ROMA TRE
UNIVERSITÀ DEGLI STUDI

STORMY TUNE

HADES
HAZARD DETECTION WITH QUANTUM SENSORS

Looking with quantum light

quantum multiparameter metrology in photonics

Marco Barbieri
NEw Quantum Optics group
Dipartimento di Scienze — Università degli Studi Roma Tre

QUANTUM FLAGSHIP

European Commission

Communication

Simulation

Sensing/Metrology

Computation

Enabling Science

QUANTUM FLAGSHIP

European Commission

1. Communication

0 – 5 years

A Core technology of quantum repeaters

B Secure point-to-point quantum links

5 – 10 years

C Quantum networks between distant cities

D Quantum credit cards

> 10 years

E Quantum repeaters with cryptography and eavesdropping detection

F Secure Europe-wide internet merging quantum and classical communication

2. Simulators

0 – 5 years

A Simulator of motion of electrons in materials

B New algorithms for quantum simulators and networks

5 – 10 years

C Development and design of new complex materials

D Versatile simulator of quantum magnetism and electricity

> 10 years

E Simulators of quantum dynamics and chemical reaction mechanisms to support drug design

3. Sensors

0 – 5 years

A Quantum sensors for niche applications (incl. gravity and magnetic sensors for health care, geosurvey and security)

B More precise atomic clocks for synchronisation of future smart networks, incl. energy grids

5 – 10 years

C Quantum sensors for larger volume applications including automotive, construction

D Handheld quantum navigation devices

> 10 years

E Gravity imaging devices based on gravity sensors

F Integrate quantum sensors with consumer applications including mobile devices

4. Computers

0 – 5 years

A Operation of a logical qubit protected by error correction or topologically

B New algorithms for quantum computers

C Small quantum processor executing technologically relevant algorithms

5 – 10 years

D Solving chemistry and materials science problems with special purpose quantum computer > 100 physical qubit

> 10 years

E Integration of quantum circuit and cryogenic classical control hardware

F General purpose quantum computers exceed computational power of classical computers

Quantum Metrology

Quantum Metrology

Quantum Metrology

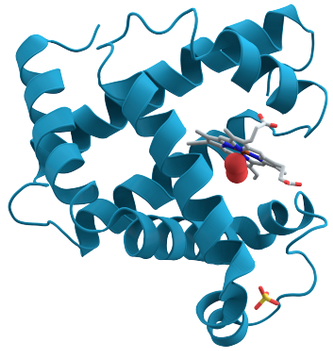
this is a photon

Quantum Metrology

this is a photon = $ this is a resource

Quantum Metrology

a photon is a resource



sample

Quantum Metrology

a photon is a resource

probing

sample

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a photon is a resource

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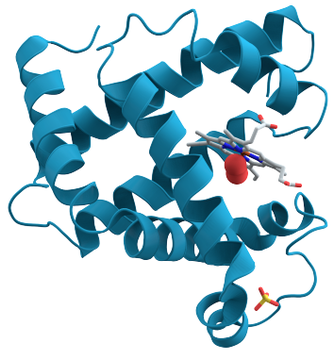

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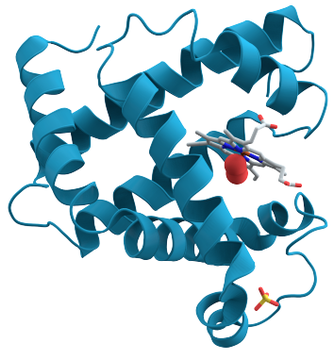

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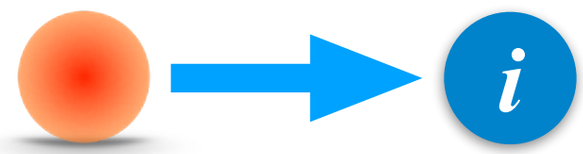
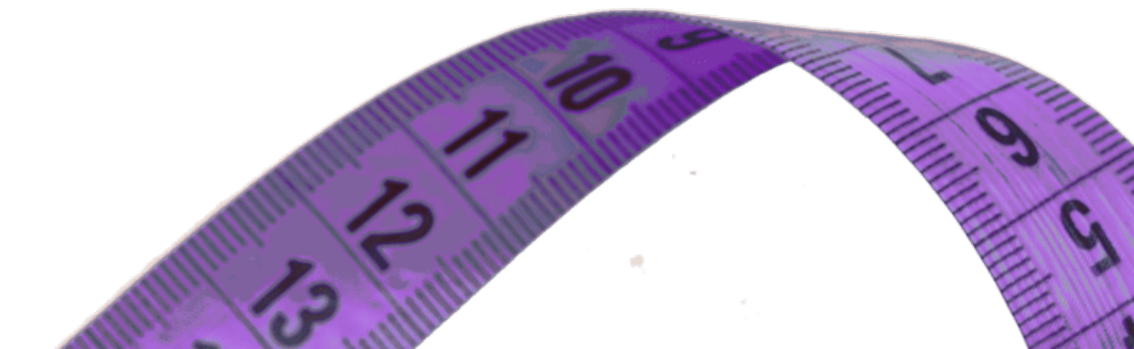
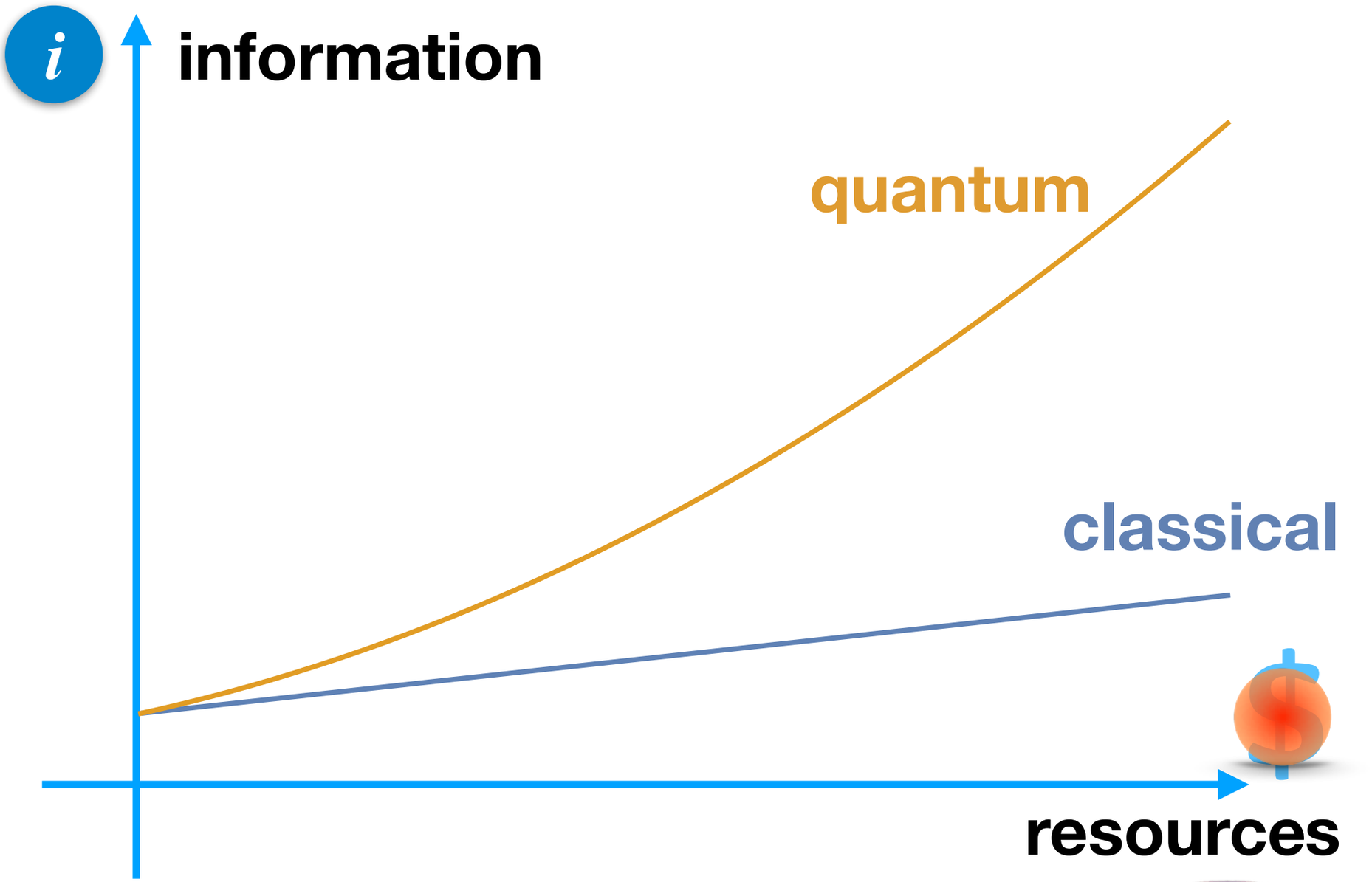


extraction of information



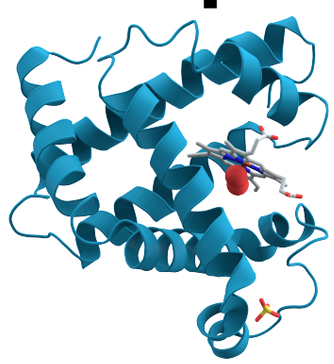
Quantum Metrology



Quantum Metrology

source

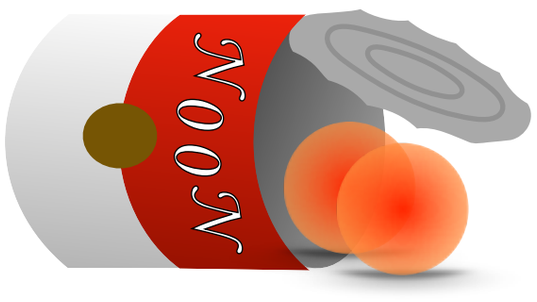
sample



detectors

Quantum Metrology

source



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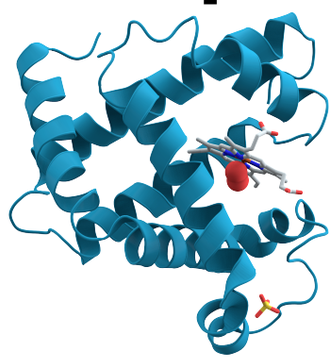

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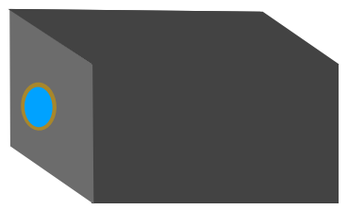
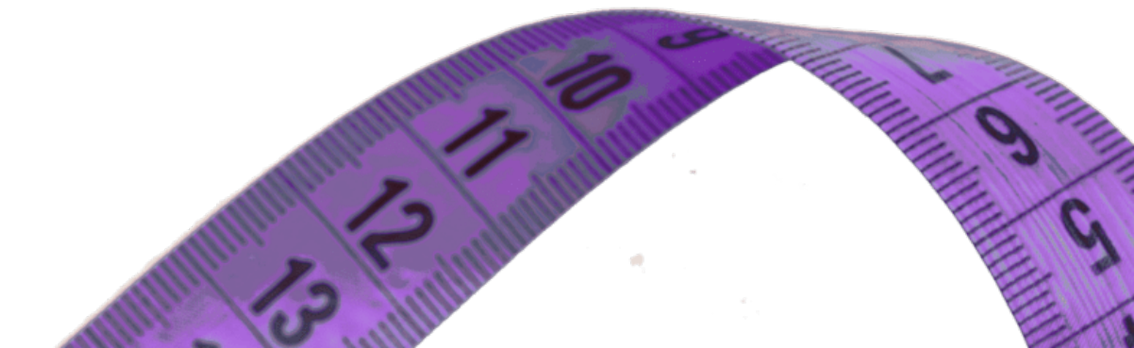


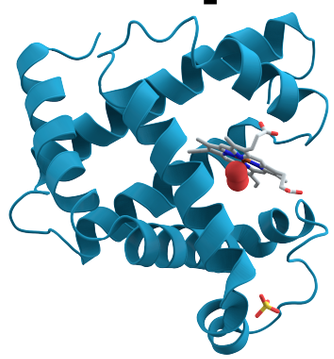
i **initialisation**



Quantum Metrology

source

sample



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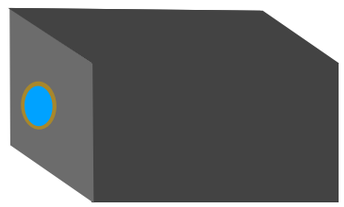
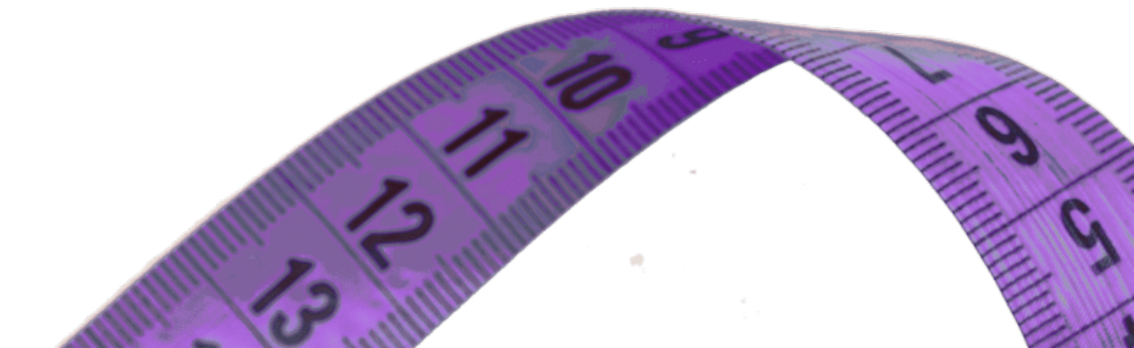


initialisation

modulation



Quantum Metrology

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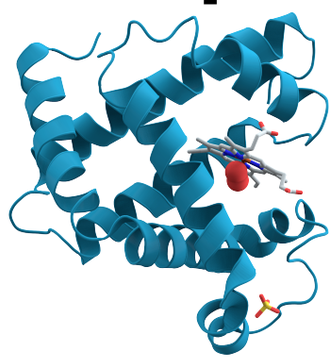

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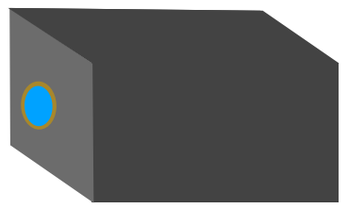
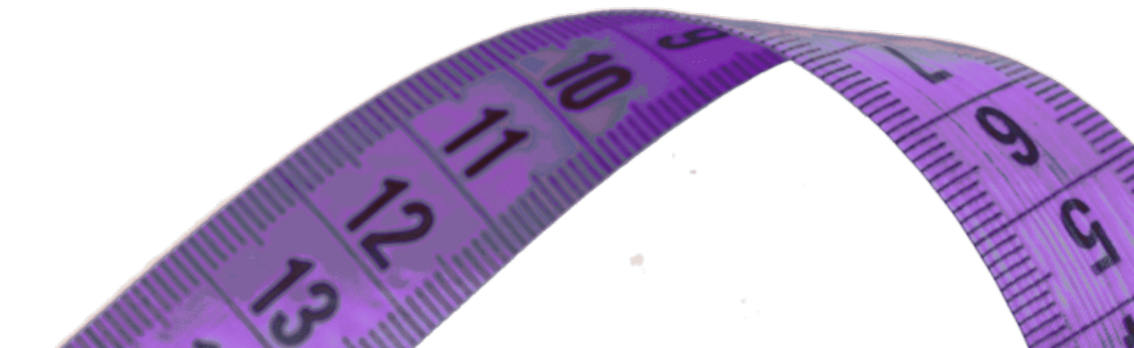


initialisation **modulation** **extraction**



Quantum Metrology

source

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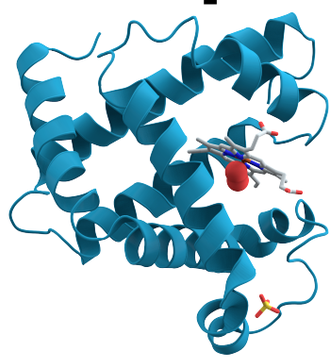

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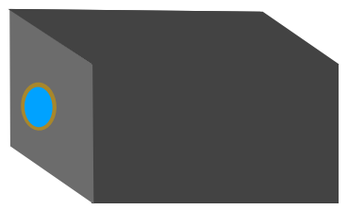
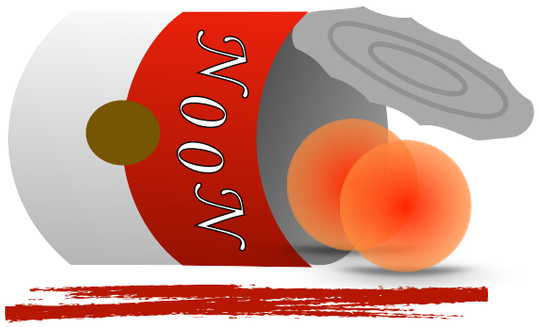


initialisation | **modulation** | **extraction**

quantum mechanics

Quantum Metrology

source



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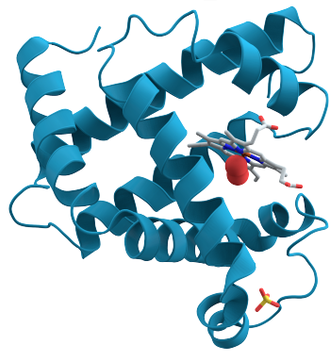

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quantum mechanics

Quantum Metrology

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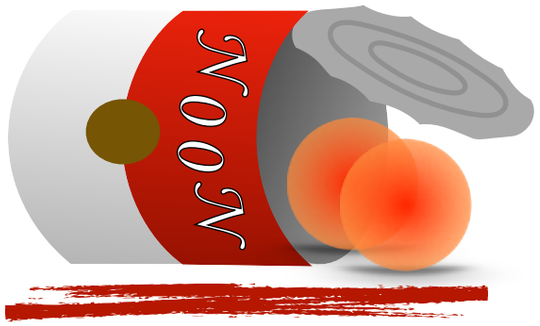

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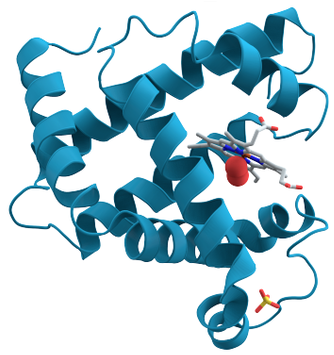

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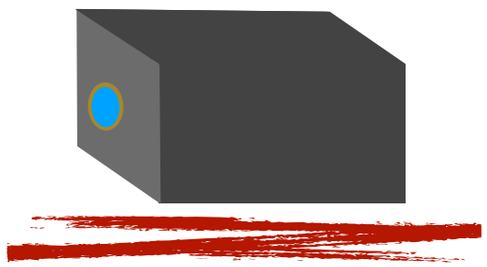

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quantum mechanics

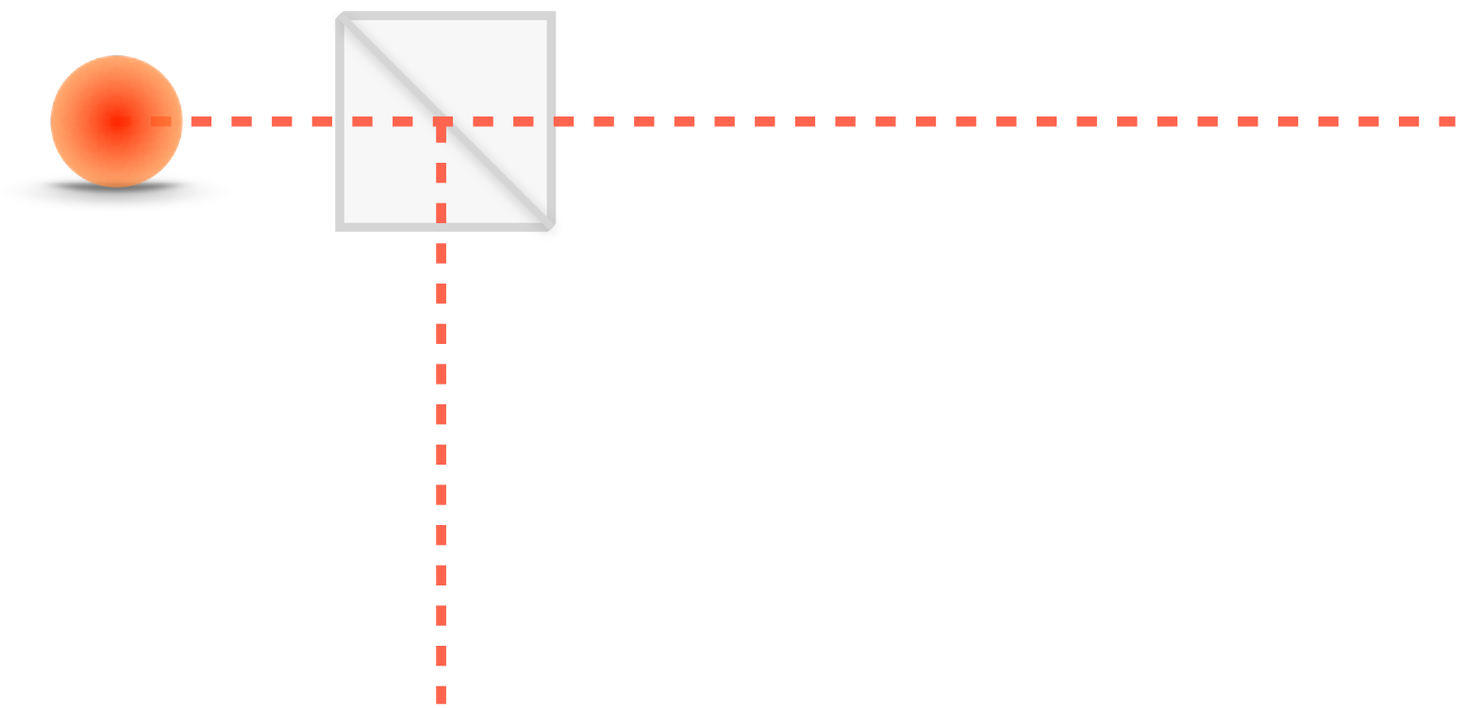
Quantum Phase Estimation

Quantum Phase Estimation

beam splitter

Quantum Phase Estimation

beam splitter



Quantum Phase Estimation

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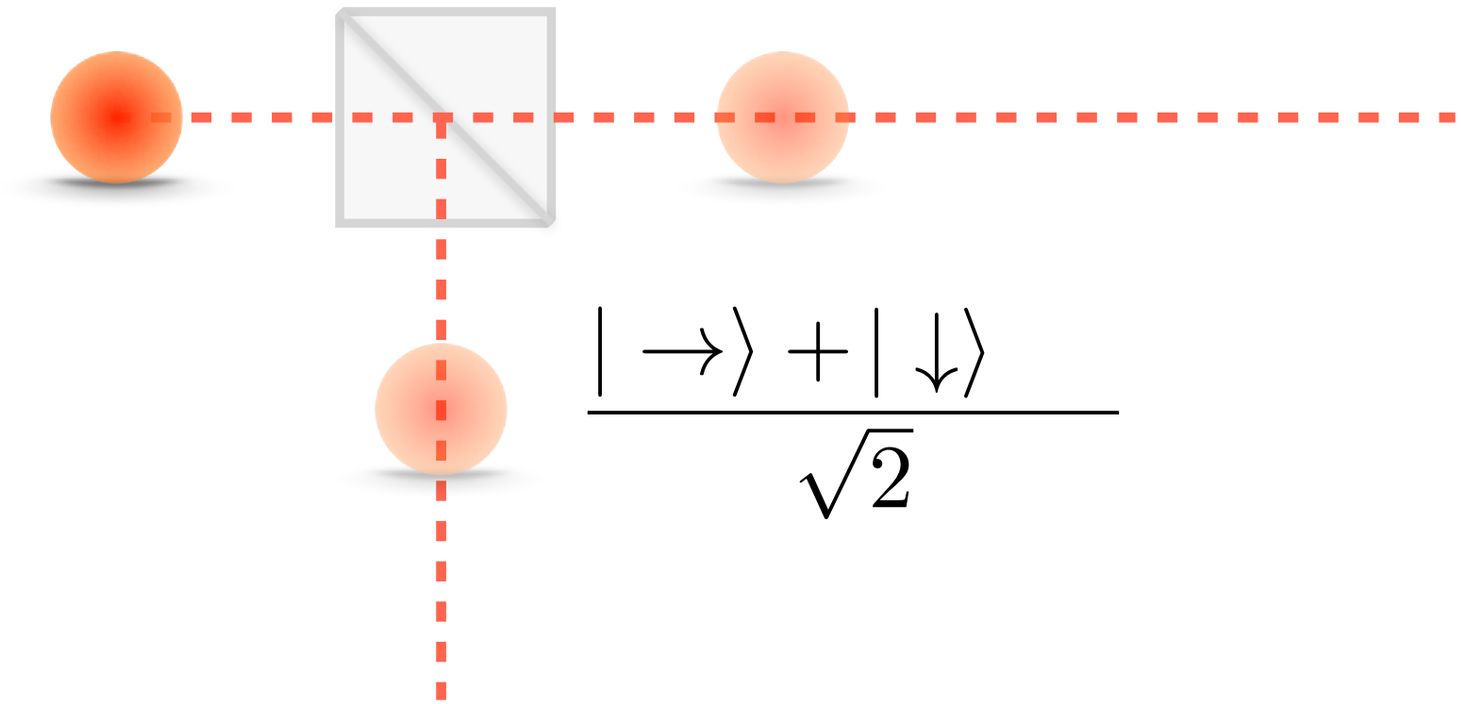
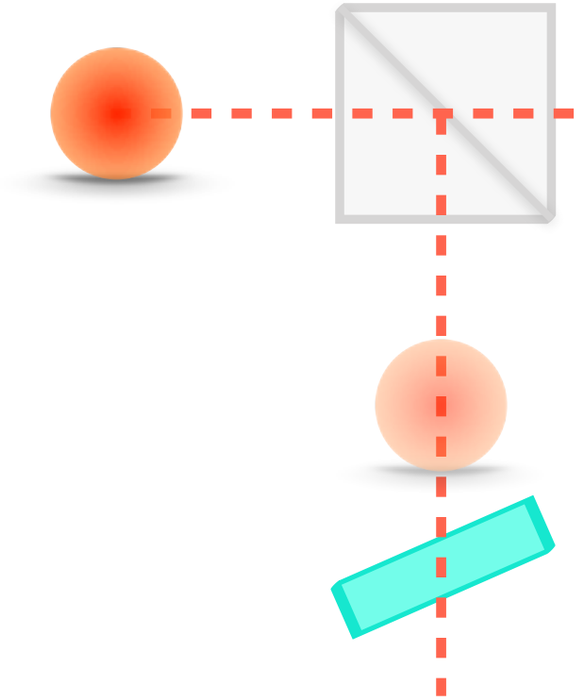


$$\frac{|\rightarrow\rangle + |\downarrow\rangle}{\sqrt{2}}$$

Quantum Phase Estimation

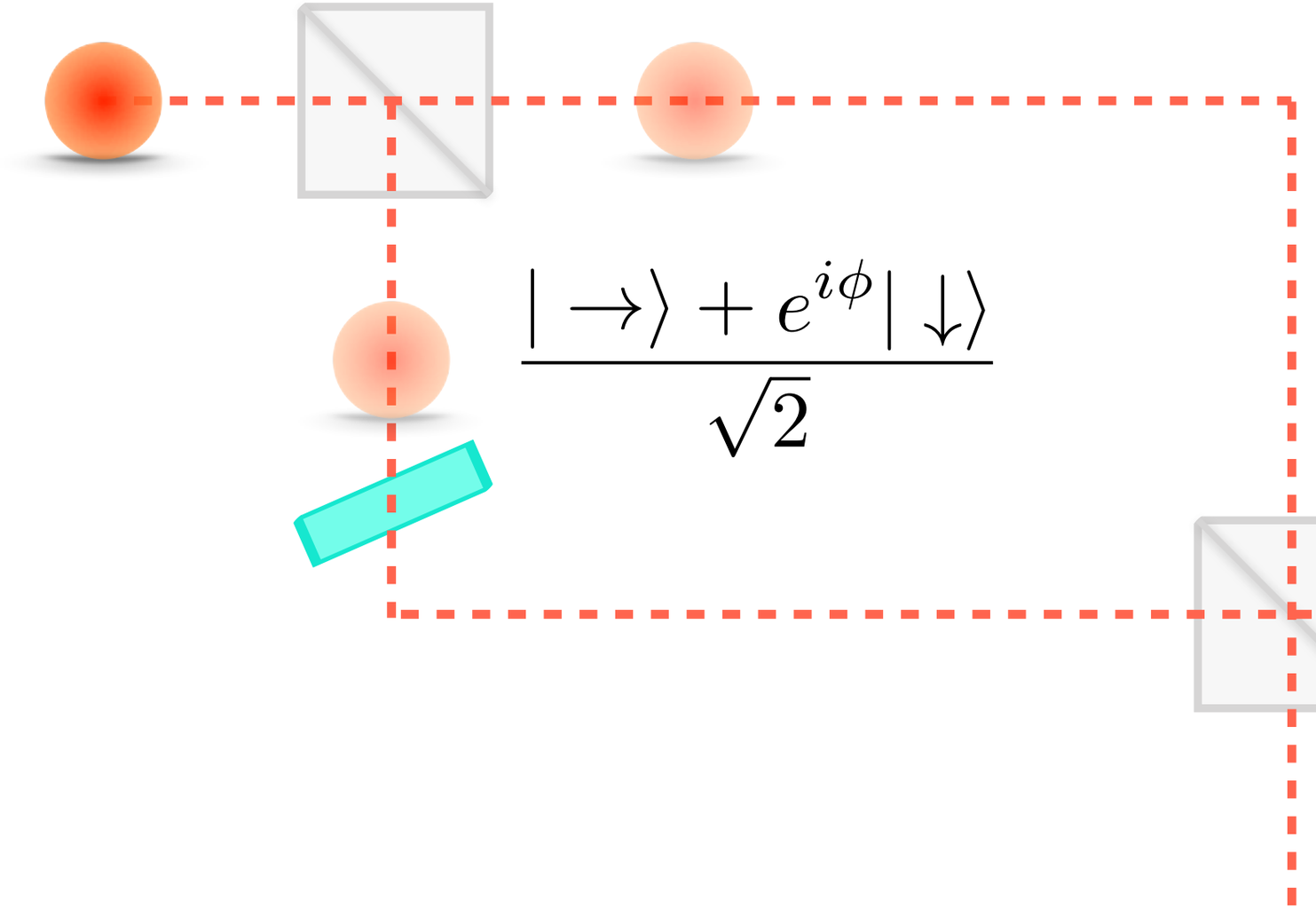
beam splitter



$$\frac{|\rightarrow\rangle + e^{i\phi}|\downarrow\rangle}{\sqrt{2}}$$

Quantum Phase Estimation

beam splitter



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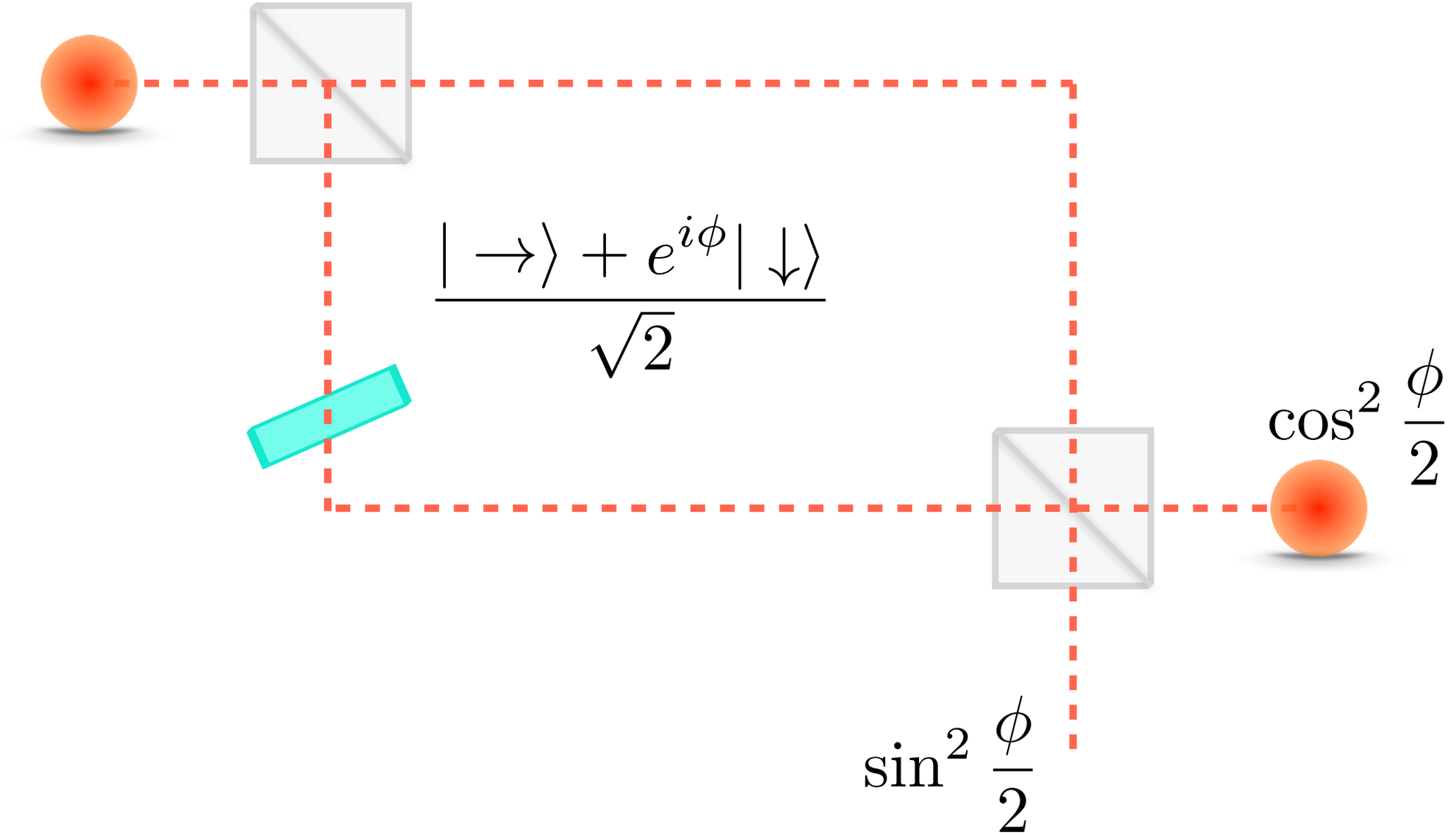

