Title: Improving Quantum State Tomography with Mutually Unbiased Bases

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Abstract: Projections onto mutually unbiased bases (MUBs) have the ability to maximize information extraction per measurement and to minimize redundancy. I present an experimental demonstration of quantum state tomography of two-qubit polarization states that takes advantage of MUBs. Estimates of the state taken with this method have a measurably higher fidelity to the true state than estimates taken using standard measurement strategies. I explain how this advantage can be understood from the structure of the measurements we use.

Improving Quantum State Estimation with Mutually Unbiased Bases

ICQI 2008
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University of Toronto

nstitute for
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Motivation

- Imagine you are given a fixed number of copies of an unknown quantum state
  - What are the optimal set of projective measurements* to determine the density matrix?

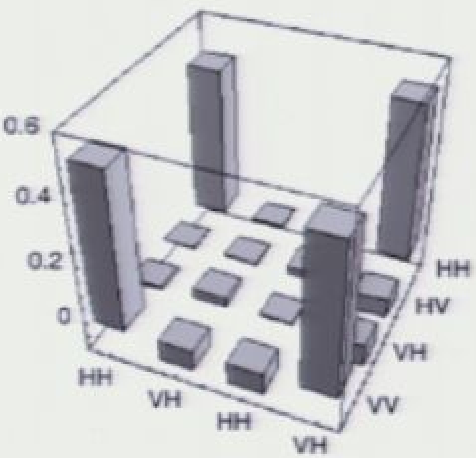
*For us experimentalists, measurements still mean PVMs.

A brief history of two-photon polarization quantum state tomography

PHYSICAL REVIEW A, VOLUME 64, 052312

Measurement of qubits

Daniel F. V. James,[1,*] Paul G. Kwiat,[2,3] William J. Munro,[4,5] and Andrew G. White[2,4]
[1]*Theoretical Division T-4, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[2]*Physics Division P-23, Los Alamos National Laboratory, Los Alamos, New Mexico 87545*
[3]*Department of Physics, University of Illinois, Urbana-Champaign, Illinois 61801*
[4]*Department of Physics, University of Queensland, Brisbane, Queensland 4072, Australia*
[5]*Hewlett-Packard Laboratories, Filton Road, Stoke Gifford, Bristol BS34 8QZ, United Kingdom*
(Received 20 March 2001; published 16 October 2001)



Includes 9 bases

ν	Mode 1	Mode 2	h_1	q_1	h_2	q_2
1	$\|H\rangle$	$\|H\rangle$	45°	0	45°	0
2	$\|H\rangle$	$\|V\rangle$	45°	0	0	0
3	$\|V\rangle$	$\|V\rangle$	0	0	0	0
4	$\|V\rangle$	$\|H\rangle$	0	0	45°	0
5	$\|R\rangle$	$\|H\rangle$	22.5°	0	45°	0
6	$\|R\rangle$	$\|V\rangle$	22.5°	0	0	0
7	$\|D\rangle$	$\|V\rangle$	22.5°	45°	0	0
8	$\|D\rangle$	$\|H\rangle$	22.5°	45°	45°	0
9	$\|D\rangle$	$\|R\rangle$	22.5°	45°	22.5°	0
10	$\|D\rangle$	$\|D\rangle$	22.5°	45°	22.5°	45°
11	$\|R\rangle$	$\|D\rangle$	22.5°	0	22.5°	45°
12	$\|H\rangle$	$\|D\rangle$	45°	0	22.5°	45°
13	$\|V\rangle$	$\|D\rangle$	0	0	22.5°	45°
14	$\|V\rangle$	$\|L\rangle$	0	0	22.5°	90°
15	$\|H\rangle$	$\|L\rangle$	45°	0	22.5°	90°
16	$\|R\rangle$	$\|L\rangle$	22.5°	0	22.5°	90°

- In the good old days, 16 projectors were all you needed
- You can completely characterize *any* state using only separable projectors

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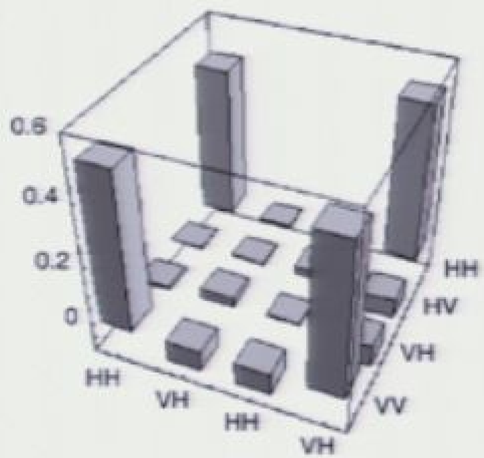

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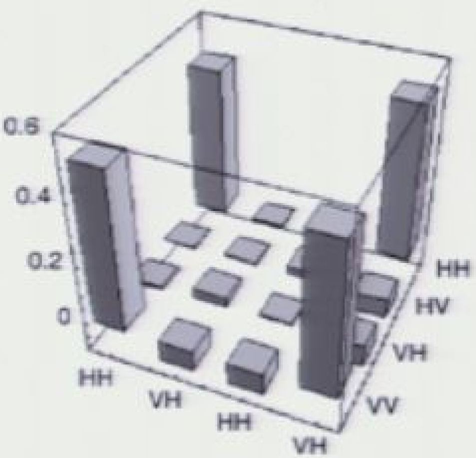

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Fixed: 36-outcome Tomography

- In order to reduce bias and obtain maximum information per photon, all outcomes should be collected

  HH, HV, VH, VV

  DH, DV, AH, AV

  RH, RV, LH, LV

  DH, DV, AH, AV

  DD, DA, AD, AA

  DR, DL, AR, AL

  RH, RV, LH, LV

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ltepeter et al. Phys. Rev. Lett. 95, 033601 (2005)

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Unbiased? No!

$|\langle HH|DH\rangle|^2=0.5$

But

$|\langle HH|DD\rangle|^2=0.25$

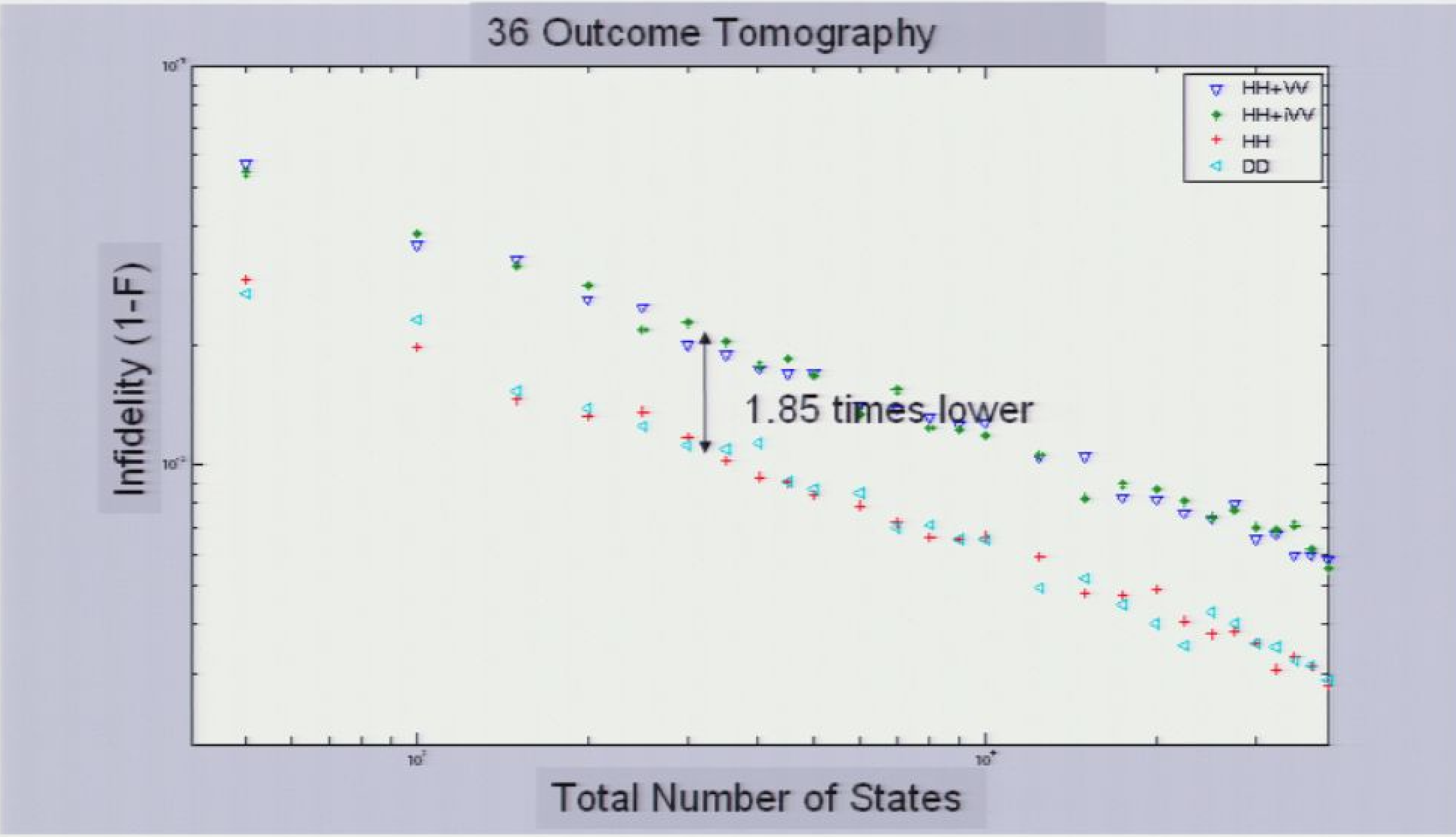
"mutual bias"

ltepeter et al. Phys. Rev. Lett. 95, 033601 (2005)

The Significance of Bias

- **Bias amounts to over-measurement of redundant information**
  - Bias wastes information by measuring what we already know
- **36-outcome tomography can only learn about correlations by doing single-photon measurements – this is wasteful**
  - Measuring |HD><HD| when you know |HH><HH| spends resources determining that the first photon is H
  - Better estimation of separable states than of entangled states

The Significance of Bias



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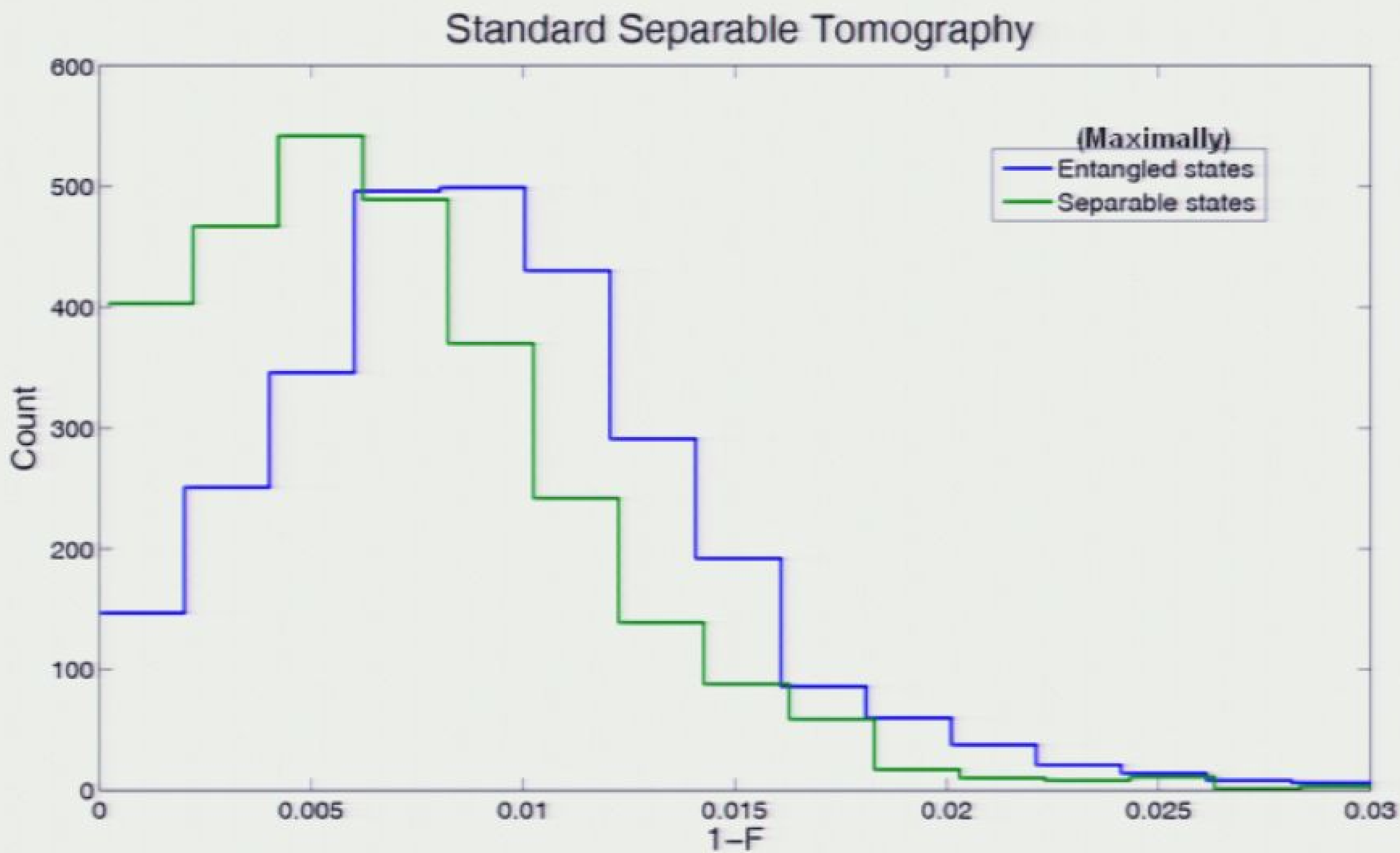


Enter Mutually Unbiased Bases (MUBs)

- Solution: Project onto measurements that all have an equal overlap with each other

$$Tr\left[P_{\alpha q} P_{\beta r}\right] = 1/N \quad \alpha \neq \beta$$

α, β label different measurement bases

q,r label different measurements operators within a basis

N is the dimension of the Hilbert space

ANNALS OF PHYSICS **191**, 363–381 (1989)

