

# Looking with quantum light ideas and perspectives in quantum metrology

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*Dipartimento di Scienze — Università degli Studi Roma Tre*

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L'AQUILA, 23 -27 SETTEMBRE 2019

# A good time to go quantum?



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**PERSPECTIVE**

## Quantum Canada

Ben Sussman<sup>1</sup>, Paul Corkum<sup>1</sup>, Alexandre Blais<sup>2</sup>, David Cory<sup>3</sup> and Andrea Damascelli<sup>4</sup>

**PERSPECTIVE**

## Europe's Quantum Flagship initiative

Max Riedel<sup>1</sup>, Matyas Kovacs<sup>2</sup>, Peter Zoller<sup>3</sup>, Jürgen Mlynek<sup>4</sup> and Tommaso Calarco<sup>5</sup>

**PERSPECTIVE**

## The US National Quantum Initiative

Michael G Raymer<sup>1,2</sup> and Christopher Monroe<sup>3,4</sup>

**PERSPECTIVE**

## Quantum information science and technology in Japan

Yoshihisa Yamamoto<sup>1</sup>, Masahide Sasaki<sup>2</sup> and Hiroki Takesue<sup>3</sup>

**PERSPECTIVE**

## Charting the Australian quantum landscape

T M Roberson<sup>1</sup> and A G White<sup>2</sup>



**QUANTUM**  
FLAGSHIP



European Commission

**5000** researchers

**10+** years

**1 b€**

**140** submitted proposals

<https://qt.eu/about>



**Q.QUANTUM**  
FLAGSHIP



**European Commission**



**Q**UANTUM  
FLAGSHIP



European Commission

**Enabling Science**



**QUANTUM**  
FLAGSHIP



European Commission

**Computation**

**Enabling Science**



**QUANTUM**  
FLAGSHIP



European Commission

**Communication**

**Computation**

**Enabling Science**



**QUANTUM**  
FLAGSHIP



European Commission

**Communication**

**Simulation**

**Computation**

**Enabling Science**



**QUANTUM**  
FLAGSHIP



European Commission

**Communication**

**Simulation**

**Sensing/Metrology**

**Computation**

**Enabling Science**



### 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

- A Simulator of motion of electrons in materials

- B New algorithms for quantum simulators and networks

- C Development and design of new complex materials

- D Versatile simulator of quantum magnetism and electricity

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

### 3. Sensors

- 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

- C Quantum sensors for larger volume applications including automotive, construction

- D Handheld quantum navigation devices

- E Gravity imaging devices based on gravity sensors

- F Integrate quantum sensors with consumer applications including mobile devices

### 4. Computers

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

- B New algorithms for quantum computers

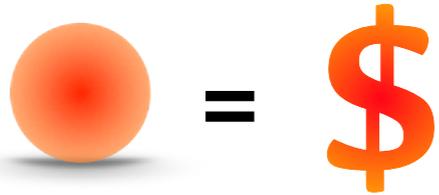
- C Small quantum processor executing technologically relevant algorithms

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

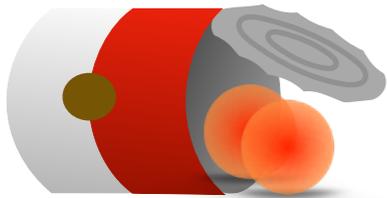
- E Integration of quantum circuit and cryogenic classical control hardware

- F General purpose quantum computers exceed computational power of classical computers

# Outline



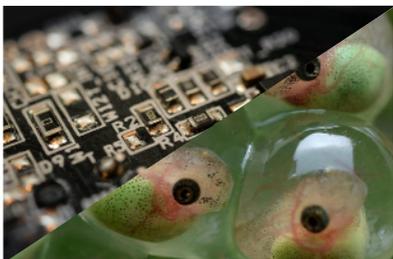
Quantum metrology: the general framework



Where we're at



Developing diagnostics



Conclusions



# Quantum Metrology





# Quantum Metrology



# Quantum Metrology

 **this is a photon**



# Quantum Metrology

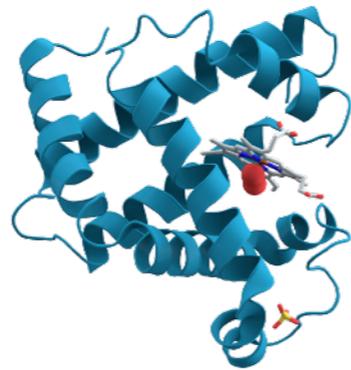
 this is a photon =  this is a resource



# Quantum Metrology



**a photon is a resource**



**sample**

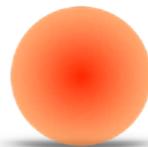
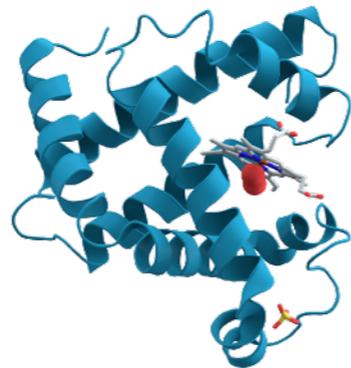


# Quantum Metrology



**a photon is a resource**

**probing**



**sample**

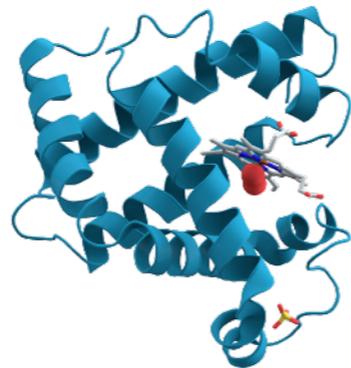


# Quantum Metrology



**a photon is a resource**

**probing**



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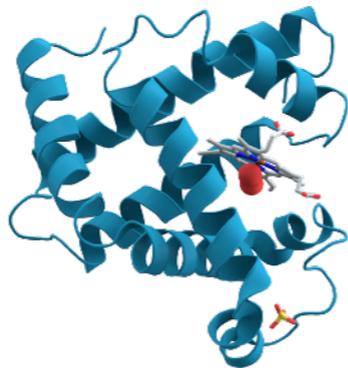


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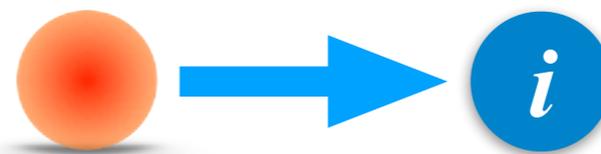


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**probing**

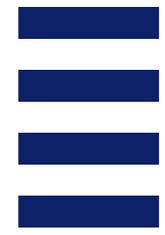


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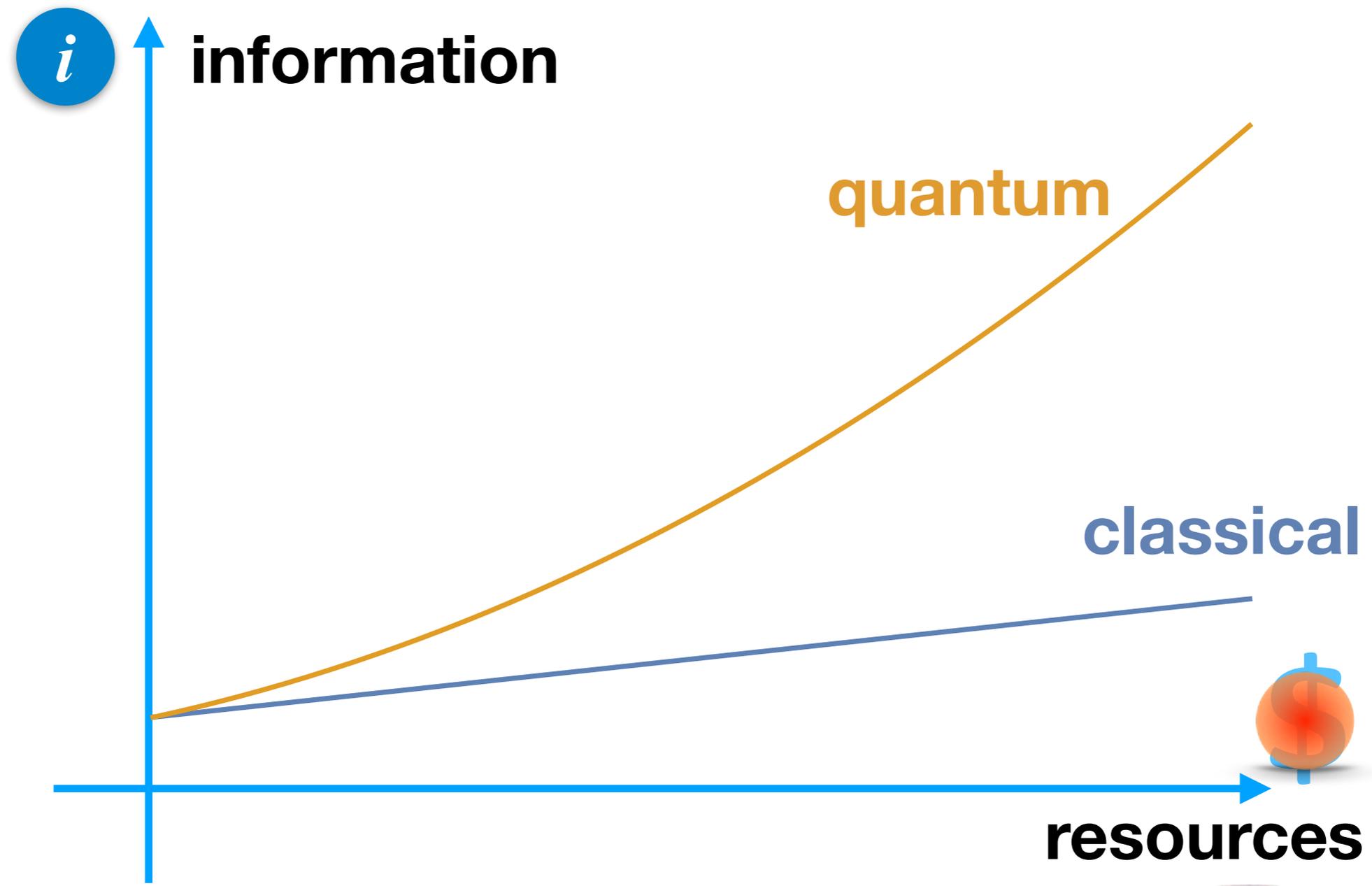


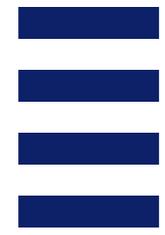
**extraction of  
information**





# Quantum Metrology



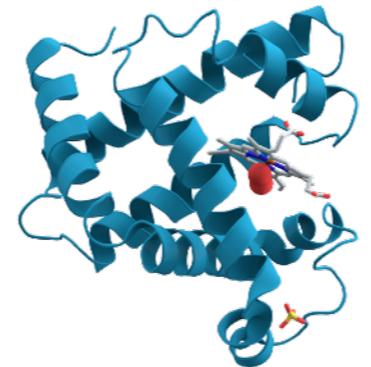


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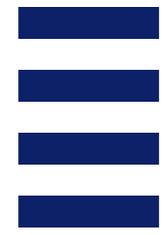


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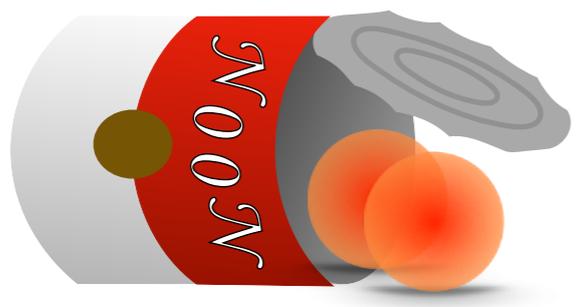
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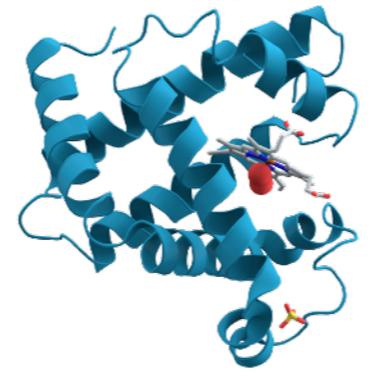


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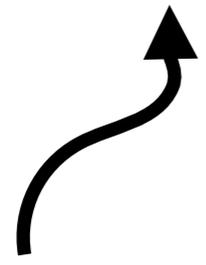
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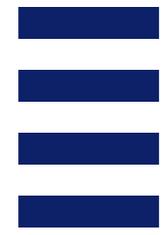


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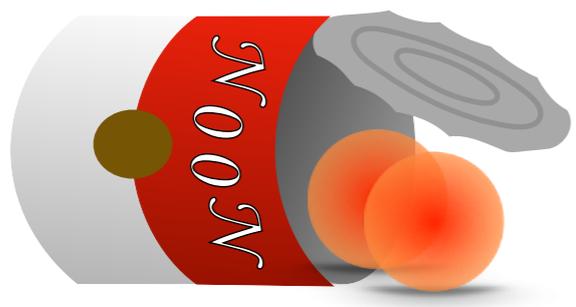
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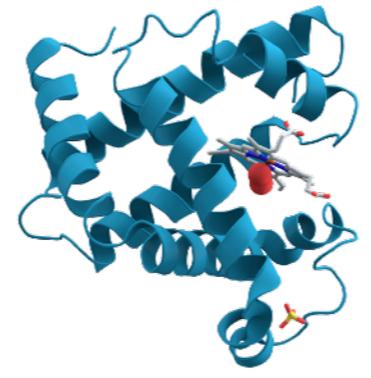


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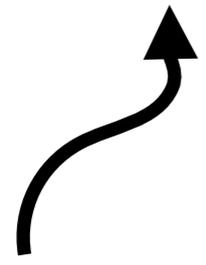
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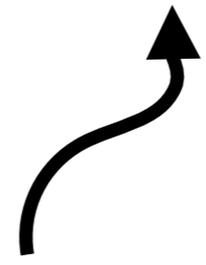
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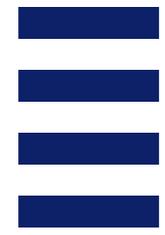


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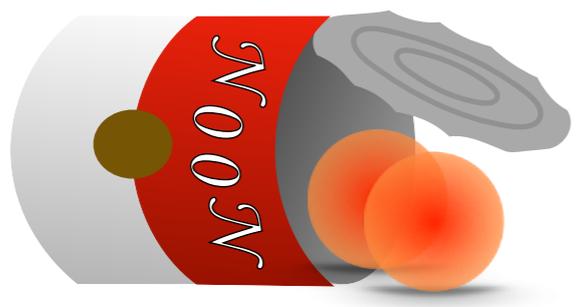
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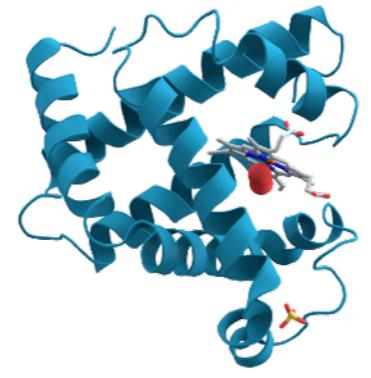


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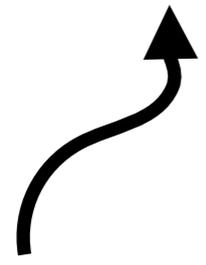
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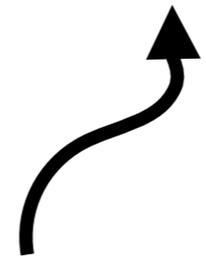
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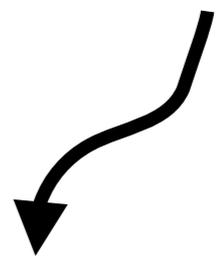
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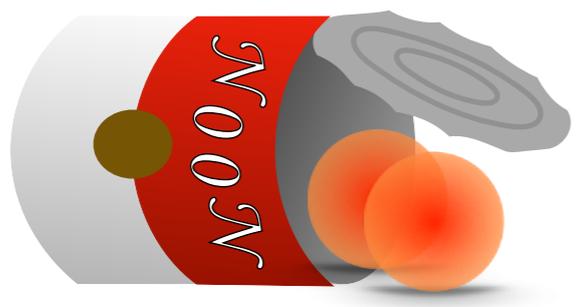


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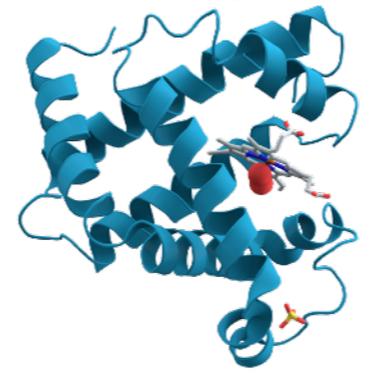


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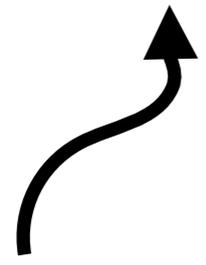
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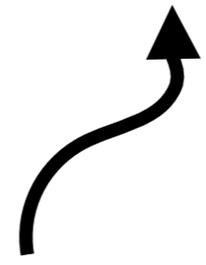
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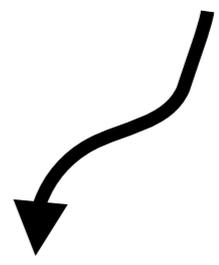
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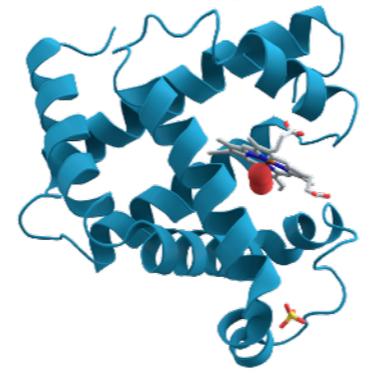
**quantum mechanics**

# Quantum Metrology

**source**



**sample**



**detectors**



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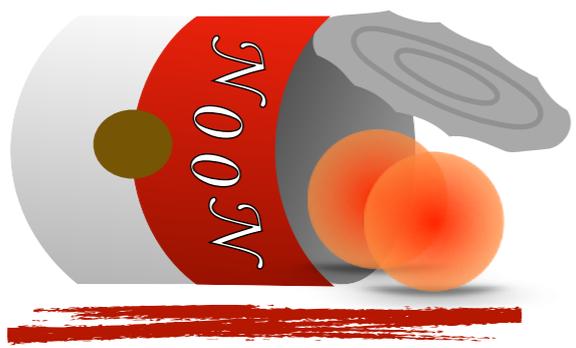
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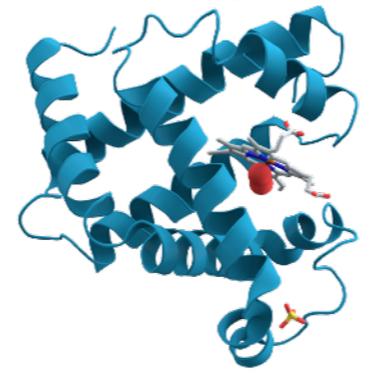
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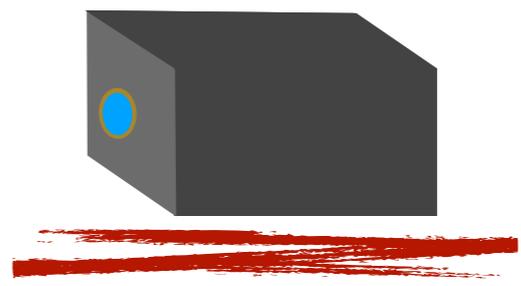
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**sample**



**detectors**

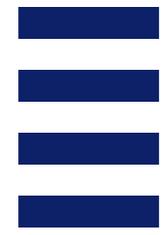


**initialisation**

**modulation**

**extraction**

**quantum mechanics**

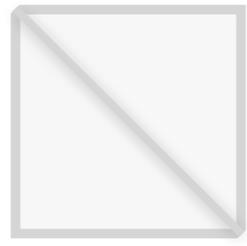


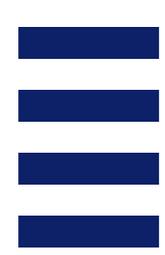
# Quantum Phase Estimation



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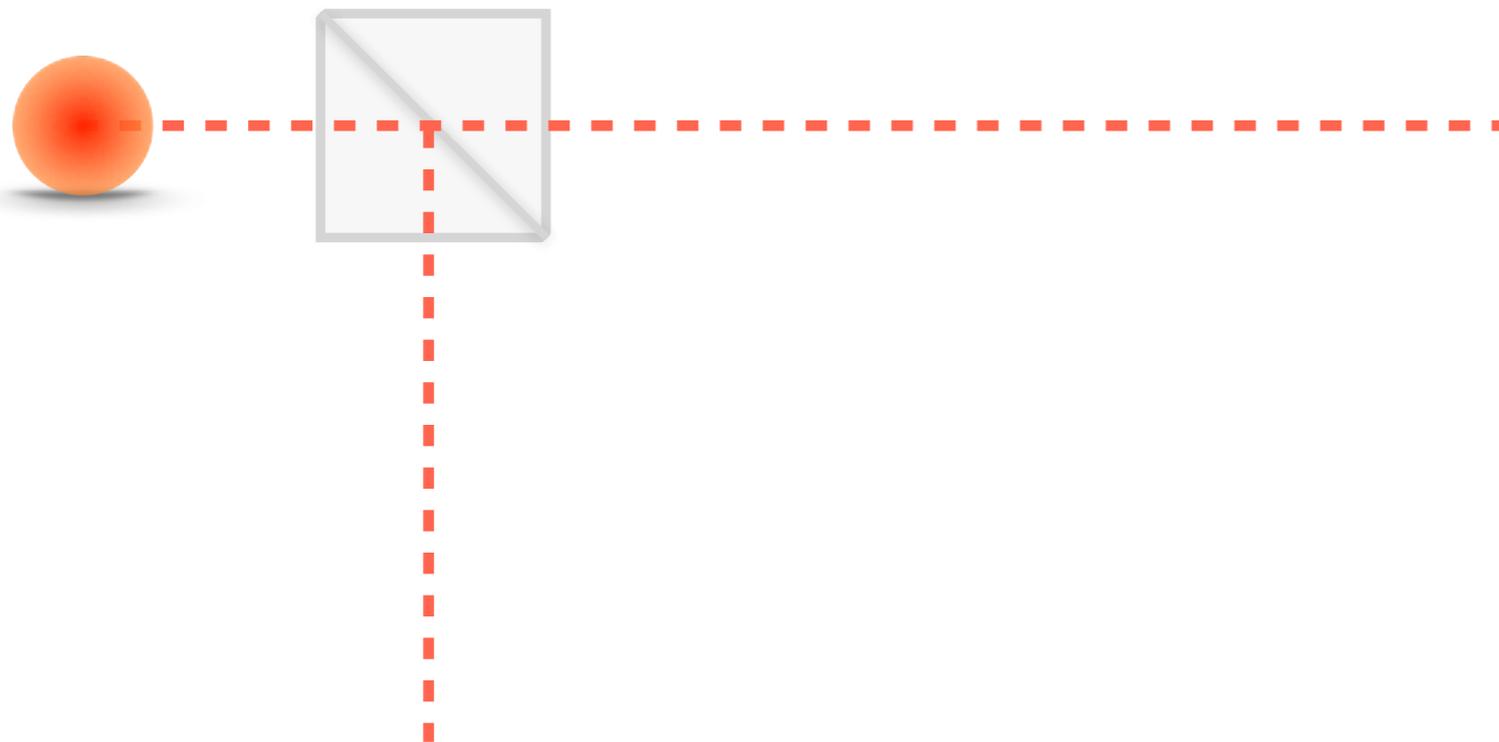
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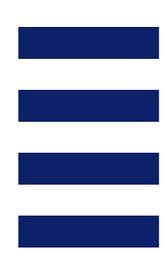




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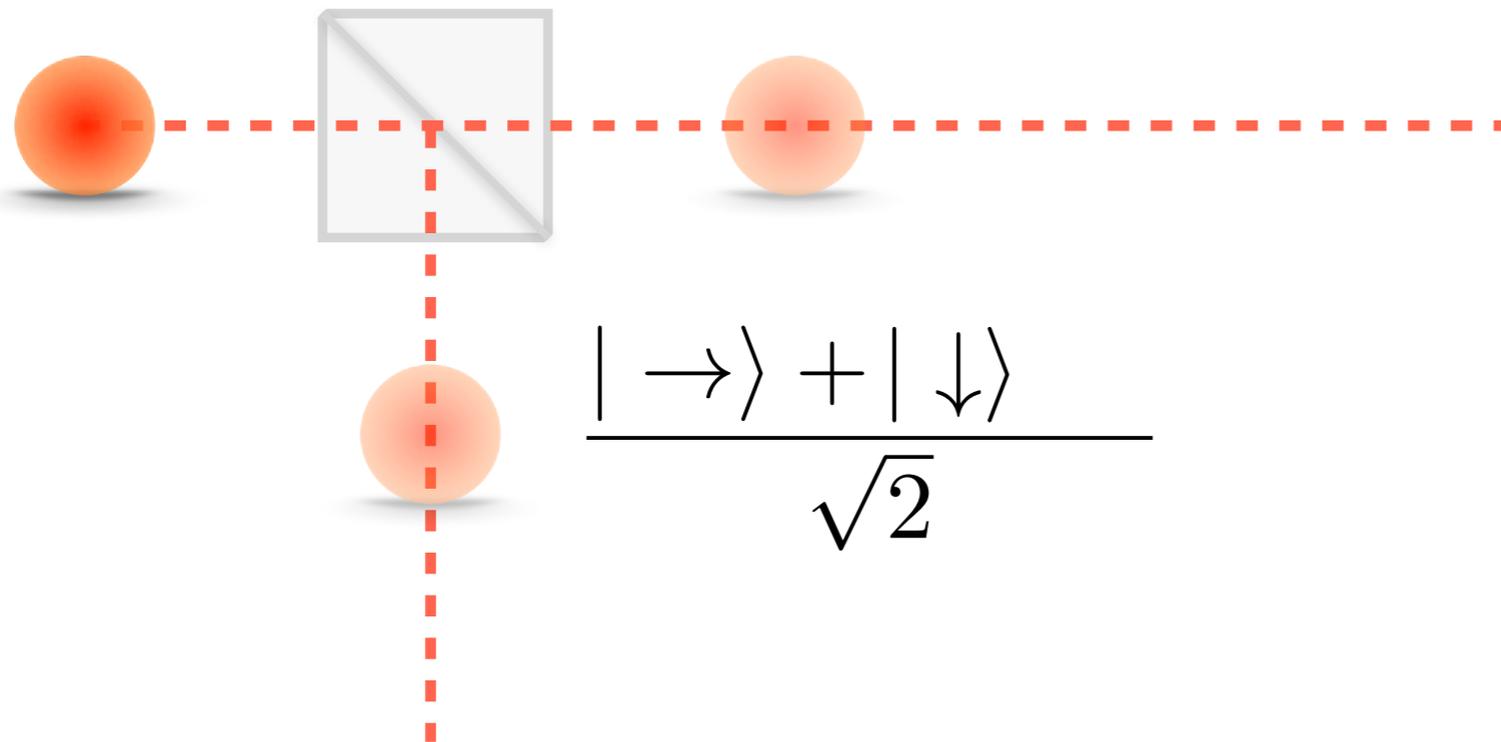
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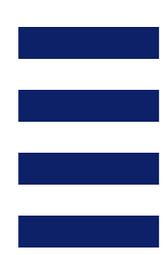




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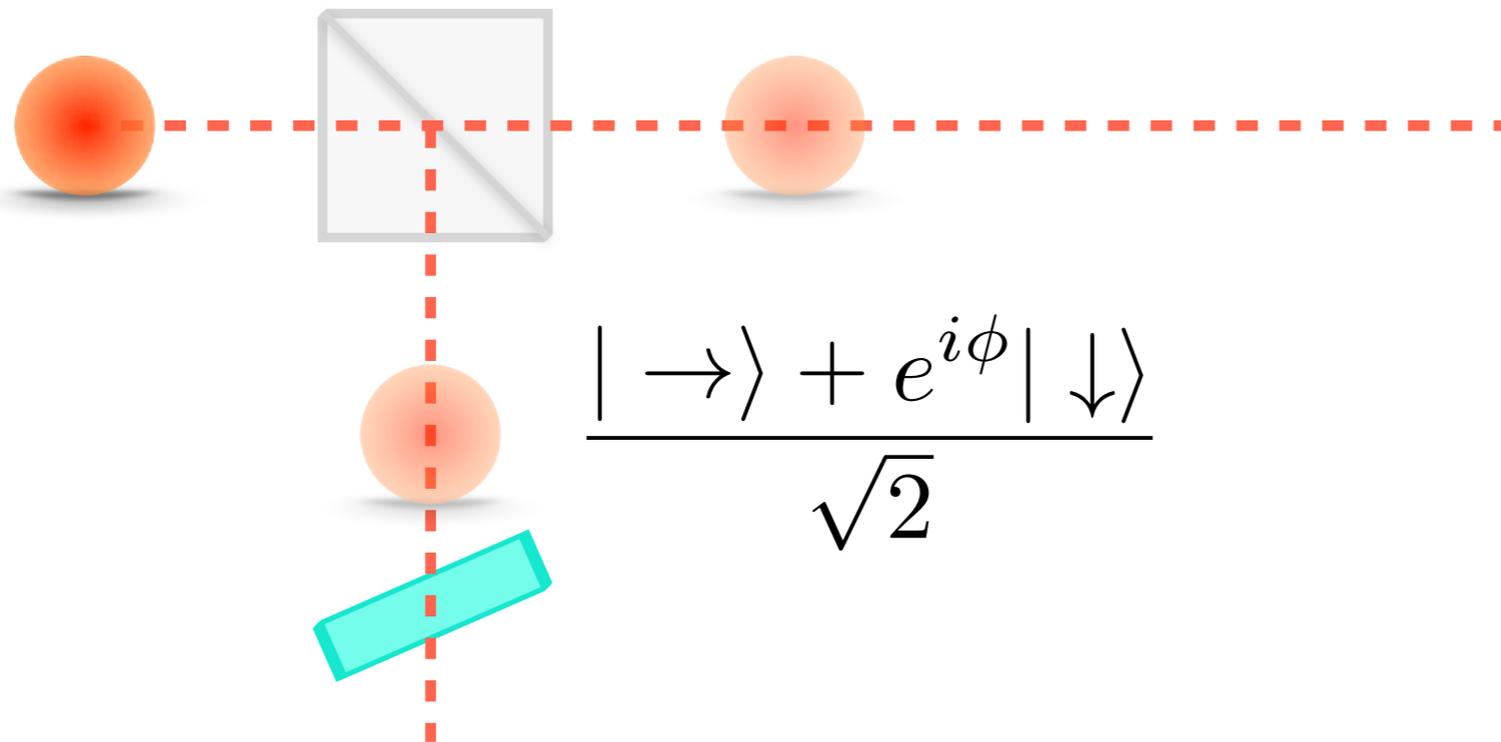
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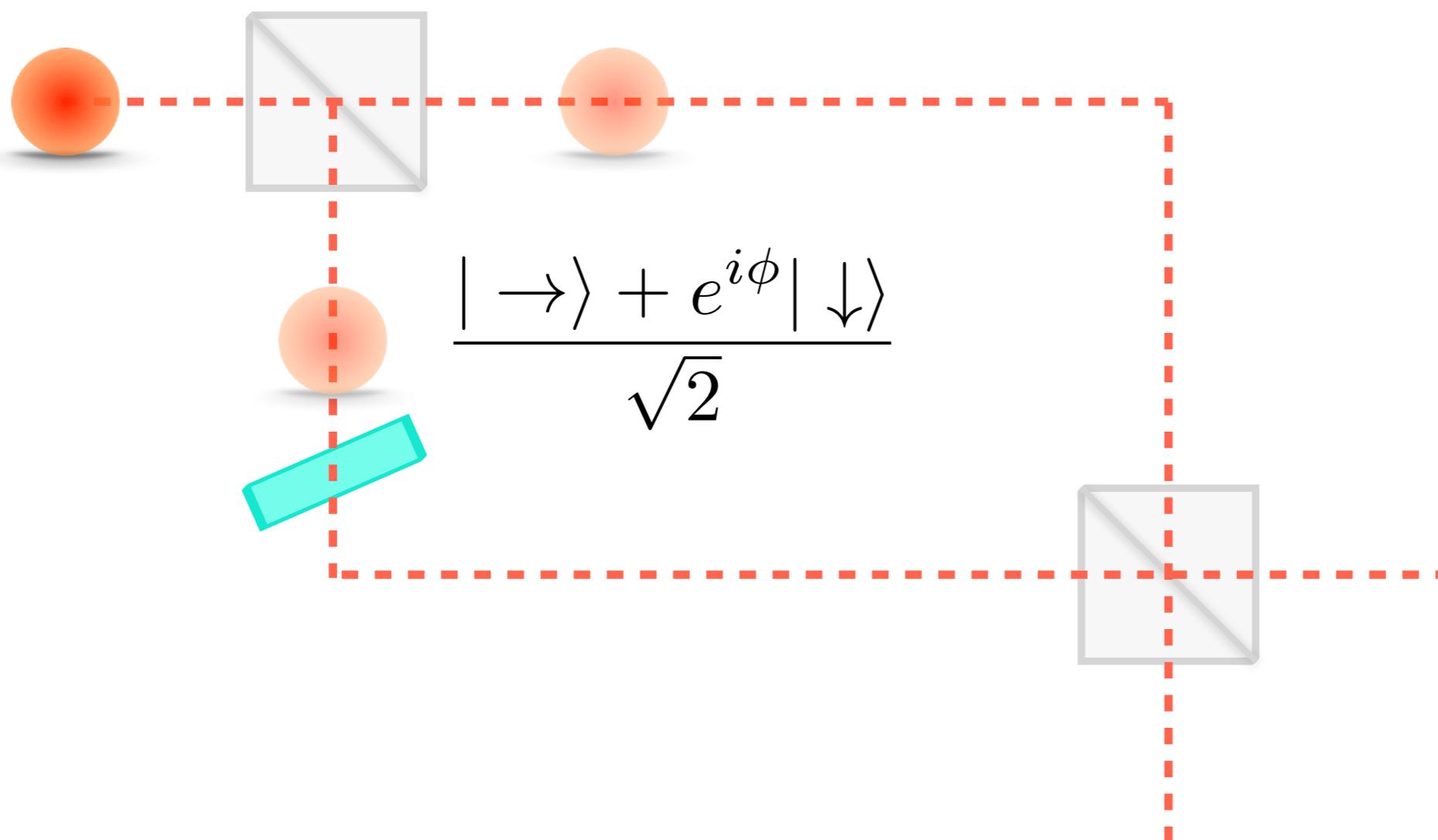
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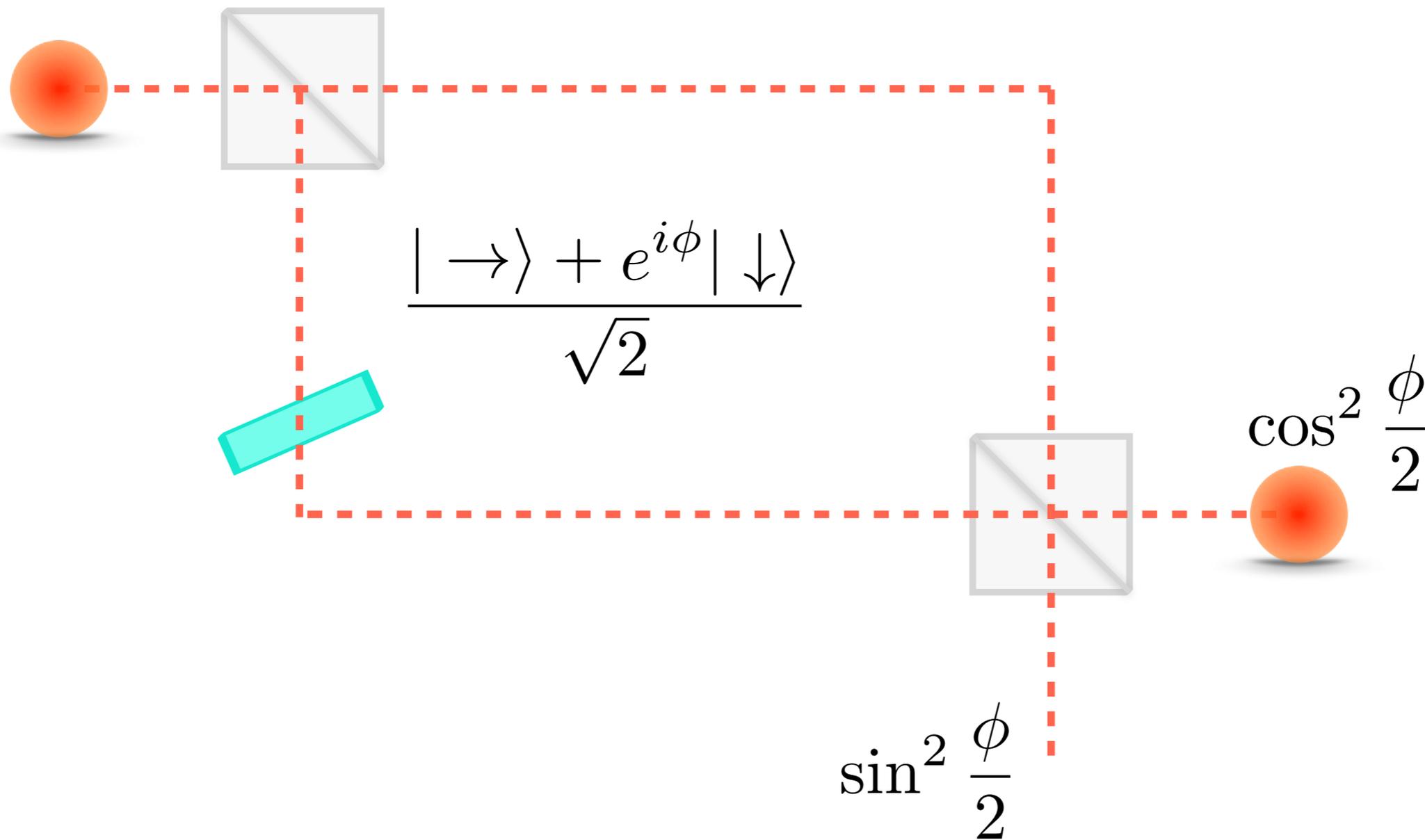
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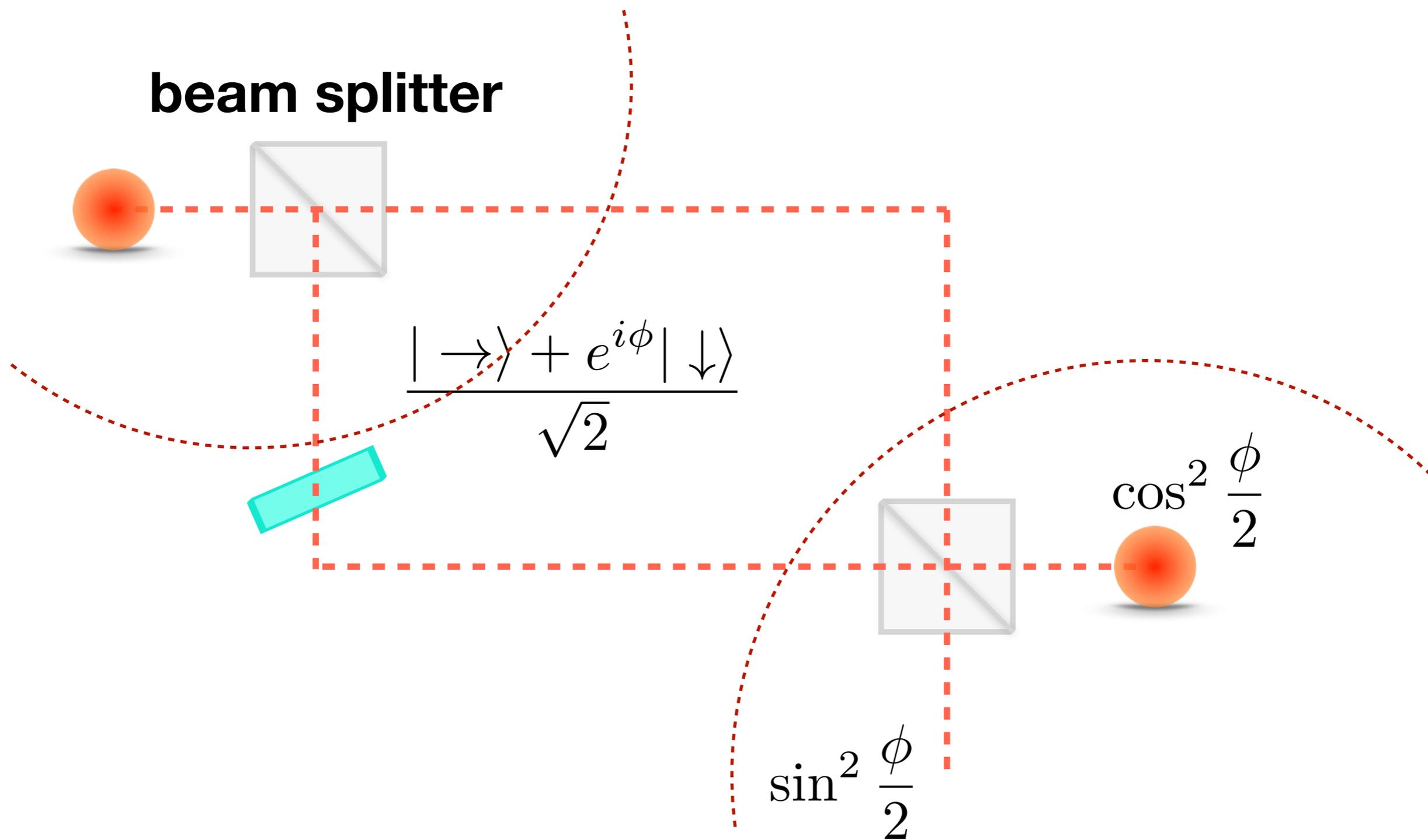


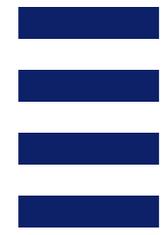
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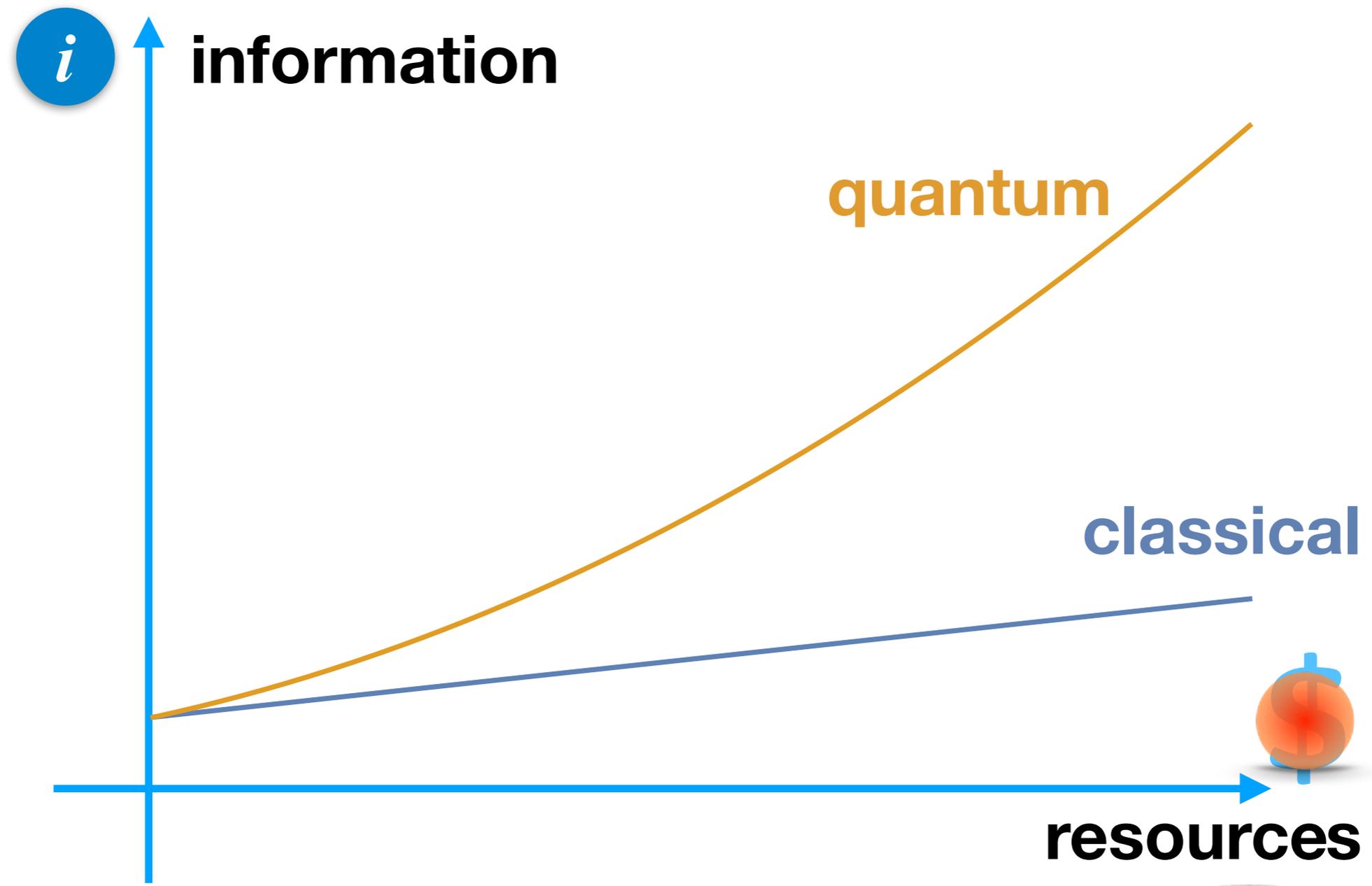


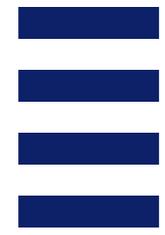
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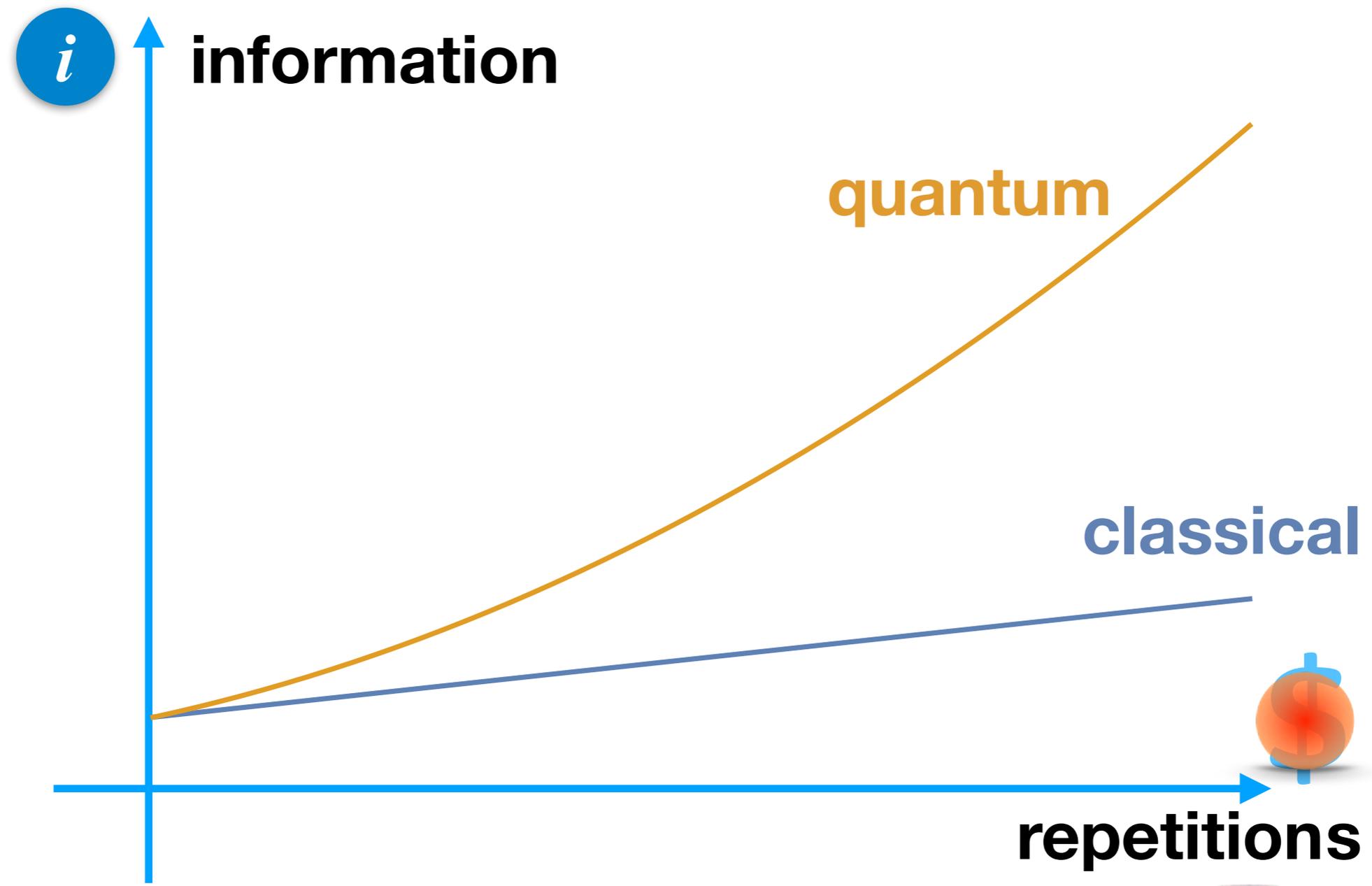


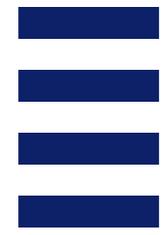
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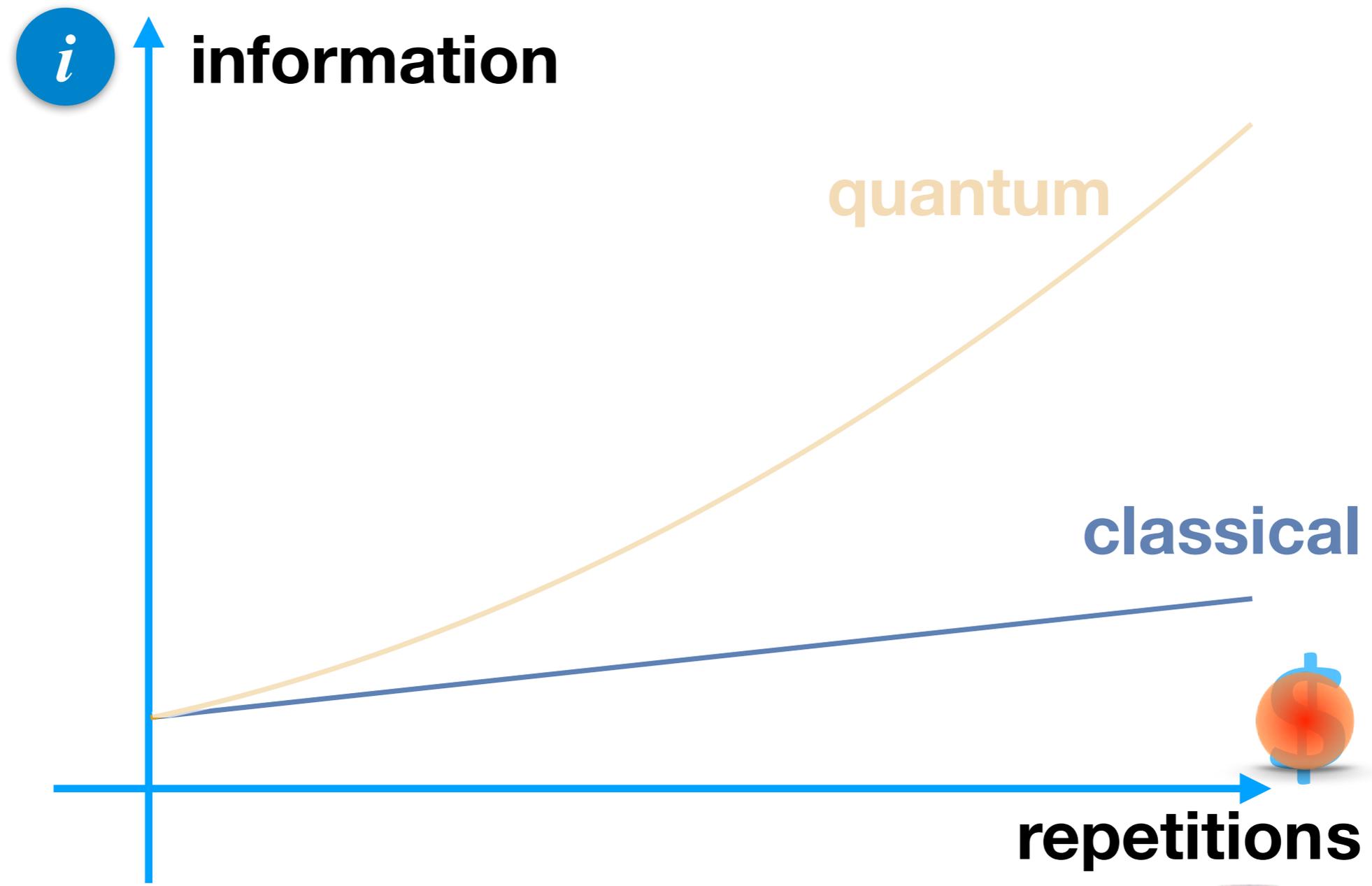


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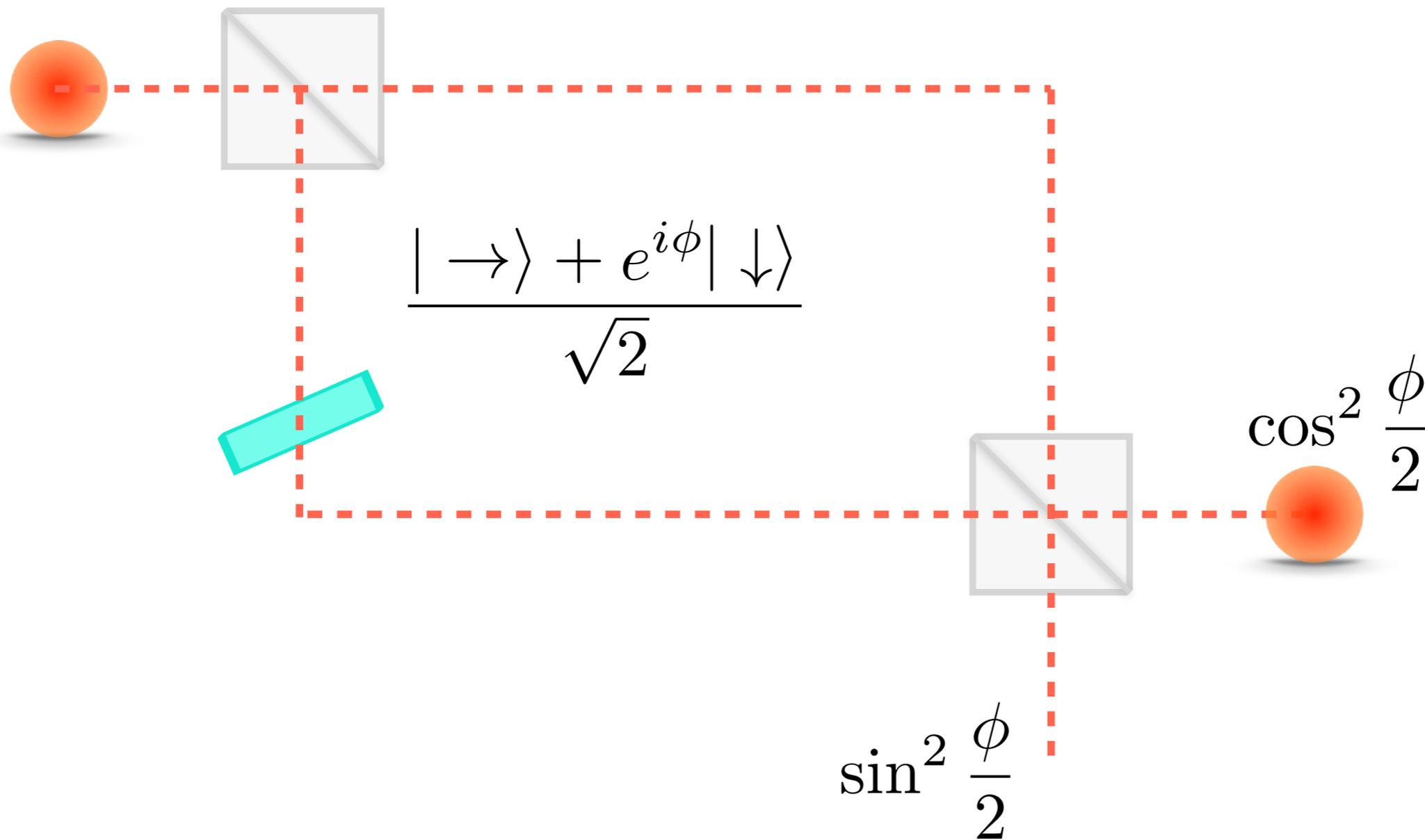