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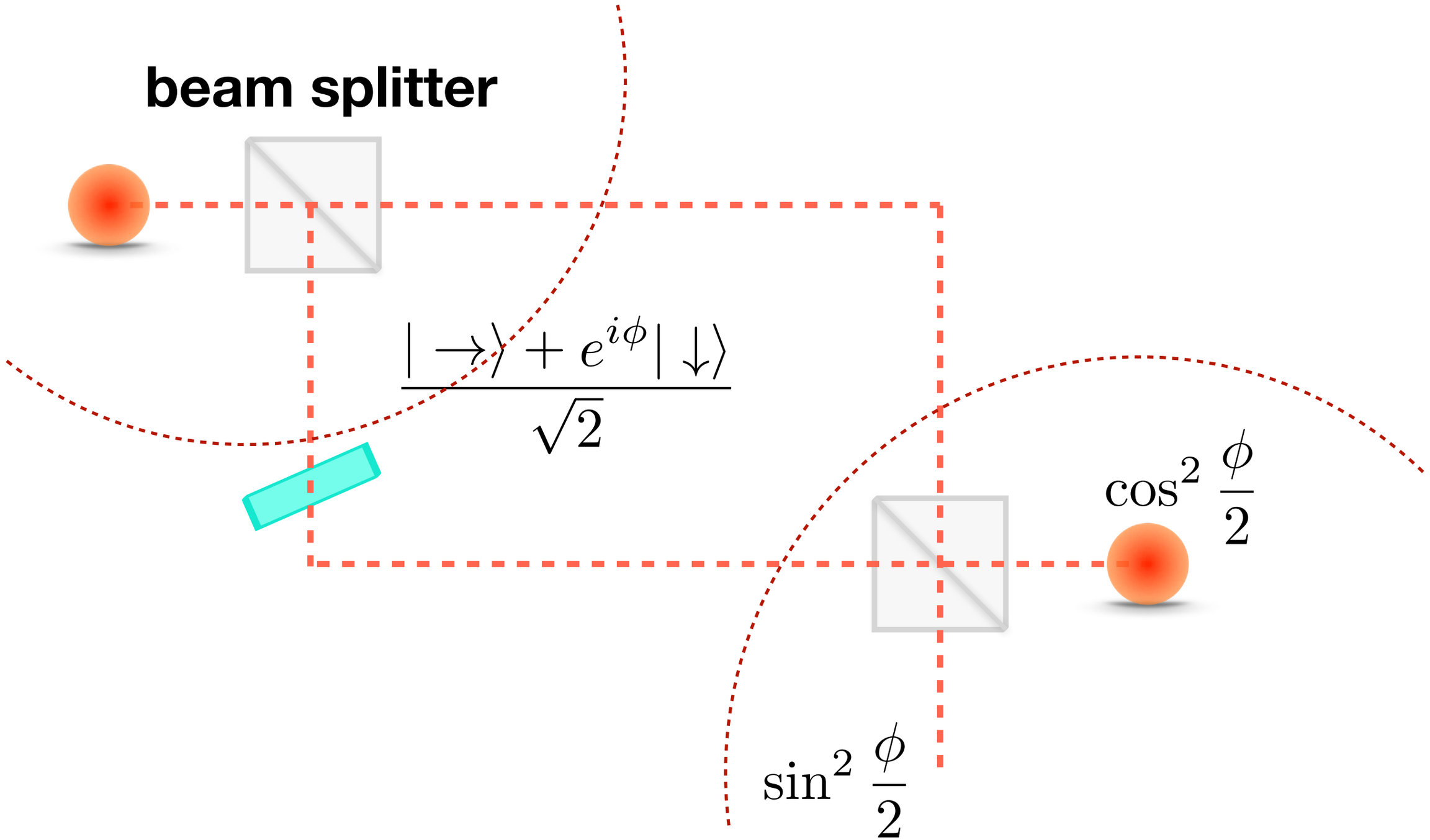
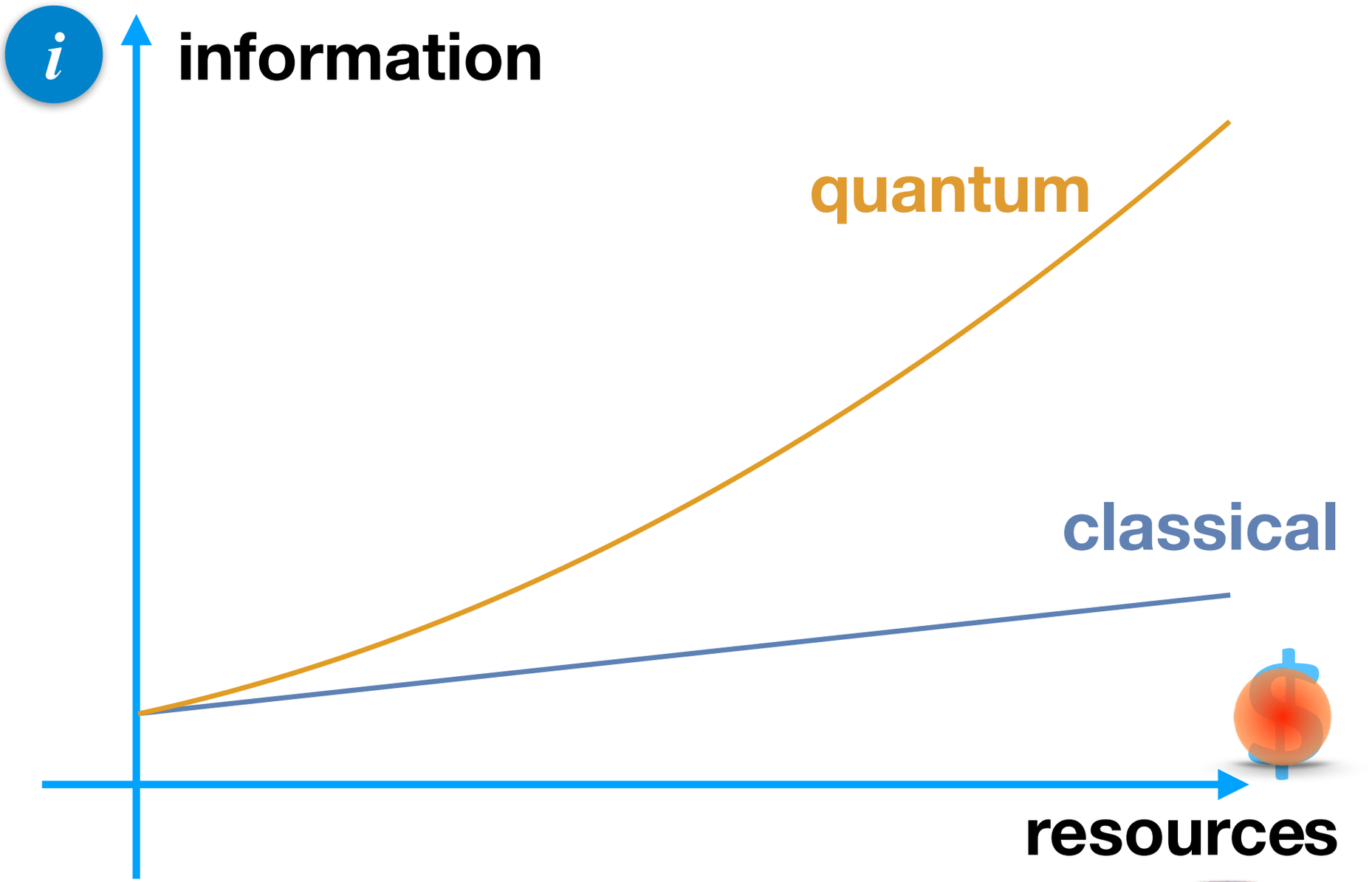


Quantum Metrology



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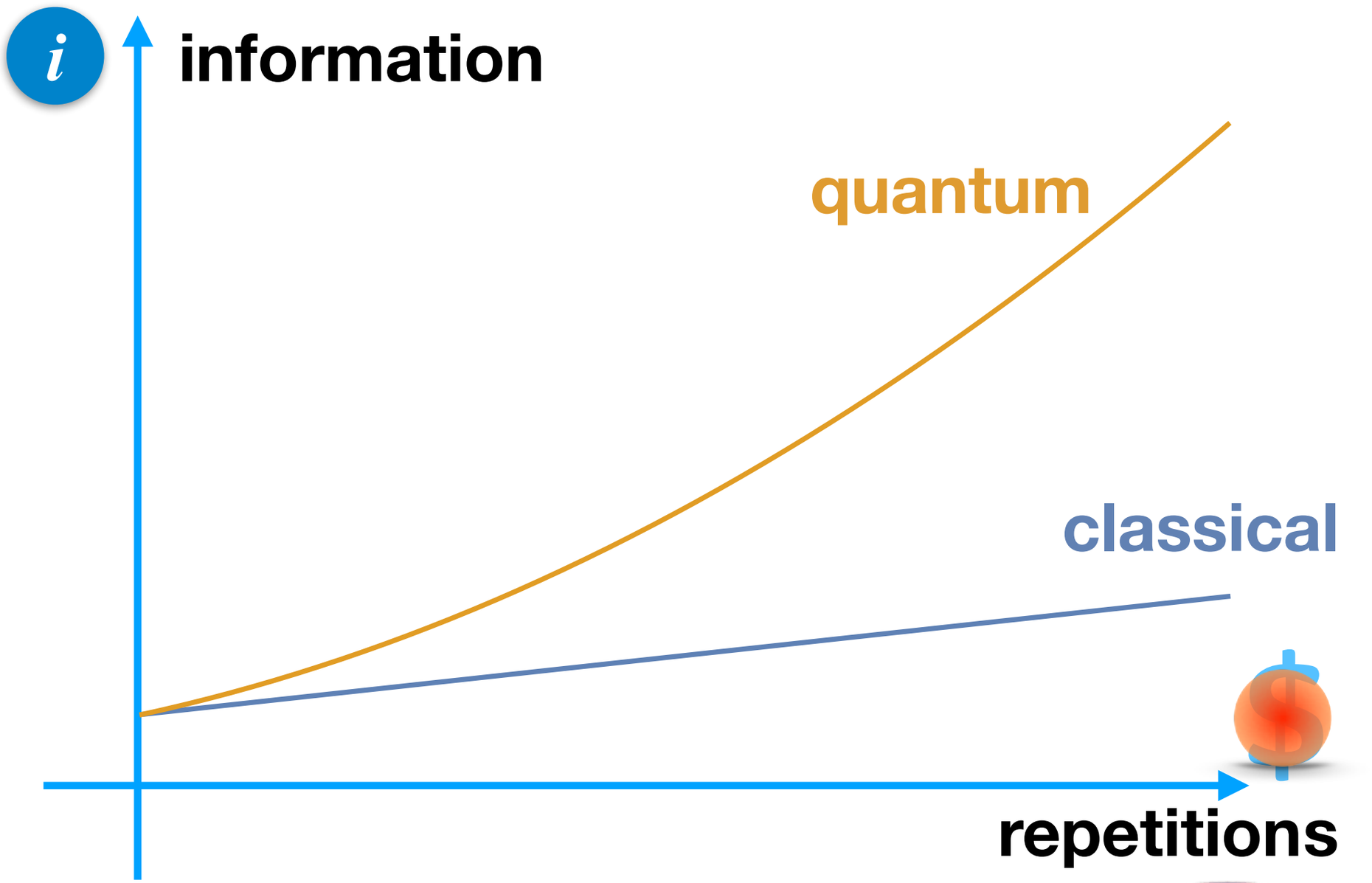

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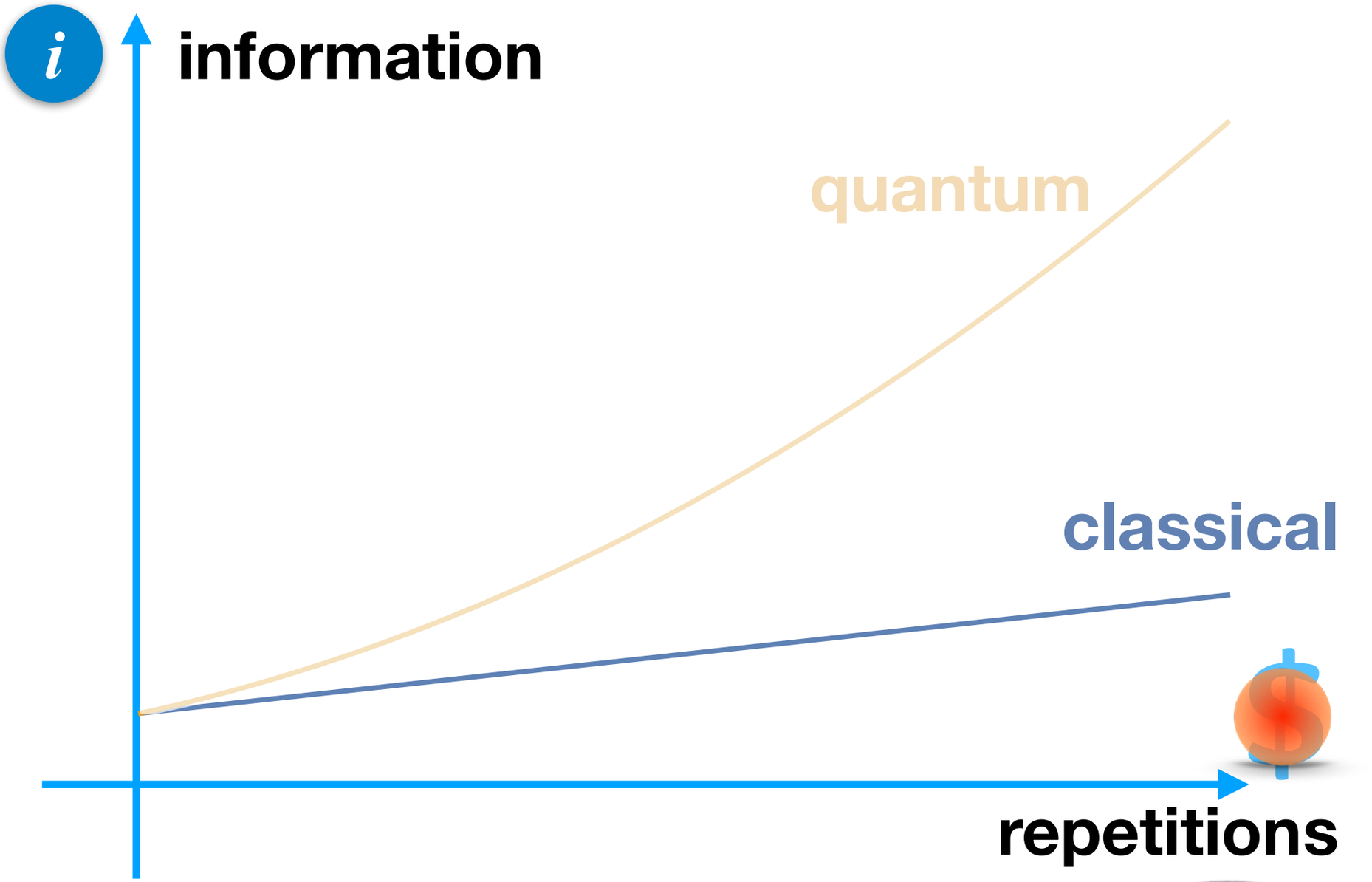

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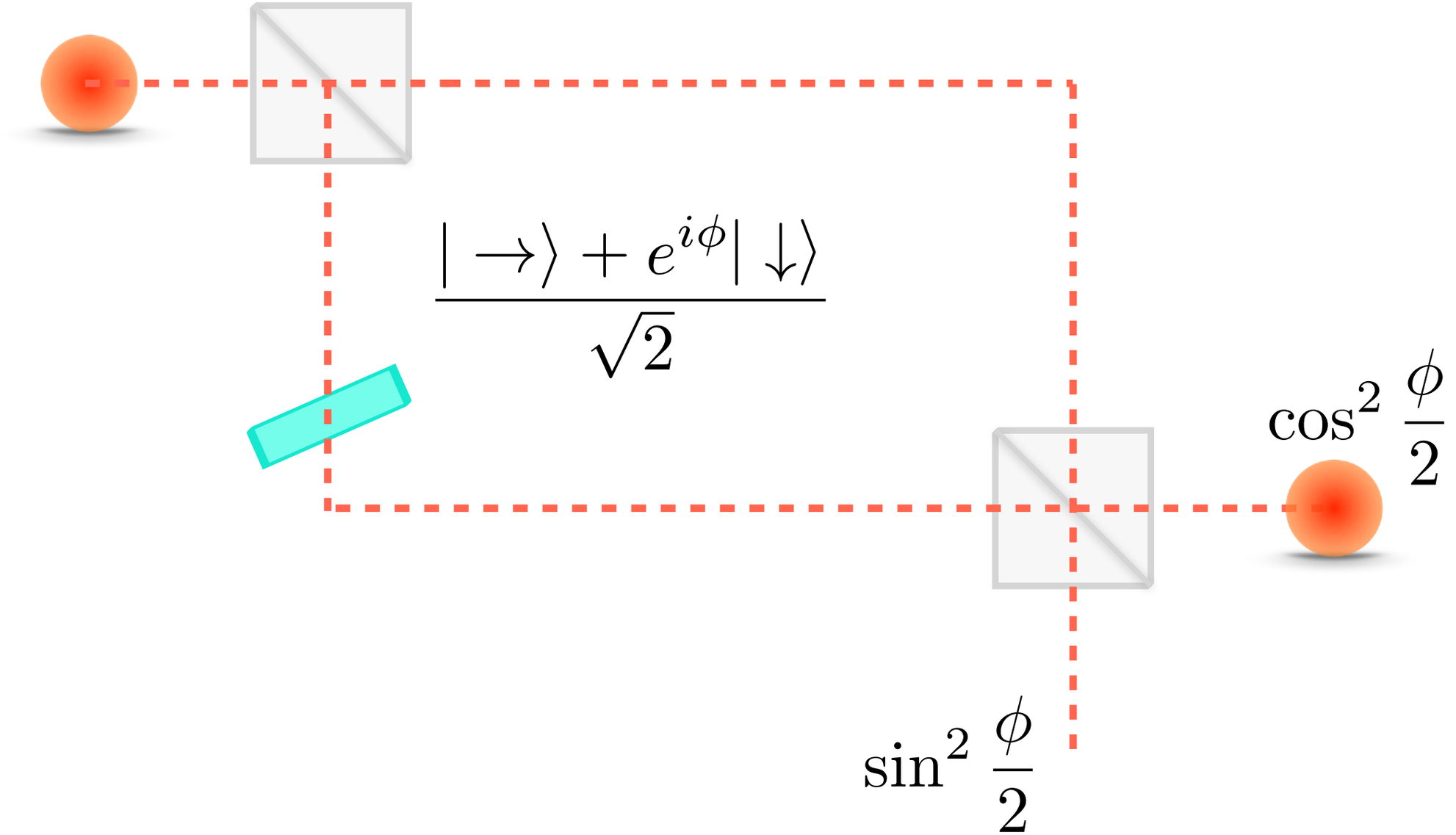

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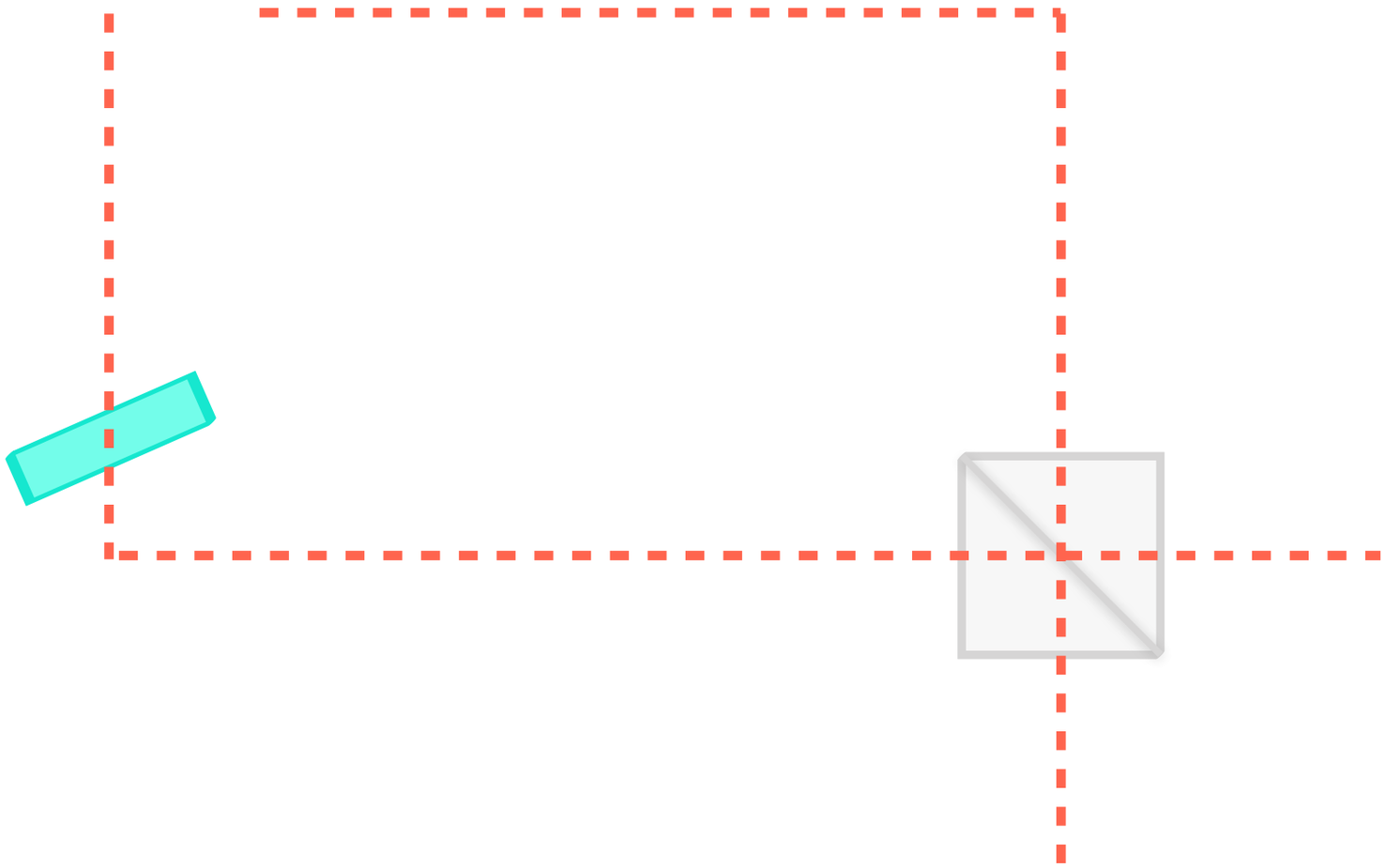

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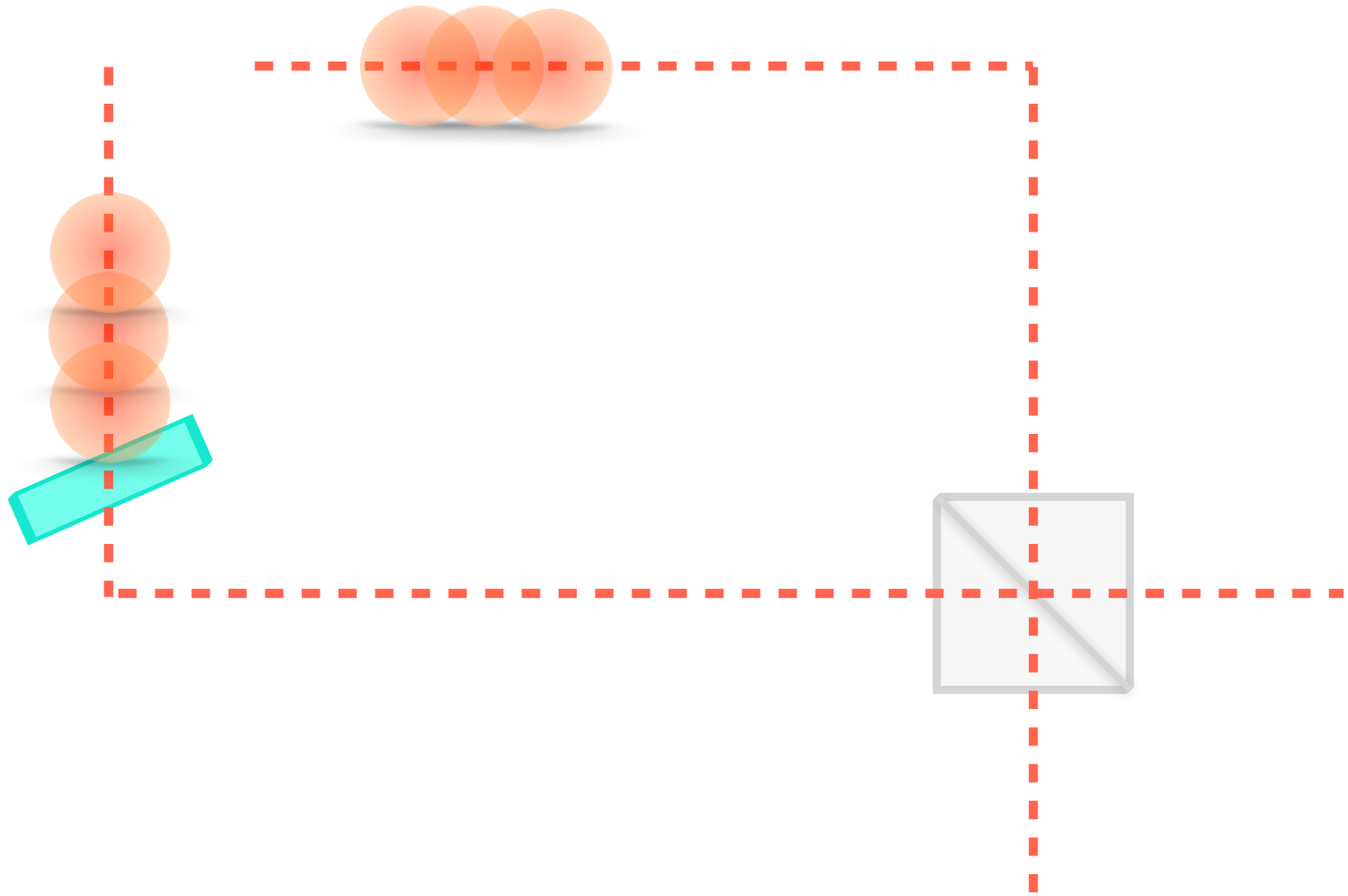

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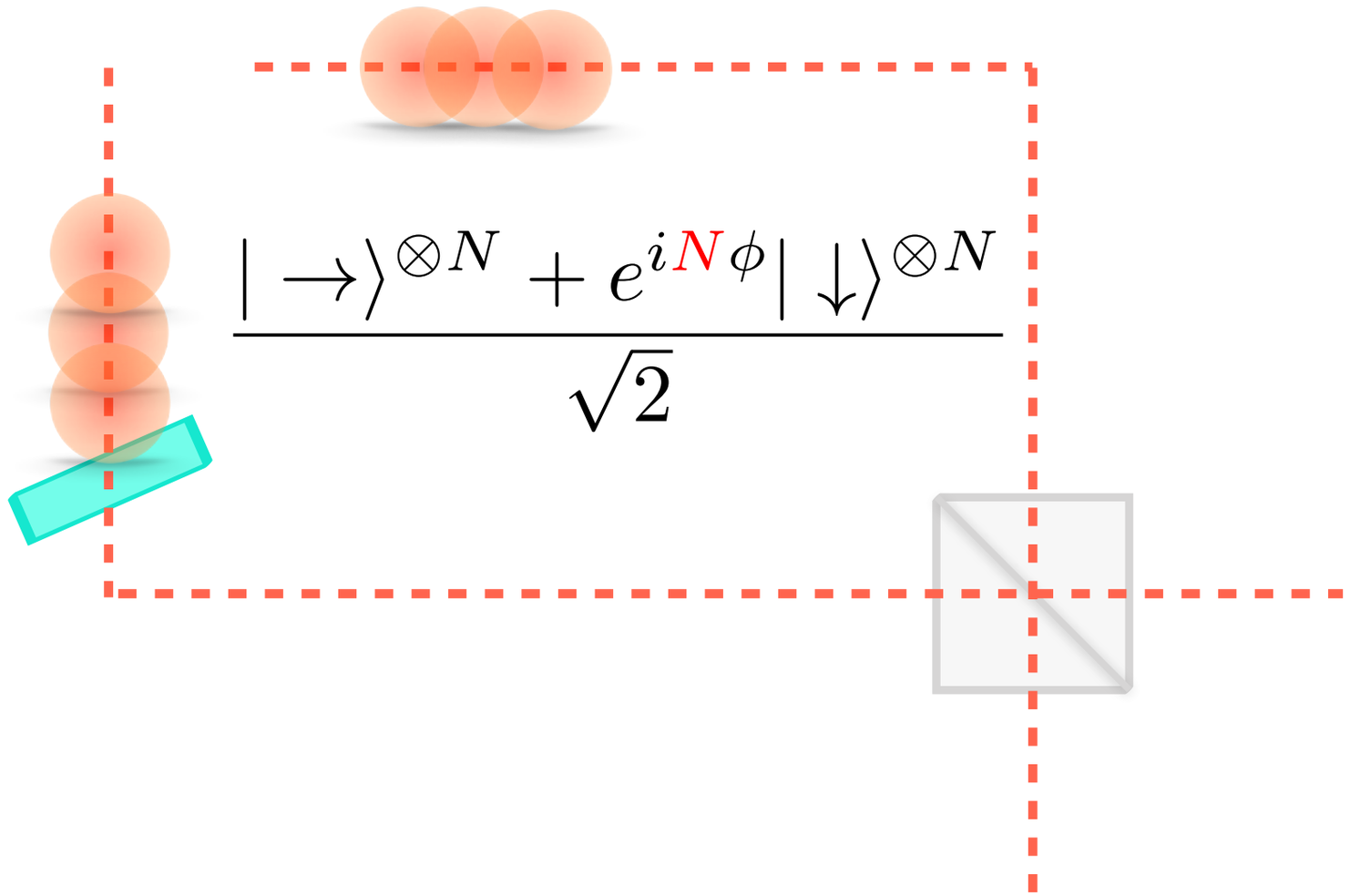

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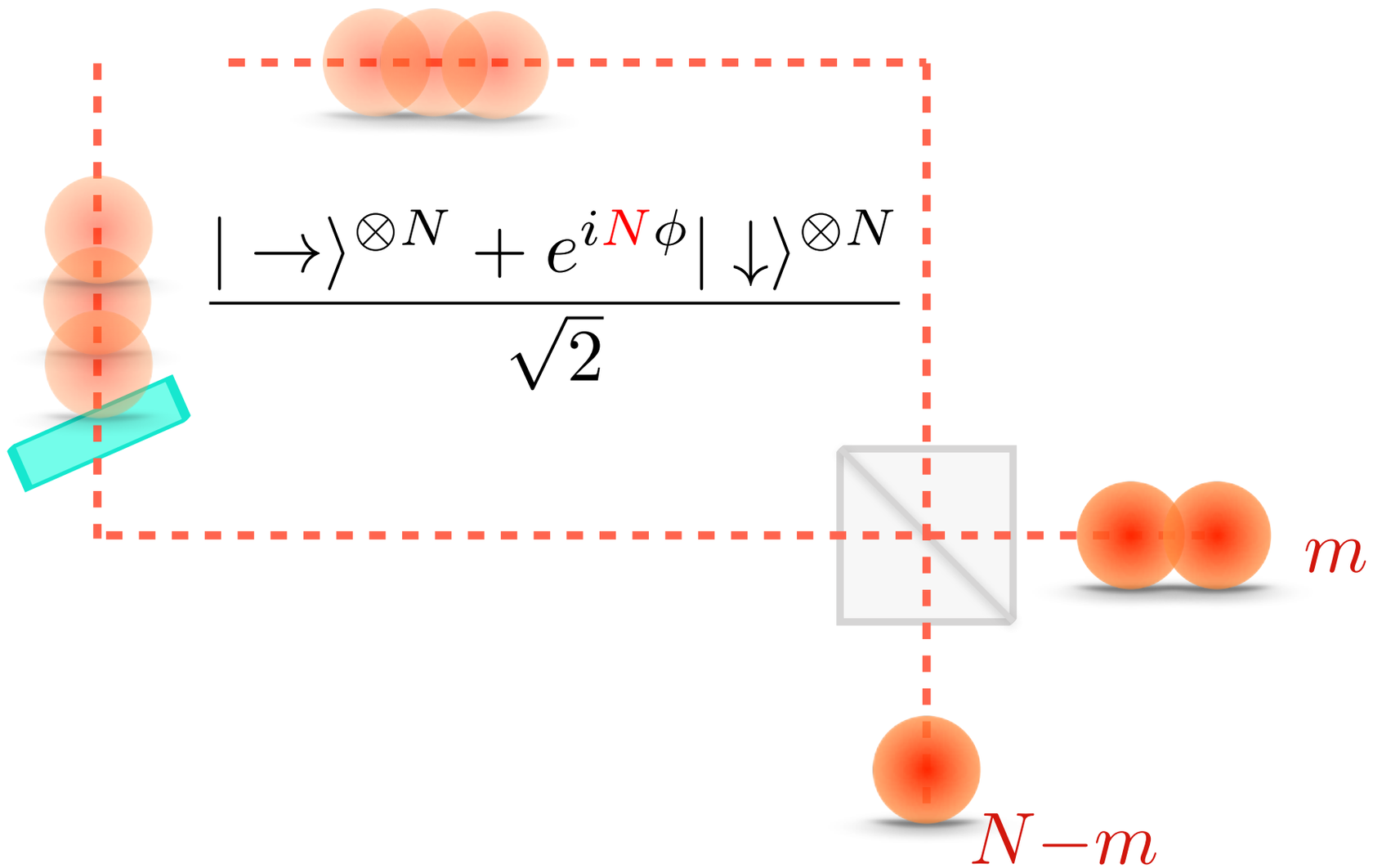