Optimal State–Determination by Mutually Unbiased Measurements

WILLIAM K. WOOTTERS AND BRIAN D. FIELDS

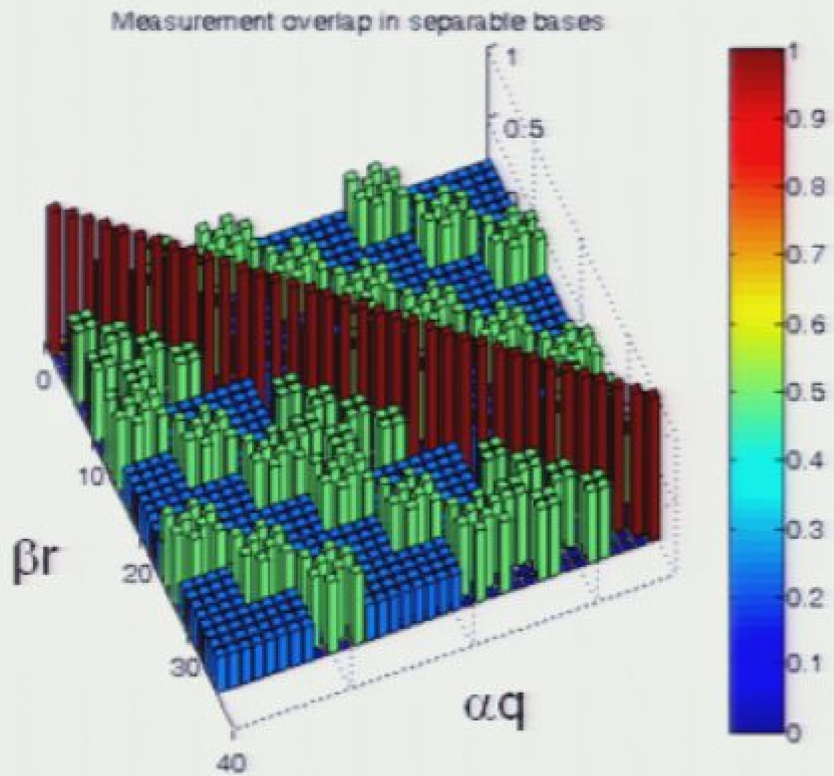
Department of Physics, Williams College, Williamstown, Massachusetts 01267

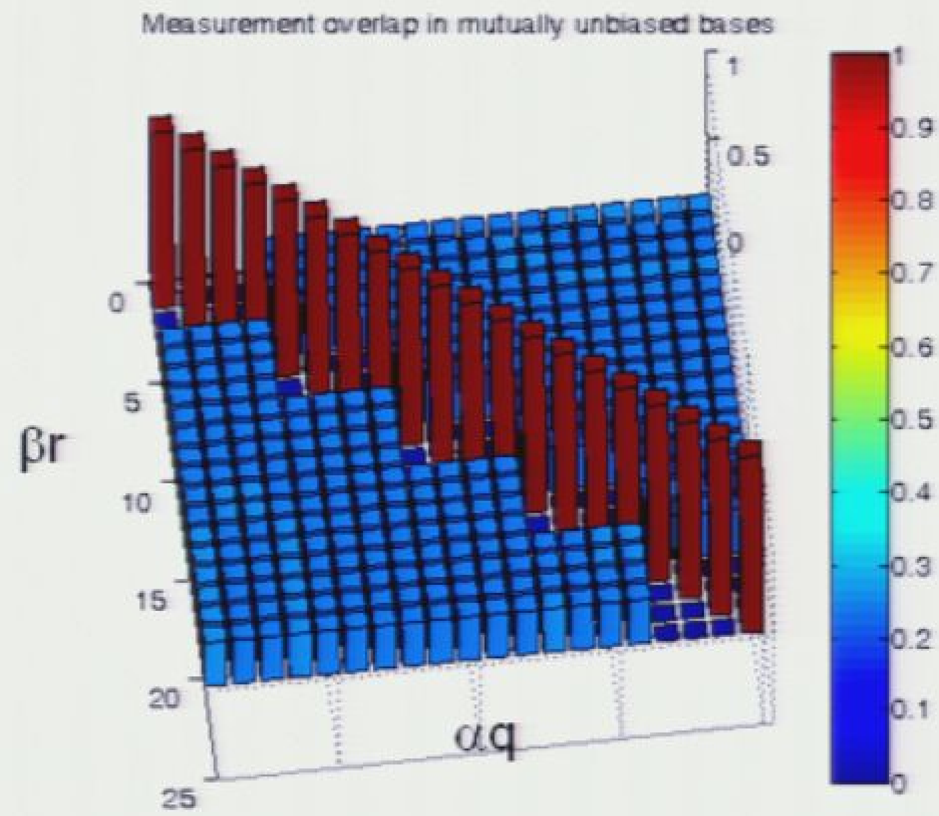
Received October 26, 1988

- Useful Properties:
  - **NO informational redundancy**
  - **After (n-1) bases are measured, no information is known about the n^{th} basis measurements**
  - **Maximum number of MUBs is N+1**

Comparison

$$Tr\left[P_{\alpha q}P_{\beta r}\right]=1/N$$





Two Qubit MUBs

		Basis	Simultaneous eigenstates of			
Separable	1	$(zz)_\pi$	σ_z^1	σ_z^2	$\sigma_z^1\sigma_z^2$	HH, HV, VH, VV
Separable	2	$(xy)_\pi$	σ_x^1	σ_y^2	$\sigma_x^1\sigma_y^2$	DR, DL, AR, AL
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Maximally Entangled	4	$(zx)_B$	$\sigma_y^1\sigma_y^2$	$\sigma_z^1\sigma_x^2$	$\sigma_x^1\sigma_z^2$	RL+iLR, RL-iLR, RR+iLL, RR-iLL
Maximally Entangled	5	$(yz)_{Bi}$	$\sigma_x^1\sigma_x^2$	$\sigma_y^1\sigma_z^2$	$\sigma_z^1\sigma_y^2$	RV+iLH, RV-iLH, RH+iLV, RH-iLV

MUBs exist whenever the dimension is the power of a prime

ay Lawrence, Caslav Brukner, Anton Zeilinger PRA 65, 032320 (2002)
. L. Romero, G. Björk, A. B. Klimov, and L. L. Sánchez-Soto, Phys. Rev. A **72**, 062310 (2005)

Measuring in MUBs

- Experimental apparatus

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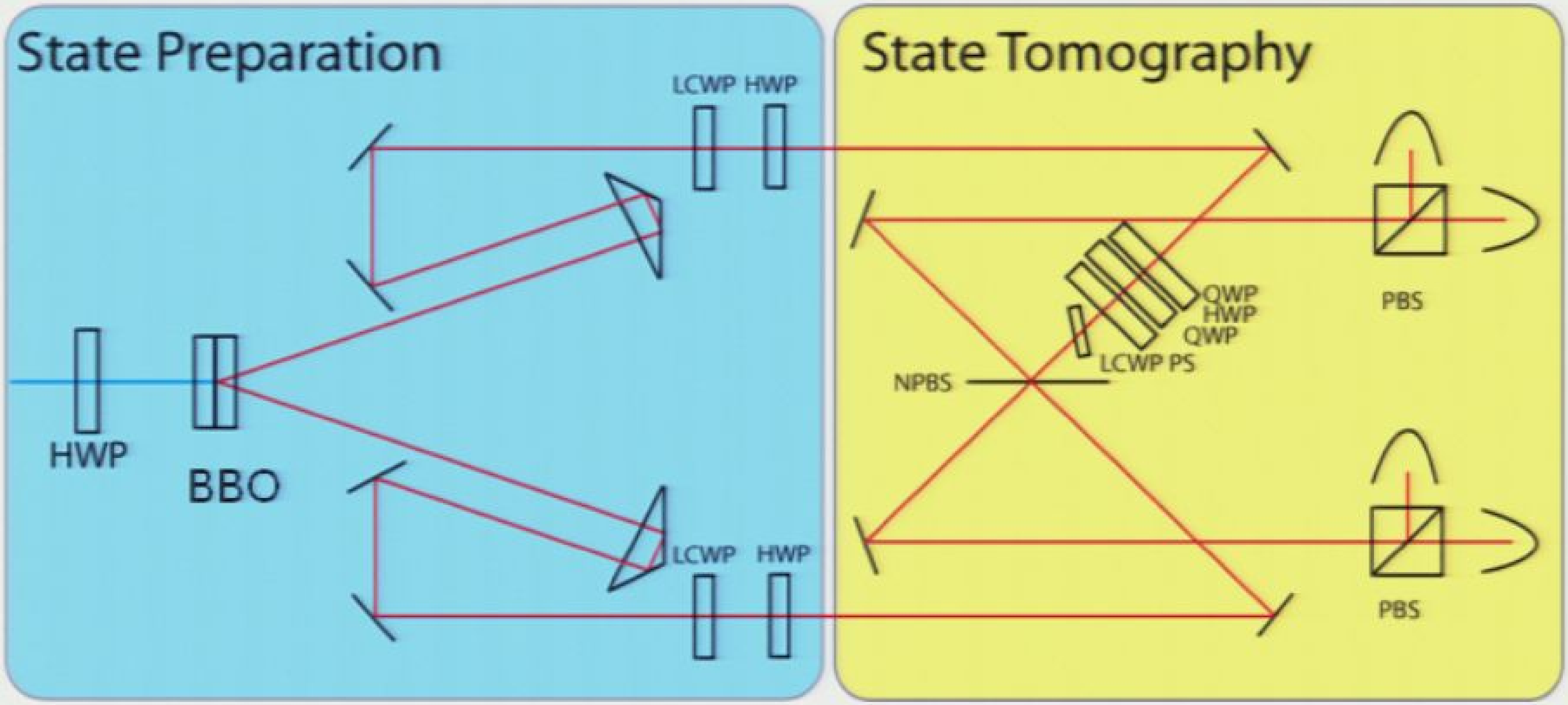

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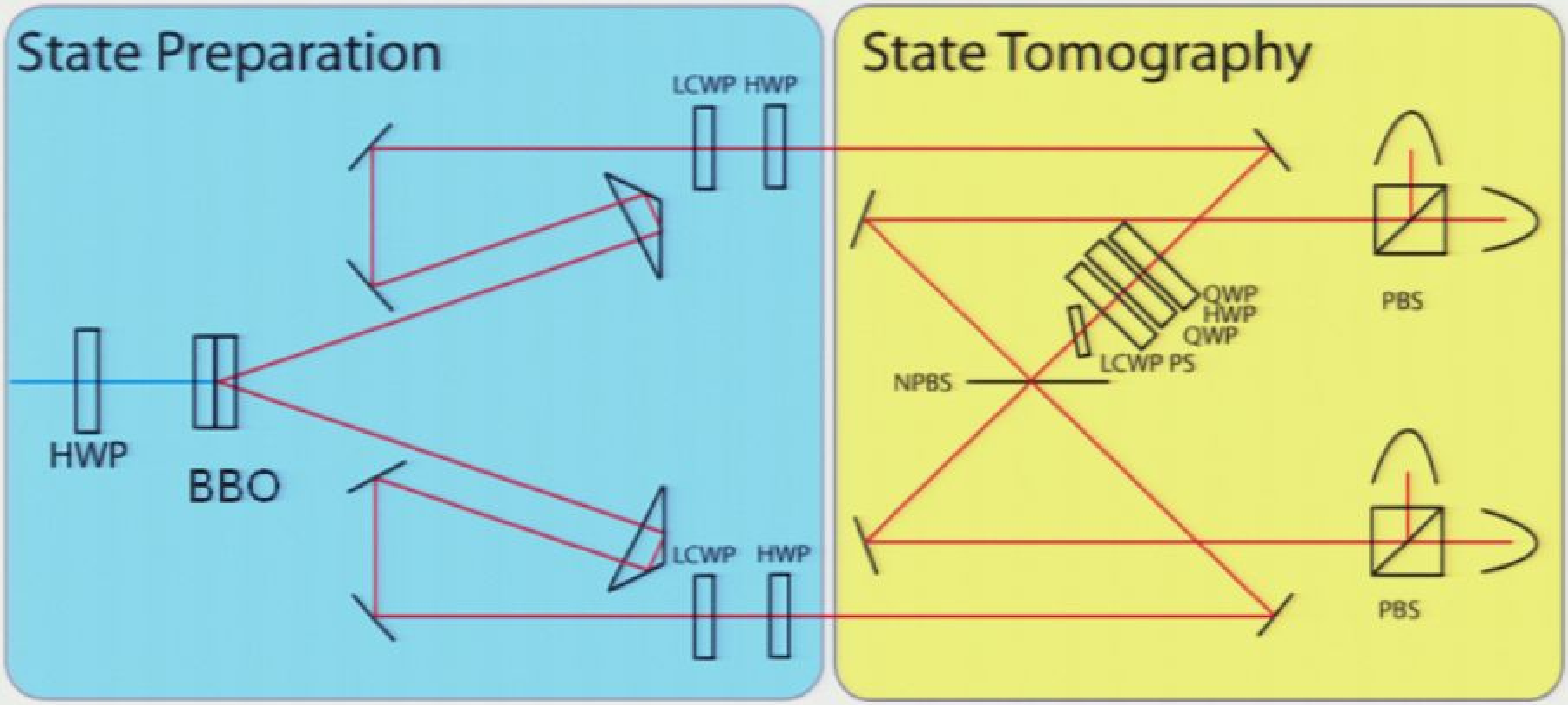

