Title: Designing Optimal States and Transformations for Quantum Optical Metrology and Communication

Date: Aug 28, 2008 02:30 PM

URL: http://pirsa.org/08080037

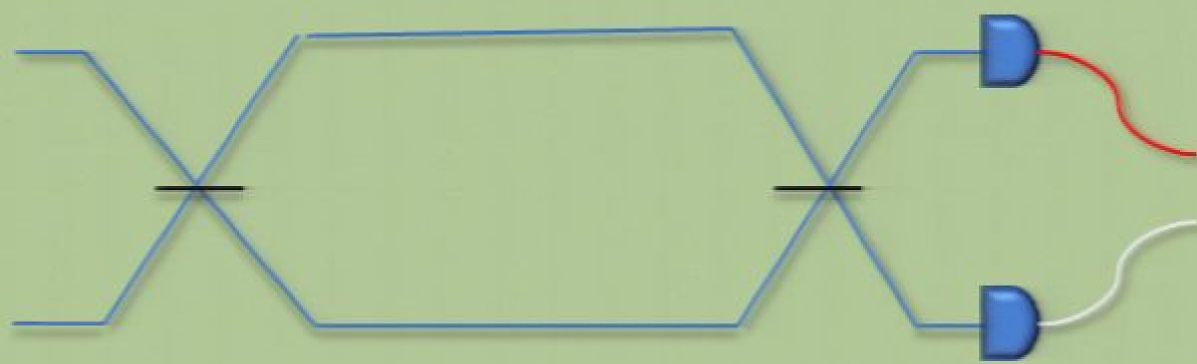
Abstract: I will briefly describe our recent progress in solving some optimization problems involving metrology with multipath entangled photon states and optimization of quantum operations on such states. We found that in the problem of super-resolution phase measurement in the presence of a loss one can single out two distinct regimes: i) low-loss regime favoring purely quantum states akin the N00N states and ii) high-loss regime where generalized coherent states become the optimal ones. Next I will describe how to optimize photon-entangling operations beyond the Knill-Laflamme-Milburn scheme and, in particular, how to exploit hyperentangled states for entanglement-assisted error correction.If time allows I will briefly review our results on generalization of the Bloch Sphere for the case of two qubits exploiting the SU(4)/Z2-SO(6) group isomorphism. References 1. D. Uskov & Jonathan P. Dowling. Quantum Optical Metrology in the Presence of a Loss (in preparation); Sean D. Huver et al, Entangled Fock States for Robust Quantum Optical Metrology, Imaging, and Sensing, arXiv:0808.1926. 2. D. Uskov et al, Maximal Success Probabilities of Linear-Optical Quantum Gates, arXiv:0808.1926. 3. M. Wilde and D. Uskov, Linear-Optical Hyperentanglement-Assisted Quantum Error-Correcting Code, arXiv:0807.4906. 4. D. Uskov and R. Rau Geometric phases and Bloch sphere constructions for SU(N), with a complete description of SU(4), Phys. Rev. A 78, 022331 (2008).

Designing Optimal States and Transformations for Quantum Metrology And Communication

Dmitry Uskov

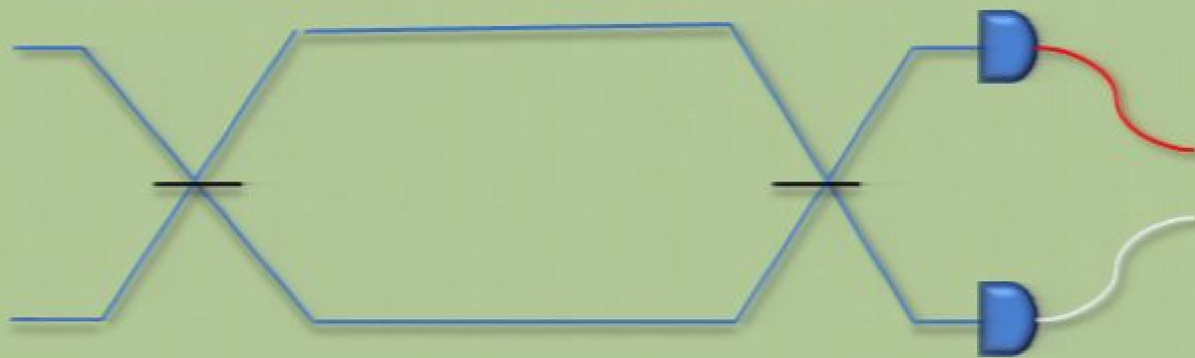
Tulane University and Hearne Institute for Theoretical Physics Louisiana State University

Phase Estimation



Phase Estimation

Mach-Zender Interferometer



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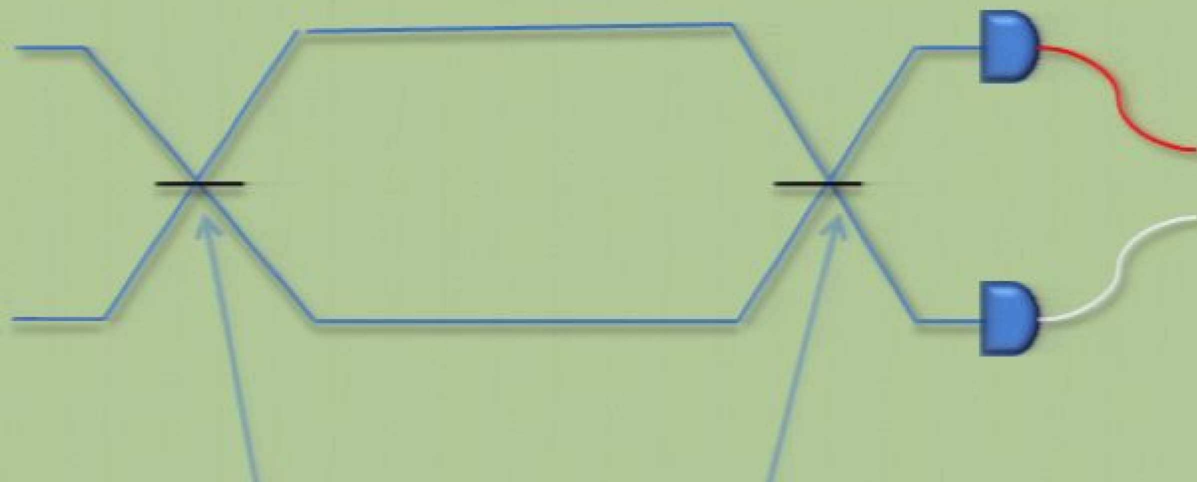

Beam splitters and phase shifters

$$\hat{U} = e^{\alpha \hat{J}_z} e^{\beta \hat{J}_y} e^{\gamma \hat{J}_z}$$

$$\hat{J}_z = i(a_1^\dagger a_1 - a_2^\dagger a_2), \hat{J}_y = (a_1^\dagger a_2 - a_1 a_2^\dagger)$$

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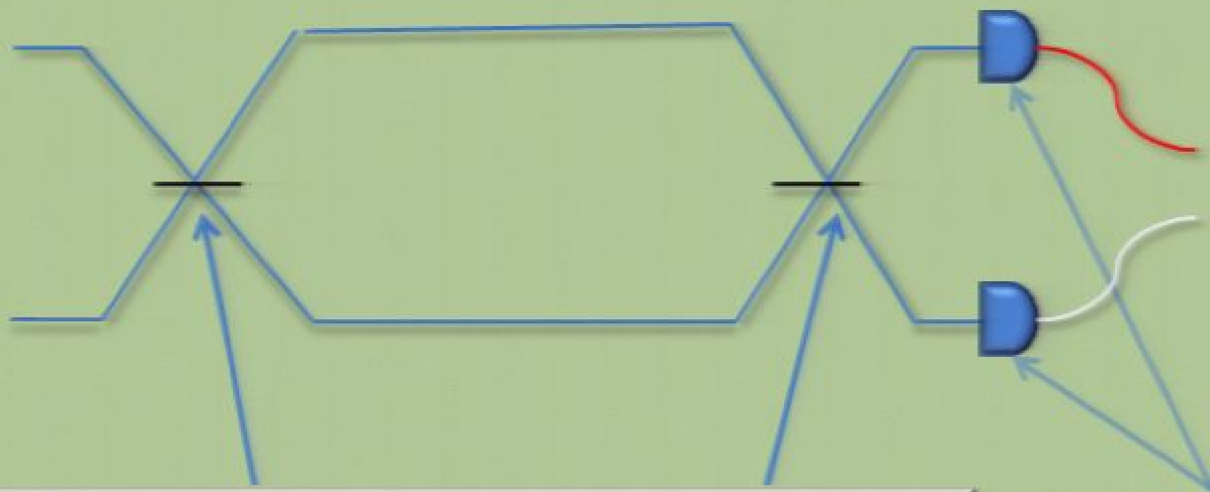