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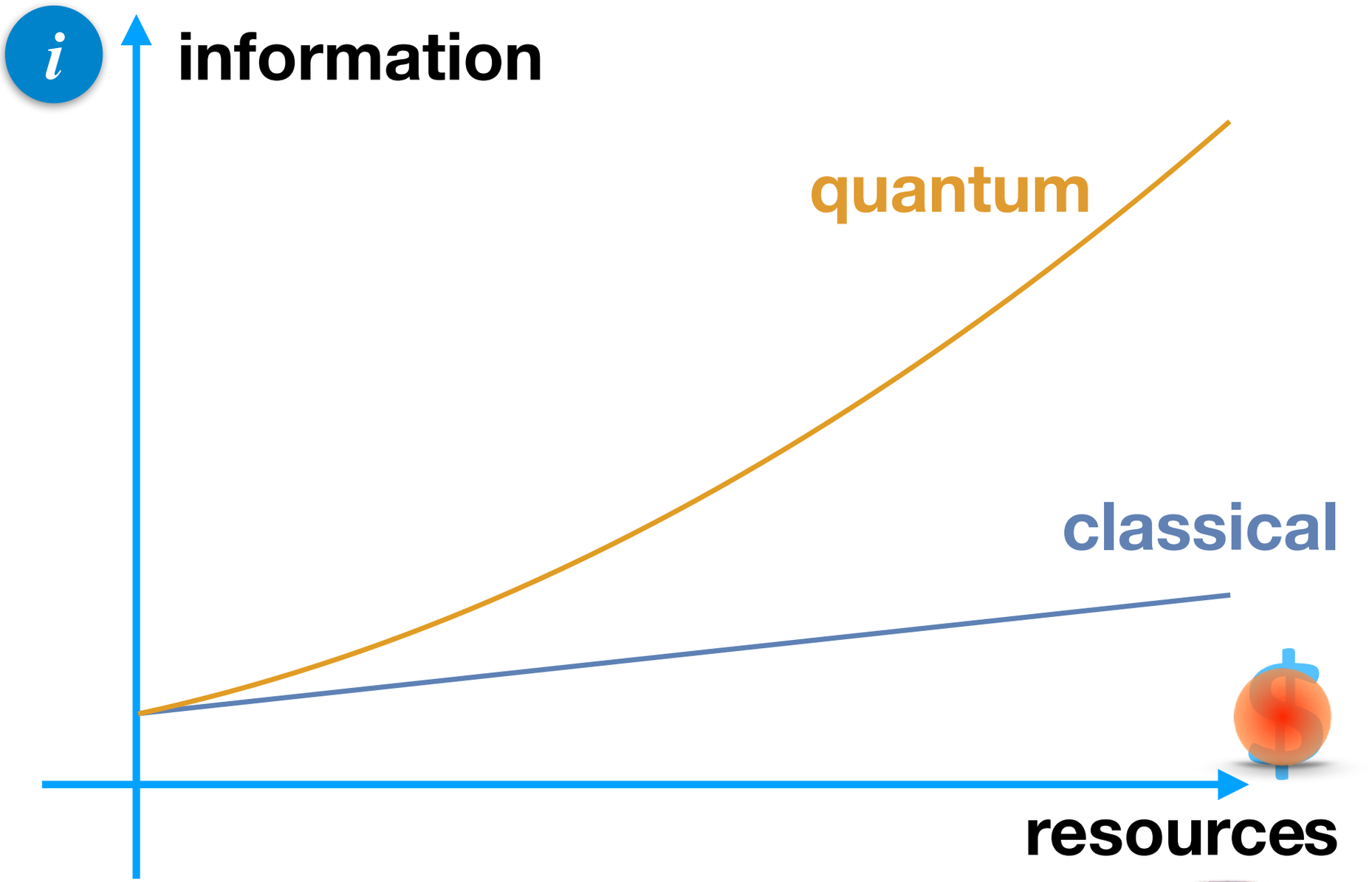

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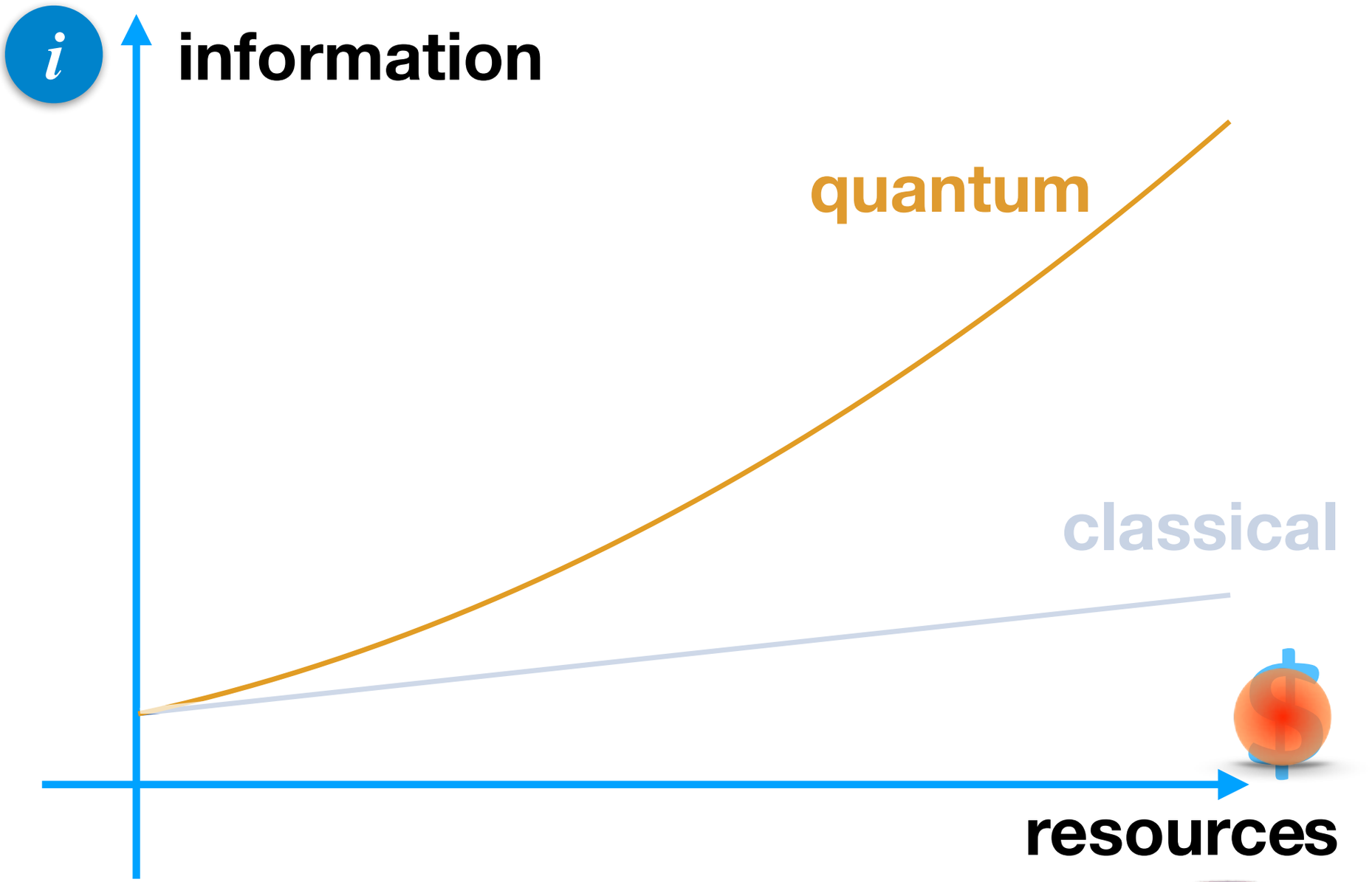

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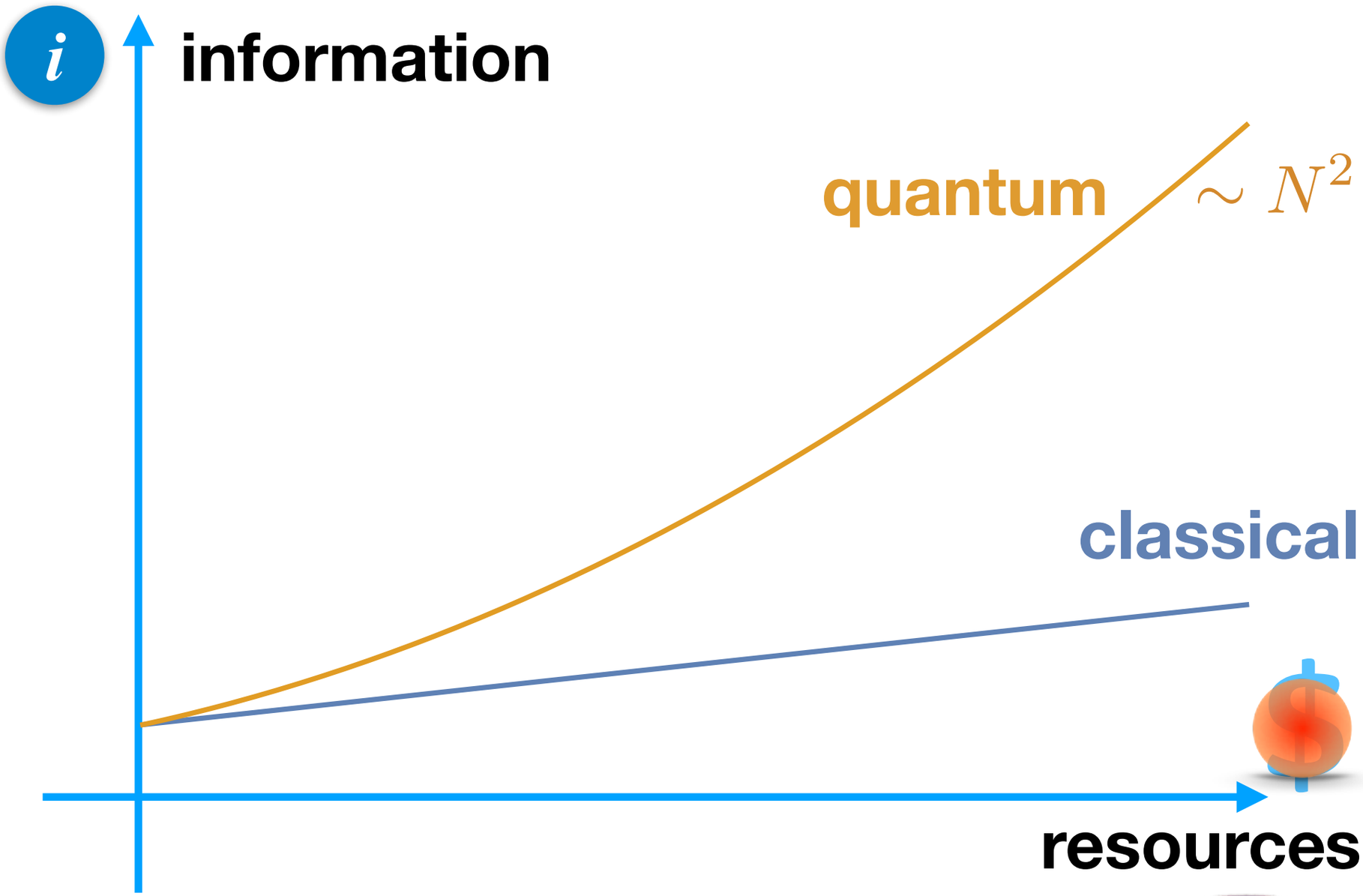

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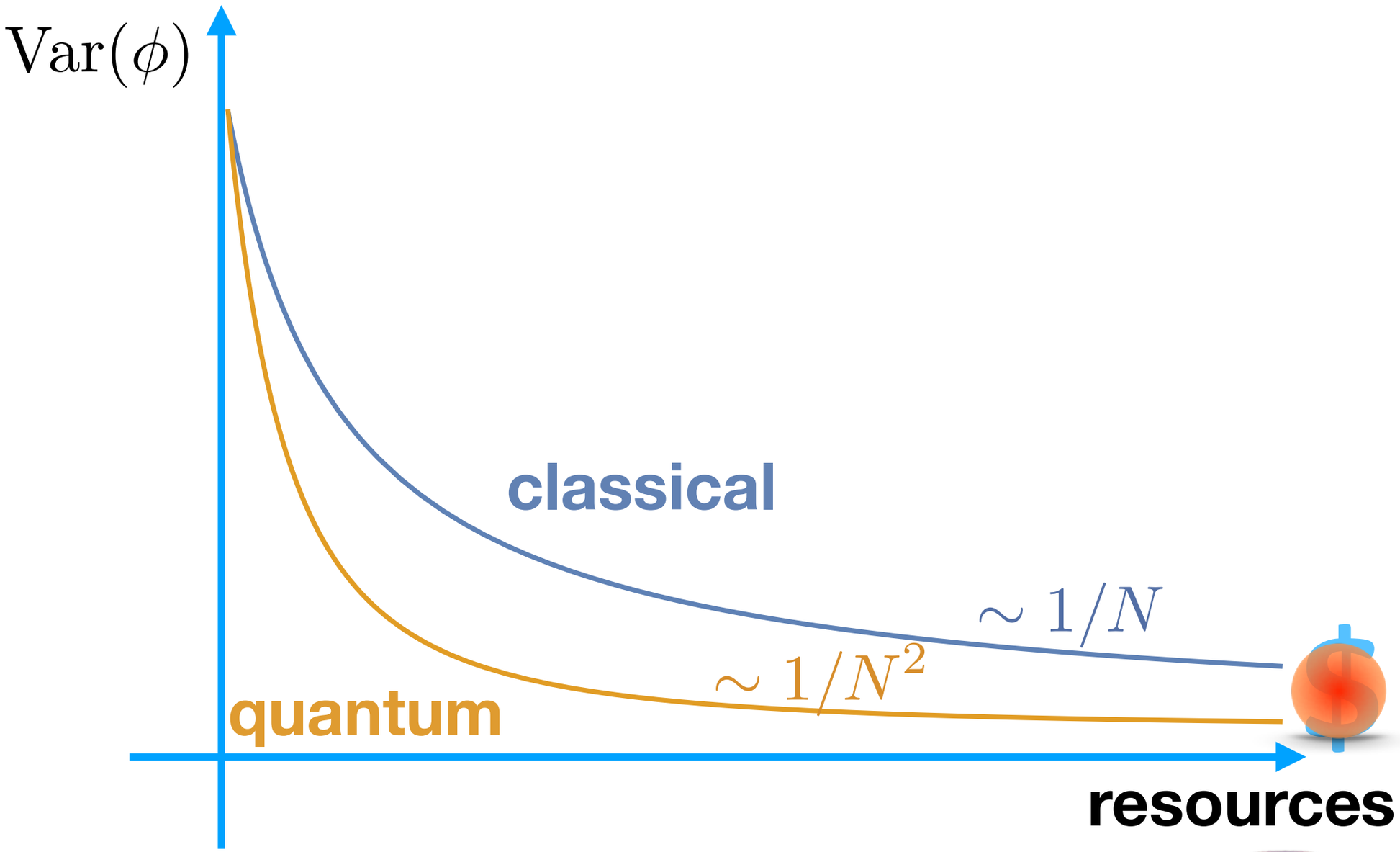
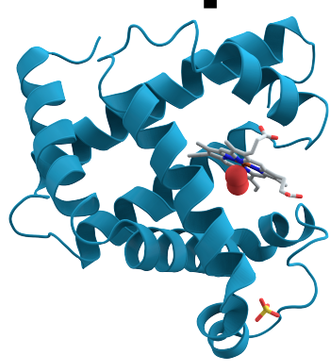


Coping with Loss

source

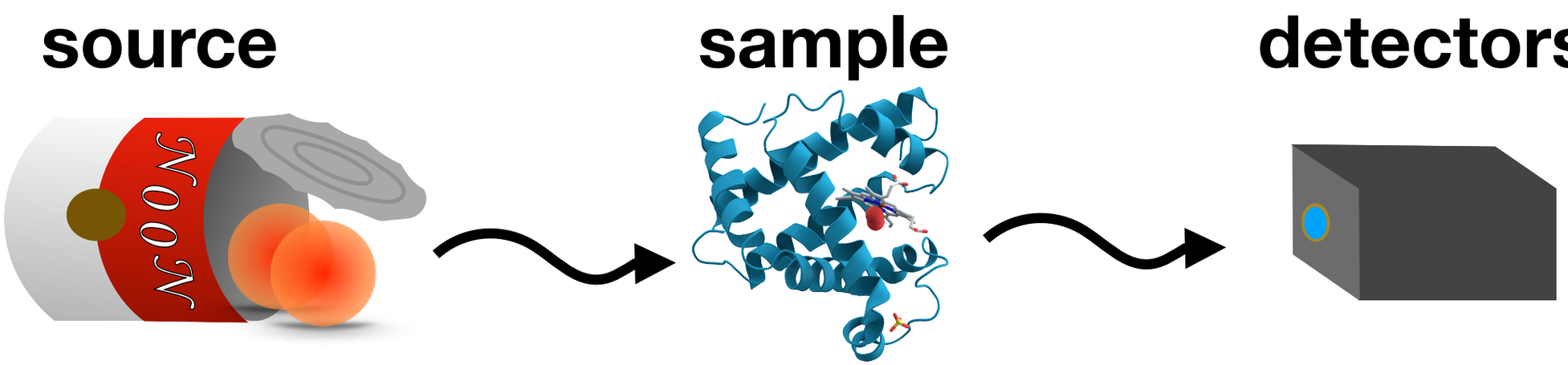
sample



detectors

R. D.-Dobrzanski et al
PRA 80, 013825 (2009)

Coping with Loss



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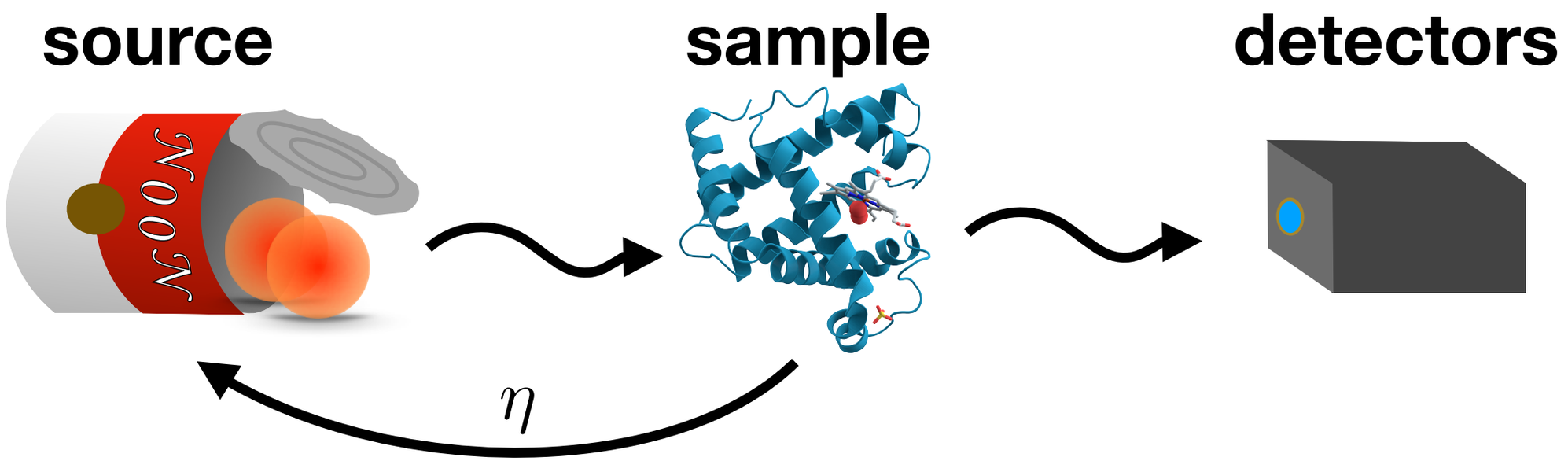

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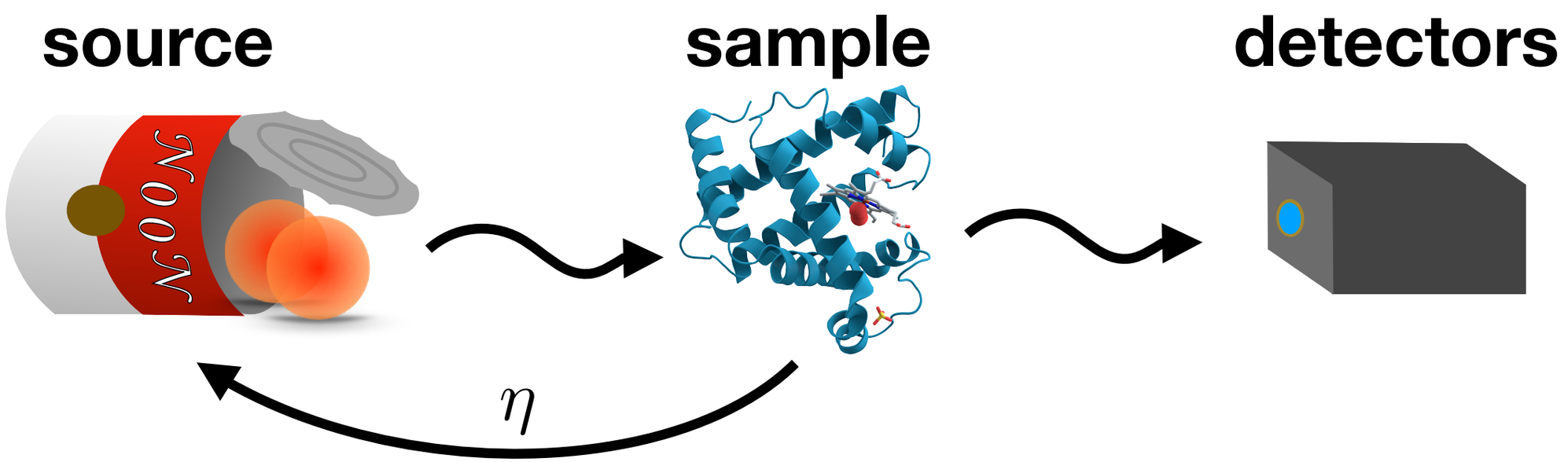
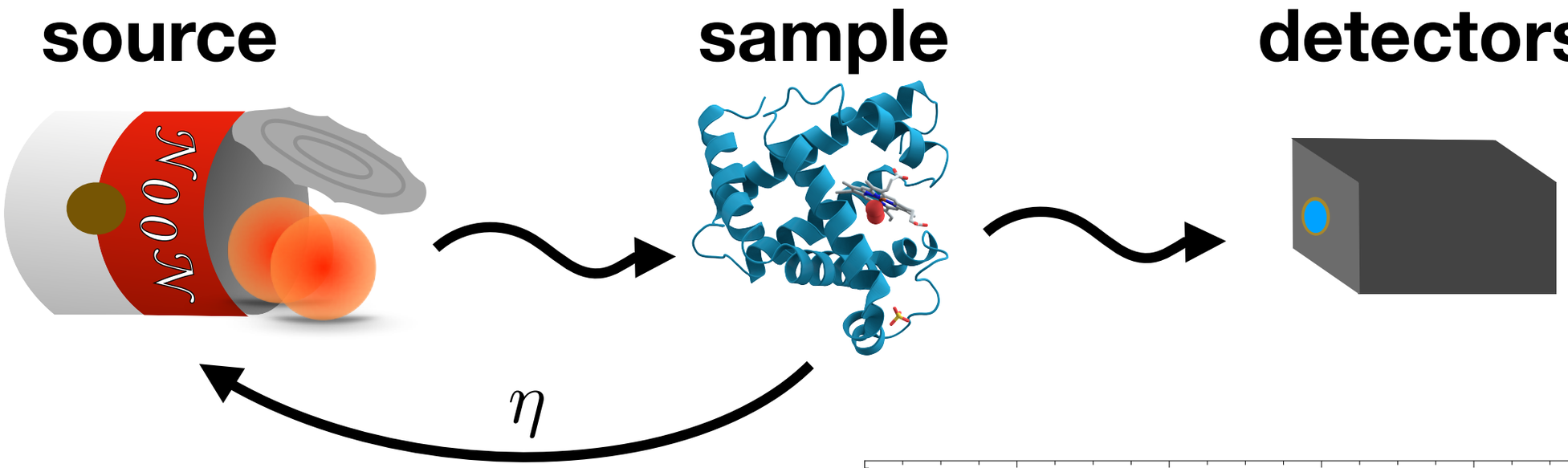


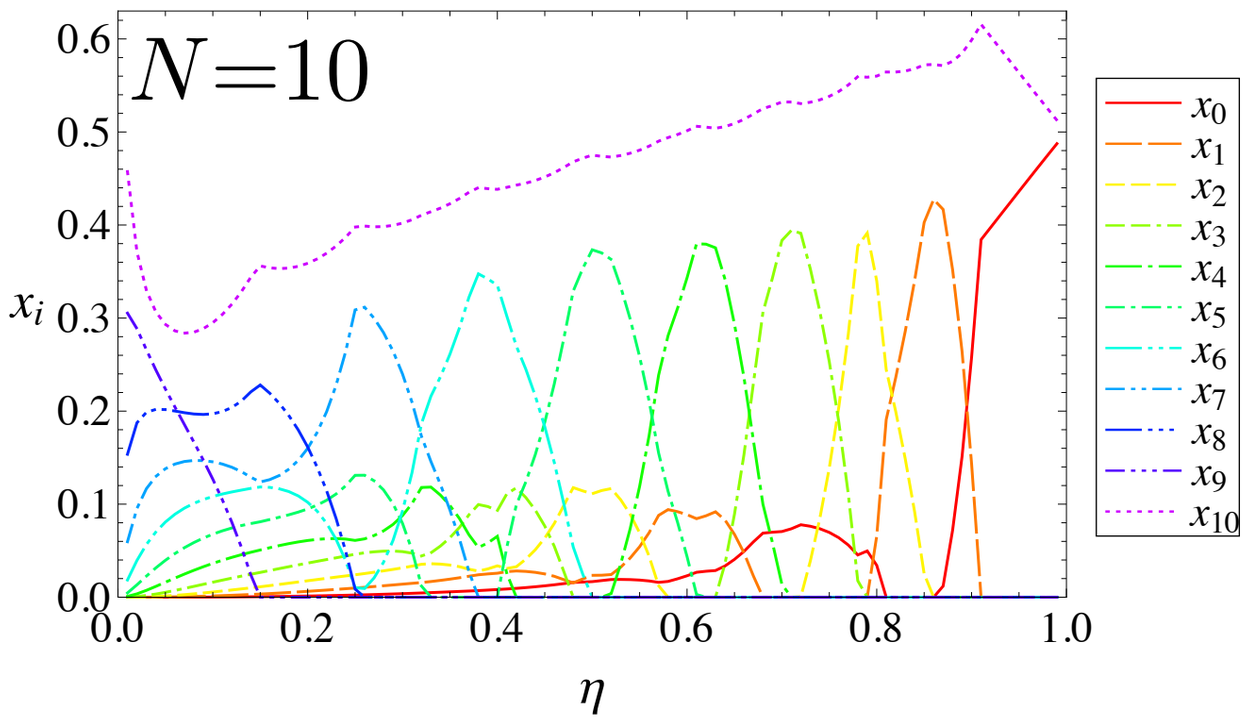
optimal state design
based on loss

R. D.-Dobrzanski et al
PRA 80, 013825 (2009)

Coping with Loss



optimal state design based on loss



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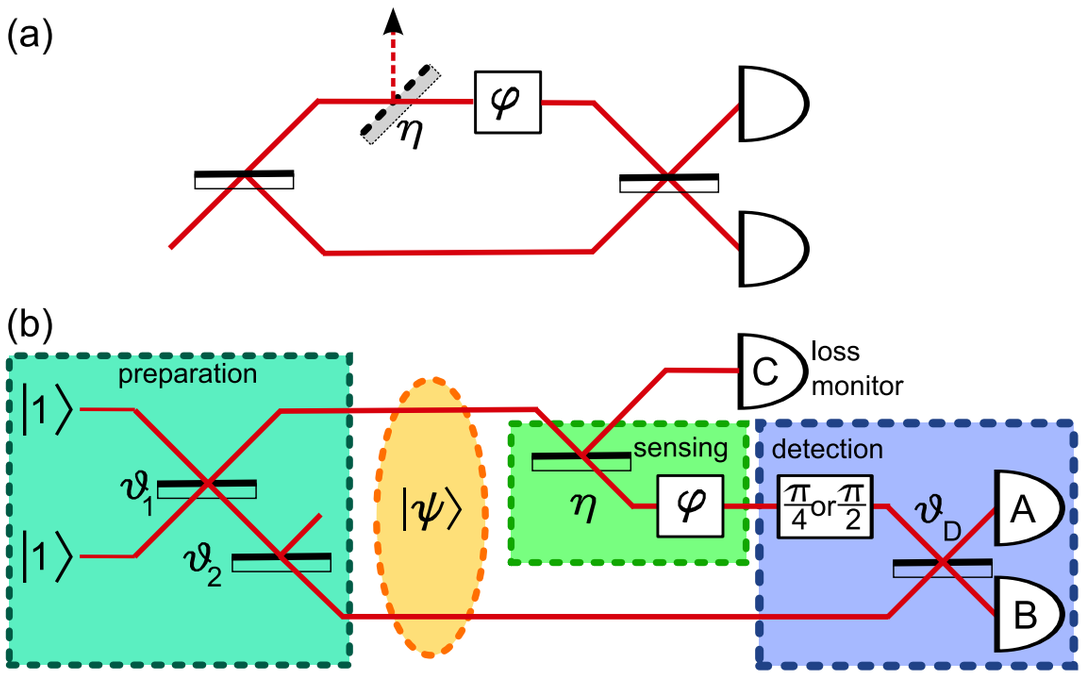
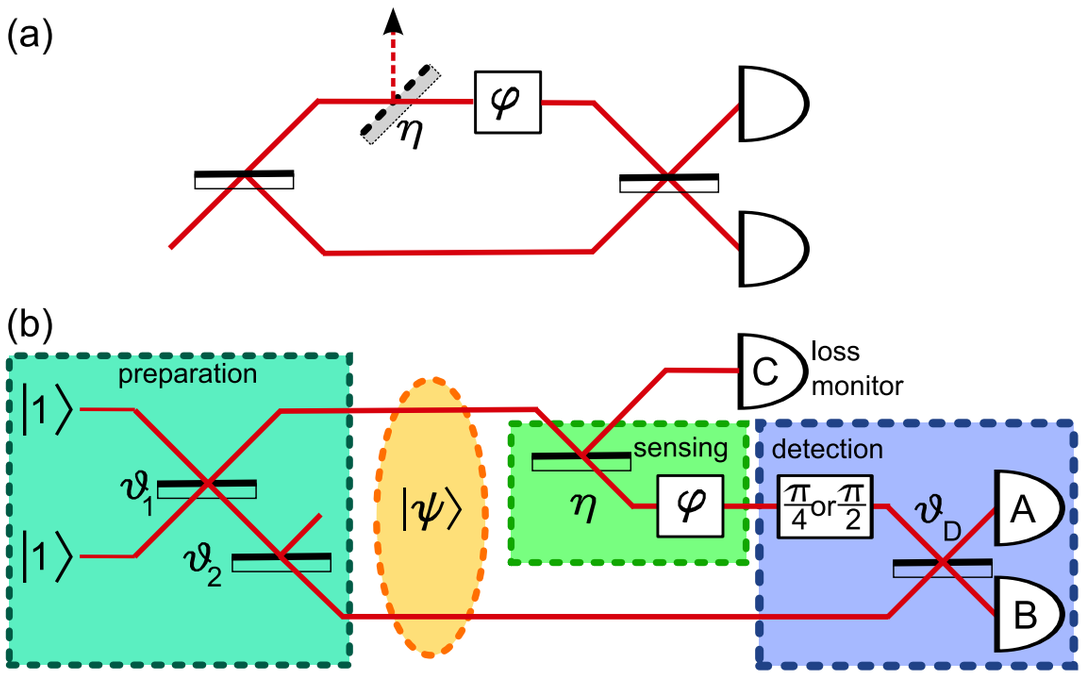
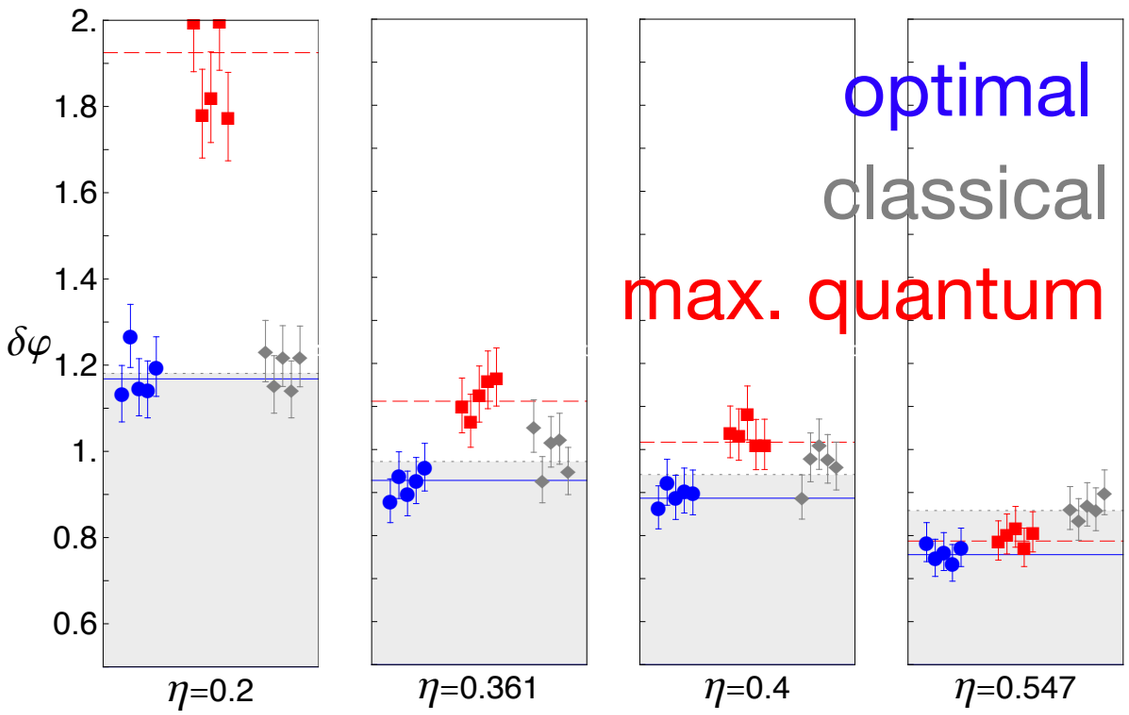


optimal state design based on loss

M. Kacprowicz et al
Nat. Photon 4, 357 (2010)

Coping with Loss





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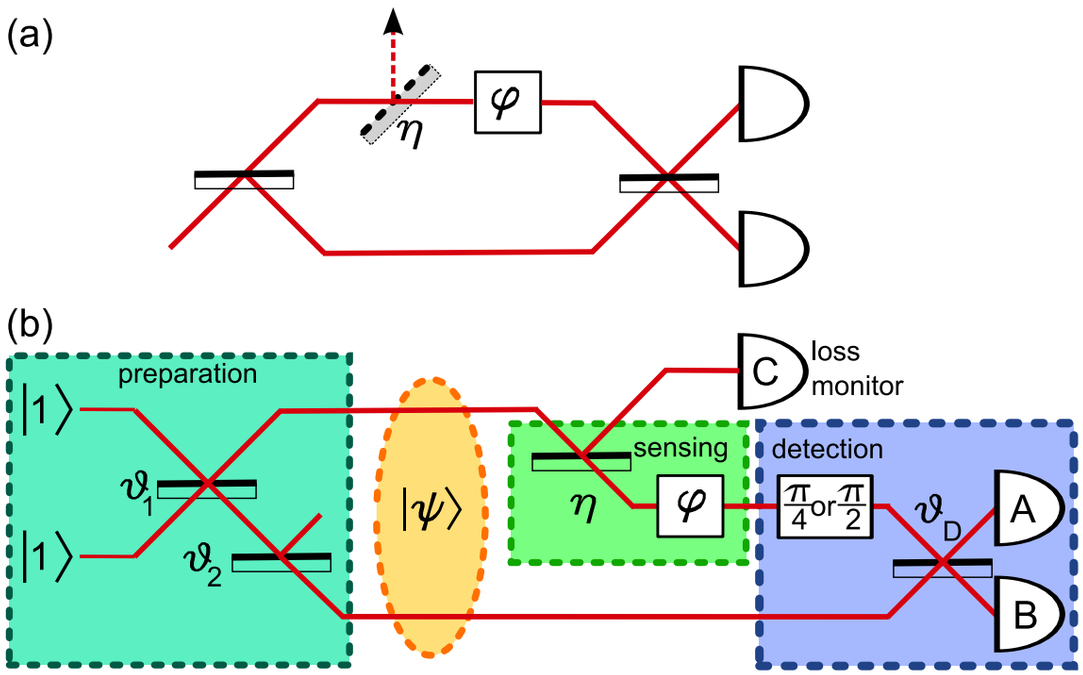
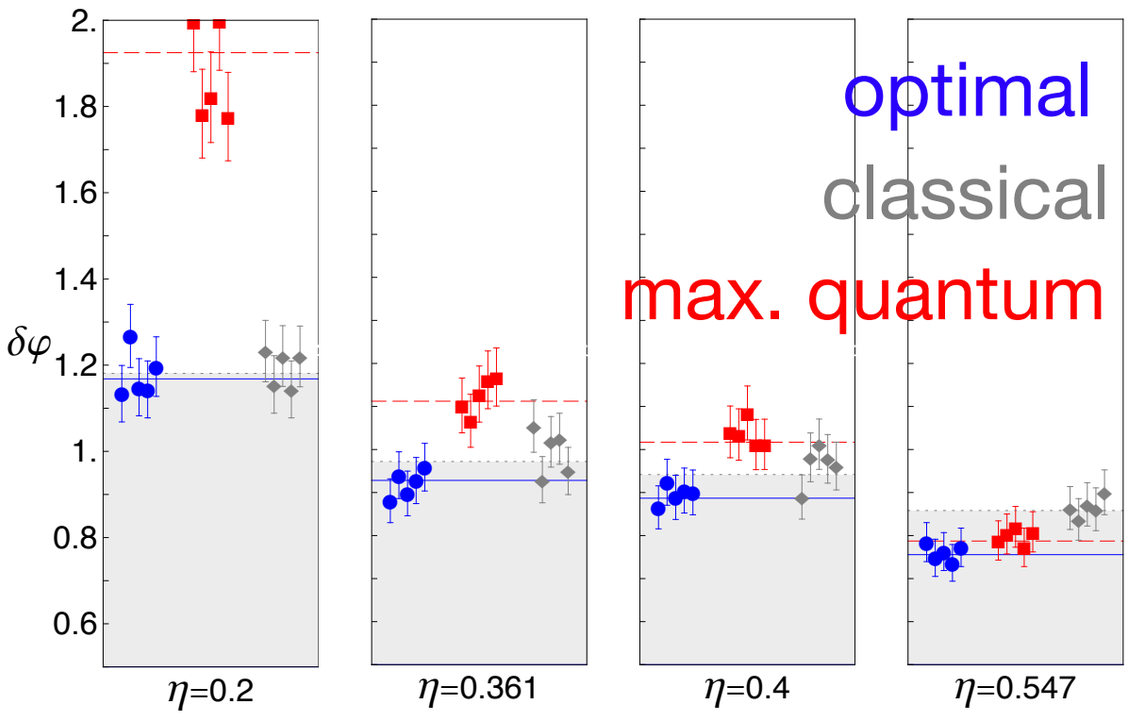