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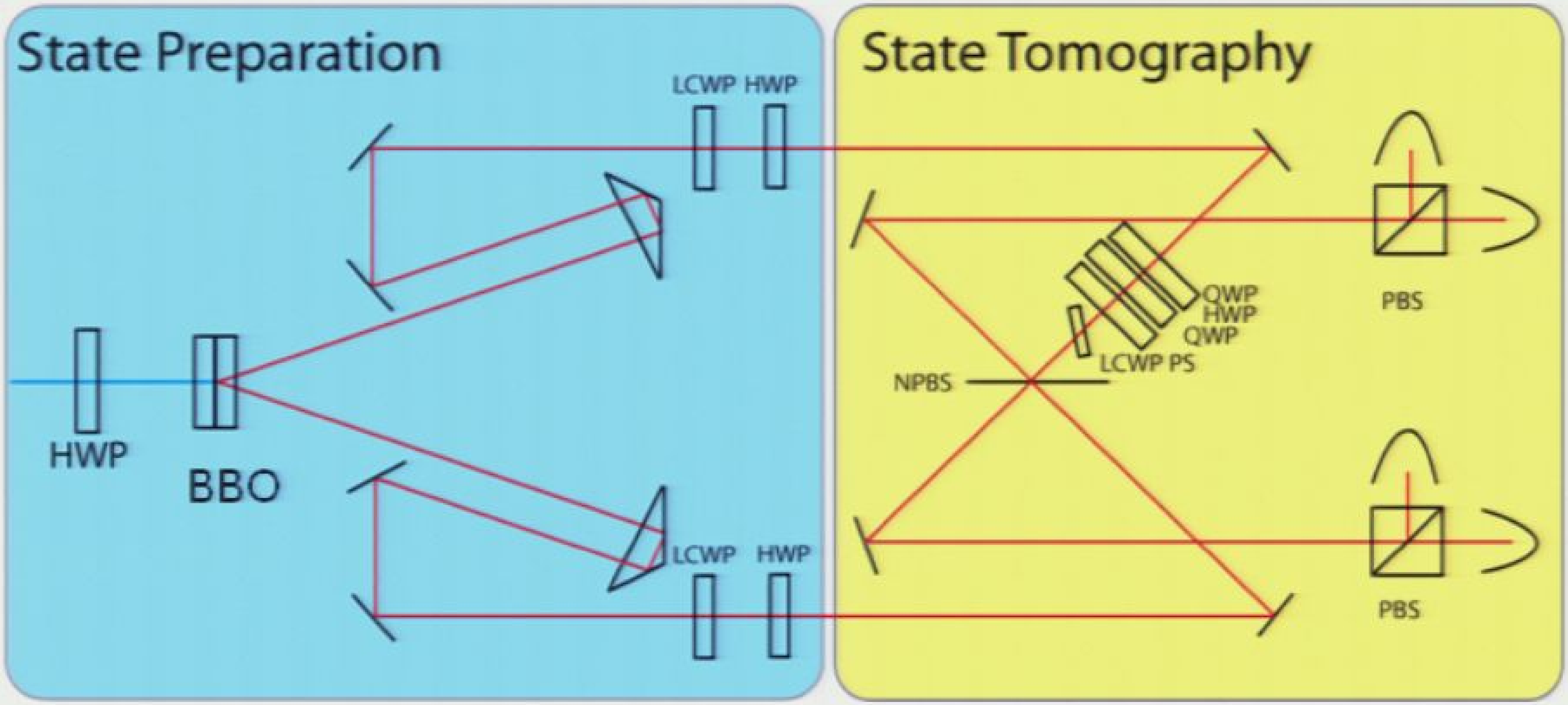

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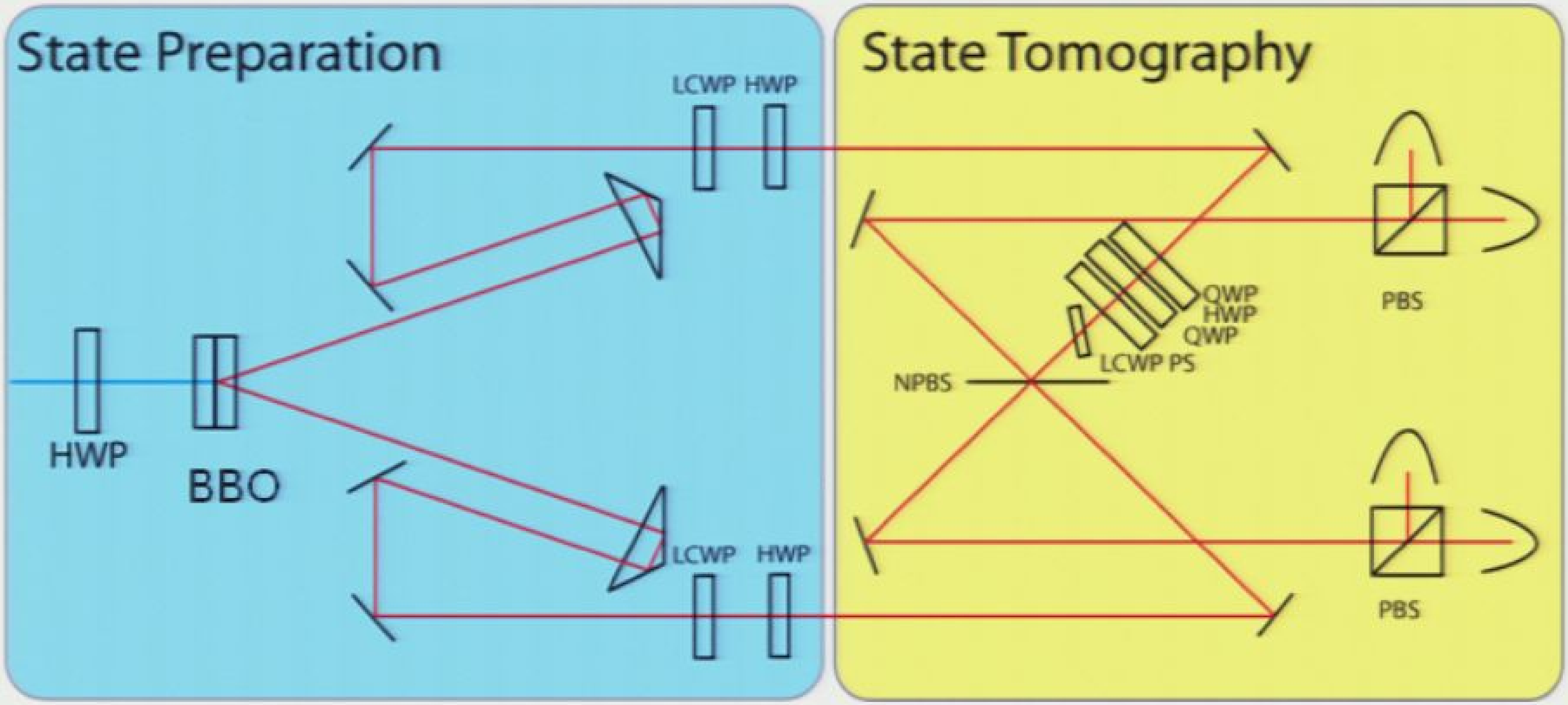

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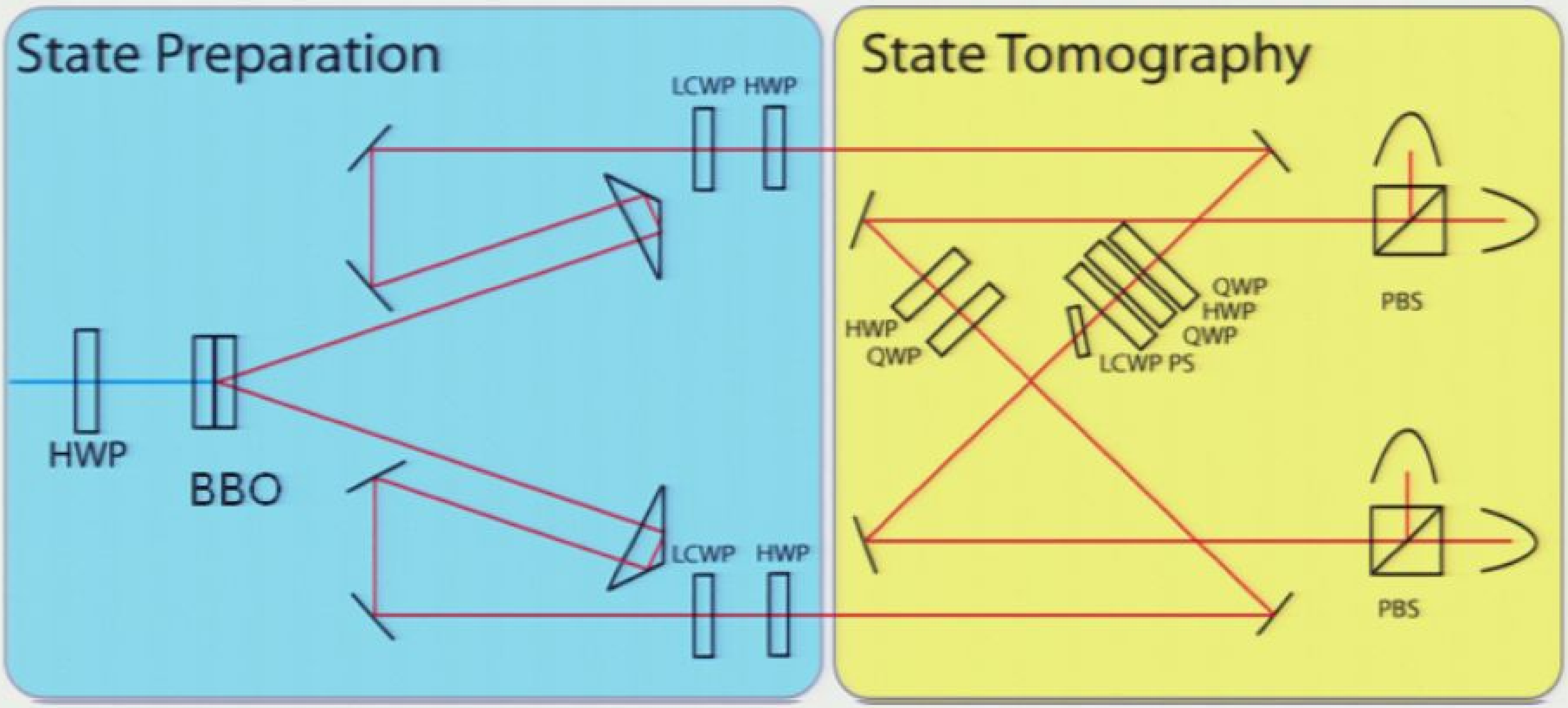

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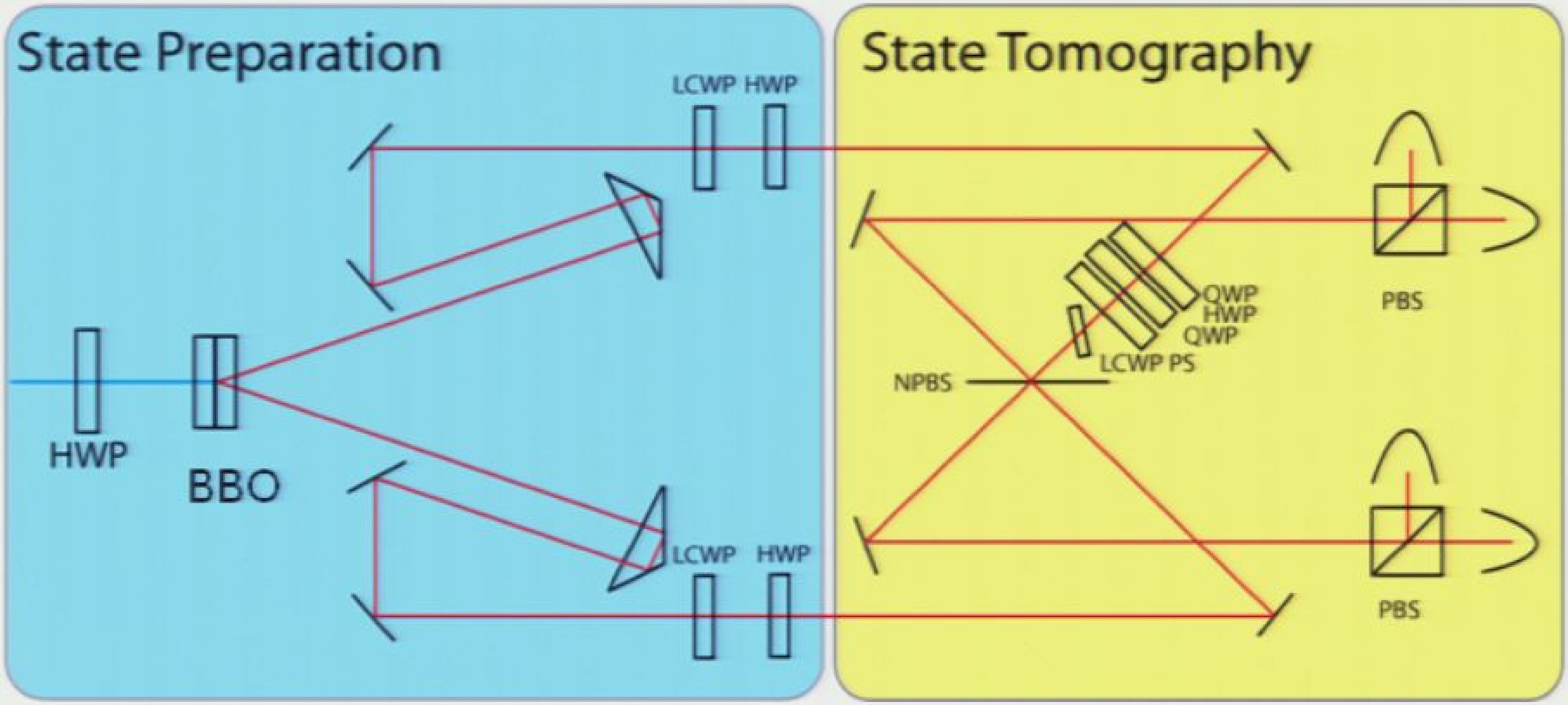