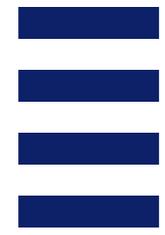
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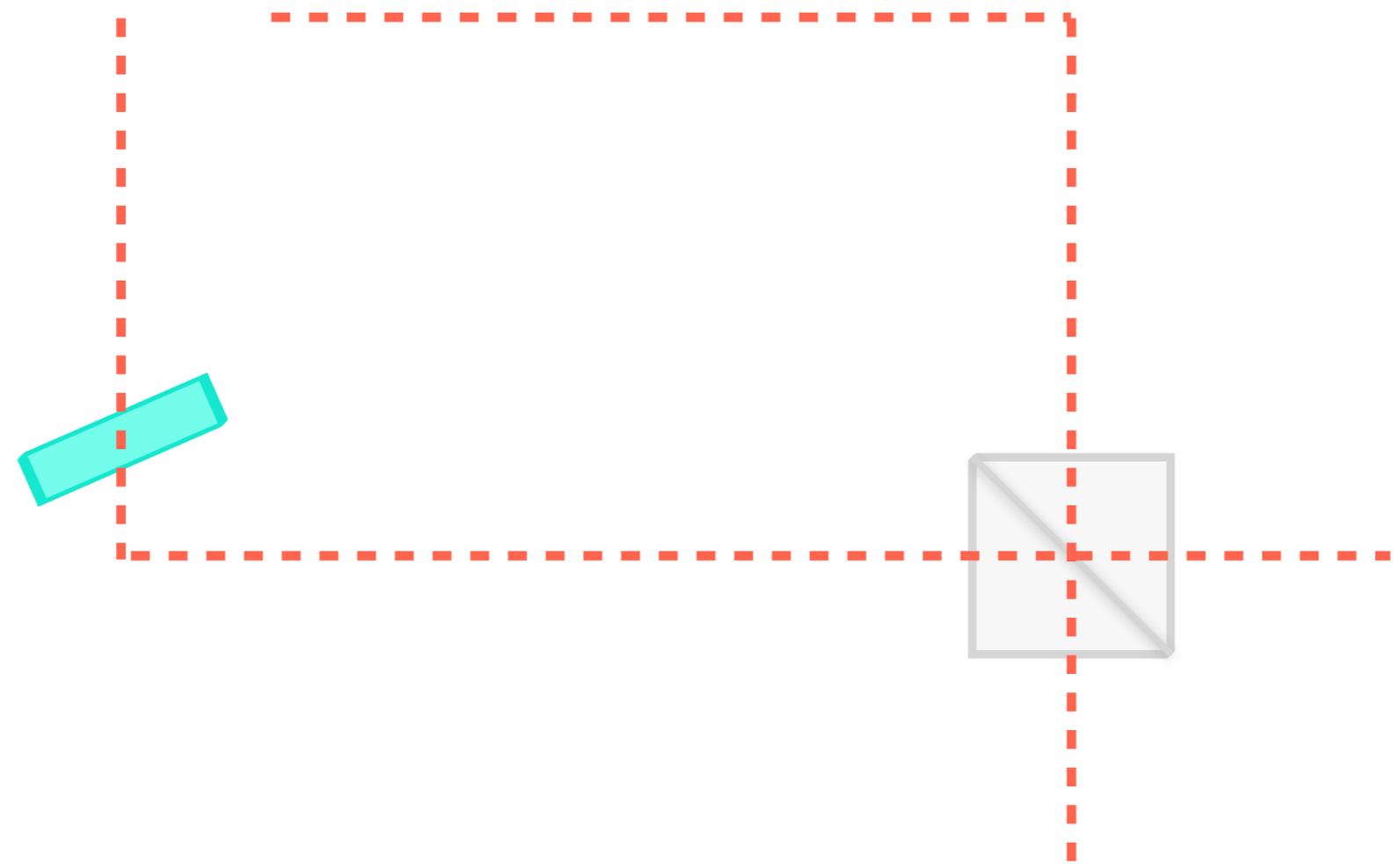
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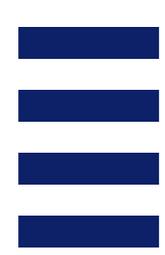
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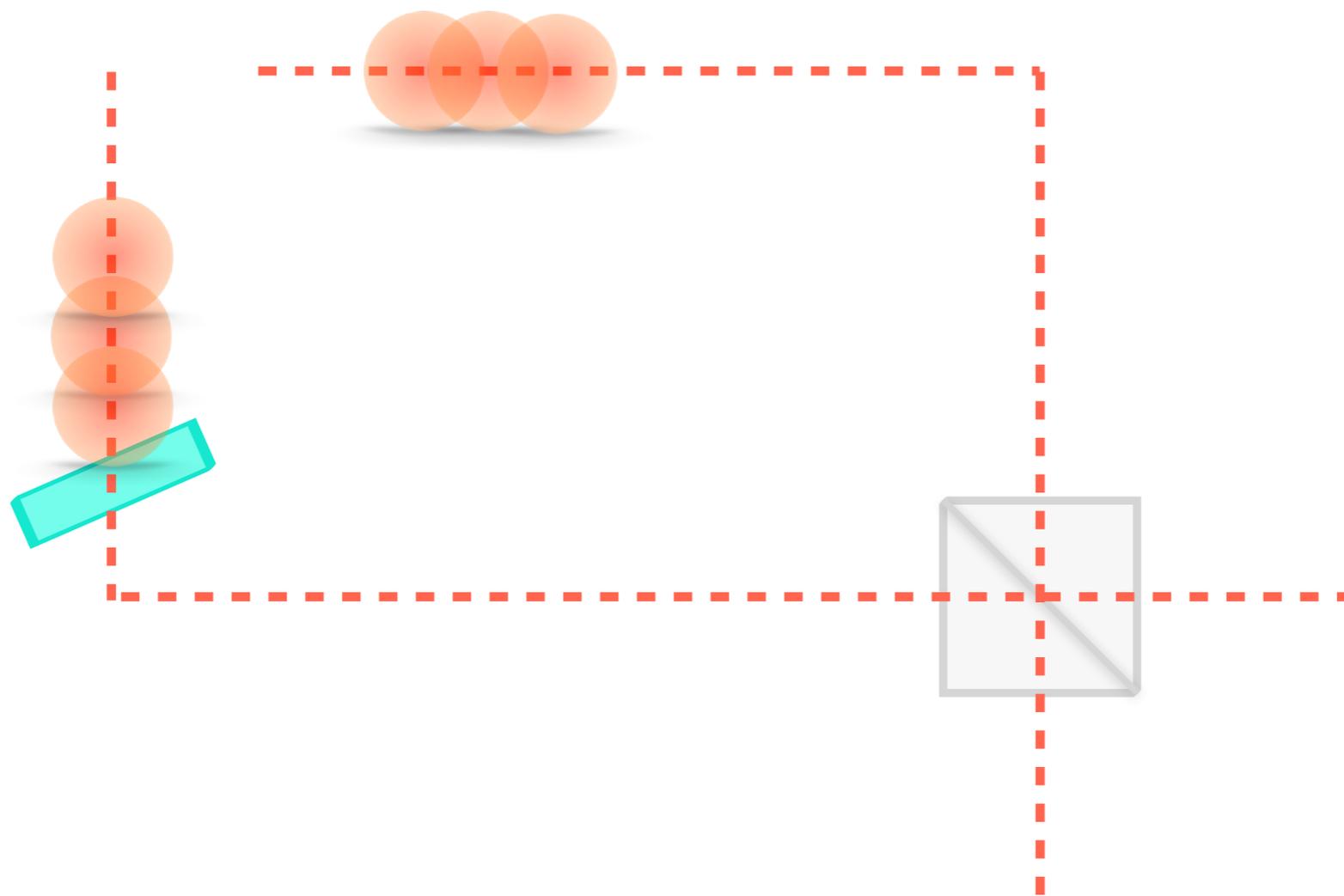


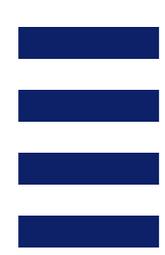
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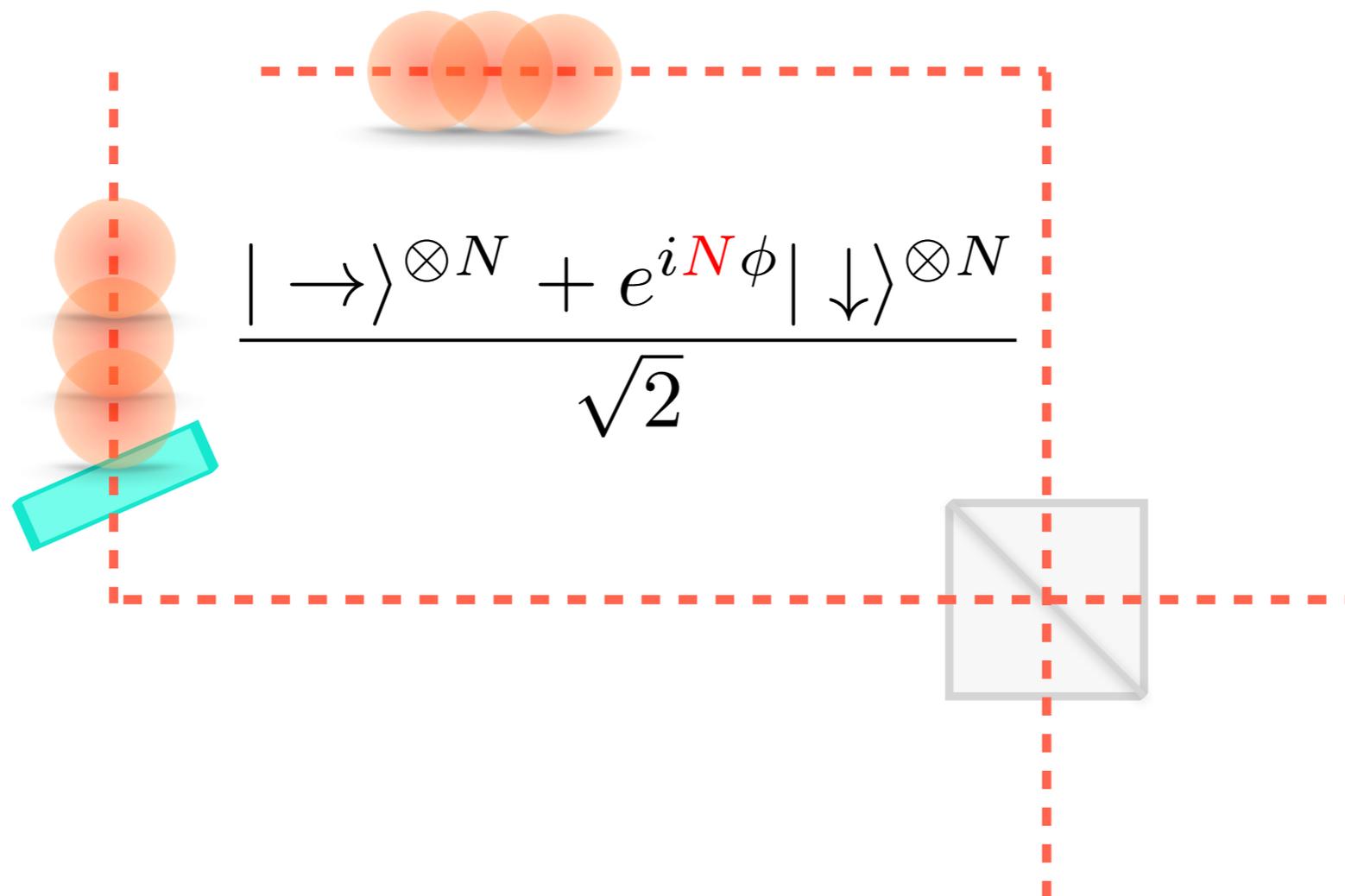


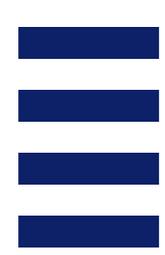
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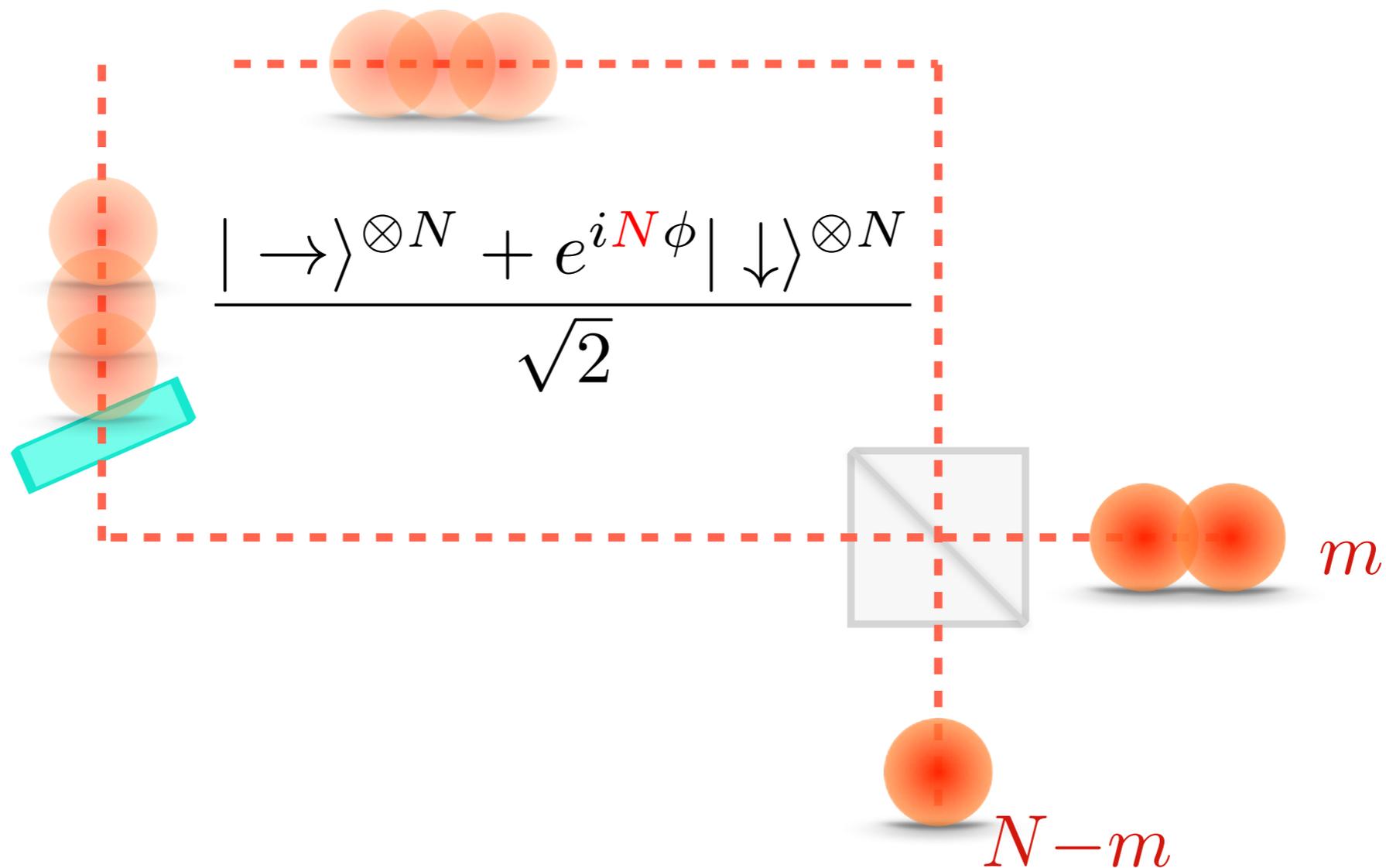


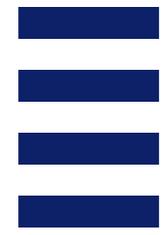
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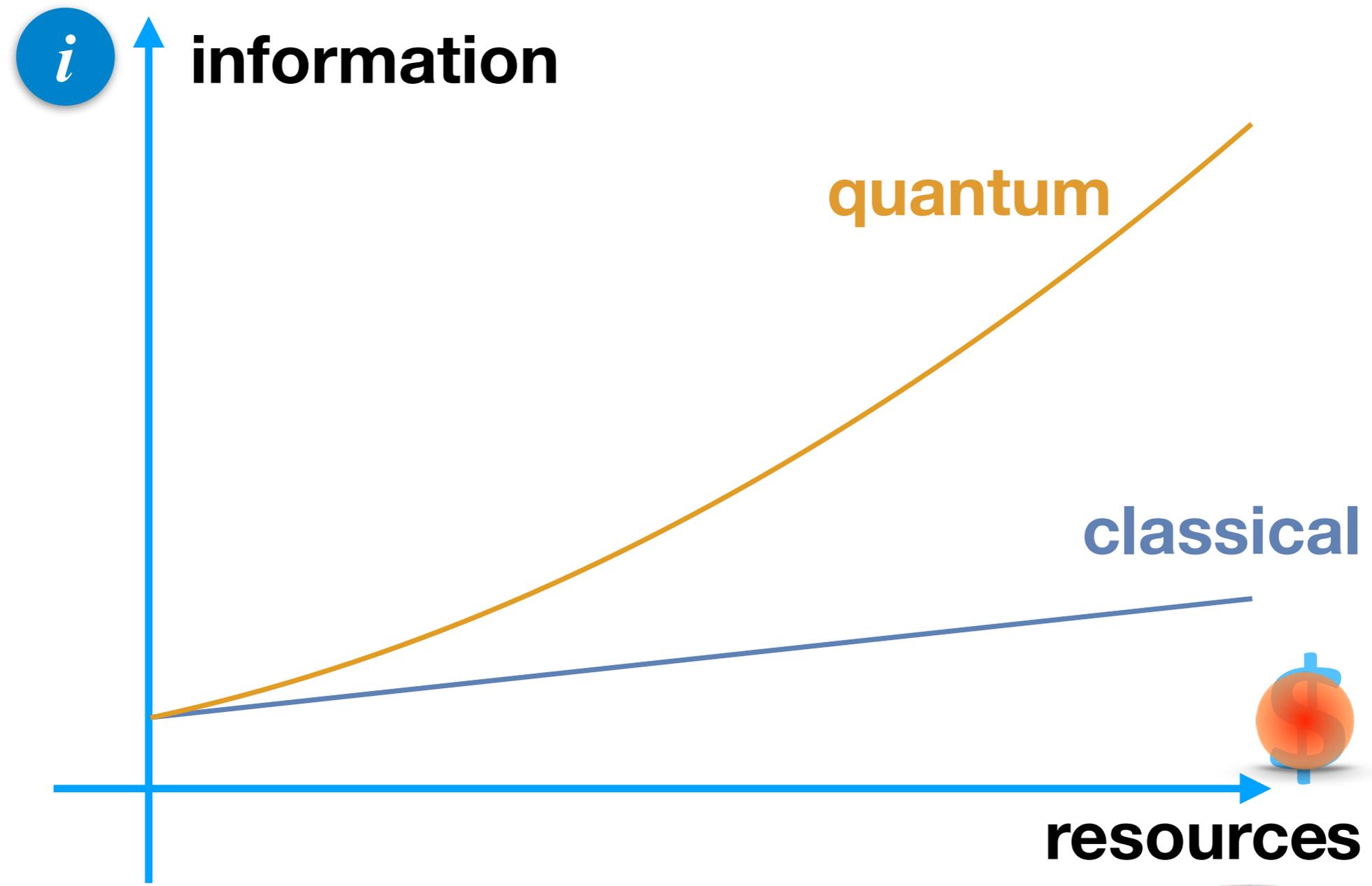


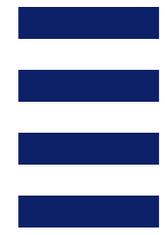
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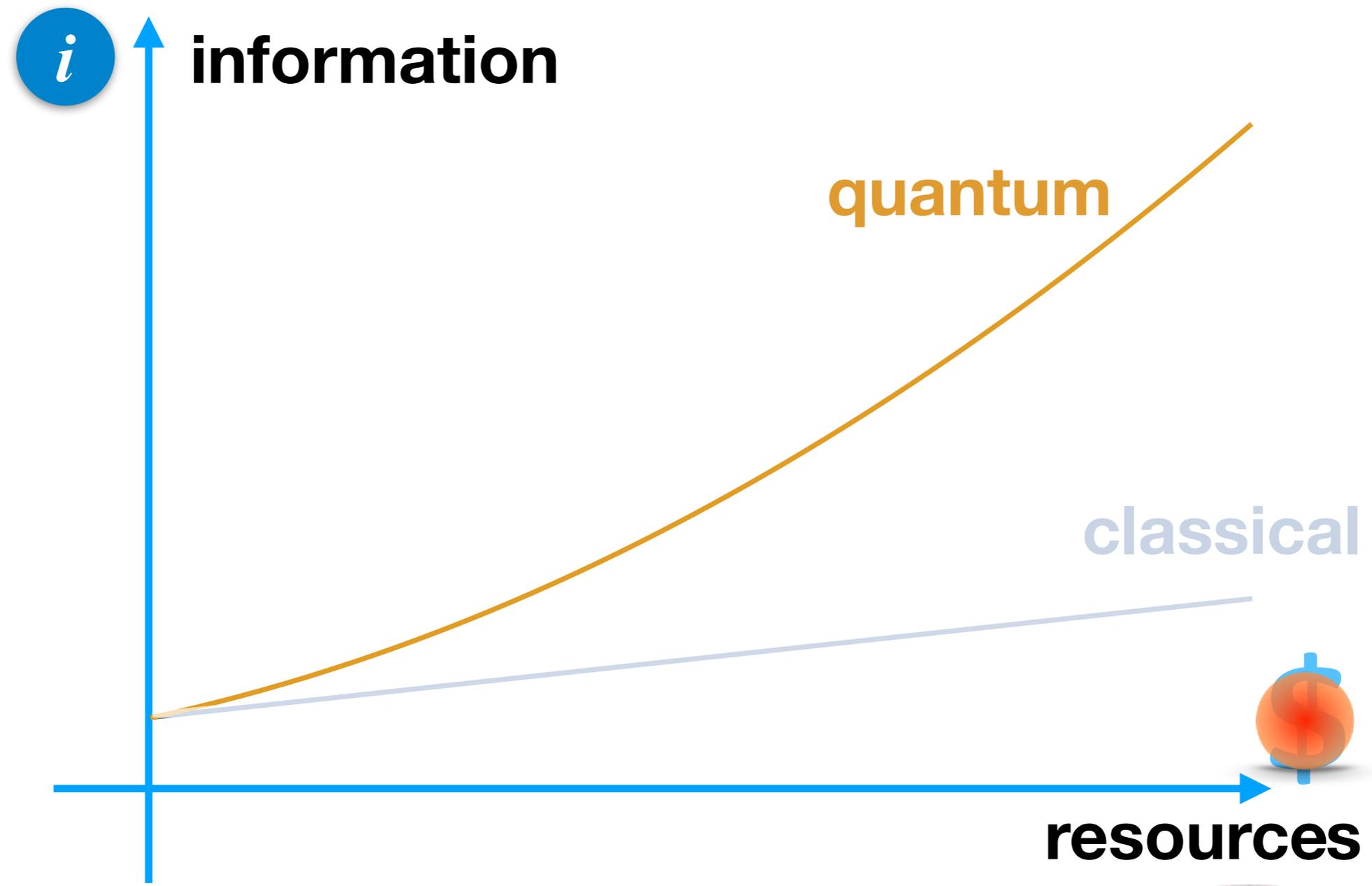


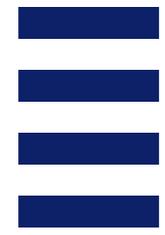
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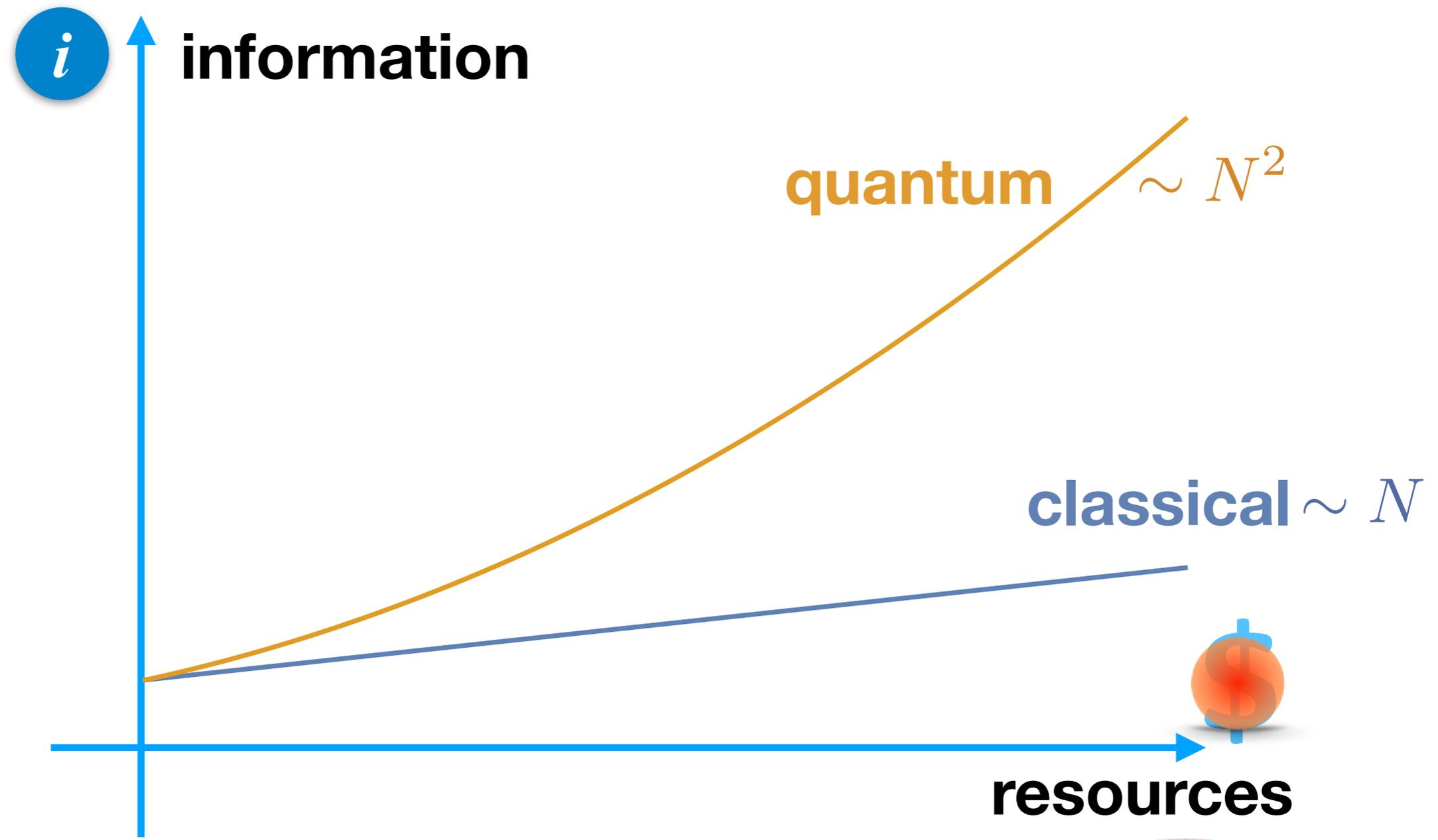


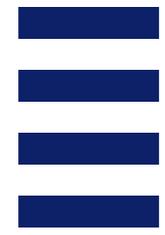
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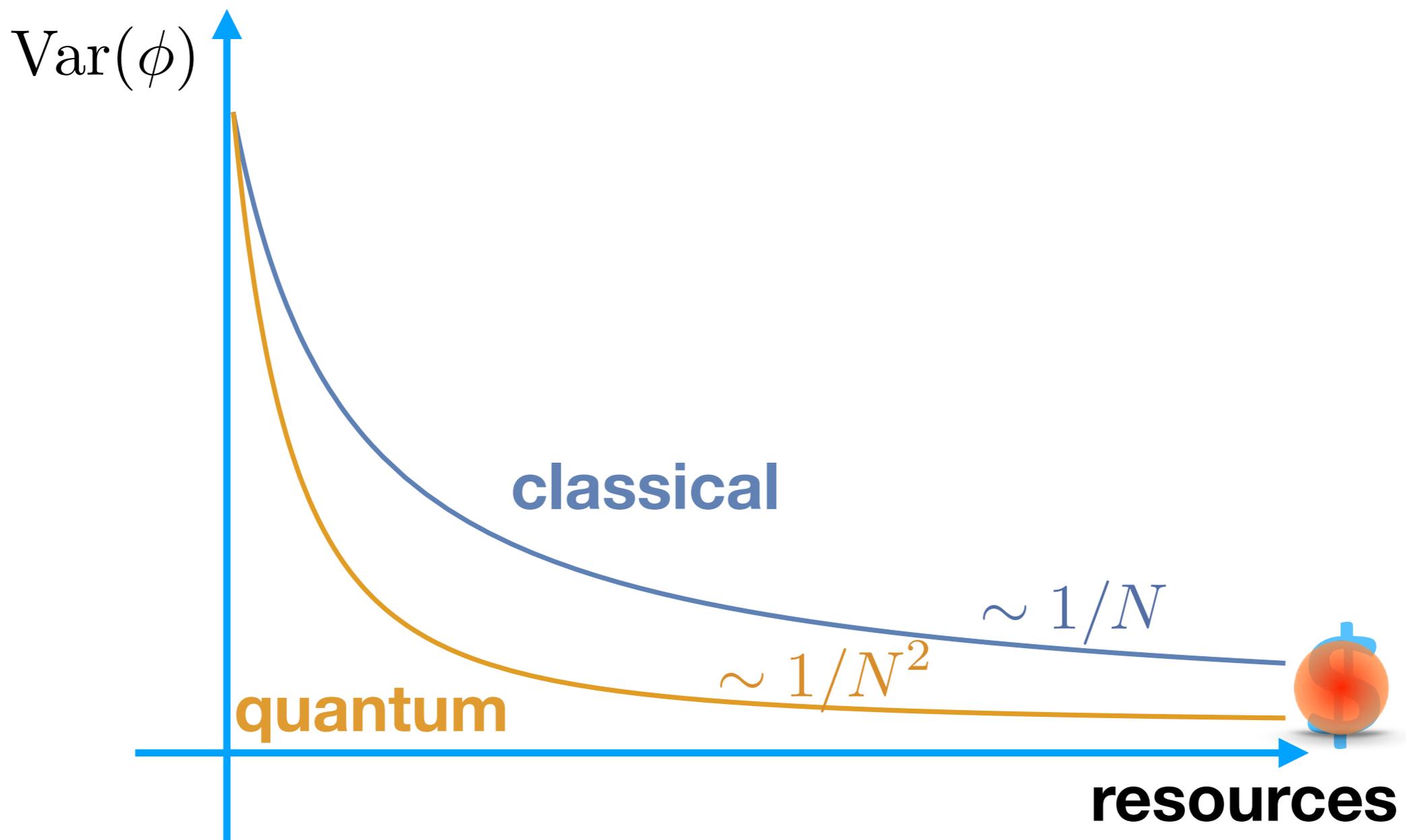


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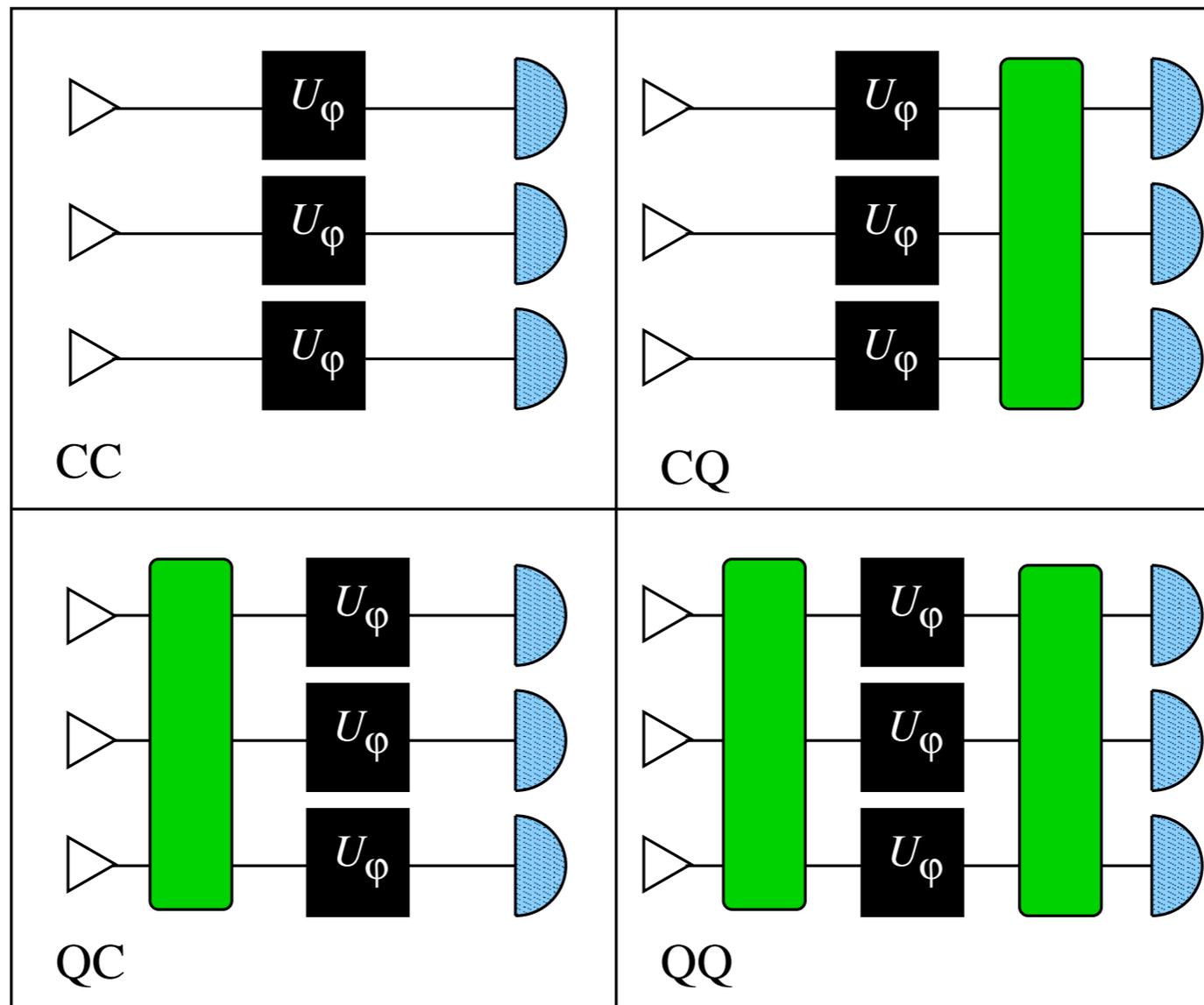


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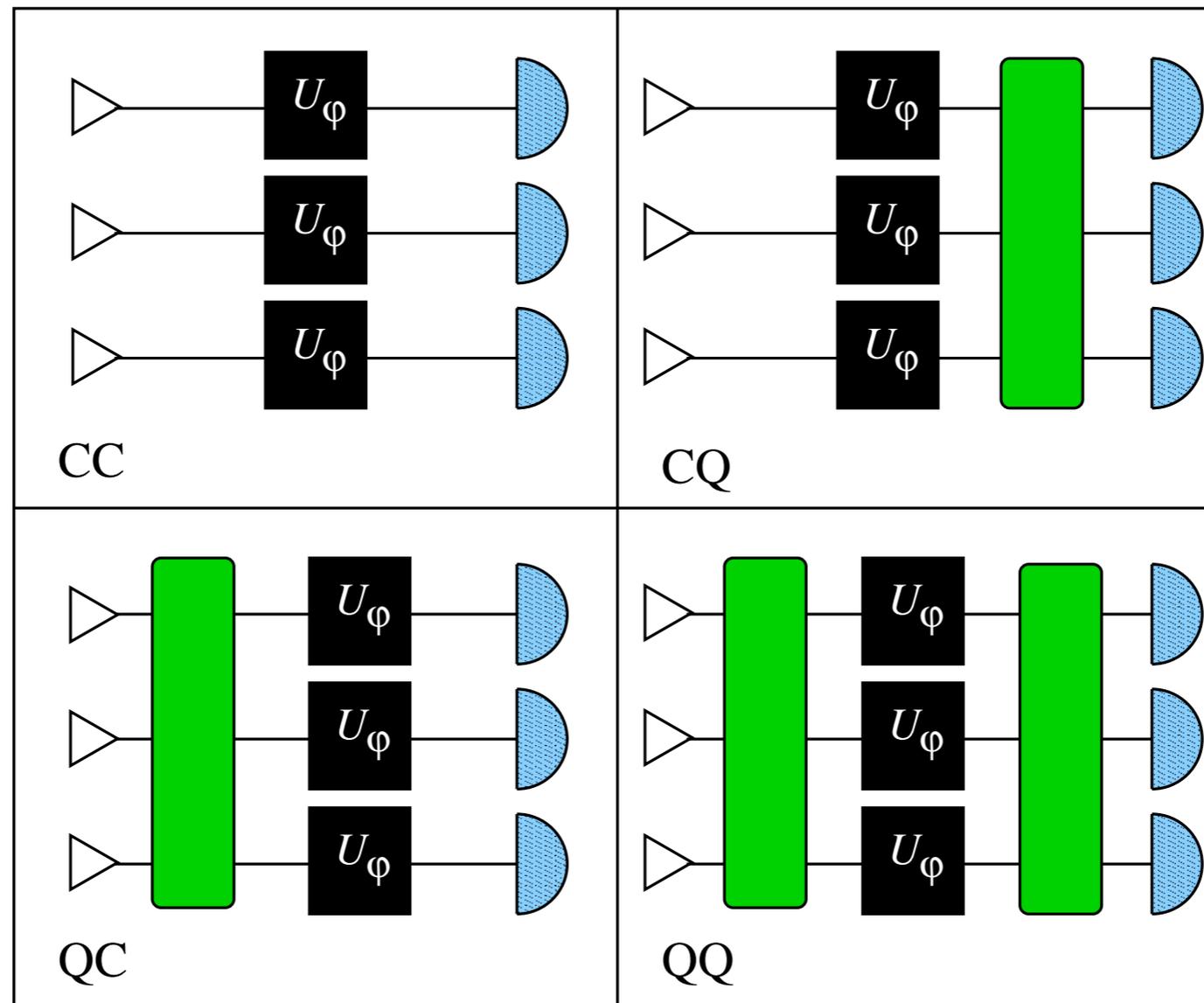
# Quantum Metrology

general framework to assess a quantum advantage



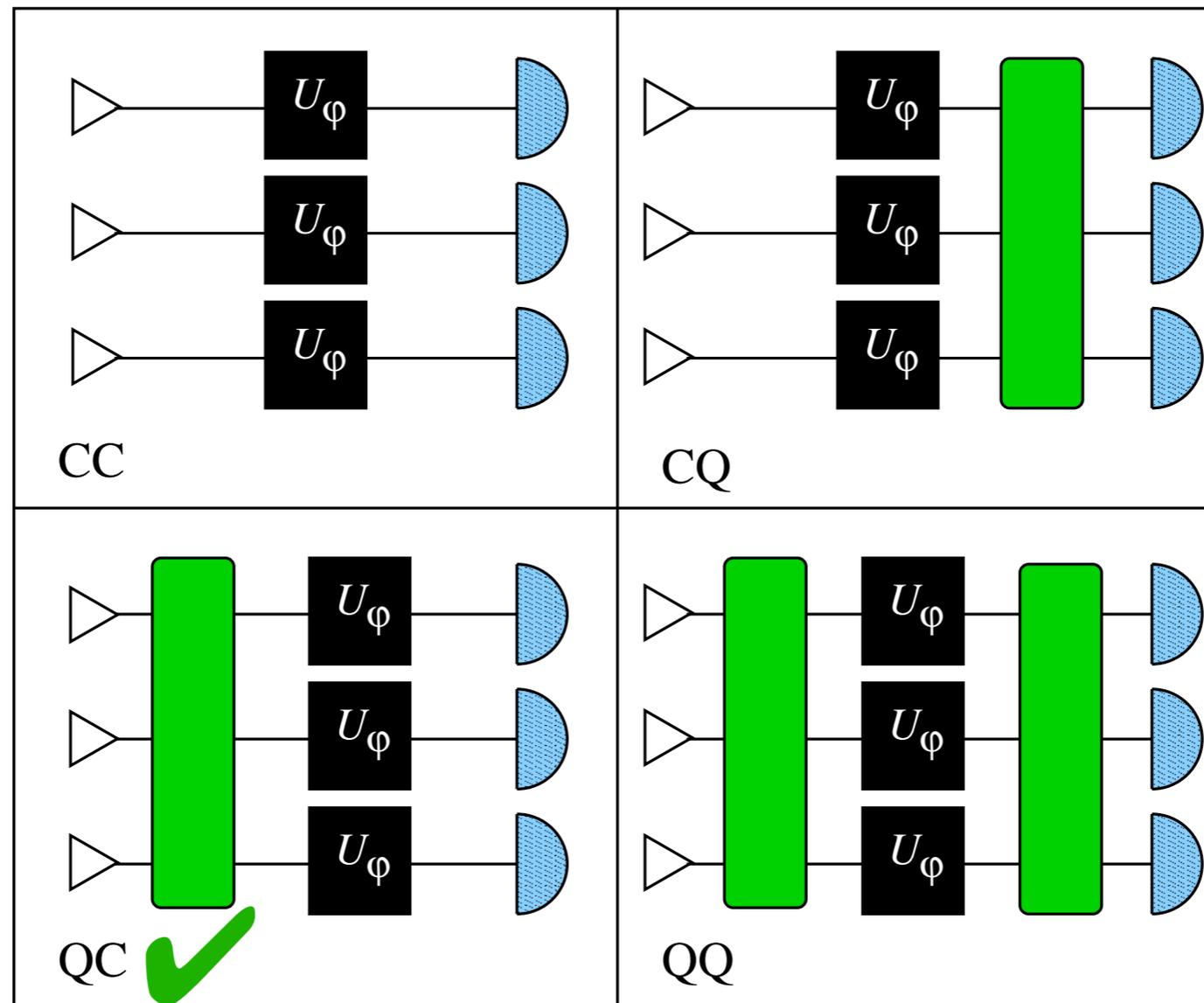
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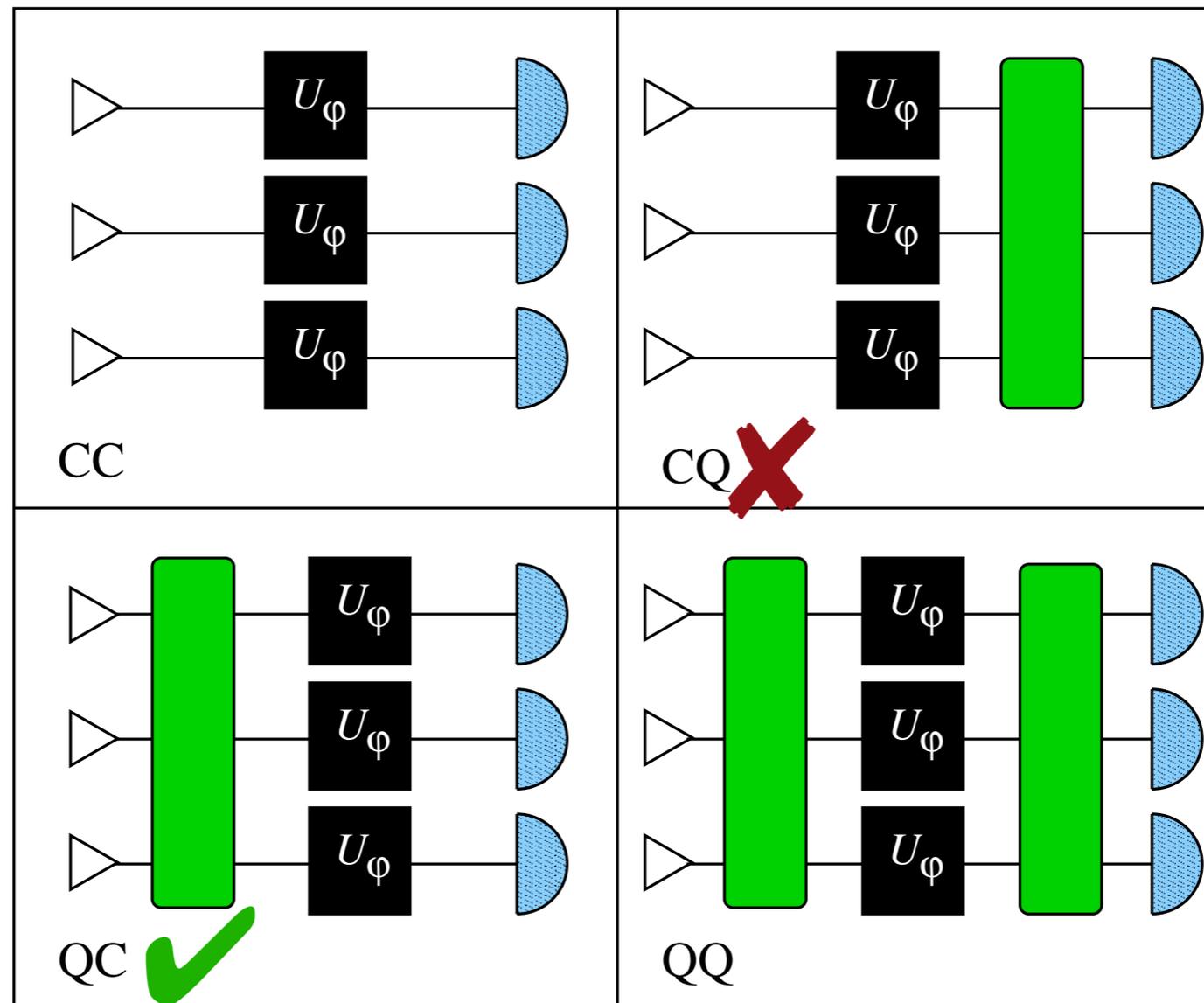
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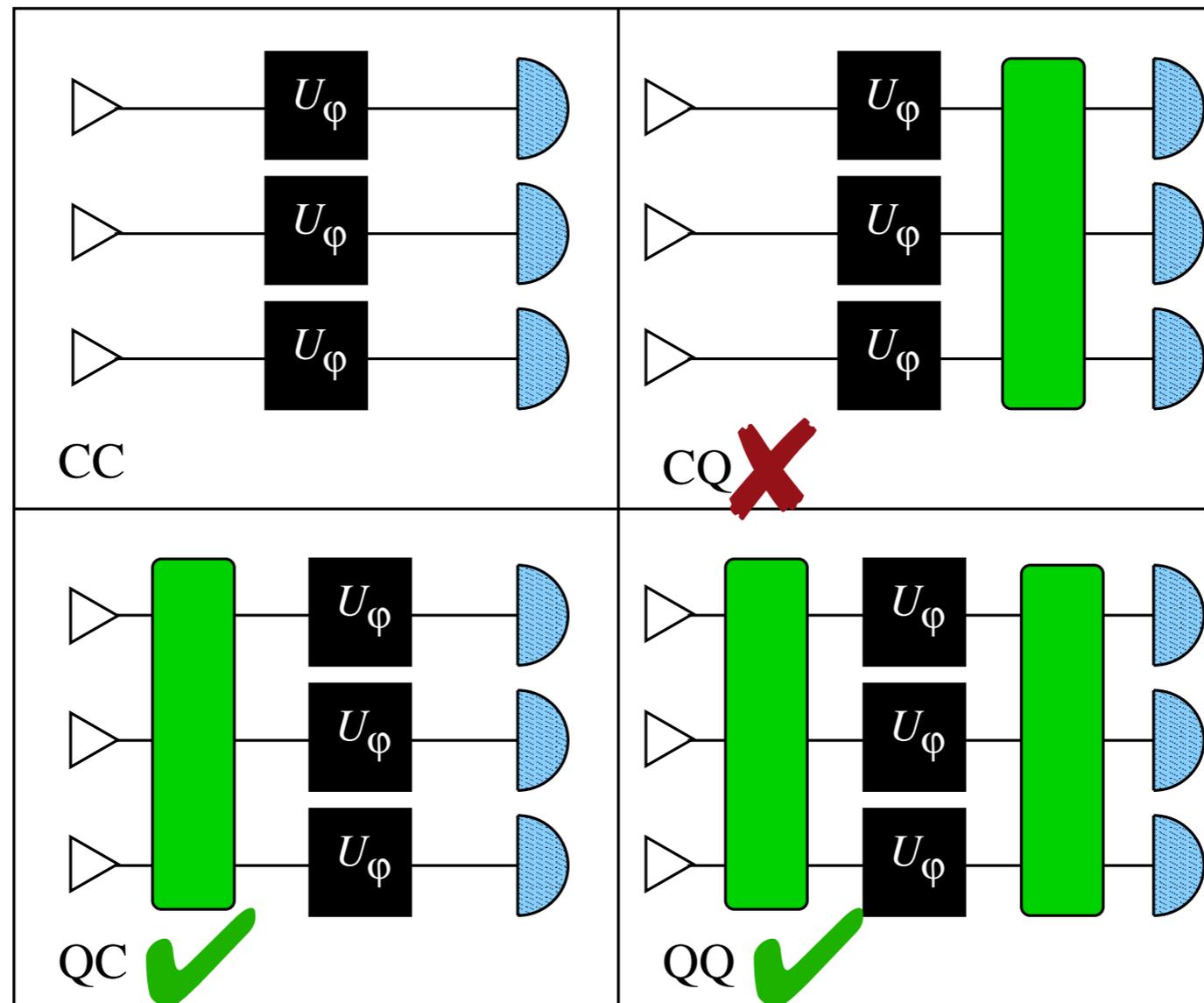
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general framework to assess a quantum advantage



# Quantum Metrology

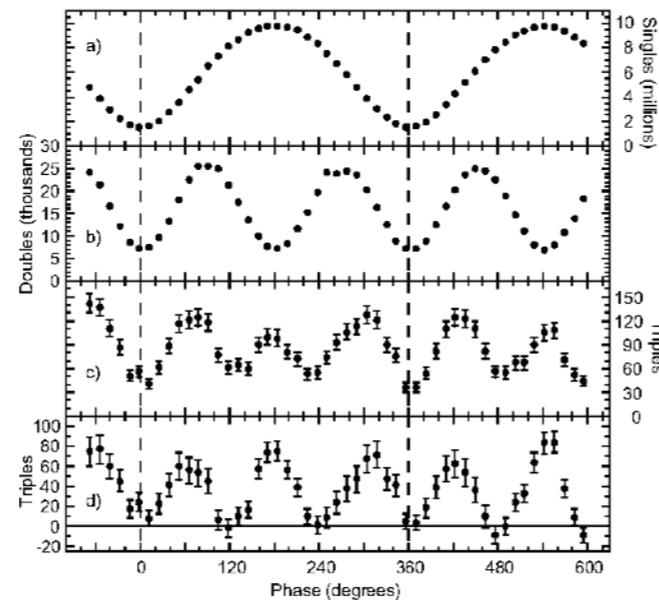
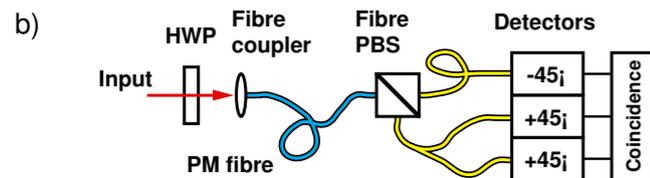
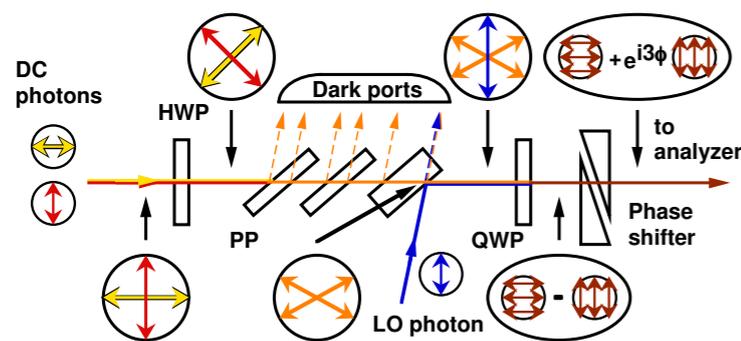
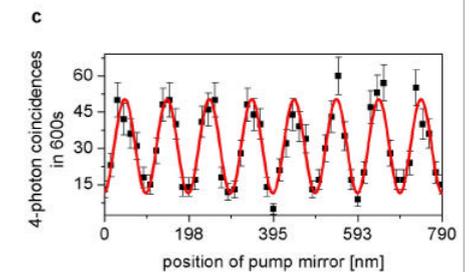
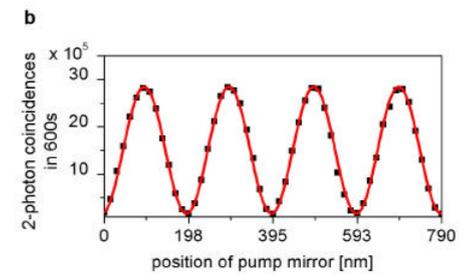
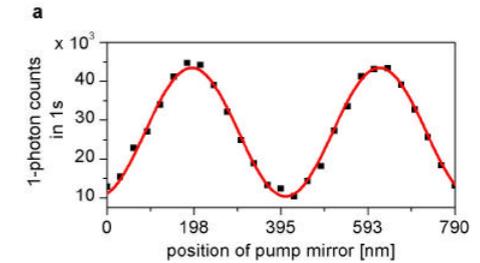
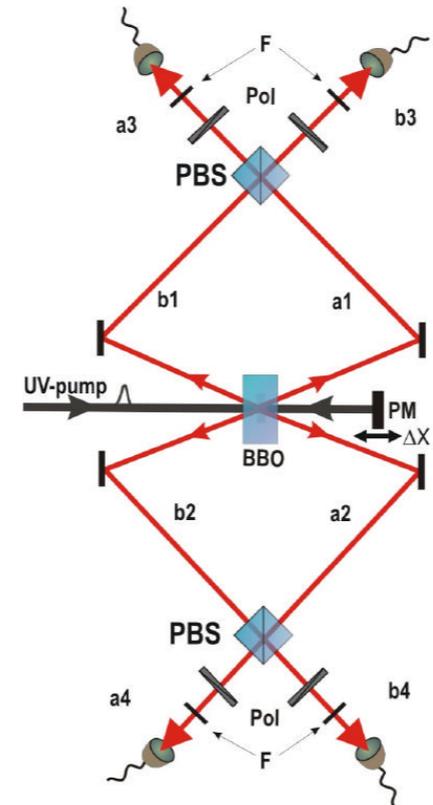
general framework to assess a quantum advantage