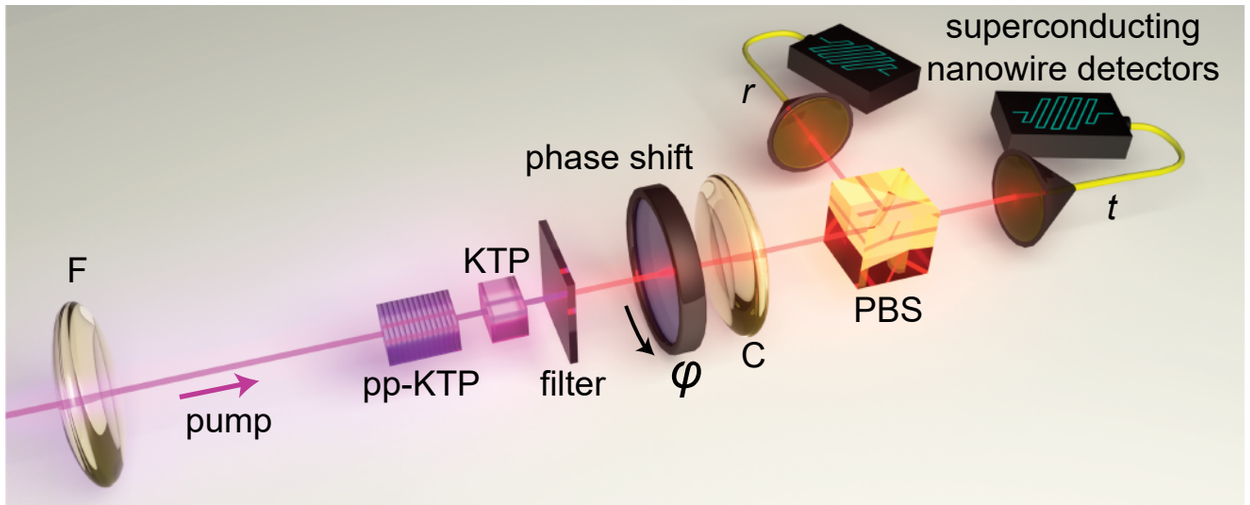


optimal state design based on loss

comparison carried out for the *detected* photons

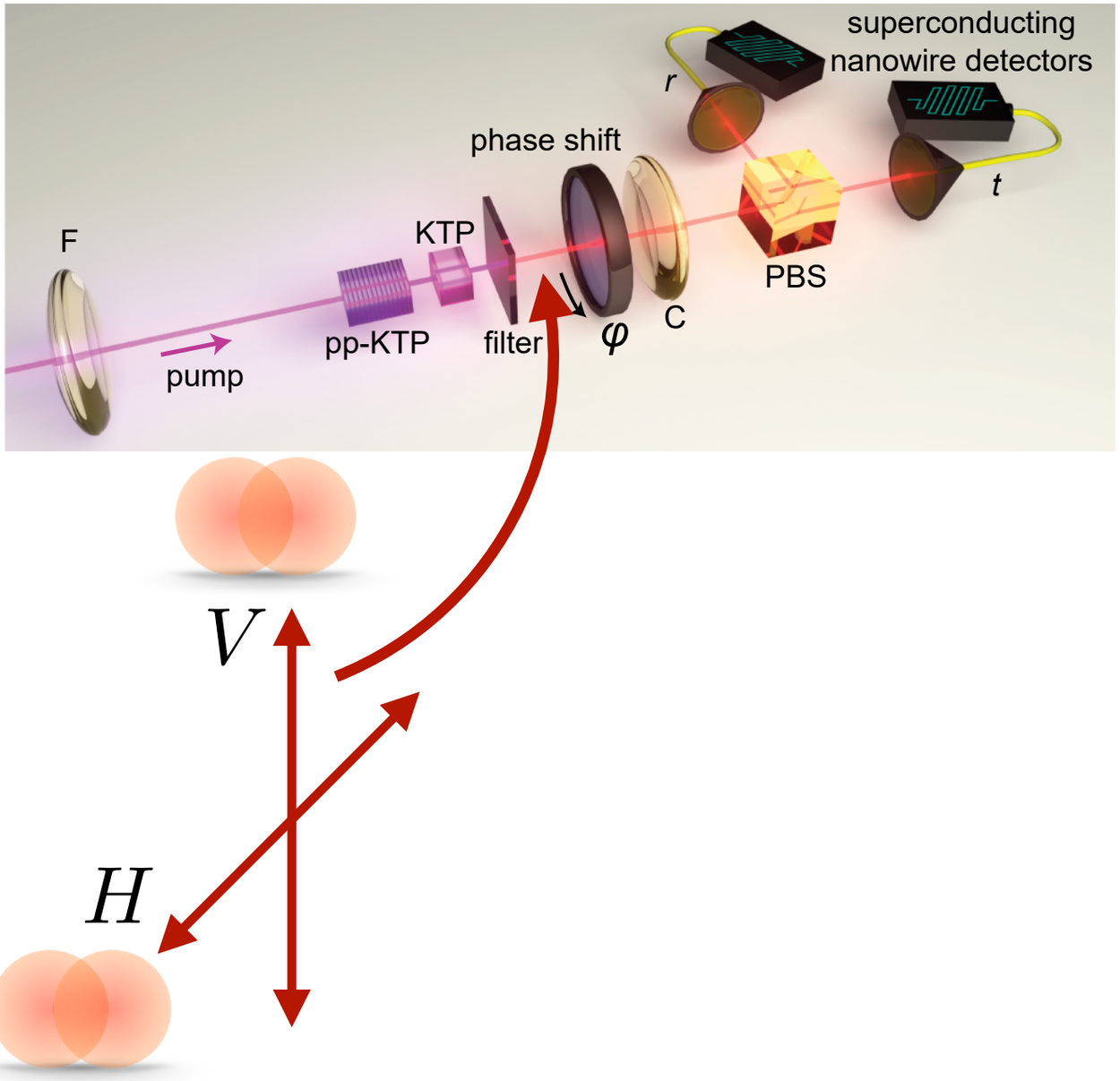
M. Kacprowicz et al
Nat. Photon 4, 357 (2010)

Coping with Loss



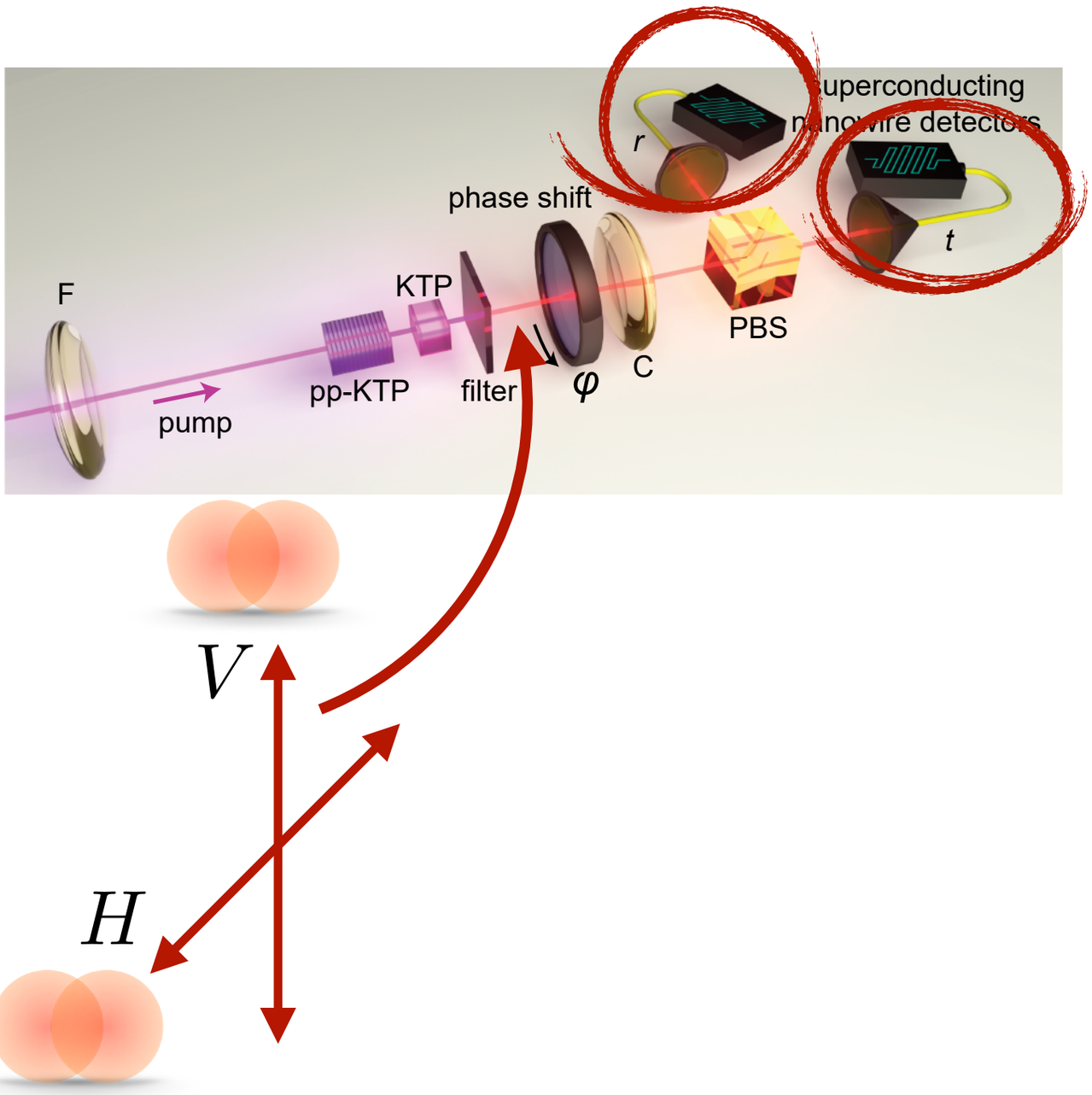
S. Slussarenko et al
Nat. Photon 11, 700 (2017)

Coping with Loss



S. Slussarenko et al
Nat. Photon 11, 700 (2017)

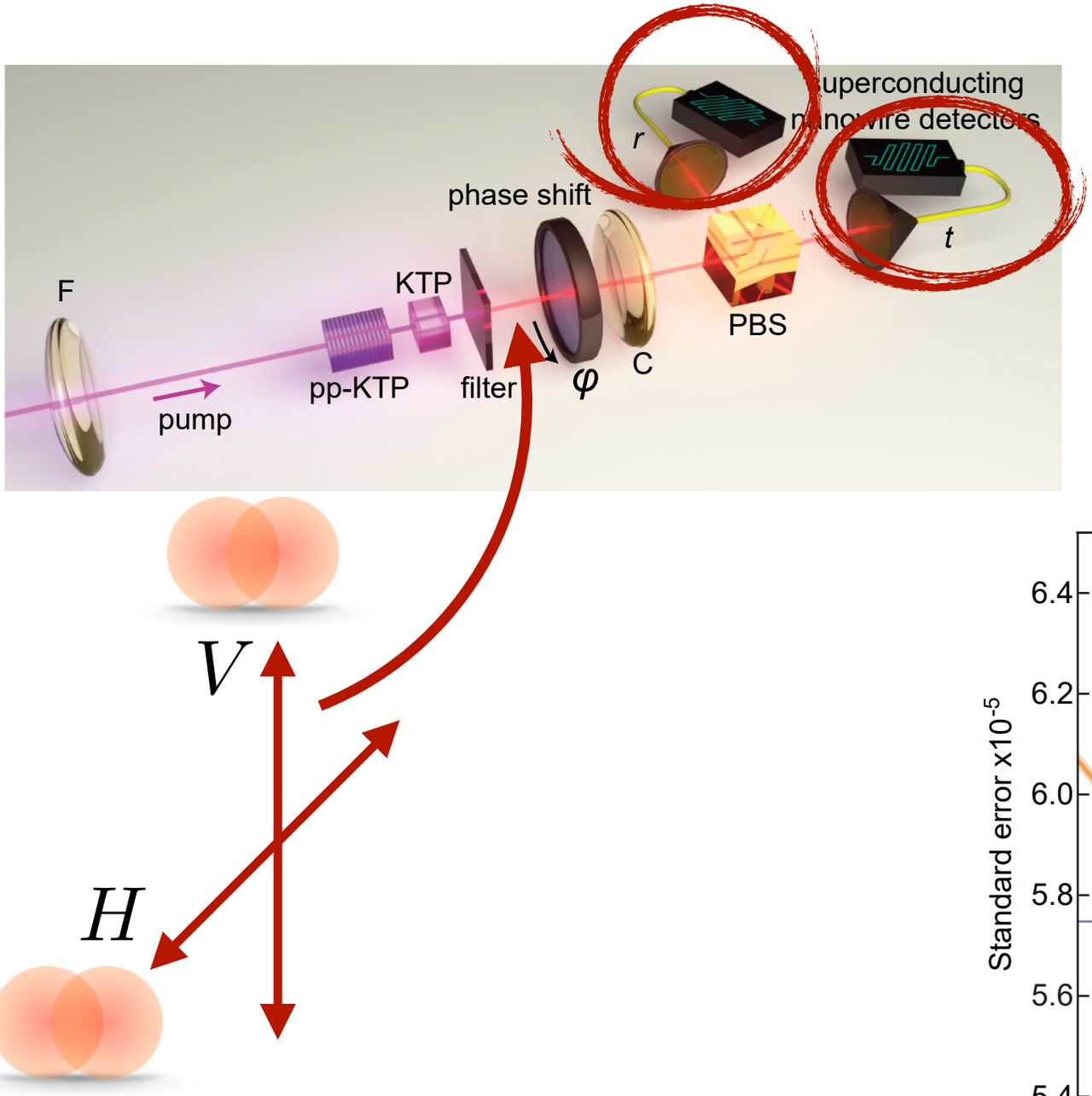
Coping with Loss



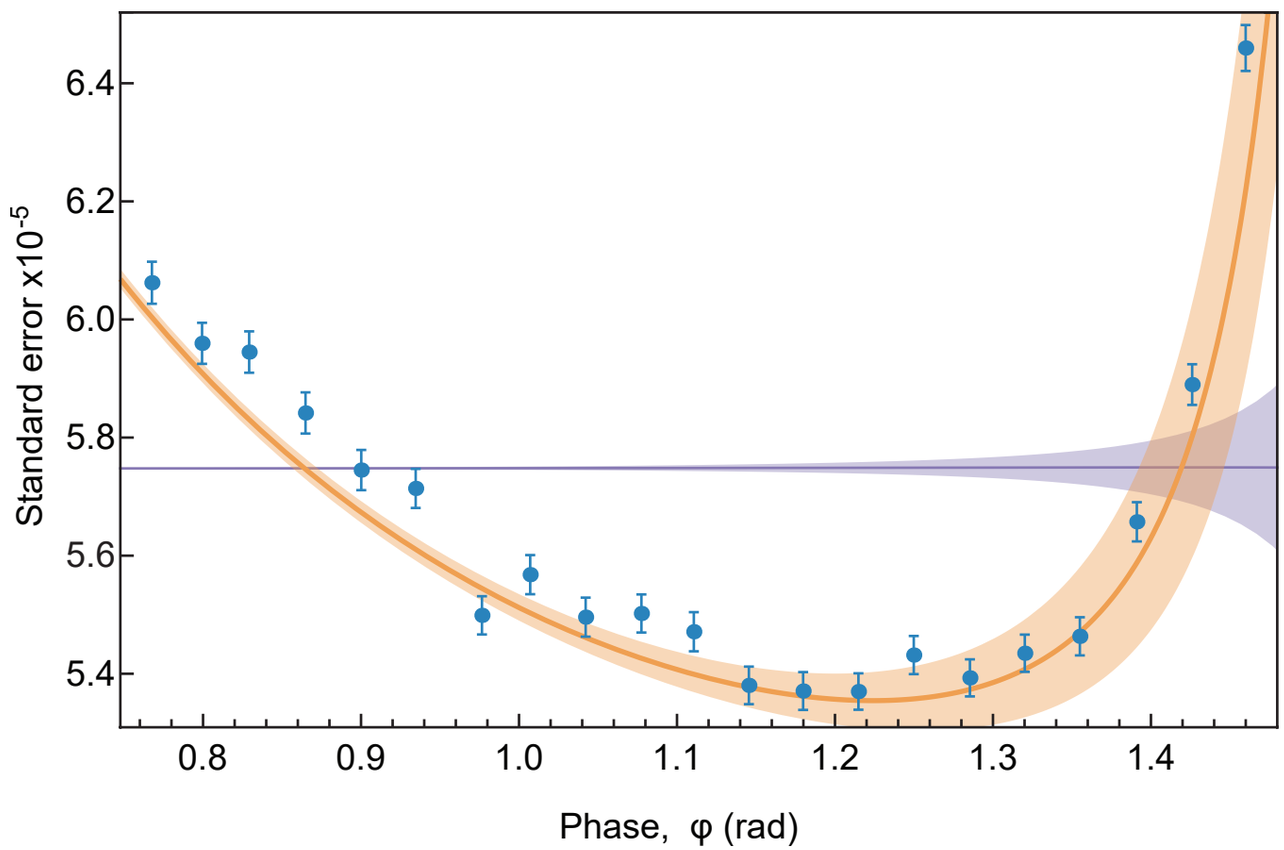
superconducting detectors

S. Slussarenko et al
Nat. Photon 11, 700 (2017)

Coping with Loss

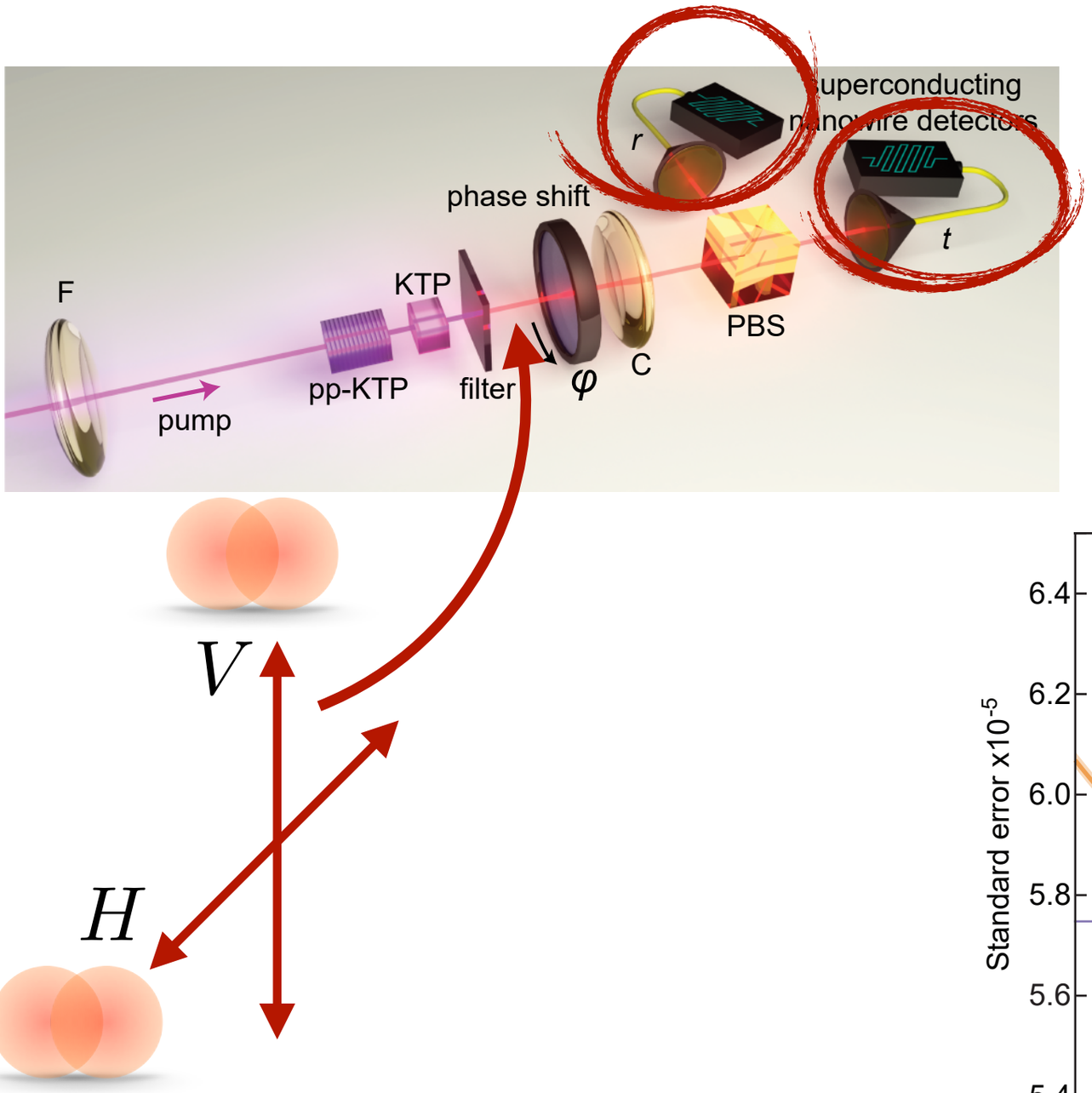


superconducting detectors



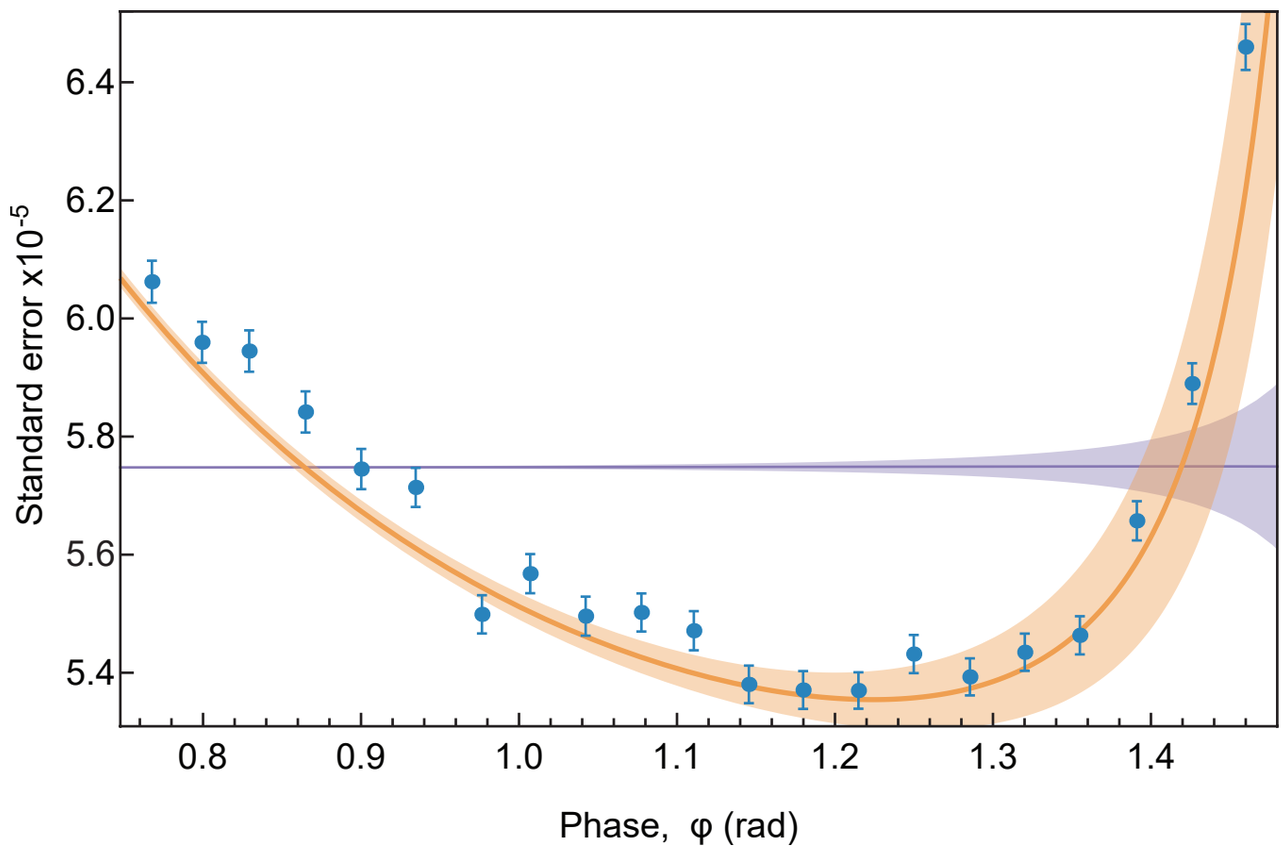
S. Slussarenko et al
Nat. Photon 11, 700 (2017)

Coping with Loss



superconducting detectors

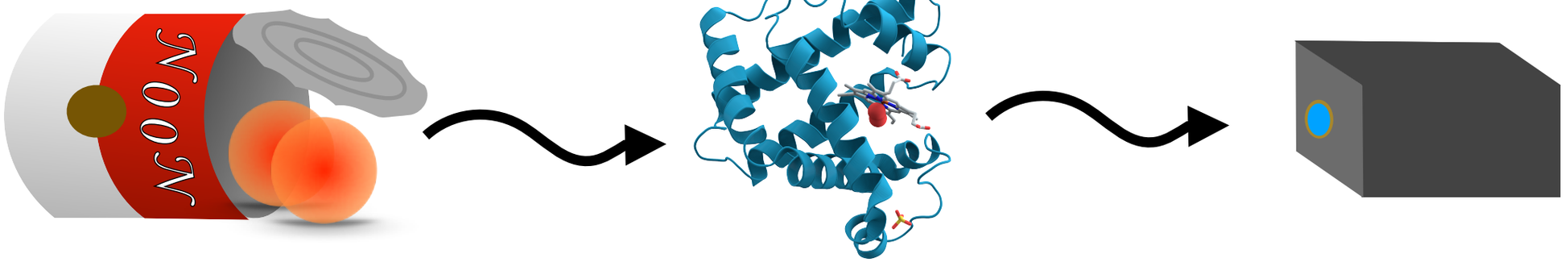
comparison carried out for *all* photons