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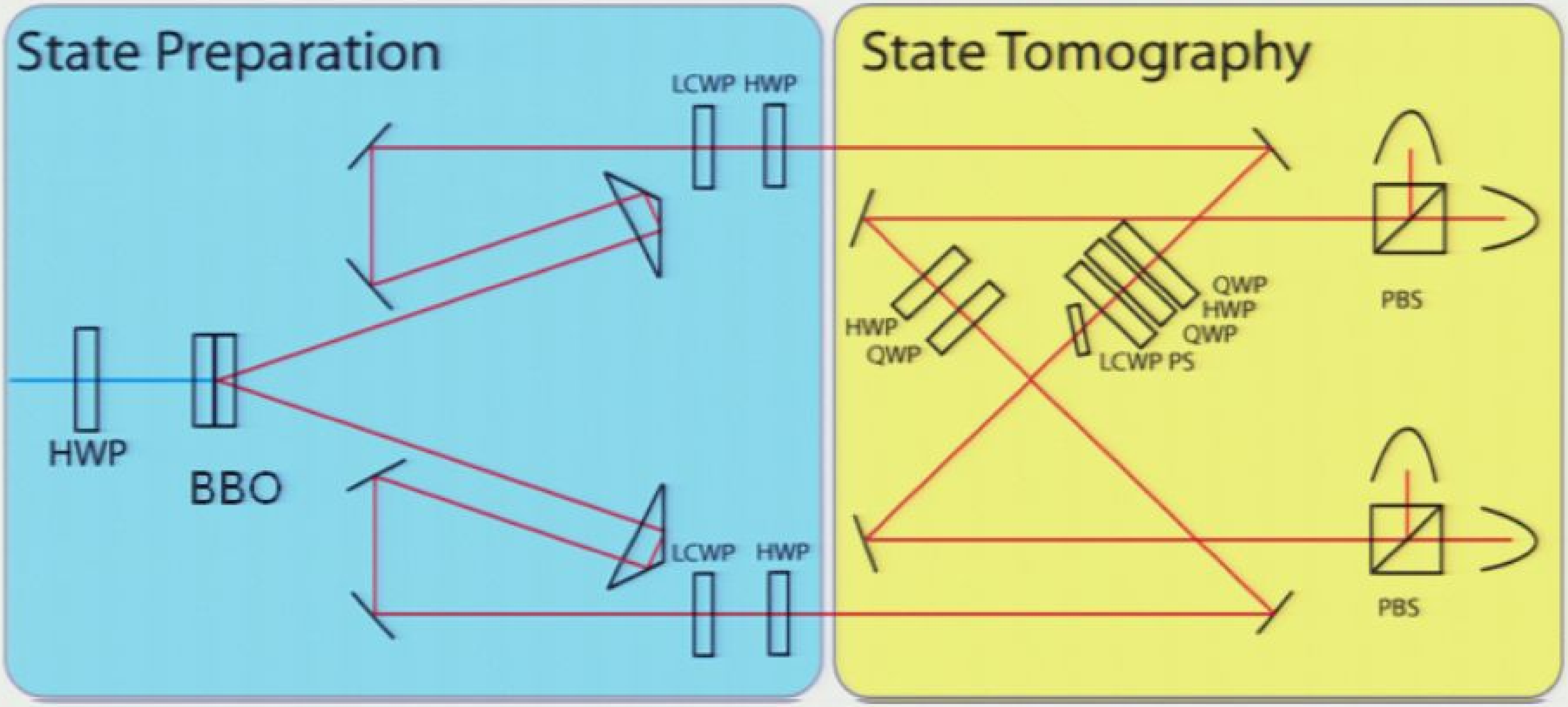
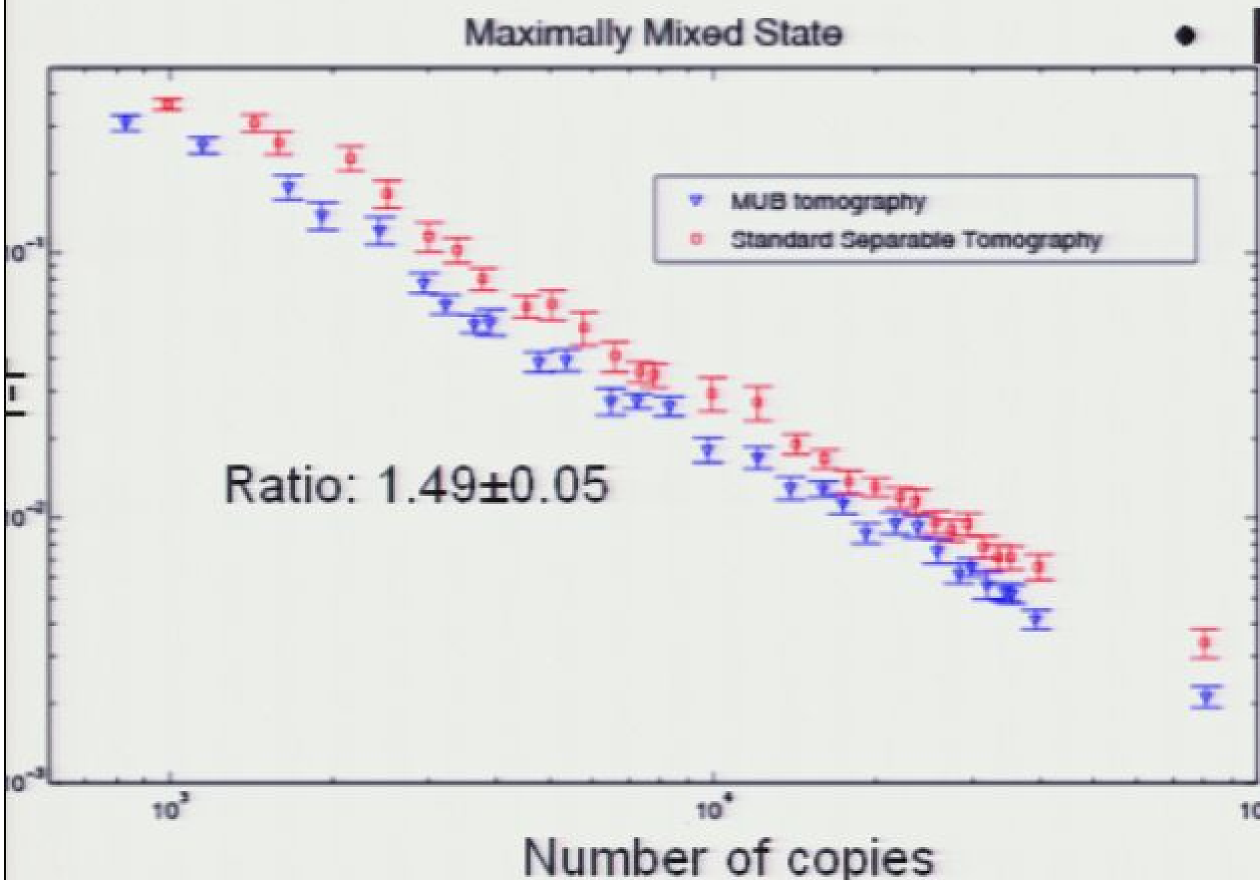


Simulations show that the limited visibility of 93% does not significantly limit the advantage of MUBs tomography

Linear optics can't do deterministic Bell State Measurements – limits the practicality of the scheme

Results: Mixed State



- Methodology:
  - Do 3000 separate tomographies with ~10 pairs per basis
  - Combine those into longer experimental runs with bigger populations
  - Infidelity=1-Fidelity

$$F(\rho,\sigma)=\left(\mathrm{tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)^2$$

Smaller number of bases means better statistics for each one.

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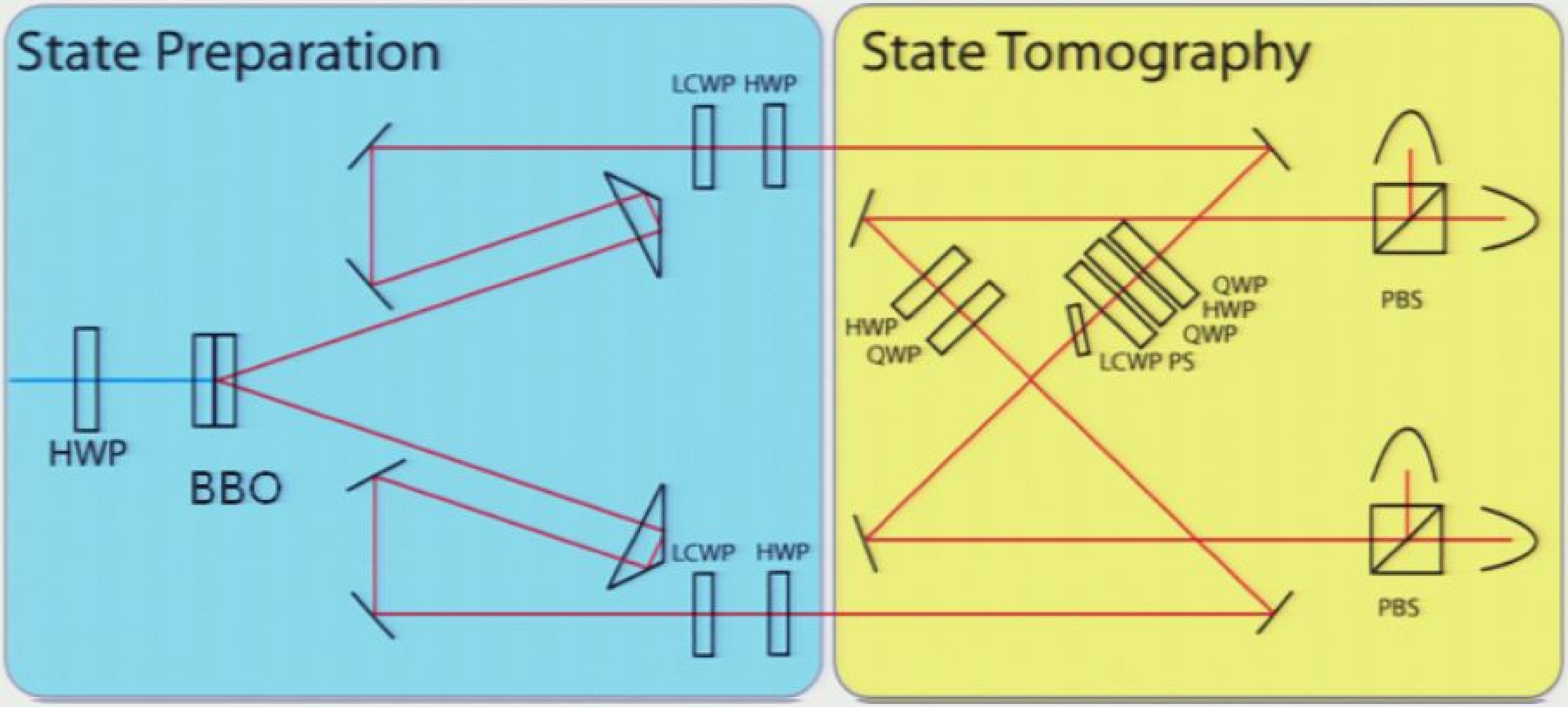

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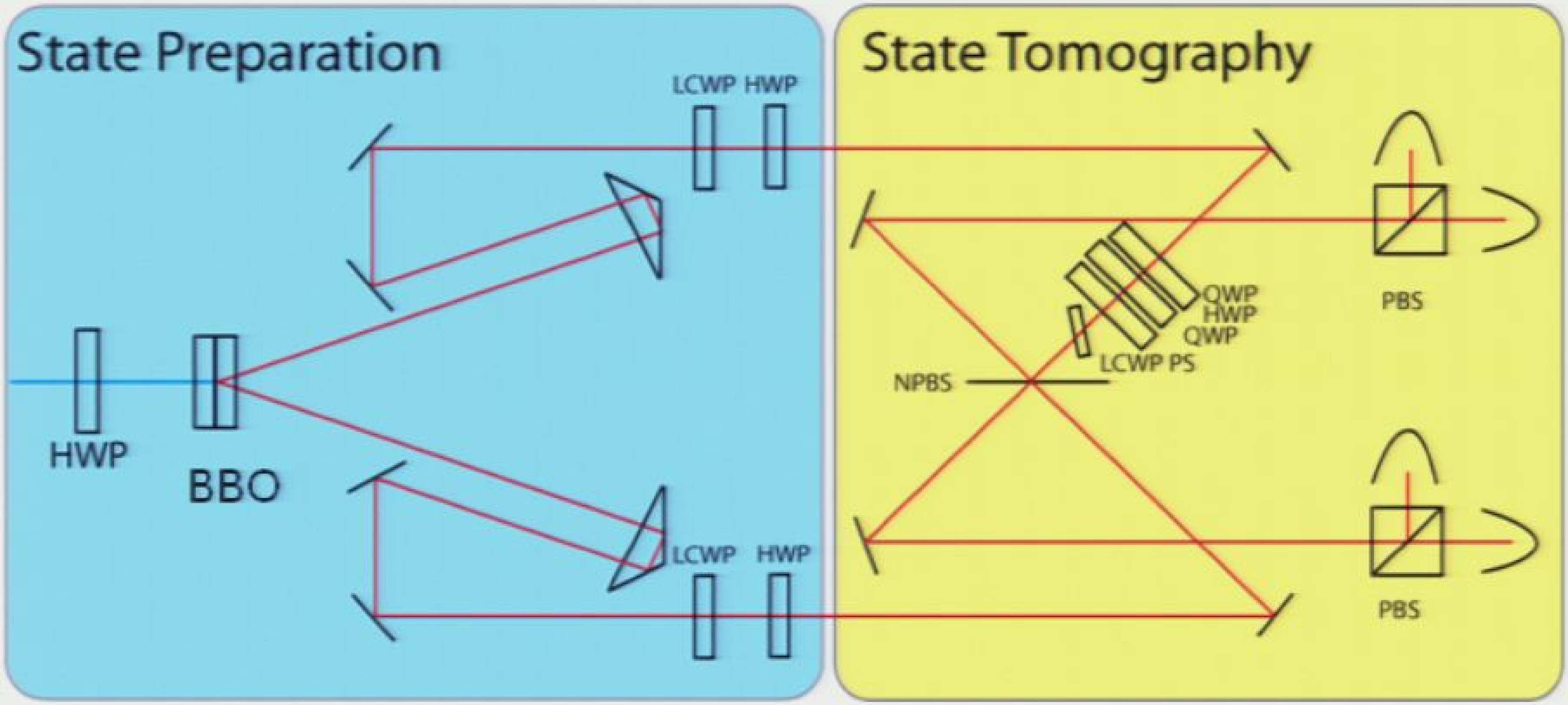