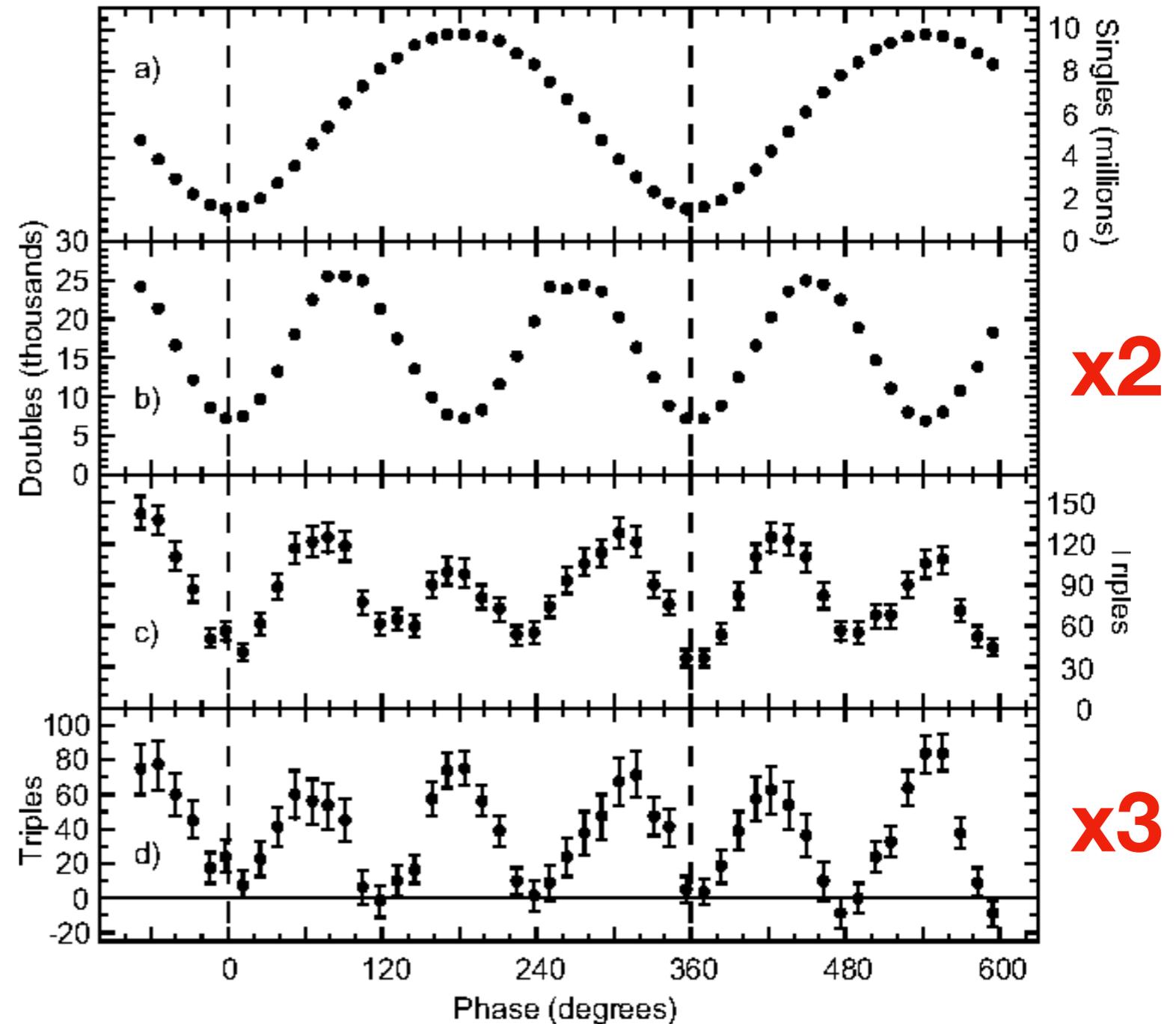
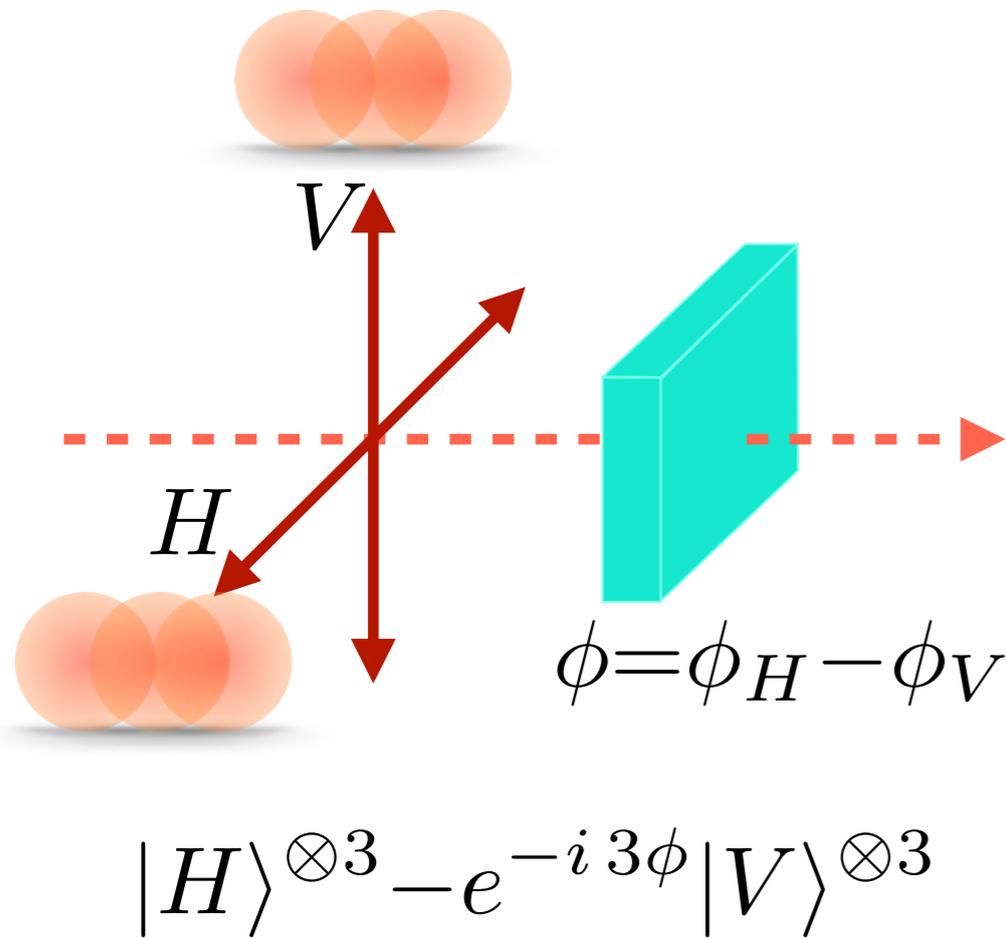
# Pioneering results

**P. Walther et al**  
**Nature 429, 158-161 (2004)**

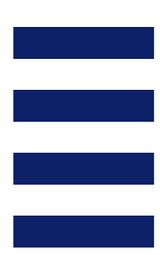


**M. Mitchell, J. Lundeen, A. Steinberg**  
**Nature 429, 161-164 (2004)**

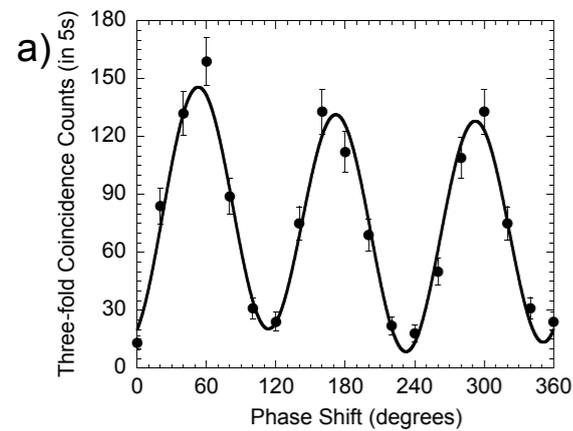
# Pioneering results



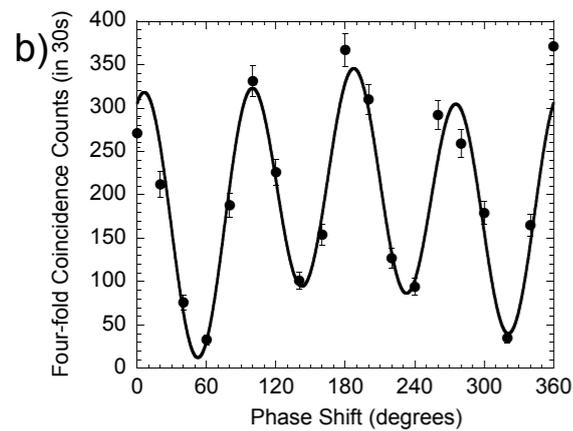
M. Mitchell, J. Lundeen, A. Steinberg  
 Nature 429, 161-164 (2004)



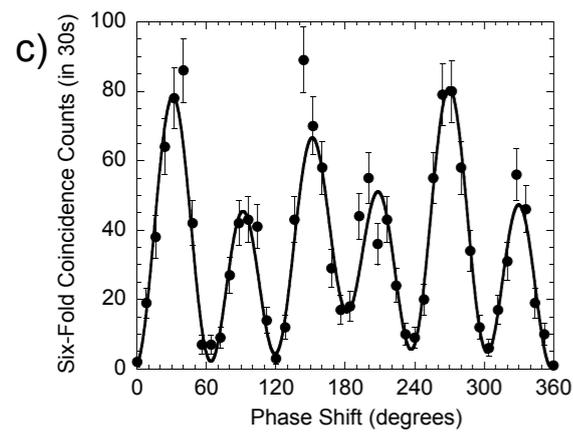
# Pioneering results



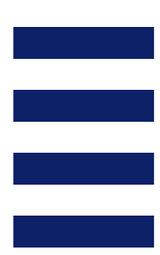
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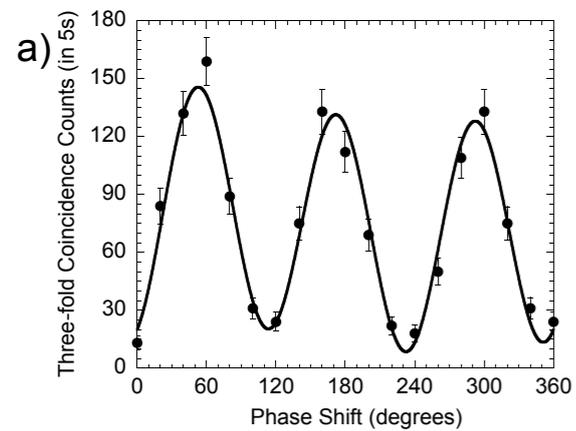
**x4**



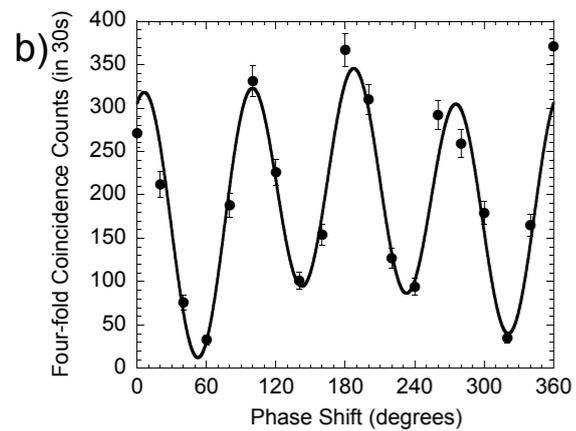
**x6**



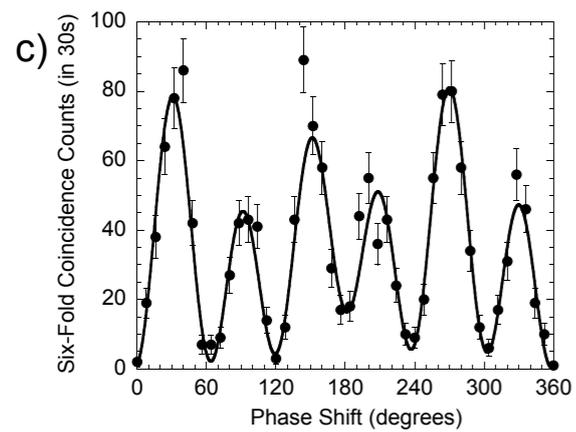
# Pioneering results



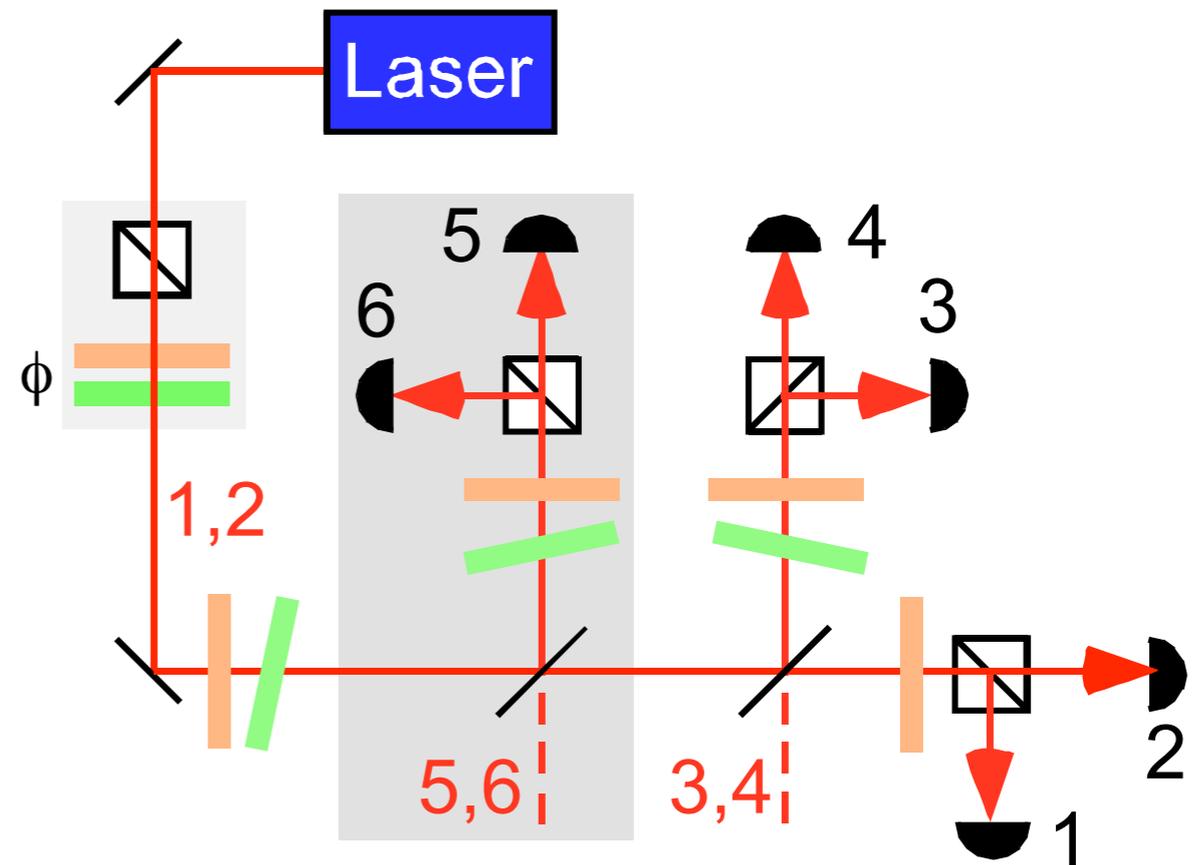
x3



x4

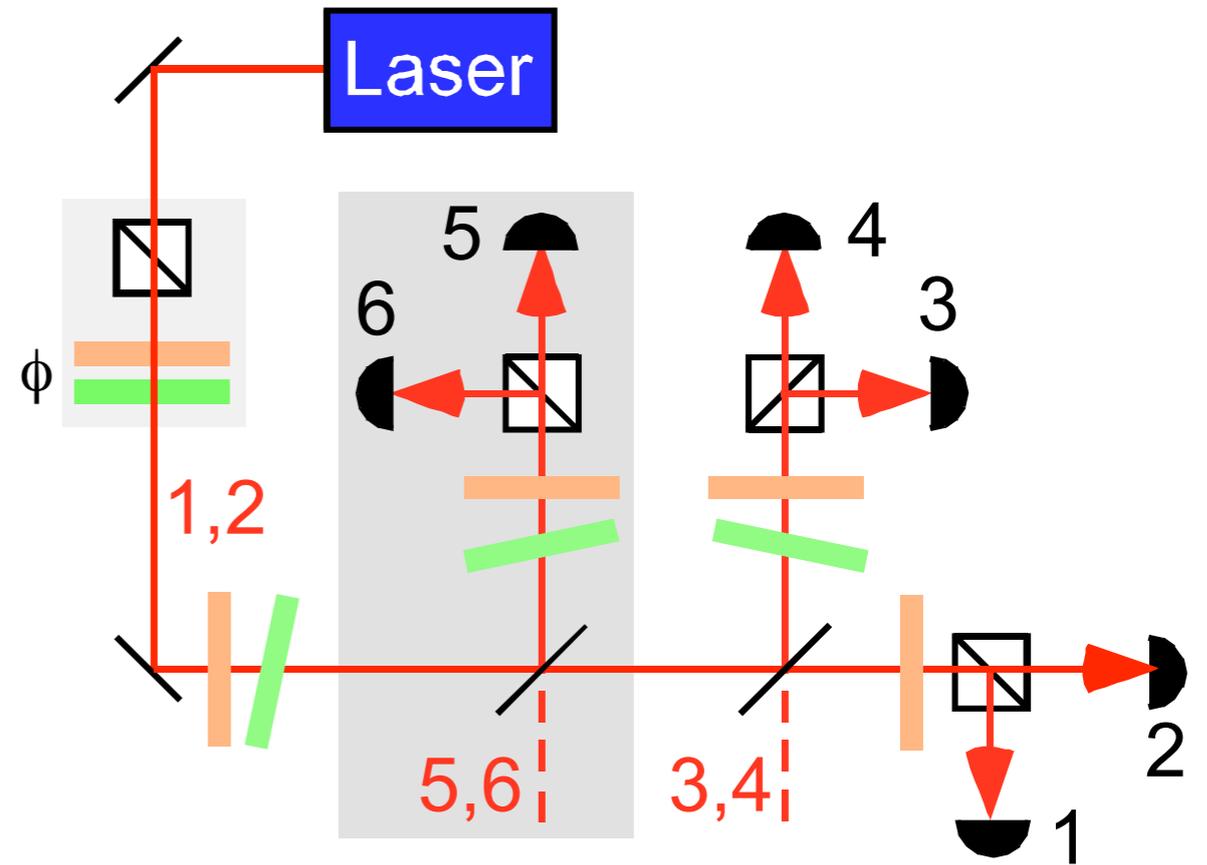
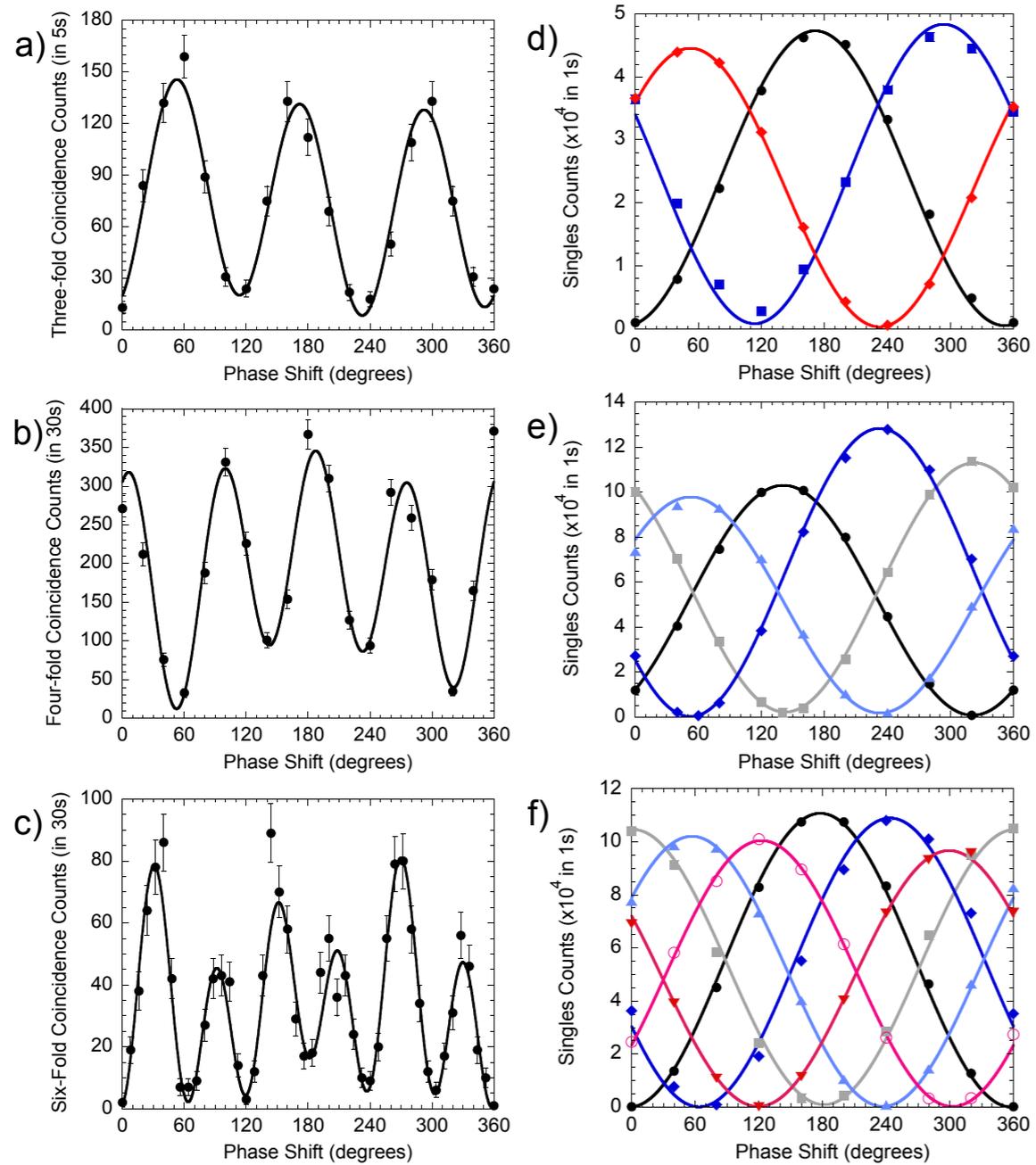


x6

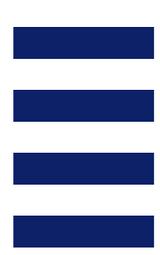




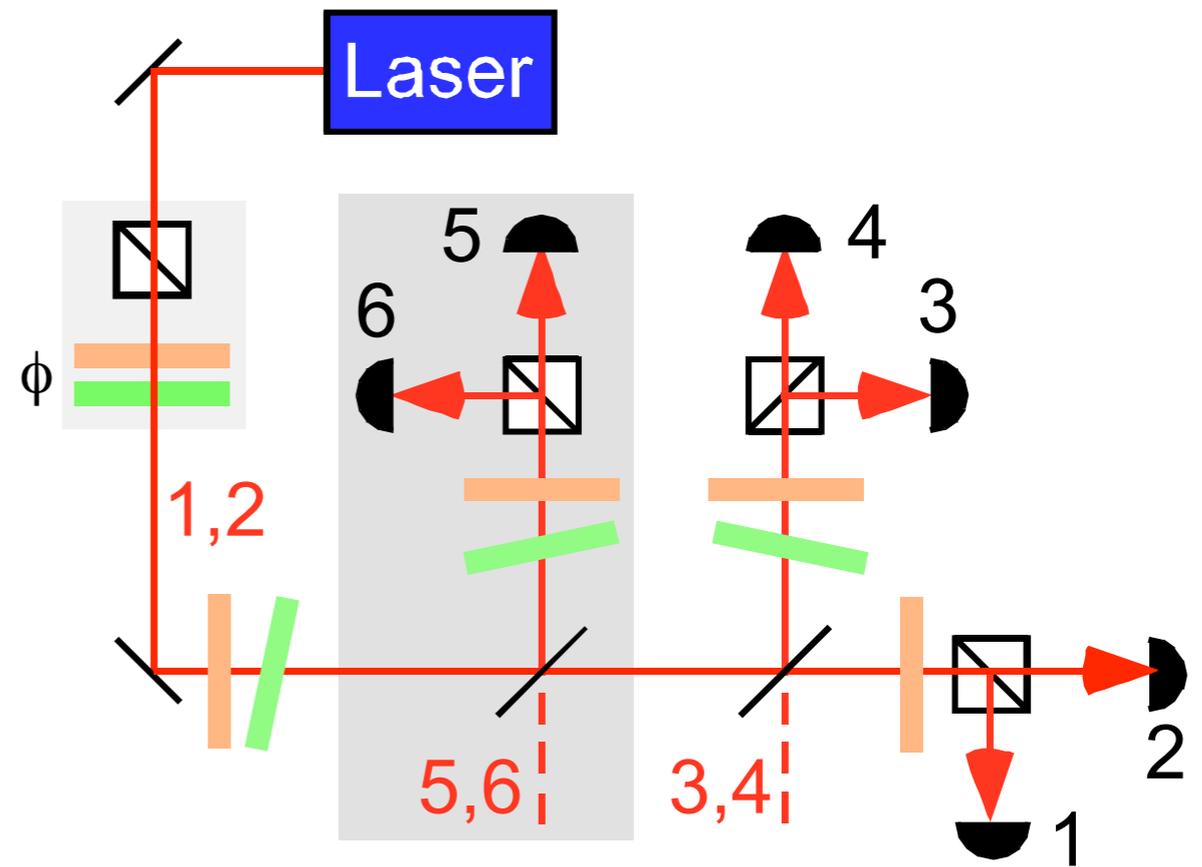
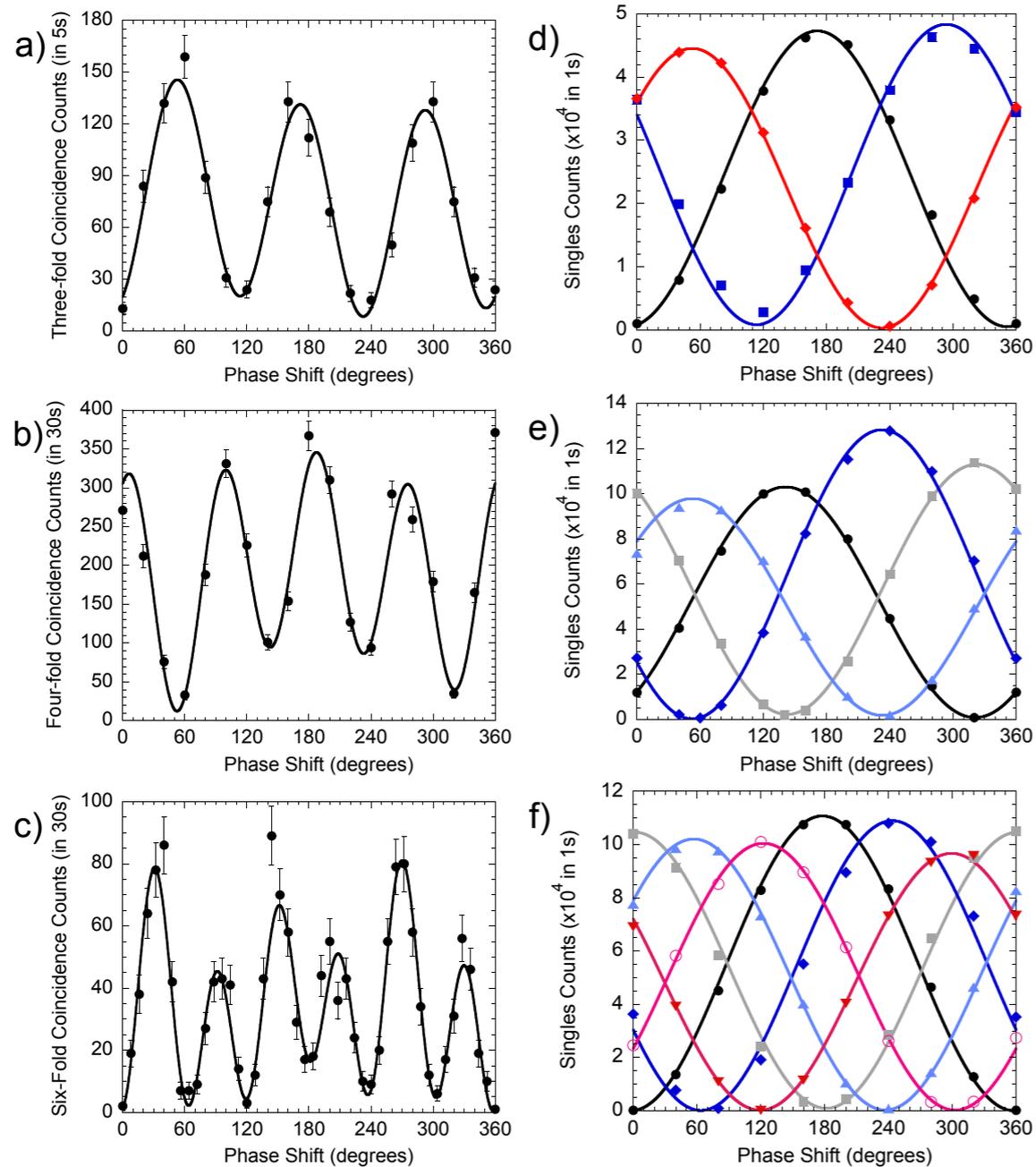
# Pioneering results



K. Resch et al  
PRL 98, 223601 (2007)



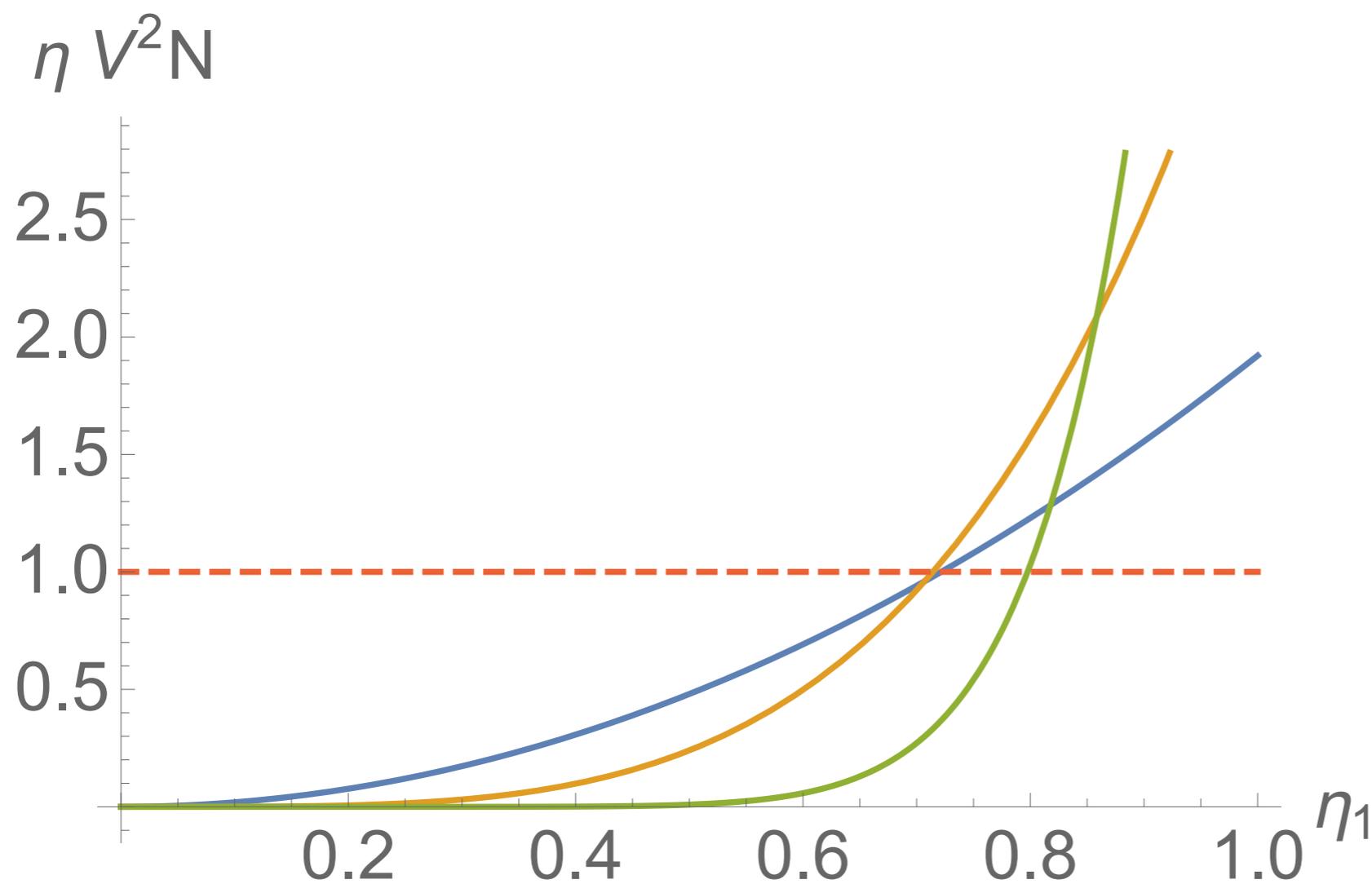
# Pioneering results



**criterion for real quantum improvement**

$$\eta V^2 N > 1$$

# Pioneering results



$$\eta V^2 N > 1$$

**typical values**

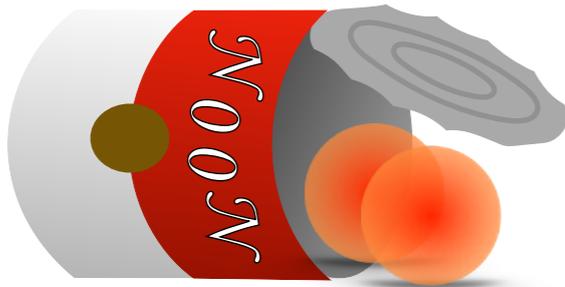
$$N \sim 2 - 6$$

$$V \sim 98\%$$

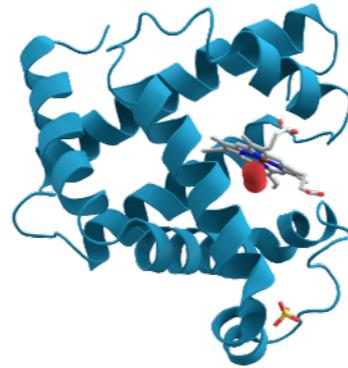
$$\eta_1 \sim 5 - 20\%$$

# ☰ Coping with Loss

**source**



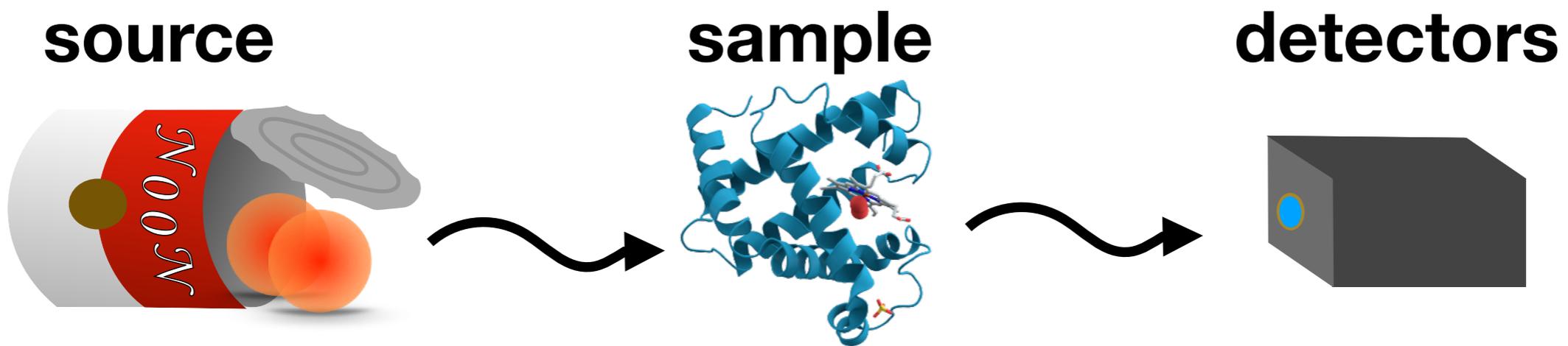
**sample**



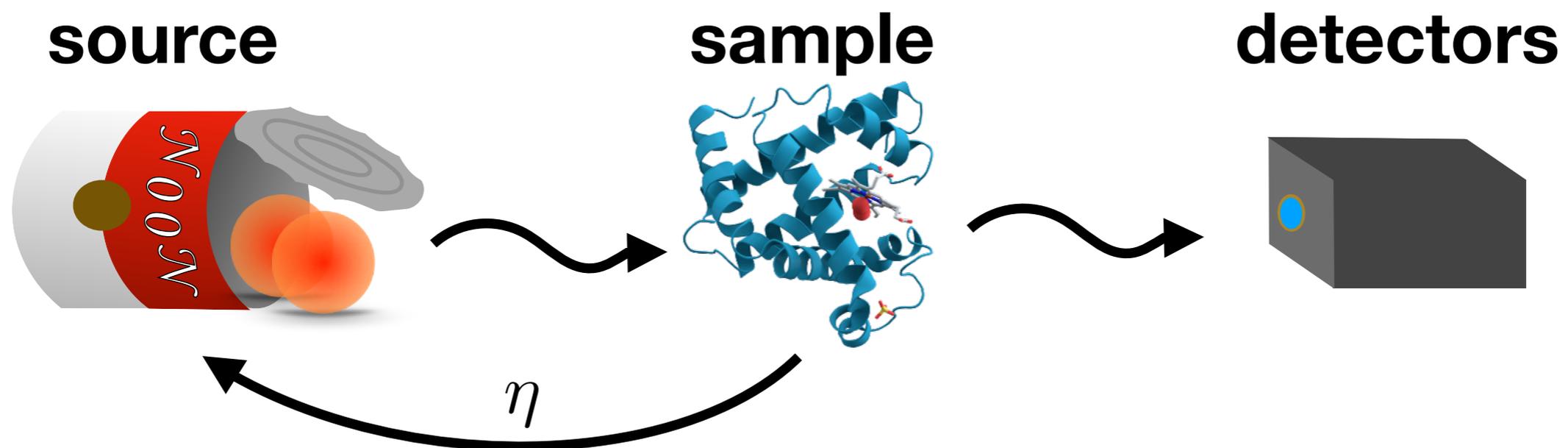
**detectors**



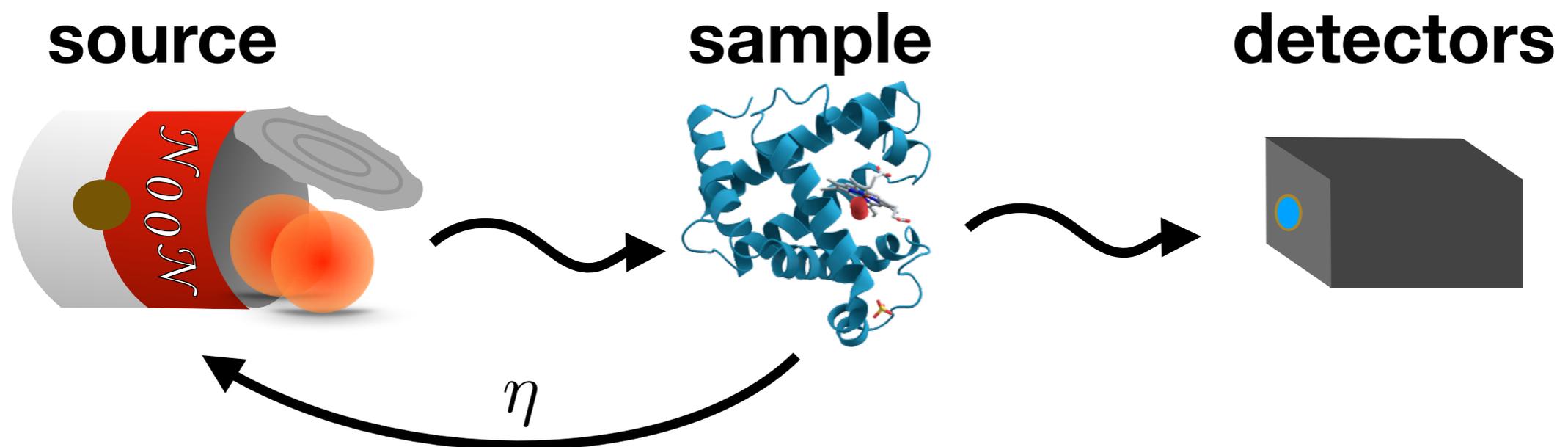
# ☰ Coping with Loss



# ☰ Coping with Loss

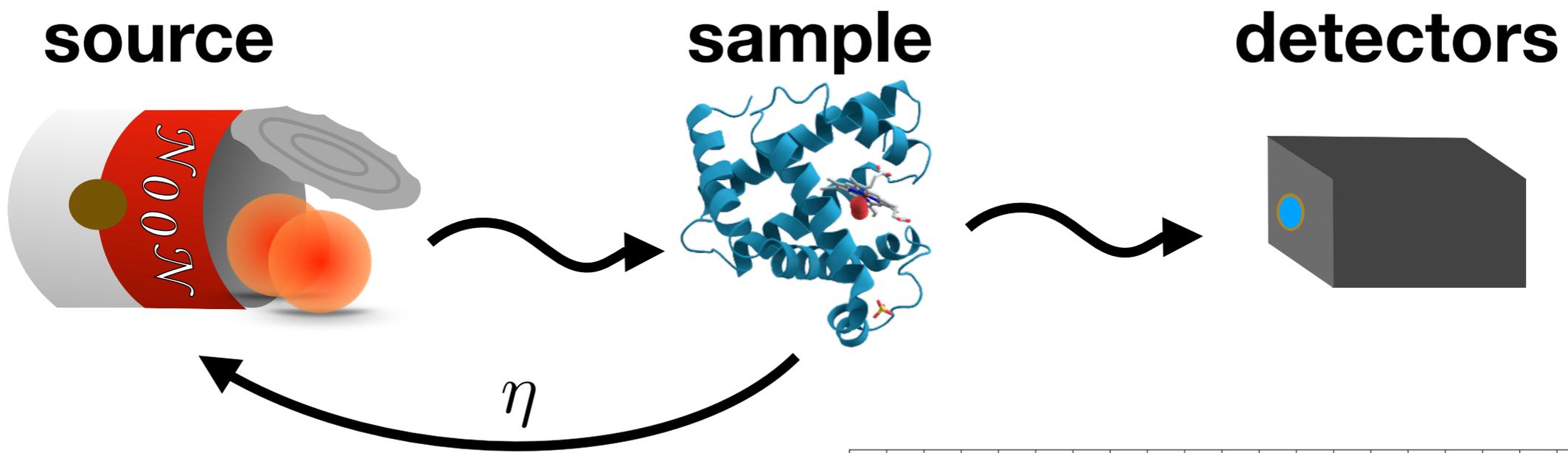


# ☰ Coping with Loss

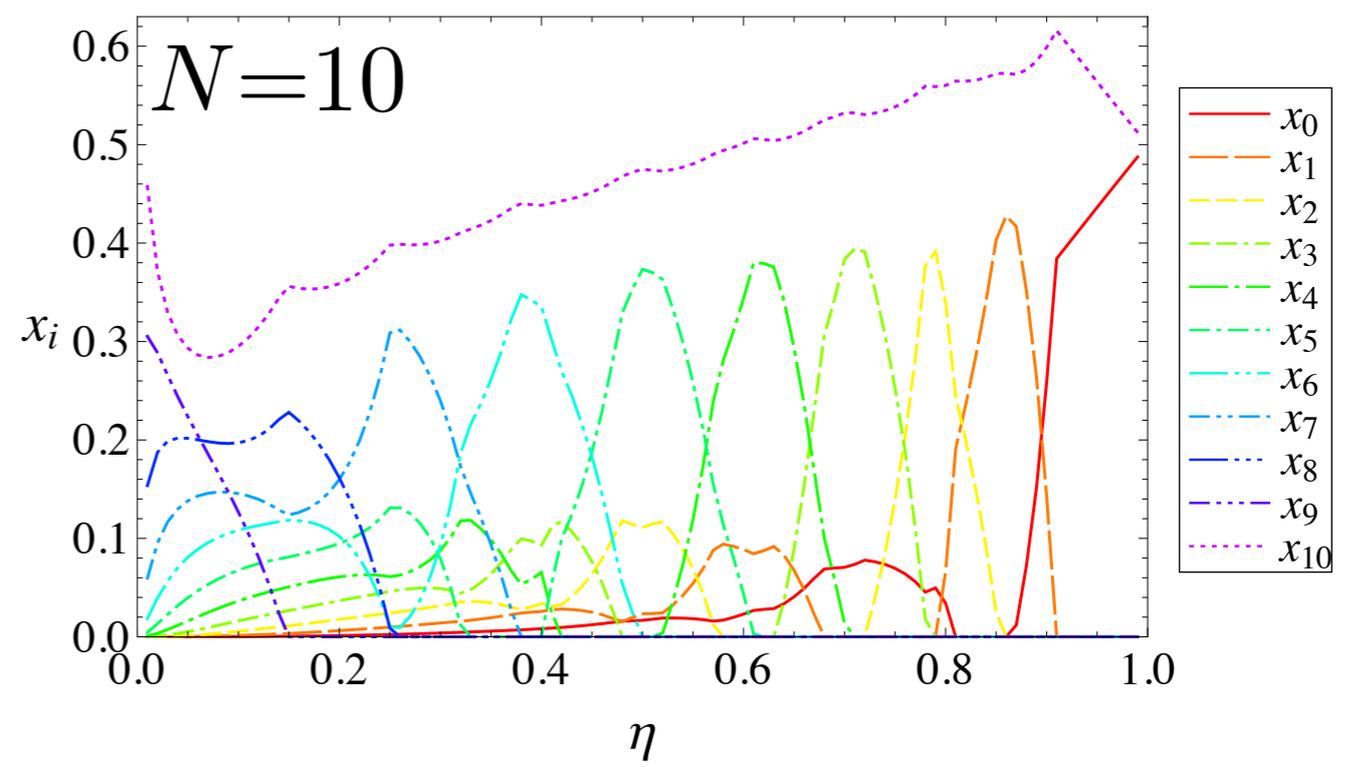


**optimal state design  
based on loss**

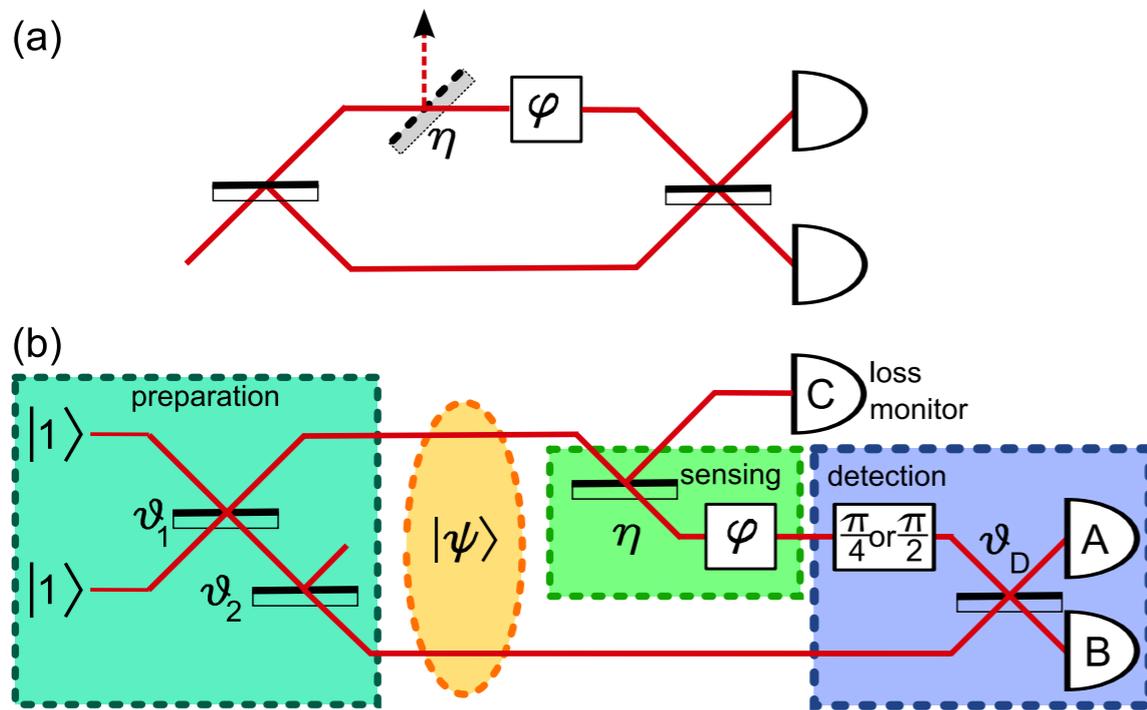
# Coping with Loss



**optimal state design  
based on loss**

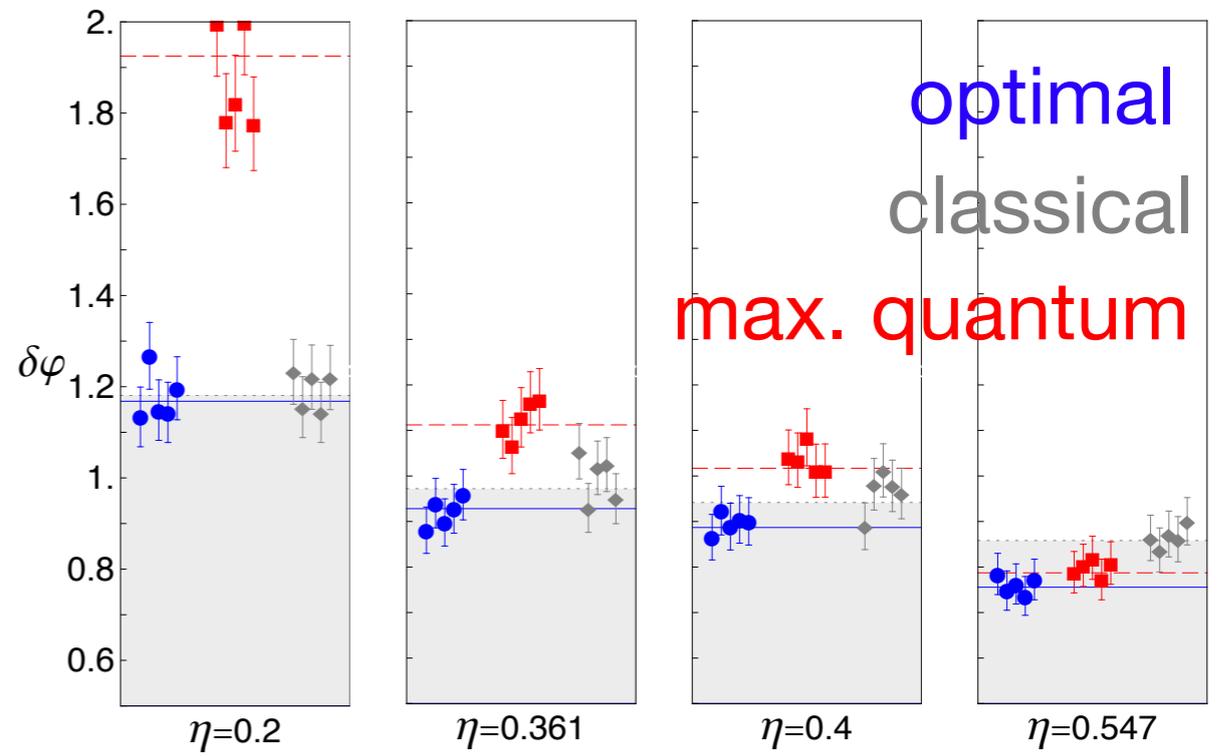
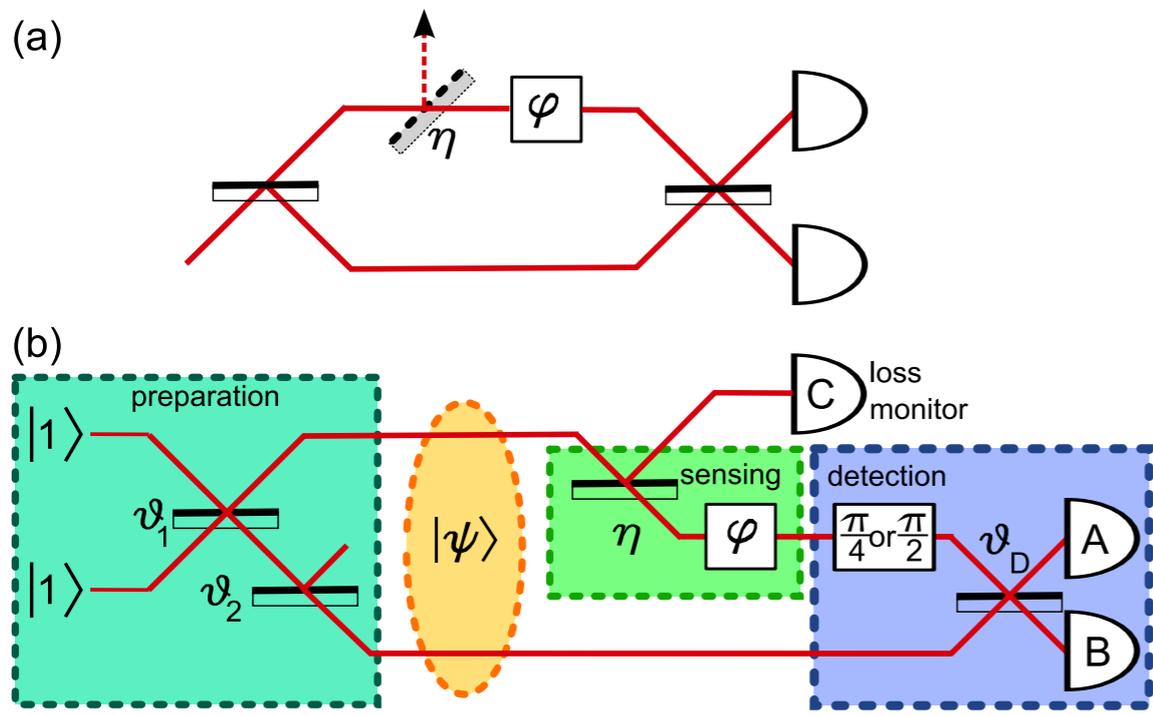


# Coping with Loss



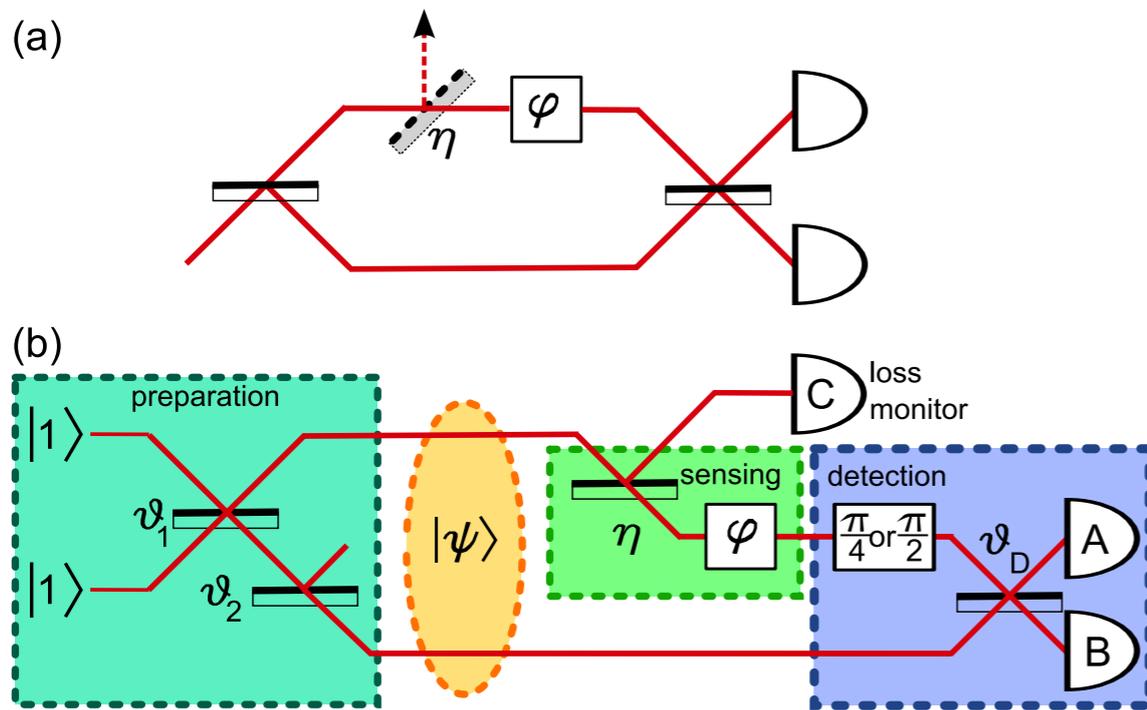
**optimal state design  
based on loss**