S. Slussarenko et al
Nat. Photon 11, 700 (2017)

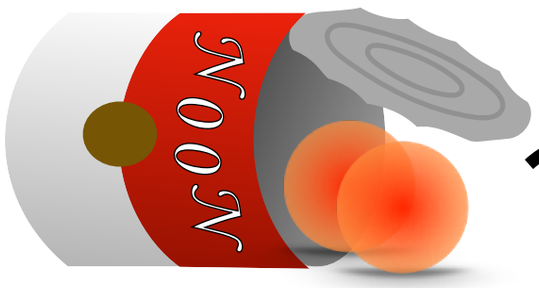
Coping with Imperfections

source **sample** **detectors**



Coping with Imperfections

source → **sample** → **detectors**

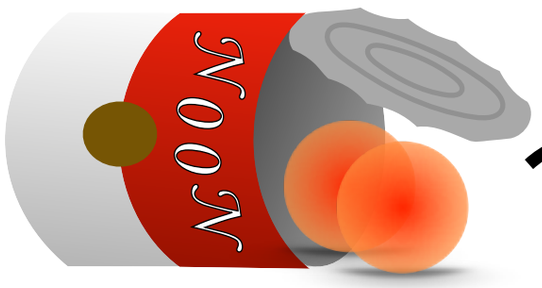


Ψ

basic science

Coping with Imperfections

source

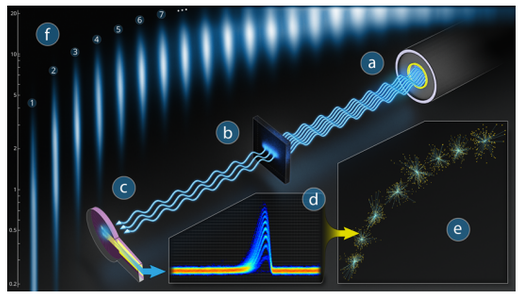


sample

detectors

Ψ

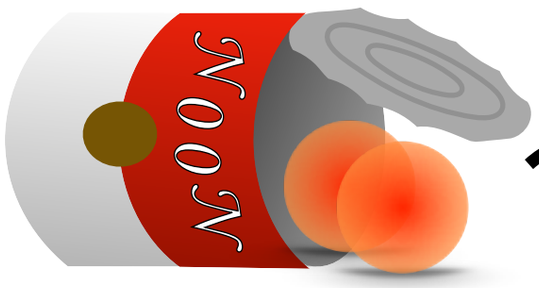
basic science



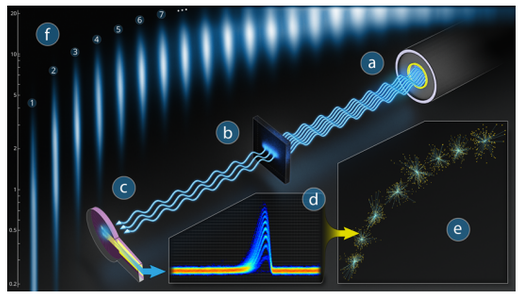
improved components

Coping with Imperfections

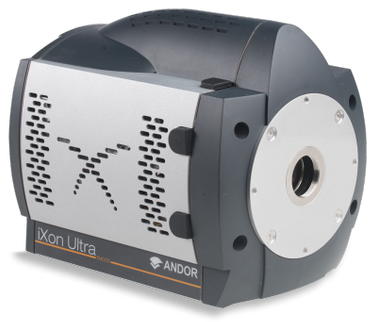
source → **sample** → **detectors**



Ψ → **basic science**

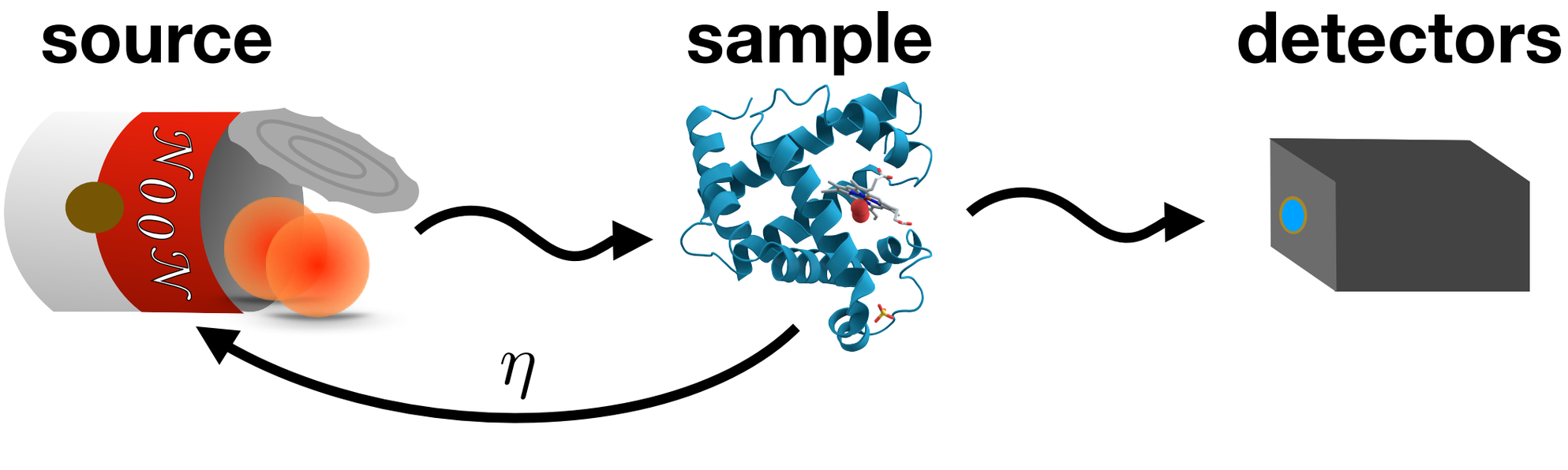


improved components

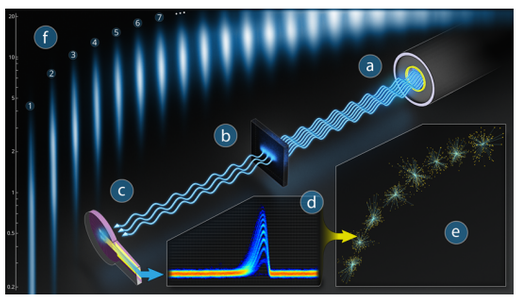


commercial device

Coping with Imperfections



Ψ

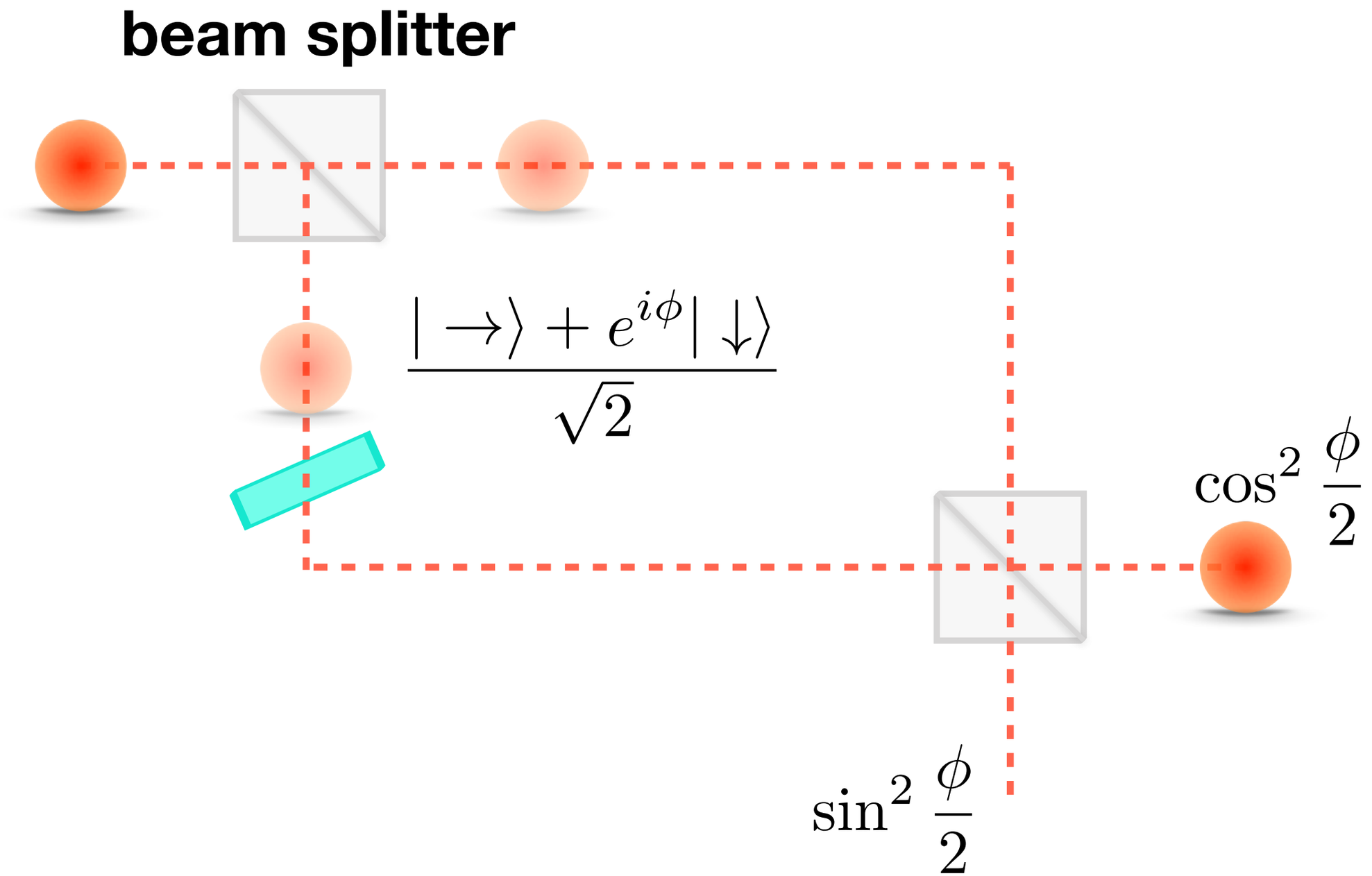


basic science

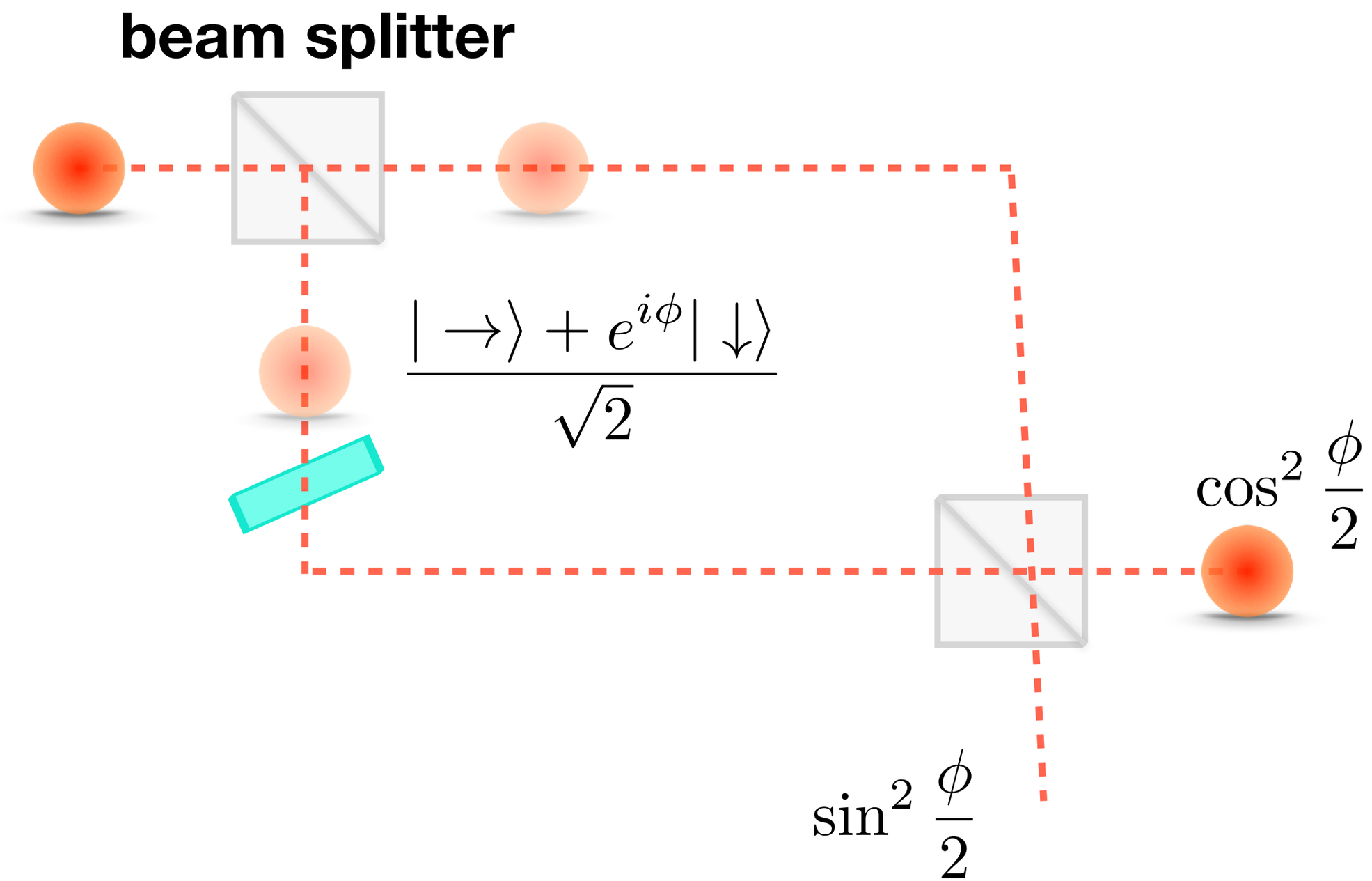
improved components

commercial device

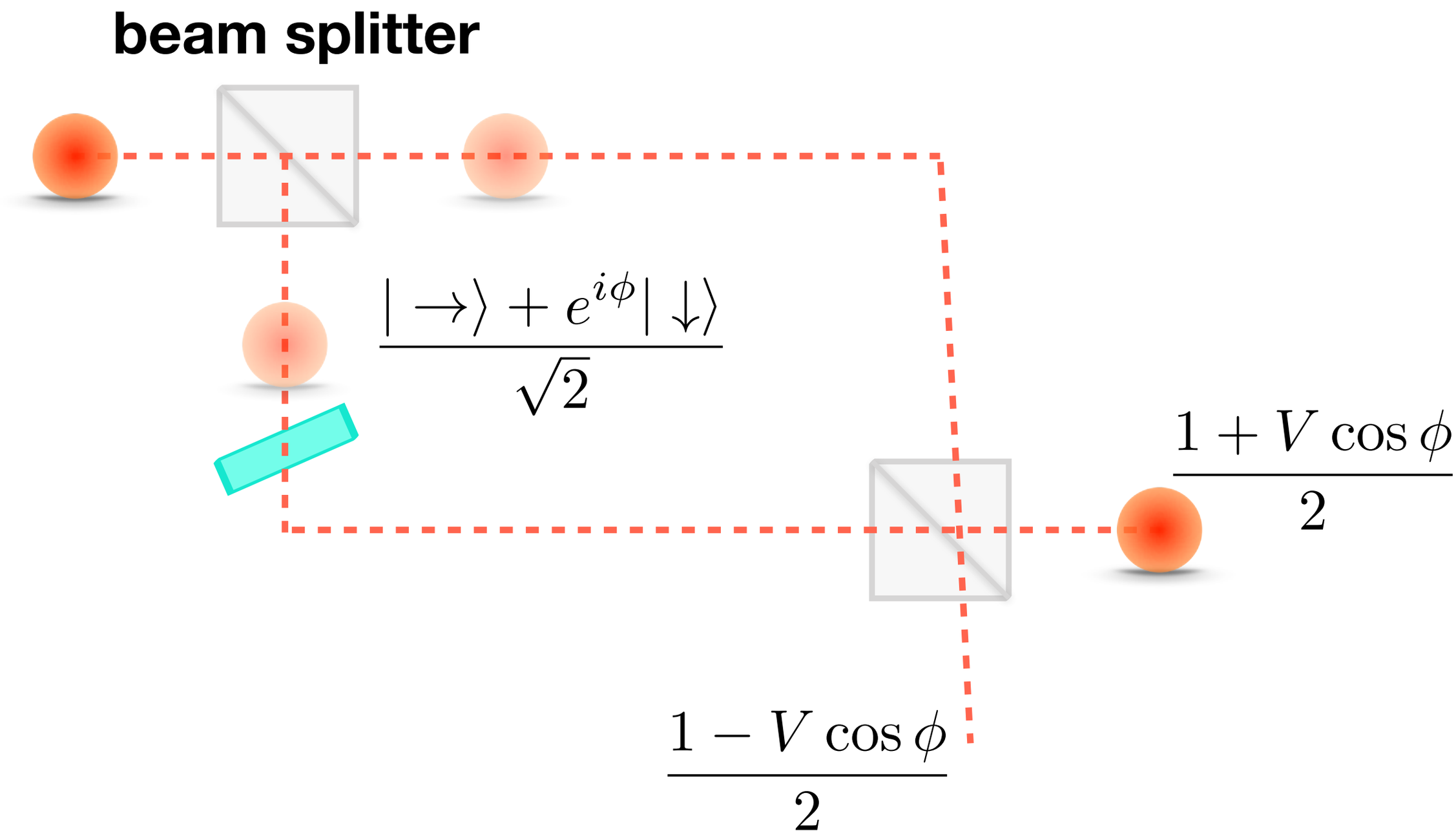
Quantum Phase Estimation



Quantum Phase Estimation

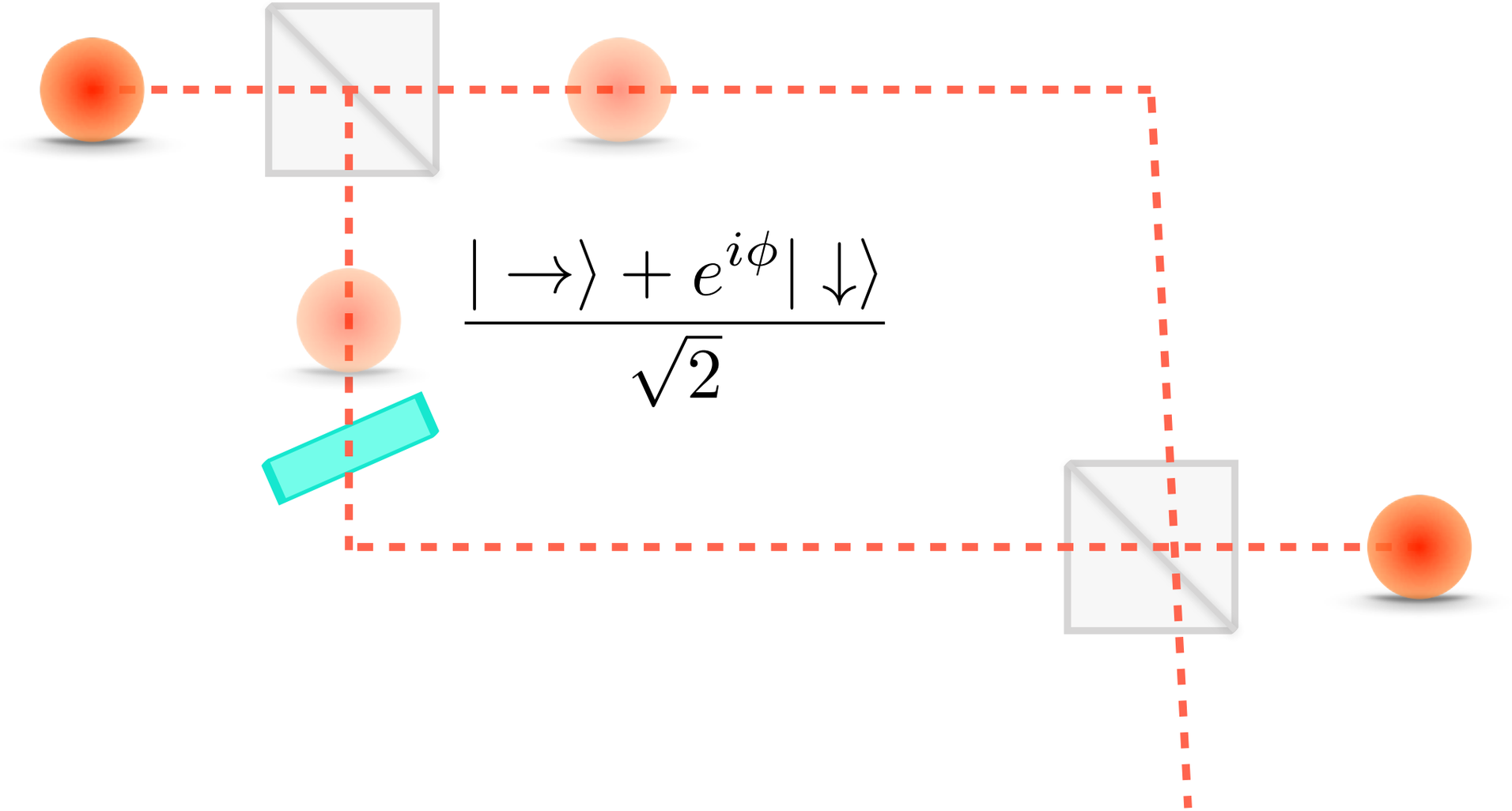


Quantum Phase Estimation

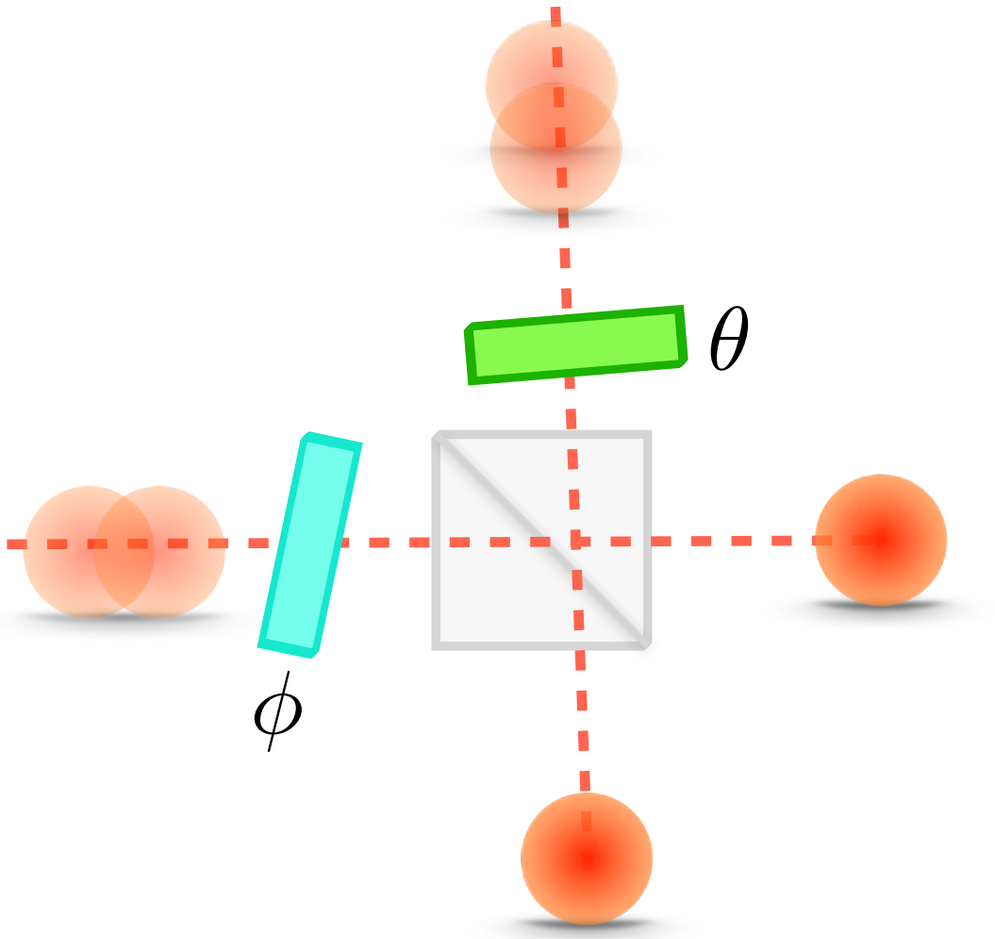


Quantum Phase Estimation

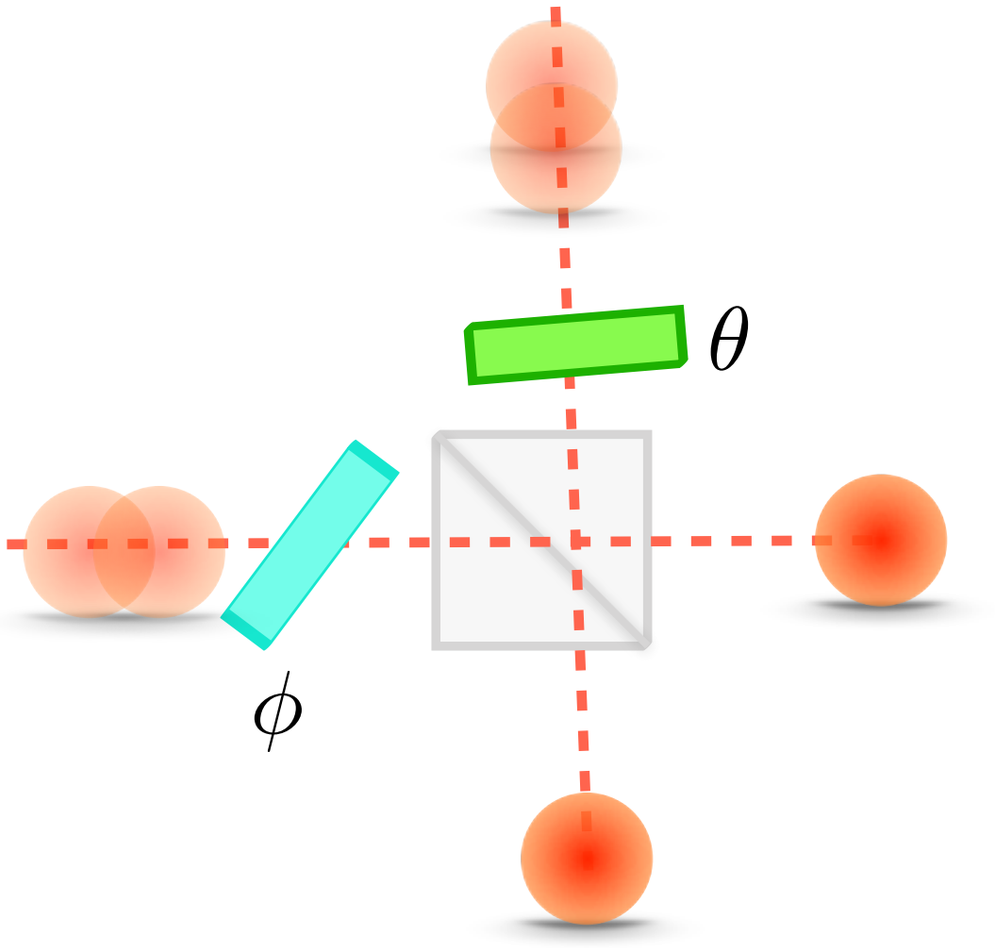
beam splitter

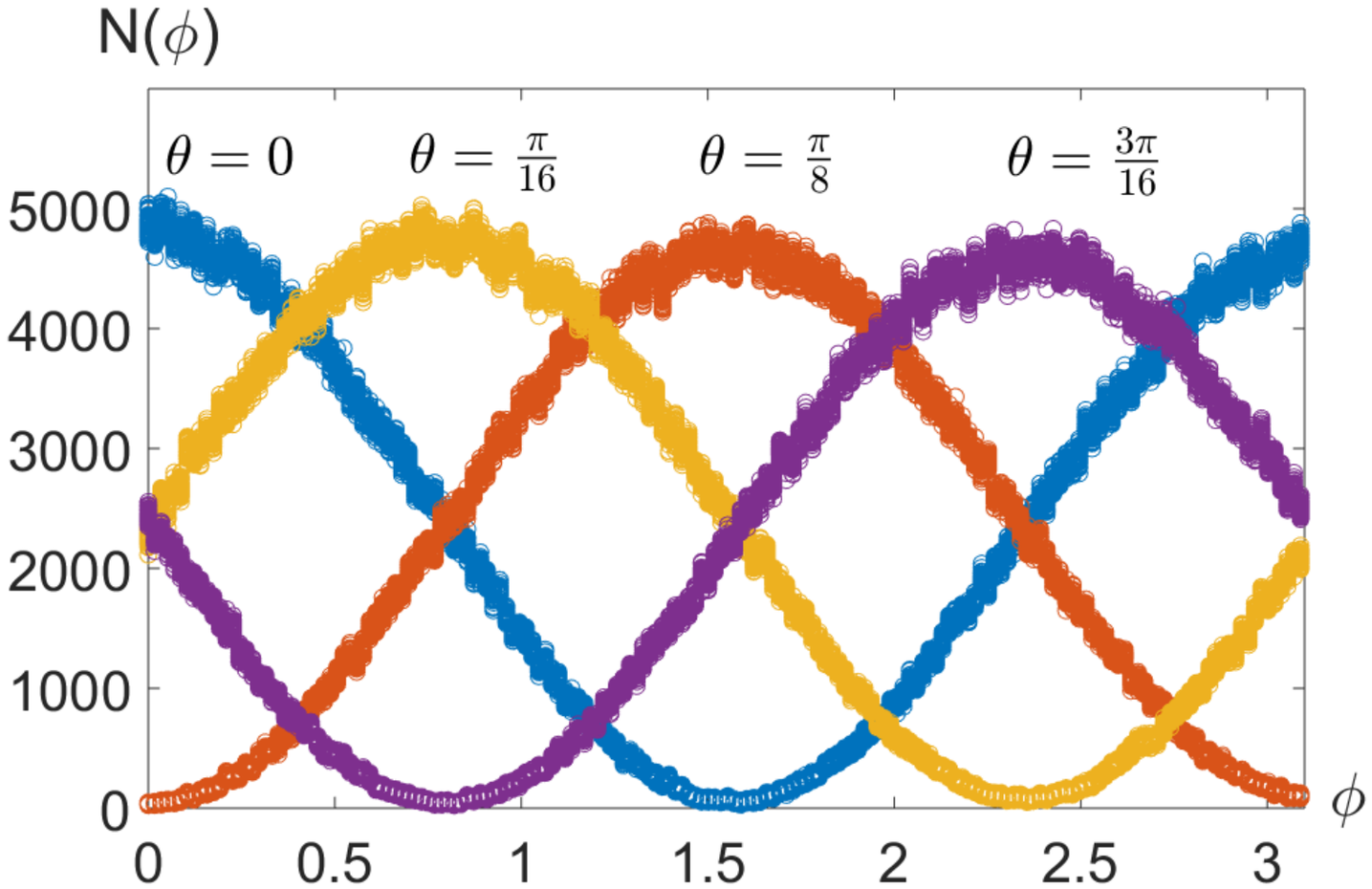


Coping with imperfections

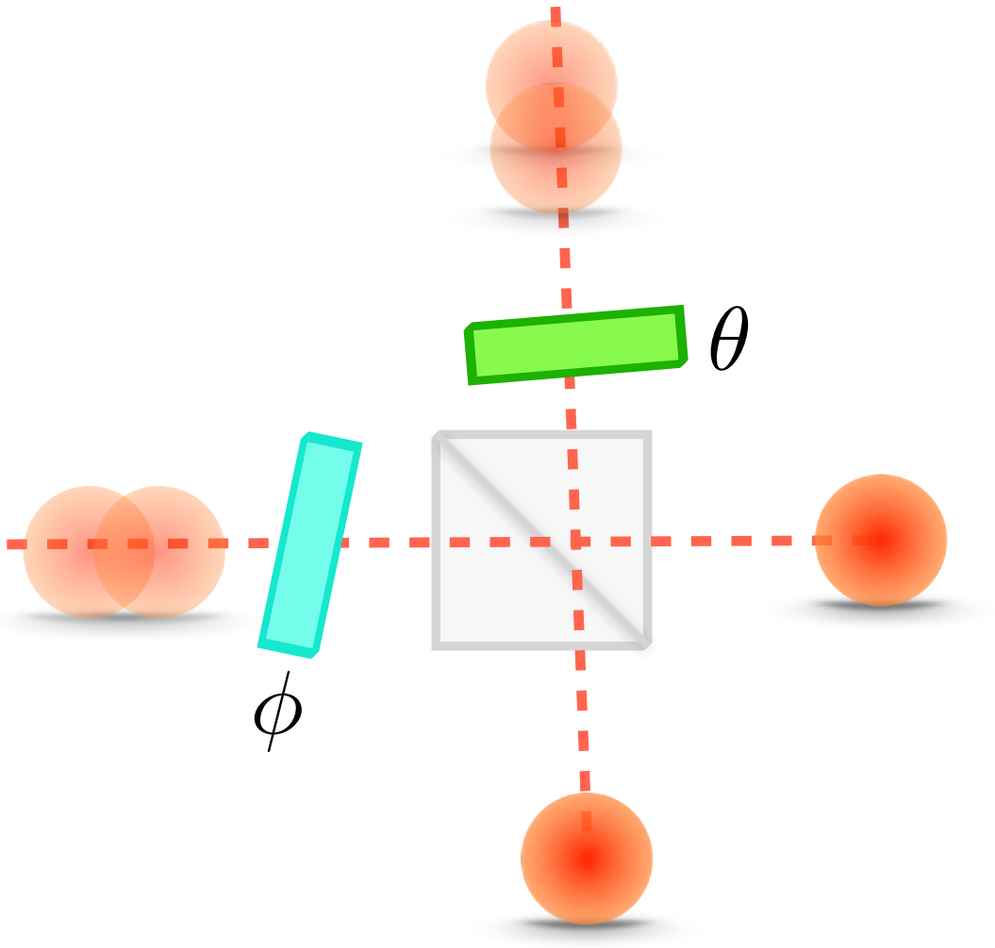


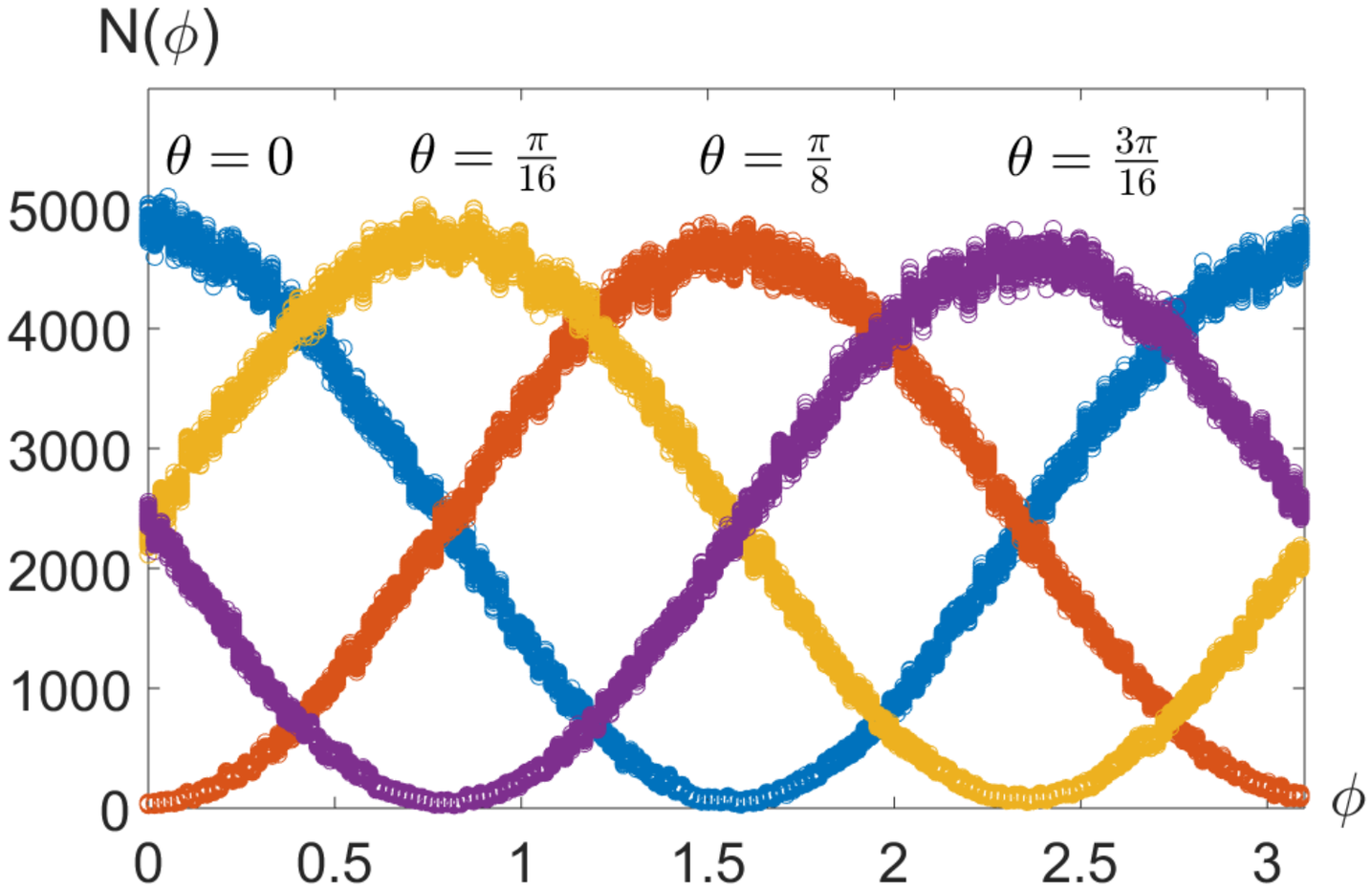
Coping with imperfections



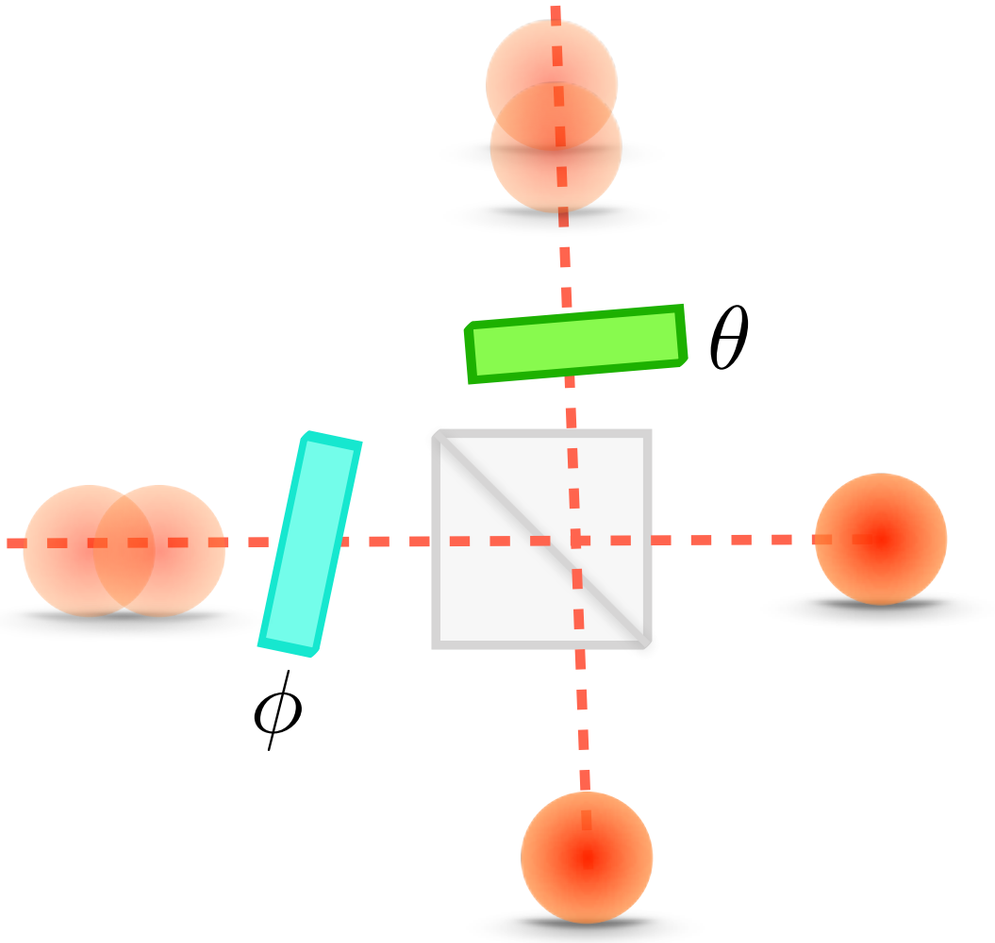


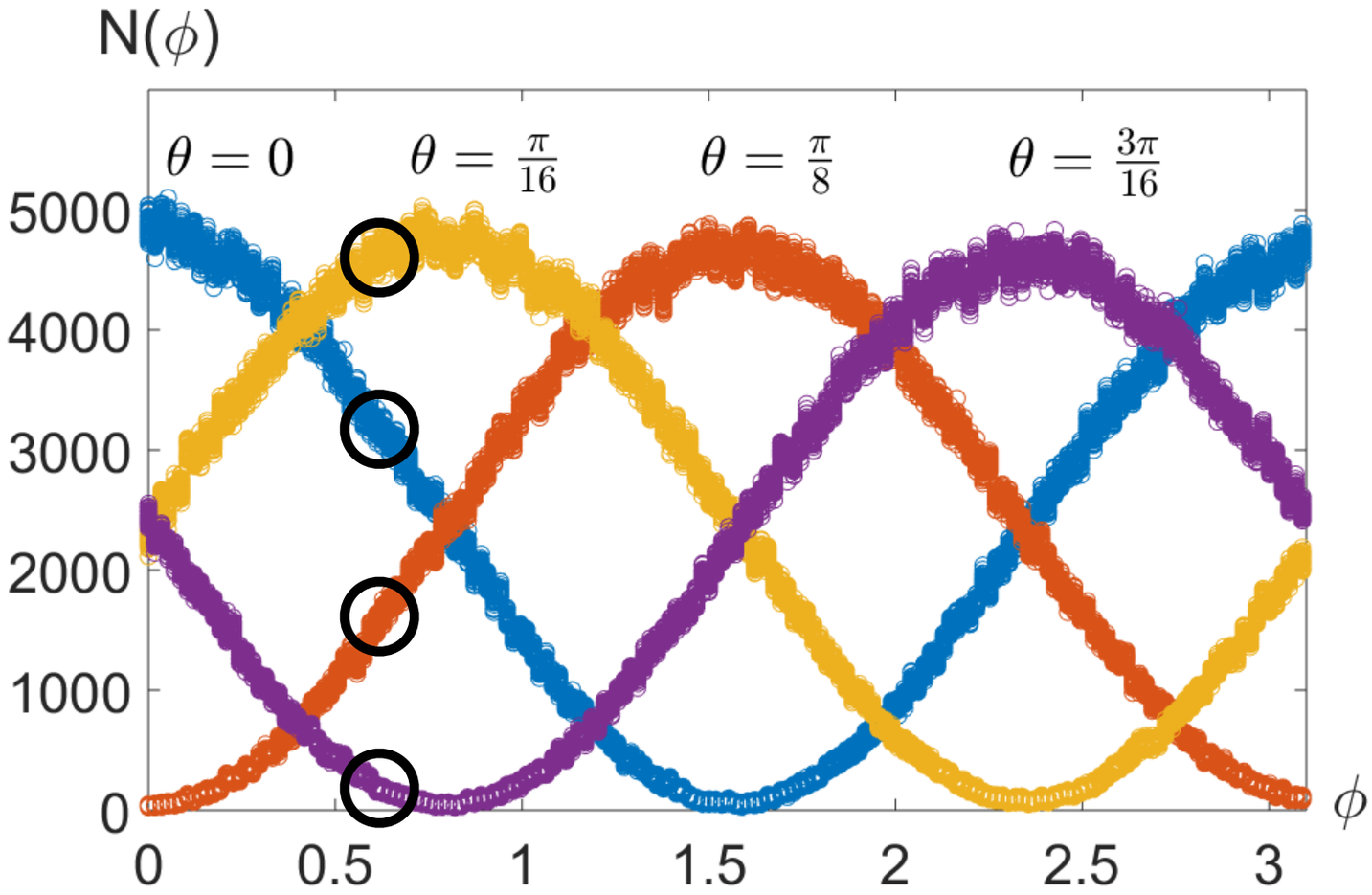
Multiparameter Estimation





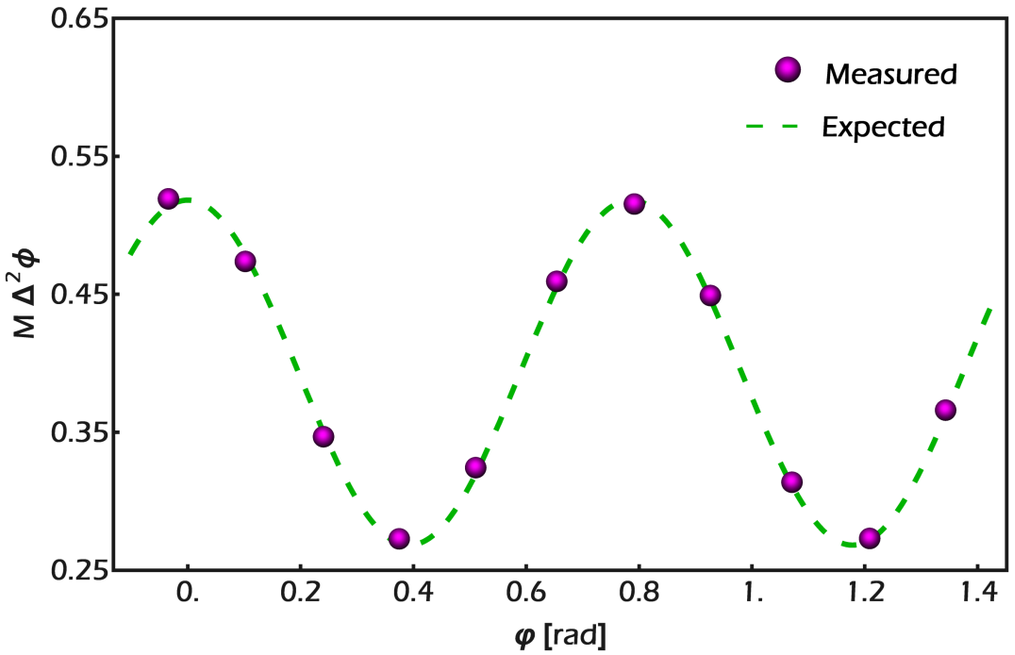
Multiparameter Estimation

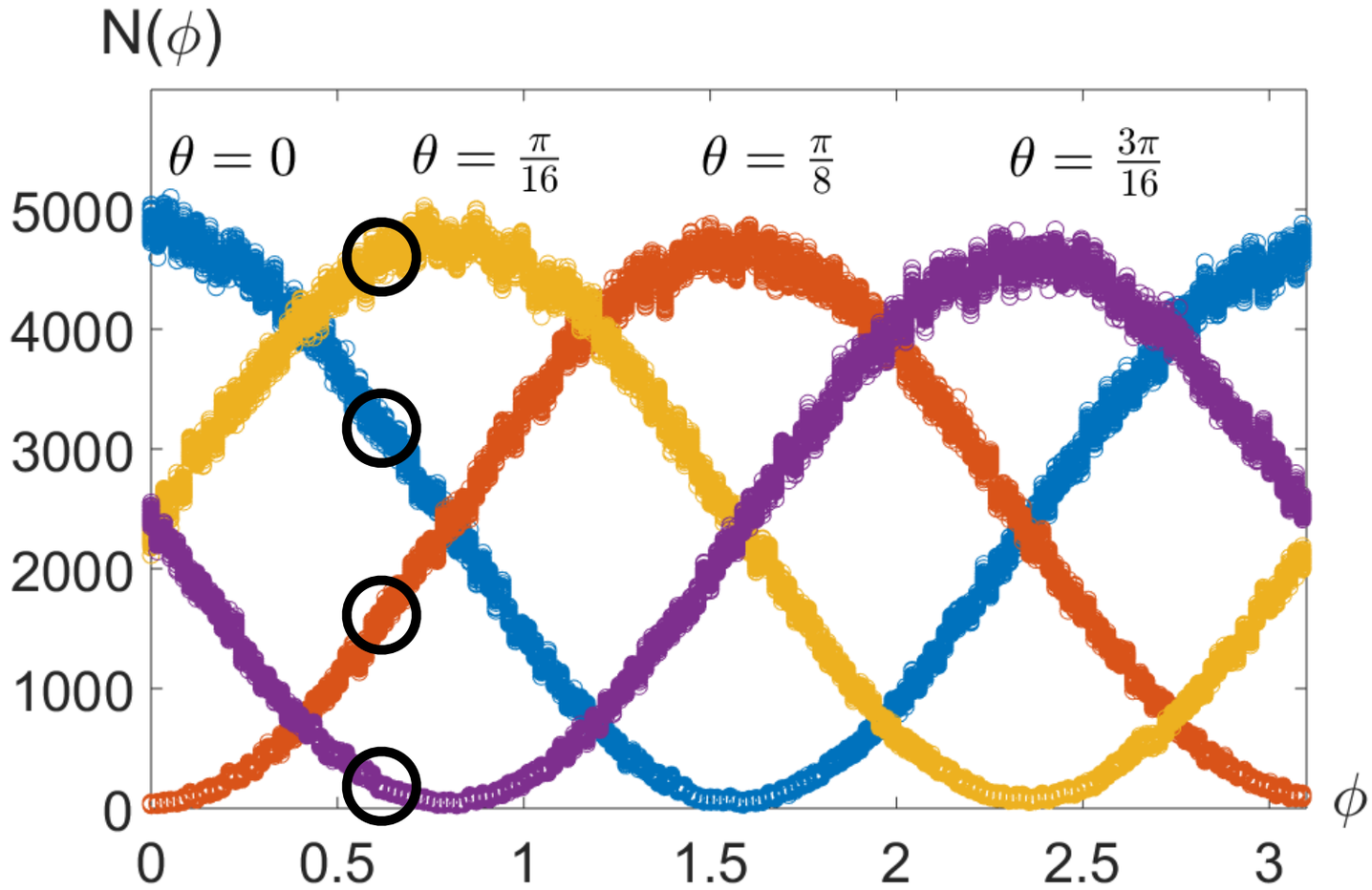




simultaneous estimation of phase and visibility