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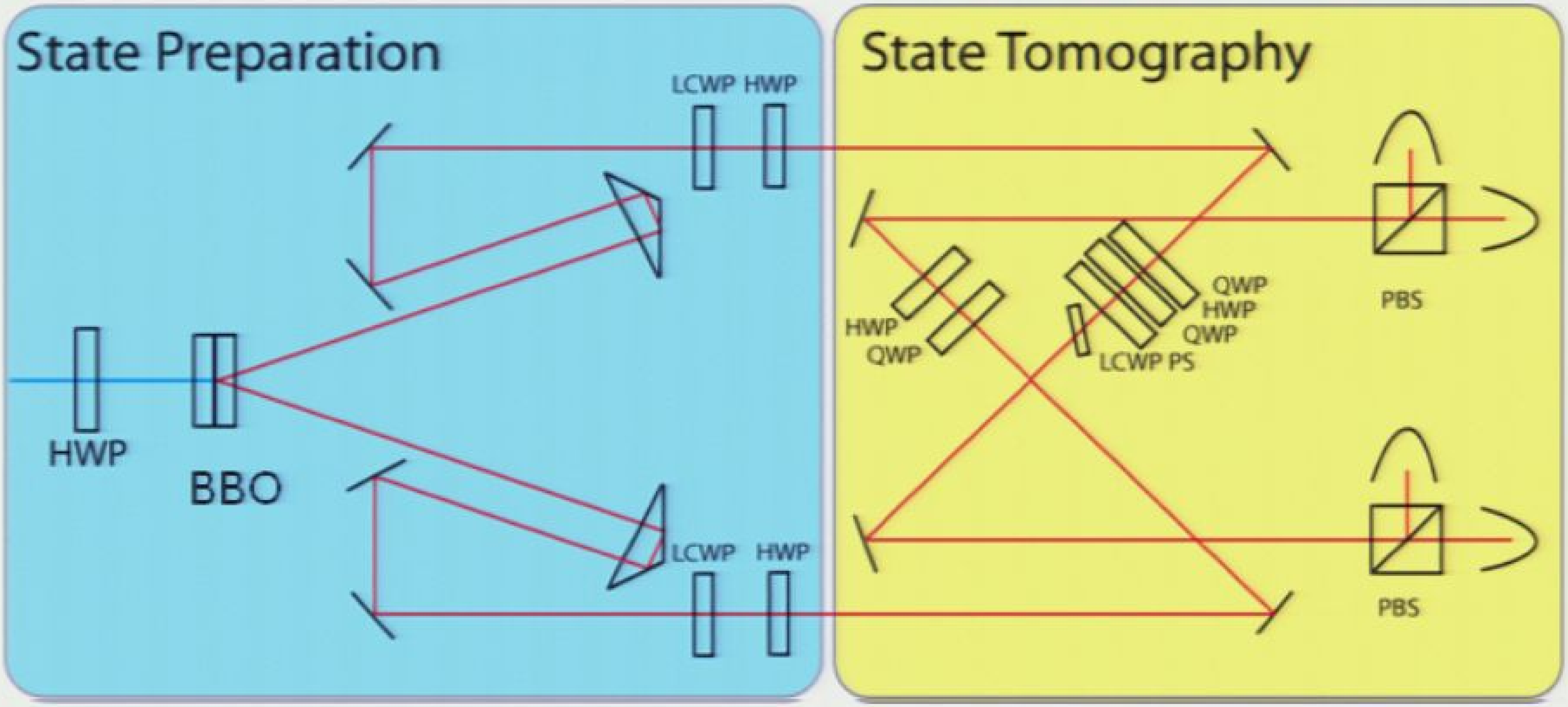

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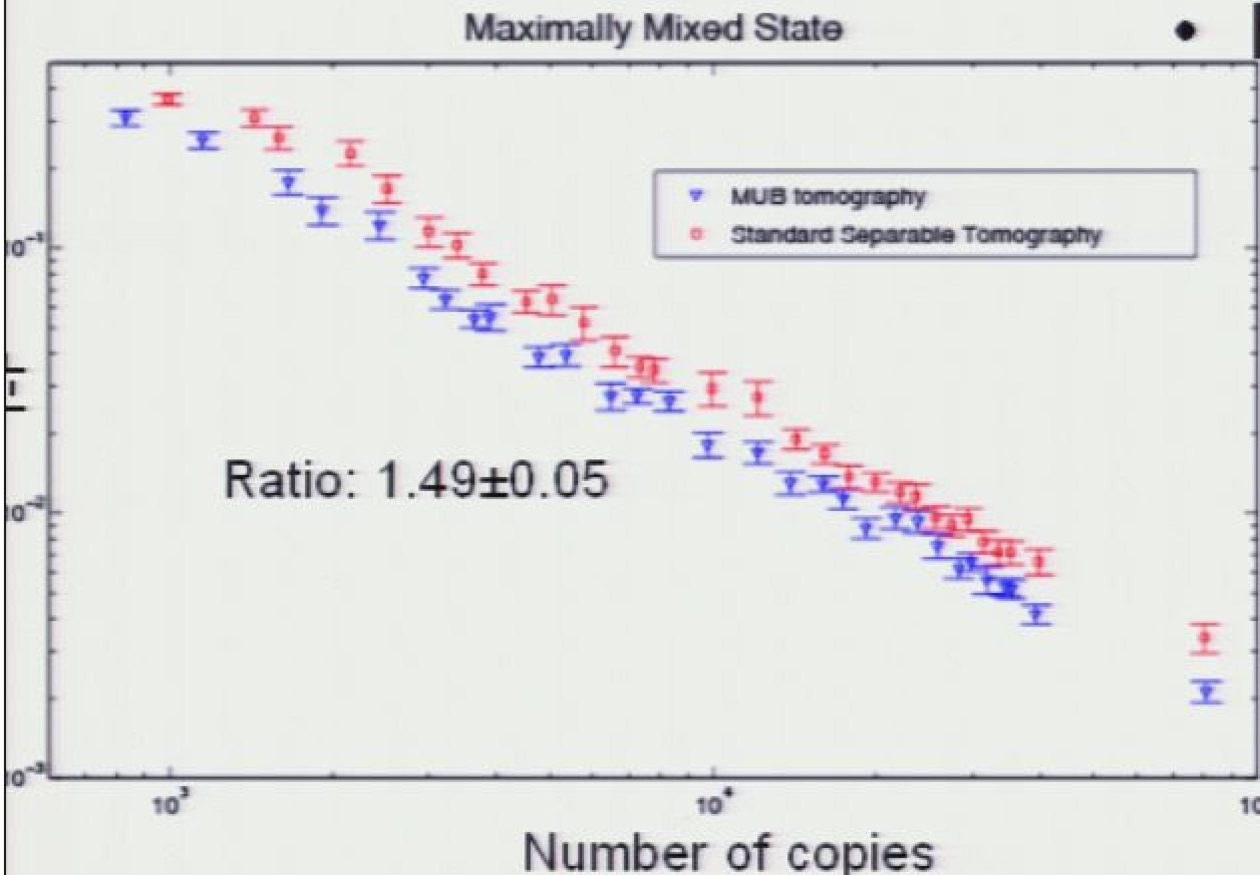

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Analysis

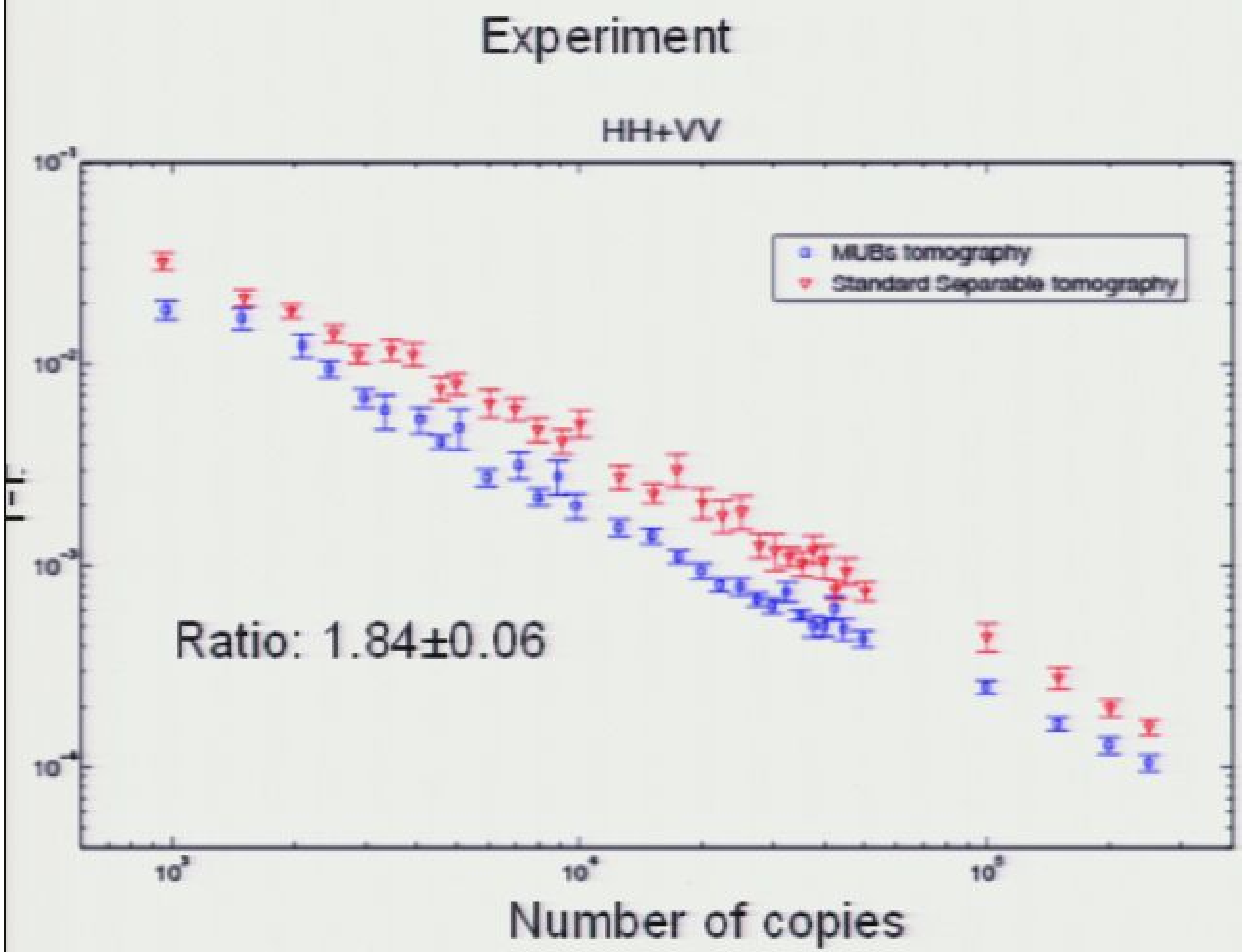
If $$\vec{P} = \mathbf{M}\vec{\rho}$$

Number of bases

Complicated expression involving mutual overlap

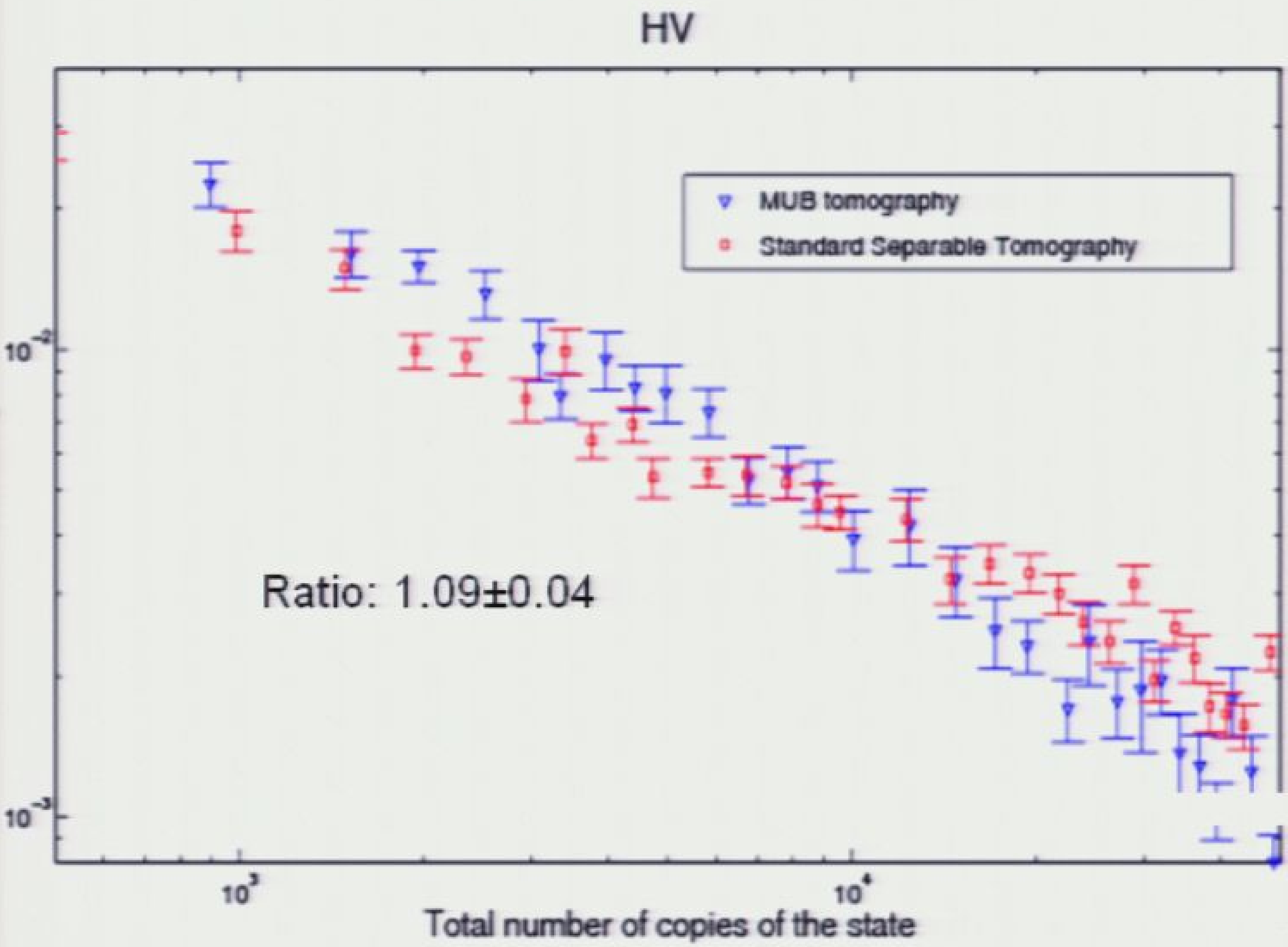
$$\frac{I_{\mathrm{SSQST}}}{I_{\mathrm{MUBs}}} = \frac{B_{\mathrm{SSQST}}}{B_{\mathrm{MUBs}}} \frac{\sum_{i=1}^{4} \sum_{kq} \left| \left(\left(\mathbf{M}_{\mathrm{SSQST}}{}^{\dagger} \mathbf{M}_{\mathrm{SSQST}} \right)^{-1} \mathbf{M}_{\mathrm{SSQST}}^{\dagger} \right)_{ii,kq} \right|^{2}}{\sum_{i=1}^{4} \sum_{kq} \left| \left(\left(\mathbf{M}_{\mathrm{MUBs}}{}^{\dagger} \mathbf{M}_{\mathrm{MUBs}} \right)^{-1} \mathbf{M}_{\mathrm{MUBs}} \right)_{ii,kq} \right|^{2}}$$