# Coping with Loss

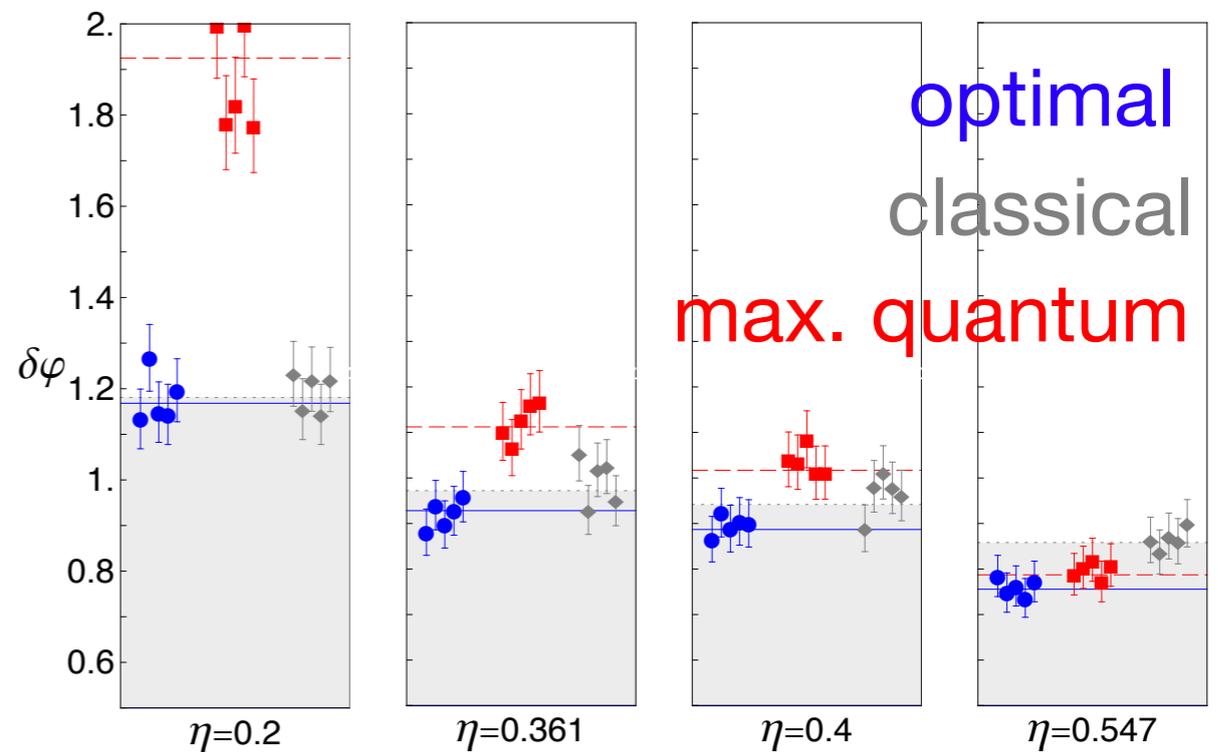


**optimal state design based on loss**

# Coping with Loss

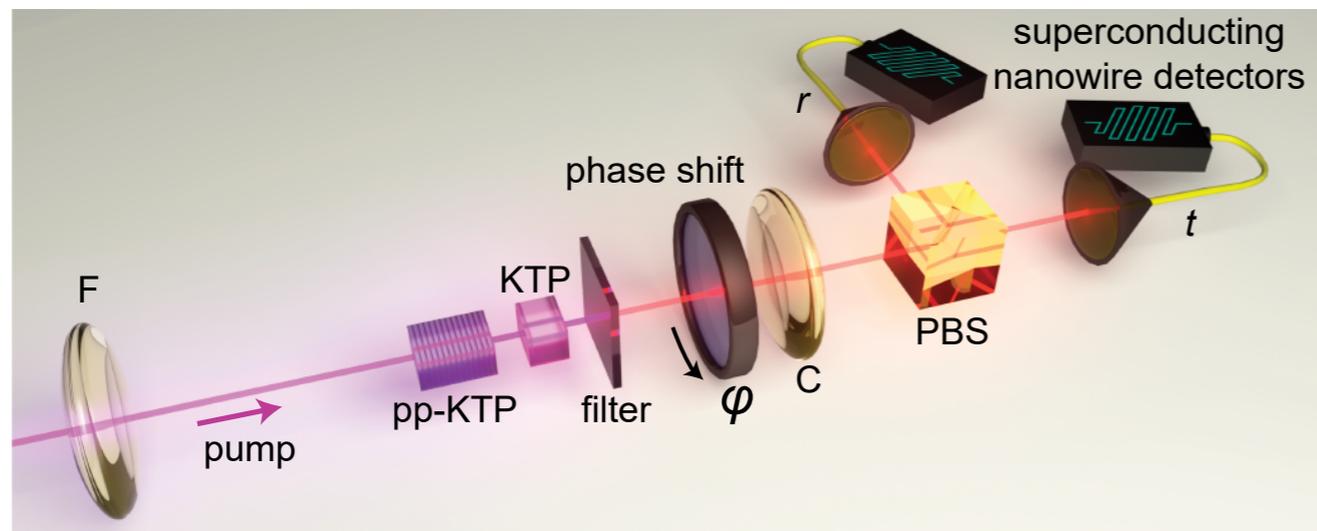


optimal state design  
based on loss

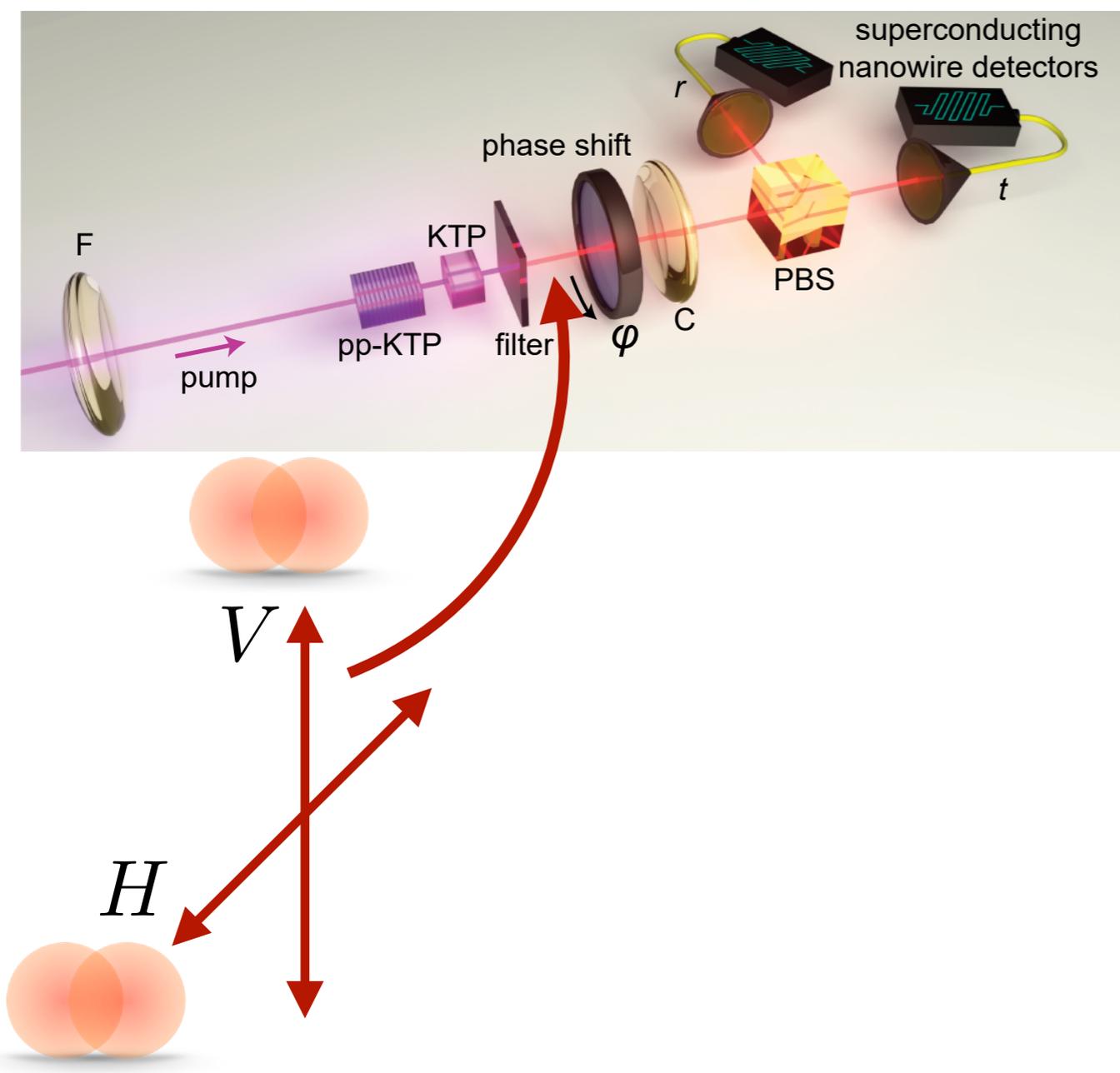


comparison carried out  
for the *detected* photons

# ☰ Coping with Loss

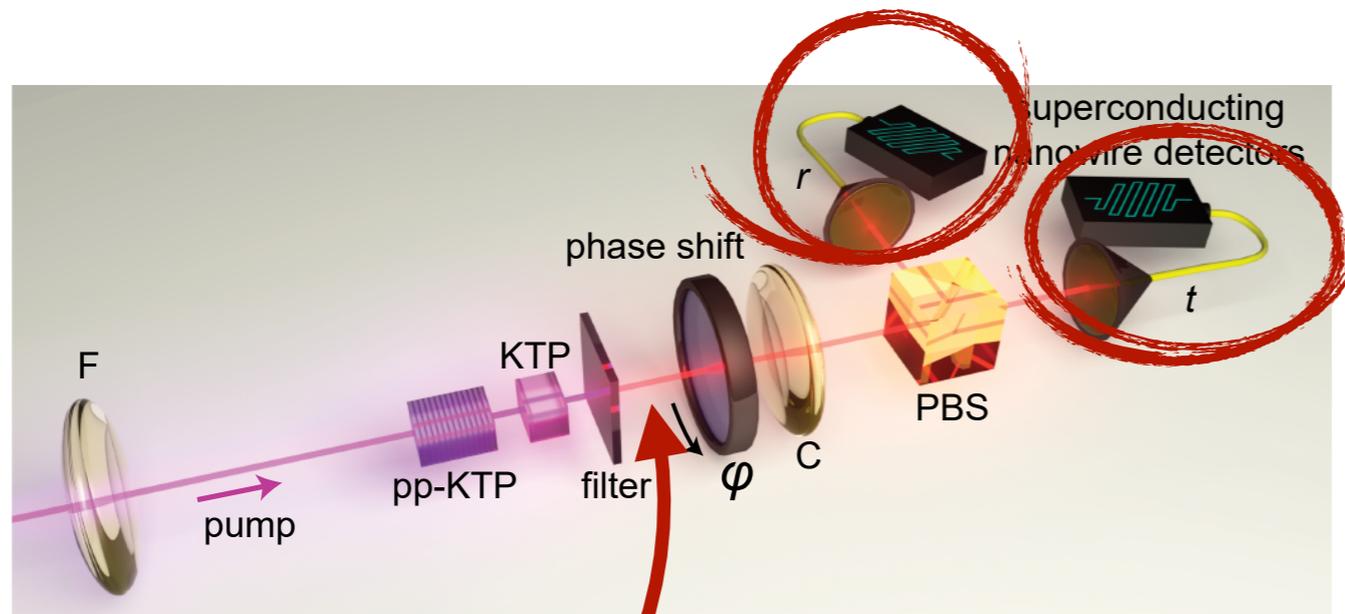


# Coping with Loss

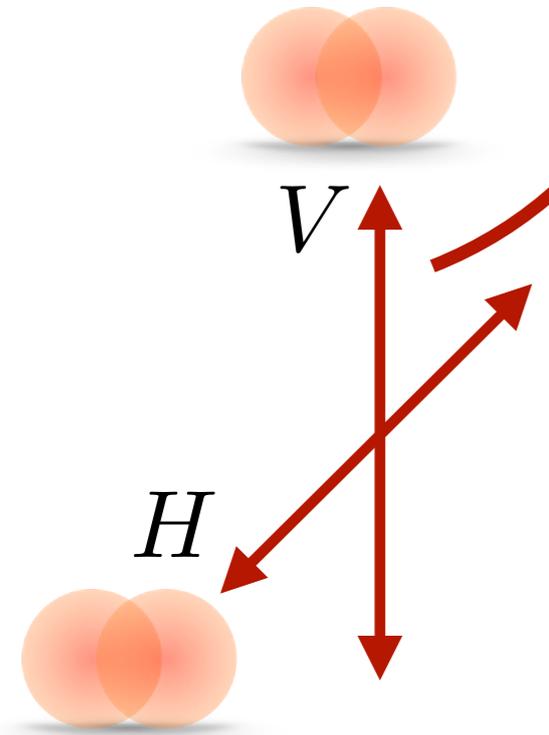


S. Slussarenko et al  
Nat. Photon 11, 700 (2017)

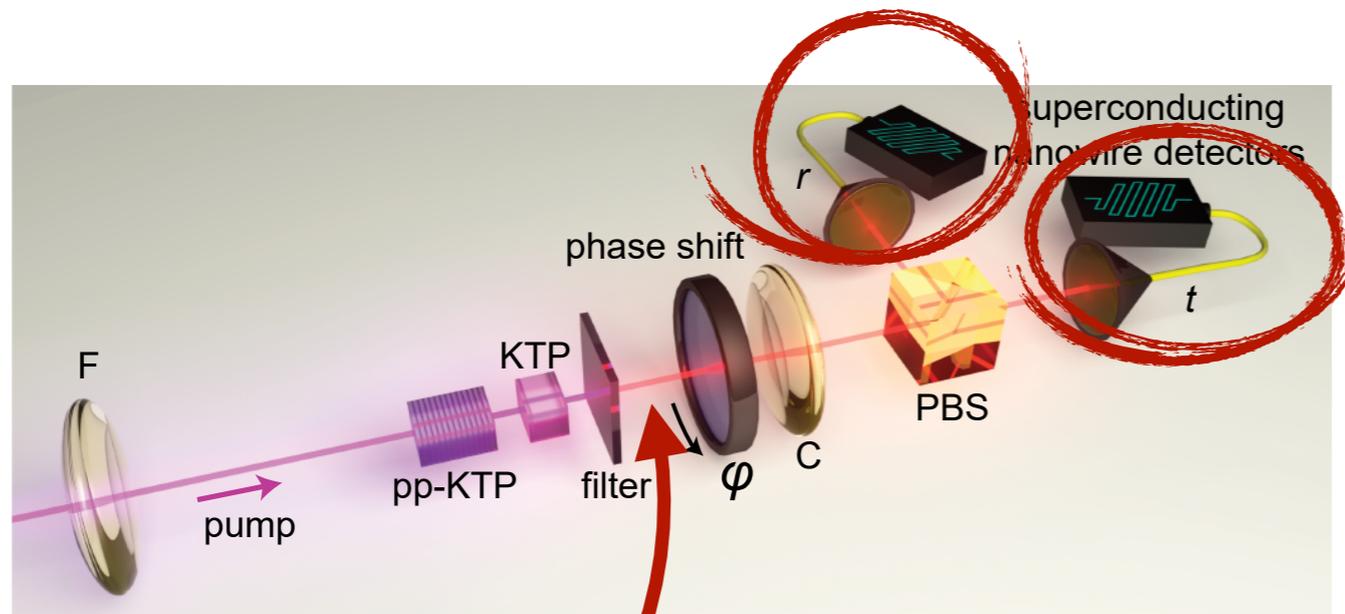
# Coping with Loss



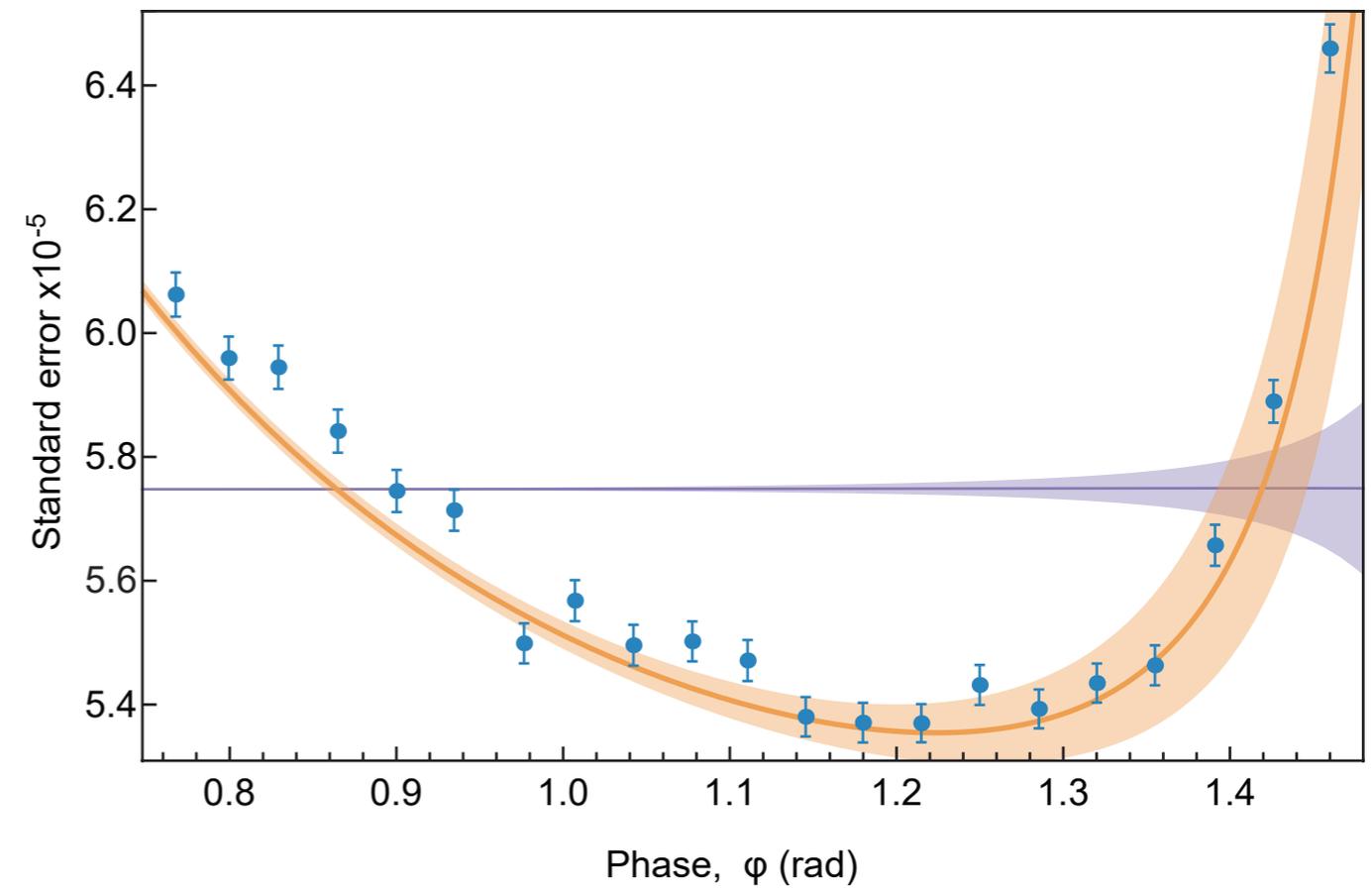
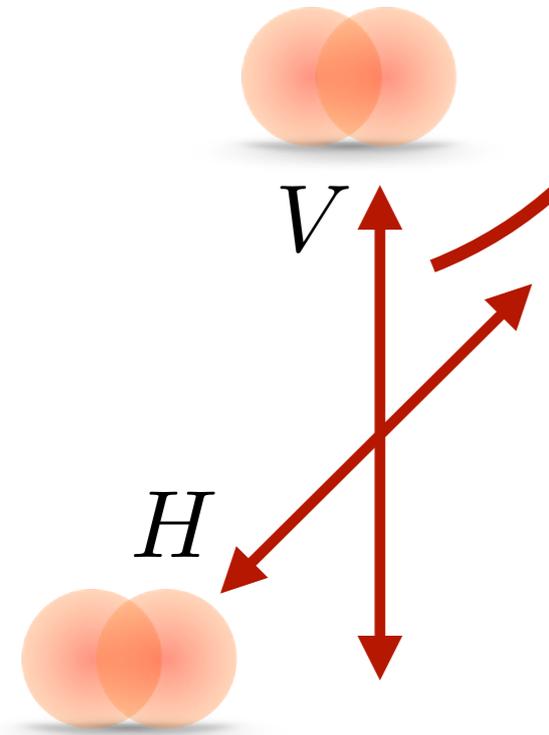
**superconducting  
detectors**



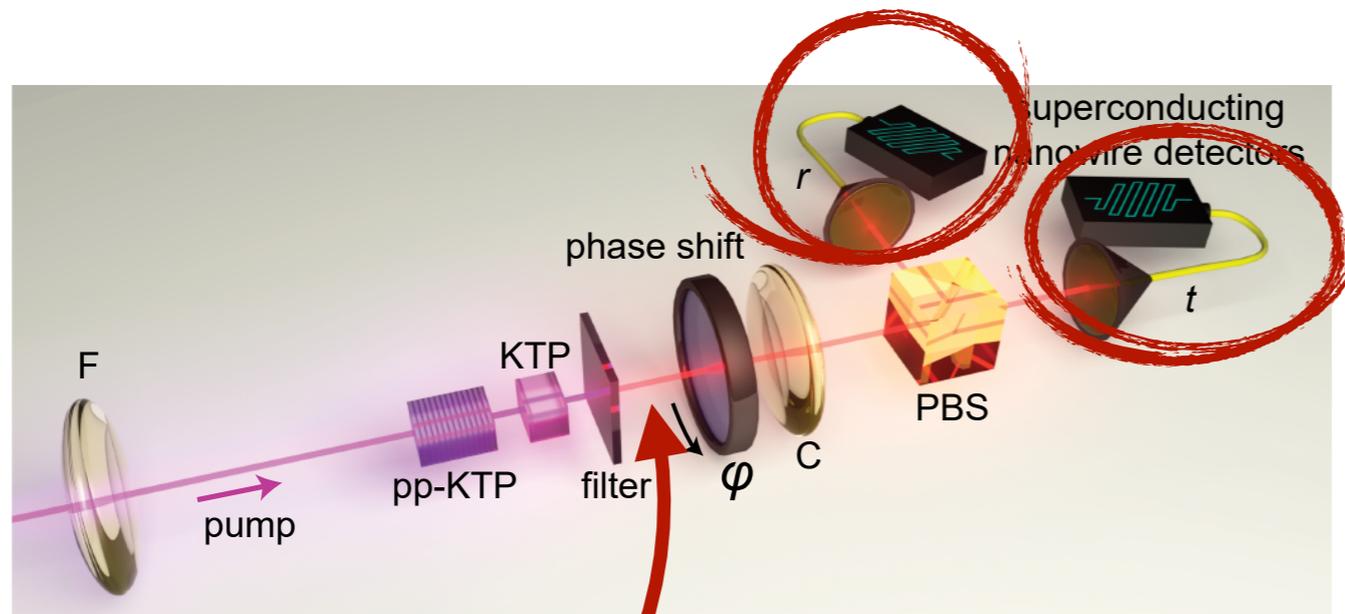
# Coping with Loss



**superconducting detectors**

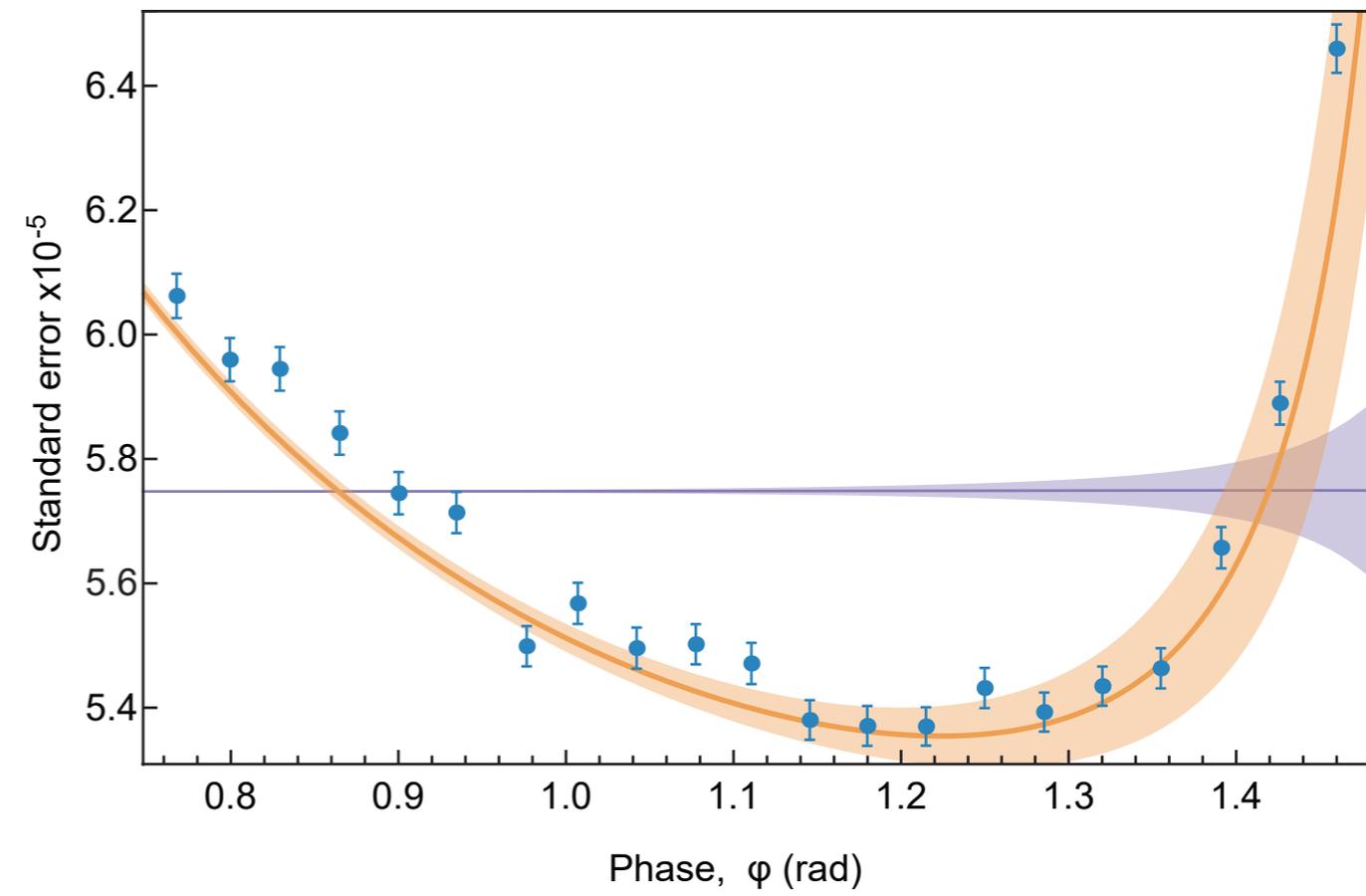
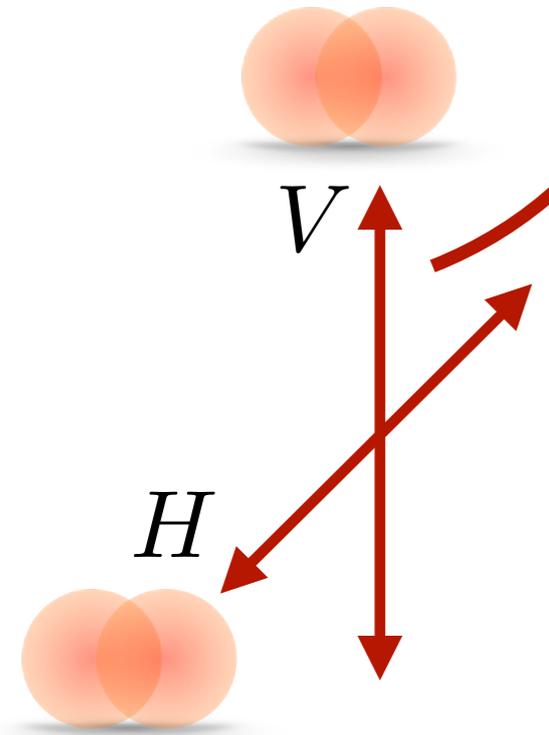


# Coping with Loss



**superconducting detectors**

**comparison carried out for *all* photons**

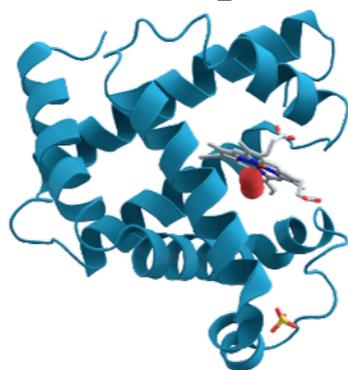


# ☰ Coping with Imperfections

**source**



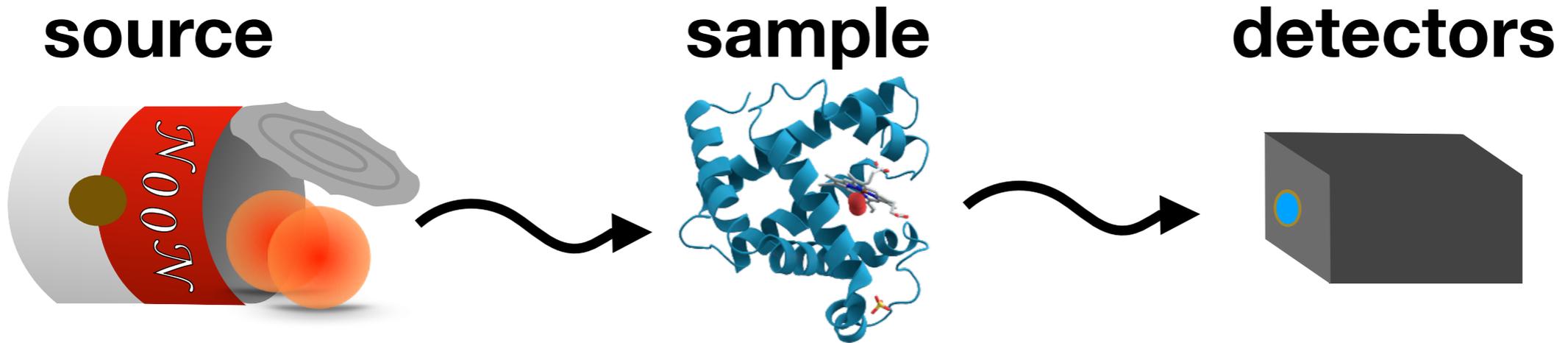
**sample**



**detectors**



# Coping with Imperfections

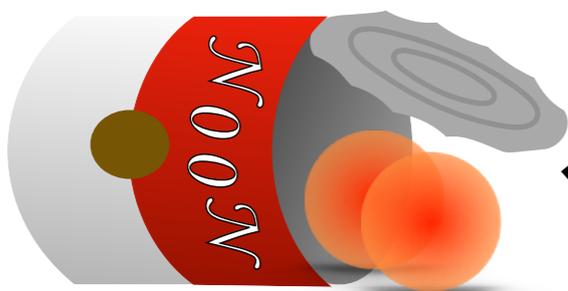


$\Psi$

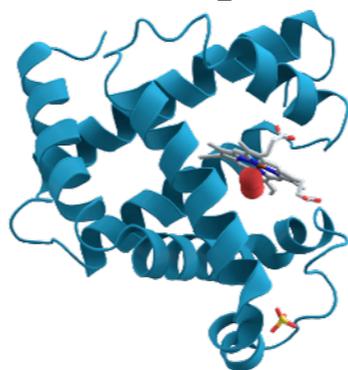
**basic  
science**

# Coping with Imperfections

**source**



**sample**

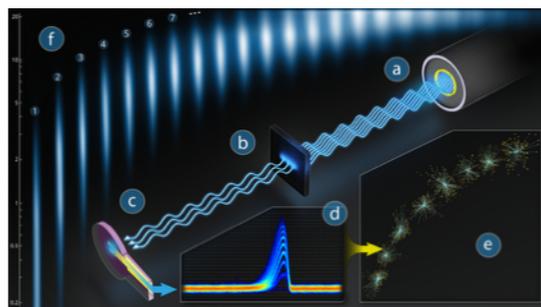


**detectors**



$\Psi$

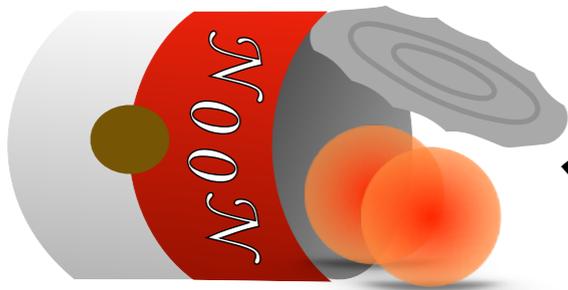
**basic  
science**



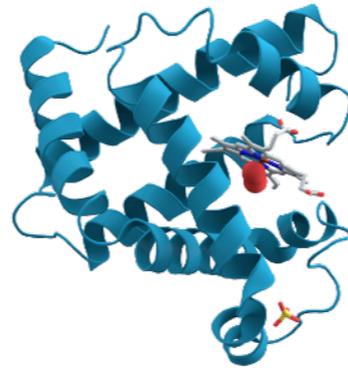
**improved  
components**

# Coping with Imperfections

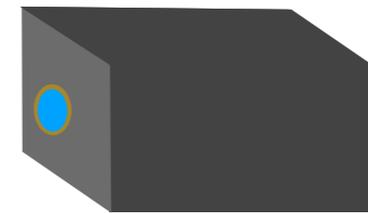
**source**



**sample**

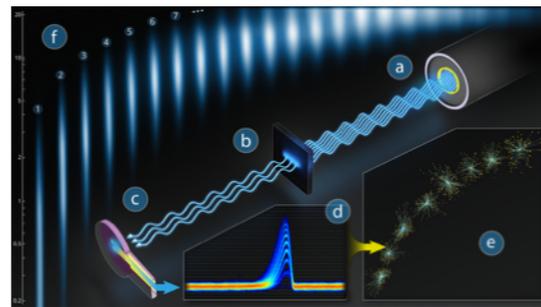


**detectors**



$\Psi$

**basic  
science**

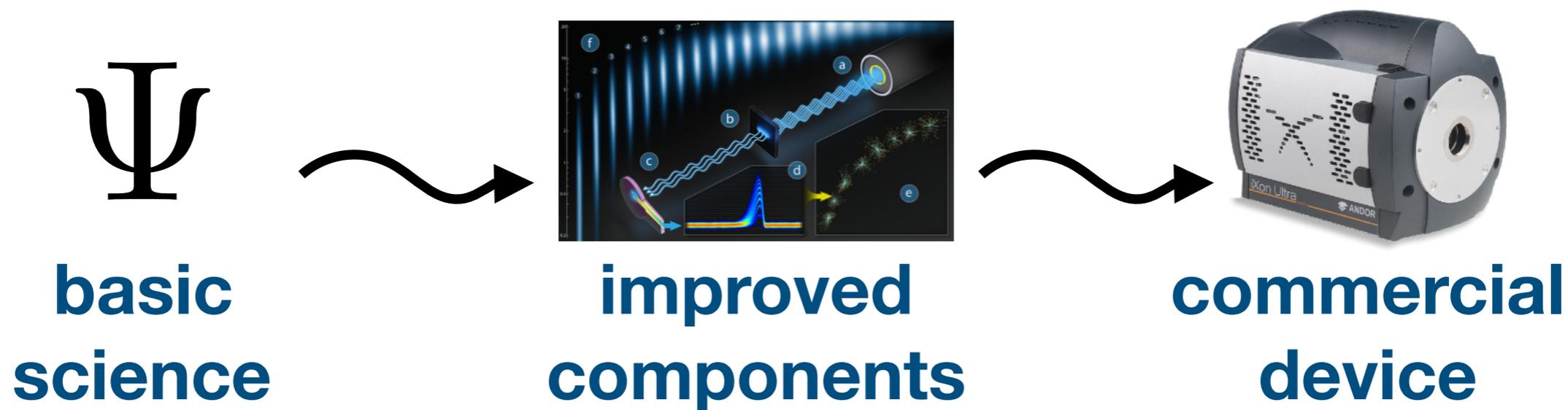
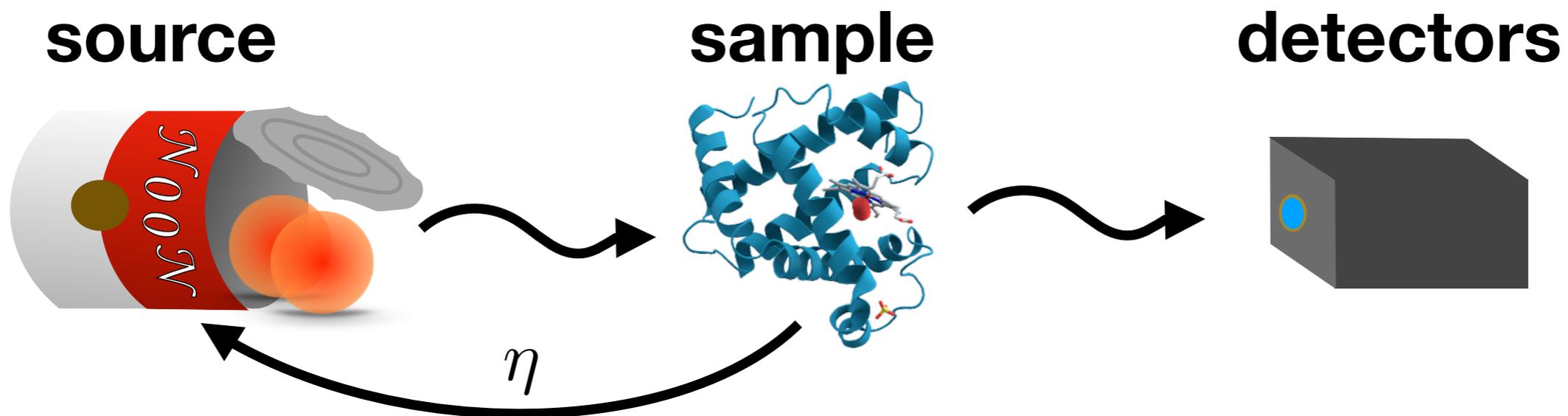