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Number resolving detectors

ideal number-resolving detectors implement POVM with Kraus operators

$$A_{\{n_1,n_2\}} = |vac\rangle\langle n_1, n_2|$$

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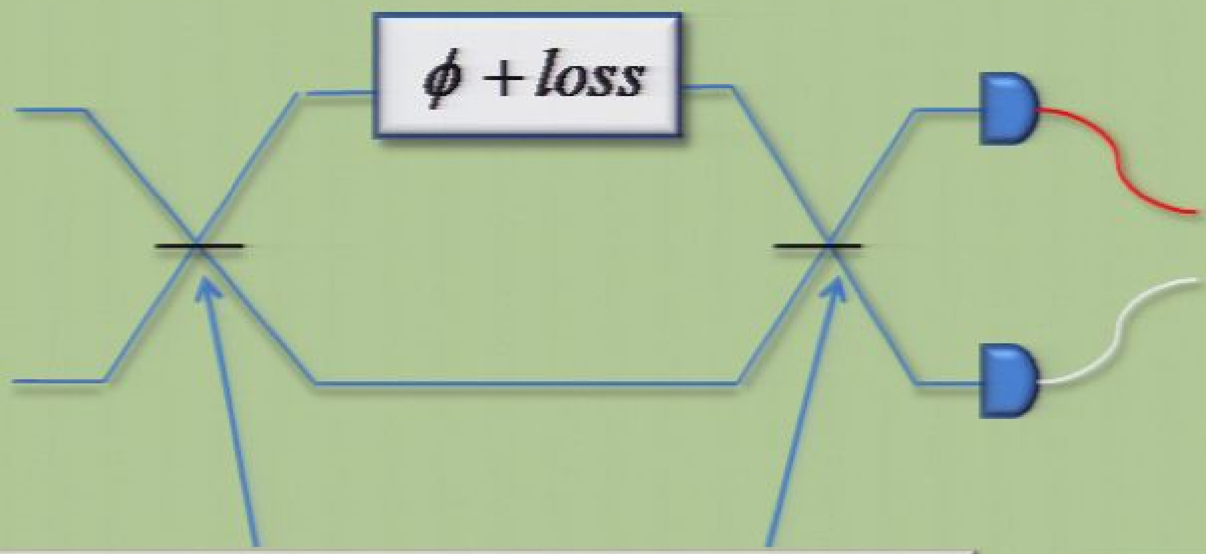

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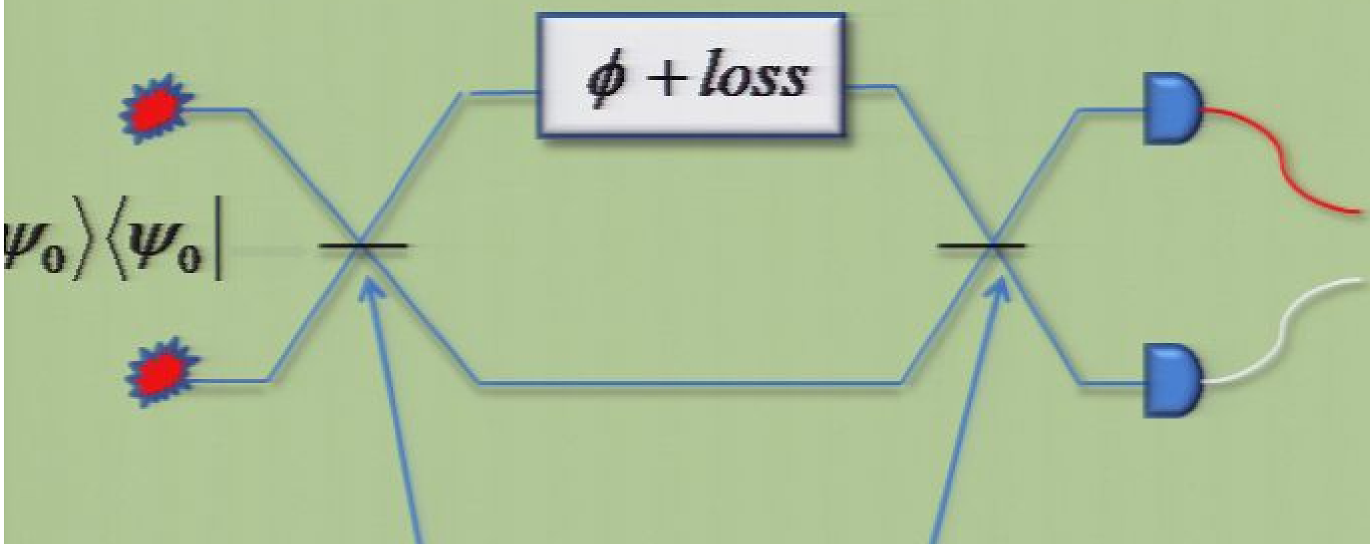

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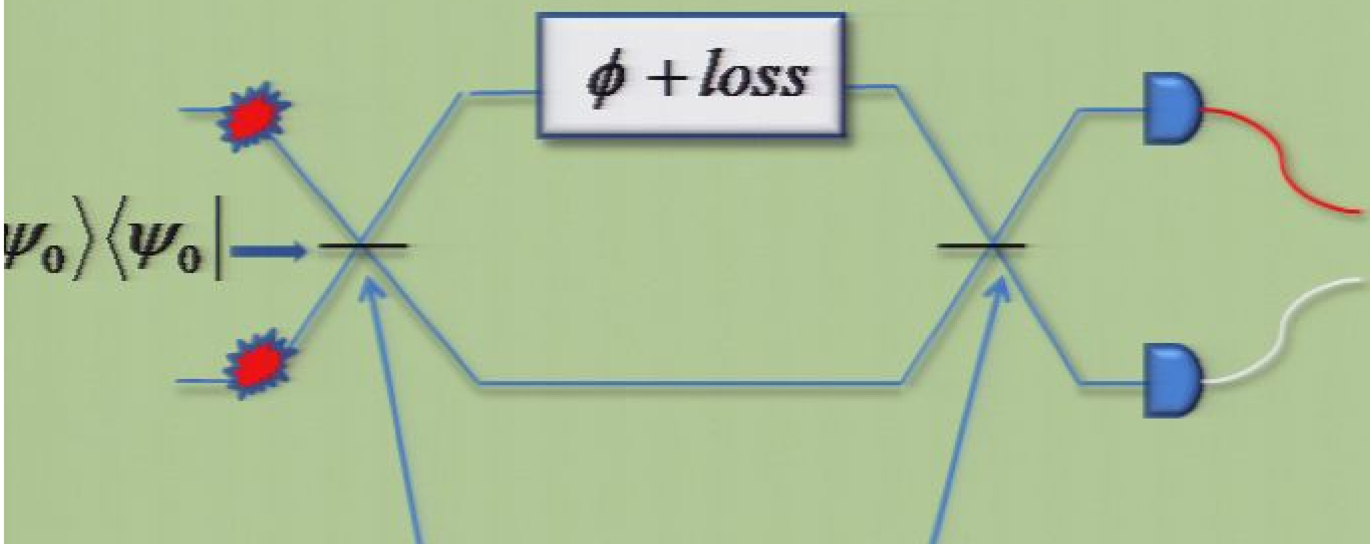

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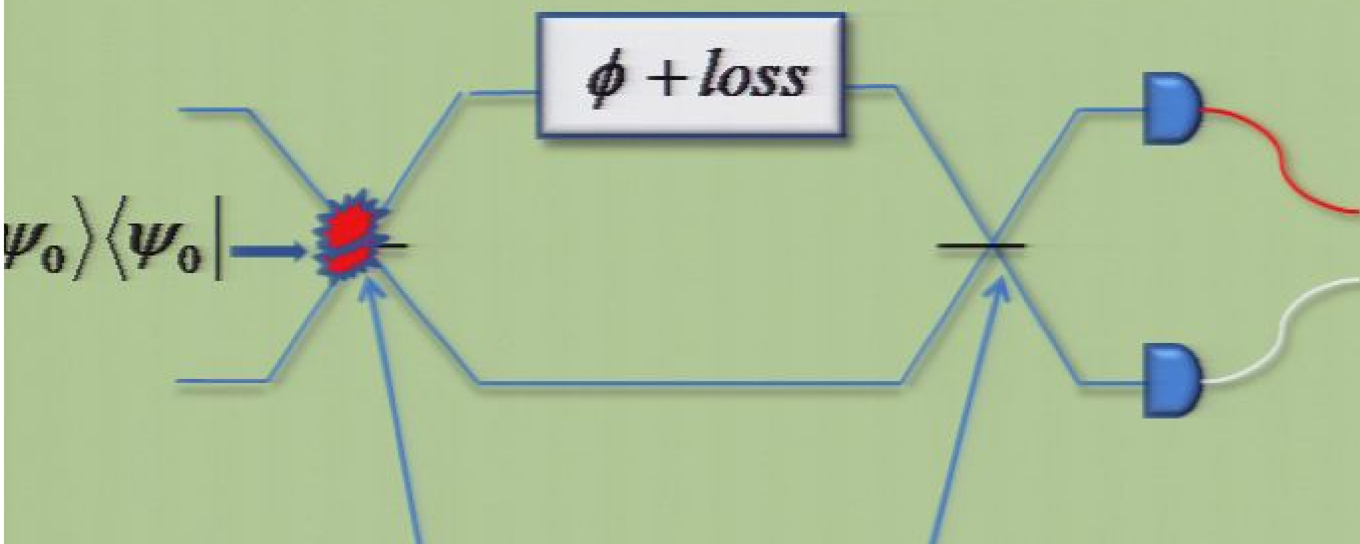