Results: Entangled States



- MUBs generally give better estimates for entangled states than separable measurements

State Dependence: Separable States



- MUBs do no worse than 36-outcome tomography at estimating separable states

Summary

- MUBs are known to be the best choice when averaged over all states
- We show experimentally that they are better for particular mixed states and entangled states and about the same for a particular separable state
- MUBs offer a real advantage in two (and more) qubit tomography

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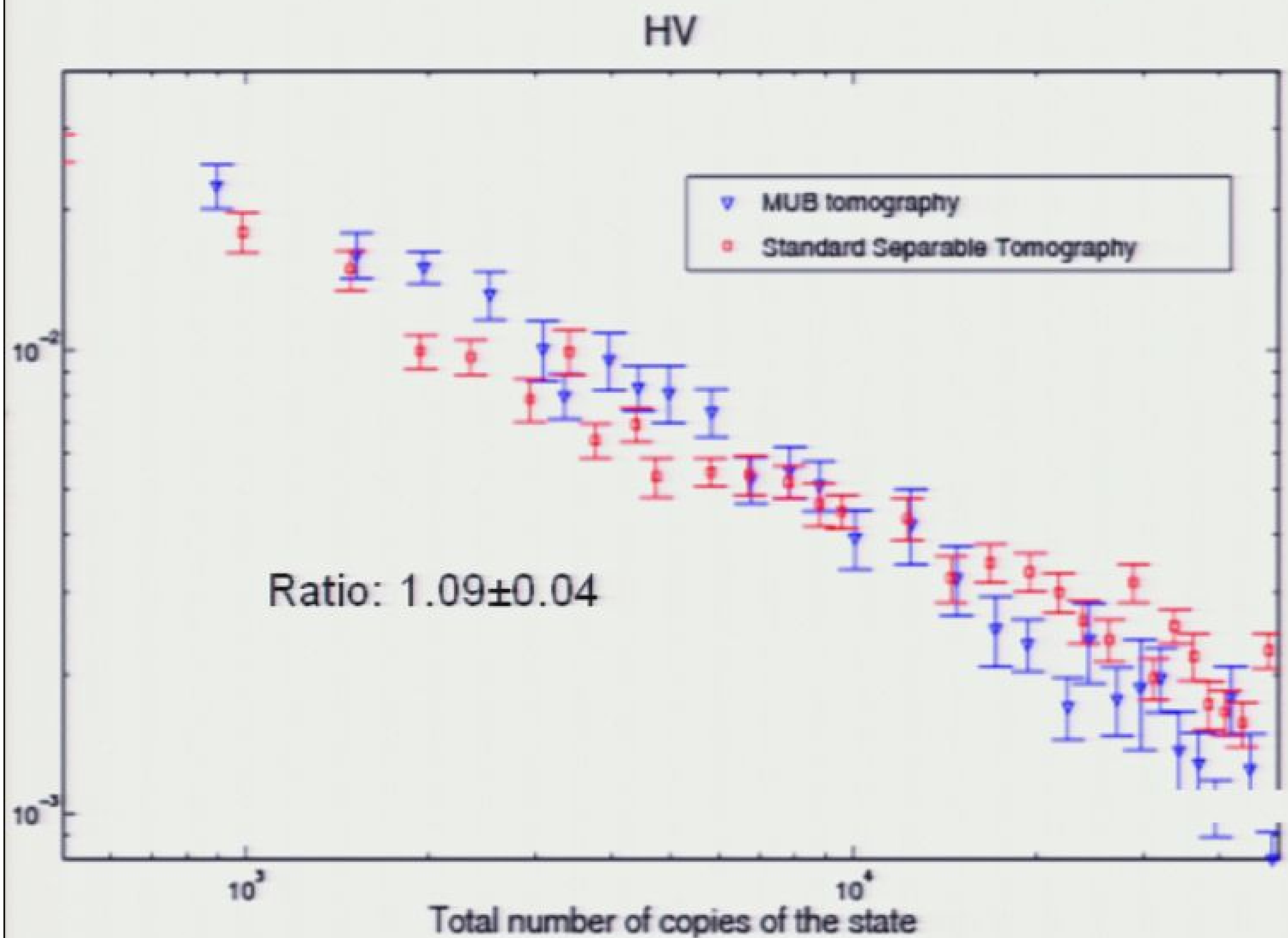

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- The Wigner function is real (but possibly negative),
- Integration yields marginal probability distributions
- Phase space must be discrete

Finite fields

- Define a field F_4 with the following addition and multiplication tables

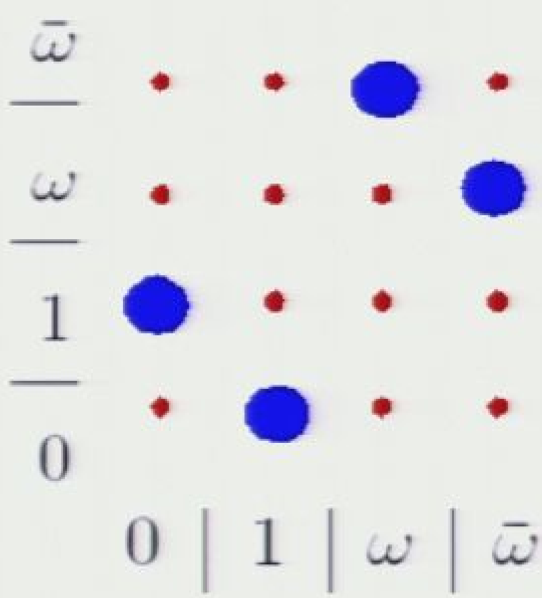
$+$	0	1	ω	$\bar{\omega}$
0	0	1	ω	$\bar{\omega}$
1	1	0	$\bar{\omega}$	ω
ω	ω	$\bar{\omega}$	0	1
$\bar{\omega}$	$\bar{\omega}$	ω	1	0

$\times$	0	1	ω	$\bar{\omega}$
0	0	0	0	0
1	0	1	ω	$\bar{\omega}$
ω	0	ω	$\bar{\omega}$	1
$\bar{\omega}$	0	$\bar{\omega}$	1	ω

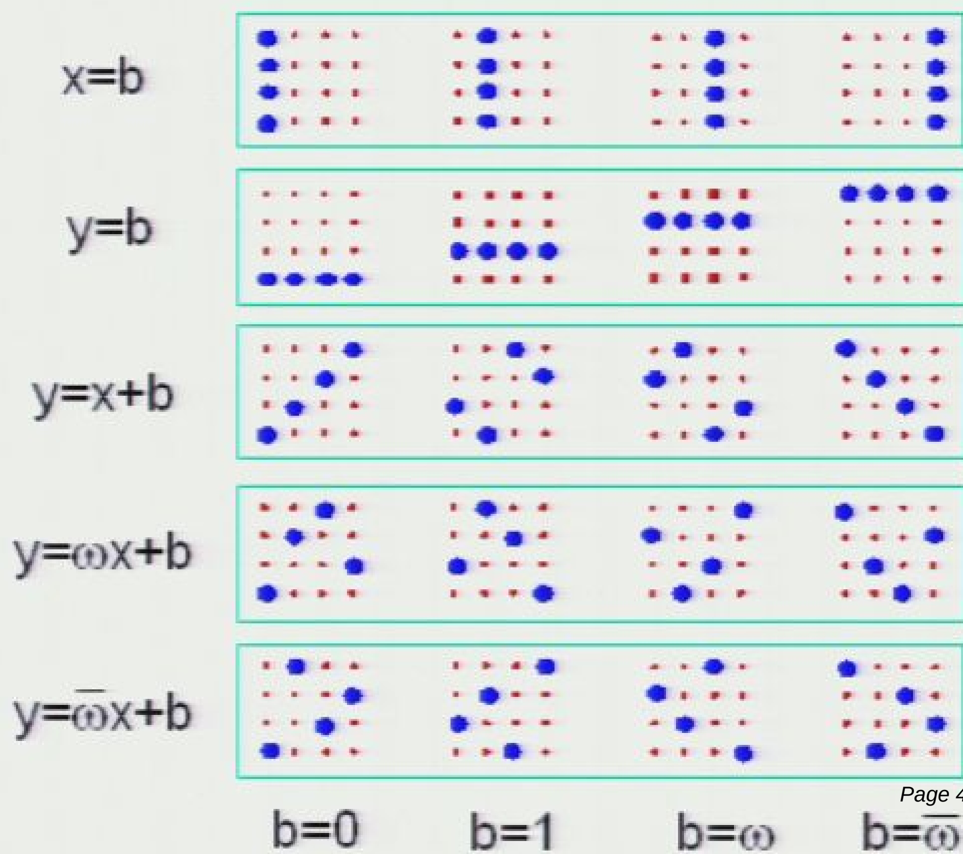
Lines in discrete phase space

- Lines/striations for 2-qubits in F_4

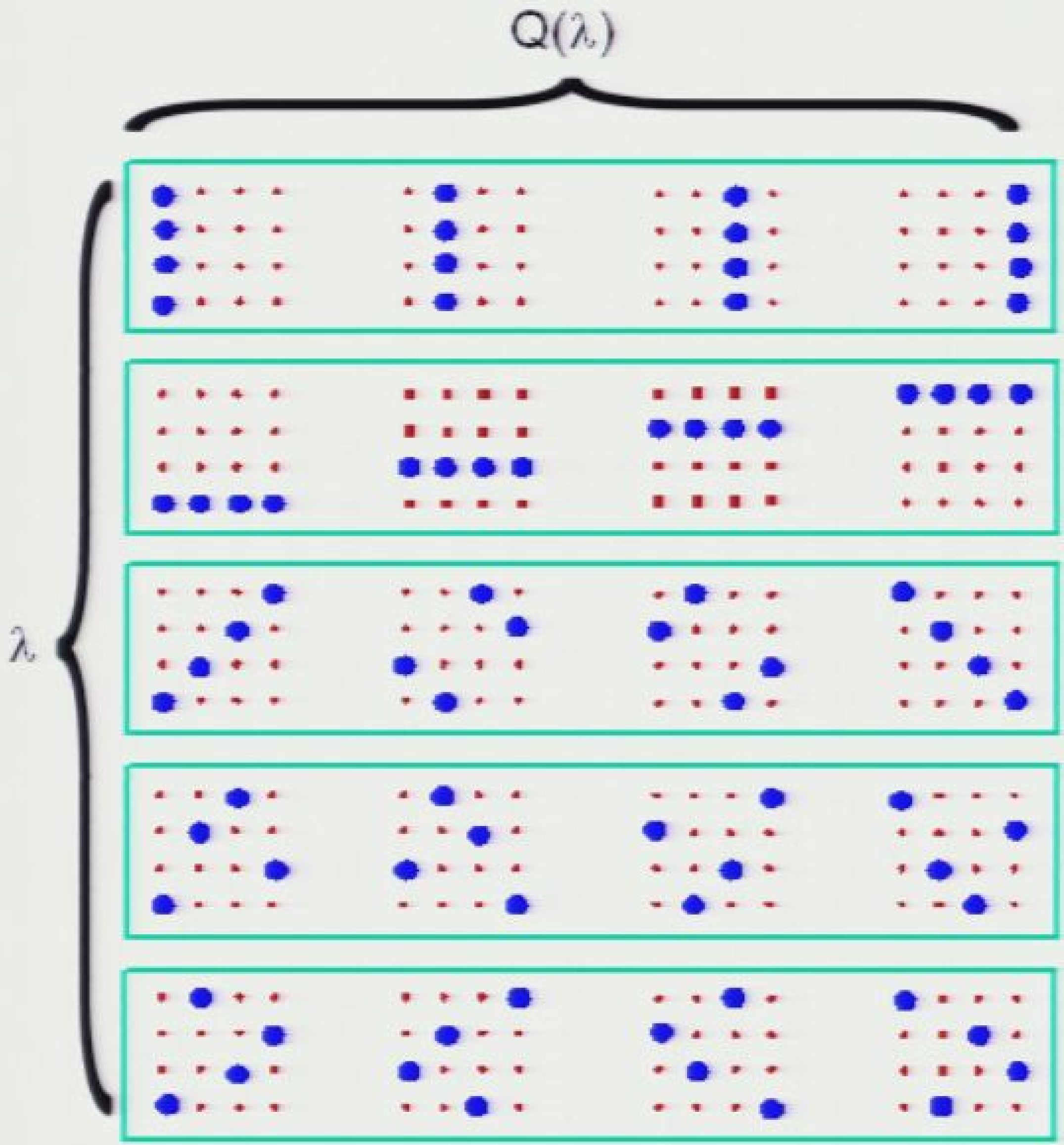
Example: y=x+1



Five families of lines of the same slope



Connection to MUBs



σ_z^1	σ_z^2	$\sigma_z^1 \sigma_z^2$
σ_x^1	σ_y^2	$\sigma_x^1 \sigma_y^2$
σ_y^1	σ_x^2	$\sigma_y^1 \sigma_x^2$
$\sigma_y^1 \sigma_y^2$	$\sigma_z^1 \sigma_x^2$	$\sigma_x^1 \sigma_z^2$
$\sigma_x^1 \sigma_x^2$	$\sigma_y^1 \sigma_z^2$	$\sigma_z^1 \sigma_y^2$

Phase-space point operators

- Sum along all lines that contain the point (x,y)

$$A_{(x,y)} = \left[\sum_{\lambda \ni (x,y)} Q(\lambda) \right] - \mathbb{I}_4$$

MUB projectors

$$W(x,y) = \frac{1}{N} \mathrm{Tr}\left(\rho A_{(x,y)}\right)$$ completeness

$$\rho = \sum_{(x,y)} W(x,y) A_{(x,y)}$$ inversion

Reconstruction

$$W(x,y) = \frac{1}{N}\mathrm{Tr}\left(\rho A_{(x,y)}\right)$$

- W(x,y) is the sum of the measured frequencies for the projectors corresponding to the lines going through (x,y)
- "Discrete inverse radon transform?"