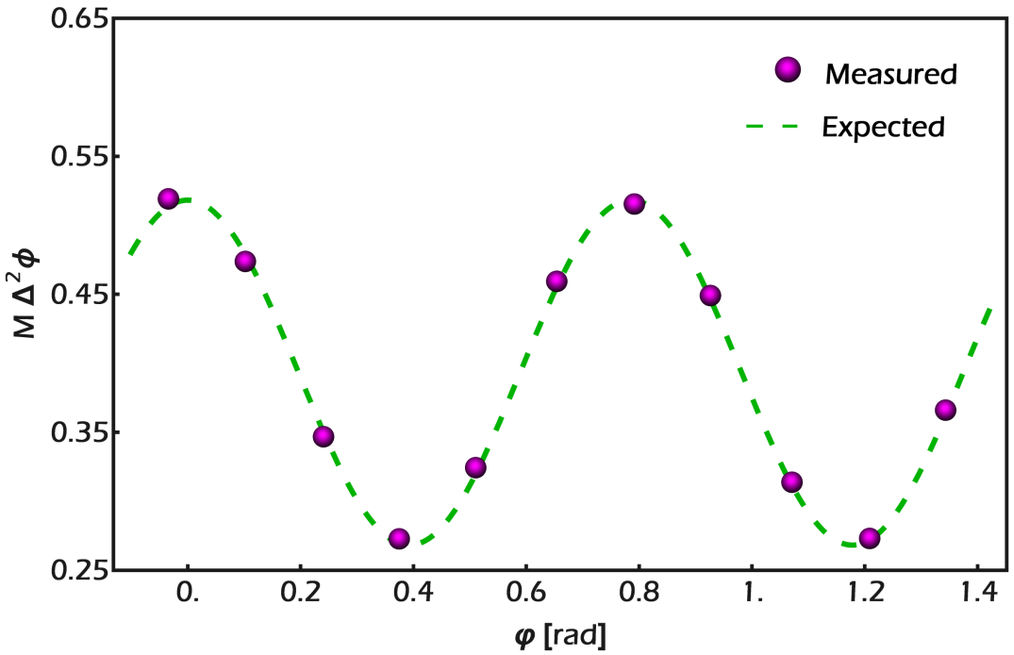
Multiparameter Estimation

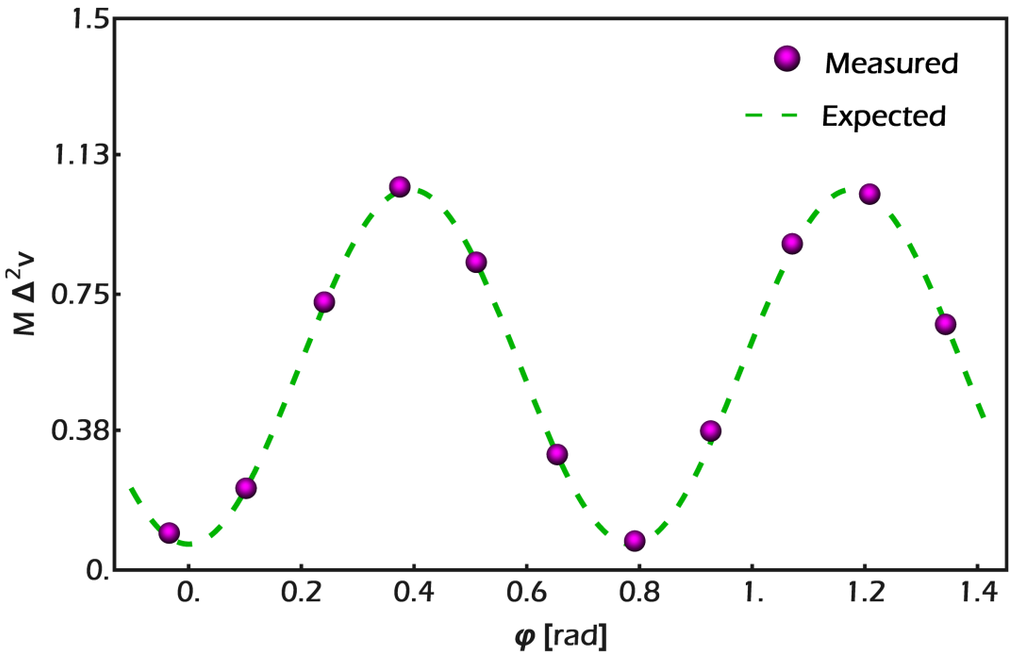




simultaneous estimation of phase and visibility

Multiparameter Estimation

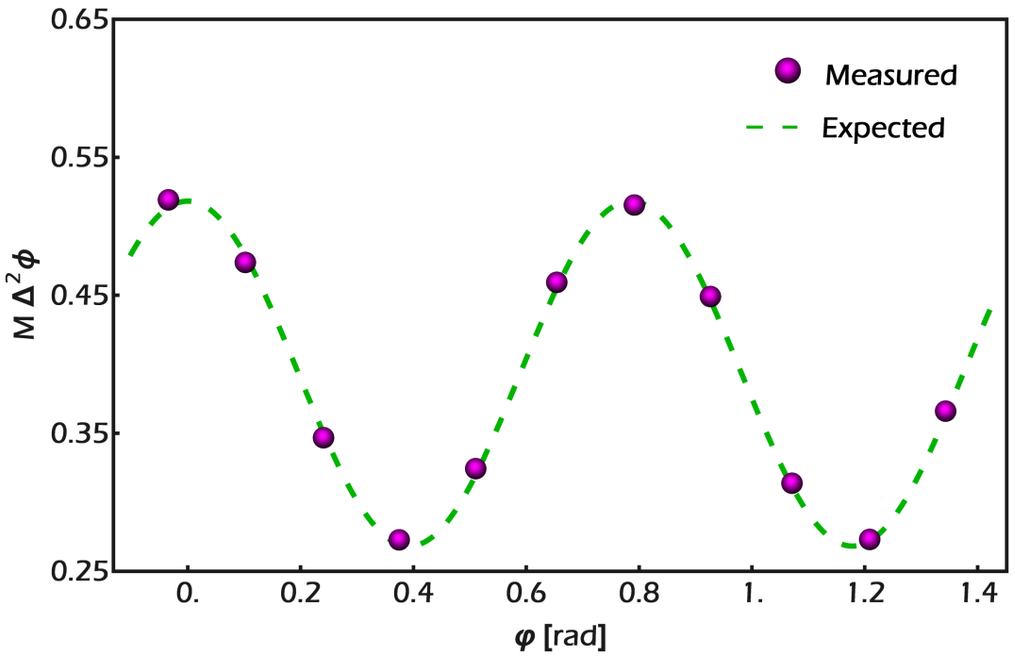


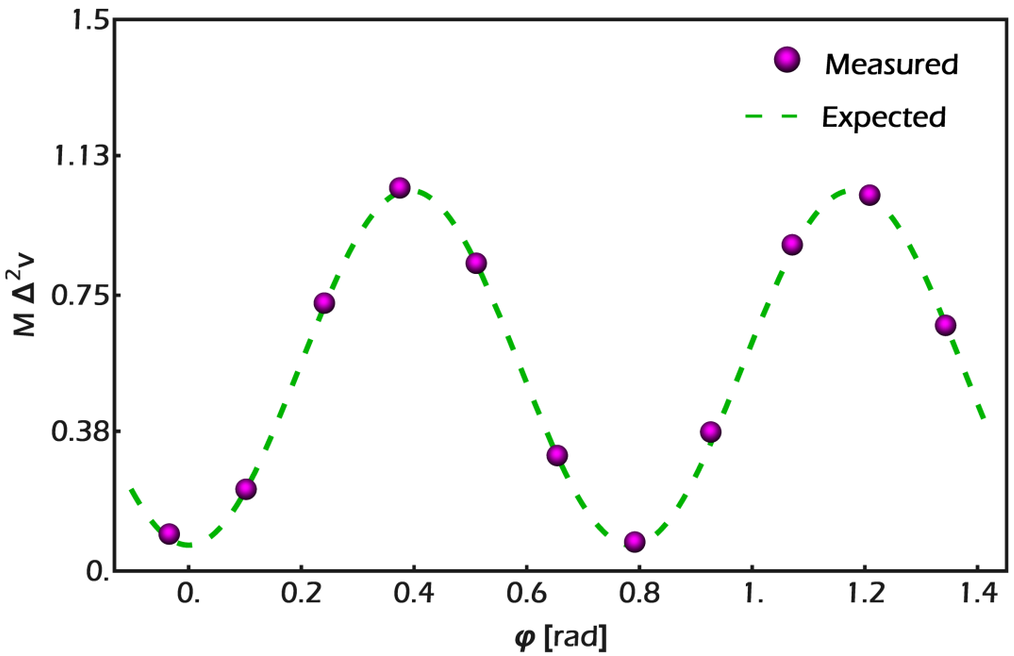


simultaneous estimation of phase and visibility

Multiparameter Estimation

simultaneous estimation of phase and visibility



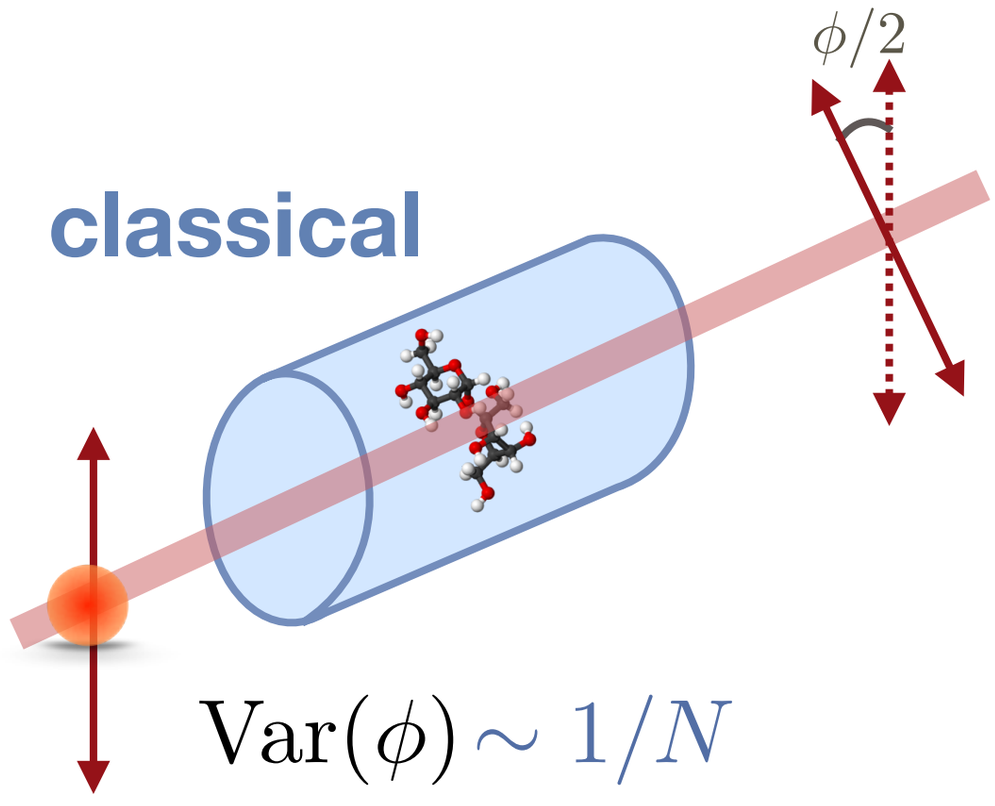


trade-off between resources invested on either parameter

sweet spots for phase/visibility estimation

Multiparameter Estimation

application to *optical activity*

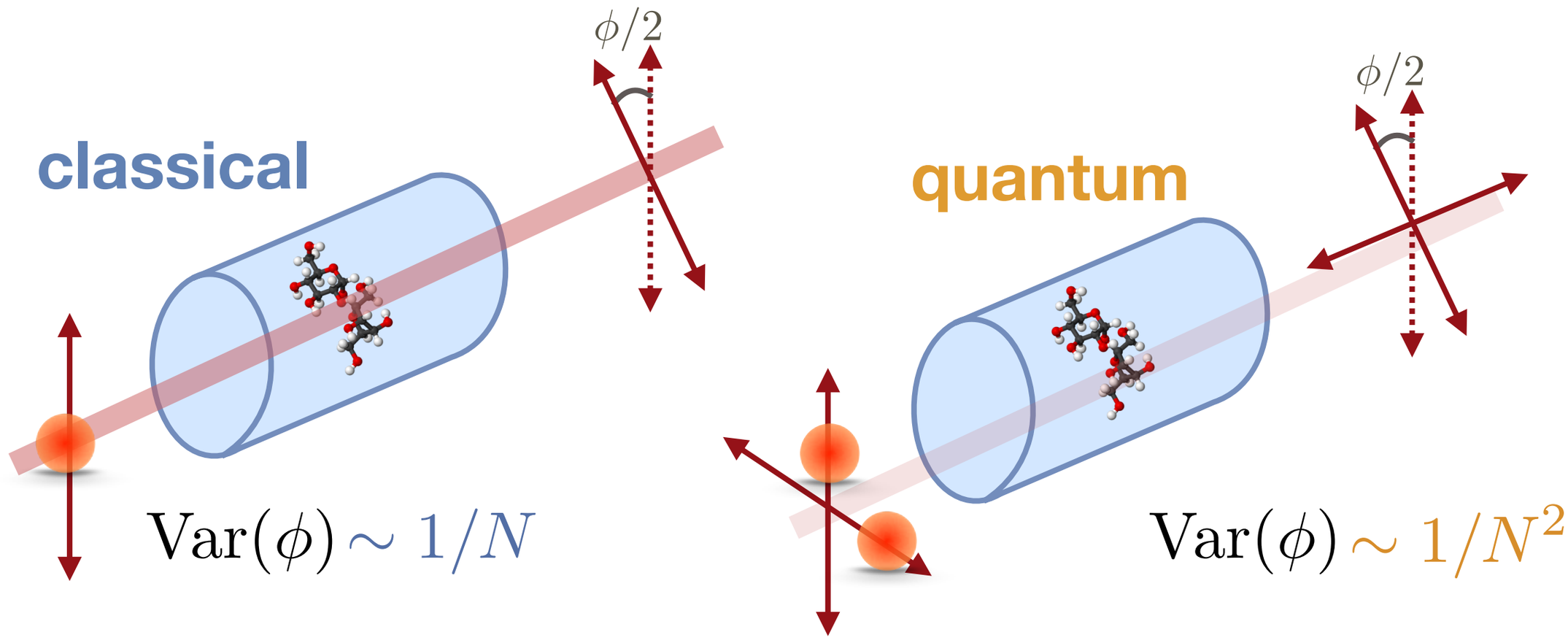


same requirements as phase estimation

N. Tischler et al., Science Adv. 2:e1601306 (2016)

Multiparameter Estimation

application to *optical activity*



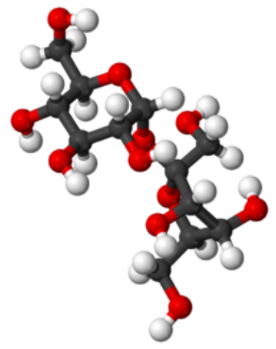
same requirements as phase estimation

N. Tischler et al., Science Adv. 2:e1601306 (2016)

Multiparameter Estimation

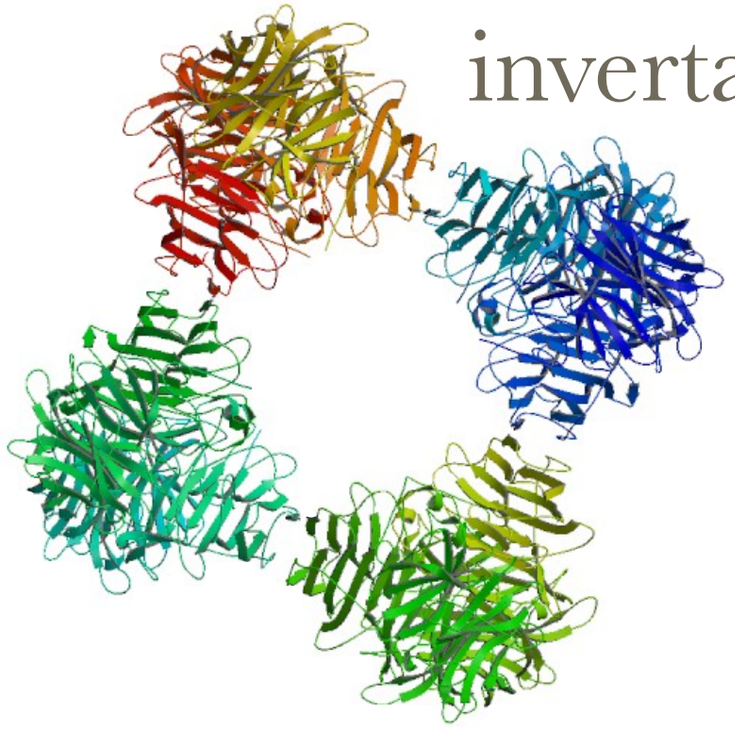
application to *changes of optical activity*

sucrose

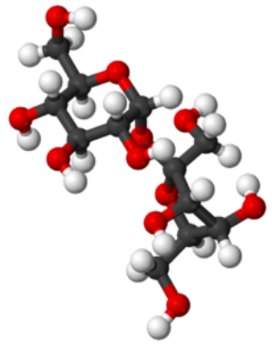


Multiparameter Estimation

application to *changes of optical activity*



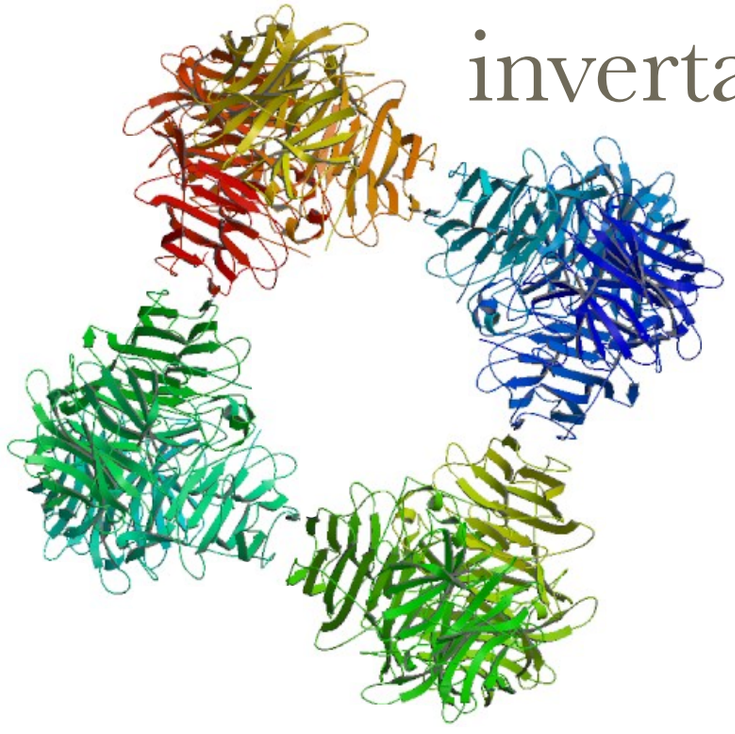
invertase



sucrose

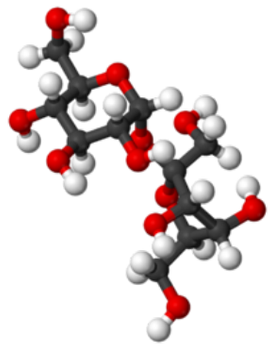
Multiparameter Estimation

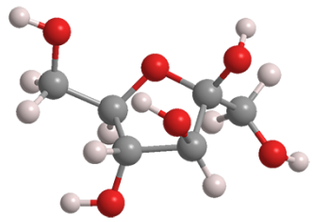
application to *changes of optical activity*



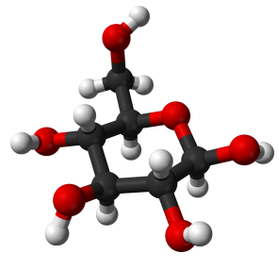
invertase

sucrose





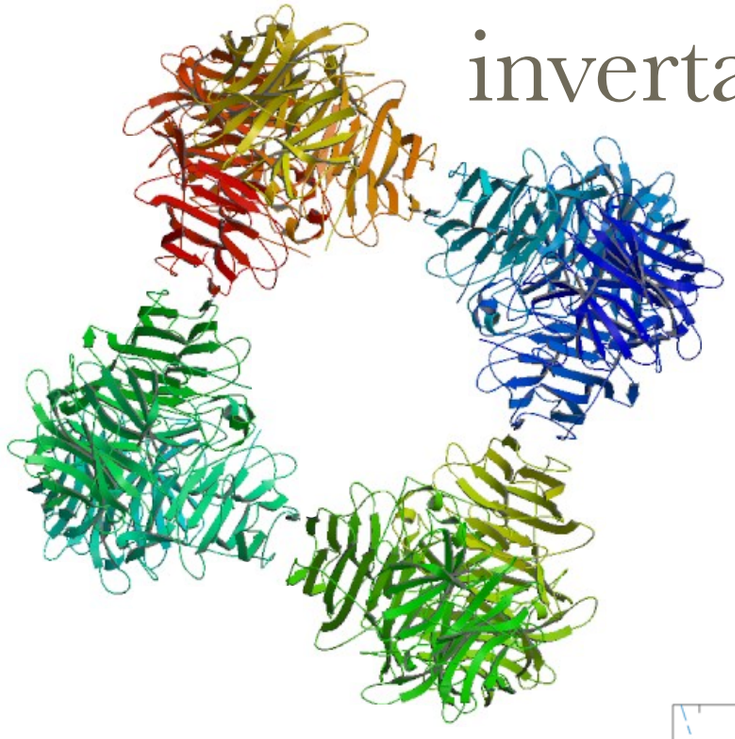
fructose



glucose

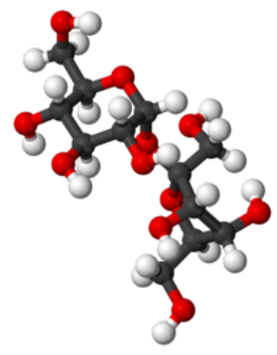
Multiparameter Estimation

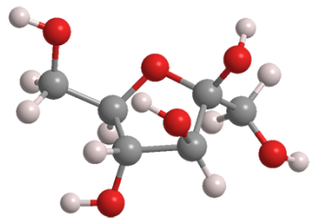
application to *changes of optical activity*