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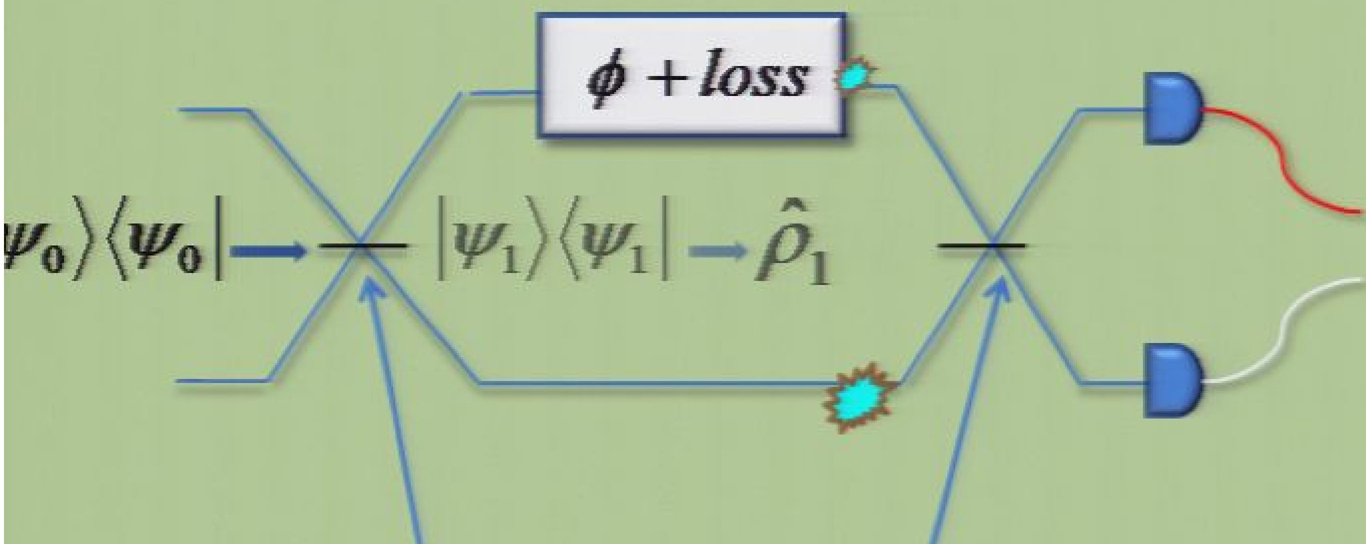

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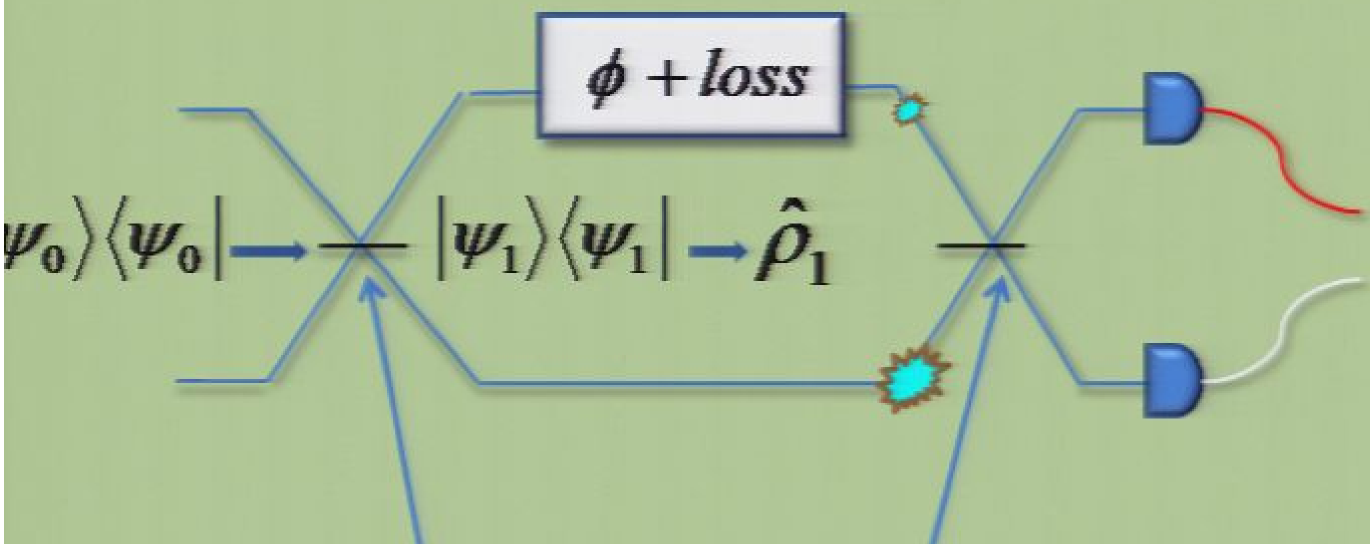

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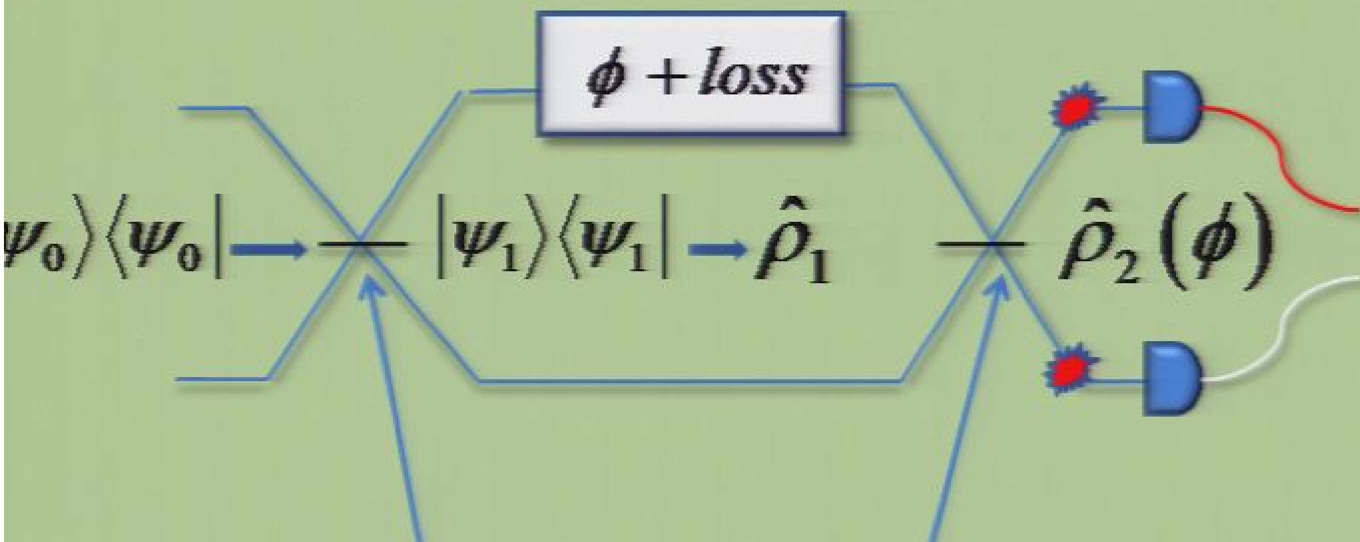

