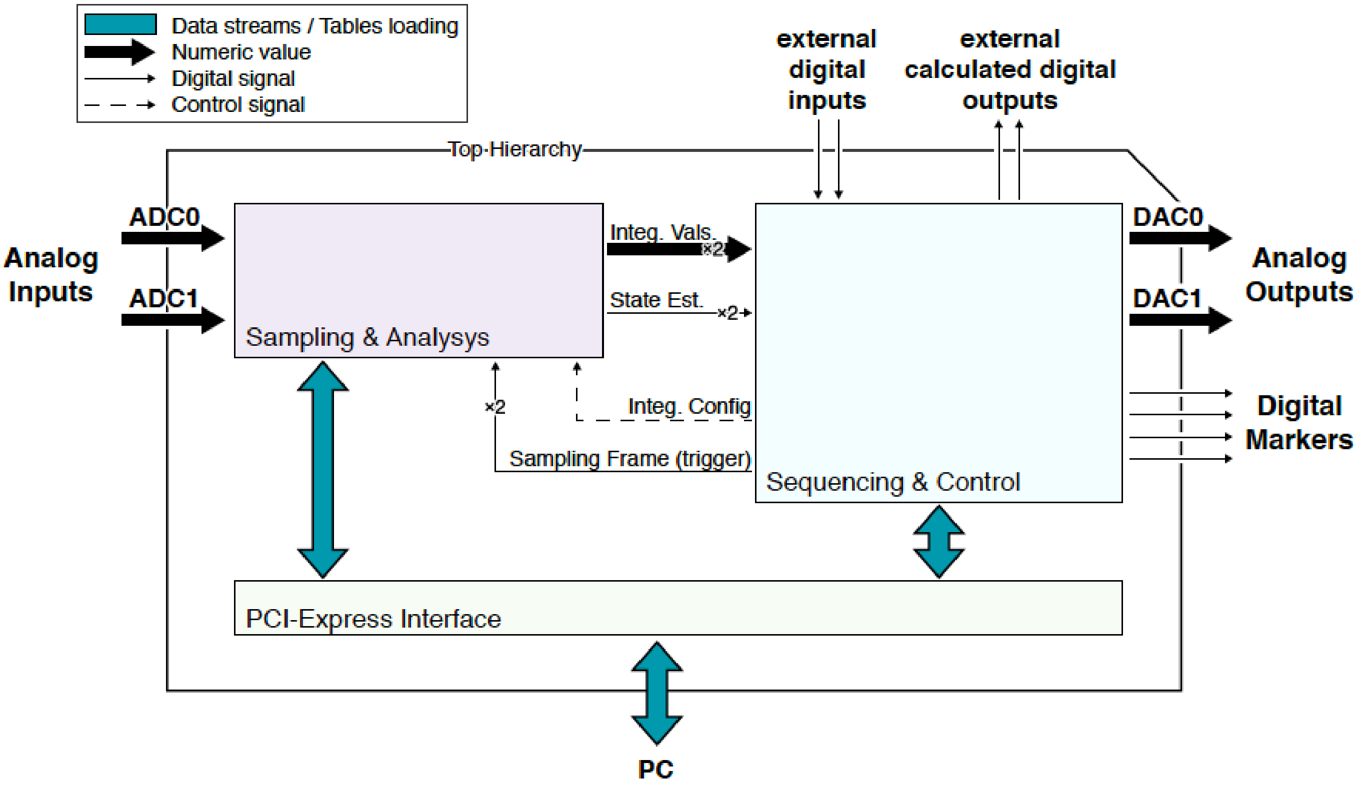


Figure 9: Top Logic Hierarchy. The incoming analog signal is sampled at 1 GHz. The samples are 12 bit deep corresponding to -1V to +1V. Each ADC is controlled independently by the two trigger signals. The integrated IQ values are 16 bit singed integers. A set of integration configurations is loaded before the experiment starts. The sequencer can choose either of them when desired. The sequencing may use these integrated value together with external digital signals to affect the flow. At the end, the main goal is to generate the analog output signals, 16 bit deep values corresponding to -500mV to +500mV.