**improved  
components**



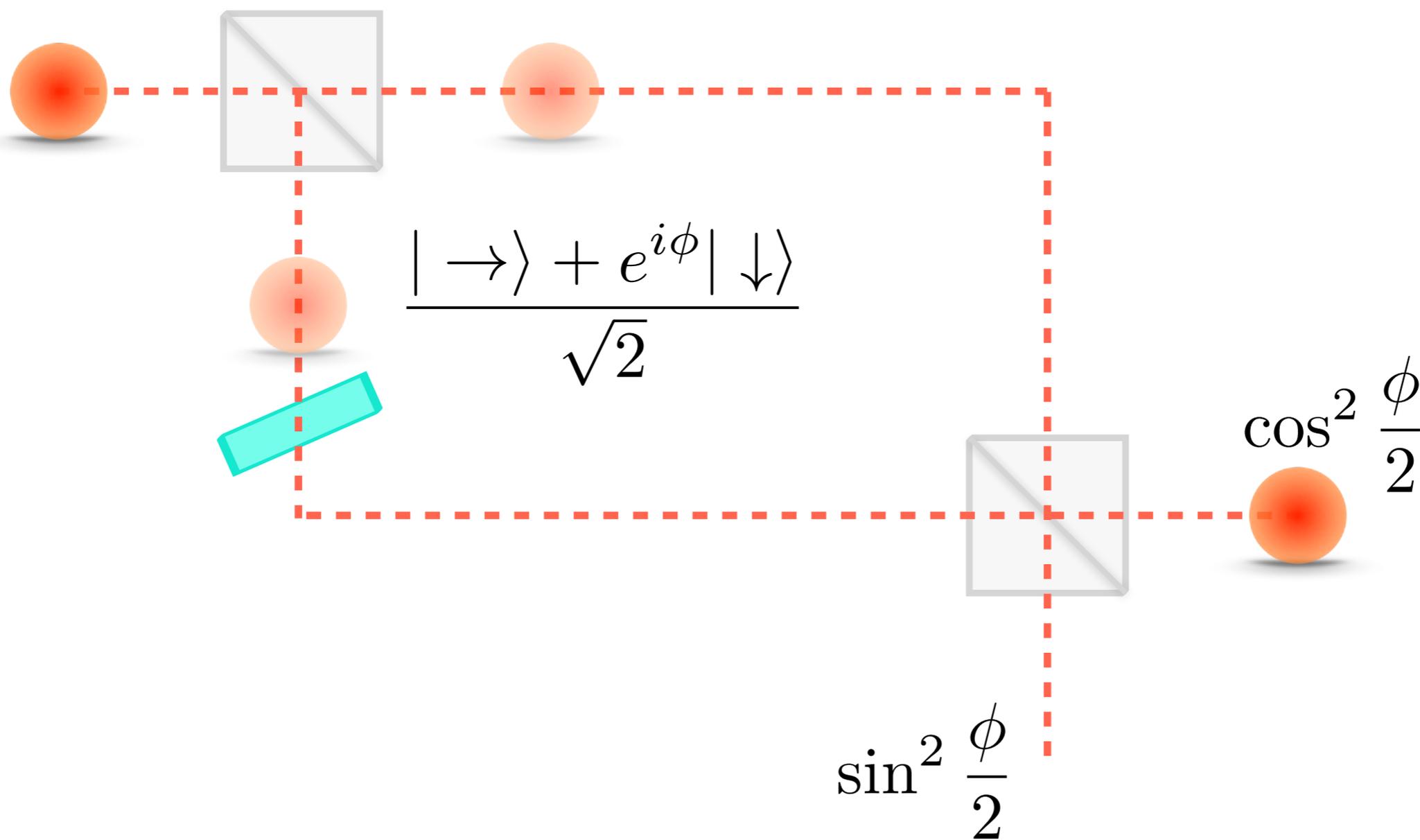
**commercial  
device**

# Coping with Imperfections



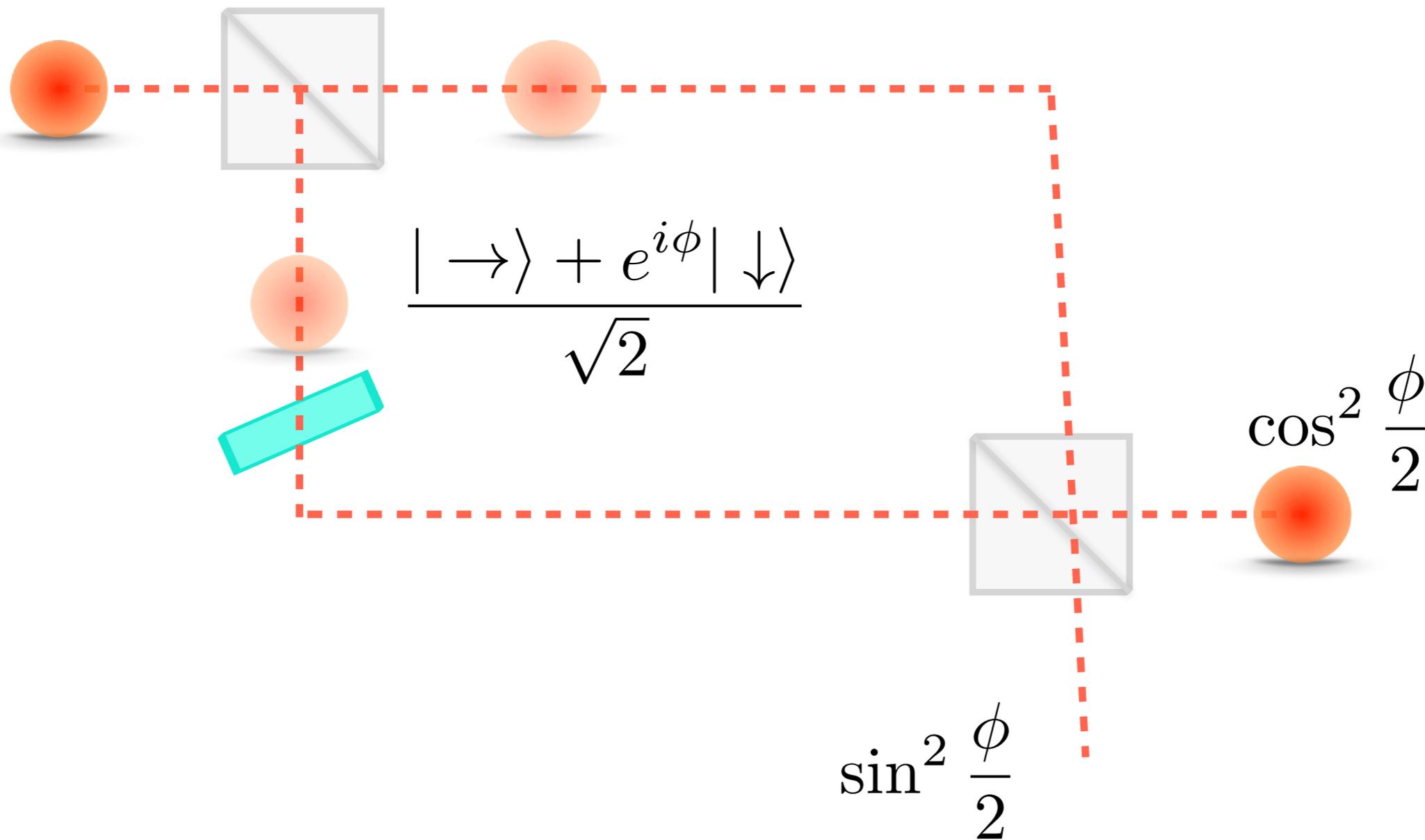
# Quantum Phase Estimation

beam splitter



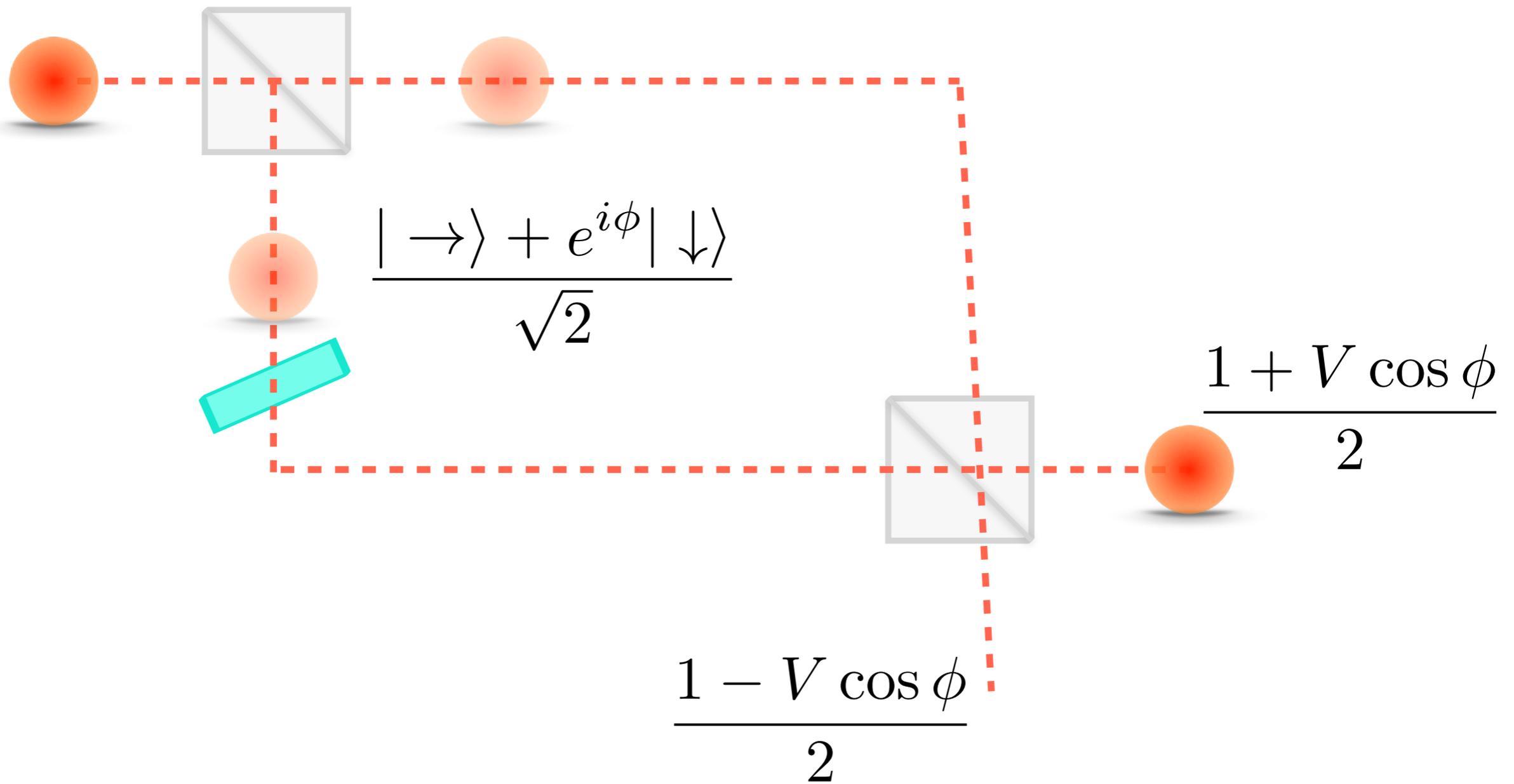
# Quantum Phase Estimation

beam splitter



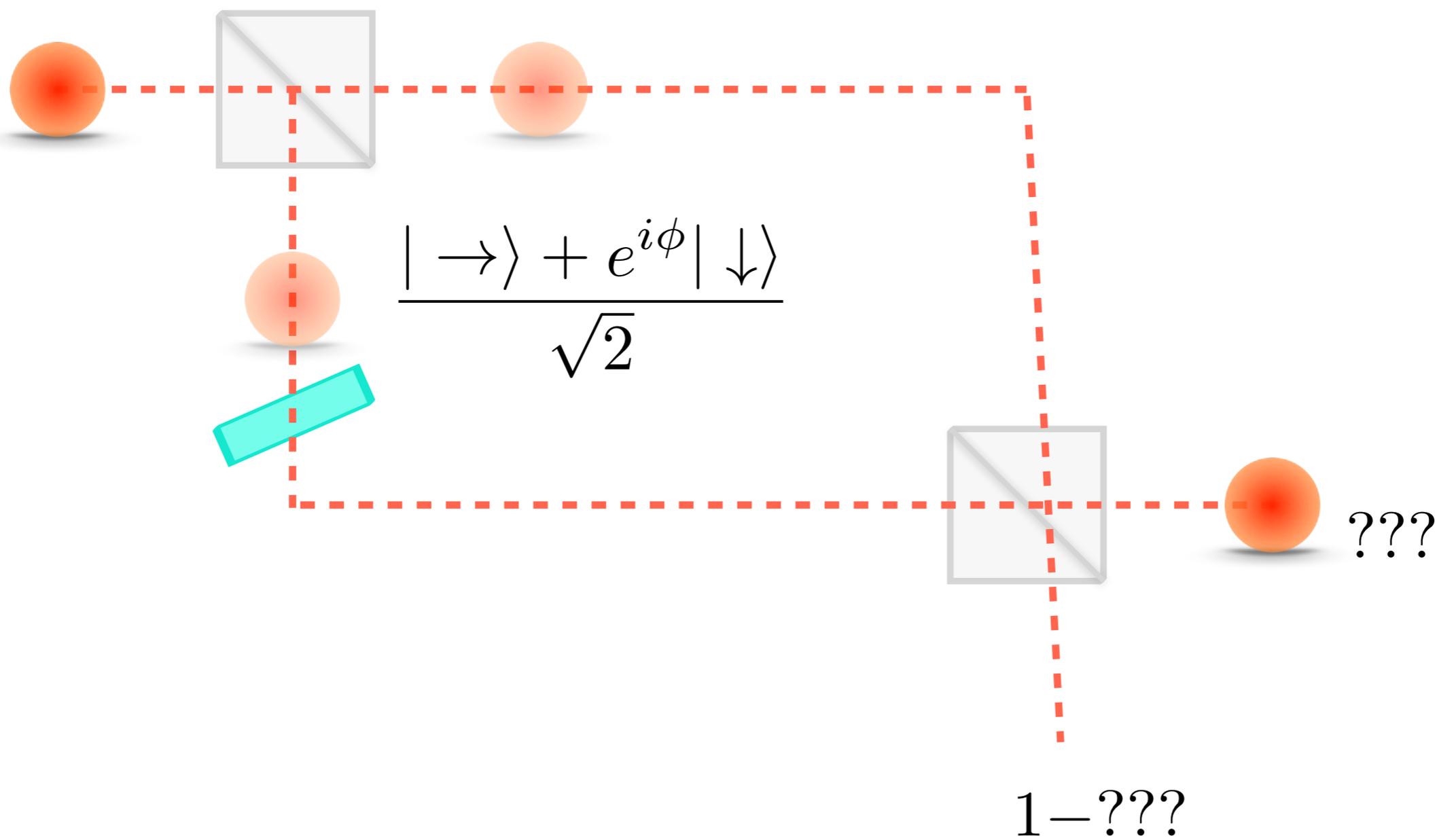
# Quantum Phase Estimation

beam splitter

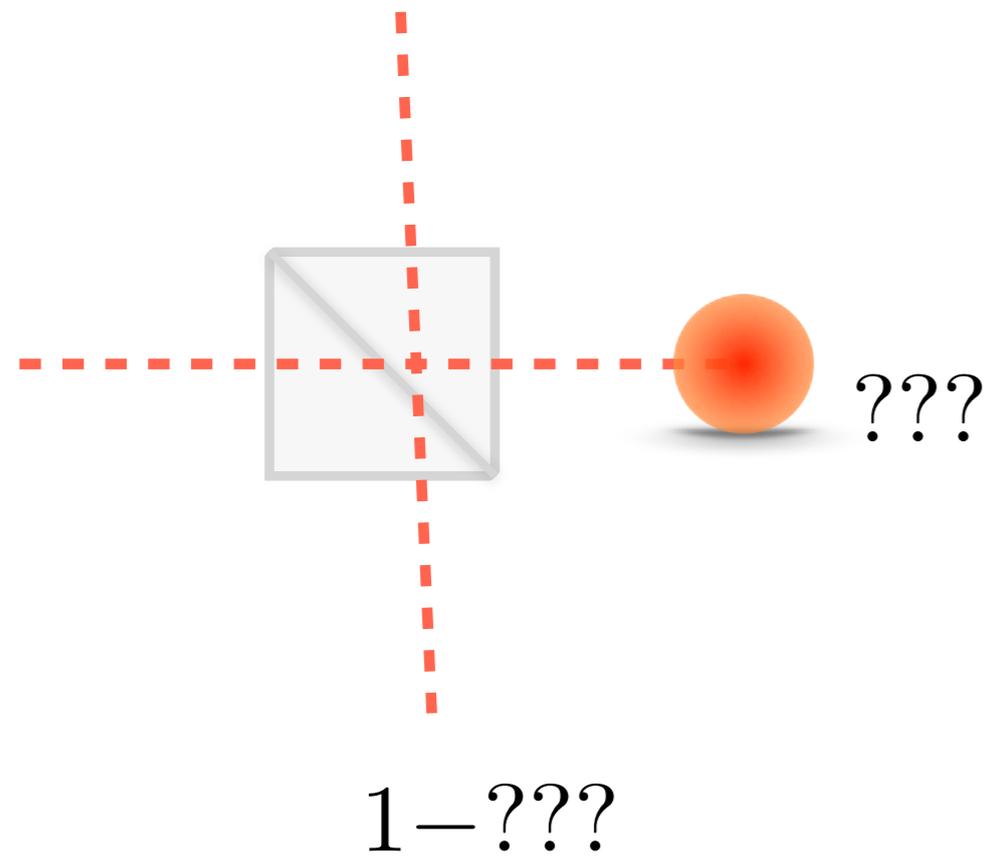


# Quantum Phase Estimation

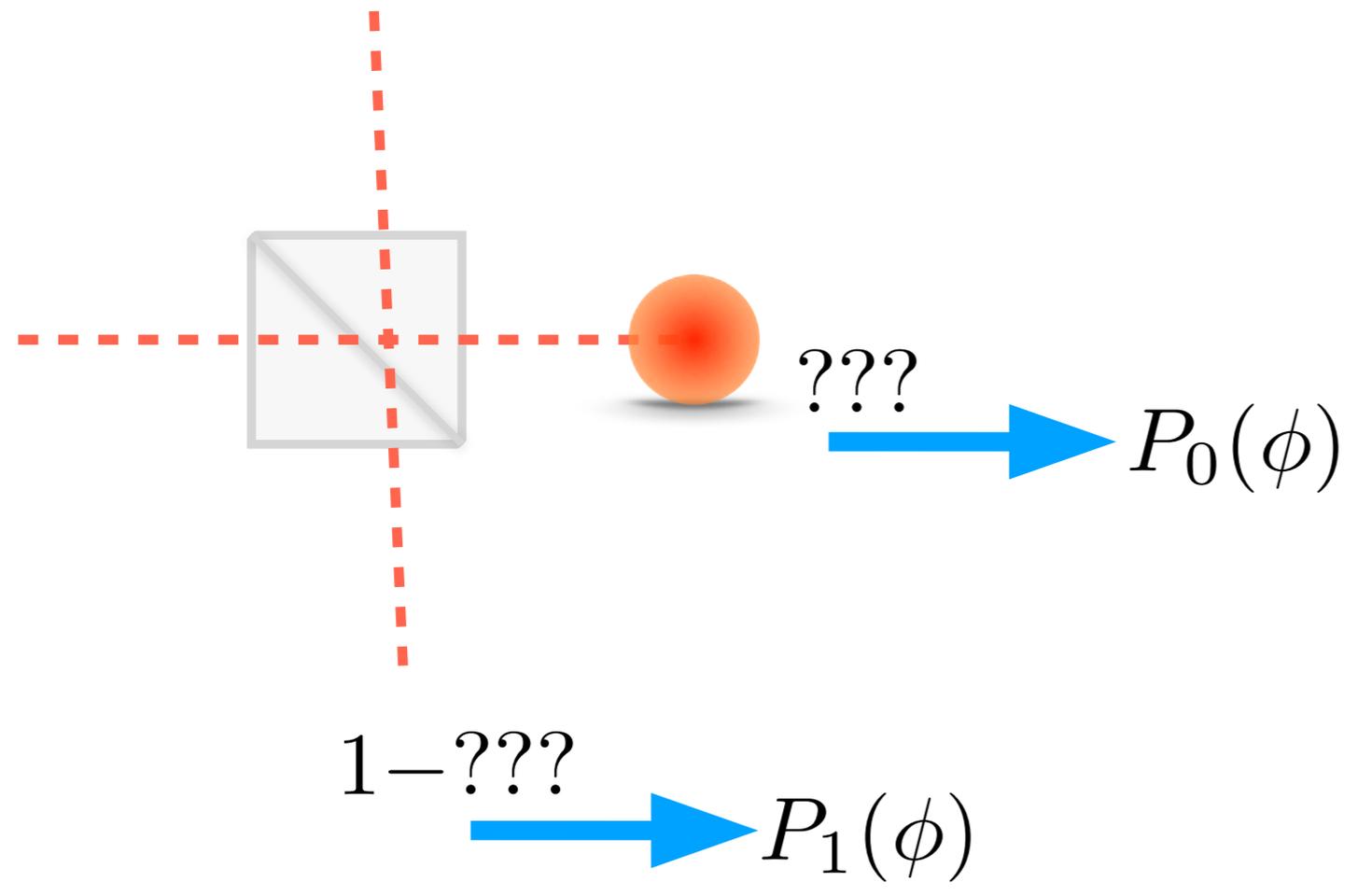
beam splitter



# ☰ Coping with Imperfections

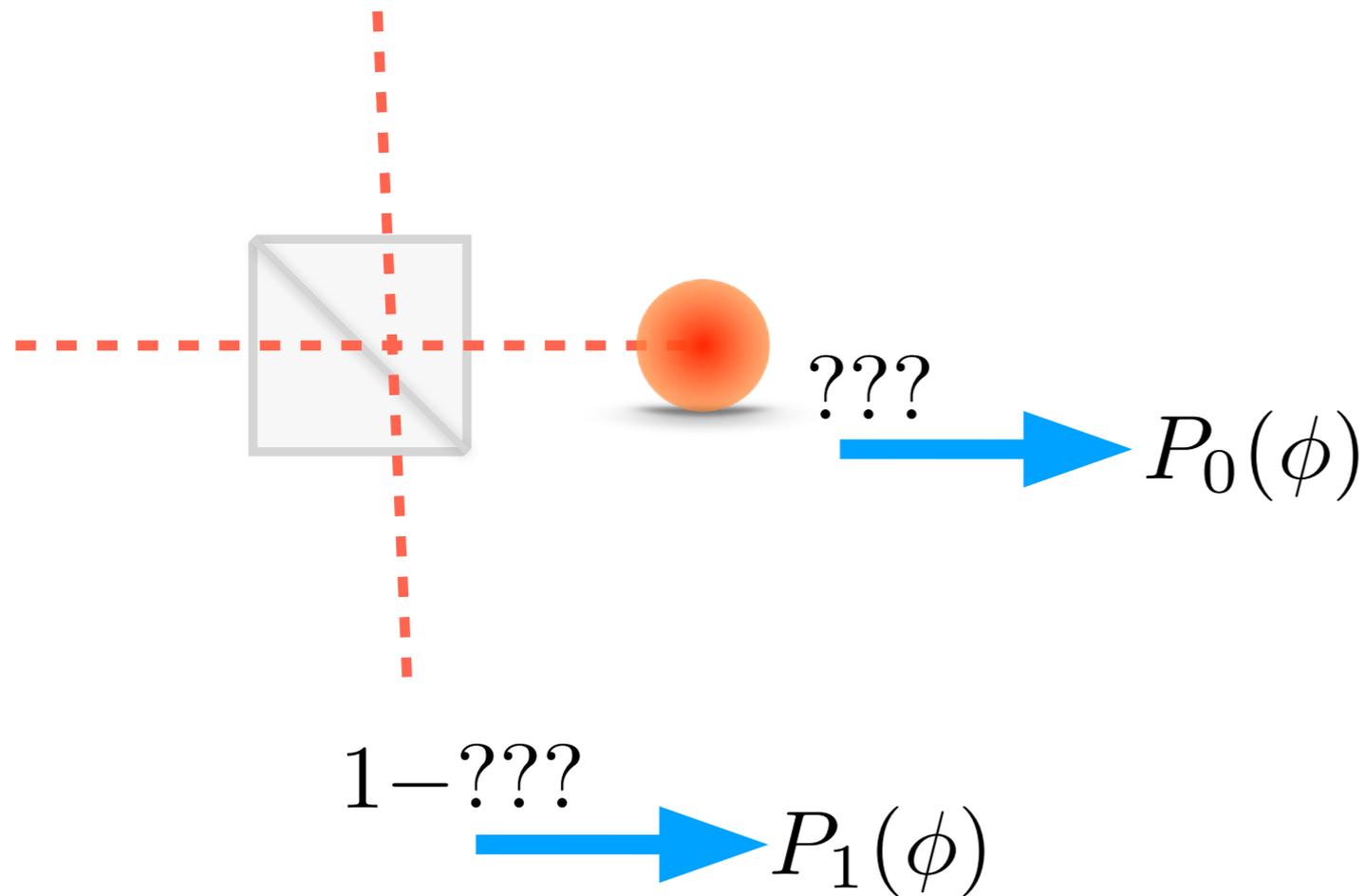


# Coping with Imperfections



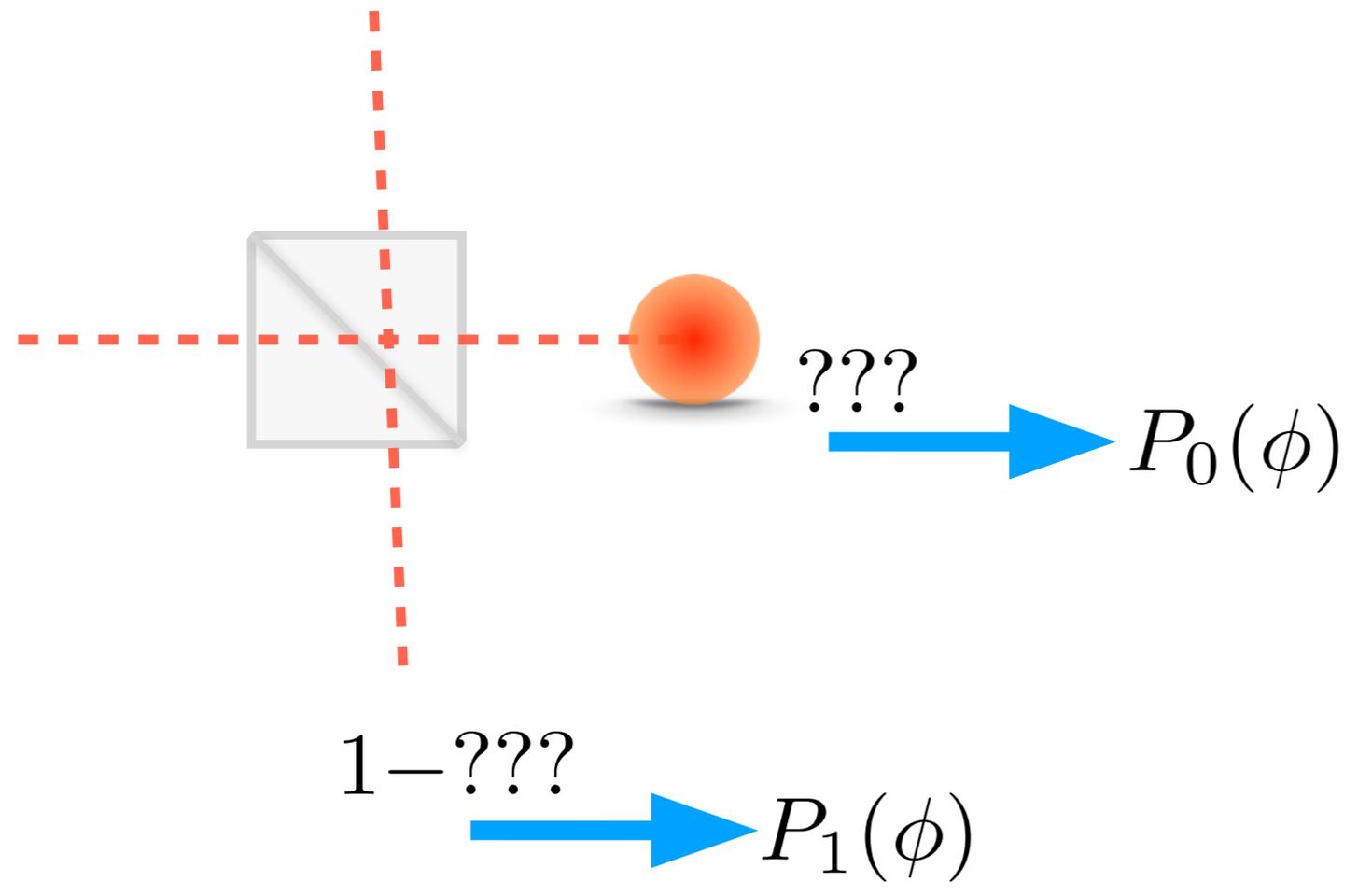
looking for a method

# Coping with Imperfections



**looking for a method  
being general**

# Coping with Imperfections

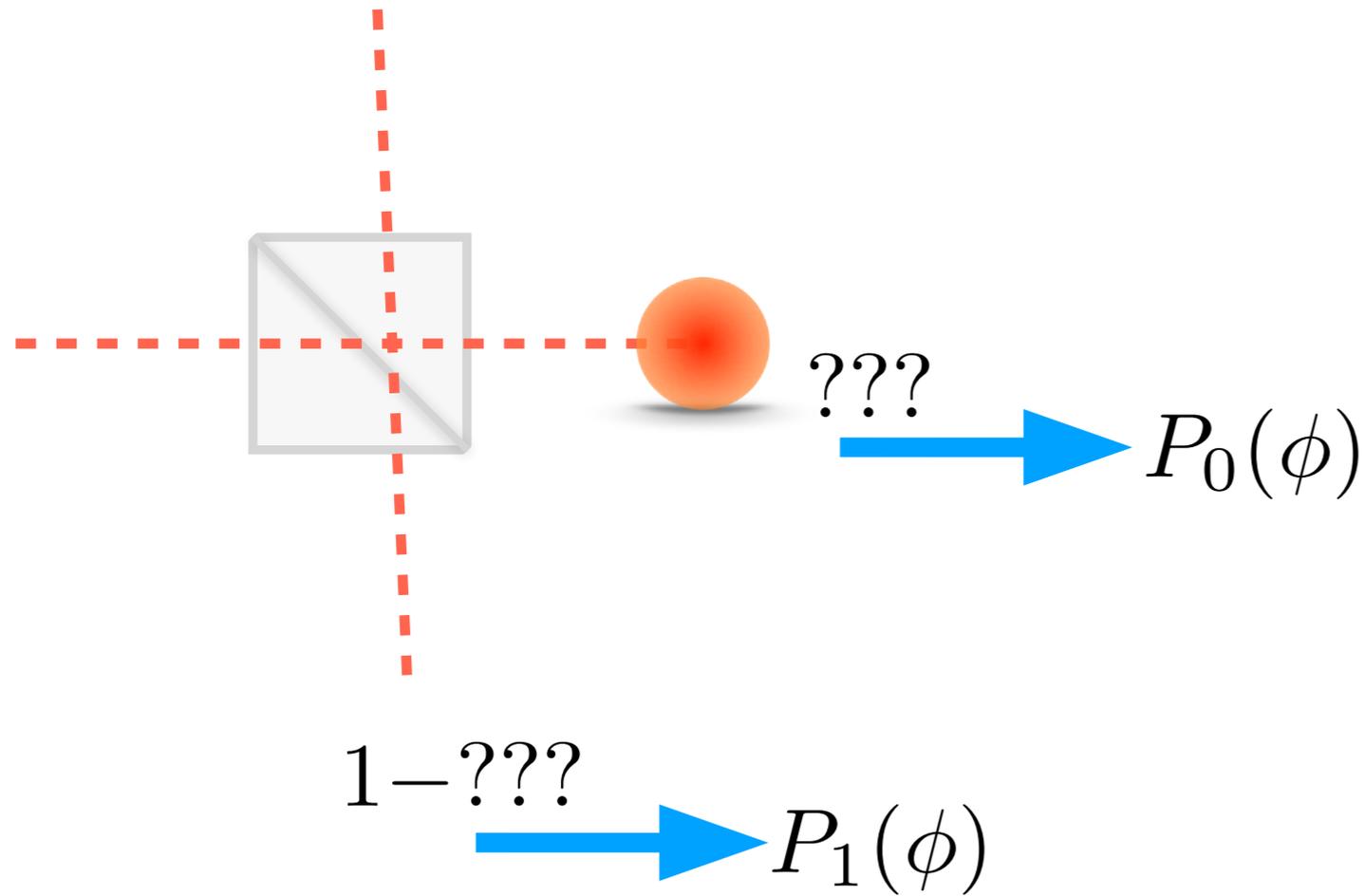


**looking for a method**

**being general**

**being economic**

# Coping with Imperfections



**looking for a method**

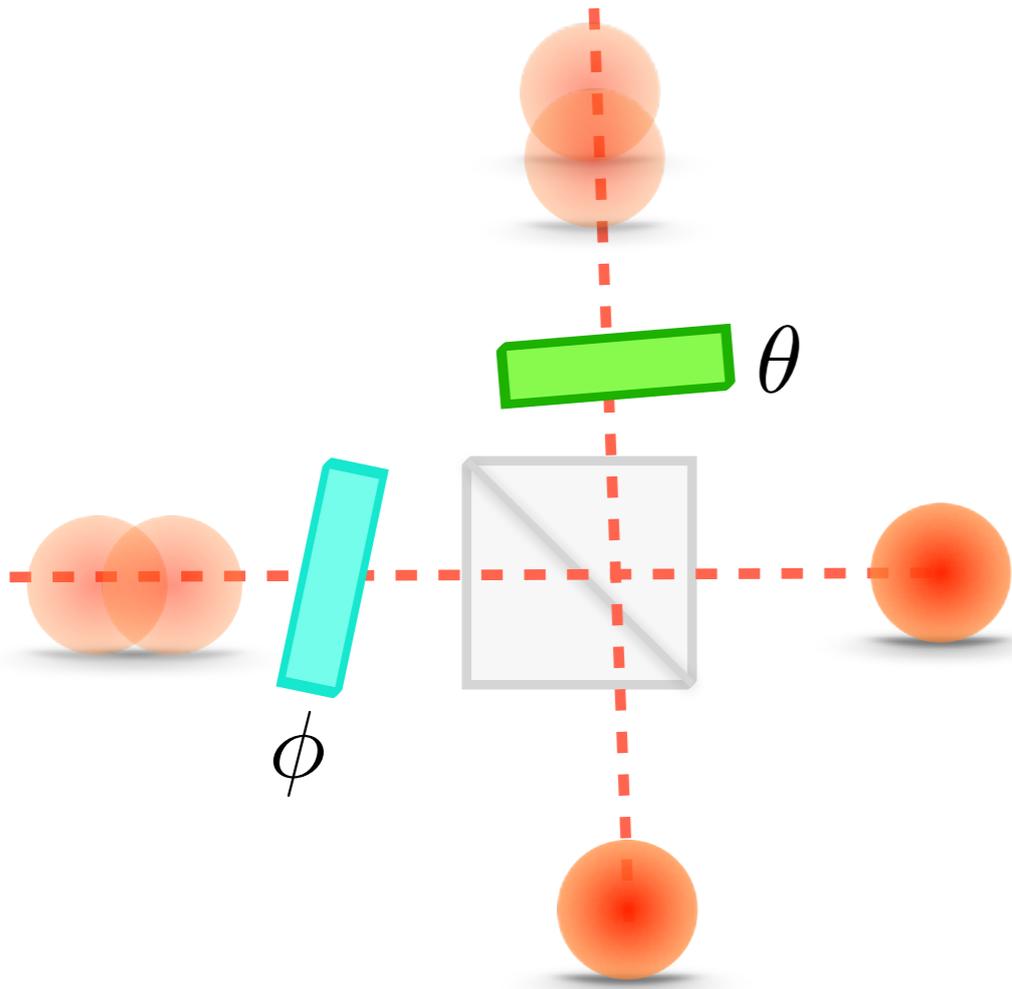
**being general**

**being economic**

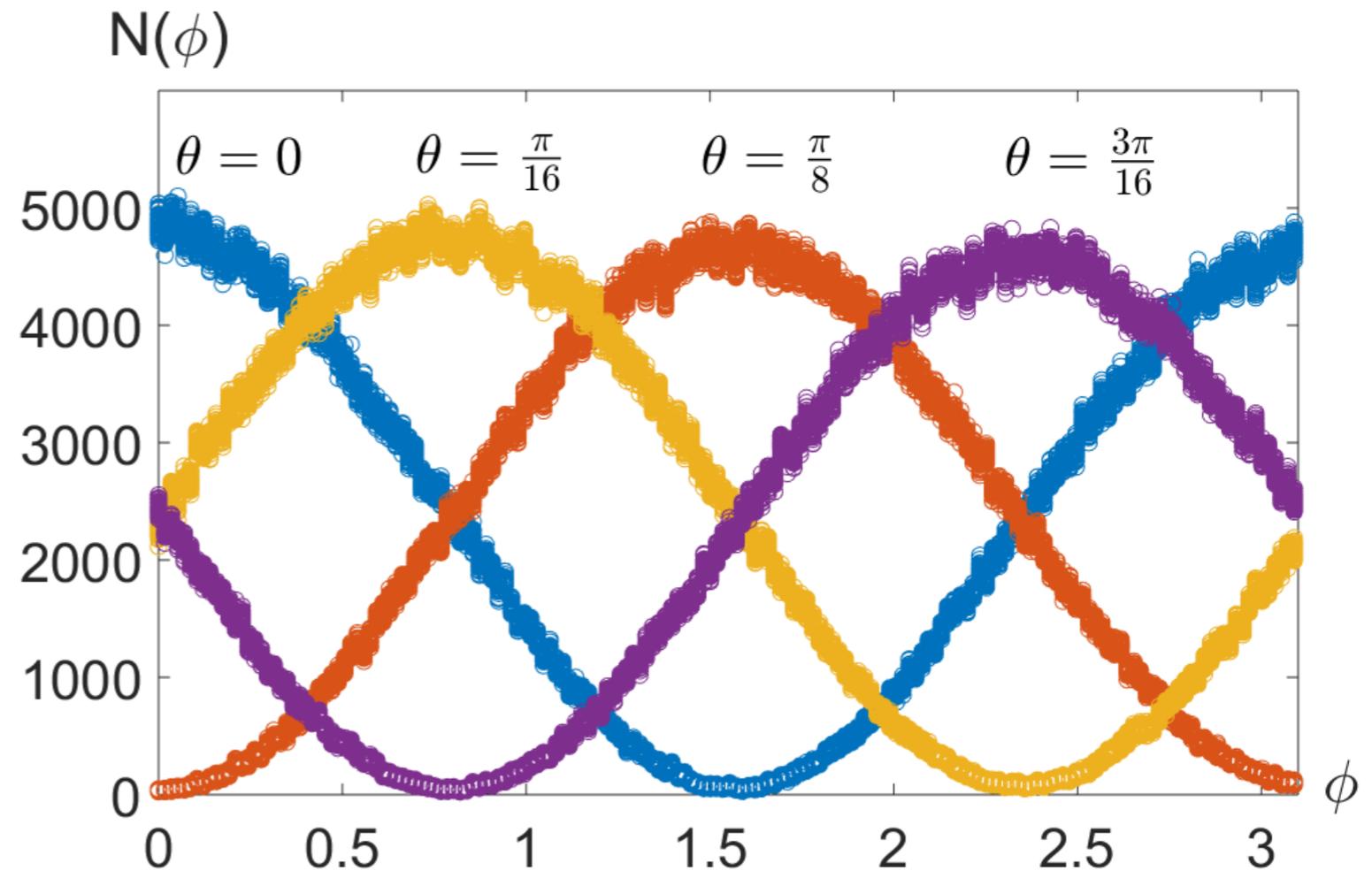
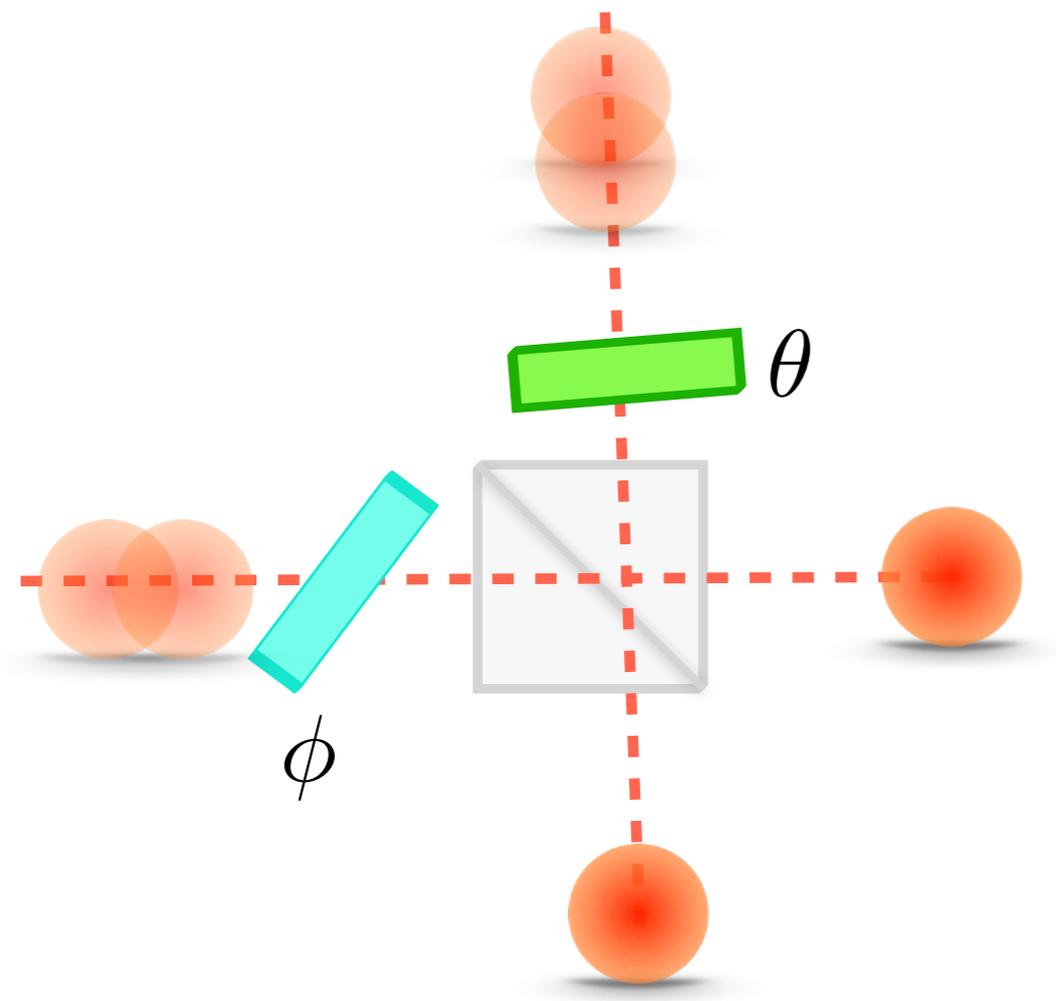
**being scalable**



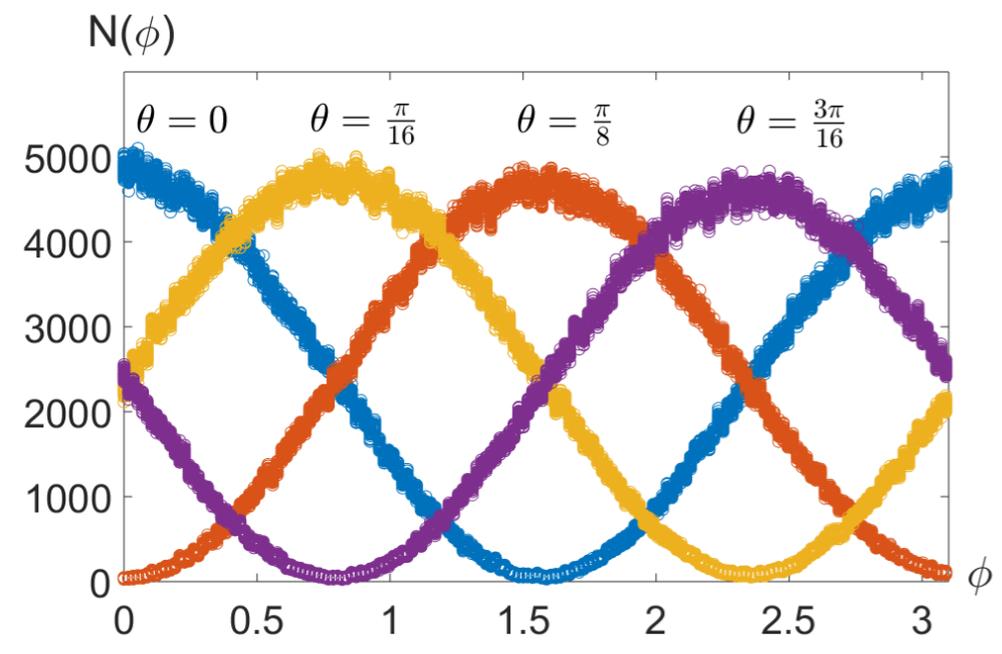
# Neural networks



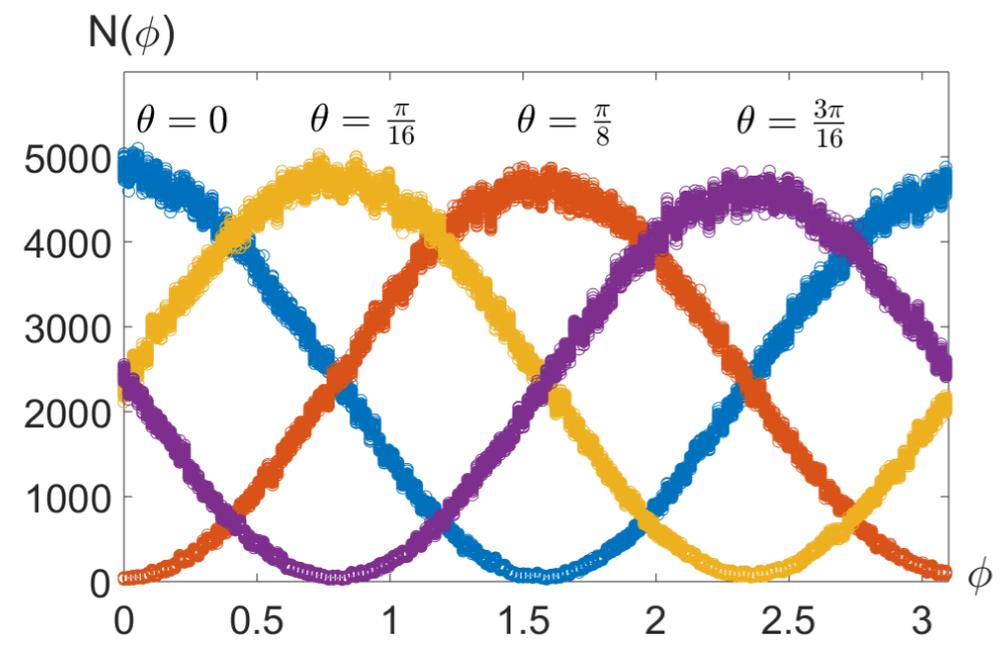
# Neural networks



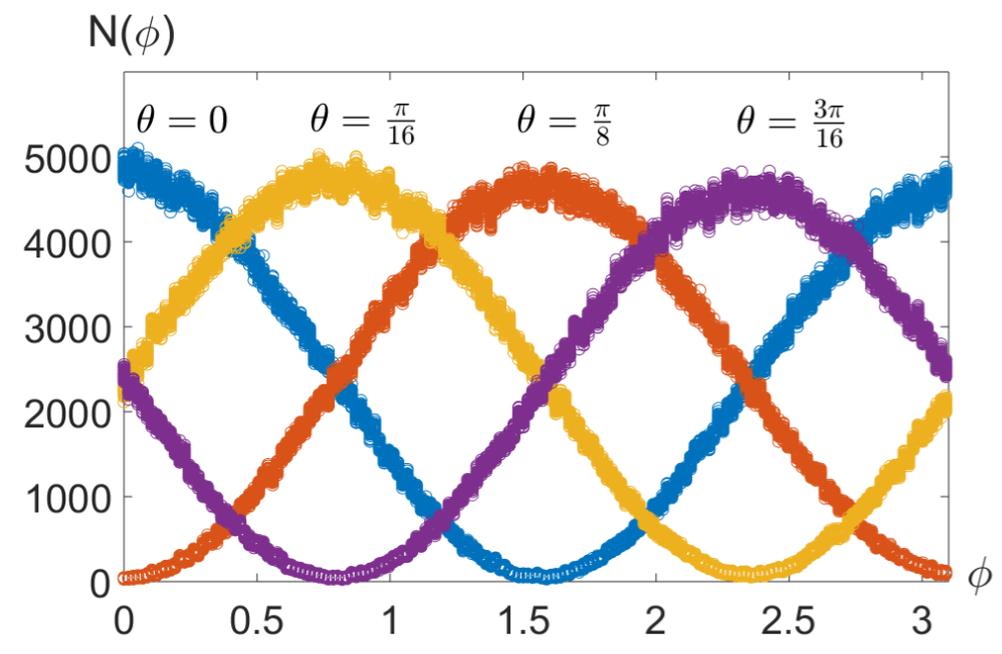
# Neural networks



# Neural networks



# Neural networks

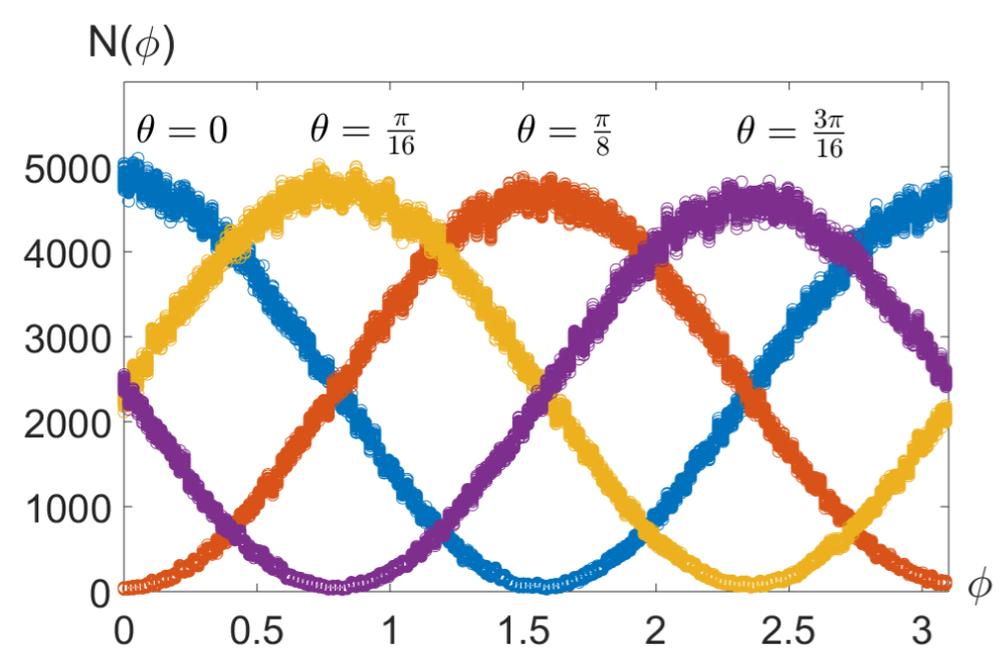


## (A) TRAINING

$\phi$	$\bar{N}$		
0	1047	...	5
$\pi/2$	503	...	493
$\pi$	9	...	1051

DATA

# Neural networks



## (A) TRAINING

$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

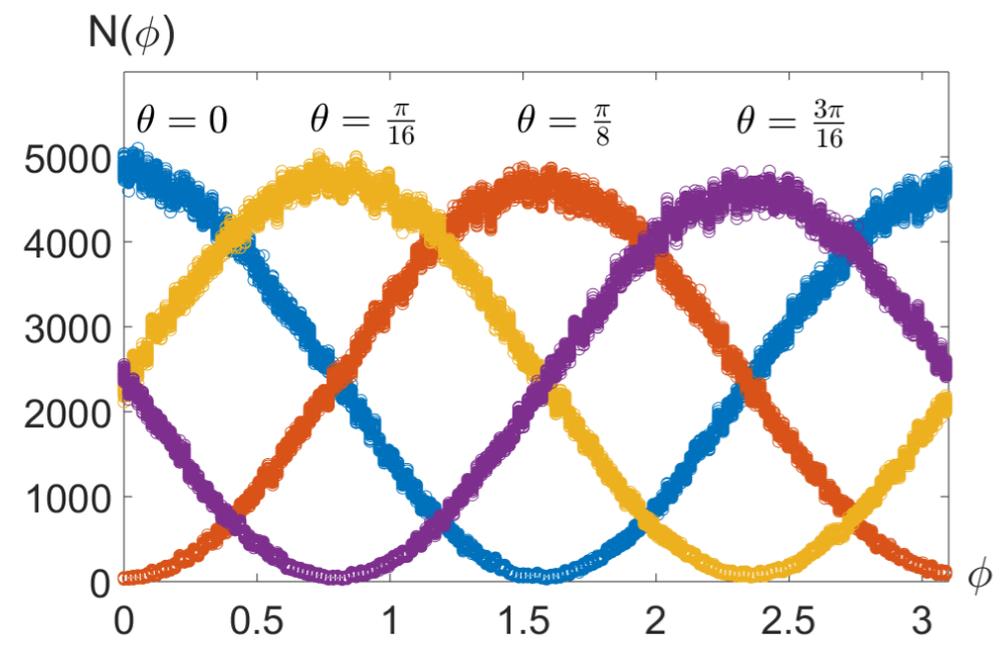
DATA



$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

BOOTSTRAPPING

# Neural networks



## (A) TRAINING

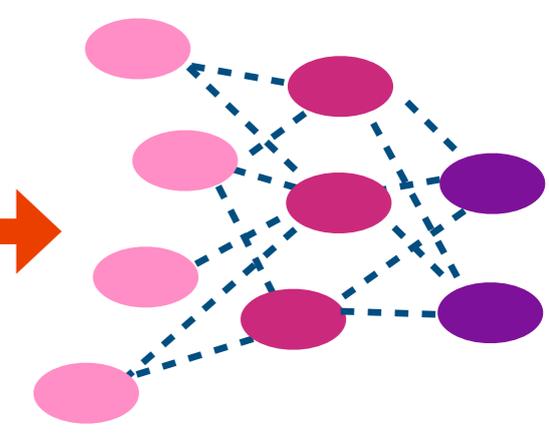
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

DATA



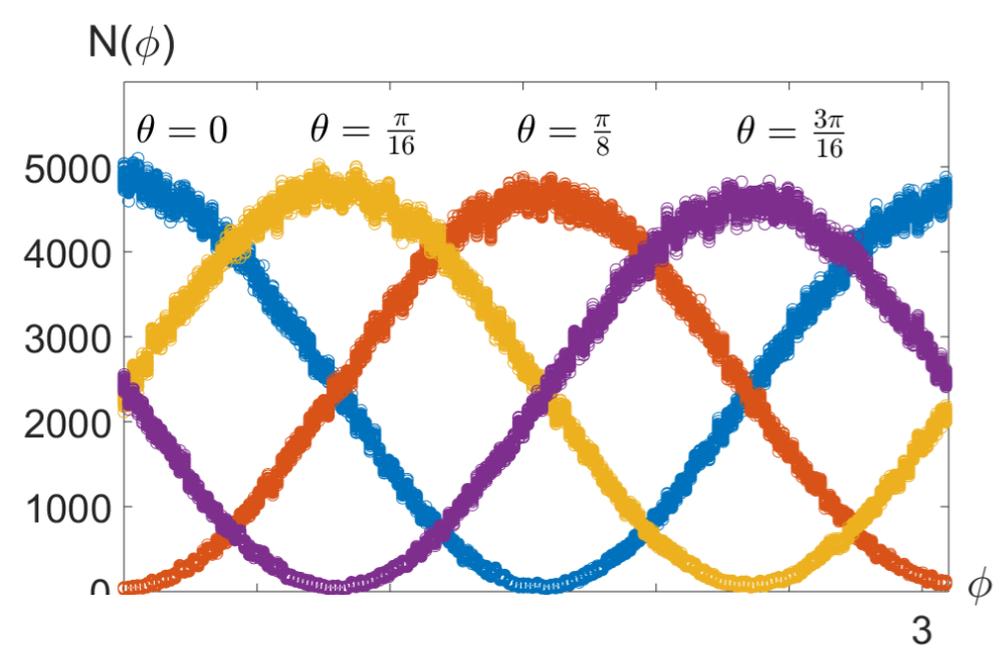
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

BOOTSTRAPPING



NEURAL NETWORK

# Neural networks



## (A) TRAINING

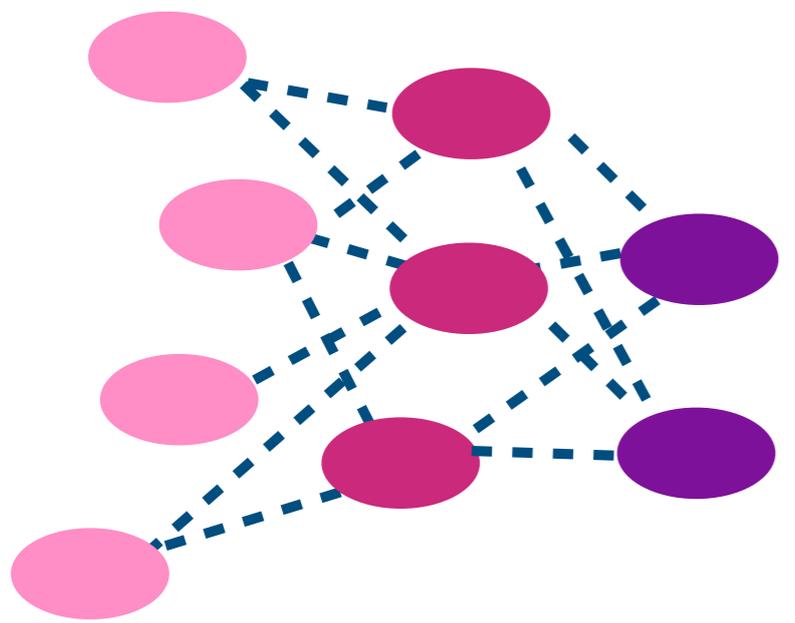
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

DATA



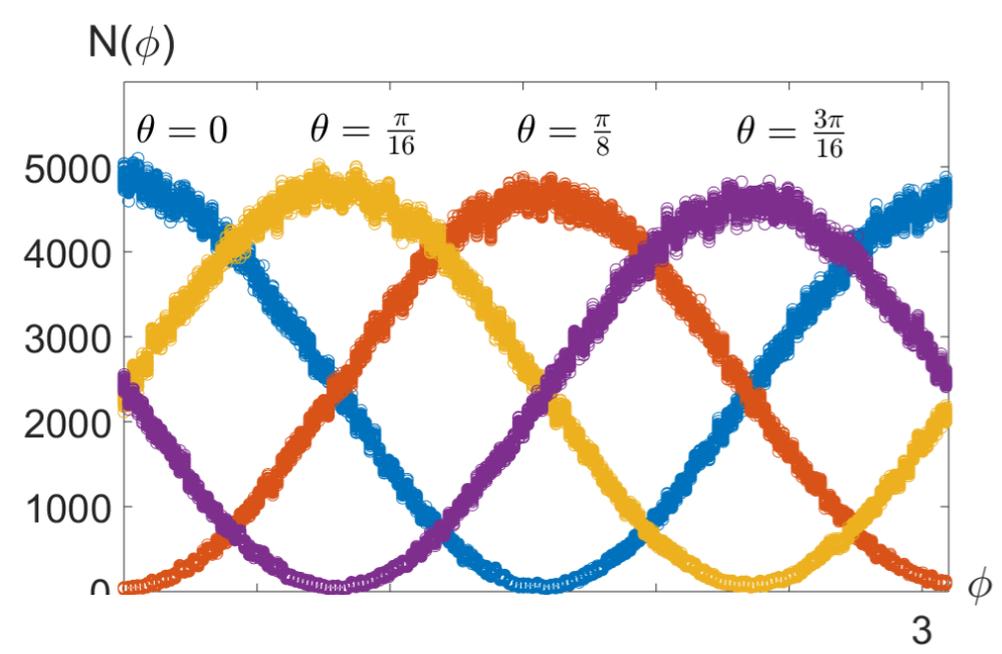
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

BOOTSTRAPPING



NEURAL NETWORK

# Neural networks



## (A) TRAINING

$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

DATA

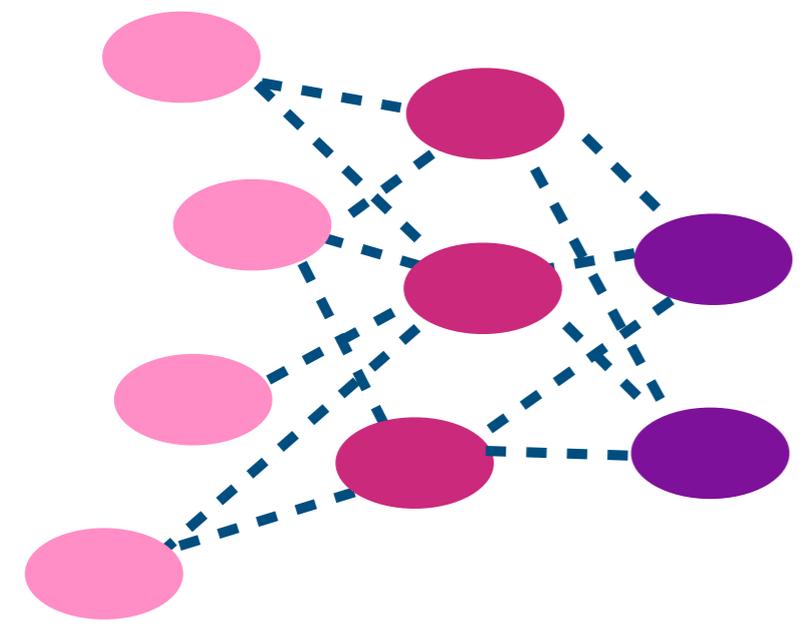


$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

BOOTSTRAPPING

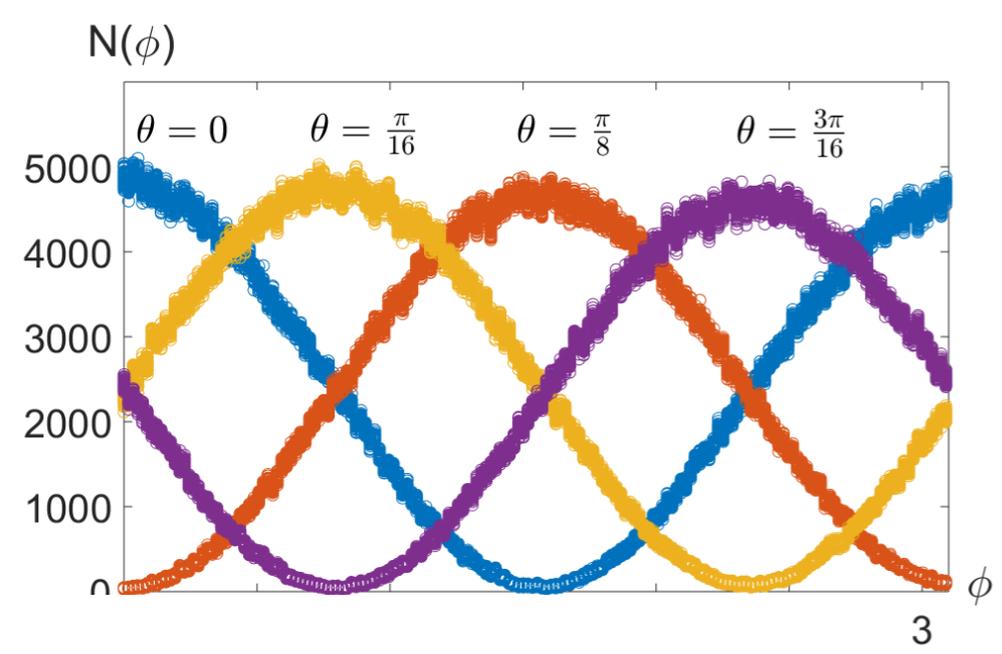


**NN are a computational model**



**NEURAL NETWORK**

# Neural networks



## (A) TRAINING

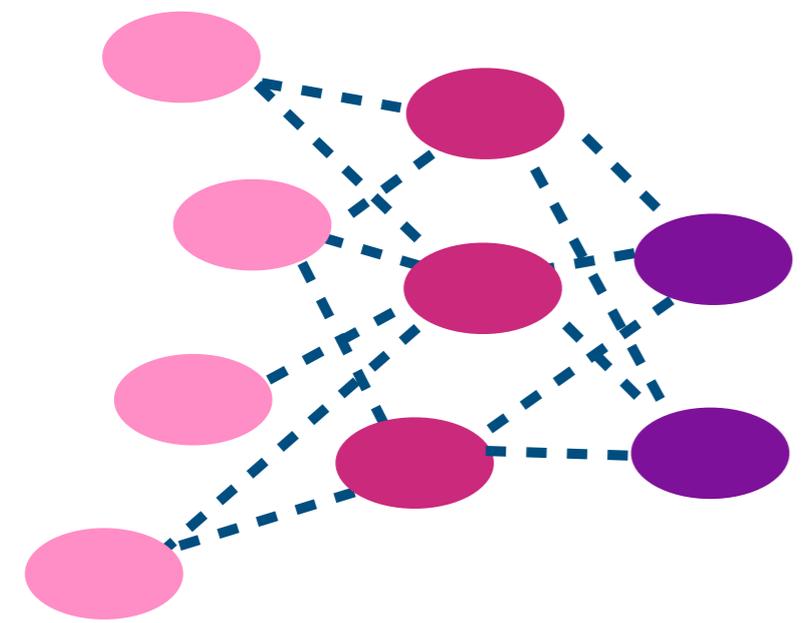
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

DATA

$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

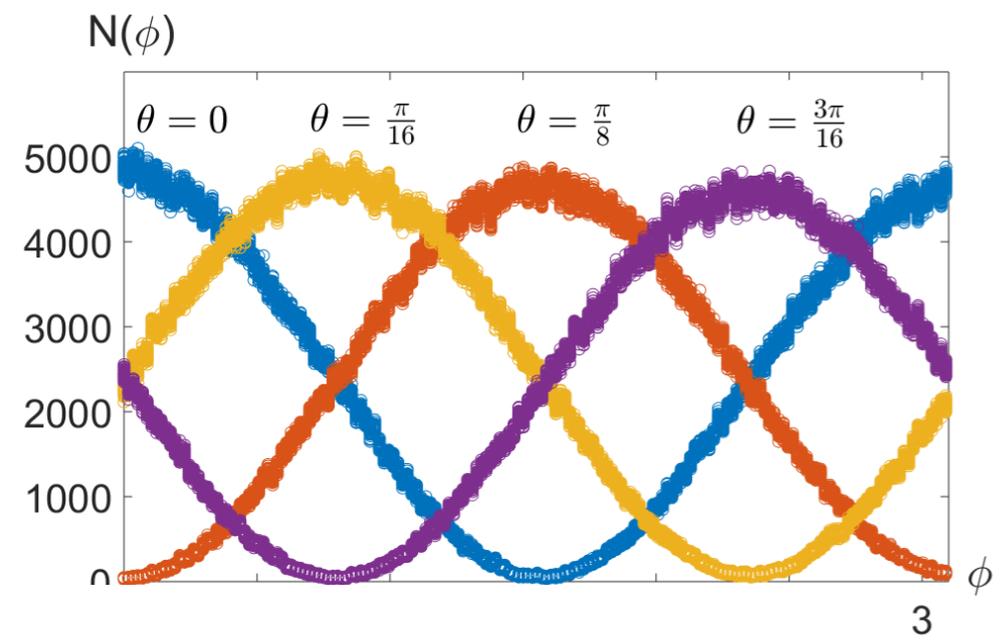
BOOTSTRAPPING

**NN are a computational model**  
**each neuron gives an output**  
**based on its inputs**



**NEURAL NETWORK**

# Neural networks



## (A) TRAINING

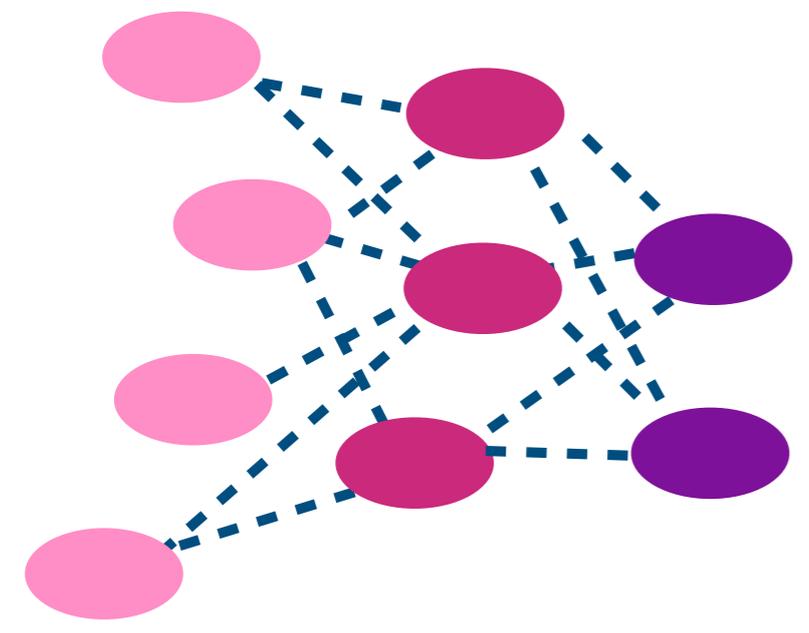
$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051

DATA

$\phi$	$\bar{N}$
0	1047 ... 5
$\pi/2$	503 ... 493
$\pi$	9 ... 1051
0	1032 ... 7
$\pi/2$	498 ... 506
$\pi$	2 ... 1033

BOOTSTRAPPING

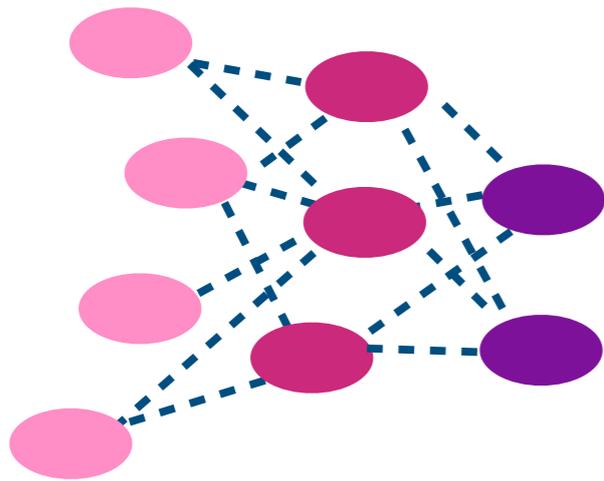
**NN are a computational model**  
**each neuron gives an output**  
**based on its inputs**  
**connection are established by**  
**a 'training' procedure**



NEURAL NETWORK

# Neural networks

$$\epsilon = \langle \phi_{\text{true}} - \phi_{\text{out}} \rangle_{\text{rms}}$$

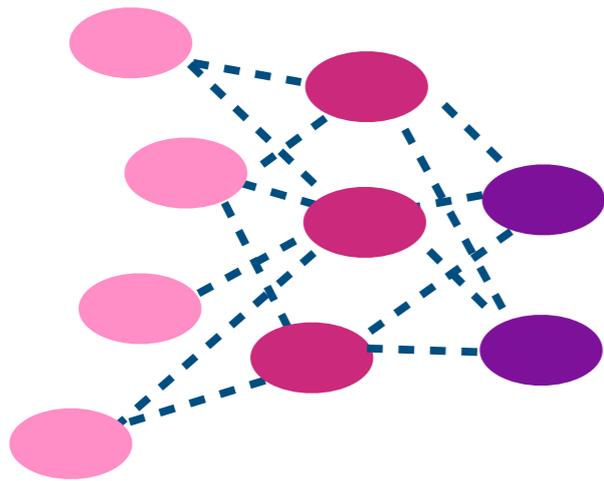


**NEURAL NETWORK**

# Neural networks

## optimal training

$$\epsilon = \langle \phi_{\text{true}} - \phi_{\text{out}} \rangle_{\text{rms}}$$