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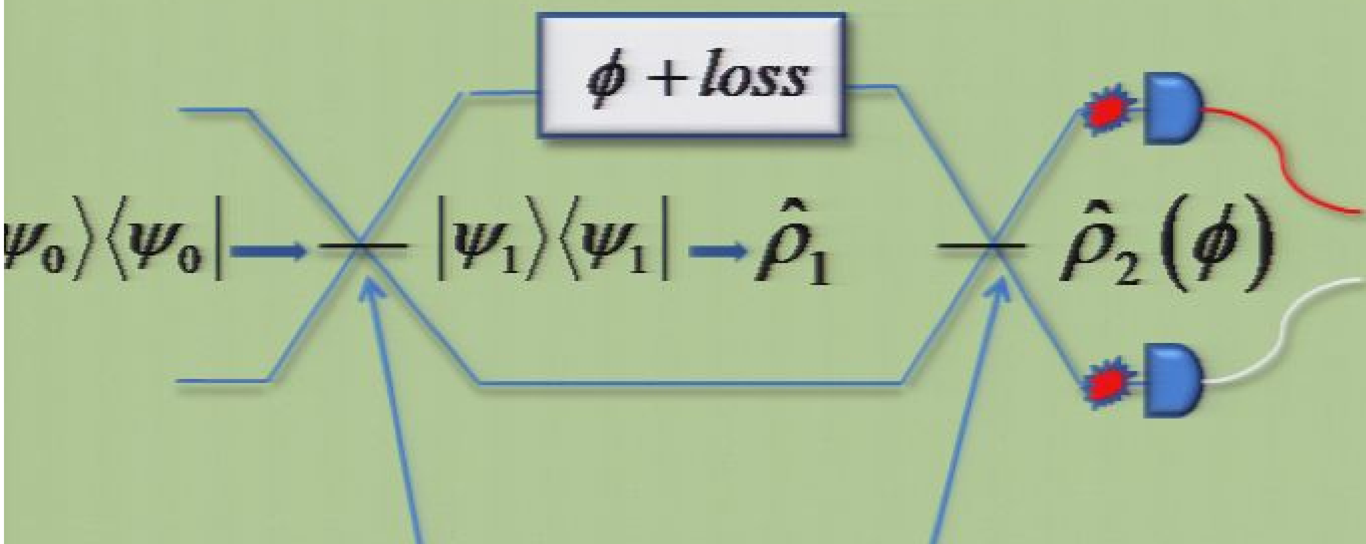

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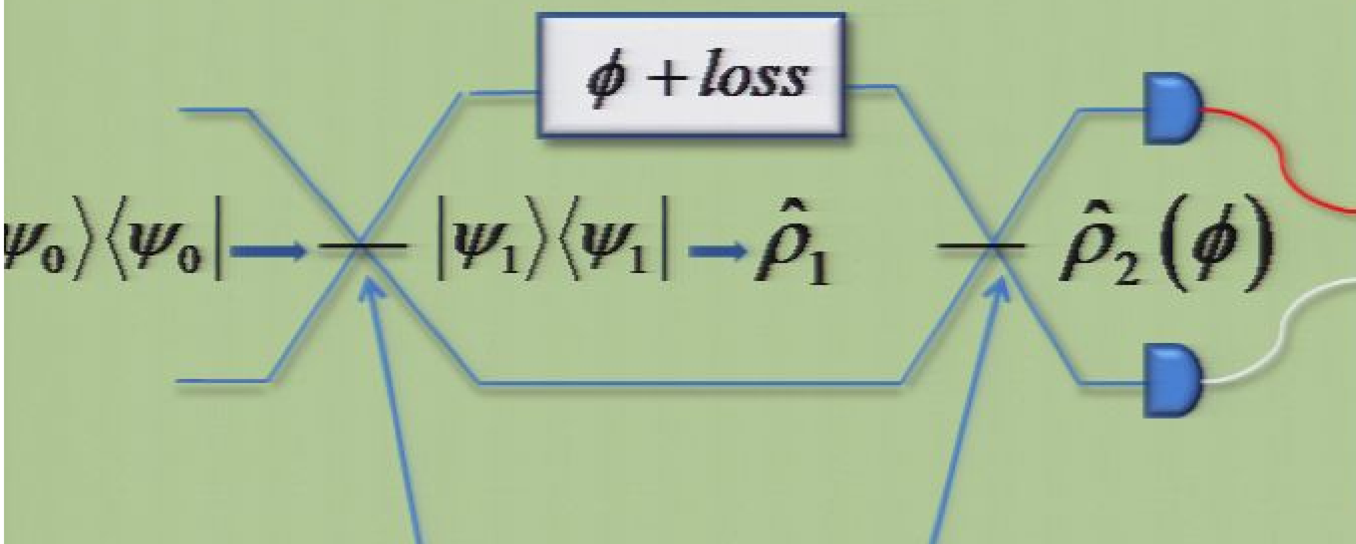

Stochastic Process

(N+1)(N+2)/2

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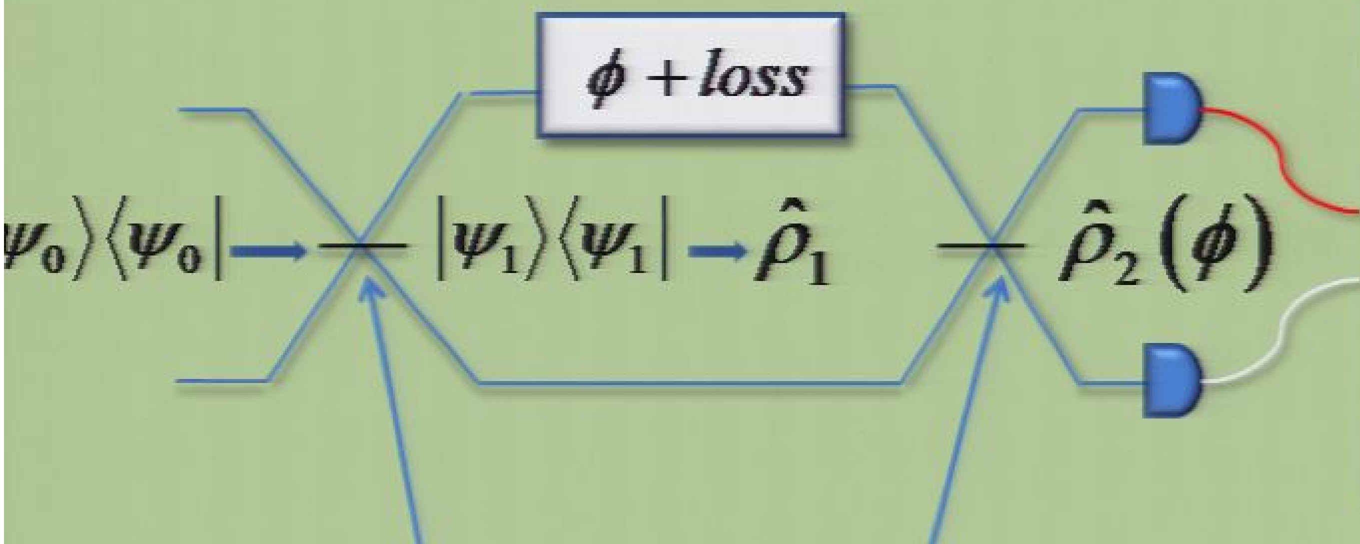

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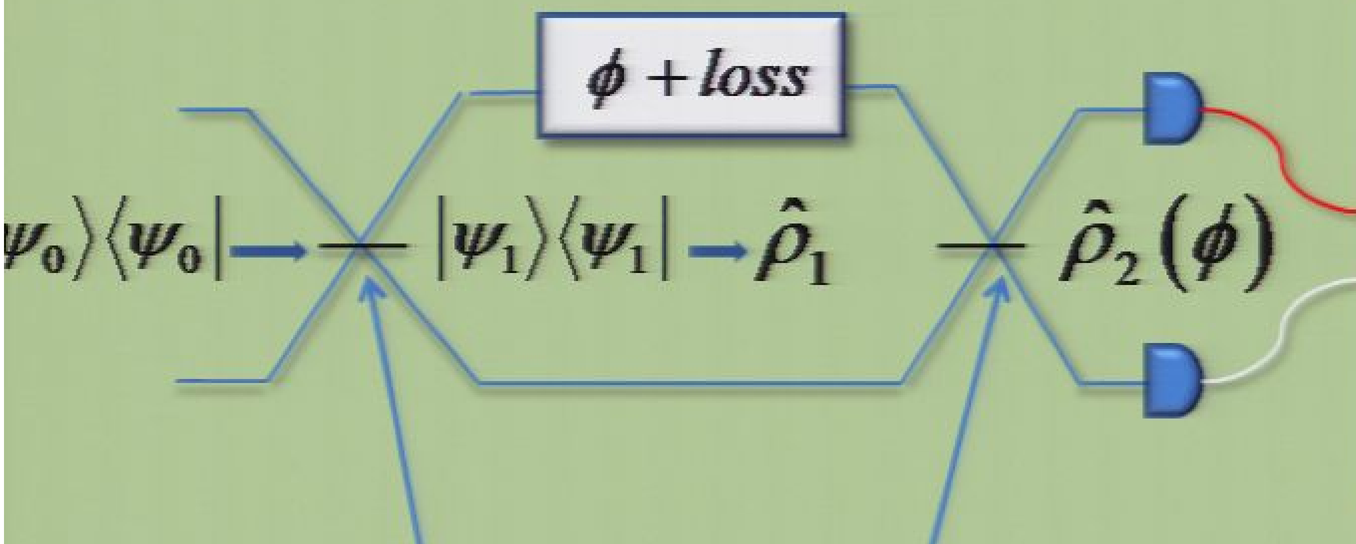