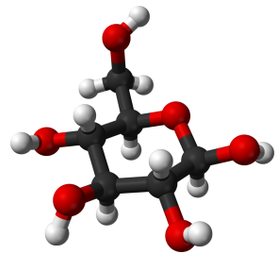
invertase

sucrose

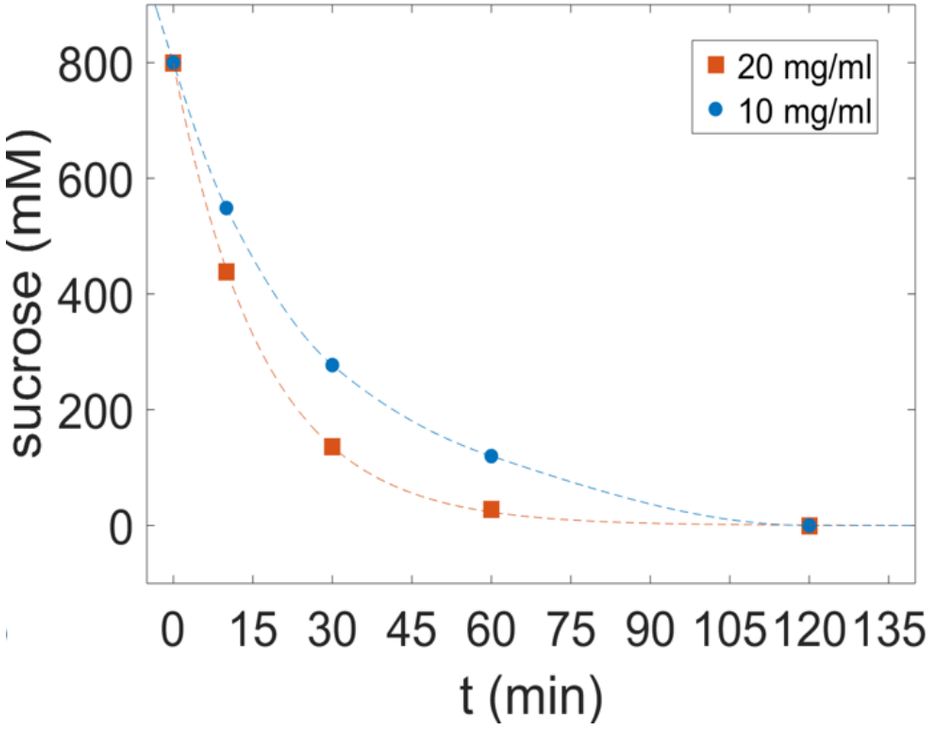




fructose

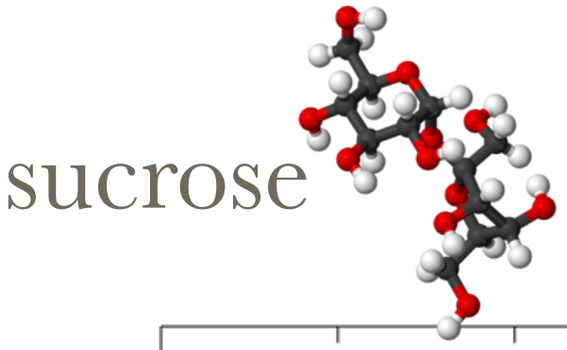


glucose

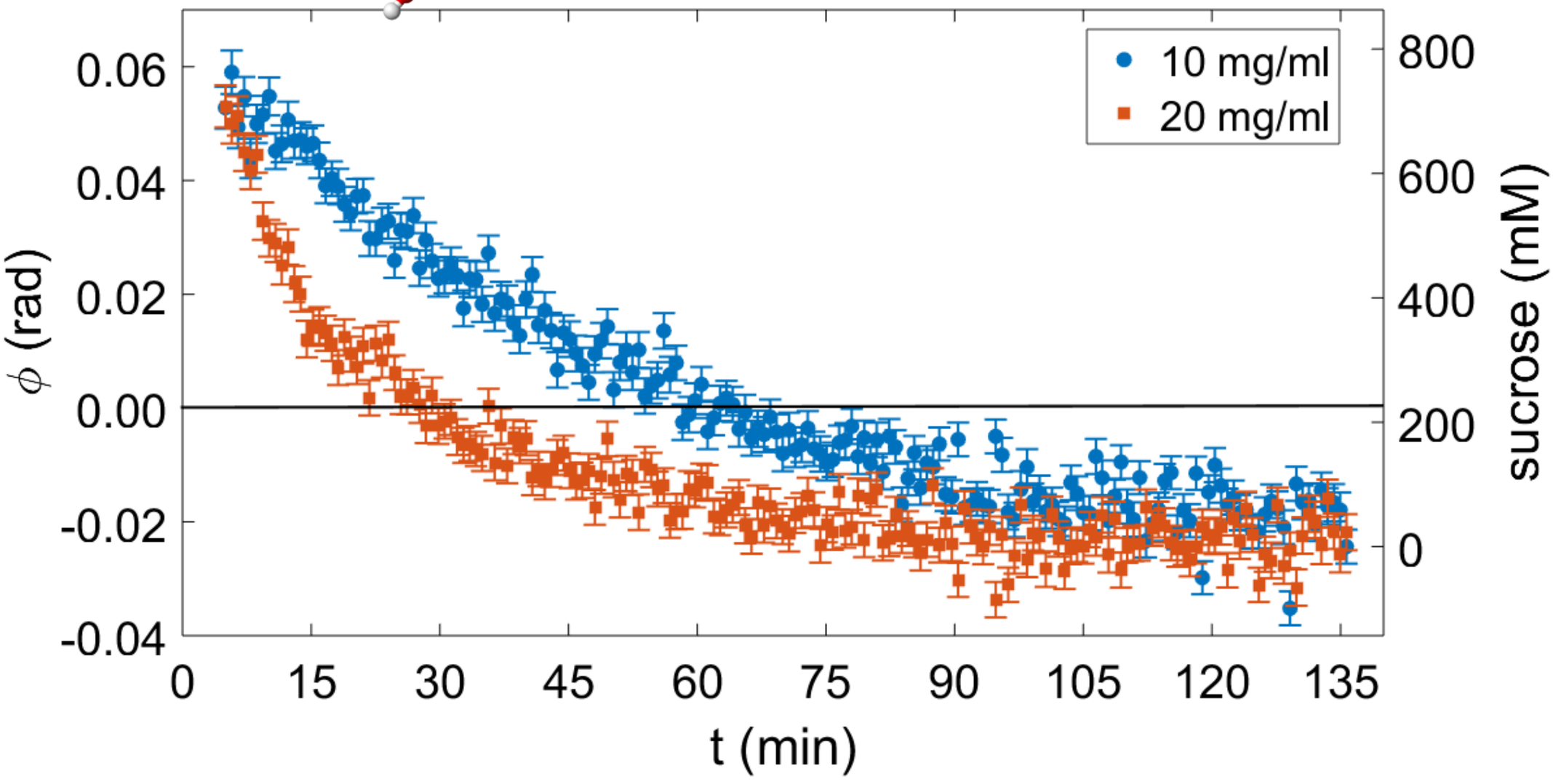


Multiparameter Estimation

application to *changes of optical activity*

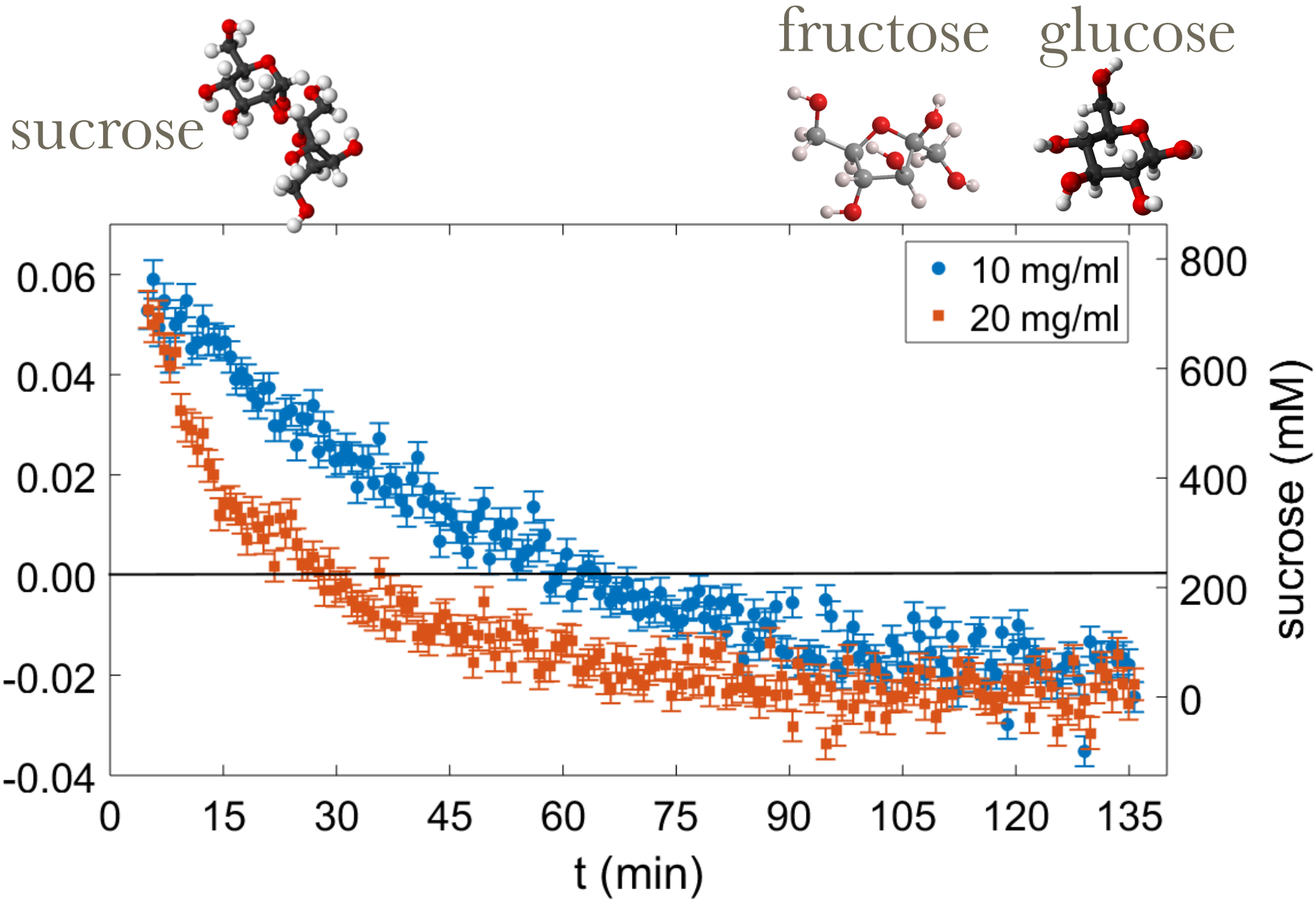


sucrose



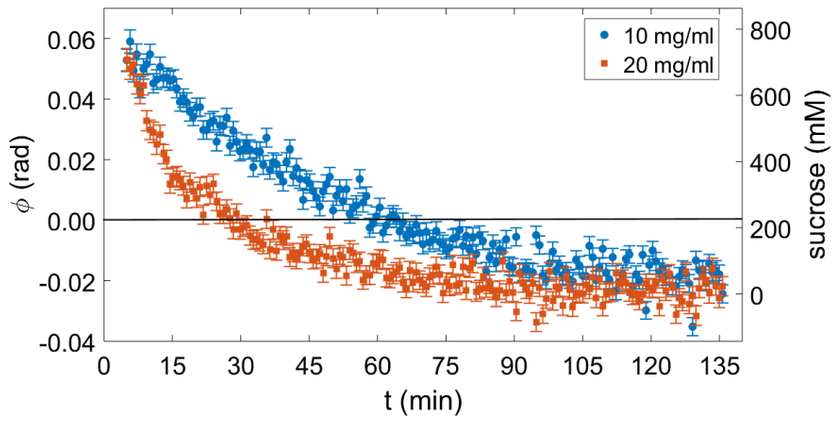
Multiparameter Estimation

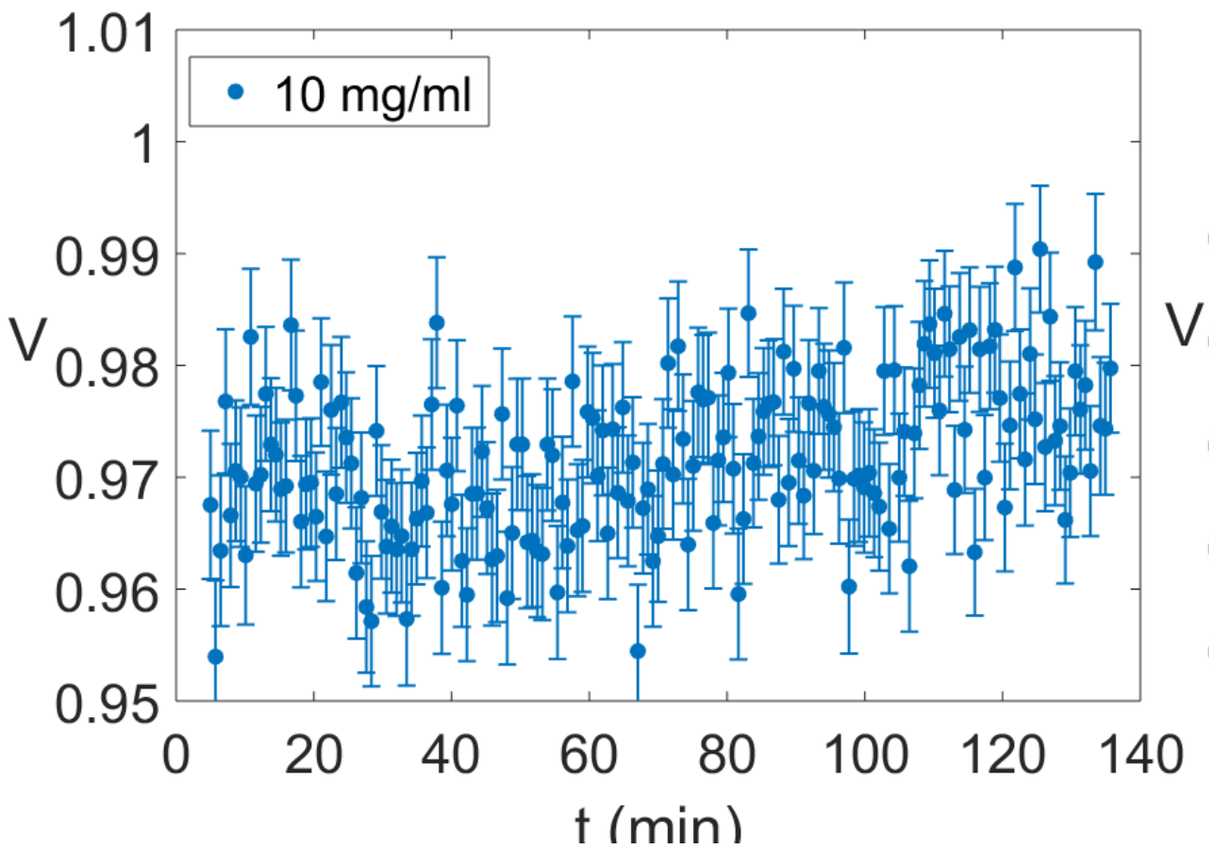
application to *changes of optical activity*

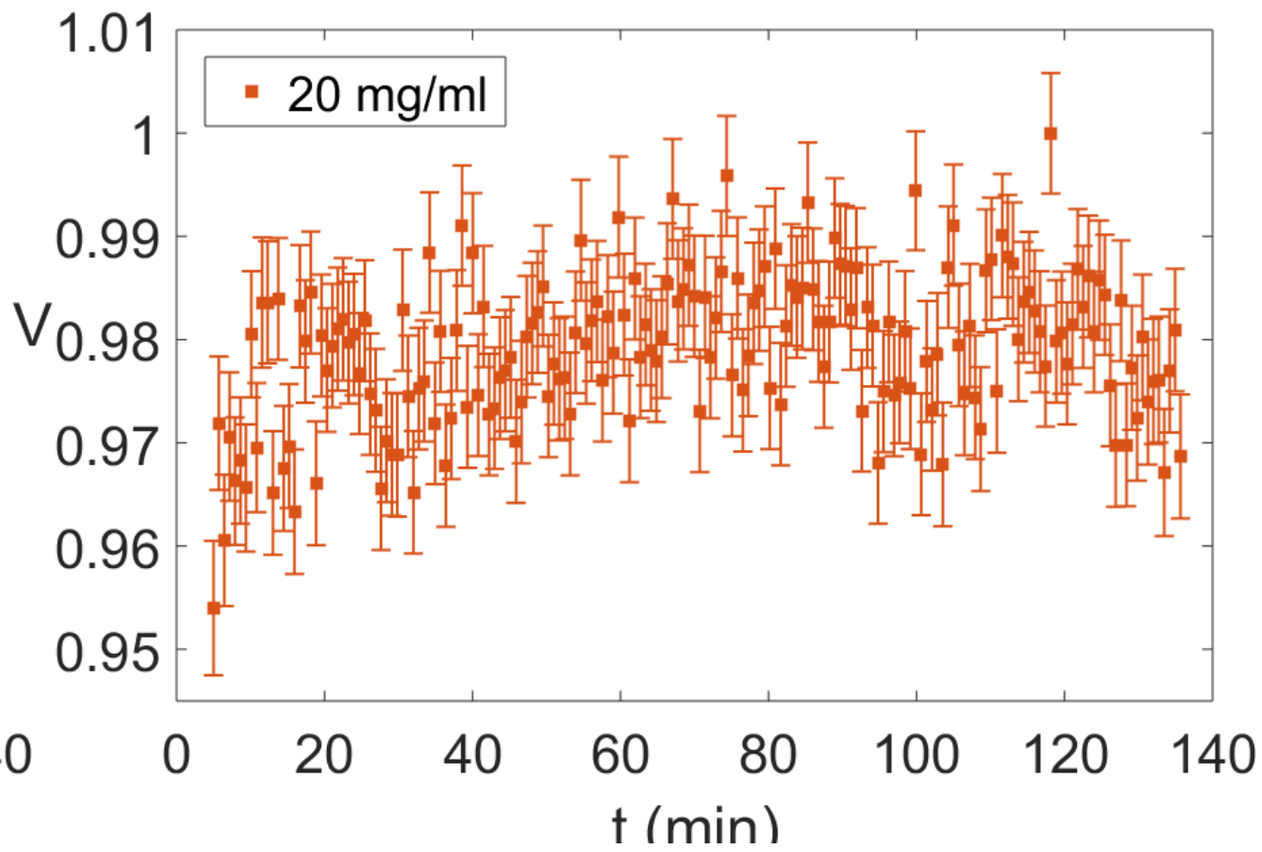


Multiparameter Estimation

application to *changes of optical activity*

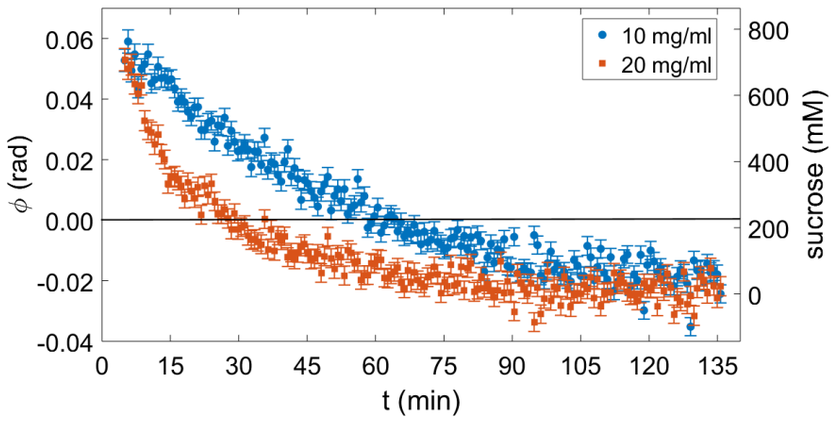


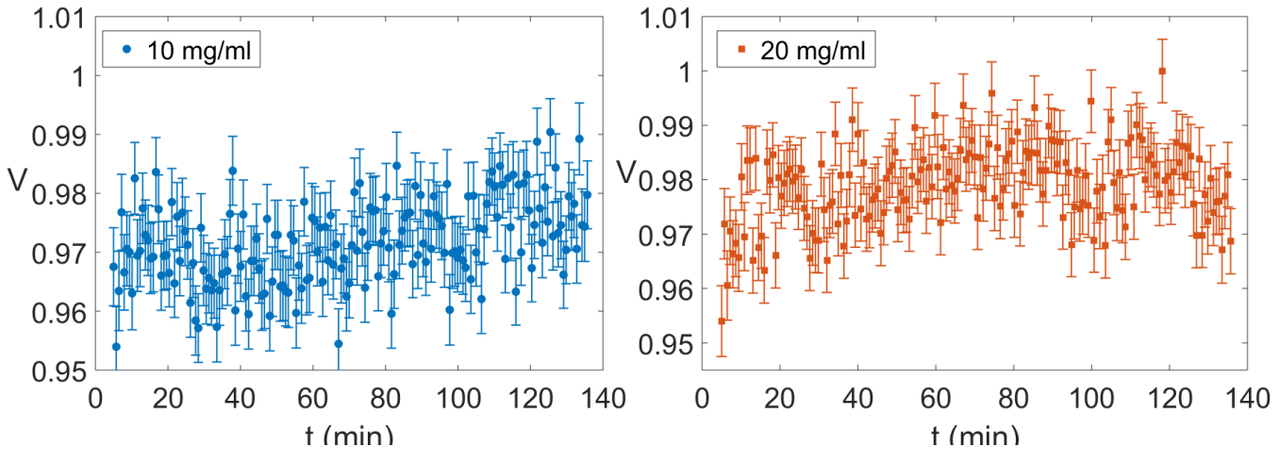


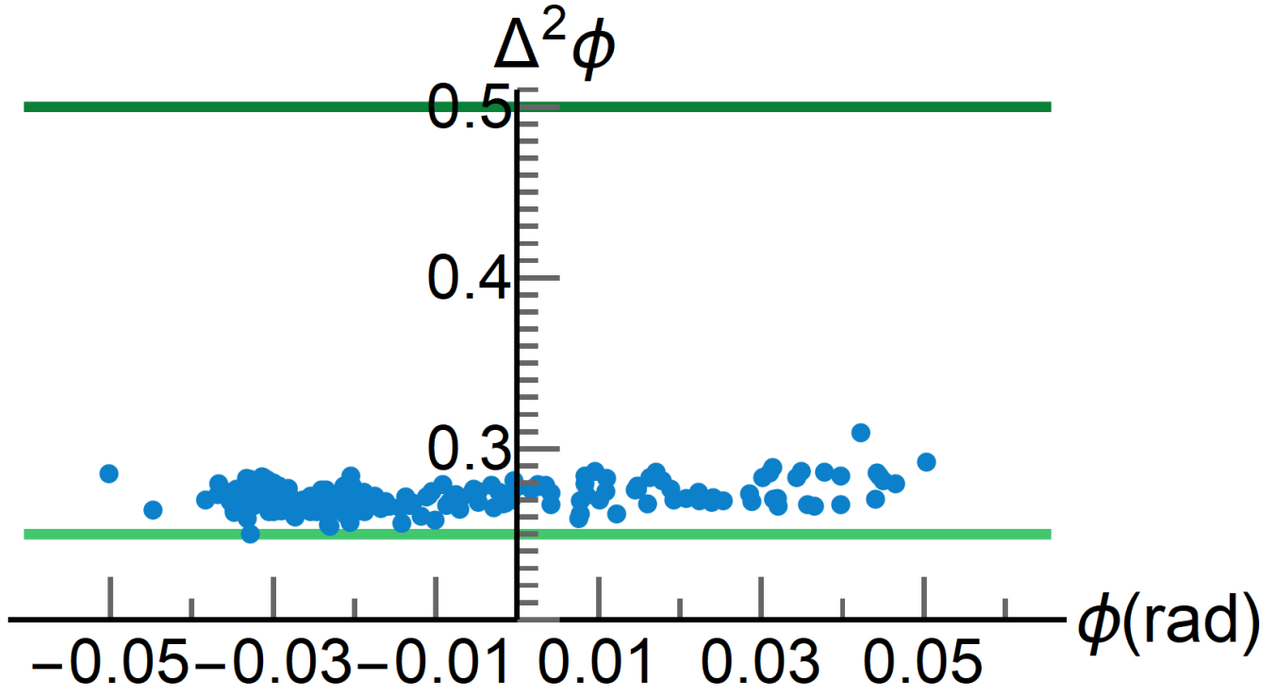


Multiparameter Estimation

application to *changes of optical activity*



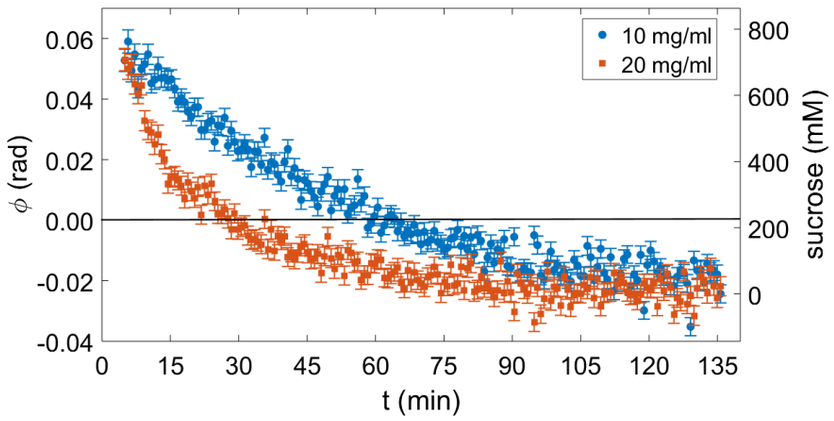


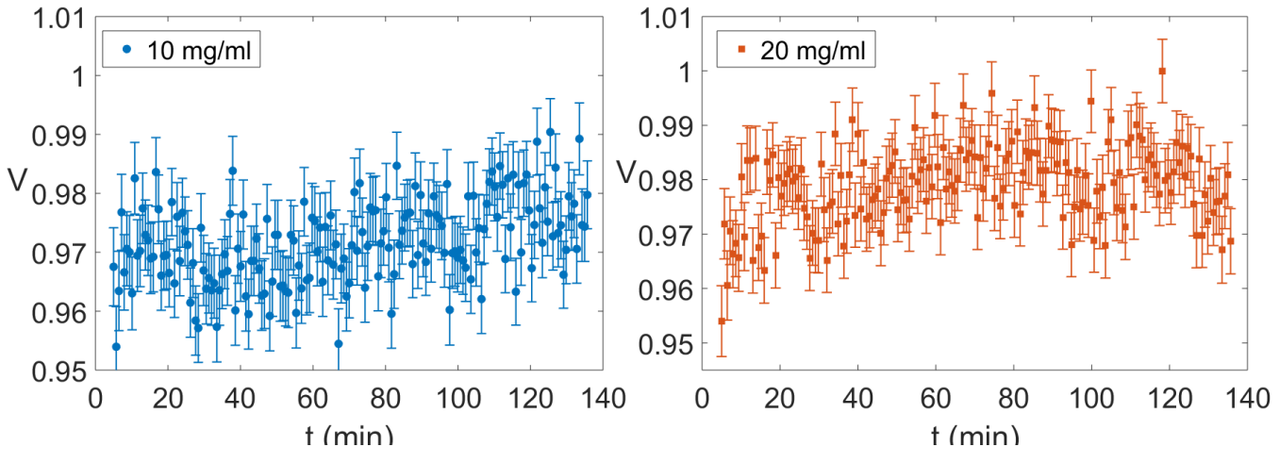


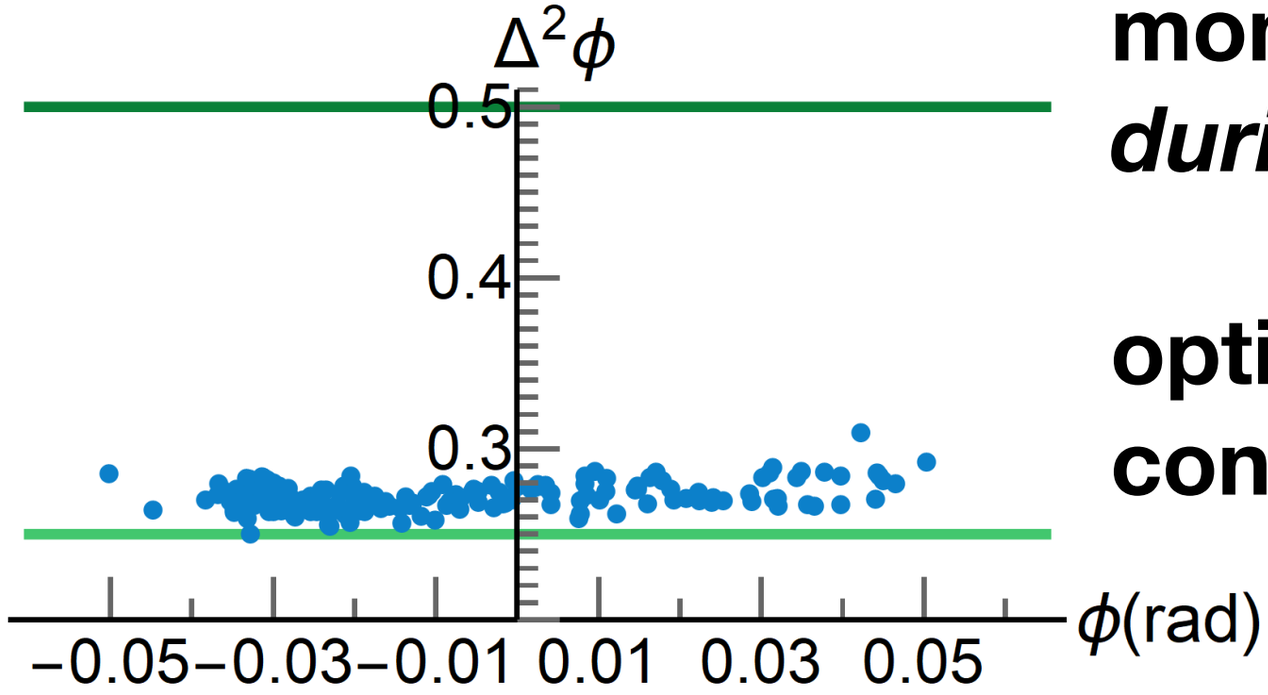
V. Cimini et al., Op. Ex. 27, 35245 (2019)

Multiparameter Estimation

application to *changes of optical activity*







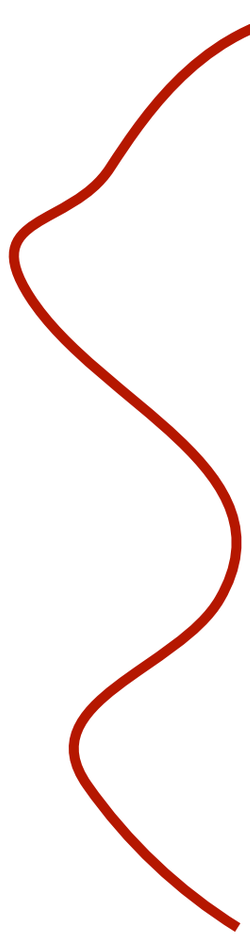
monitoring the exp conditions *during* the measurement

optimising the measurement conditions via adaptation

V. Cimini et al., Op. Ex. 27, 35245 (2019)

Function Estimation

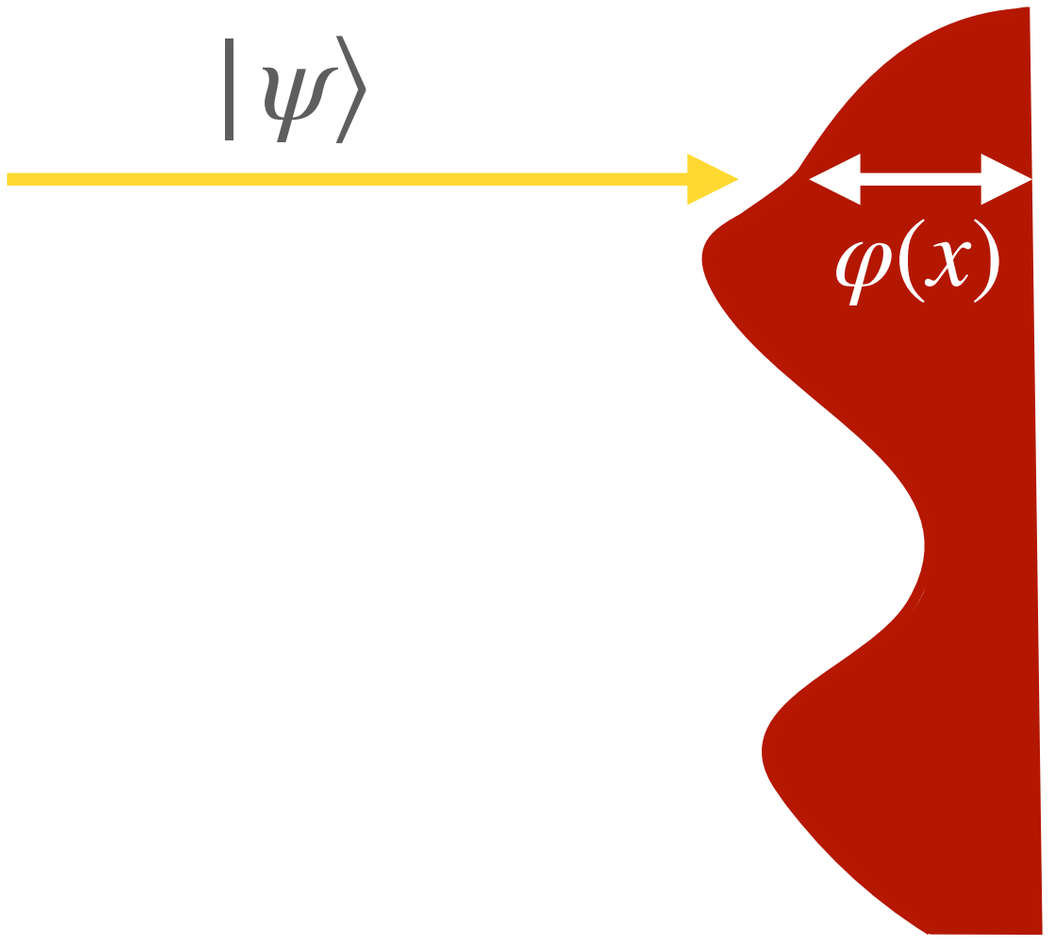
estimating a function with quantum enhancement