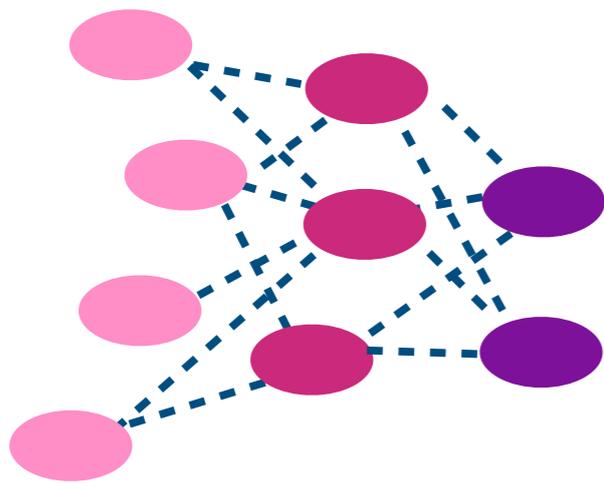


NEURAL NETWORK

# Neural networks

## optimal training

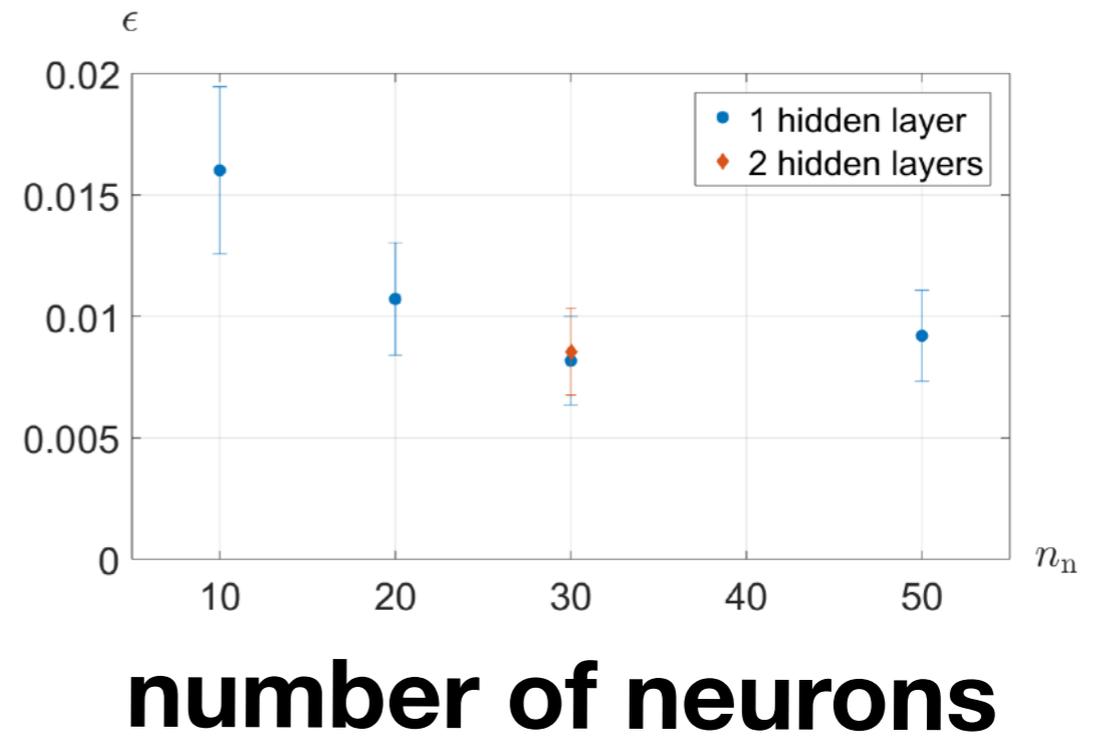
$$\epsilon = \langle \phi_{\text{true}} - \phi_{\text{out}} \rangle_{\text{rms}}$$



NEURAL NETWORK

residual error

*from simulations!*

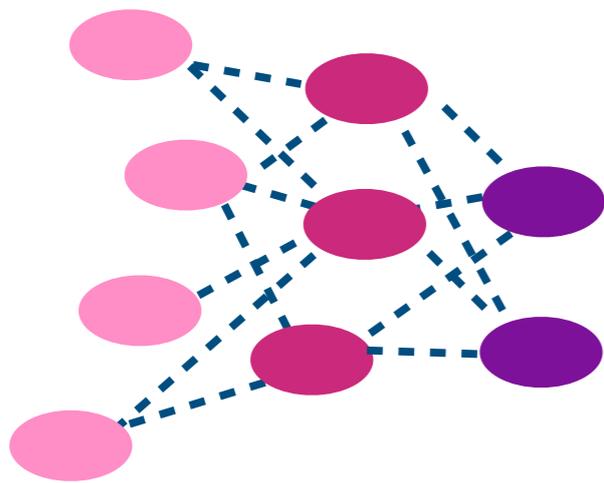


number of neurons

# Neural networks

## optimal training

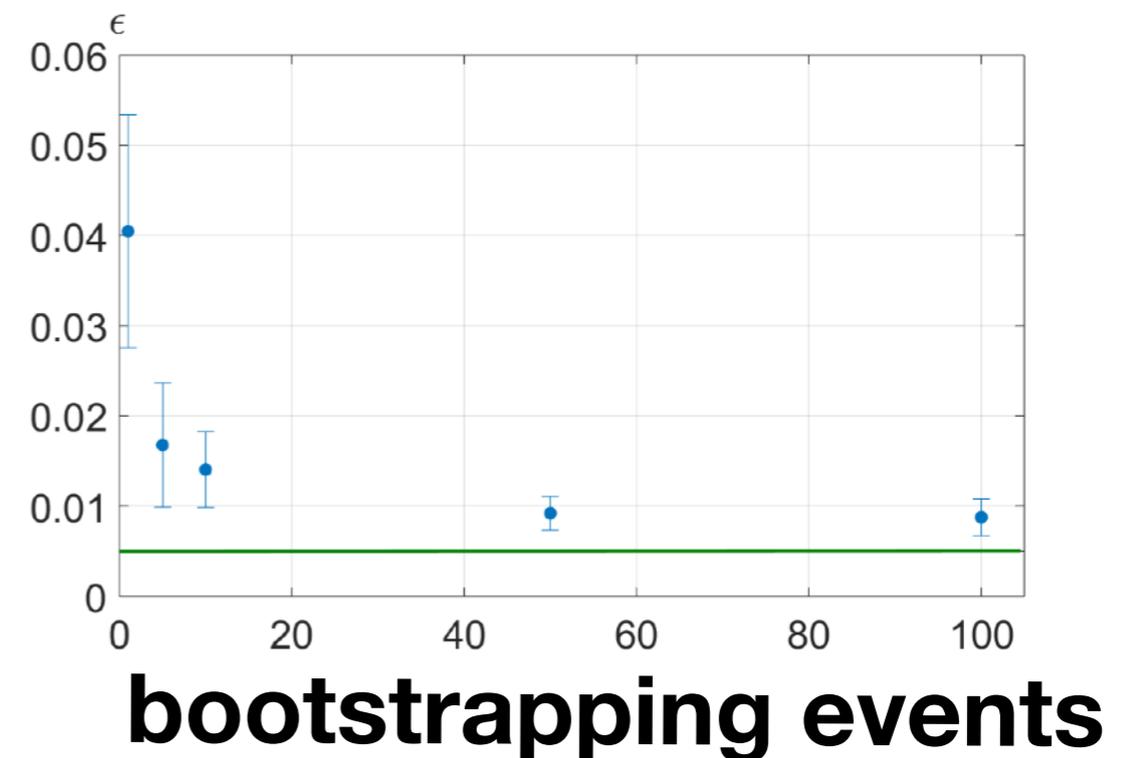
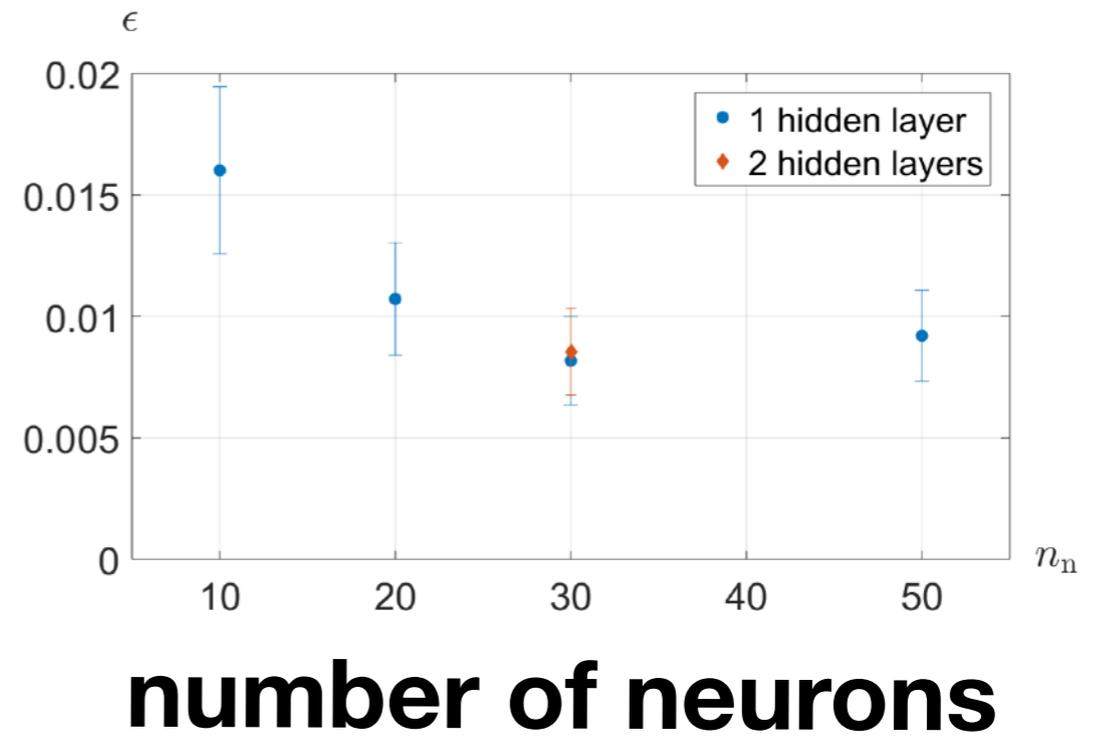
$$\epsilon = \langle \phi_{\text{true}} - \phi_{\text{out}} \rangle_{\text{rms}}$$



NEURAL NETWORK

residual error

*from simulations!*

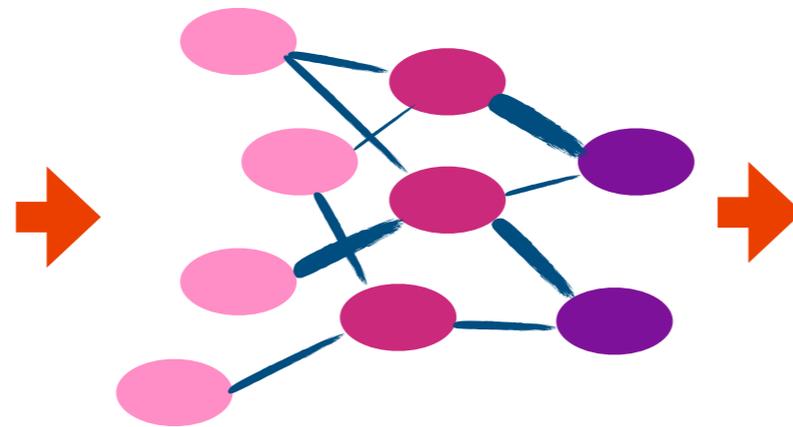


# Neural networks

## (B) ESTIMATION

$$\frac{\bar{N}_0}{736 \dots 319}$$

INPUT



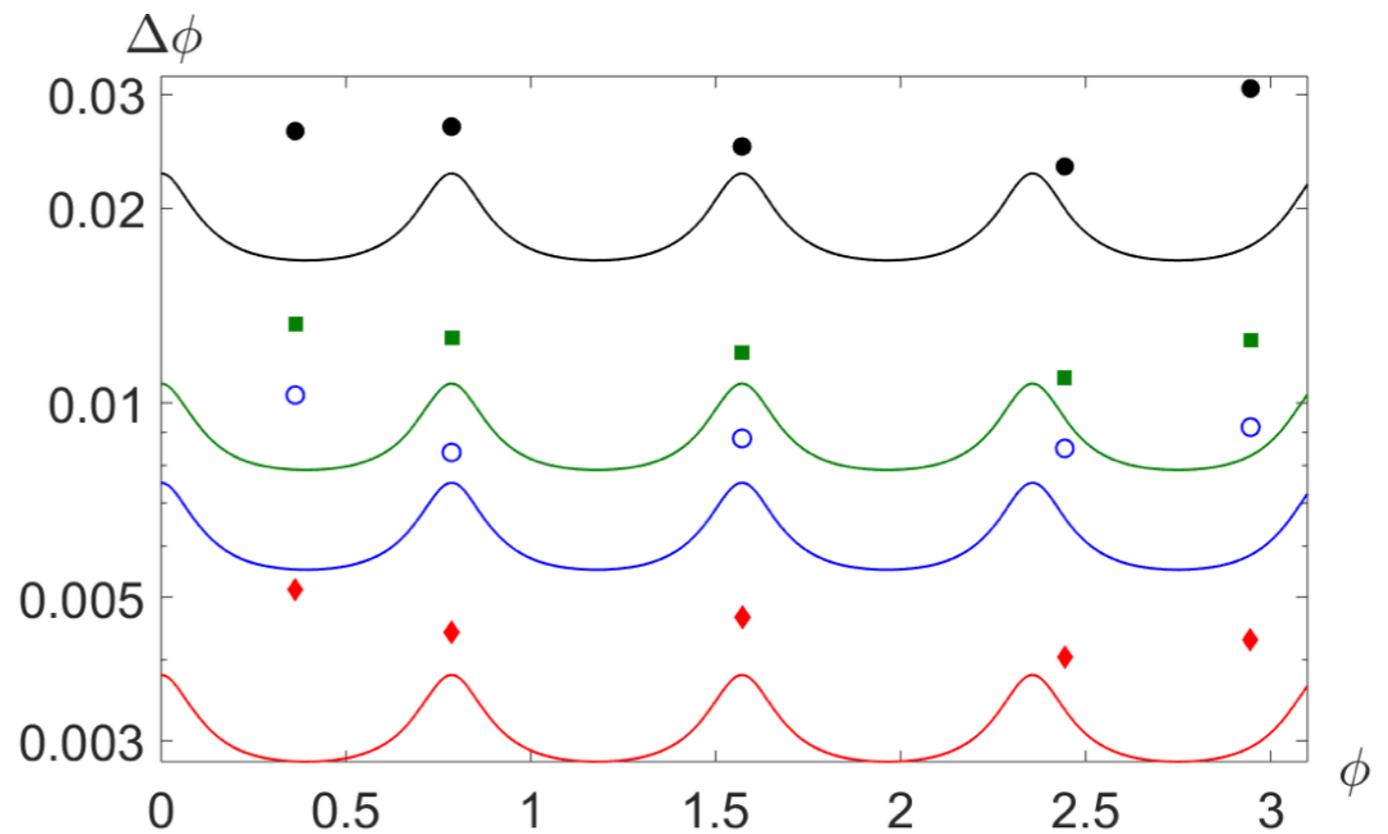
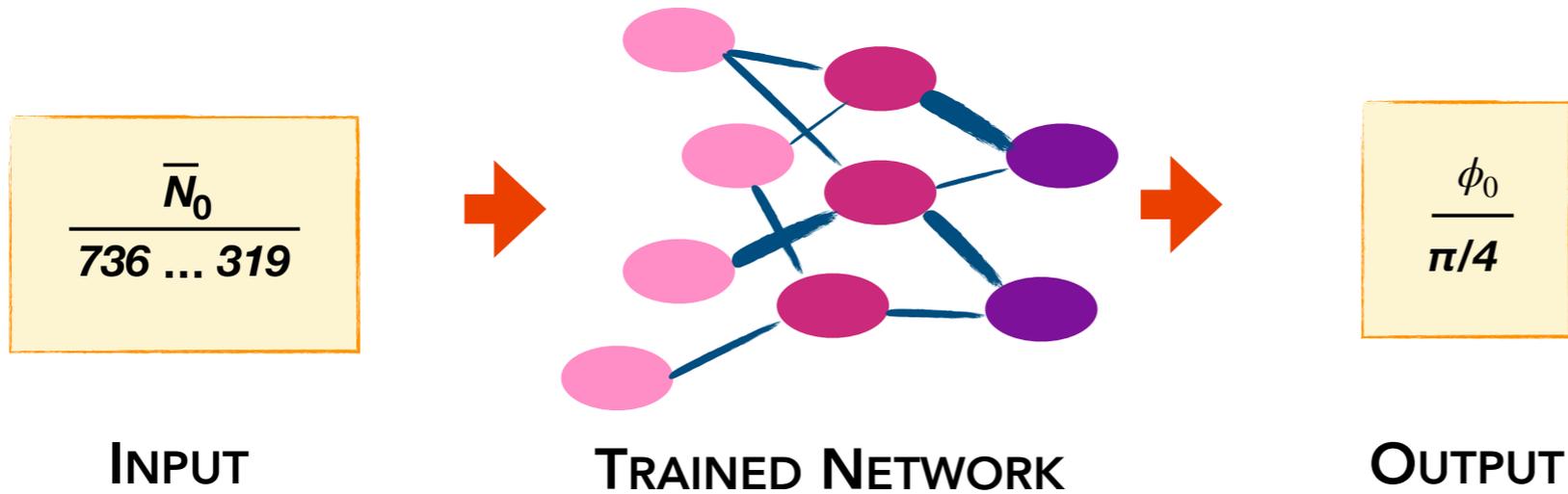
TRAINED NETWORK

$$\frac{\phi_0}{\pi/4}$$

OUTPUT

# Neural networks

## (B) ESTIMATION

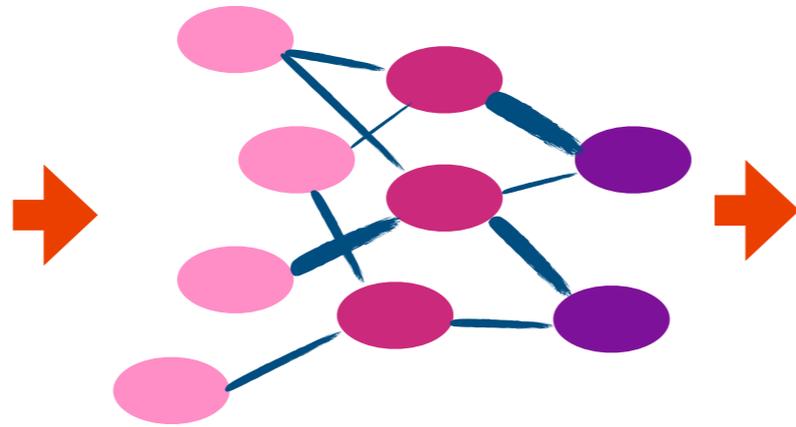


# Neural networks

## (B) ESTIMATION

$$\frac{\bar{N}_0}{736 \dots 319}$$

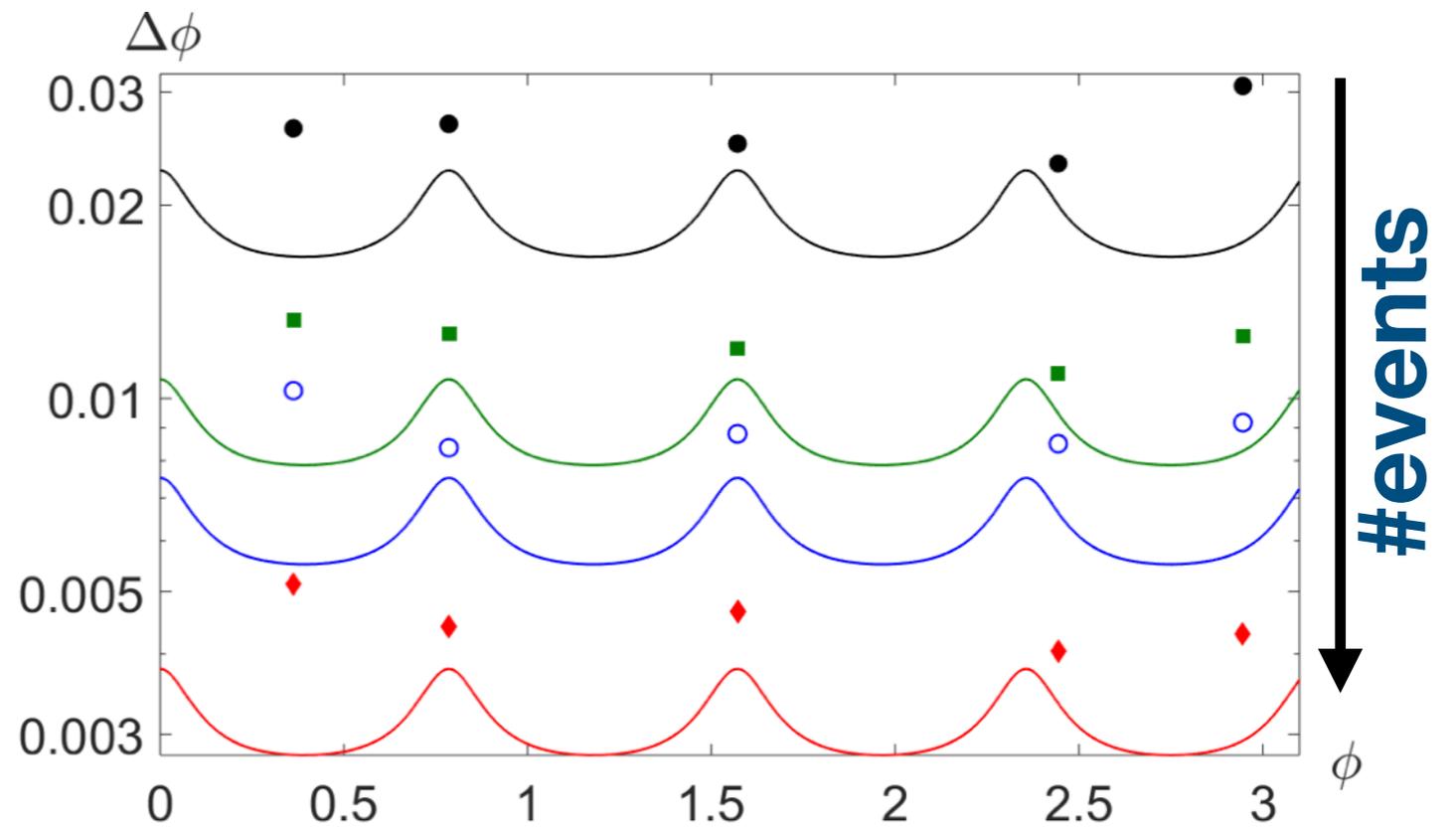
INPUT



TRAINED NETWORK

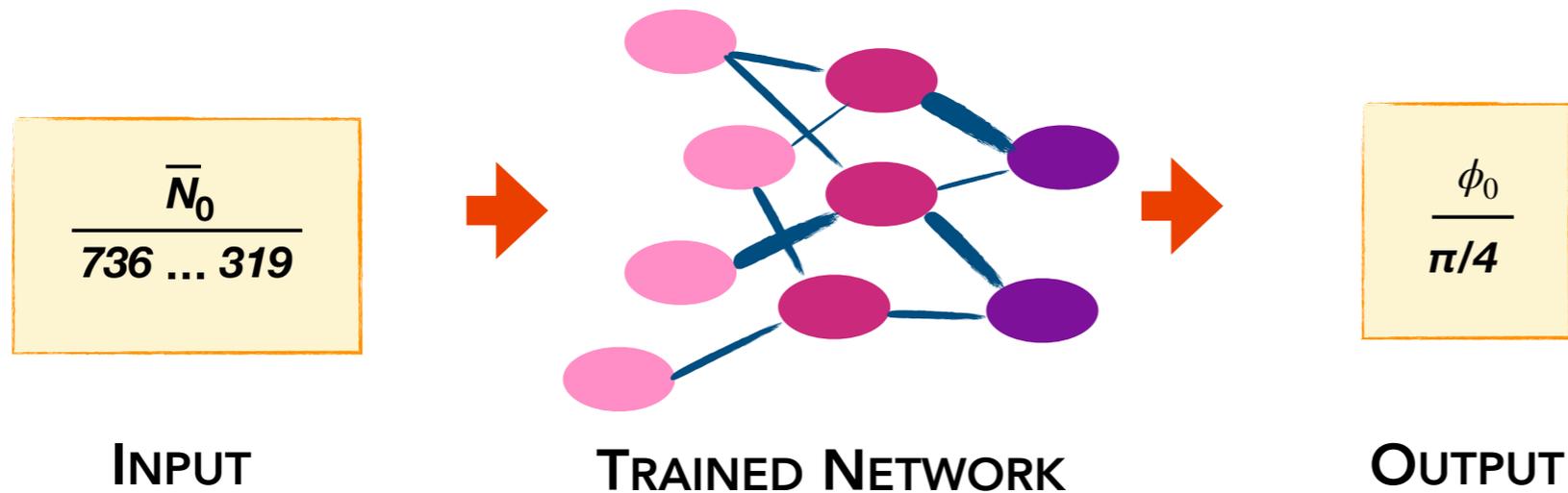
$$\frac{\phi_0}{\pi/4}$$

OUTPUT



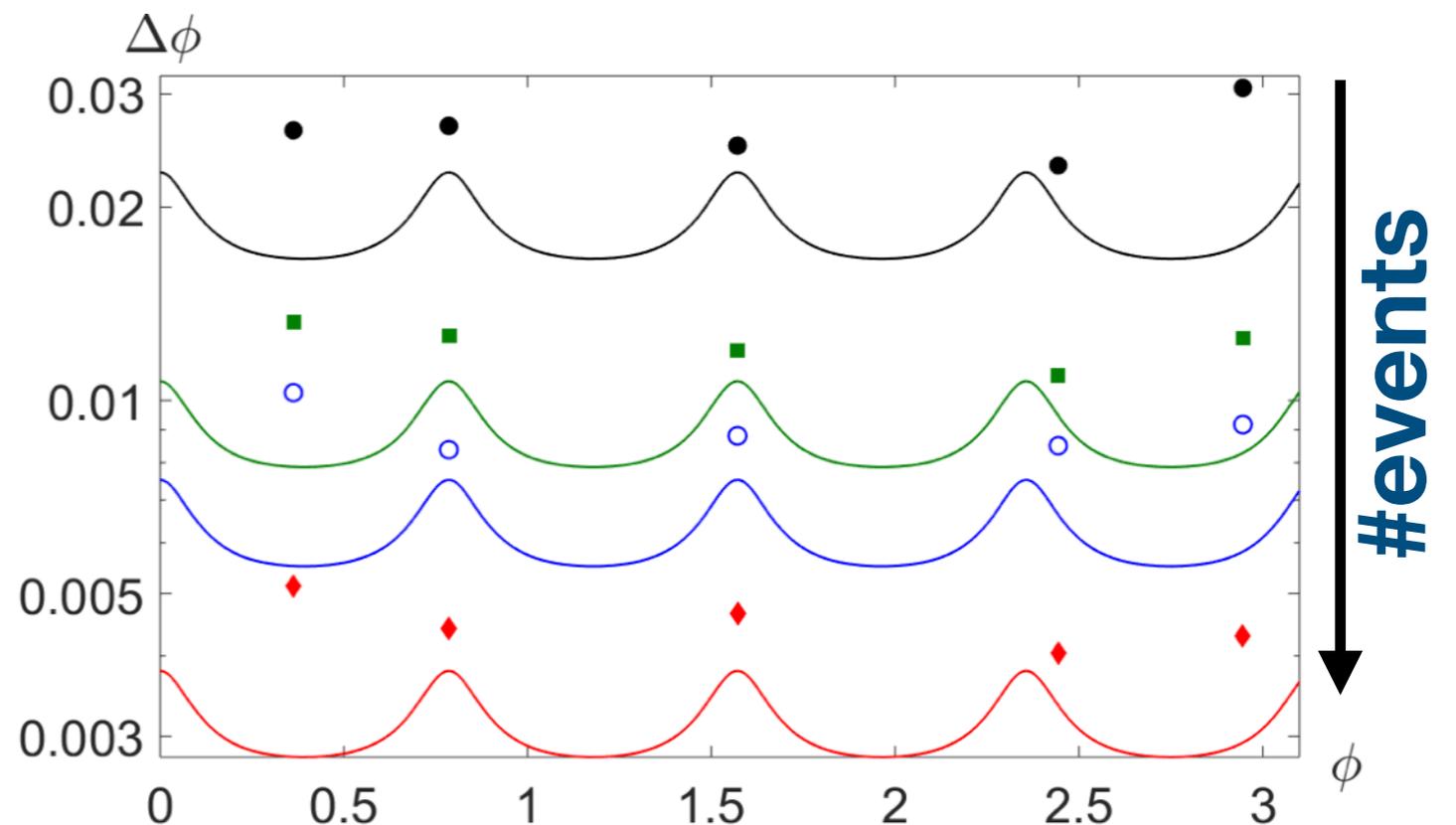
# Neural networks

## (B) ESTIMATION



**estimation close to the ultimate limit**

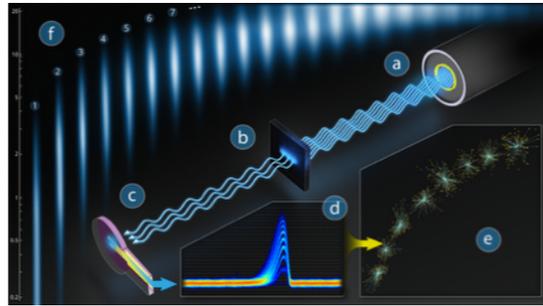
**performance limited by the training set size**