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Kramer-Rao Bound

$$(\delta\phi_e)^2 = 1/\Im$$

Classical Limit	Heisenberg Limit
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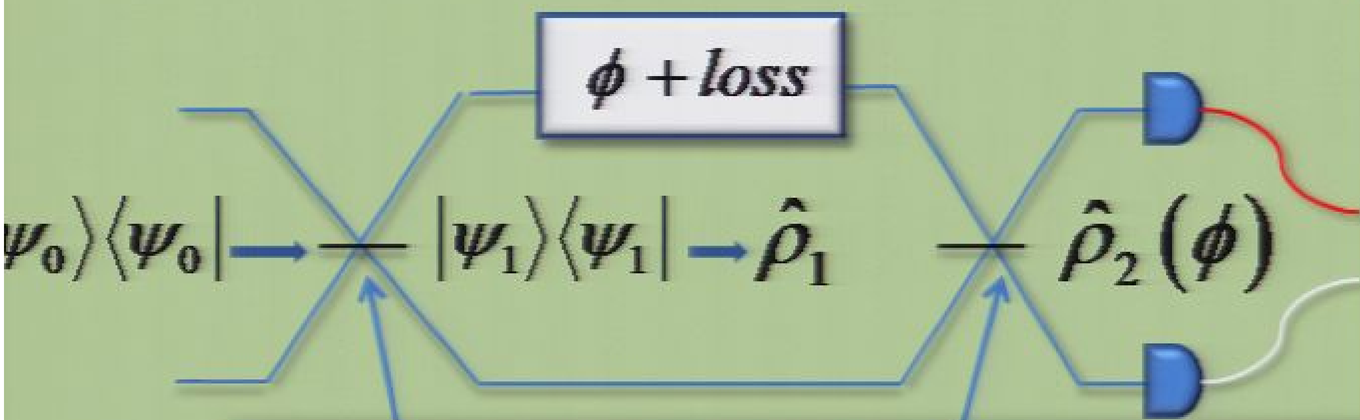

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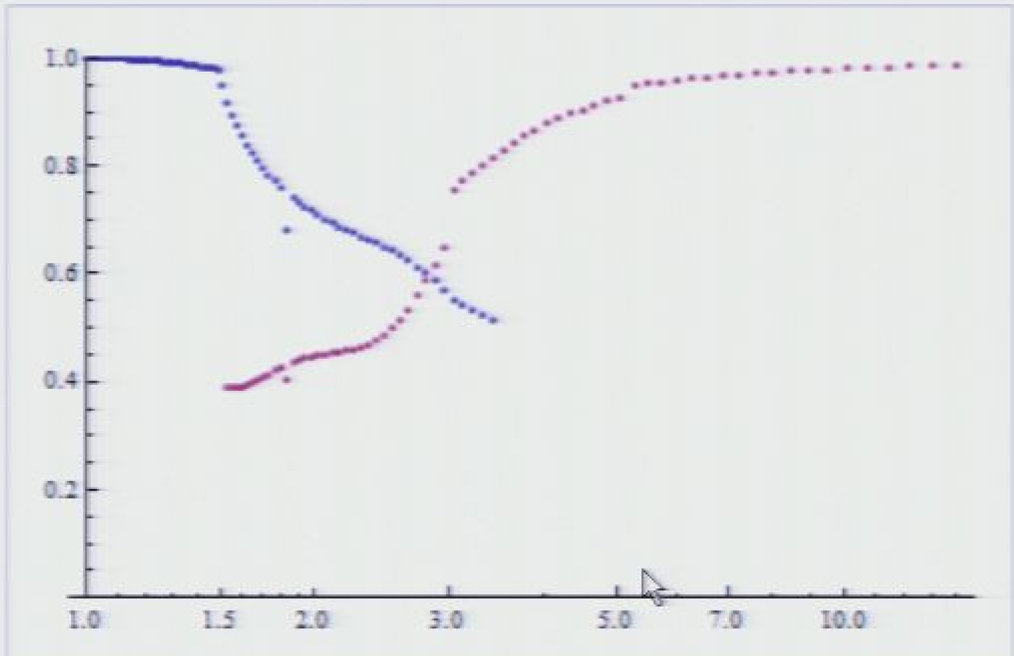
PerimeterTalk2.nb

```
vvvv = << vvv.dat;
vpr = << vprlomov.dat;

Manipulate[
 ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
  PlotRange → {0, 1}], {m, 1, 11, 1}]
```

m



PerimeterTalk1.nb *

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PlotLabel →
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  >          | 0 , 3 >"], {fi, 0, π/nph}]
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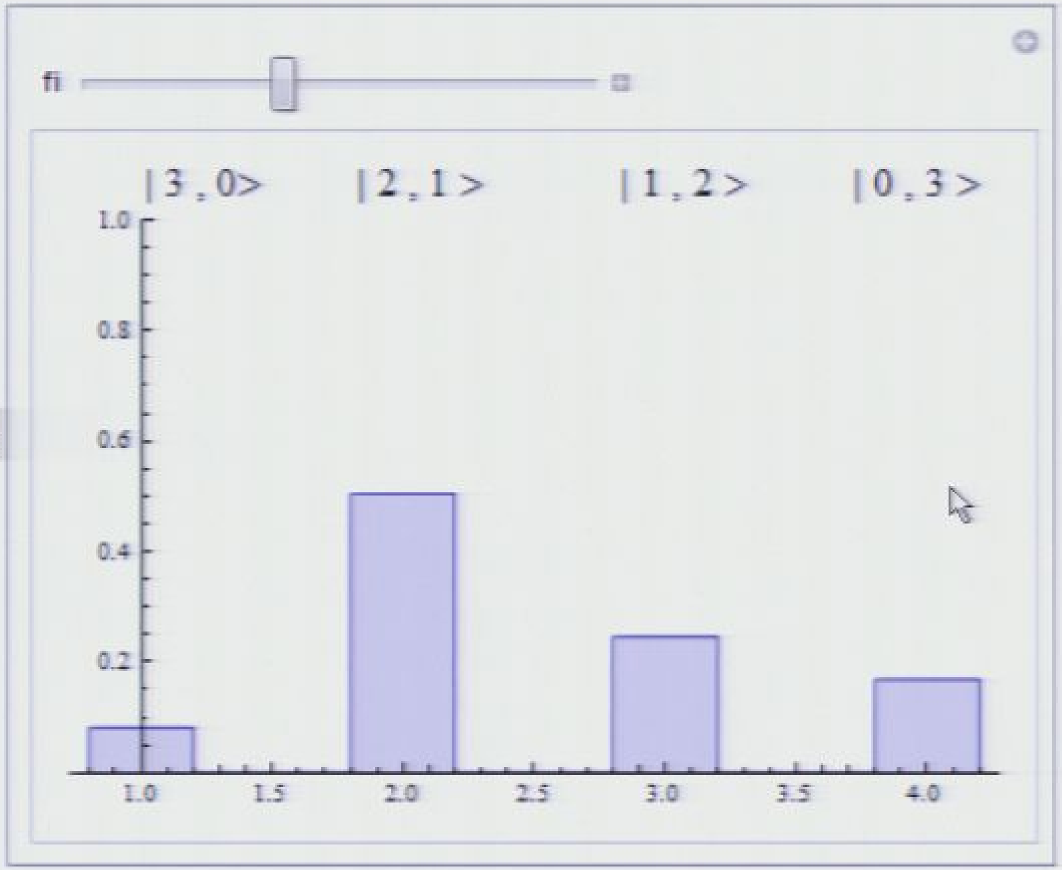