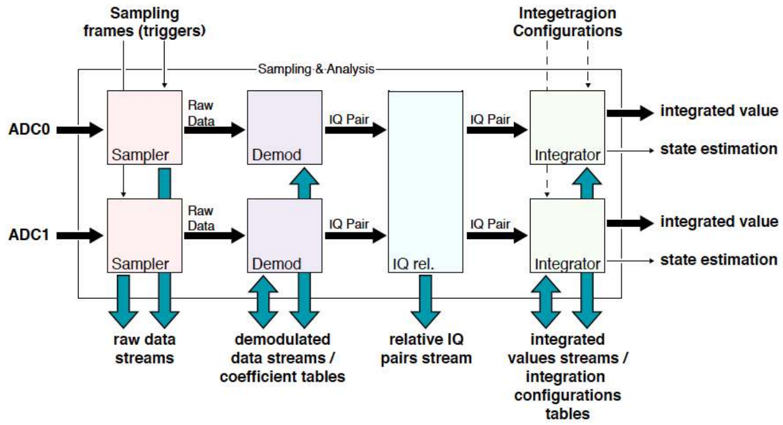


Figure 10: Sampling & Analysis. The raw data is sampled according to the triggers (each channel independently, 12 bit signed integer). It is then demodulated using coefficient table (50 MHz sine and cosine with some amplitude and phase). The results are two IQ-pairs treated as 2.16 signed values. We may then use the first IQ-pair as a reference and rotate the other. The output of the IQ rel. component is also 2.16 signed valued IQ-pairs. It is then integrated according to the desired configuration which includes (for example) the weight for each IQ-pair. All the configurations are stored in tables.

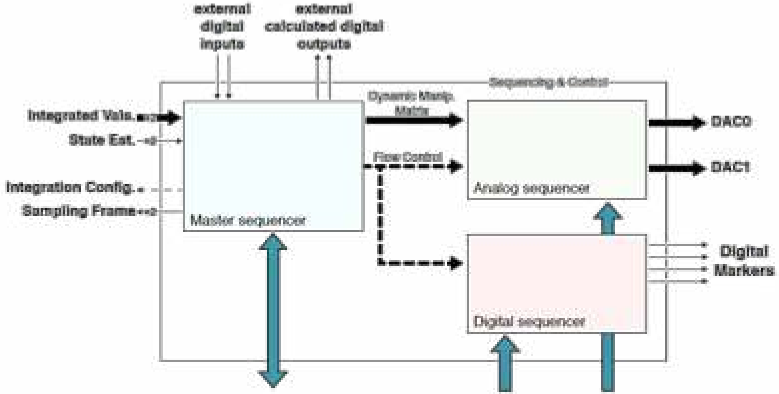
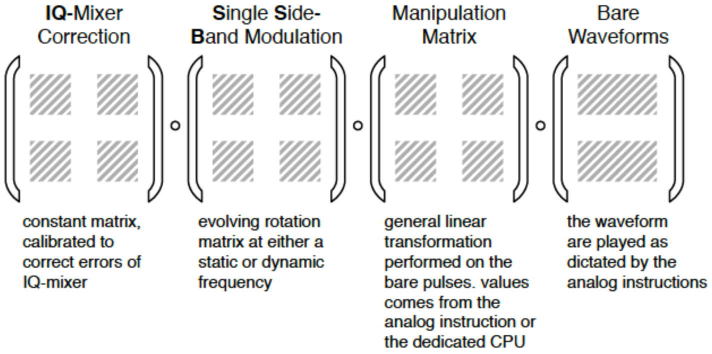


Figure 11: Sequencing & Control. The master sequence produces everything needed to control the flow of the experiment. This includes the internal result which affects branching, manipulation mixers for the analog sequence, updating the integration configuration, triggering data sampling and reporting to the outside world. The job of the analog and digital sequences is much more simple, they go according to their instructions, affected by the flow signals and outputs the results.