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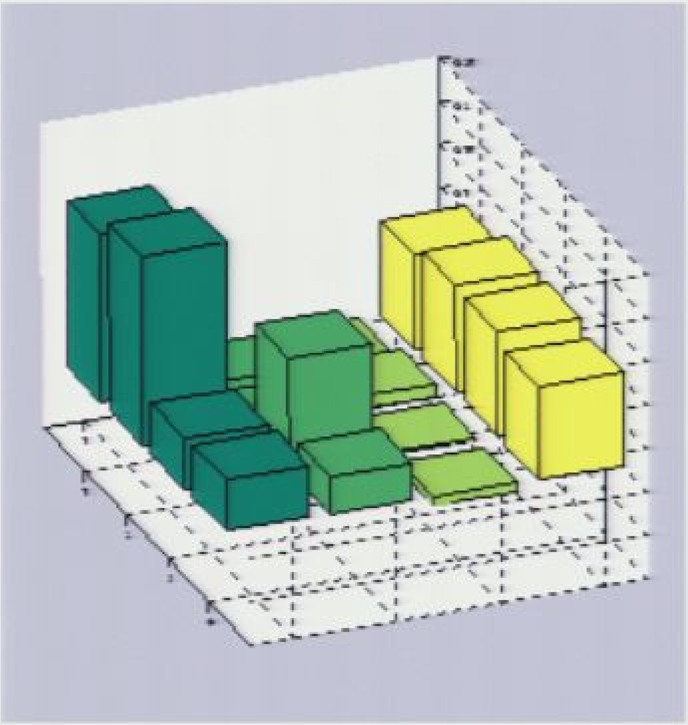
Results



	0	1	ω	$\bar{\omega}$
$\bar{\omega}$	0.1913	−0.0803	−0.0001	0.1079
ω	0.2160	−0.0790	0.0135	0.1239
1	0.0579	0.1286	0.0030	0.1193
0	0.0602	0.0420	−0.0106	0.1064

ZZ

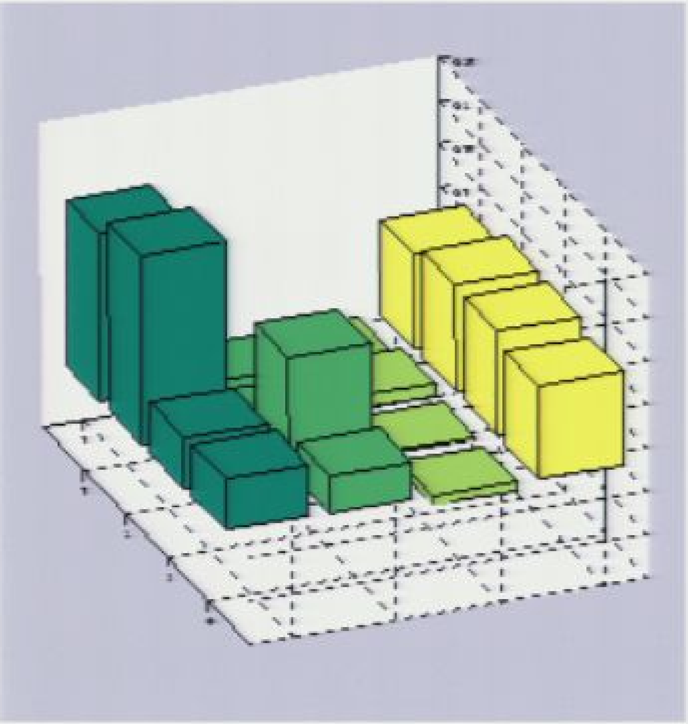
Compare to HH+VV XY

	0	1	ω	$\bar{\omega}$
$\bar{\omega}$	0.25	−0.125	0	0.125
ω	0.25	−0.125	0	0.125
1	0	0.125	0	0.125
0	0	0.125	0	0.125

Conclusions

- Mutually unbiased bases can reduce redundant information collected in quantum state tomography
  - Reduces the infidelity with the true state by a factor of up to 1.84 as compared to 36-outcome tomography
  - Works even for imperfect entangling measurements
- Also leads to a very simple reconstruction of the discrete Wigner function

Results



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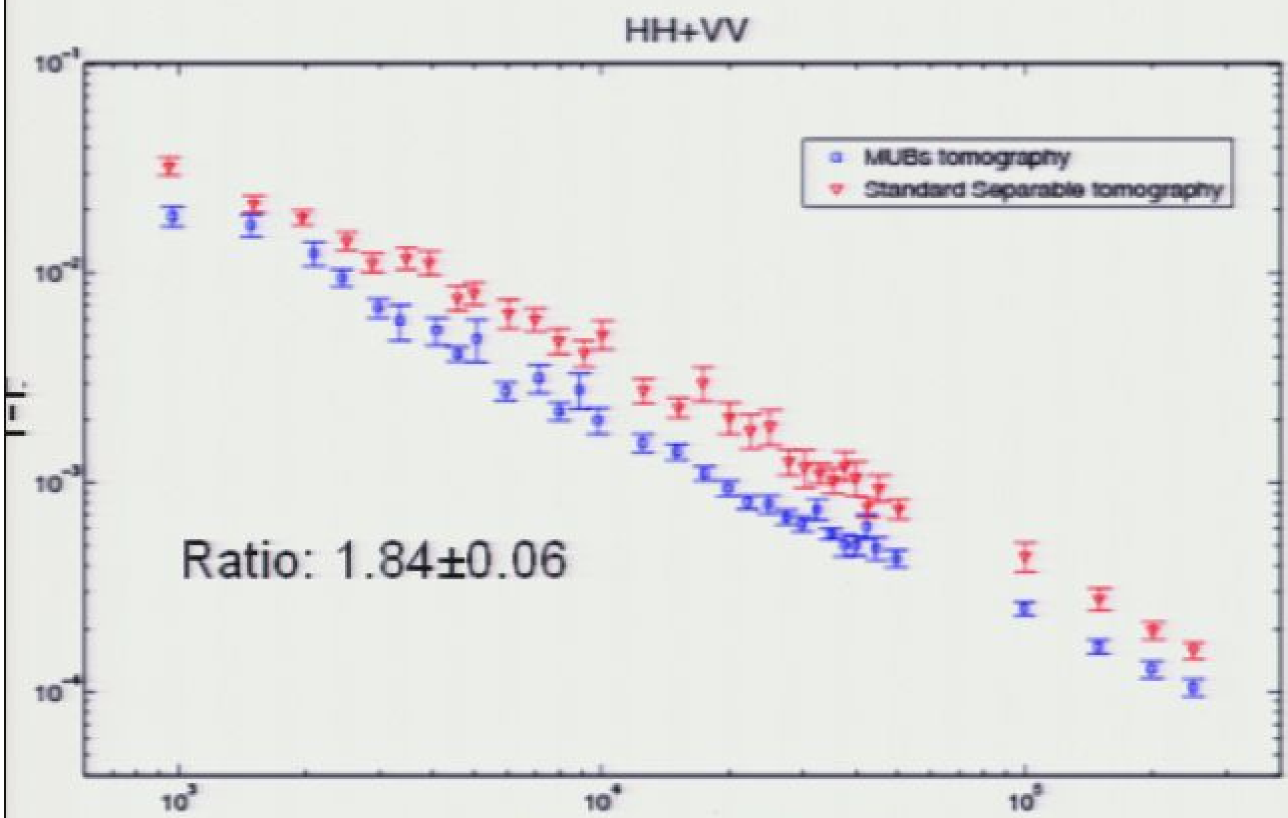
Discrete Wigner Functions

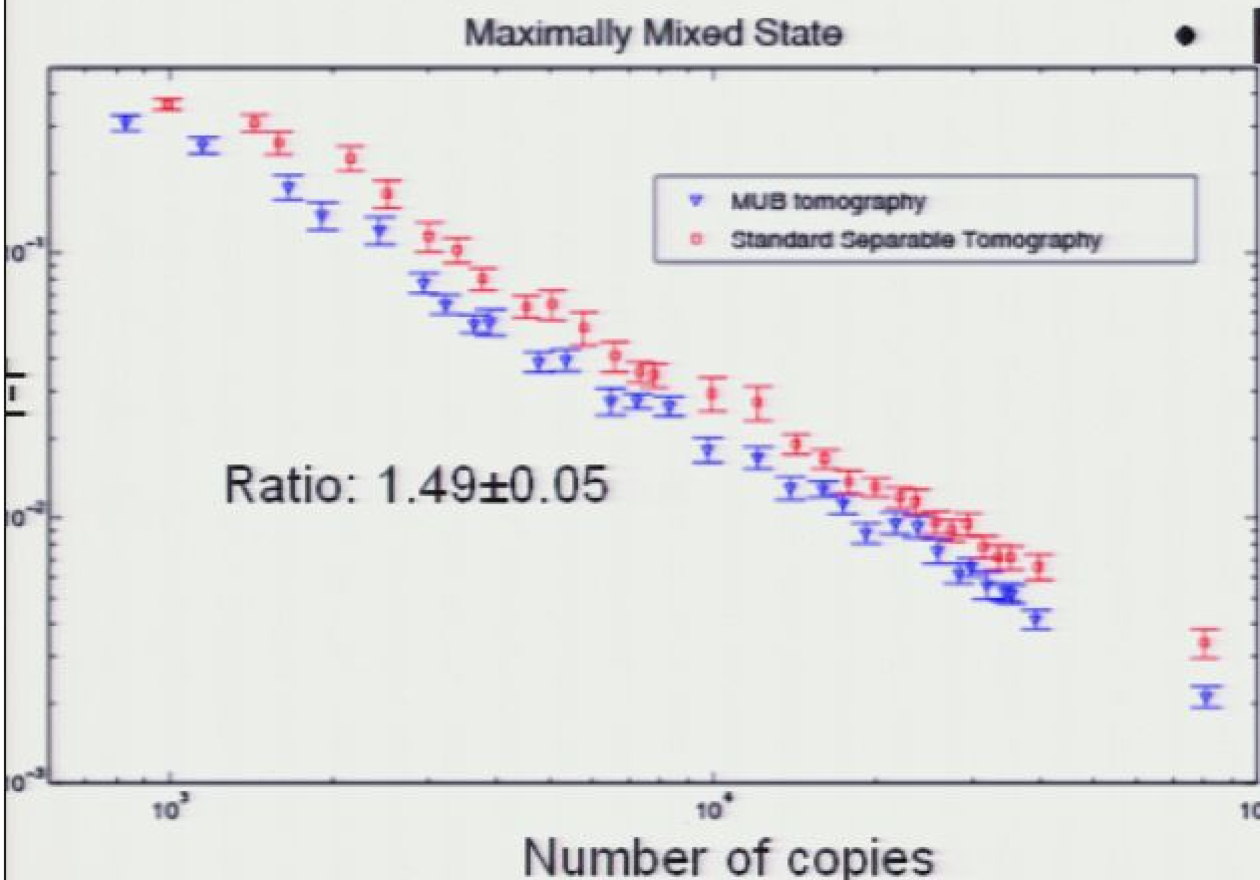
Results: Entangled States

Experiment



- MUBs generally give better estimates for entangled states than separable measurements

Results: Mixed State



- Methodology:
  - Do 3000 separate tomographies with ~10 pairs per basis
  - Combine those into longer experimental runs with bigger populations
  - Infidelity=1-Fidelity