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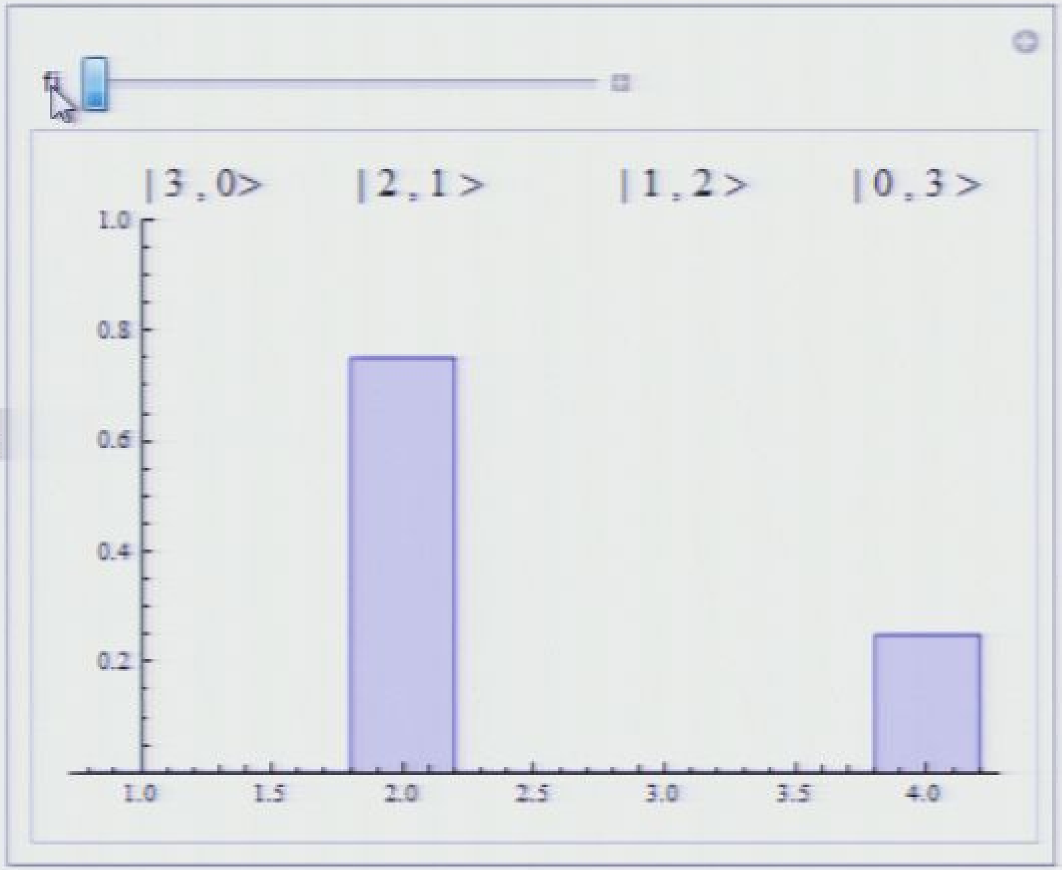

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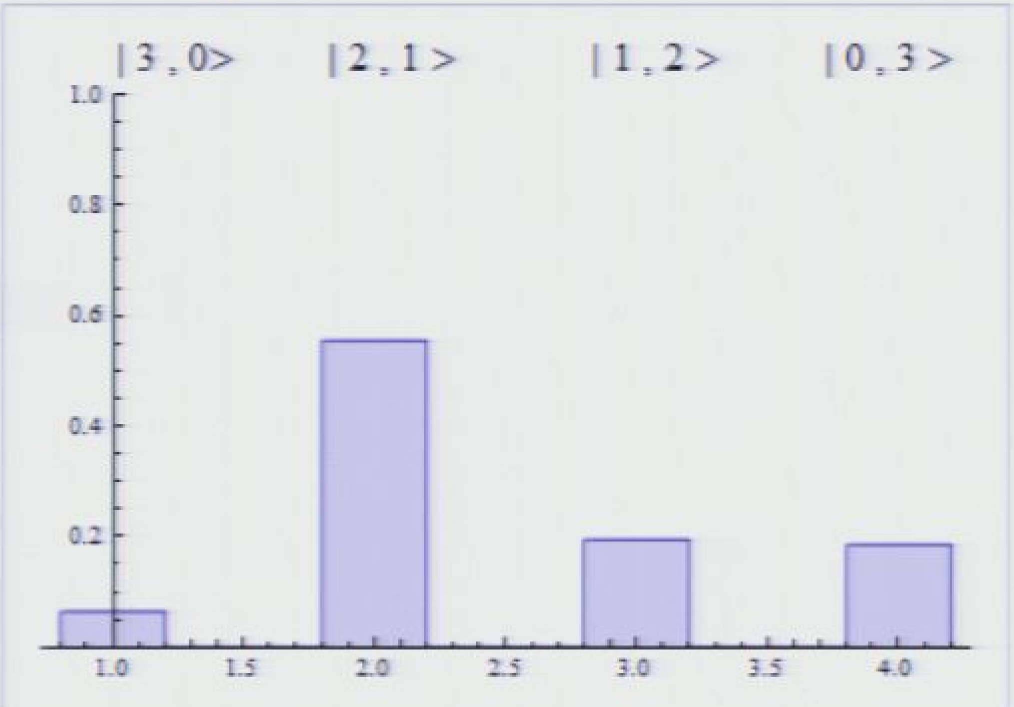

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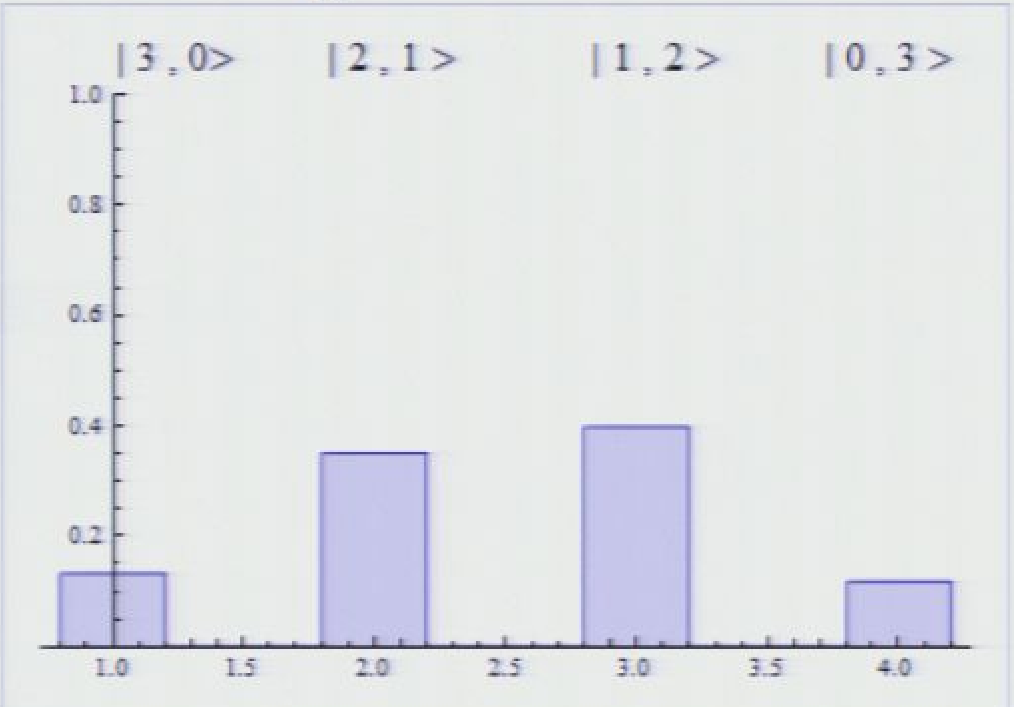

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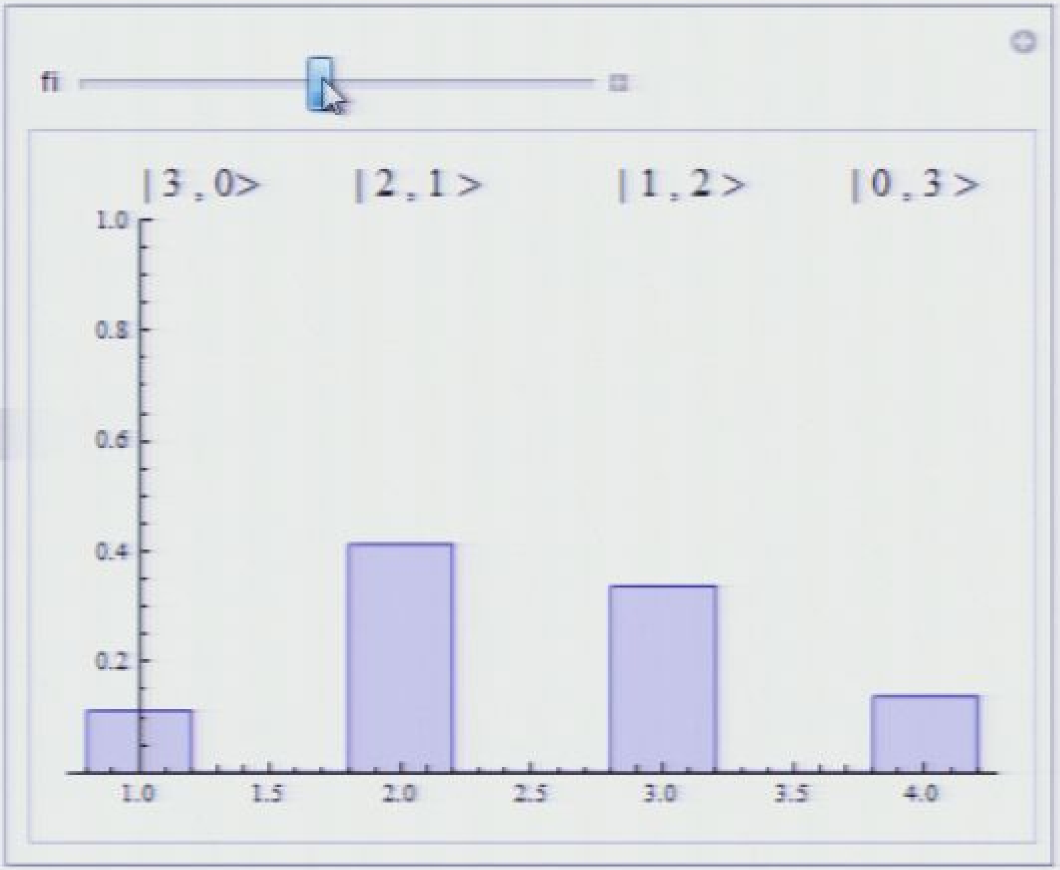