N. Kura et al
PRL 124, 010507 (2020)

Function Estimation

estimating a function with quantum enhancement



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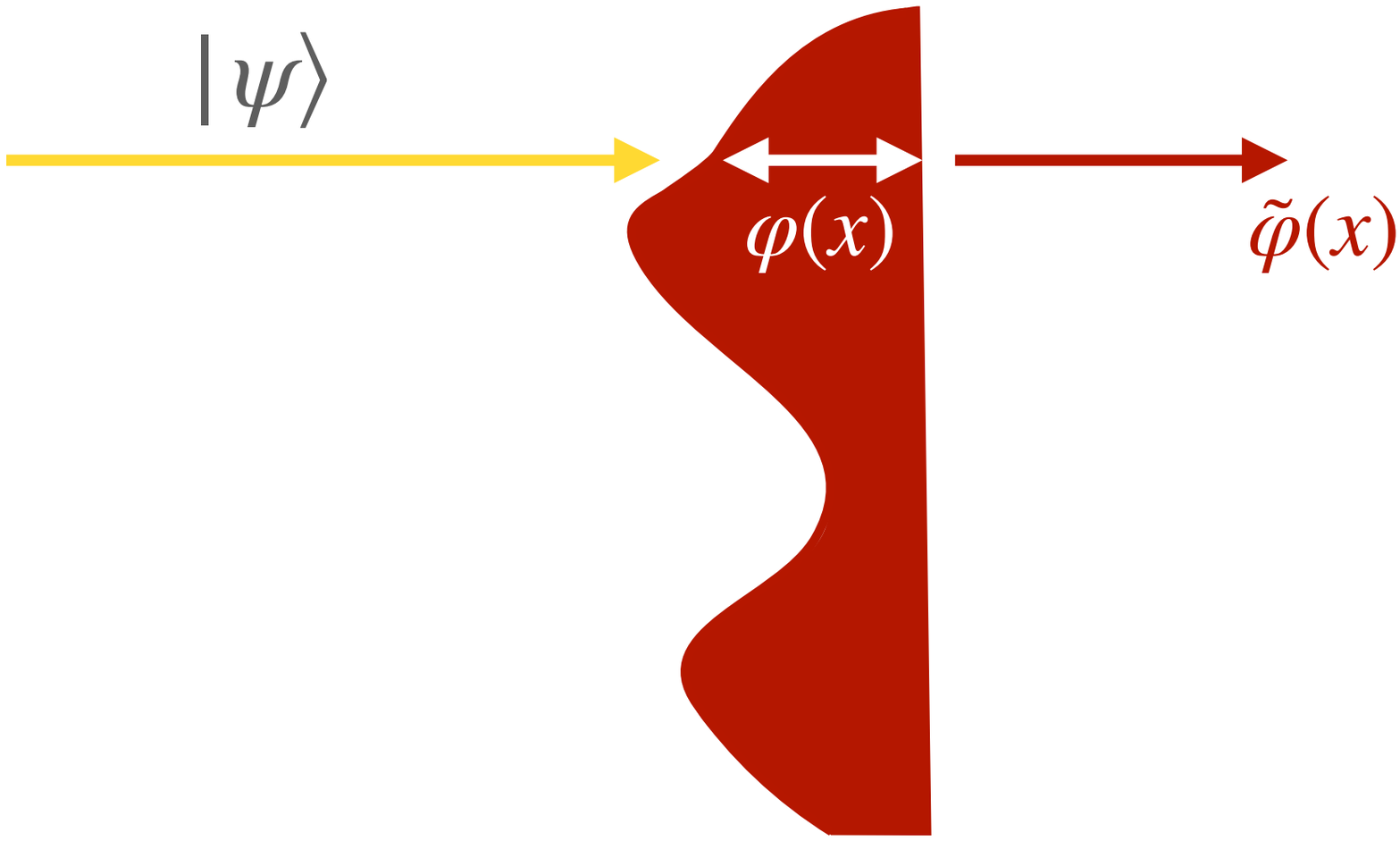

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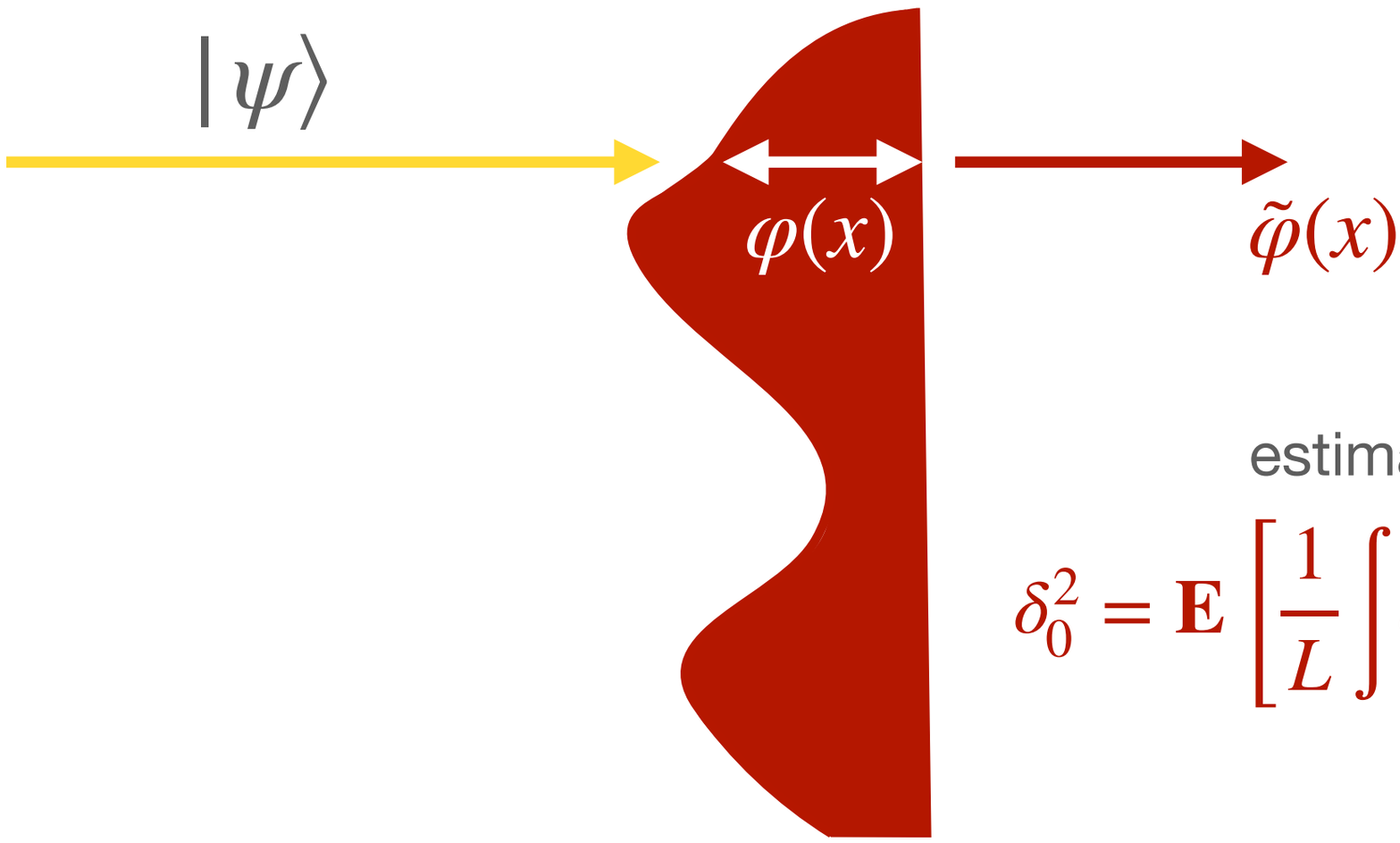

estimation error

$$\delta_0^2 = \mathbf{E}\left[\frac{1}{L}\int dx\,|\,\varphi(x) - \tilde{\varphi}(x)\,|^2\right]$$

N. Kura et al
PRL 124, 010507 (2020)

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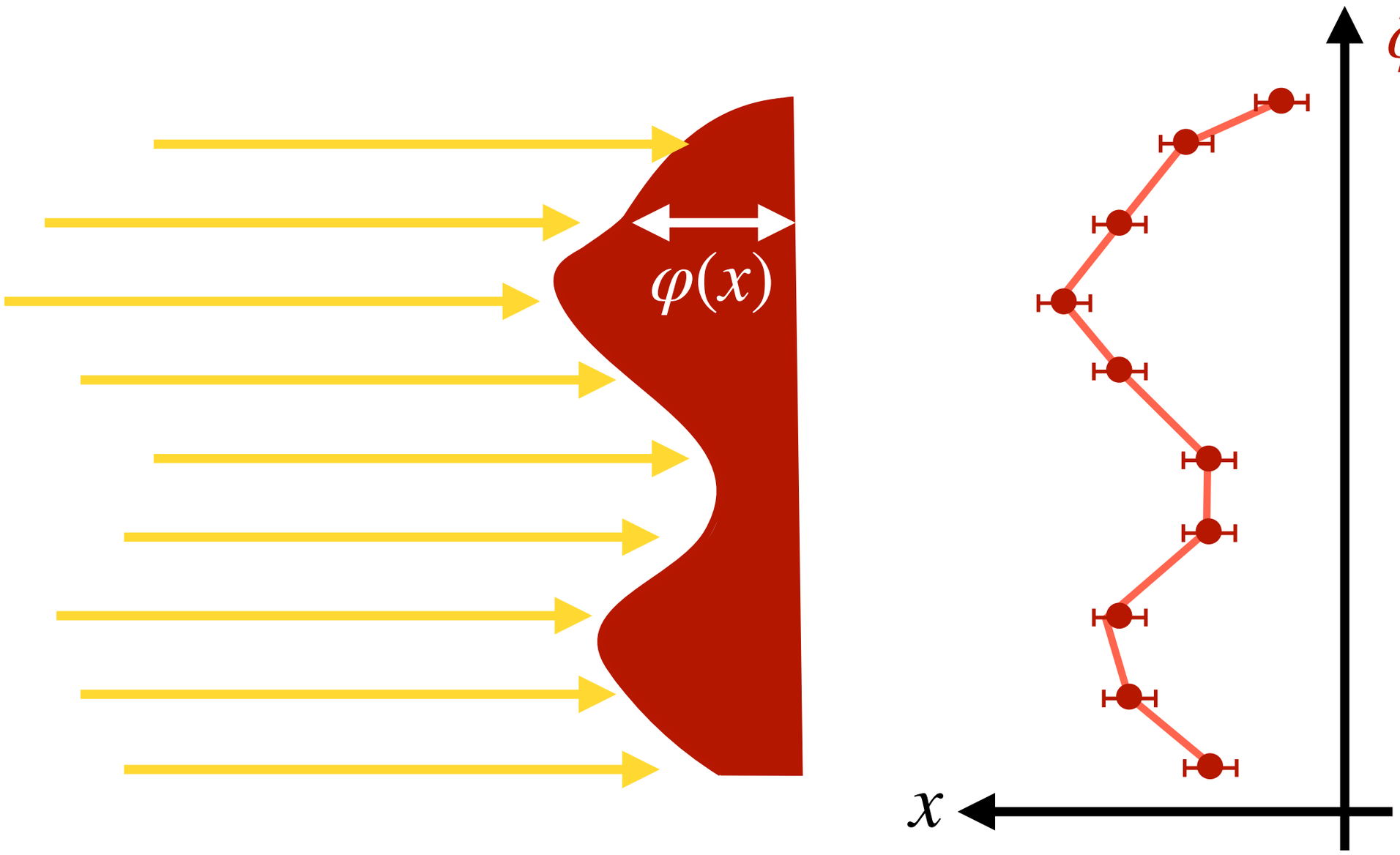
estimating a function with quantum enhancement



N. Kura et al
PRL 124, 010507 (2020)

Function Estimation

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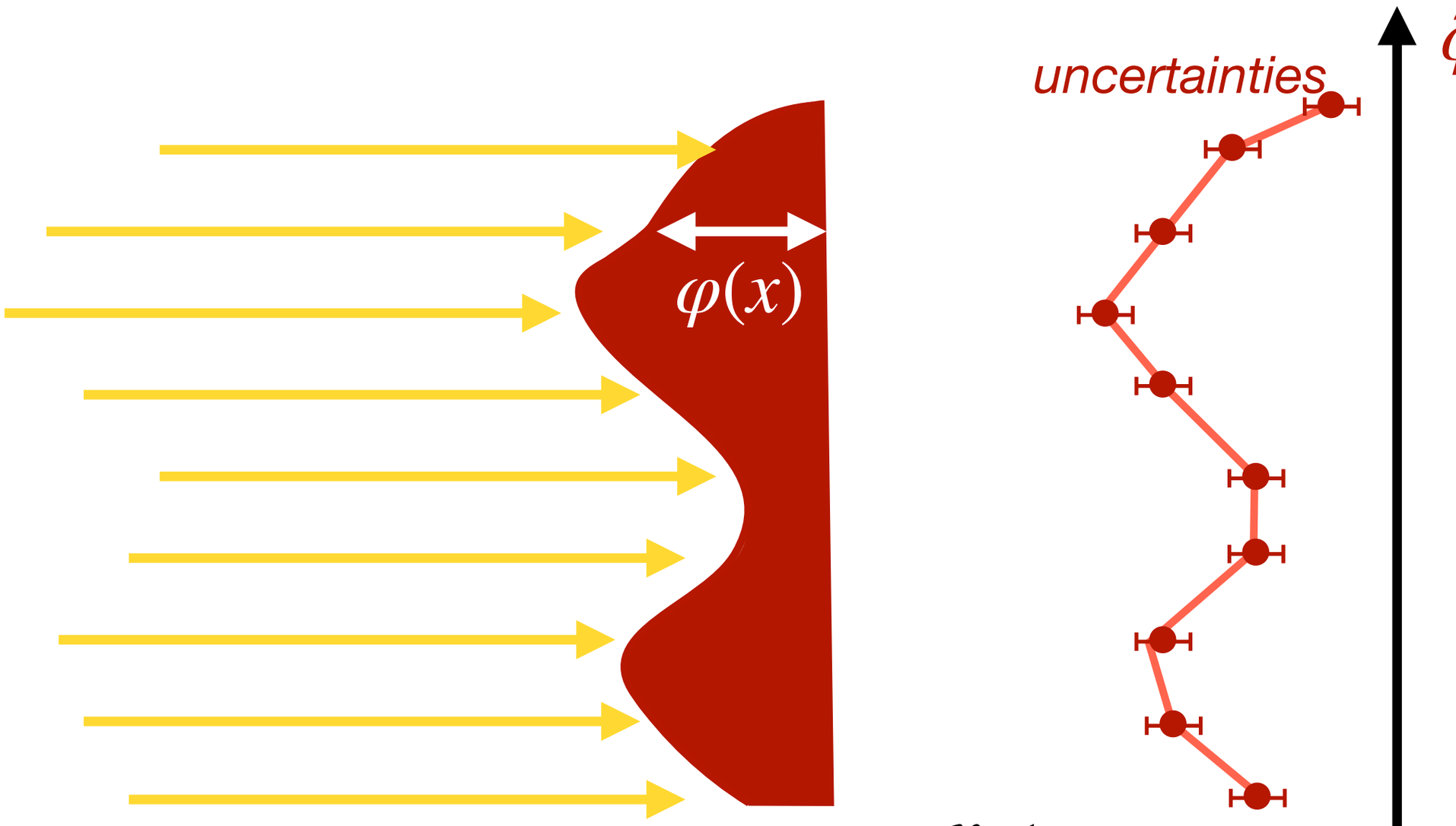

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PRL 124, 010507 (2020)

Function Estimation

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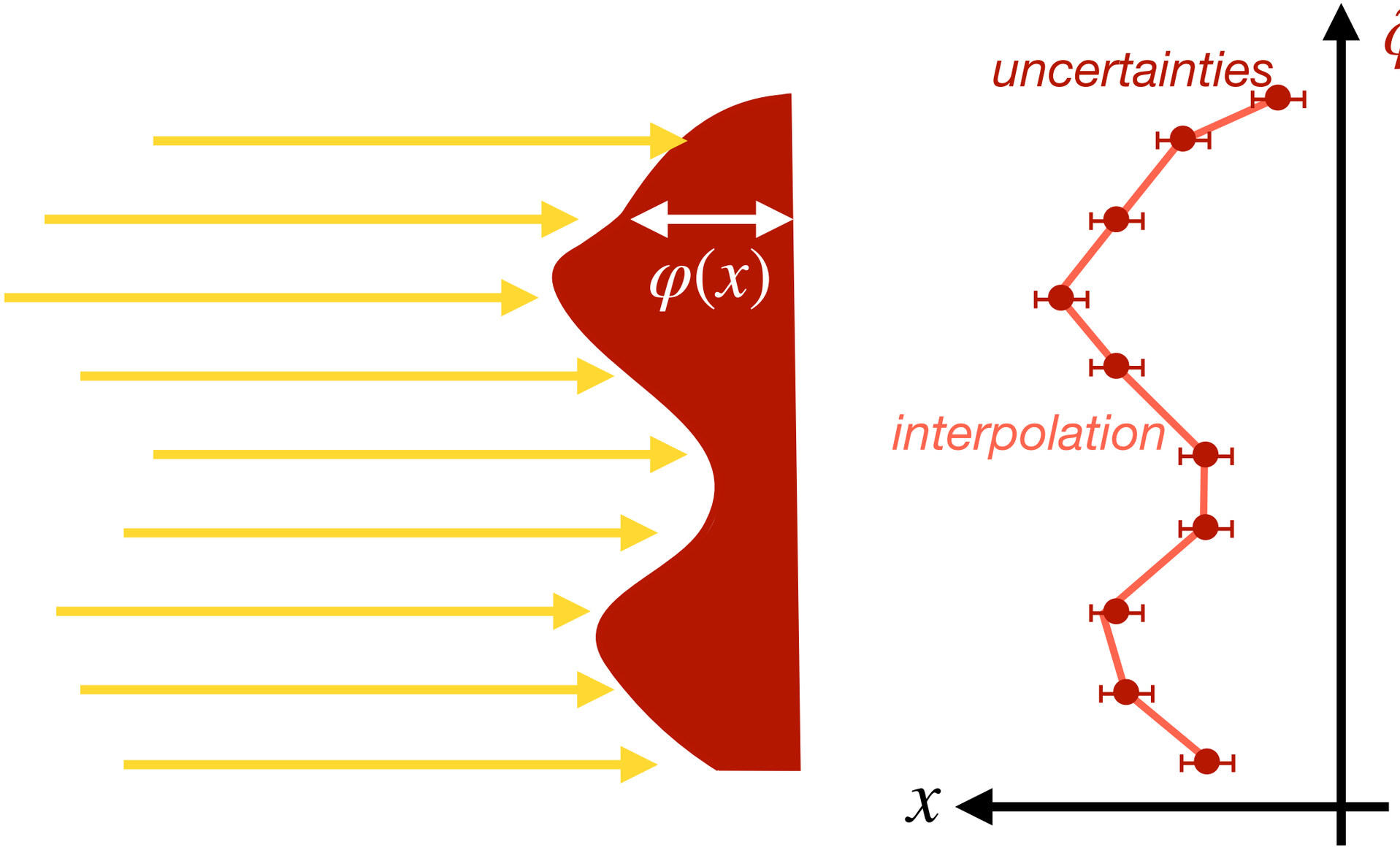


N. Kura et al
PRL 124, 010507 (2020)

Function Estimation

our experimental system

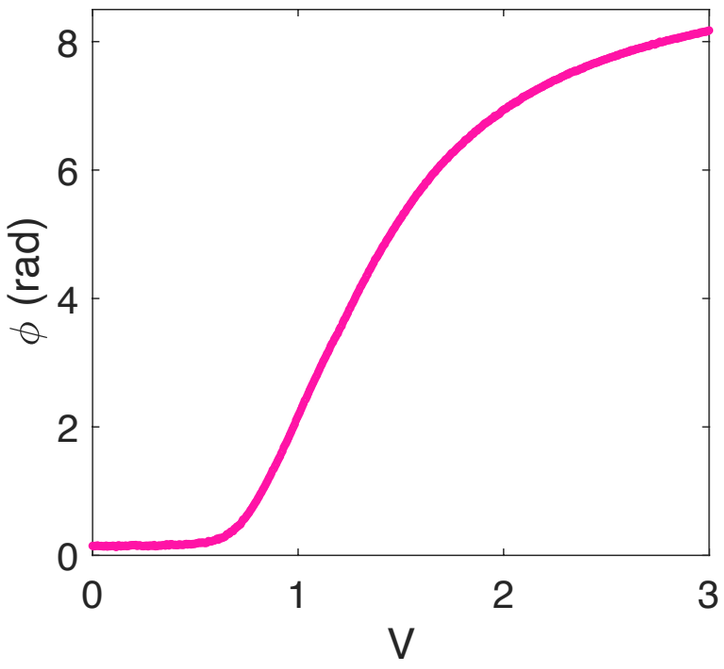
voltage-controlled phase retarder

I. Gianani et al. PRA 103, 1171 (2021)

Function Estimation

our experimental system

voltage-controlled phase retarder



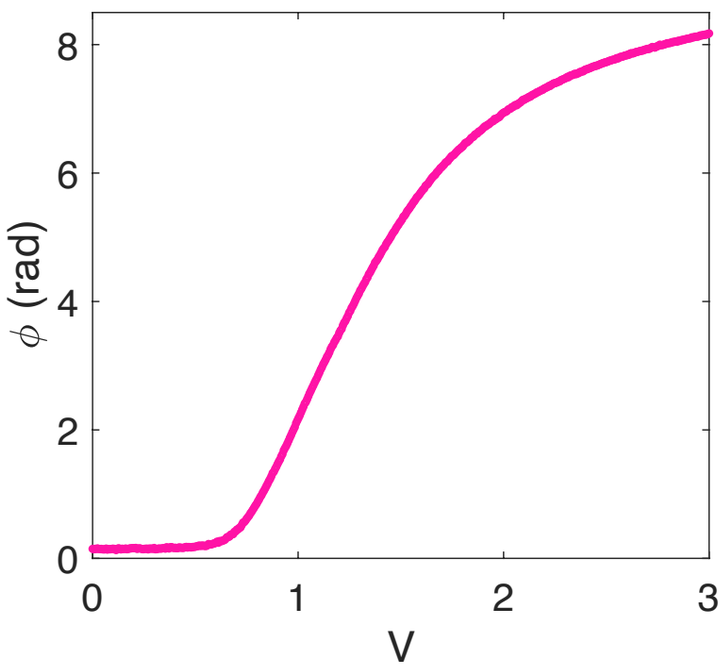
reference function

I. Gianani et al. PRA 103, 1171 (2021)

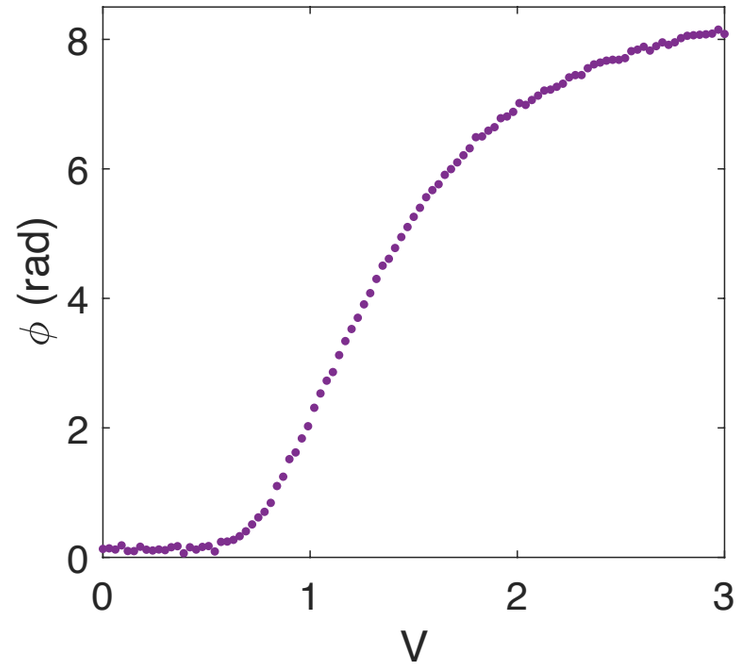
Function Estimation

our experimental system

voltage-controlled phase retarder



reference function



estimate by quantum phase measurements

I. Gianani et al. PRA 103, 1171 (2021)

Function Estimation

different strategies to reconstruct the function

Function Estimation

different strategies to reconstruct the function

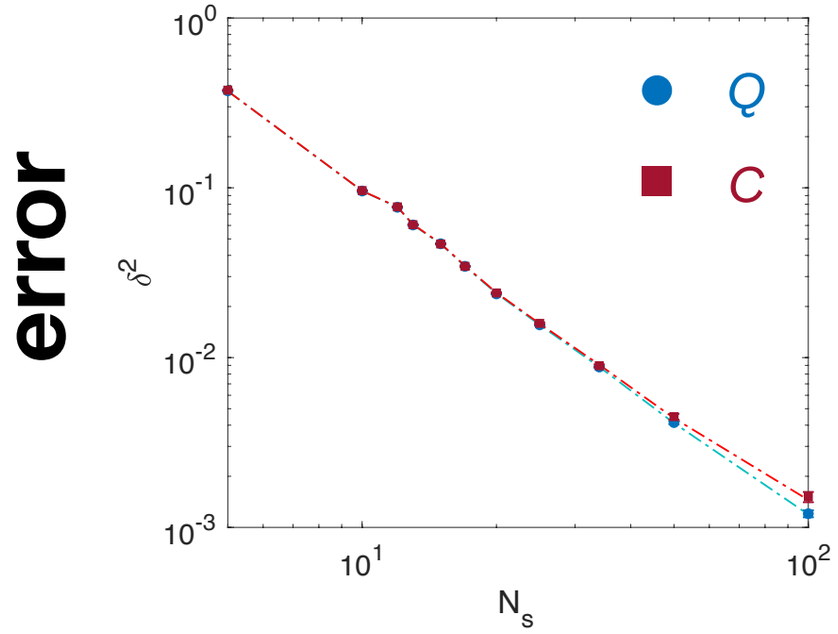
error

sampled points

Function Estimation

different strategies to reconstruct the function

nearest neighbours



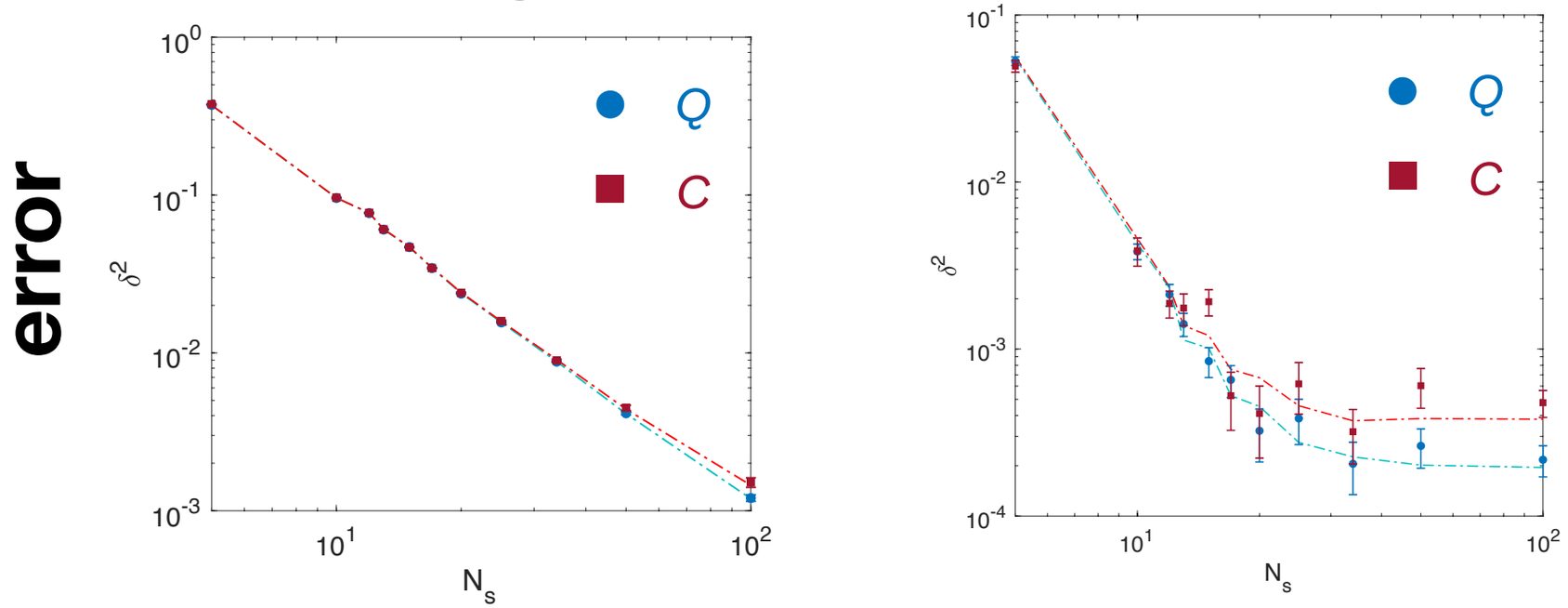
sampled points

Function Estimation

different strategies to reconstruct the function

nearest neighbours

linear



sampled points

Function Estimation

different strategies to reconstruct the function

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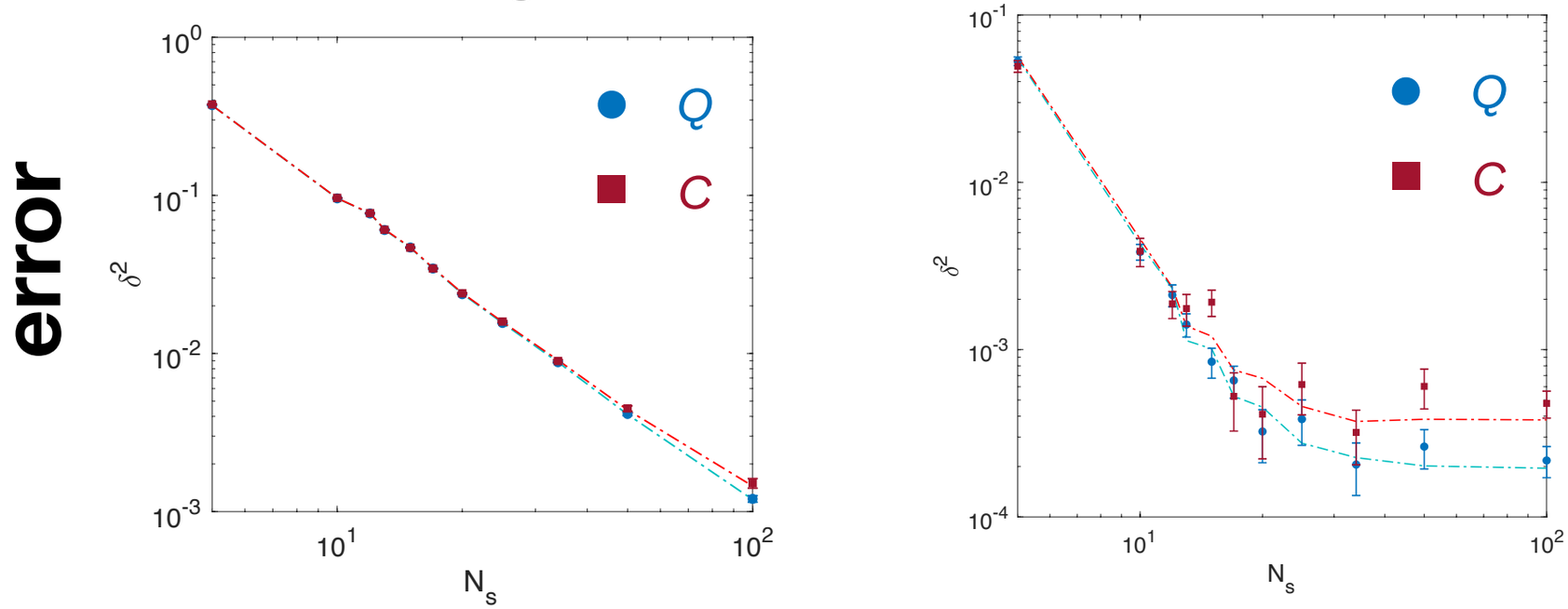
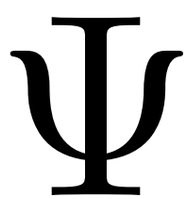


sampled points

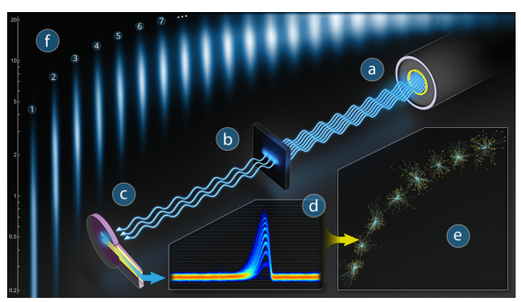
“quantum magic” does not mean “quantum magic” out

The take-home message



basic

science



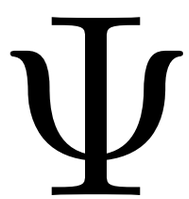
improved

components

commercial

device

The take-home message



basic

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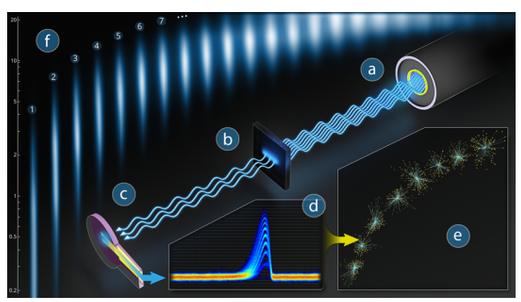

improved

components

commercial

device

diagnosis
and control

ROMA TRE
UNIVERSITÀ DEGLI STUDI

Thanks for your Attention