# ☰ Coping with Imperfections

$\Psi$

**basic  
science**

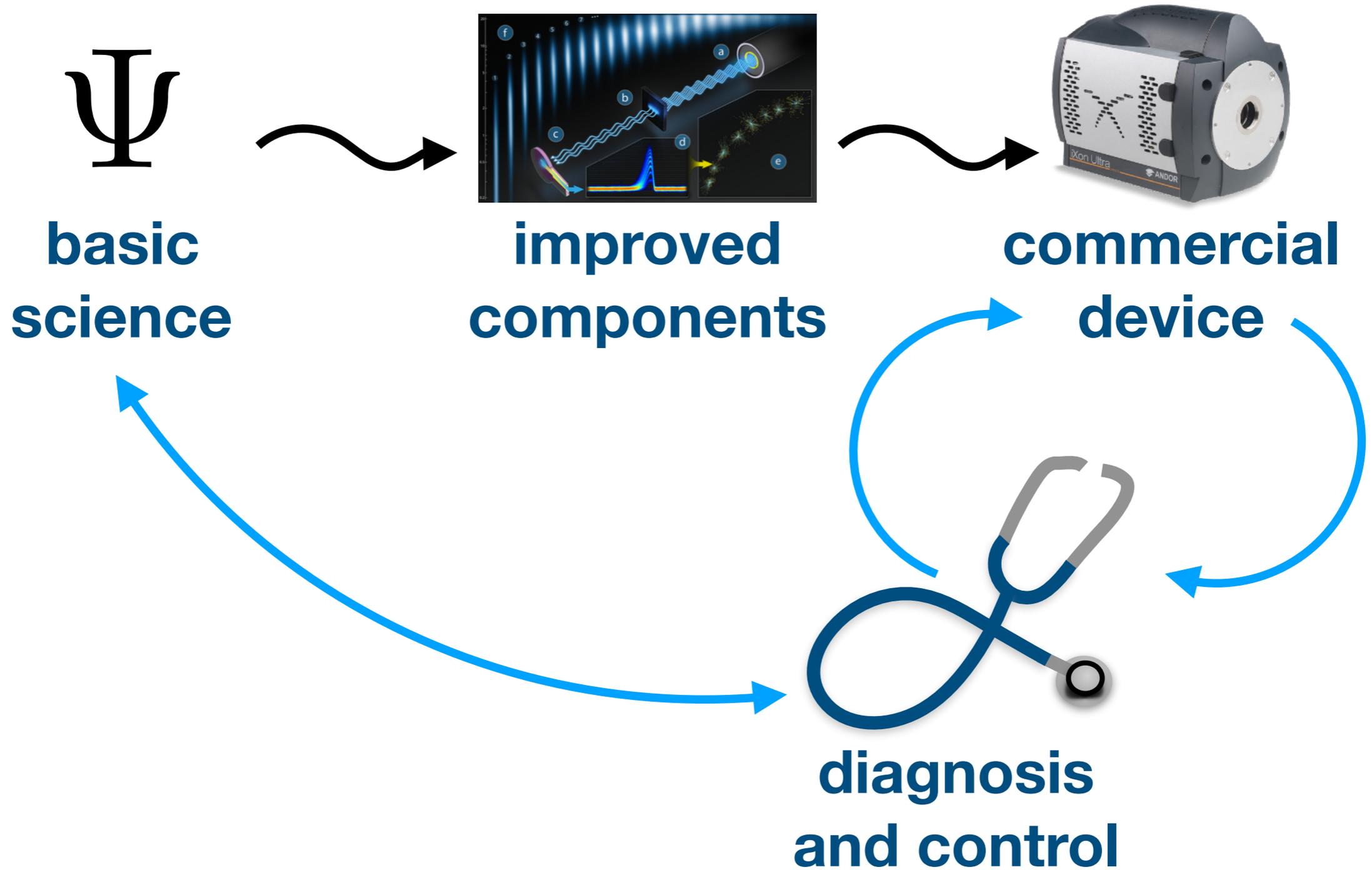


**improved  
components**



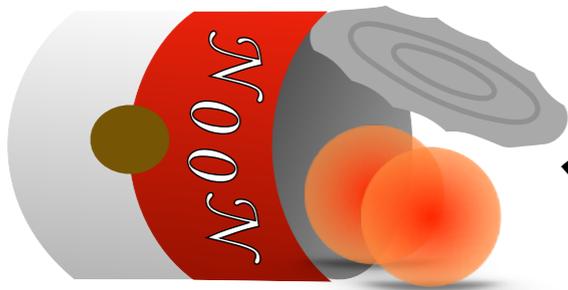
**commercial  
device**

# Coping with Imperfections

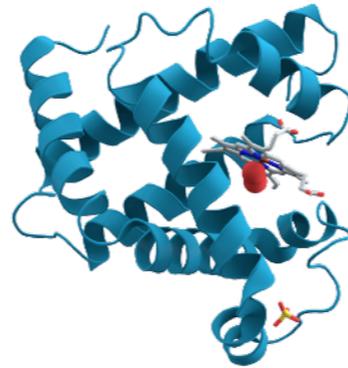


# ☰ Multiparameter Estimation

**source**



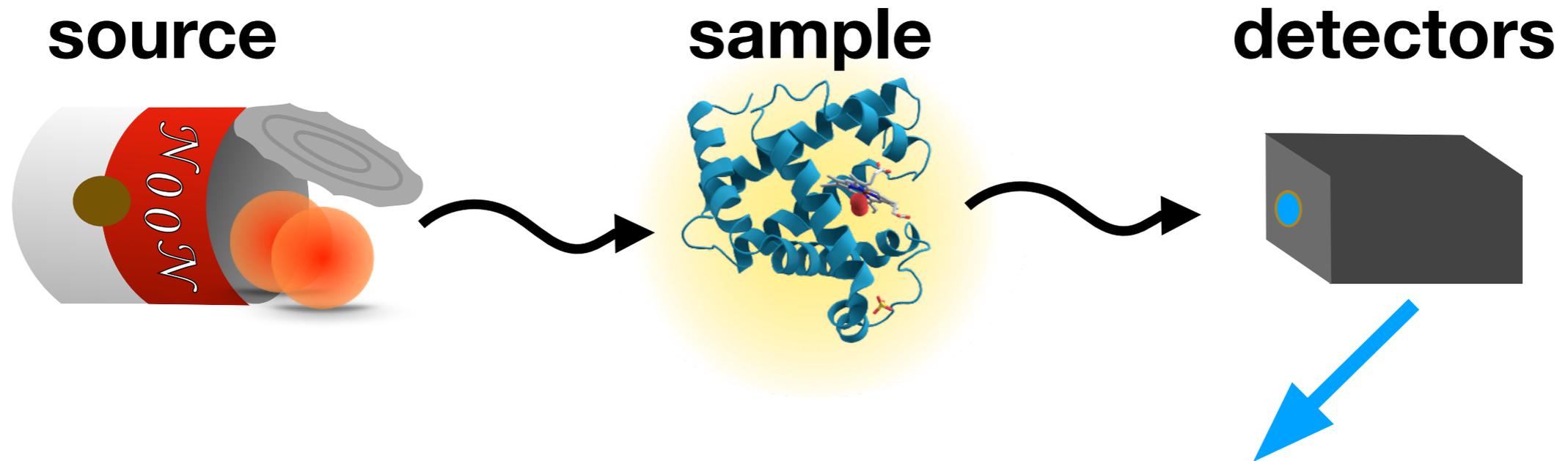
**sample**



**detectors**

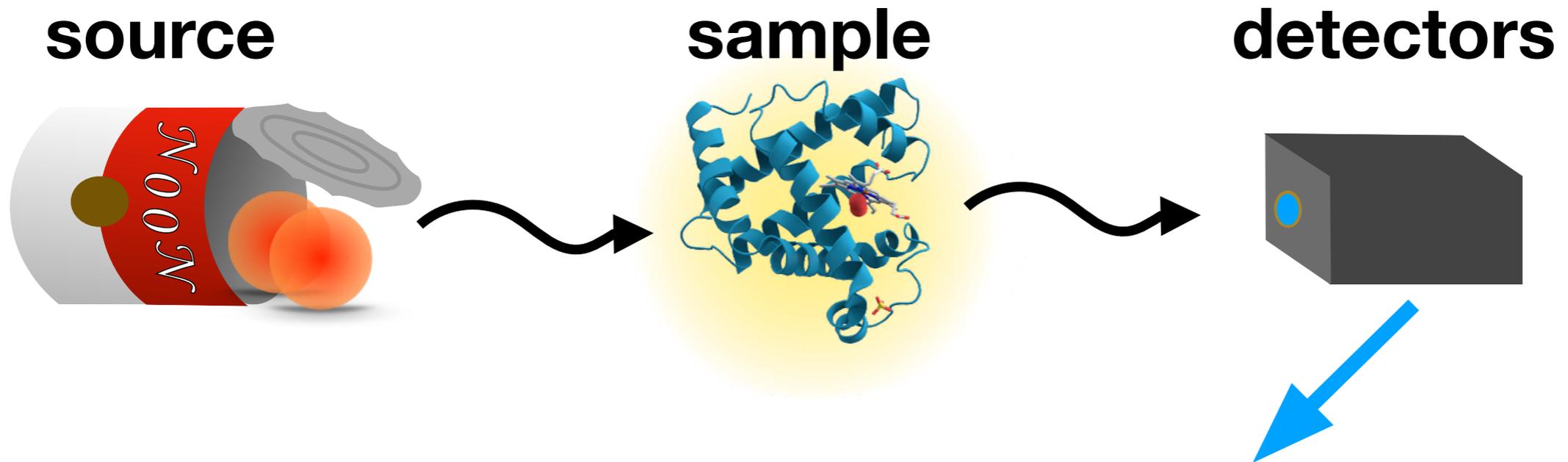


# Multiparameter Estimation



$\phi$  phase estimation

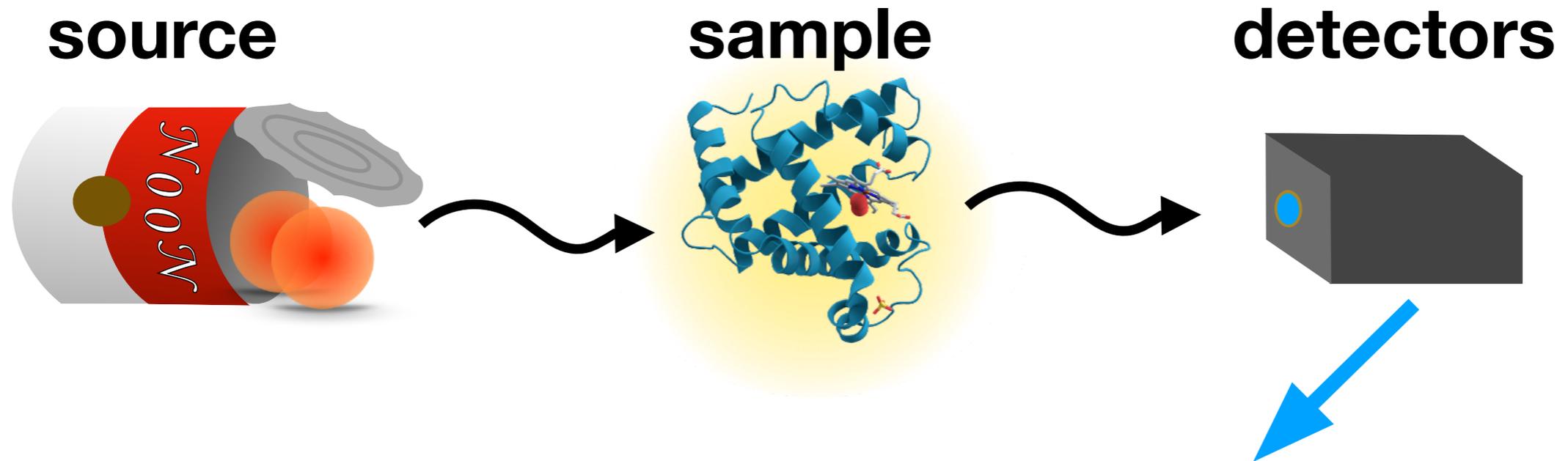
# Multiparameter Estimation



$\phi$  **phase estimation**

$\phi_1, \phi_2, \phi_3 \dots$  **multi-phase estimation**

# Multiparameter Estimation

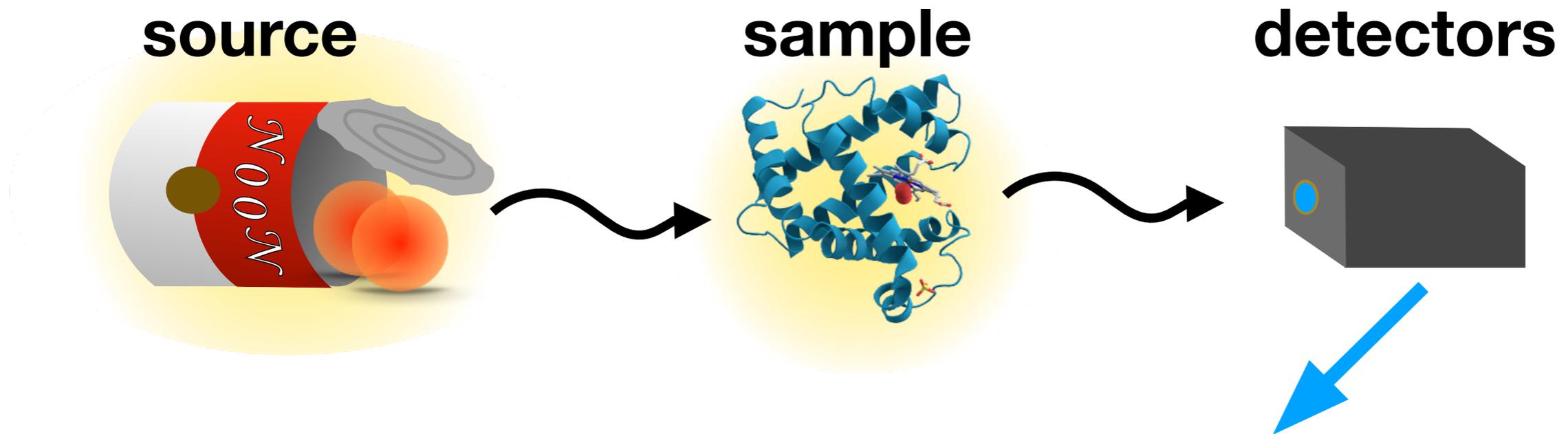


$\phi$  **phase estimation**

$\phi_1, \phi_2, \phi_3 \dots$  **multi-phase estimation**

$\phi \quad \eta$  **phase and loss**

# Multiparameter Estimation

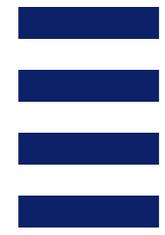


$\phi$  phase estimation

$\phi_1, \phi_2, \phi_3 \dots$  multi-phase estimation

$\phi \quad \eta$  phase and loss

$\phi \quad V$  phase and visibility

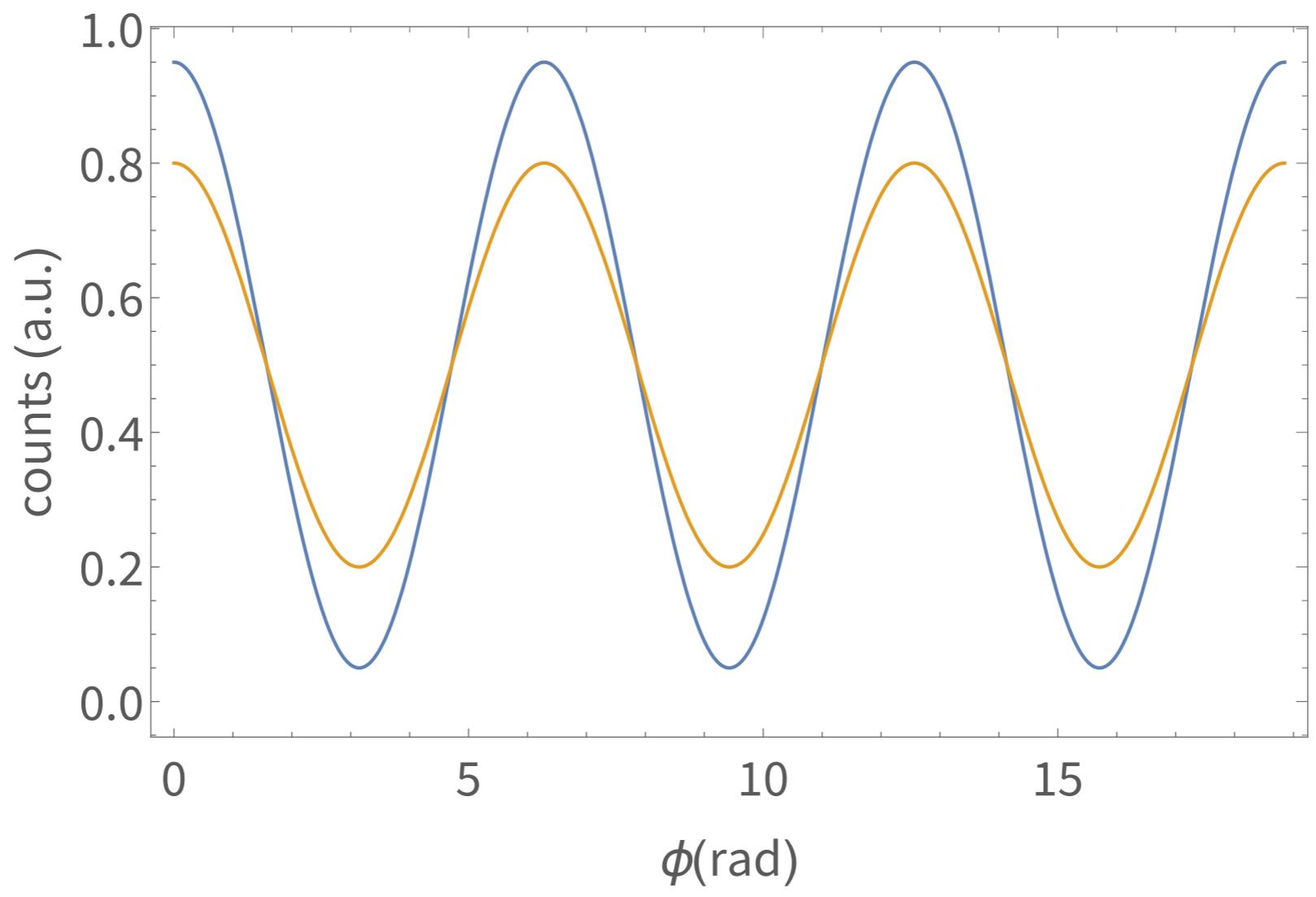


# Multiparameter Estimation

**phase and visibility**

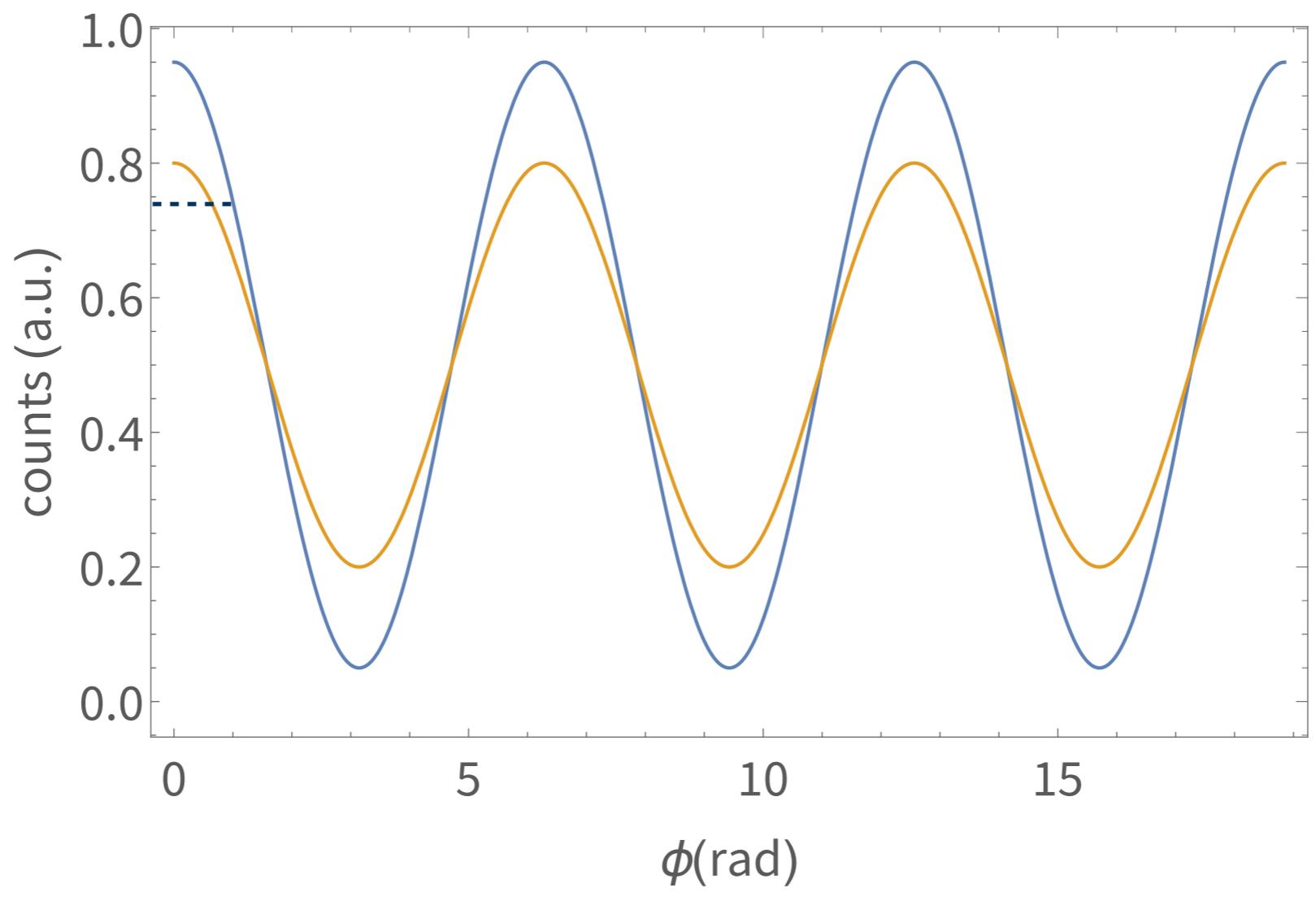
# Multiparameter Estimation

## phase and visibility



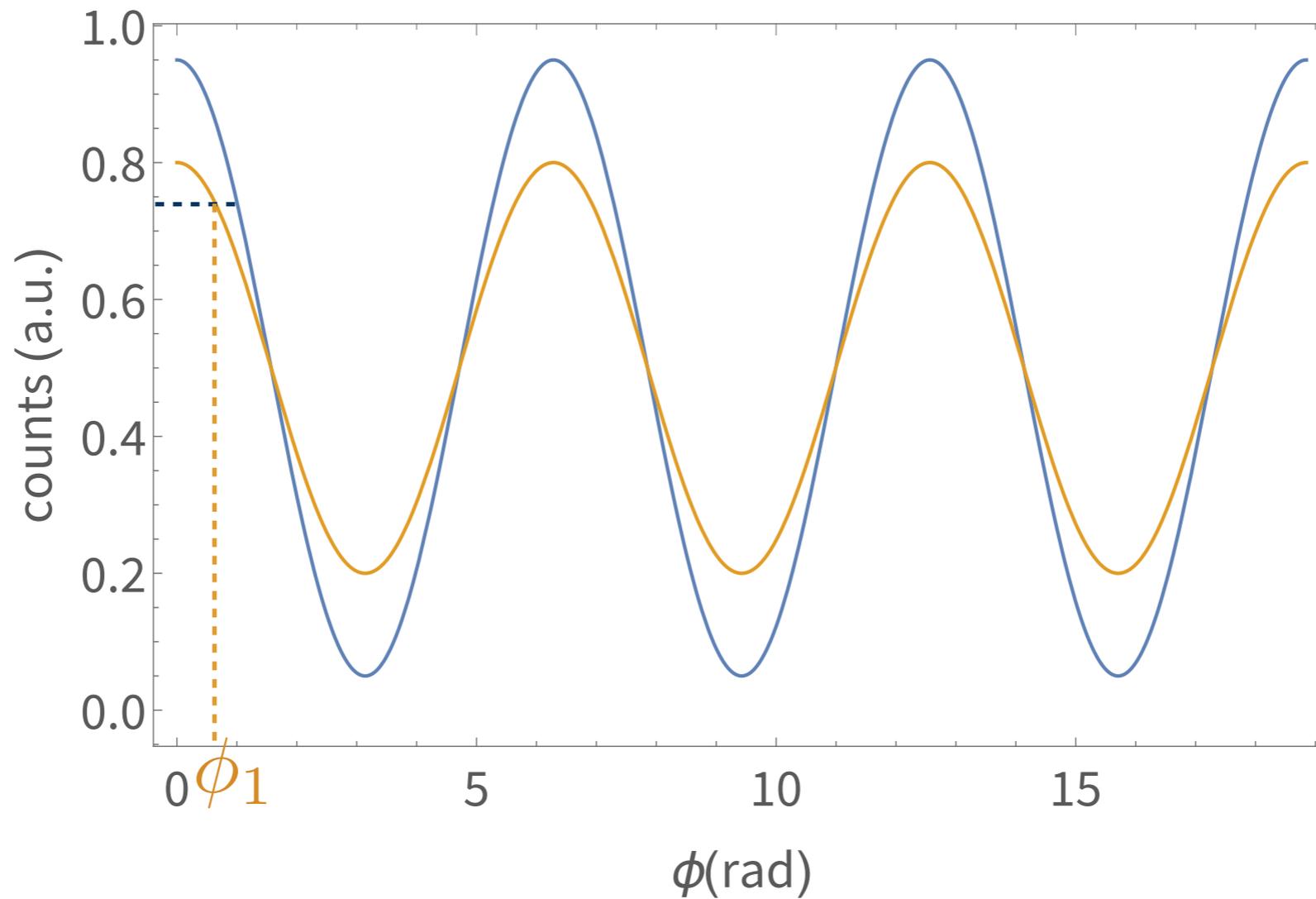
# Multiparameter Estimation

## phase and visibility



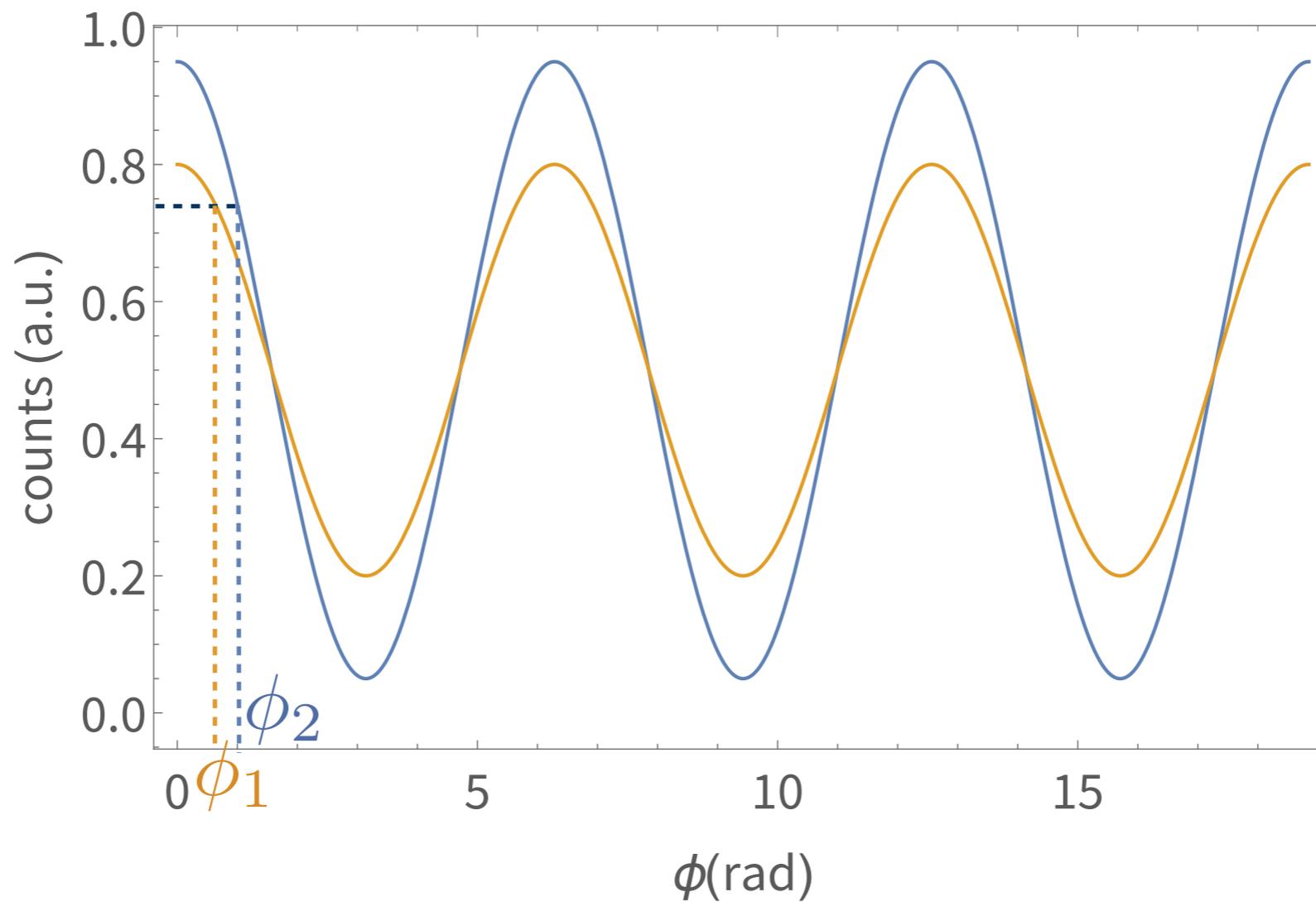
# Multiparameter Estimation

## phase and visibility



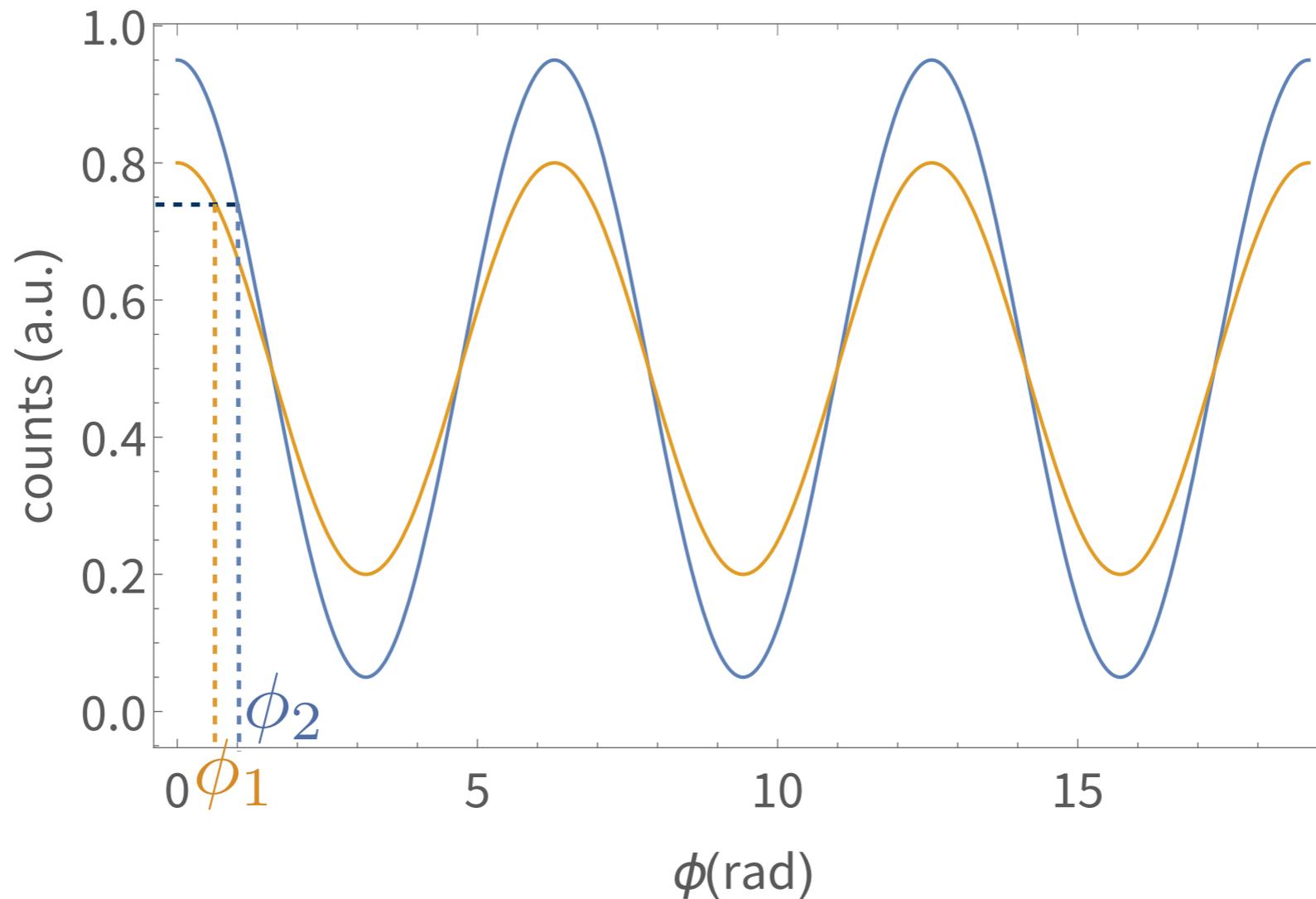
# Multiparameter Estimation

## phase and visibility



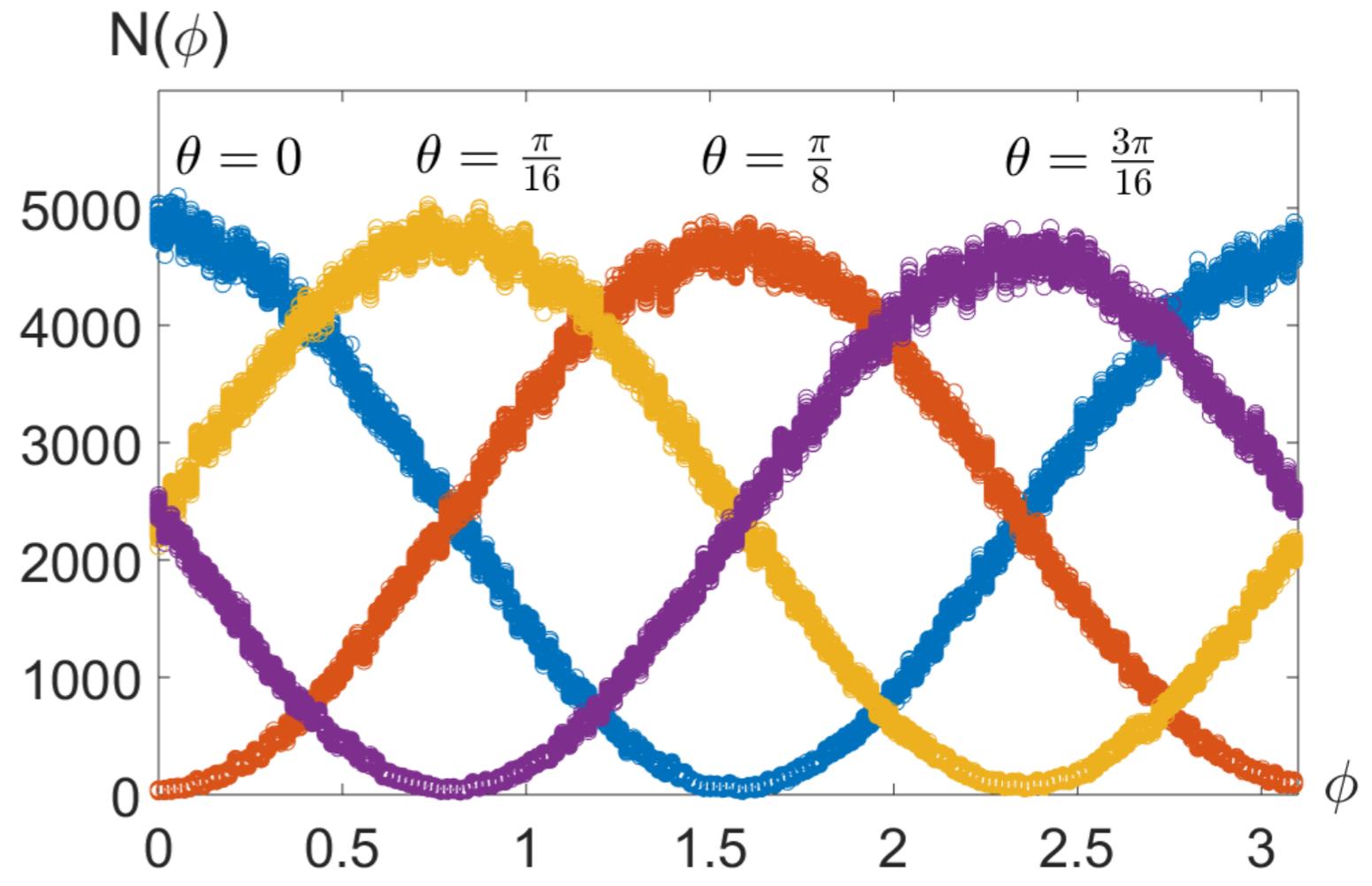
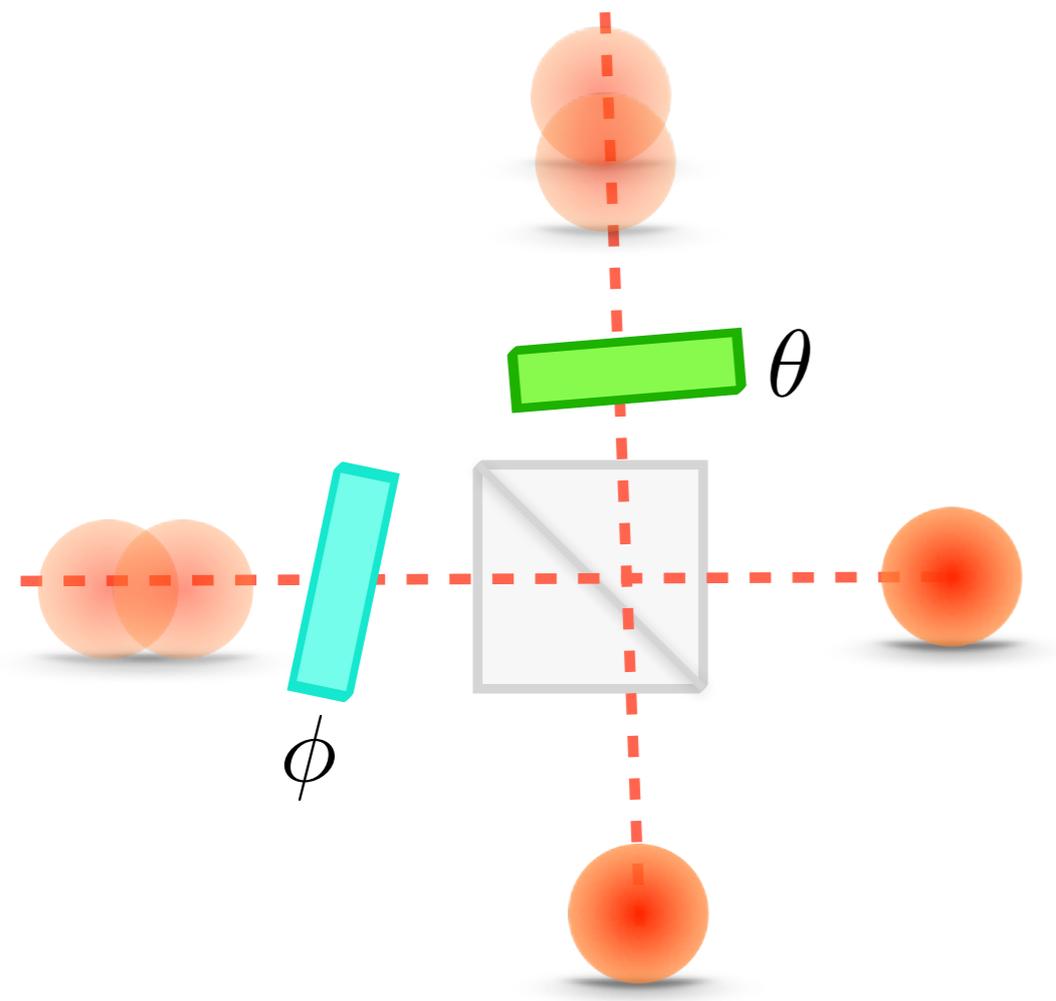
# Multiparameter Estimation

## phase and visibility

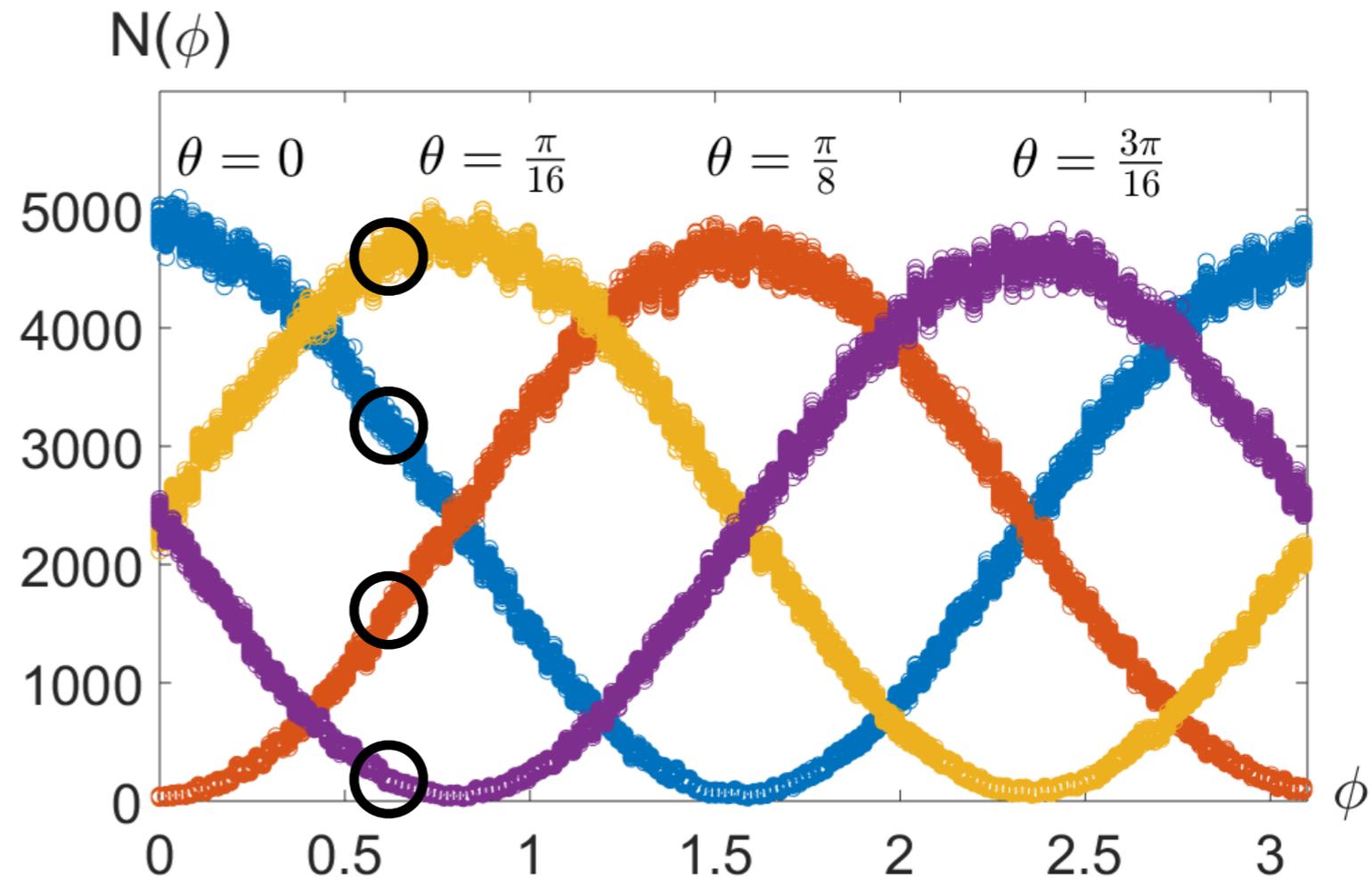
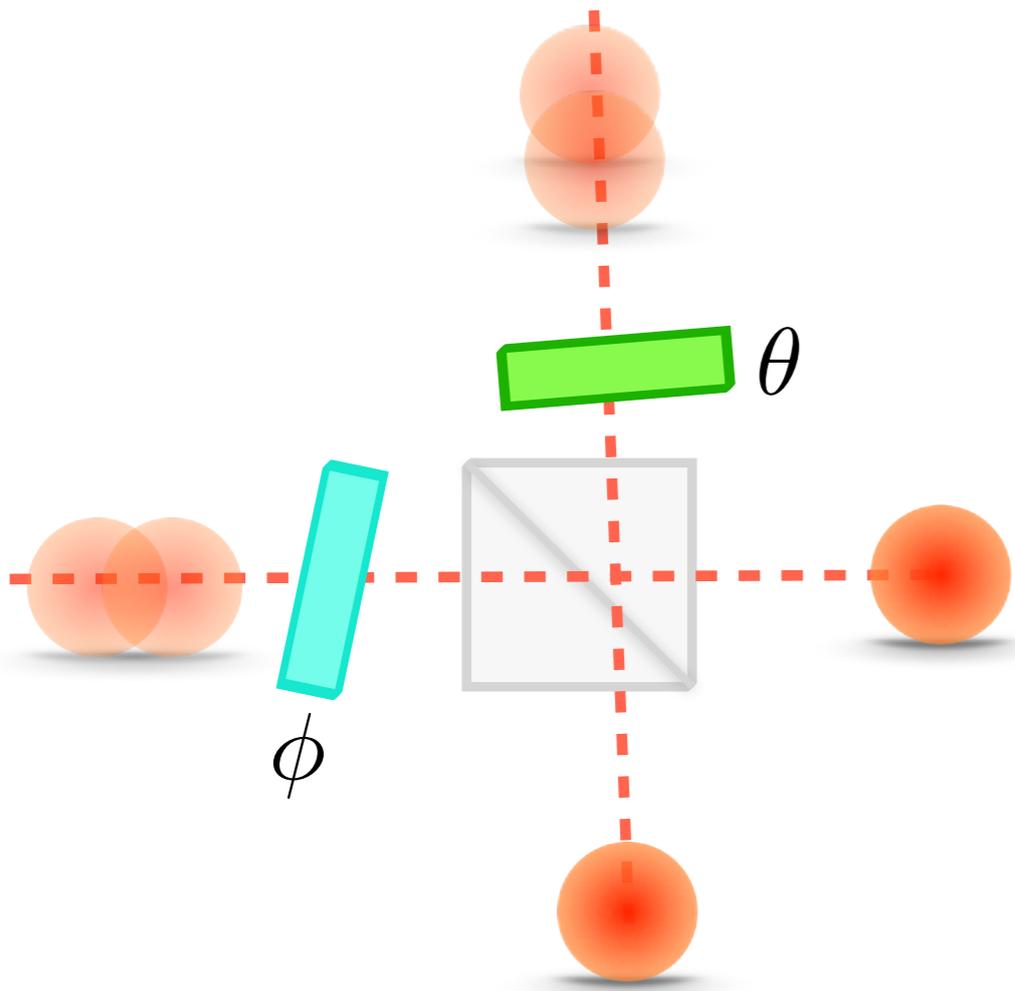


- Visibility affects phase estimation
- The values of  $v$  and  $\phi$  should be known simultaneously

# Multiparameter Estimation

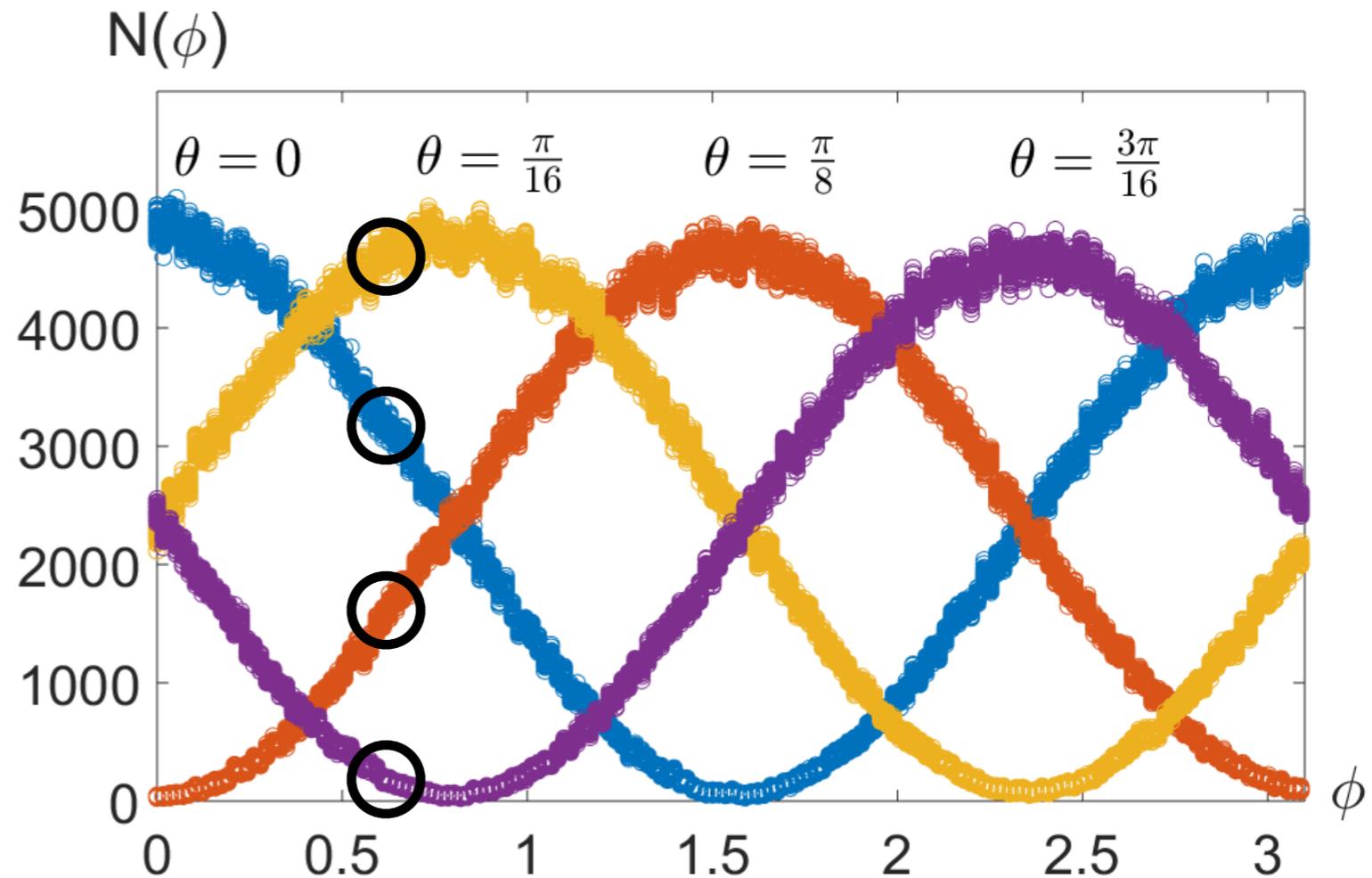
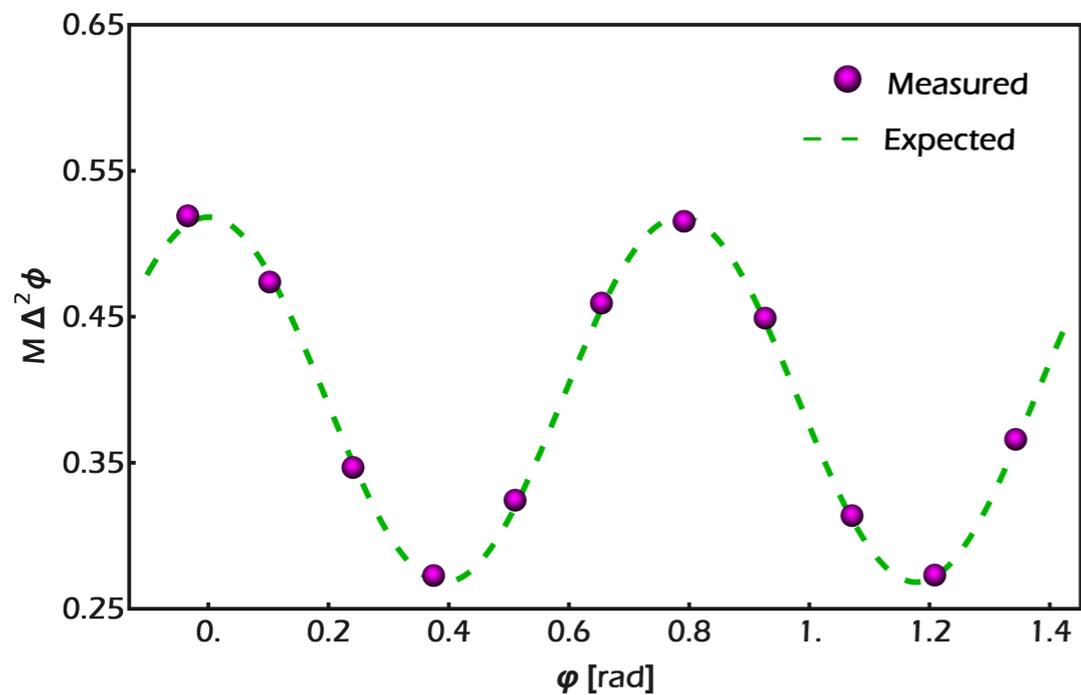


# Multiparameter Estimation



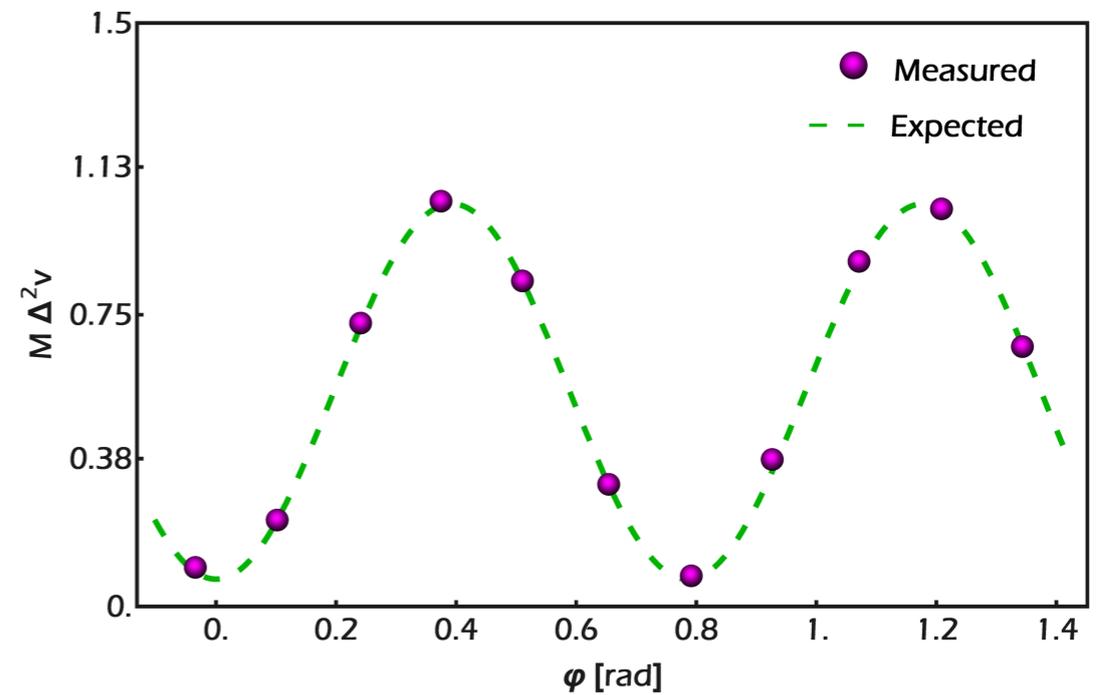
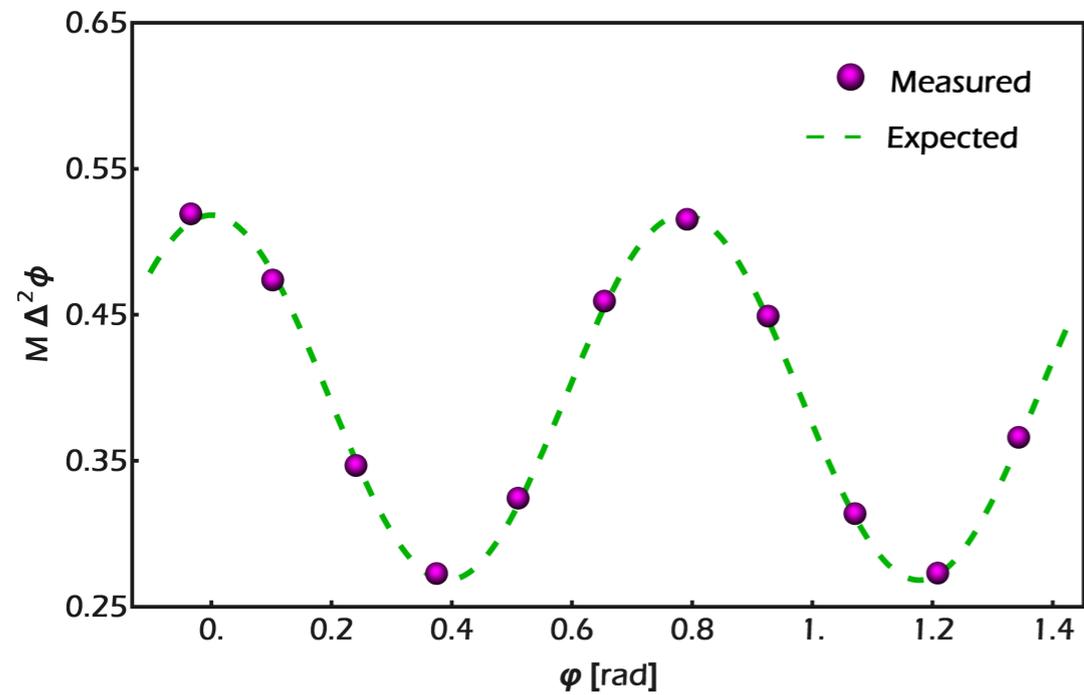
**simultaneous estimation of phase and visibility**

# Multiparameter Estimation



**simultaneous estimation of phase and visibility**

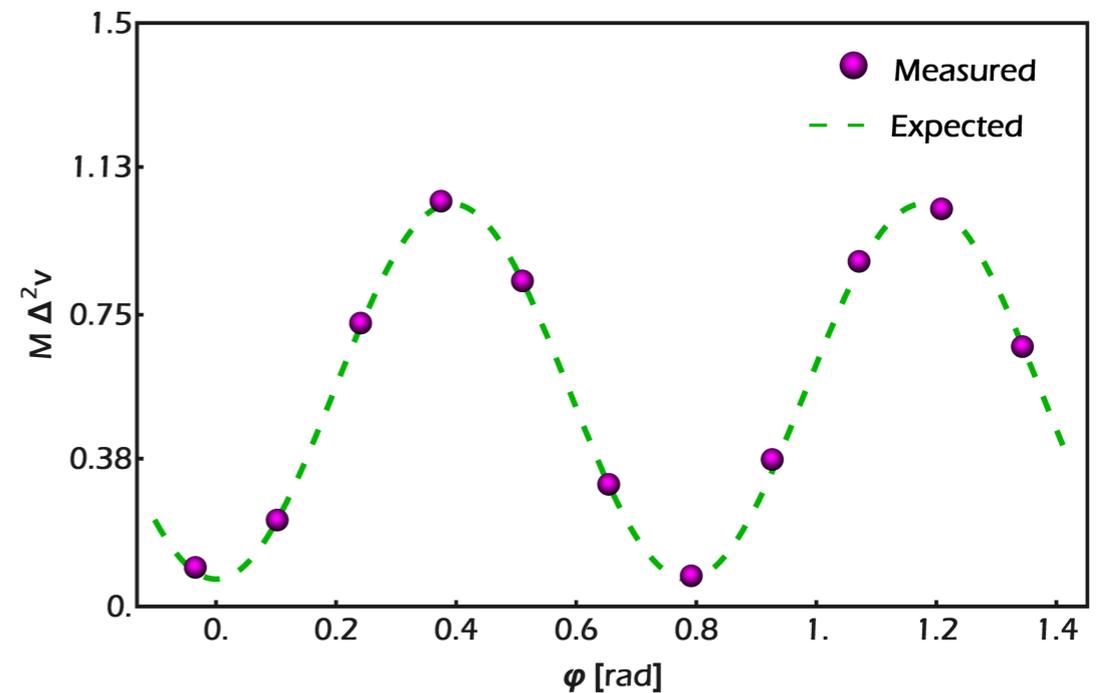
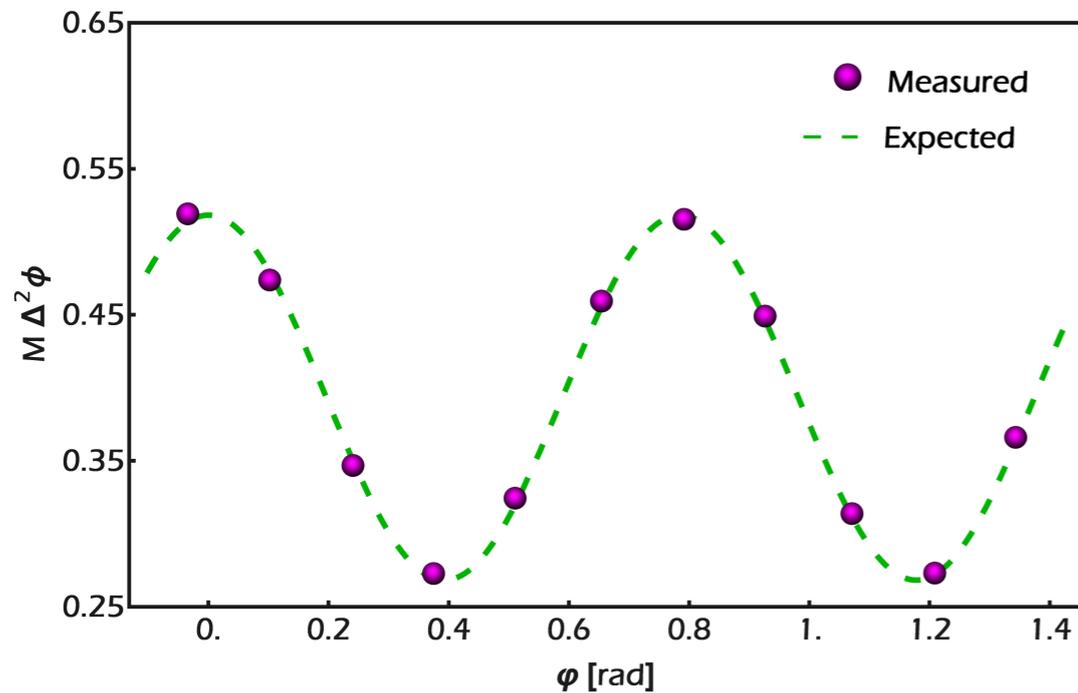
# Multiparameter Estimation



**simultaneous estimation of phase and visibility**

# Multiparameter Estimation

## simultaneous estimation of phase and visibility

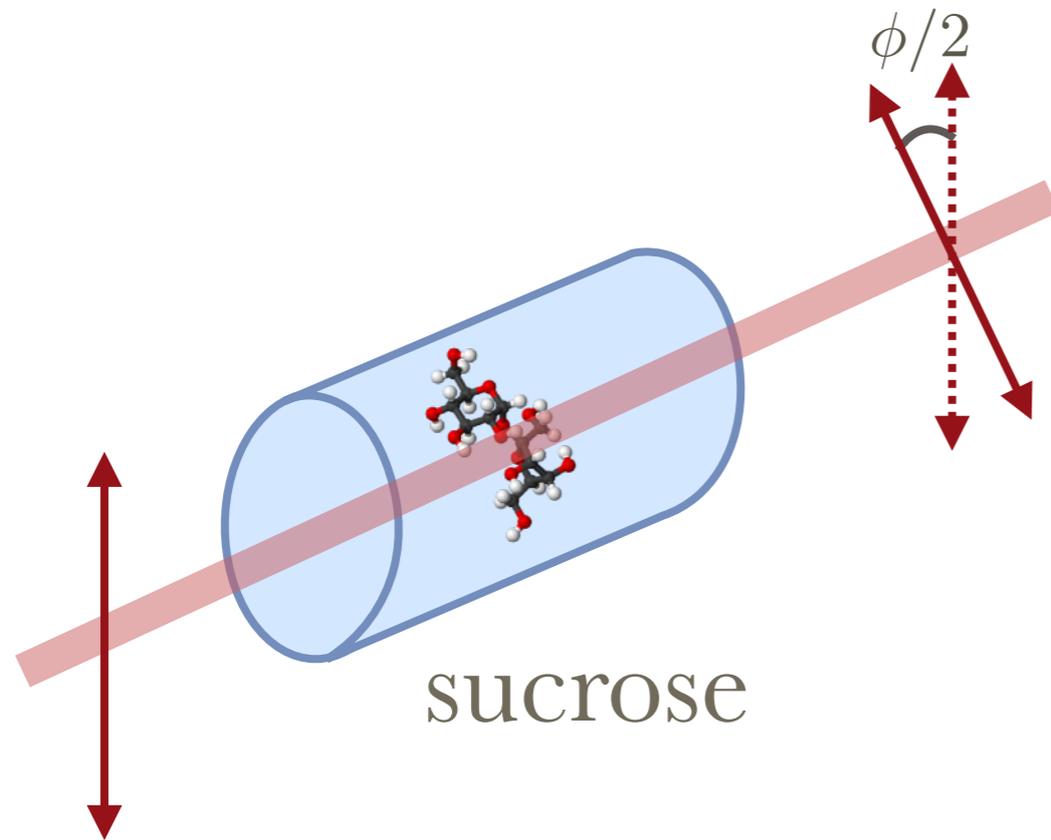


**trade-off between resources invested on either parameter**

**sweet spots for phase/visibility estimation**

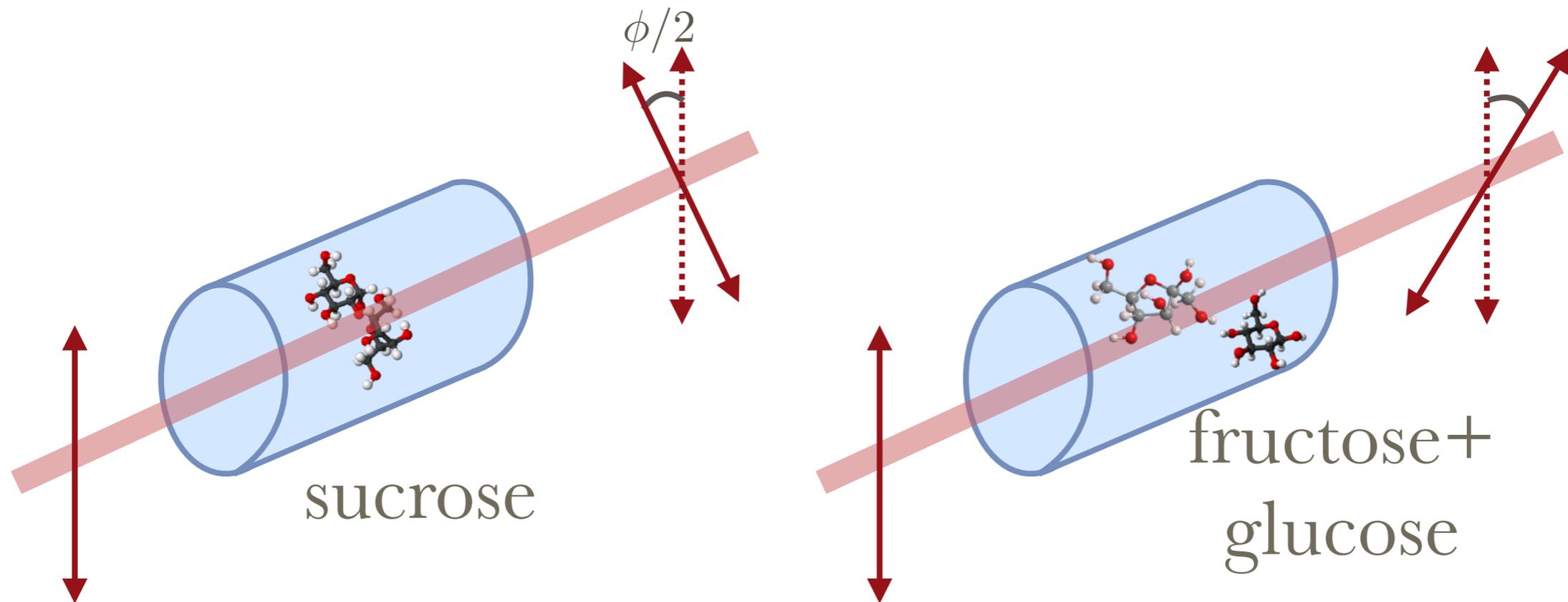
# Multiparameter Estimation

application to *optical activity*



# Multiparameter Estimation

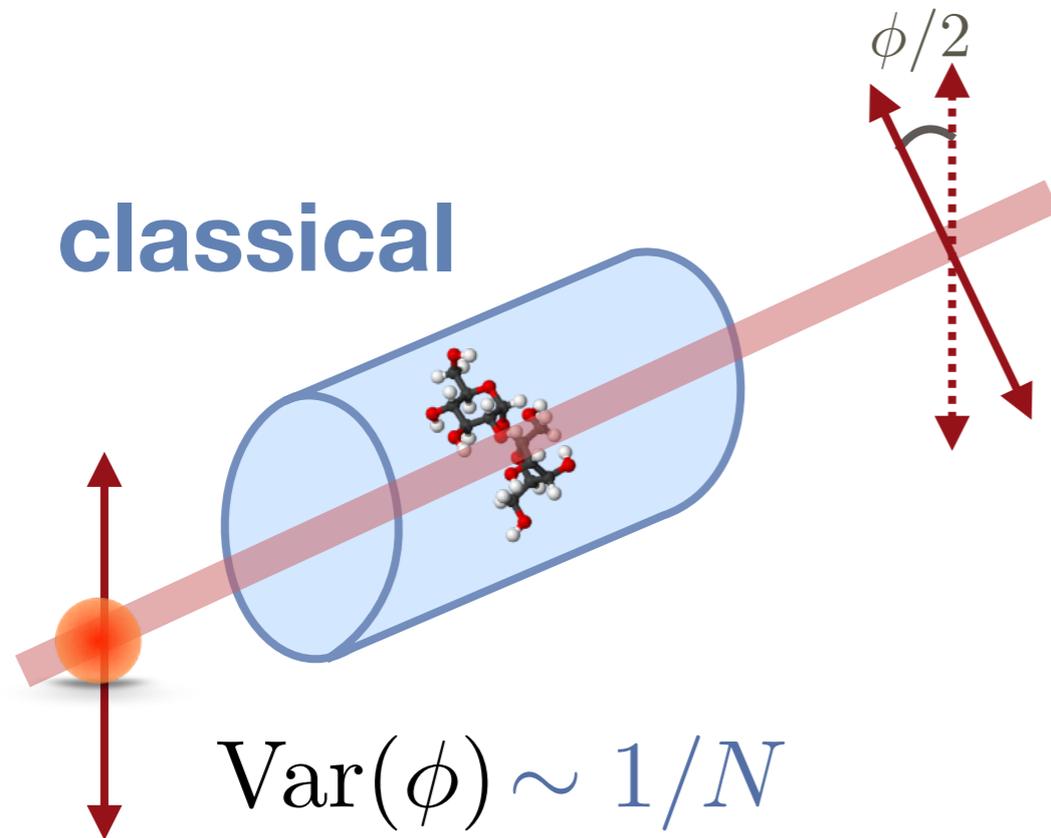
application to *optical activity*



same requirements as phase estimation

# Multiparameter Estimation

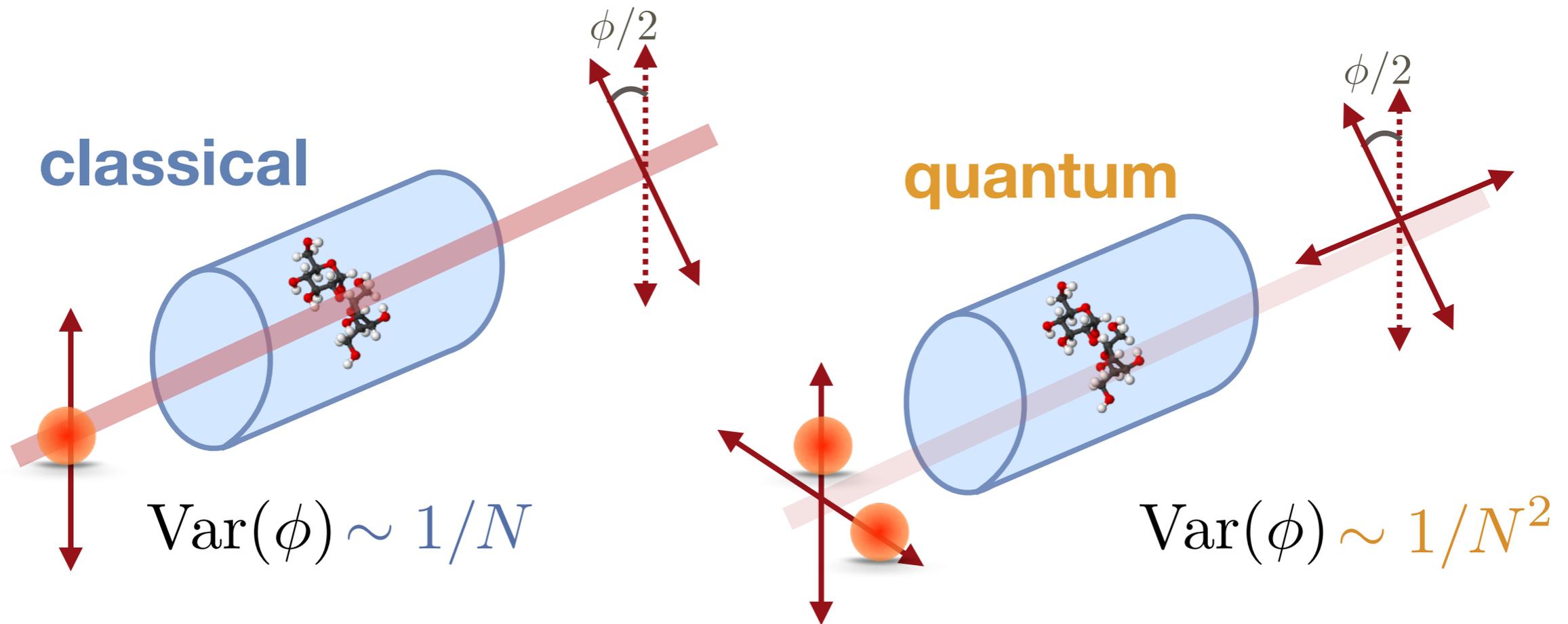
application to *optical activity*



same requirements as phase estimation

# Multiparameter Estimation

application to *optical activity*

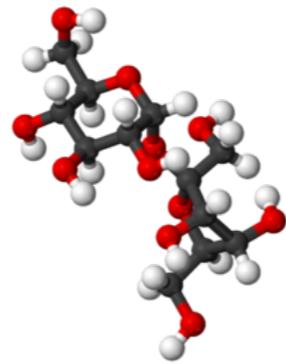


same requirements as phase estimation

# ☰ Multiparameter Estimation

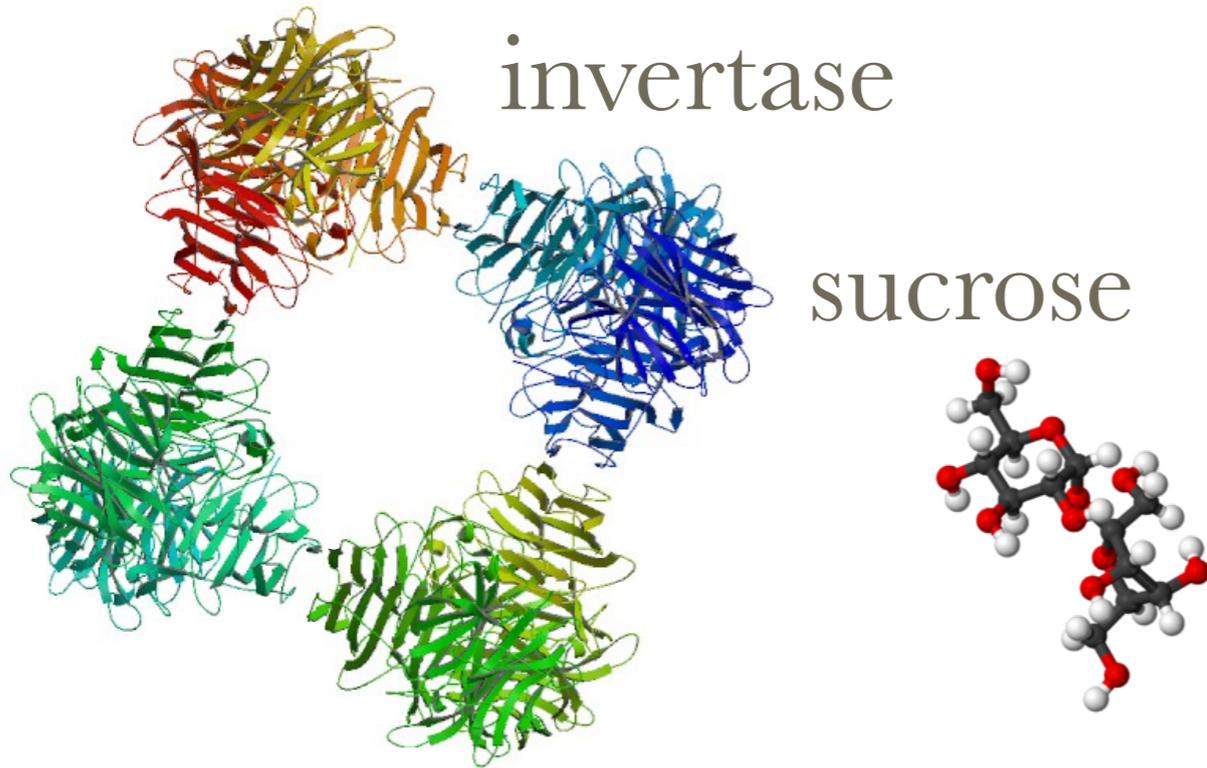
application to *changes of optical activity*

sucrose



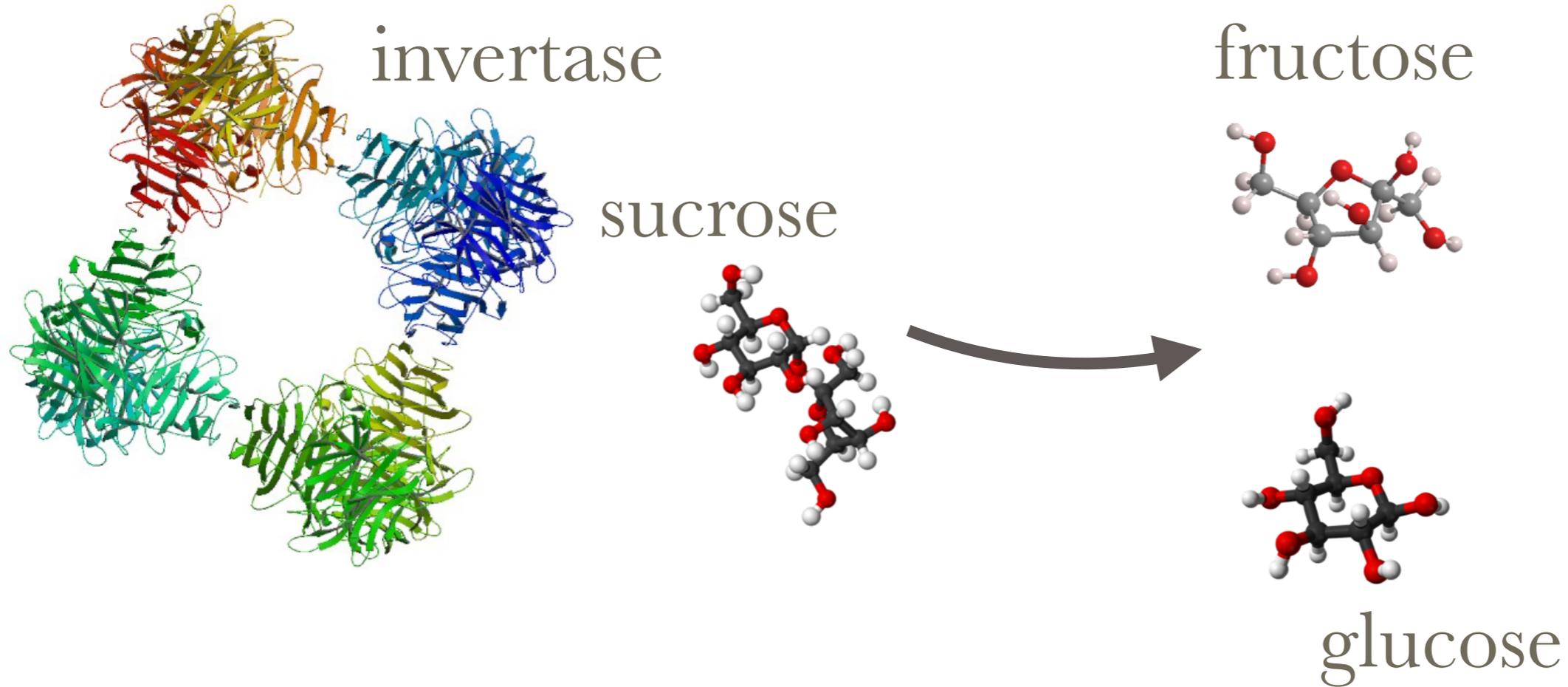
# ≡ Multiparameter Estimation

application to *changes of optical activity*



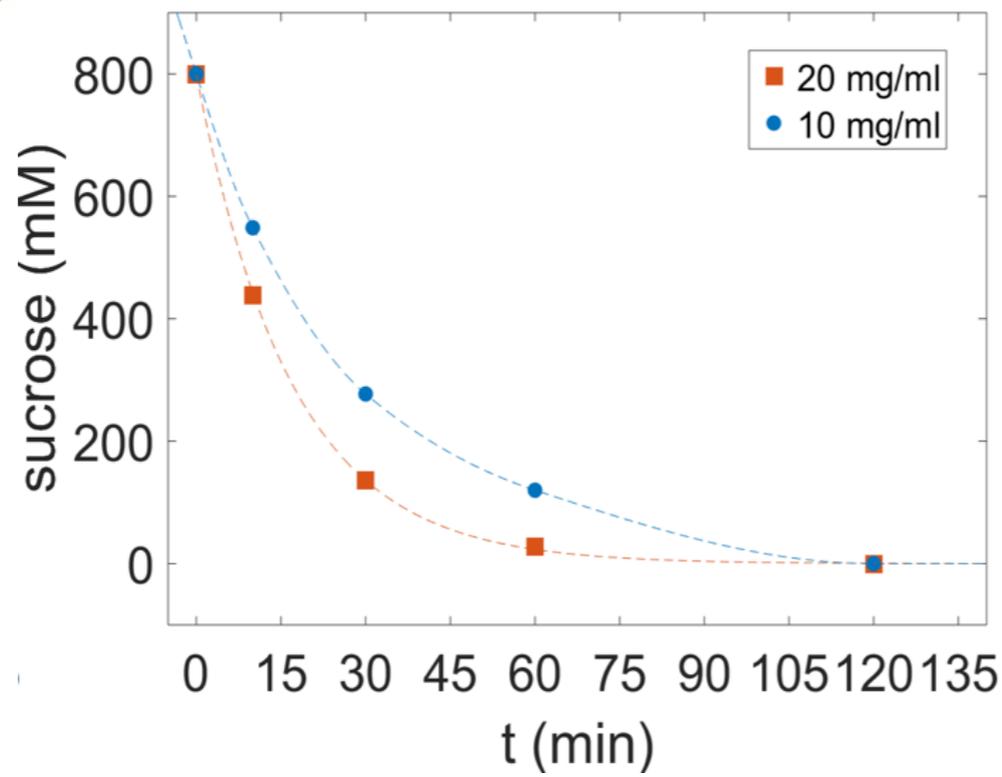
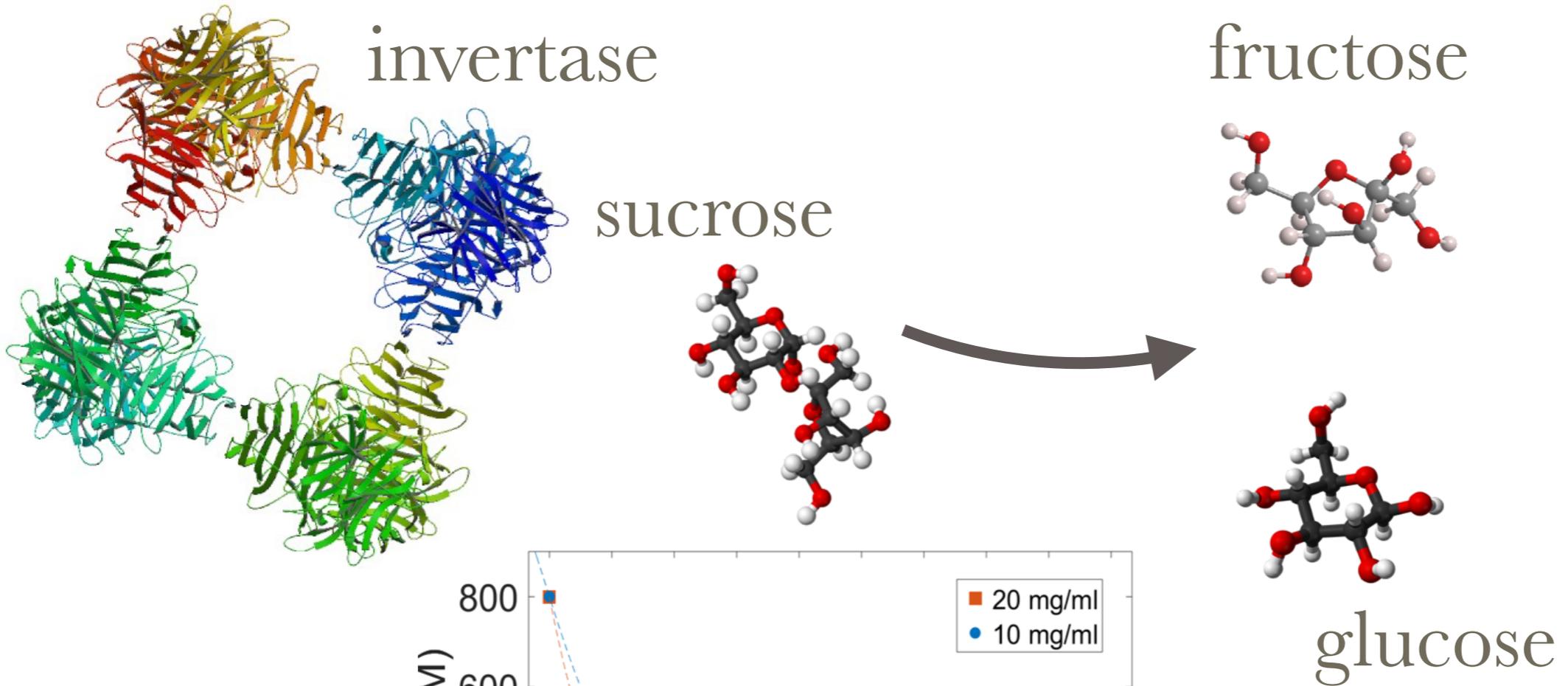
# Multiparameter Estimation