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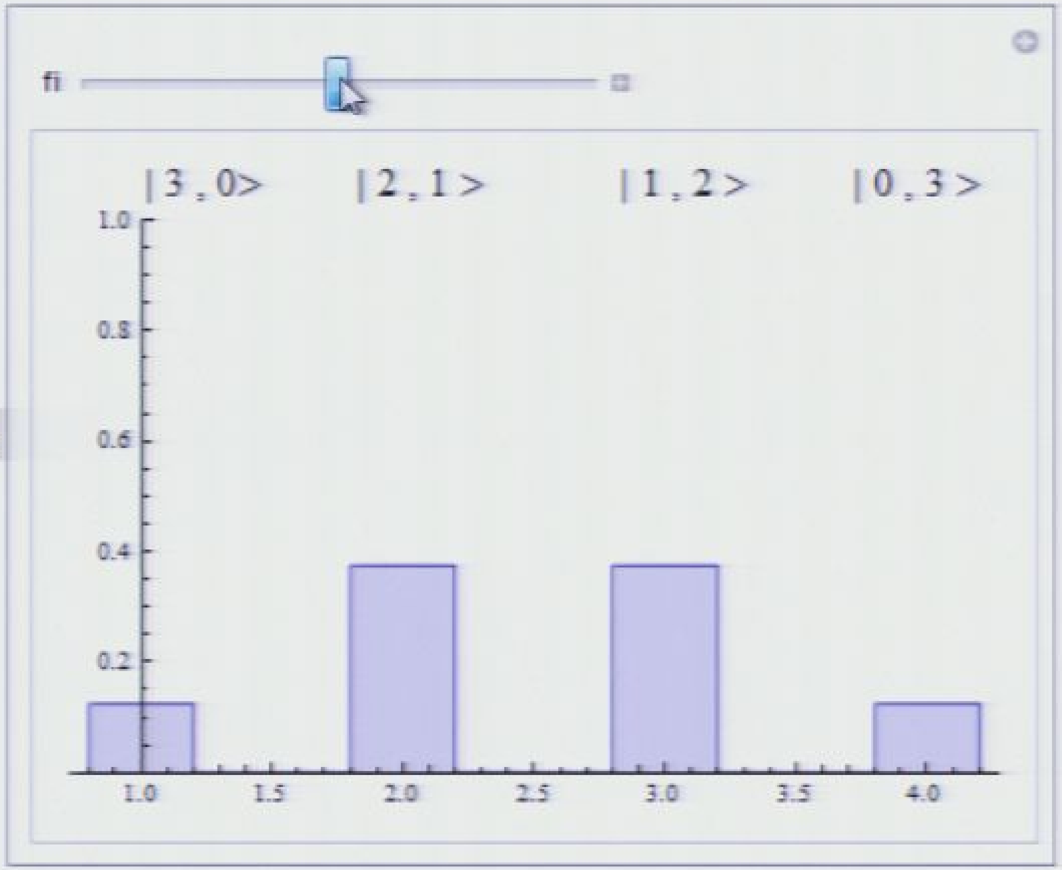

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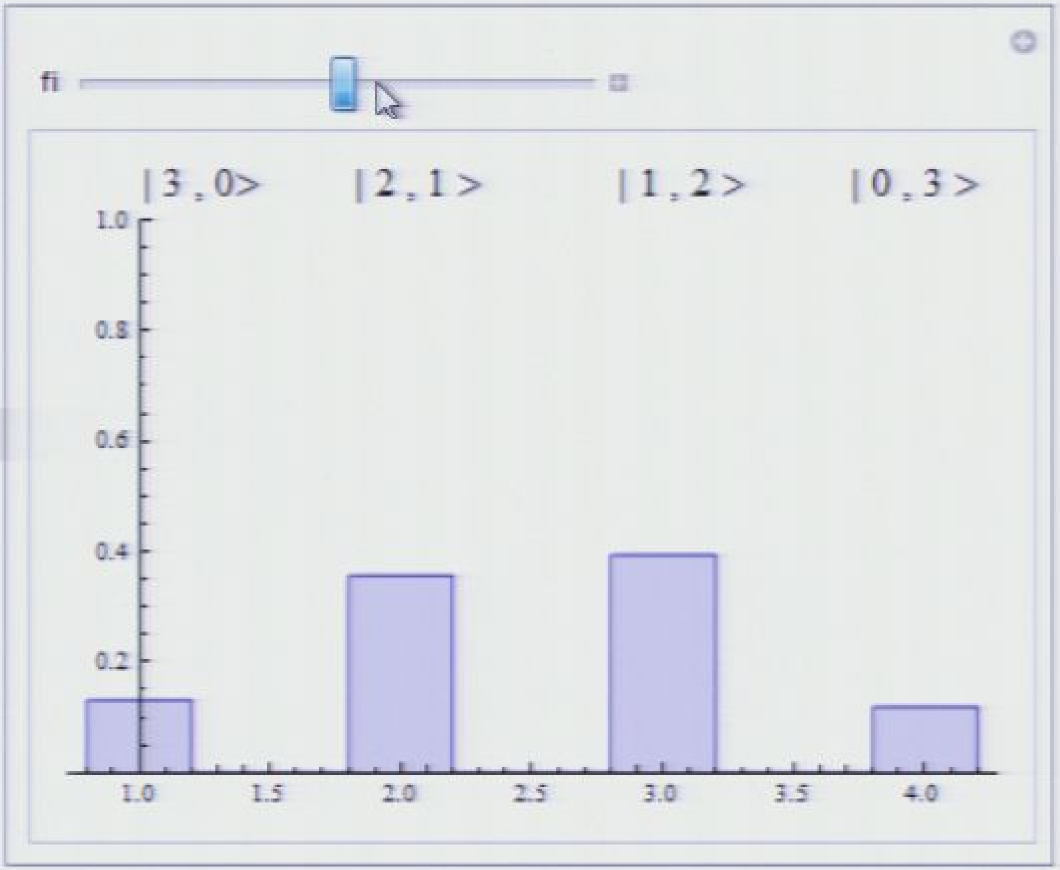

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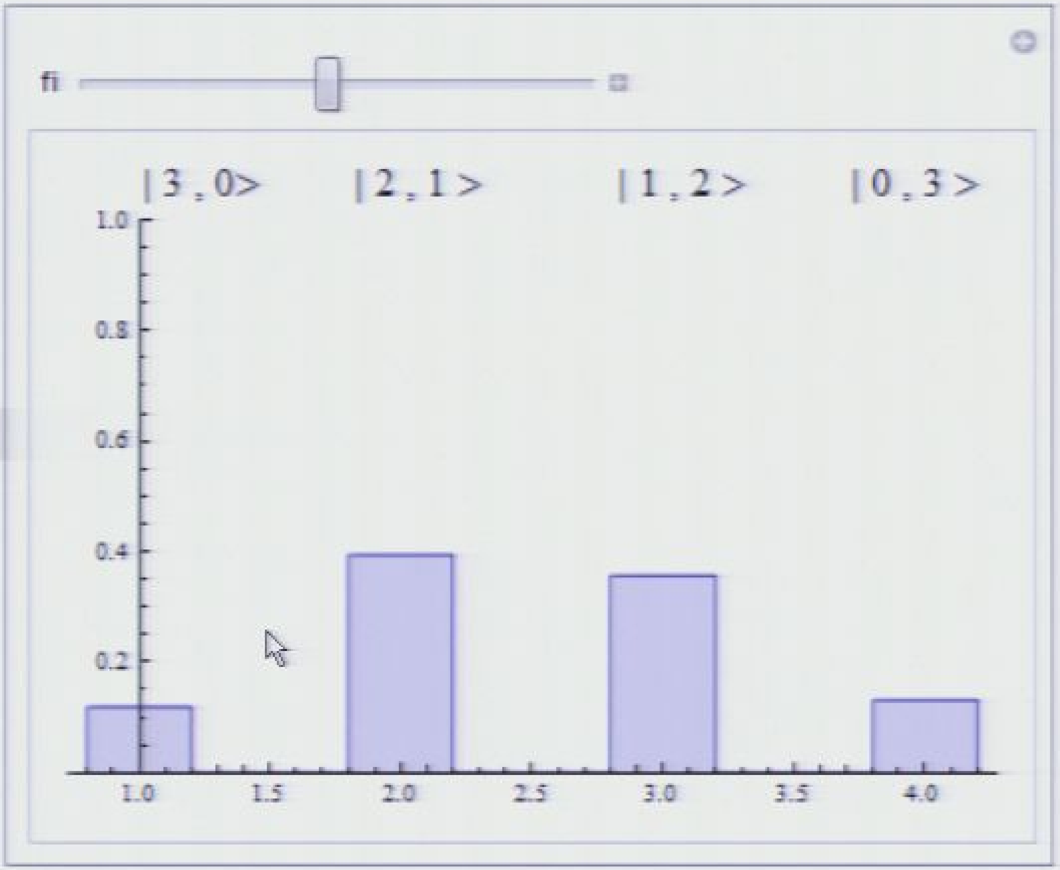