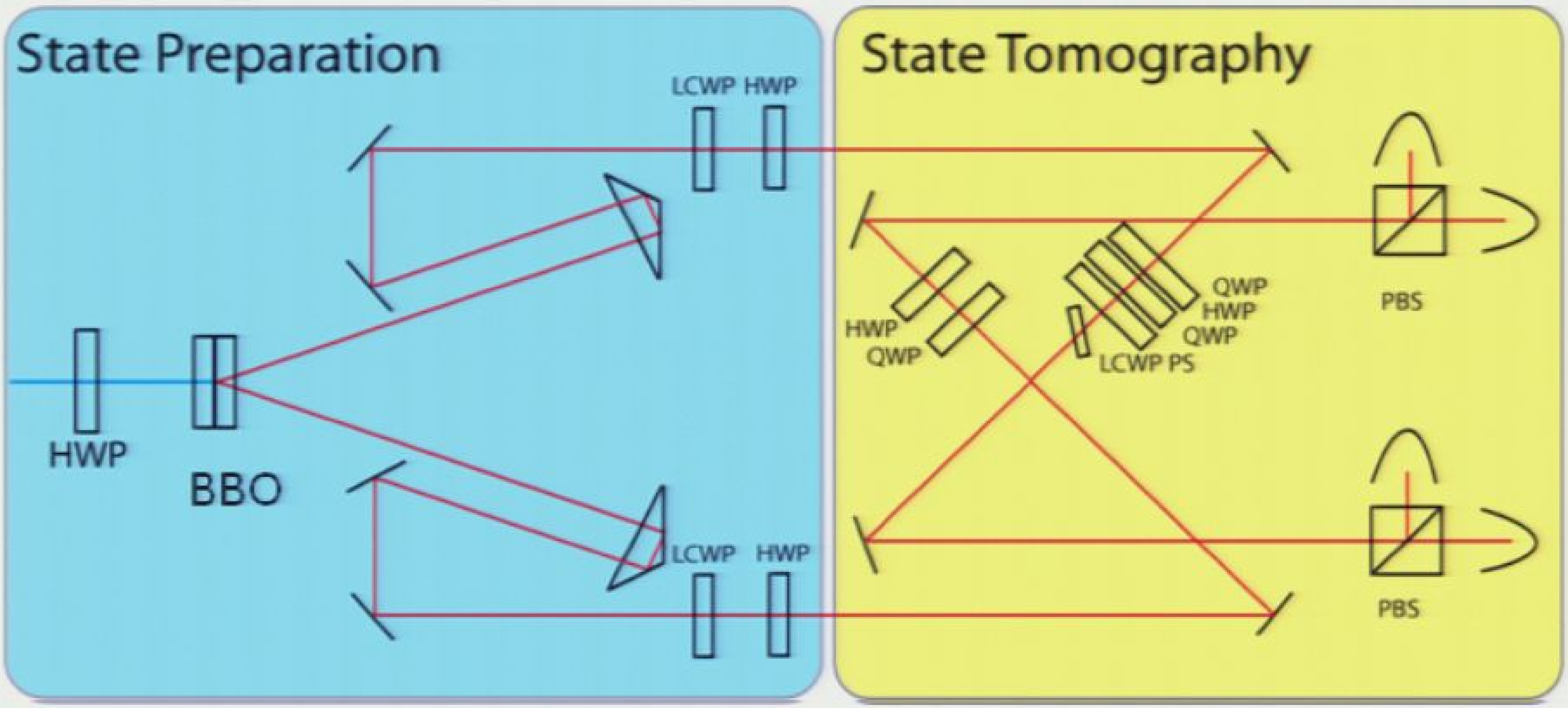
$$F(\rho,\sigma) = \left(\mathrm{tr}\sqrt{\sqrt{\rho}\sigma\sqrt{\rho}}\right)^2$$

Smaller number of bases means better statistics for each one.

Measuring in MUBs

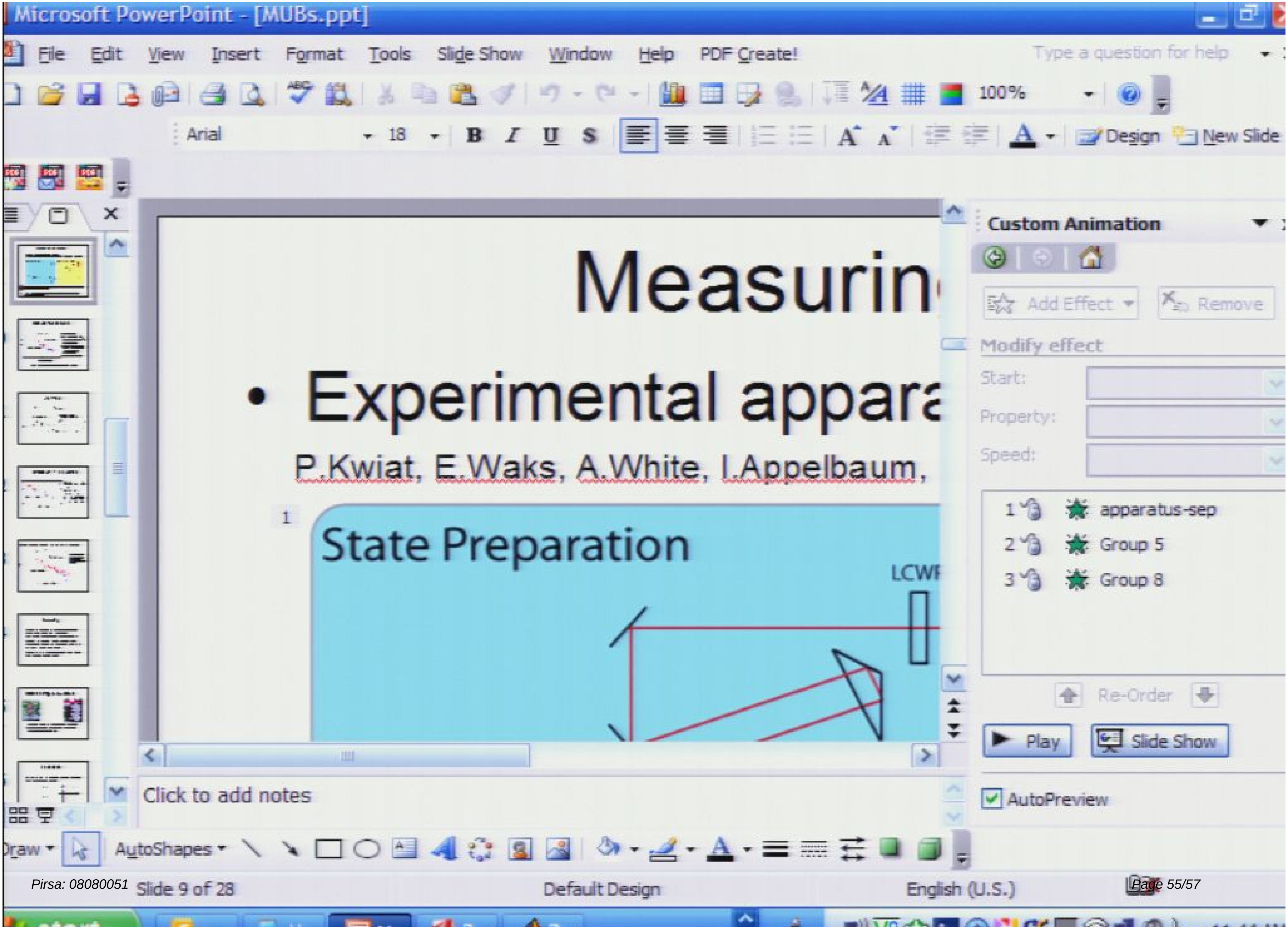
- Experimental apparatus

P.Kwiat, E.Waks, A.White, I.Appelbaum, and P.Eberhard Phys. Rev. A **60**, R773 (1999)



Simulations show that the limited visibility of 93% does not significantly limit the advantage of MUBs tomography

Linear optics can't do deterministic Bell State Measurements – limits the practicality of the scheme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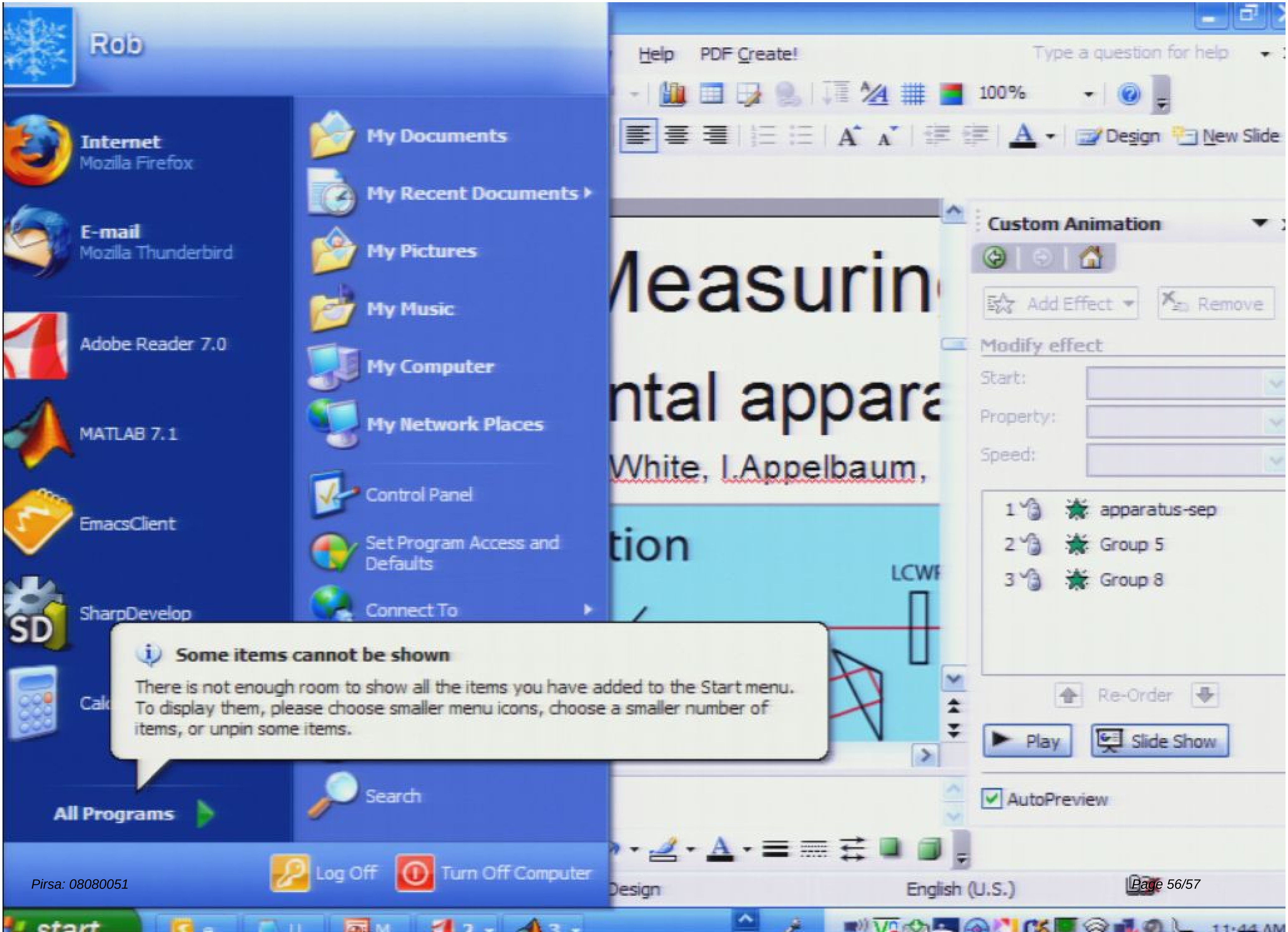
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My Music
My Computer
My Network Places
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There is not enough room to show all the items you have added to the Start menu. To display them, please choose smaller menu icons, choose a smaller number of items, or unpin some items.
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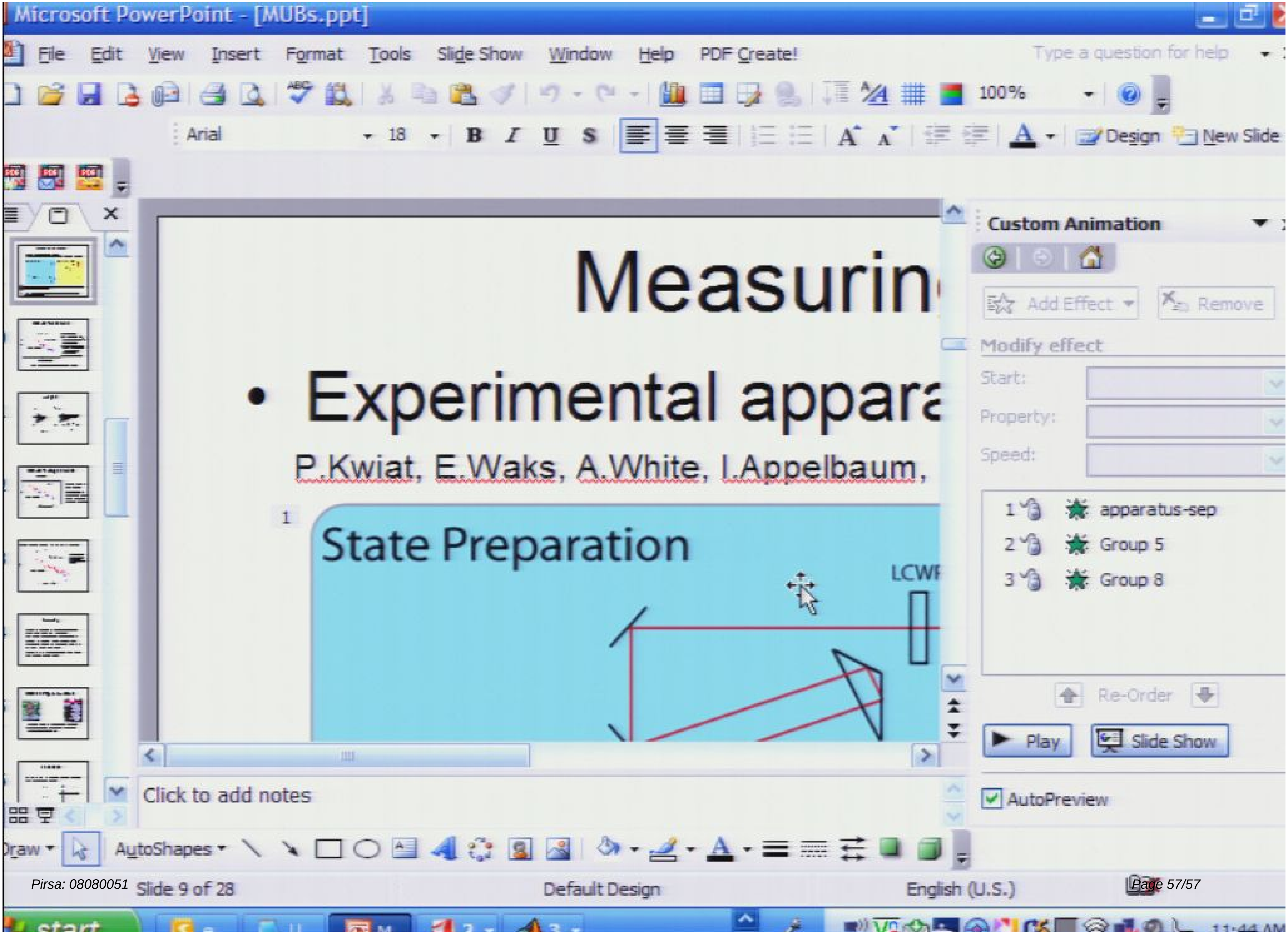
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