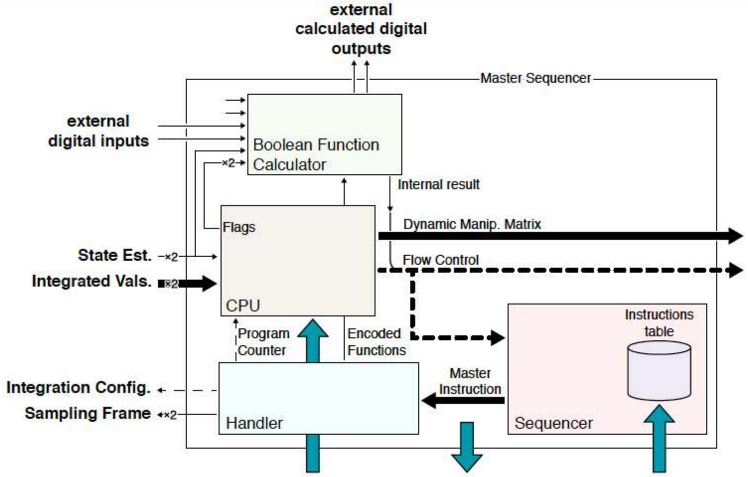
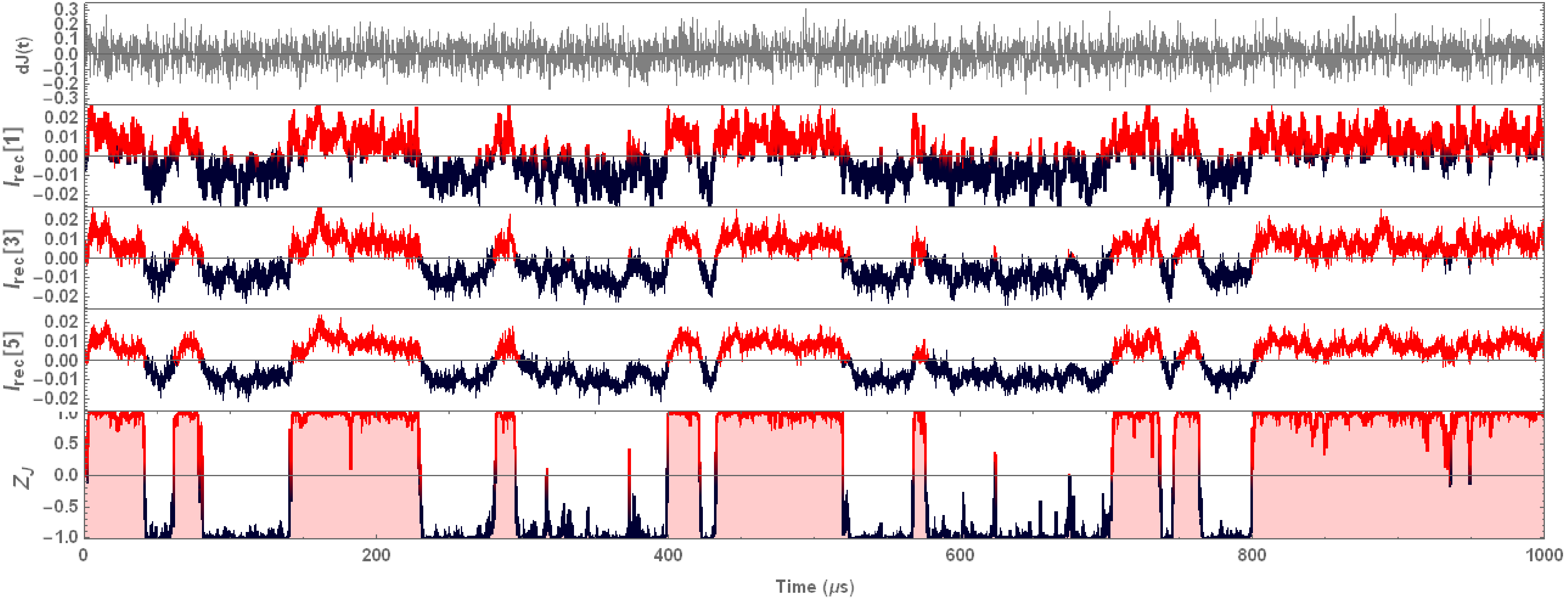