application to *changes of optical activity*



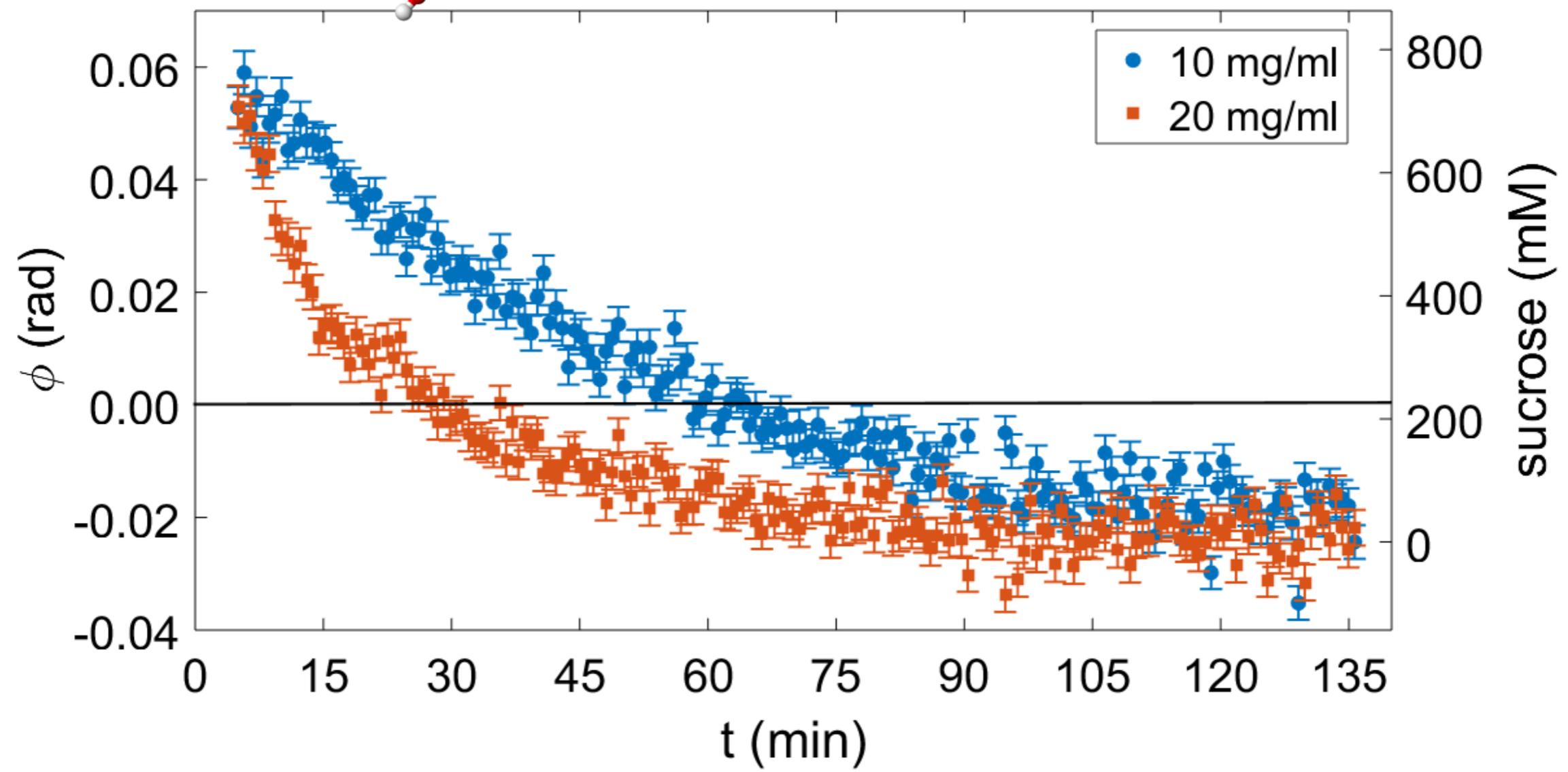
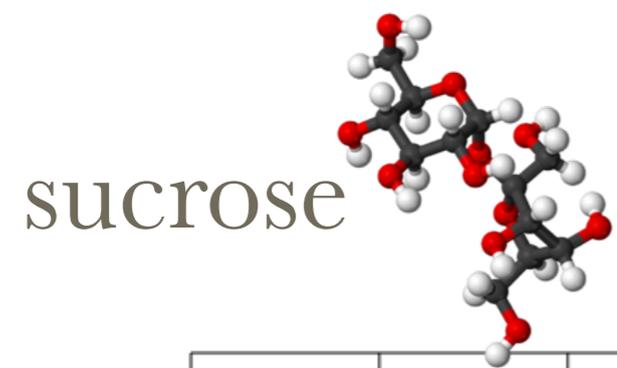
# Multiparameter Estimation

application to *changes of optical activity*



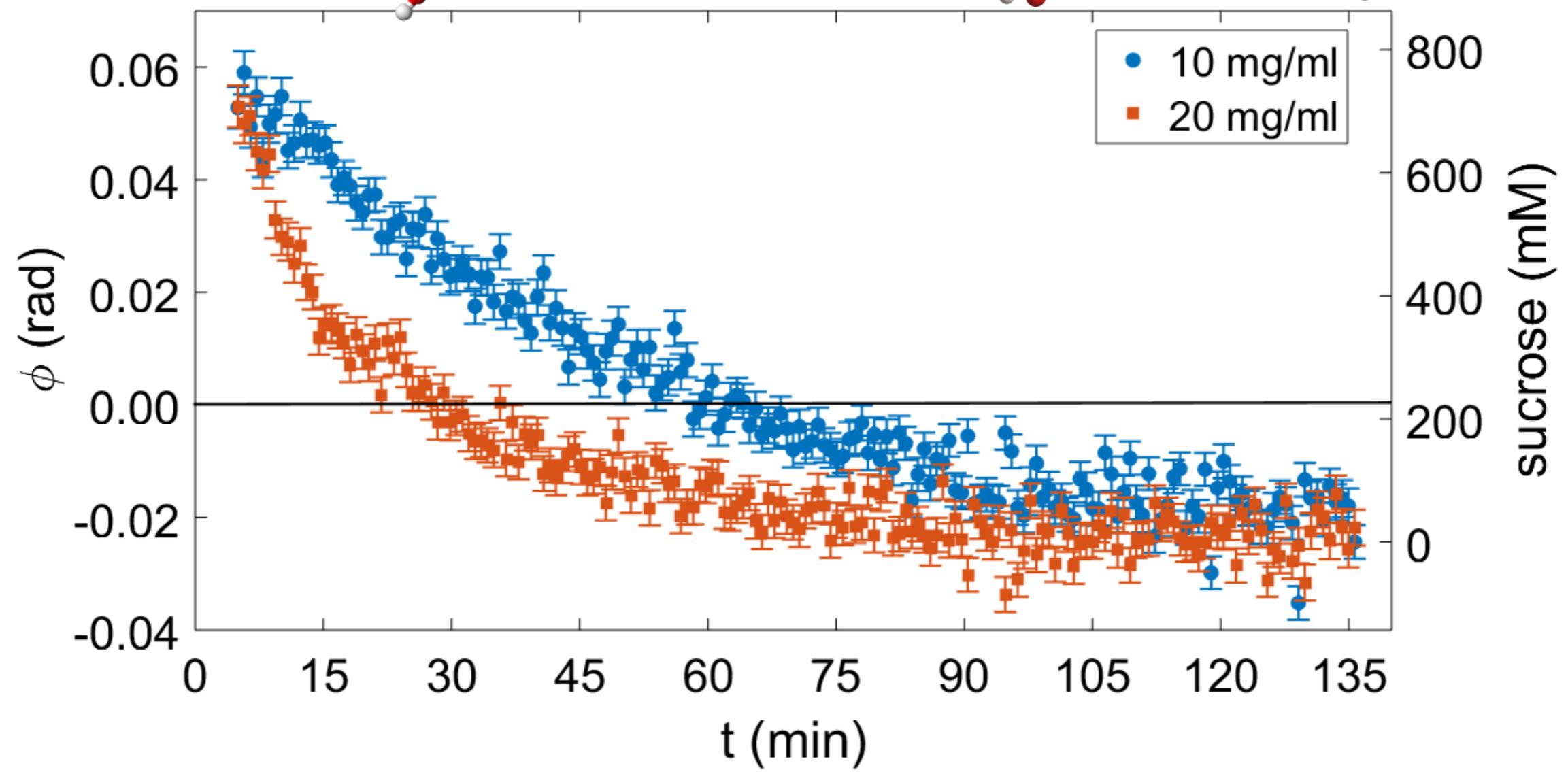
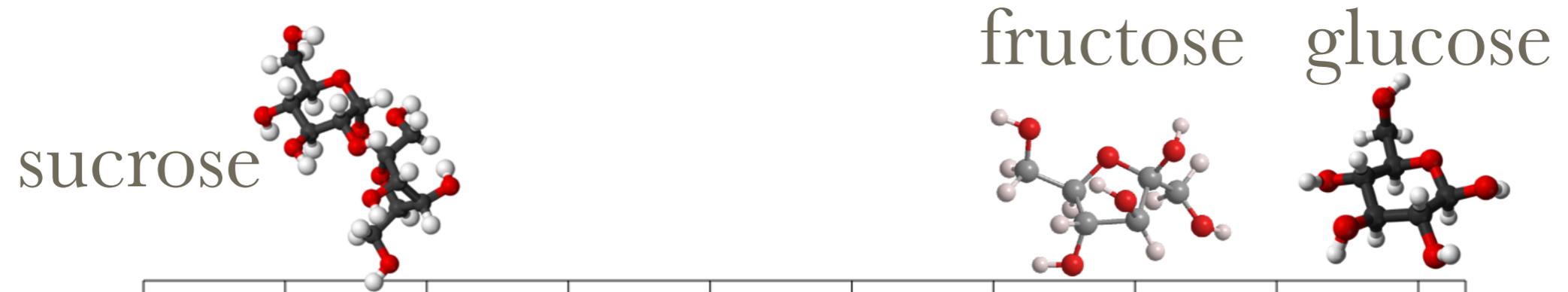
# Multiparameter Estimation

application to *changes of optical activity*



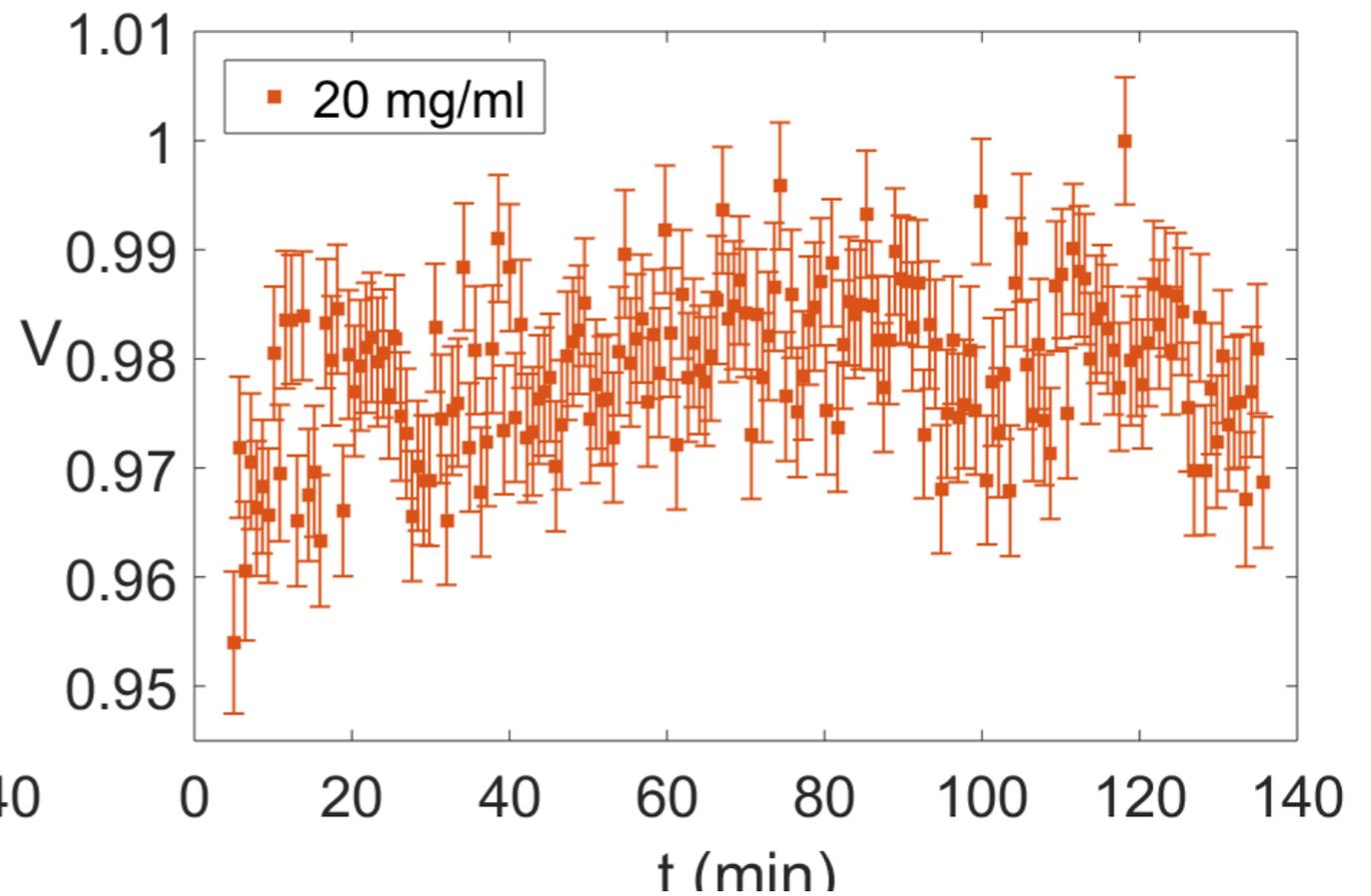
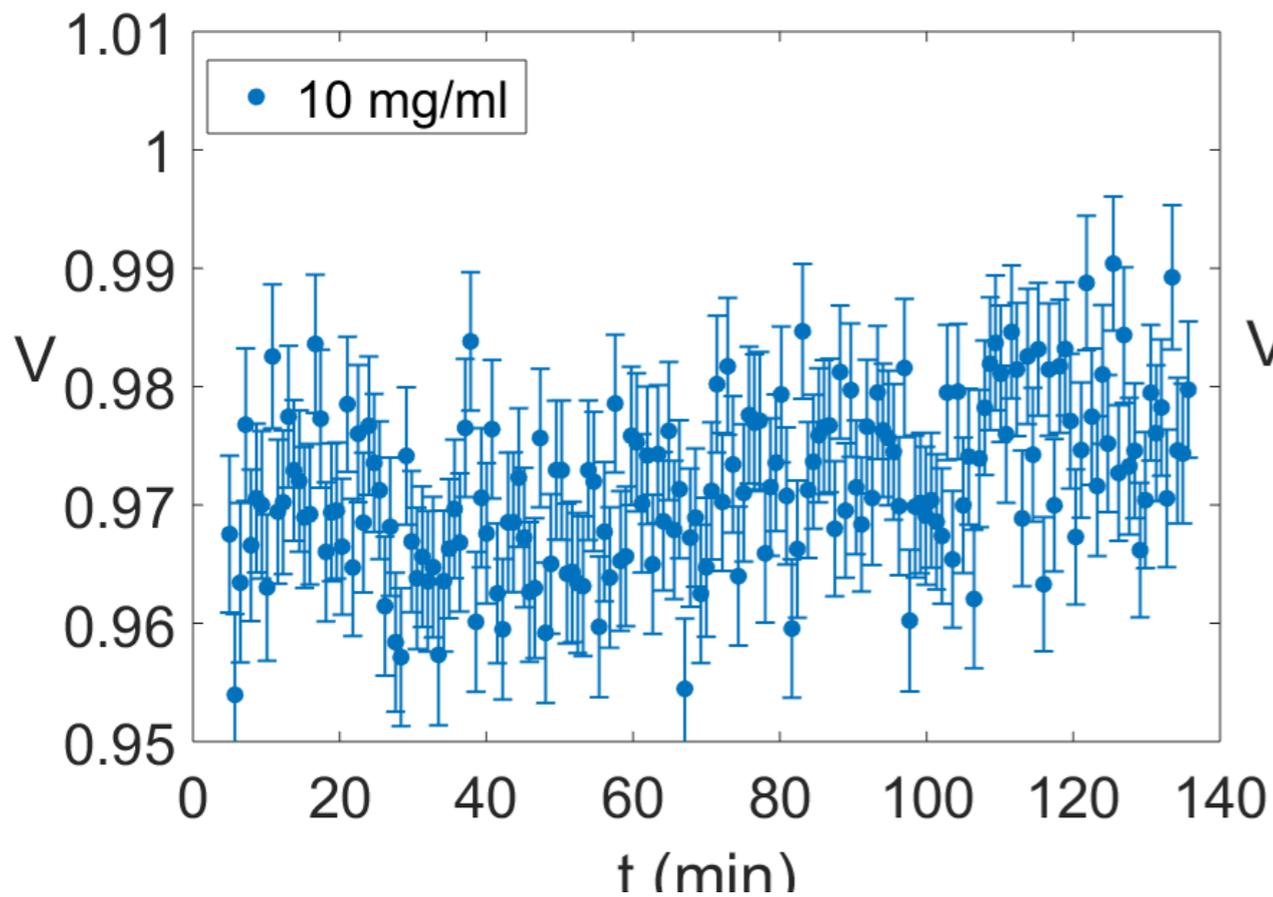
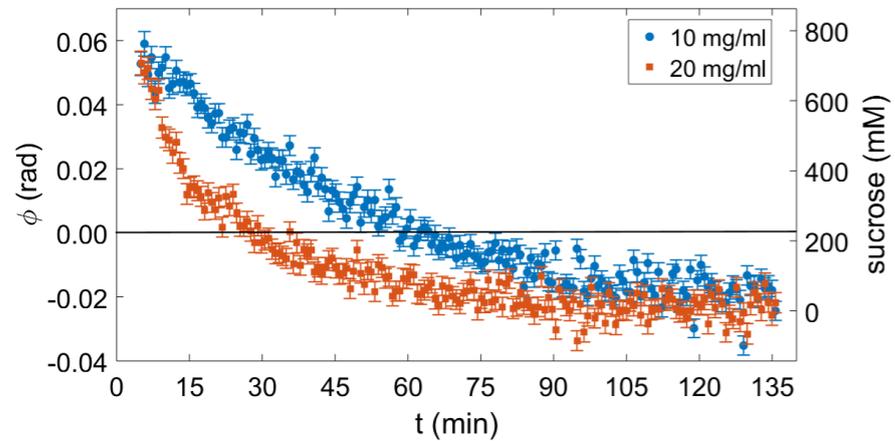
# Multiparameter Estimation

application to *changes of optical activity*



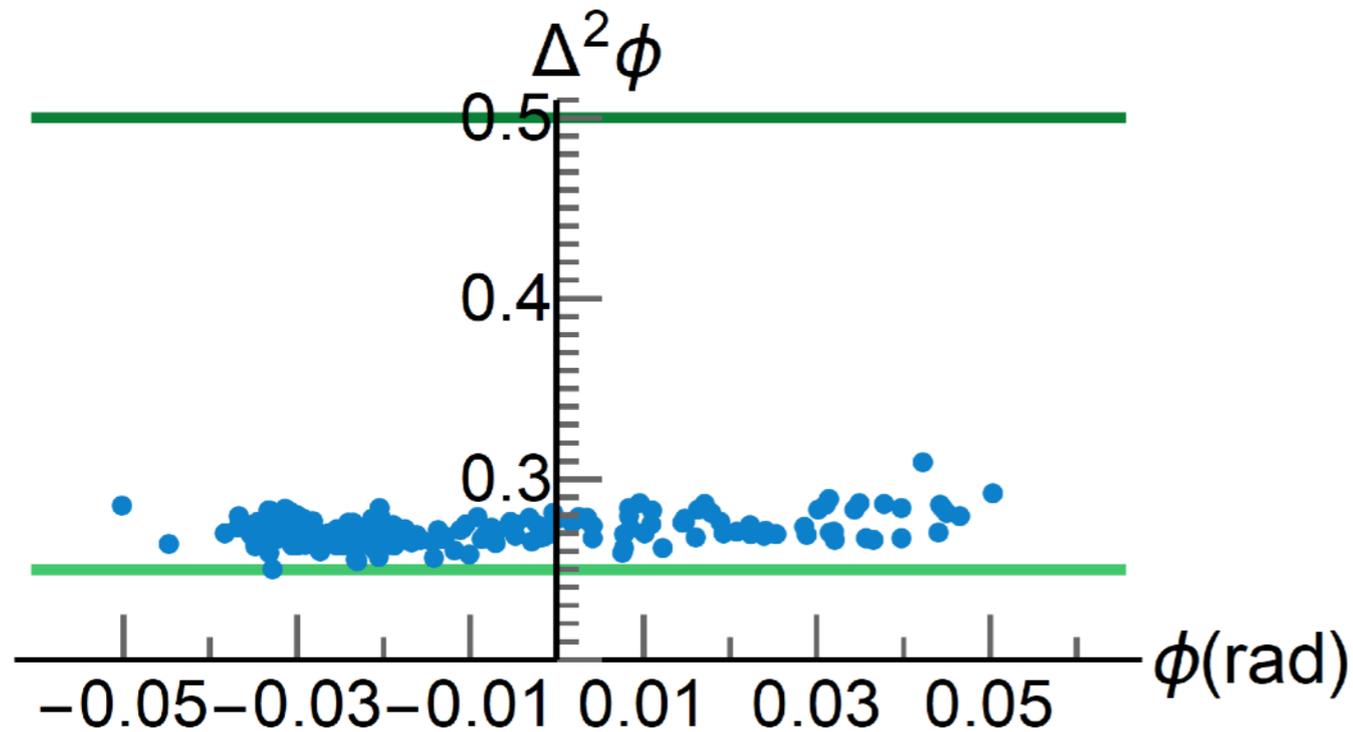
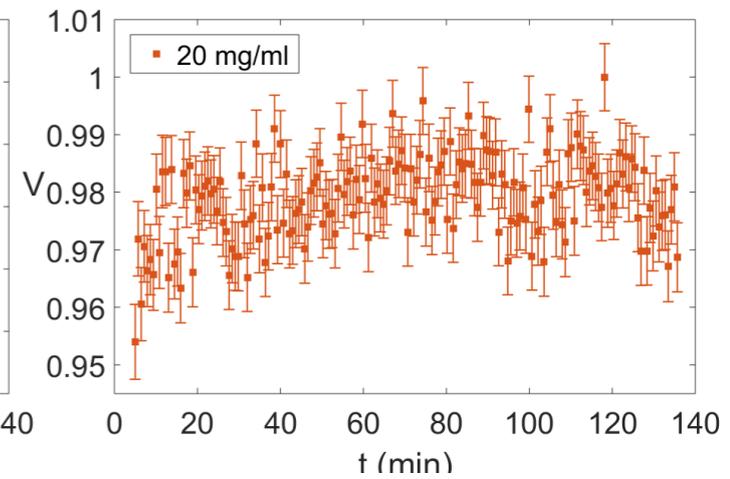
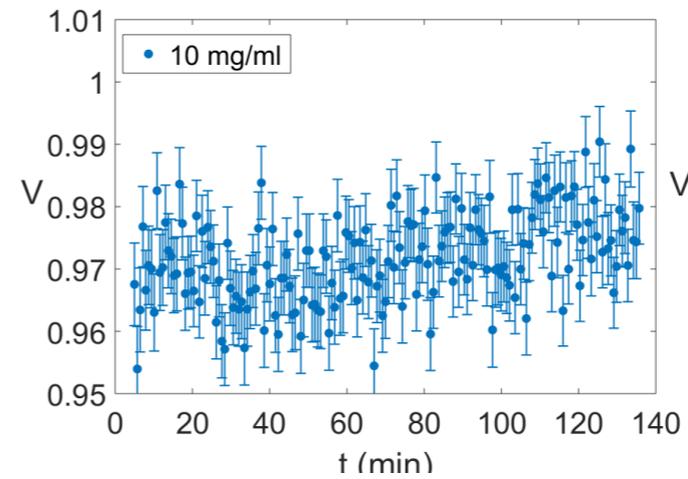
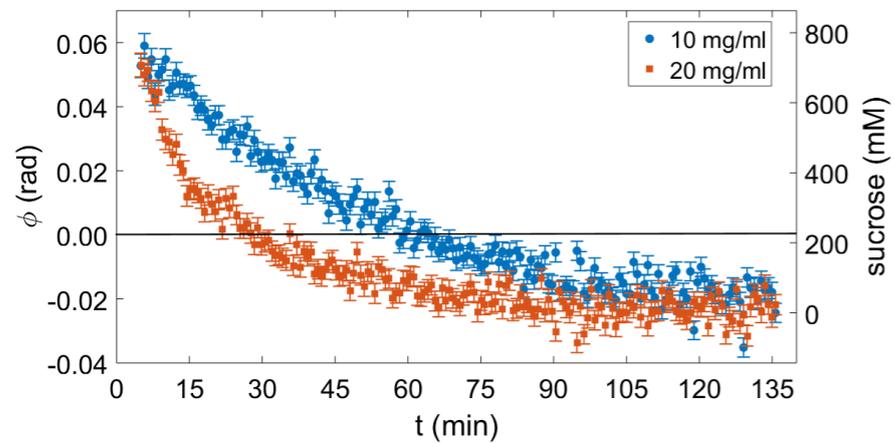
# Multiparameter Estimation

## application to *changes of optical activity*



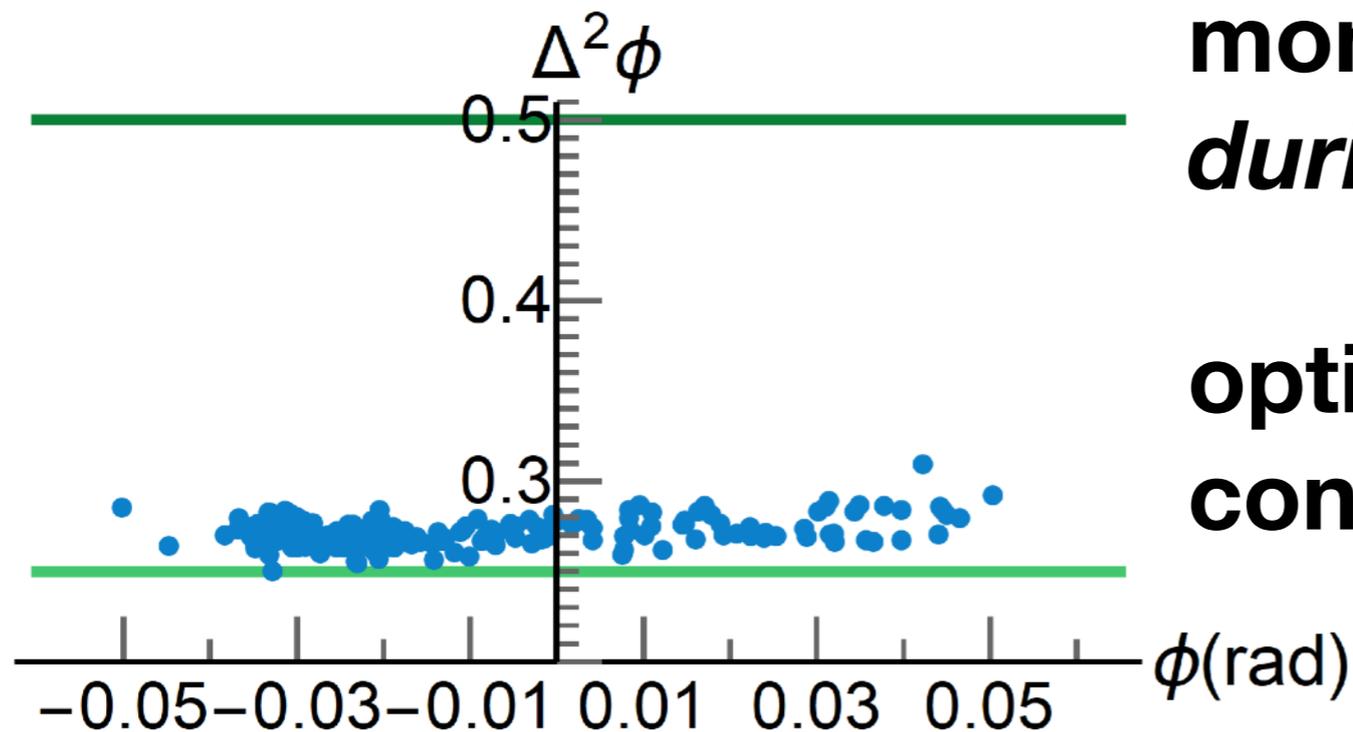
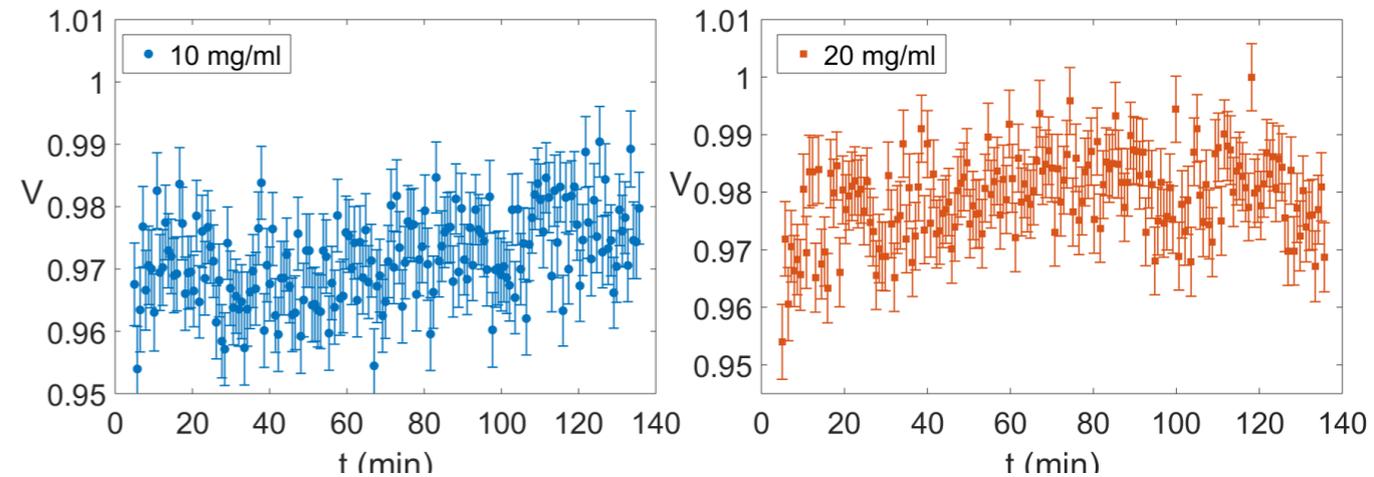
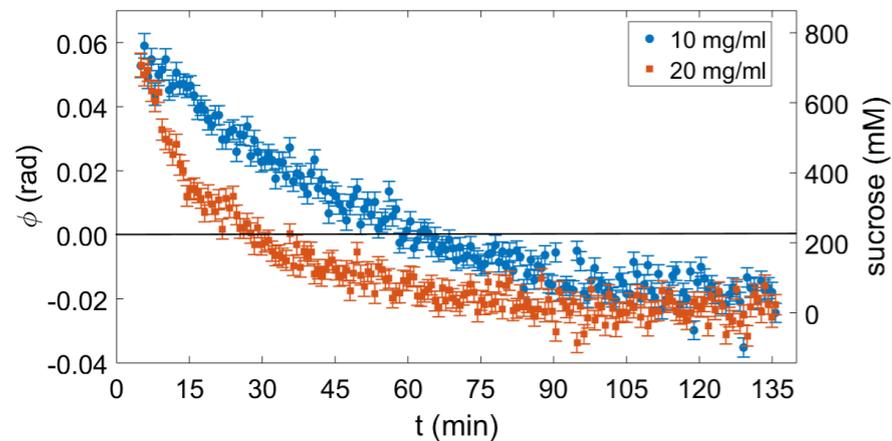
# Multiparameter Estimation

## application to *changes of optical activity*



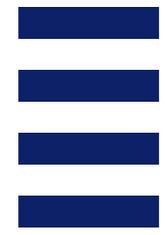
# Multiparameter Estimation

## application to *changes of optical activity*



**monitoring the exp conditions  
*during* the measurement**

**optimising the measurement  
conditions via adaptation**



# In Quest for Technology

## the ideal single-photon source



- On-demand source
- Single spatial mode
- Single temporal mode
- No two-photon component

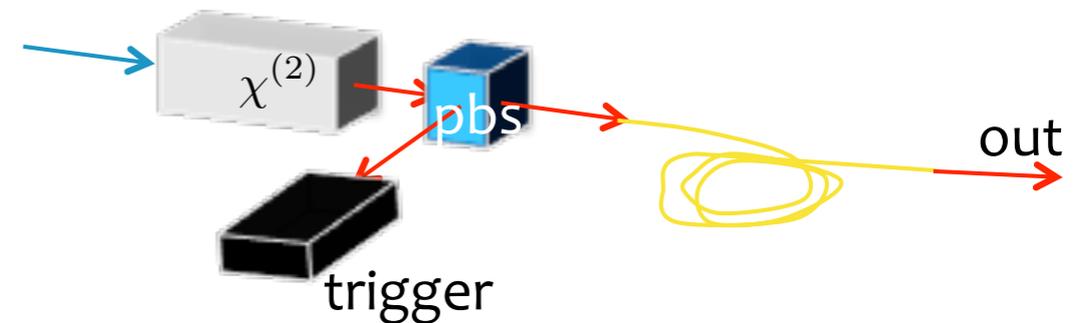
# In Quest for Technology

## the ideal single-photon source



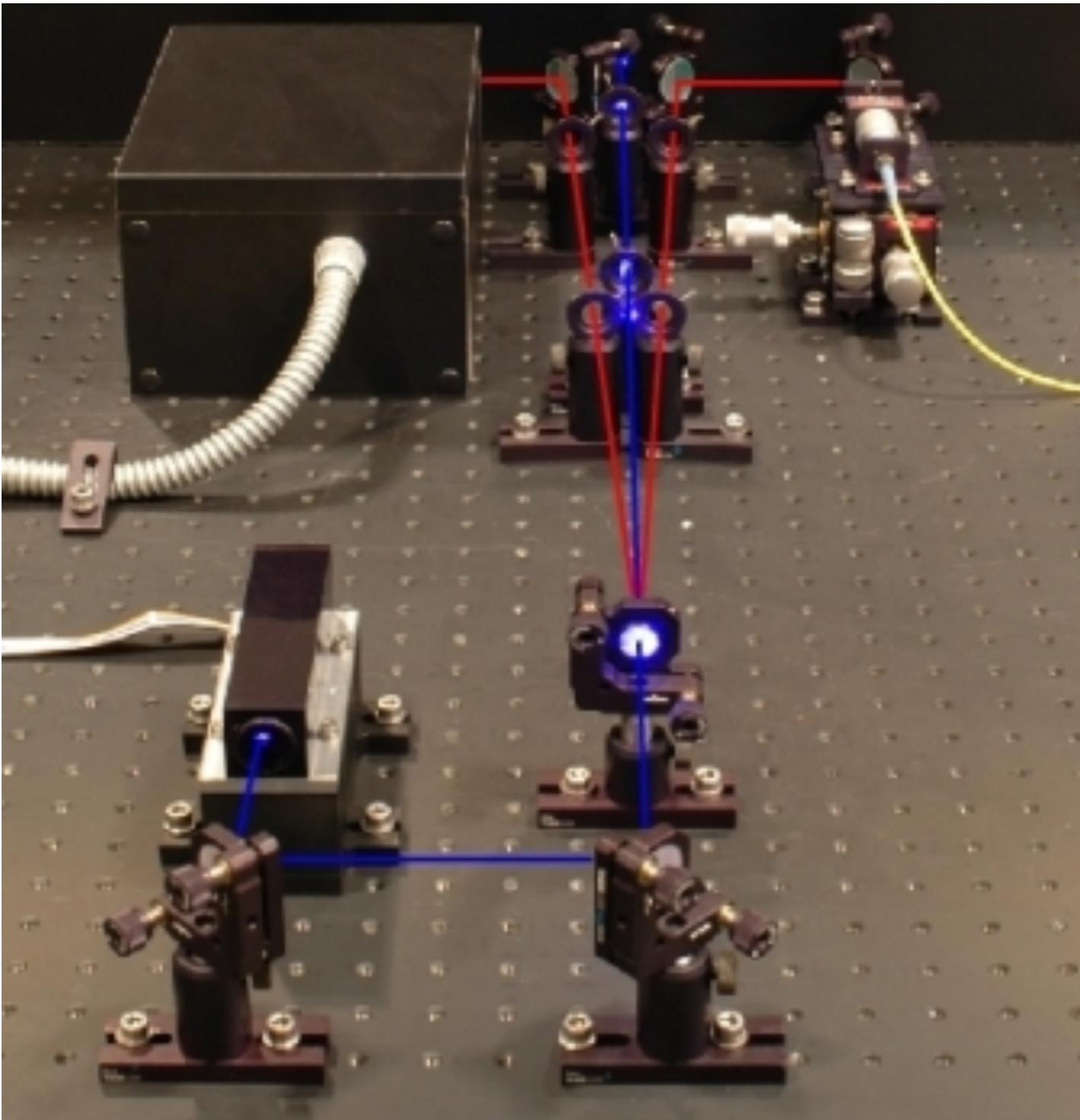
- On-demand source
- Single spatial mode
- Single temporal mode
- No two-photon component

## what we actually use

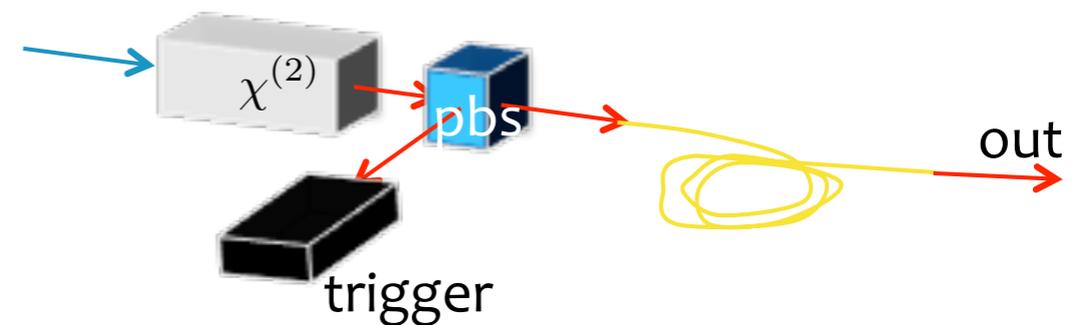


- Triggered source
- Single spatial mode
- Filtered temporal mode
- Trade-off between brightness and quality

# In Quest for Technology



what we actually use

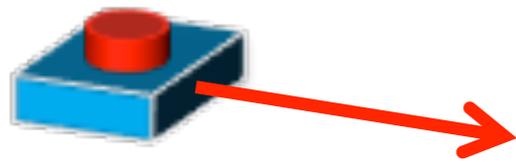


- Triggered source
- Single spatial mode
- Filtered temporal mode
- Trade-off between brightness and quality

P. Kwiat et al., PRL 75,  
4337 (1995)

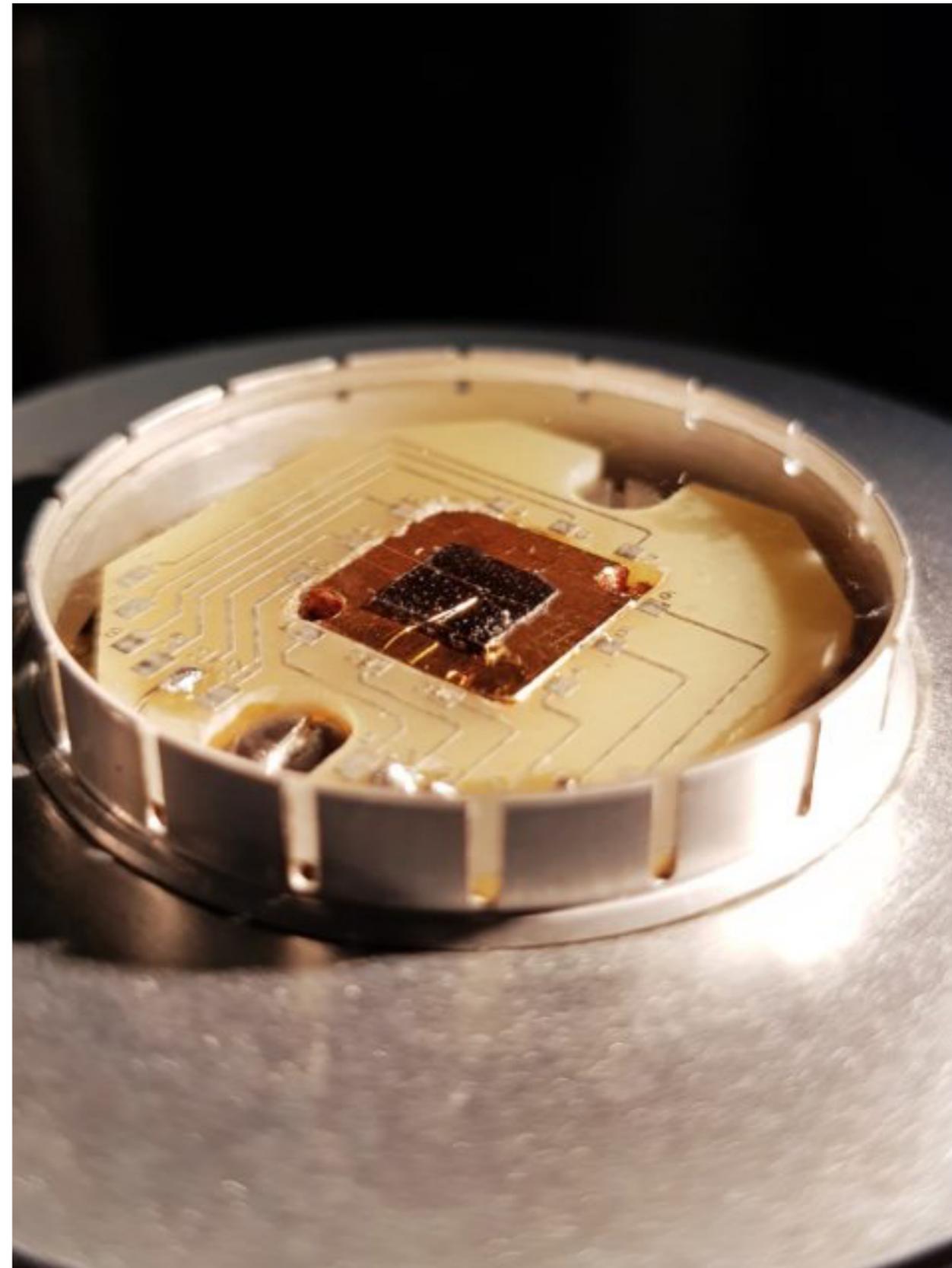
# In Quest for Technology

**the ideal single-photon source**

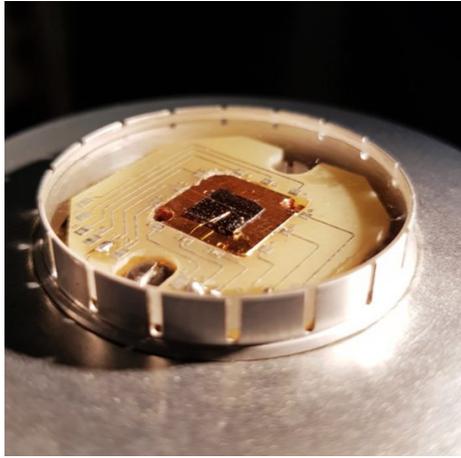


- On-demand source
- Single spatial mode
- Single temporal mode
- No two-photon component

**J. Loredó et al., PRL 118,  
135503 (2017)**

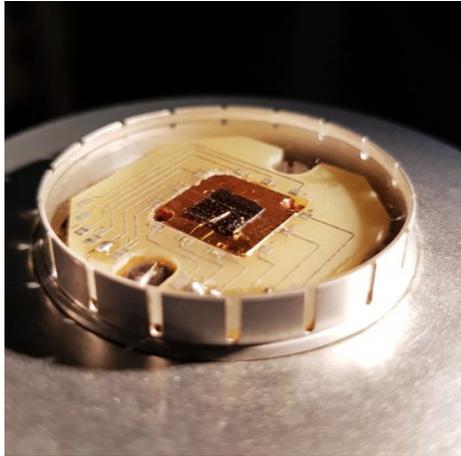


# In Quest for Technology

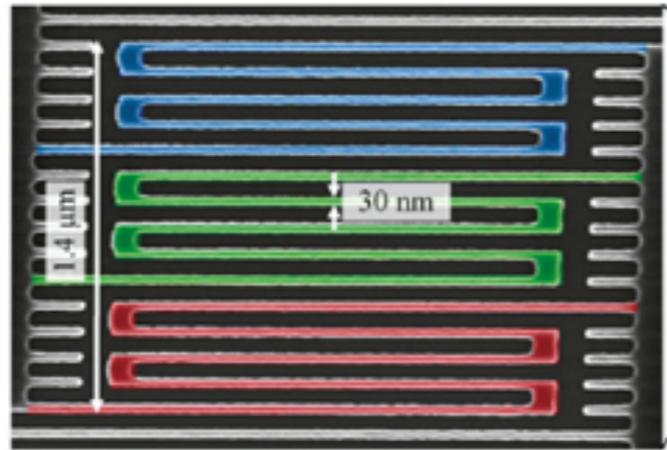


**nearly-ideal photon  
sources**

# In Quest for Technology

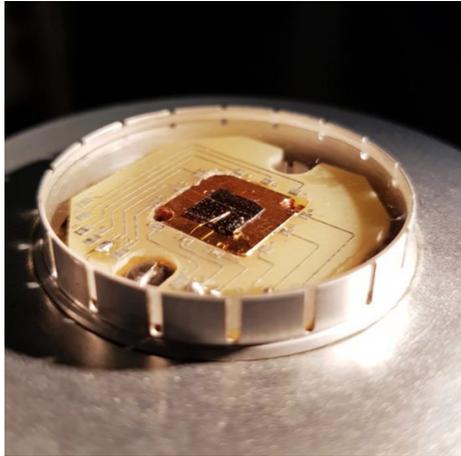


**nearly-ideal photon sources**

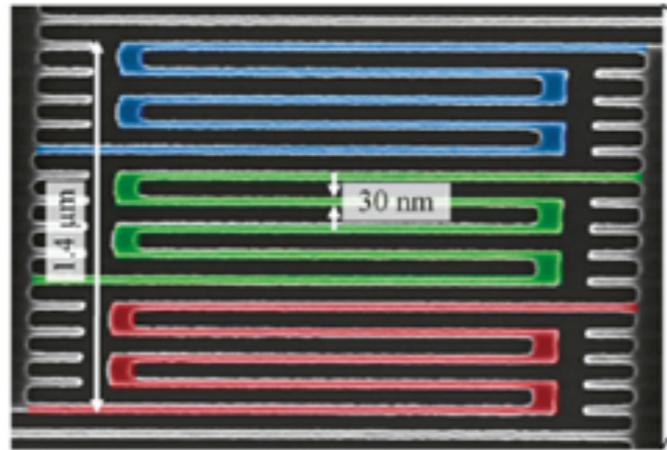


**high-efficiency detectors**

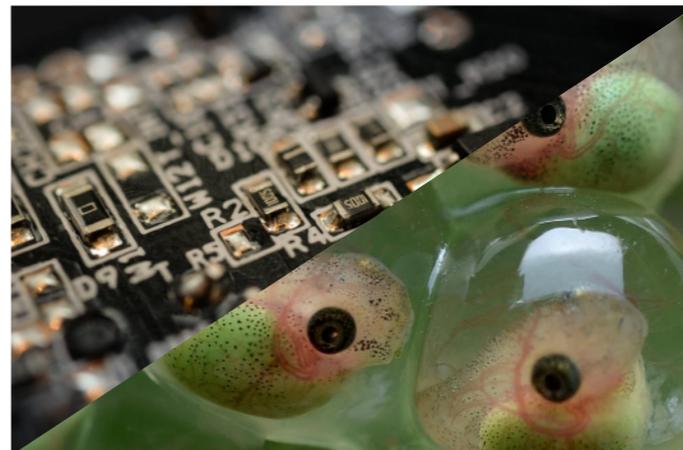
# In Quest for Technology



**nearly-ideal photon sources**



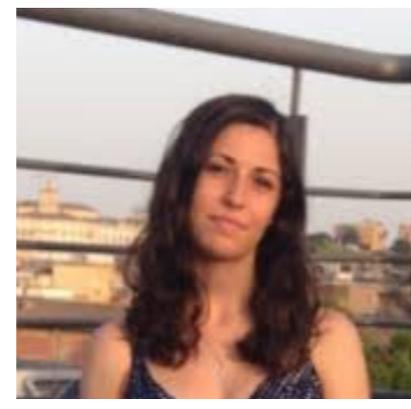
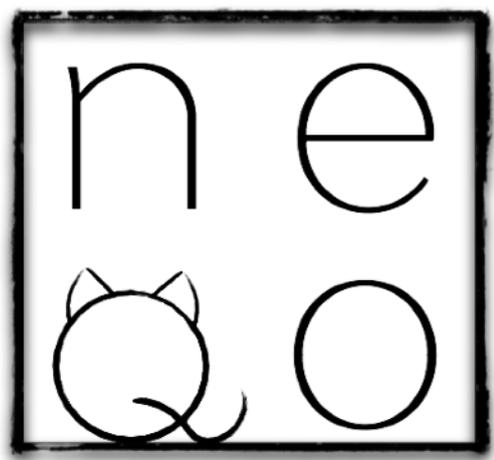
**high-efficiency detectors**



**new approaches**

# Personnel

## *Calibration of quantum sensors by neural networks*



**Valeria Cimini**



**Ilaria Gianani**



**mb**

**V. Cimini et al., arXiv:  
1904.10392 (2019)**

**ROMA  
TRE  
UNIVERSITÀ DEGLI STUDI**  
**Electrical  
Meas' Group**



**Fabio Leccese**



**Fabio Sciarrino**



**Nicolò Spagnolo**

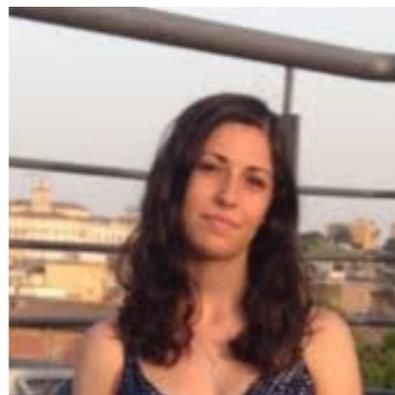
**Quantum Lab**

# Personnel

## *Multiparameter approach to quantum phase estimation with limited visibility*



**E. Roccia**



**V. Cimini**



**M. Sbroscia**



**M.A. Ricci**



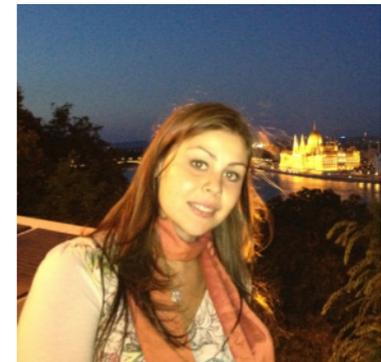
**I. Gianani**



**mb**



**L. Mancino**



**L. Ruggiero**



**M.G. Genoni**

**E. Roccia et al. Optica 5, 1171 (2018)**

# Personnel

## *Adaptive tracking of enzymatic reactions with quantum light*



V. Cimini



M. Sbroscia



M. Mellini



I. Gianani



mb



L. Leoni



G. Rampioni

V. Cimini et al. arXiv:  
1906.0578 (2019)



**Thanks for your Attention**