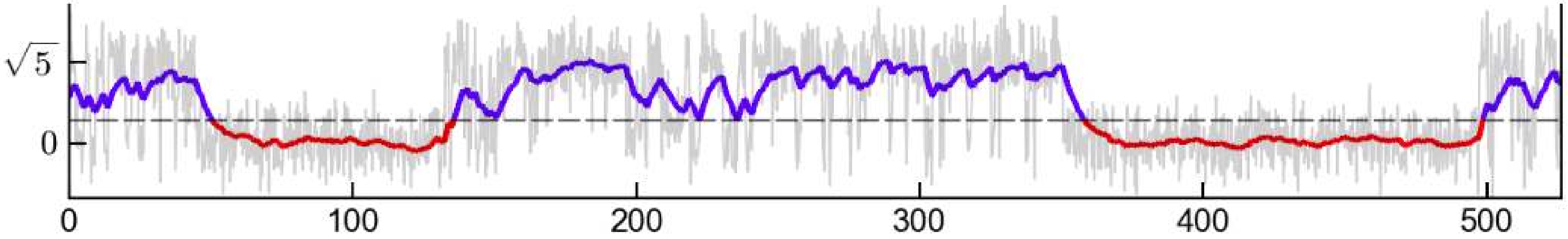
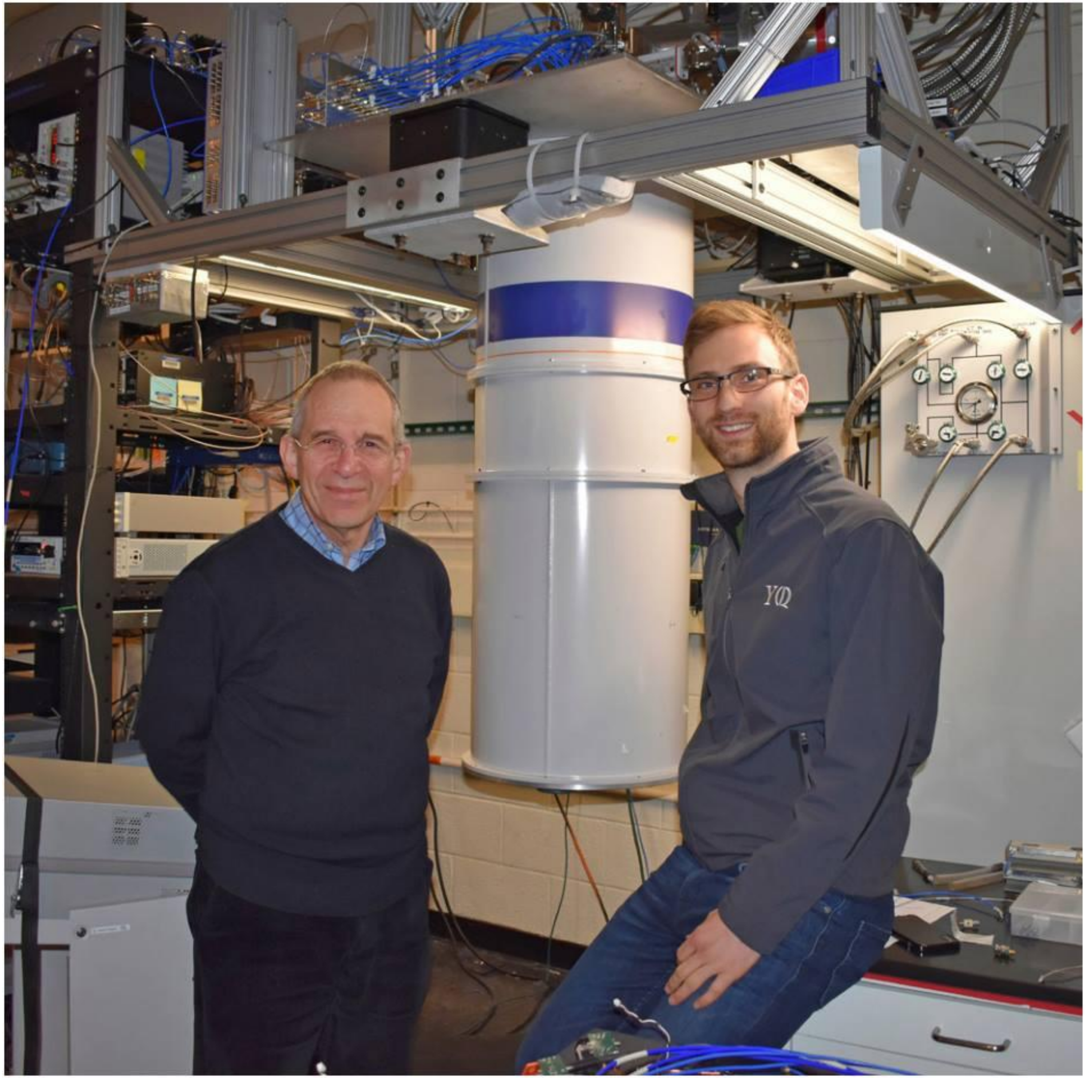


Figure 12: Master Sequencer. The instructions (like any other sequence) are loaded into a table. According to the

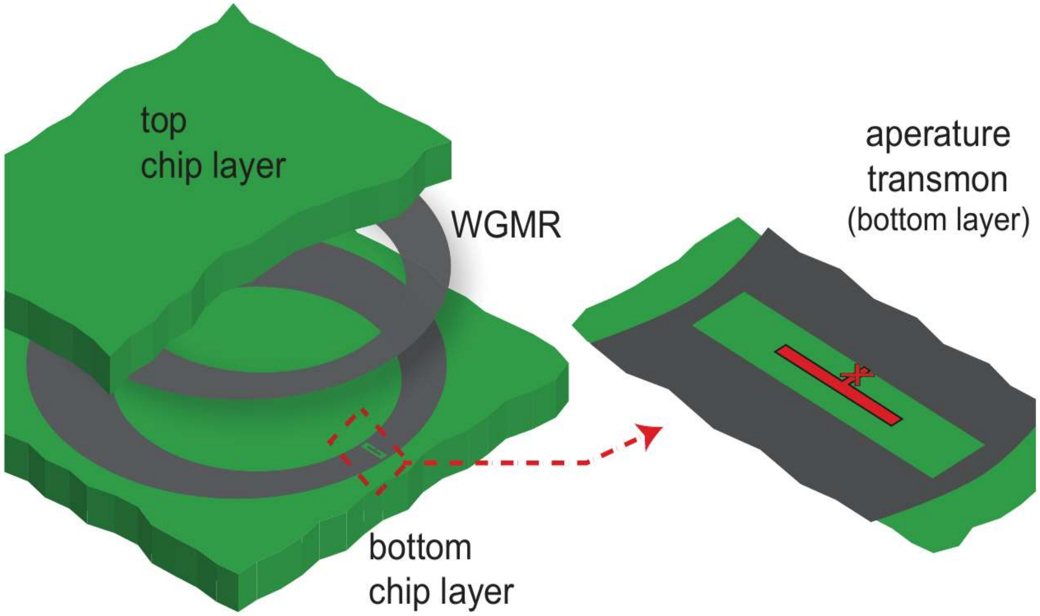

dJ(t)
$I_{rec}[1]$
$I_{rec}[3]$
$I_{rec}[5]$
Z_J
Time (μs)



$\sqrt{5}$
0
0
100
200
300
400
500

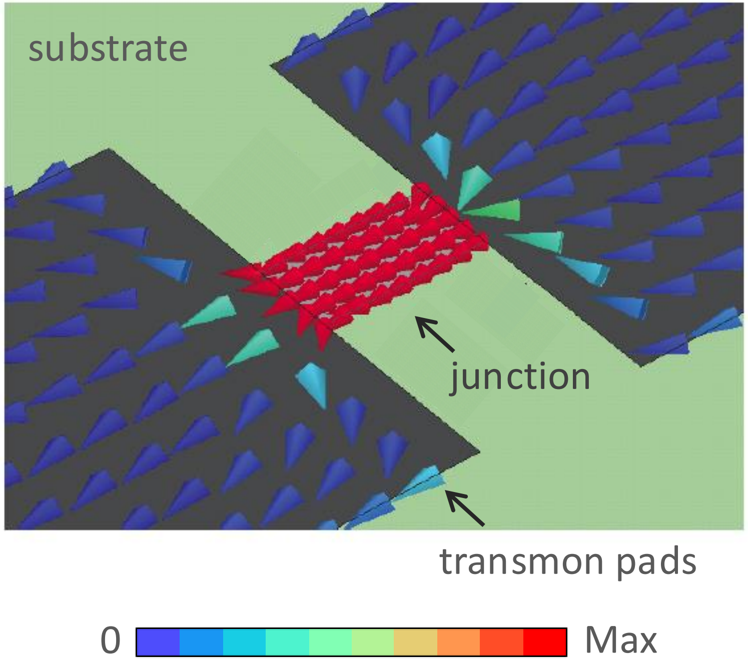

YQ

Multilayer (2.5D) cQED



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

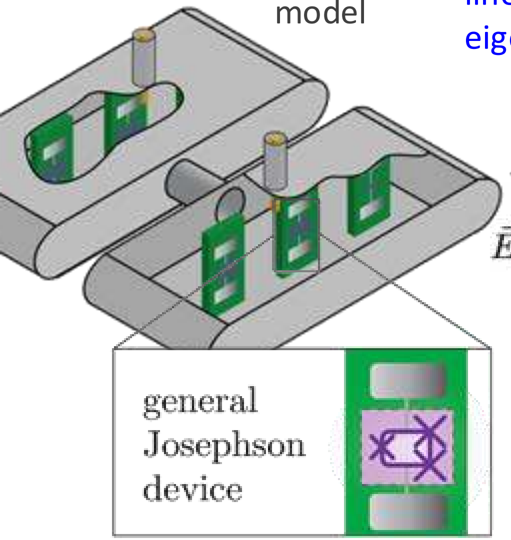
Circuit quantization 2.0 (EPR approach)

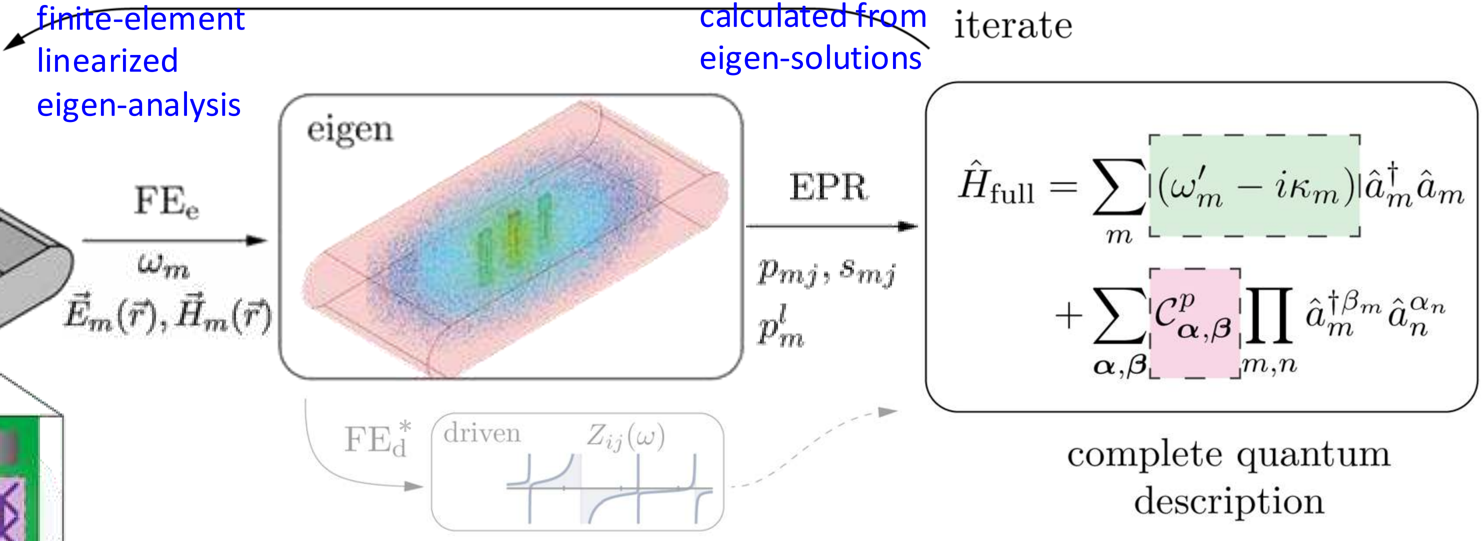


Current-density magnitude

Minev *et al.*, in prep. (2018)

Overview of energy approach





Energy-participation ratio (EPR) approach:
- describes any order and strength non-linearity
- describes arbitrary (composite) non-linear inductive devices
- first-principle derivation
- <u>zero</u> 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), …

To catch and reverse a quantum jump mid-flight

Nature 570, 200 (2019)
(Thesis: arXiv:1902.10355)




Nintendo Corp.

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Quantum computing fundamental & applied

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nature
International journal of science

Letter | Published: 03 June 2019

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