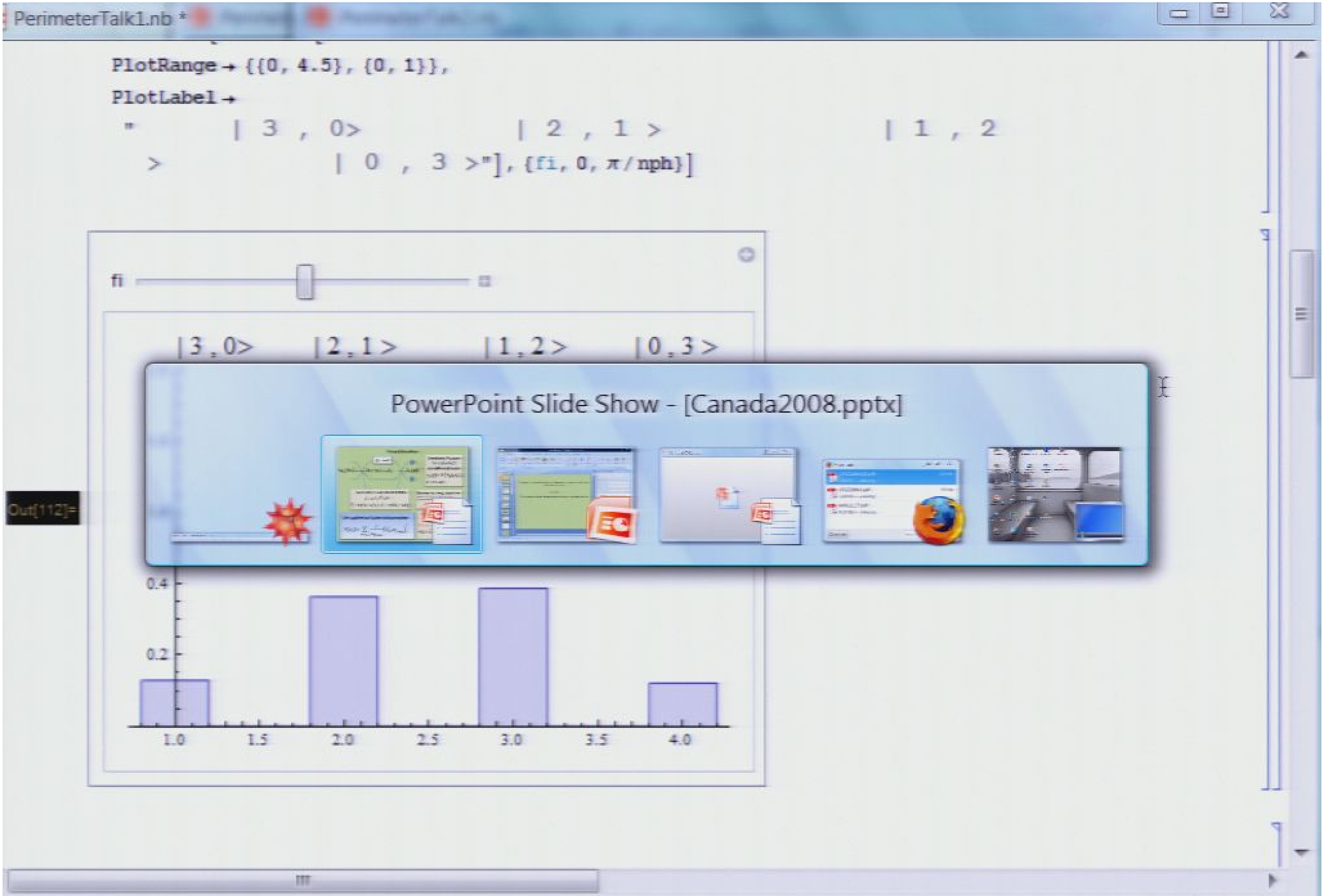
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|3,0> |2,1> |1,2> |0,3>
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0.4
0.2
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1.5
2.0
2.5
3.0
3.5
4.0

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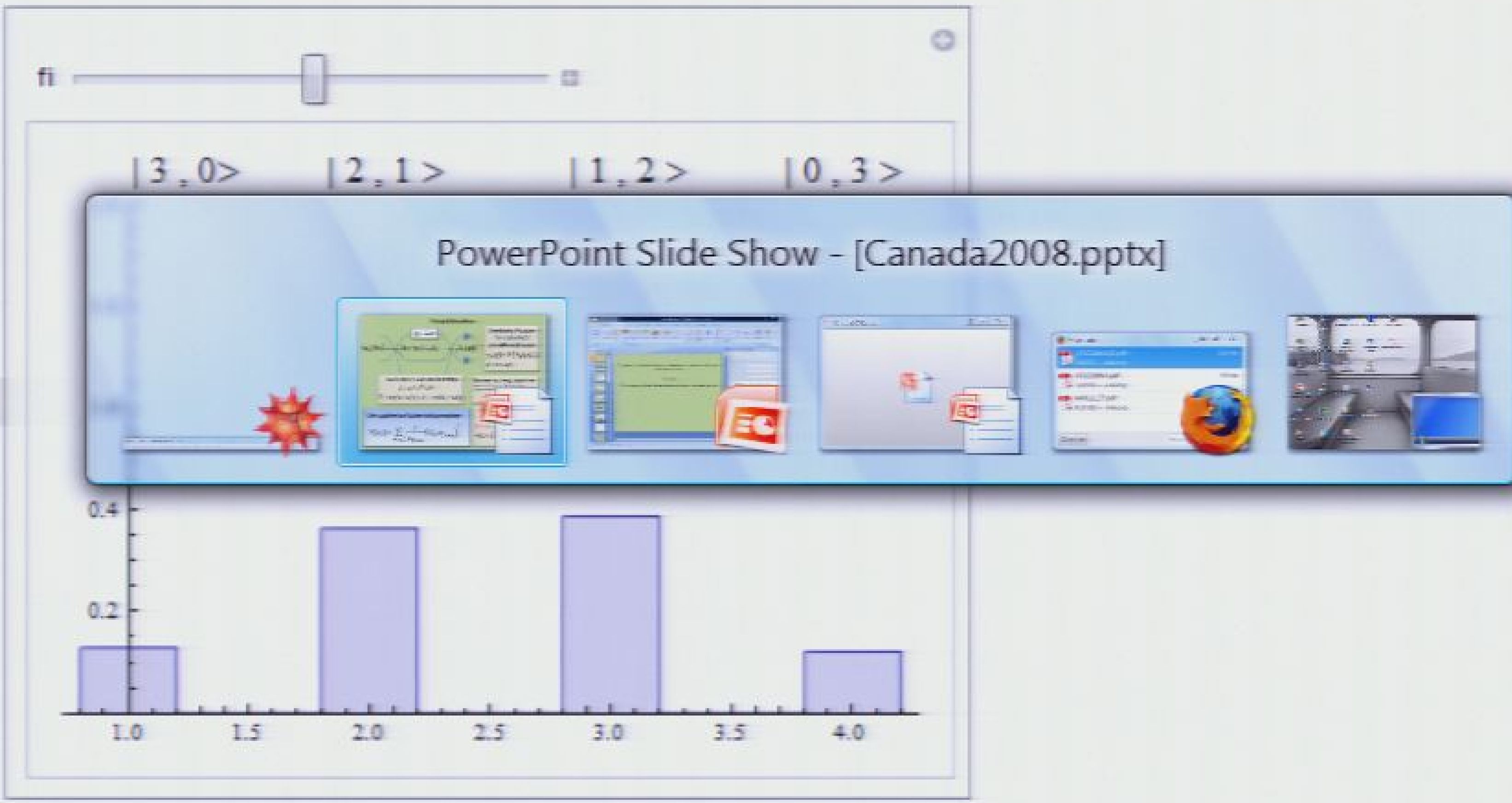

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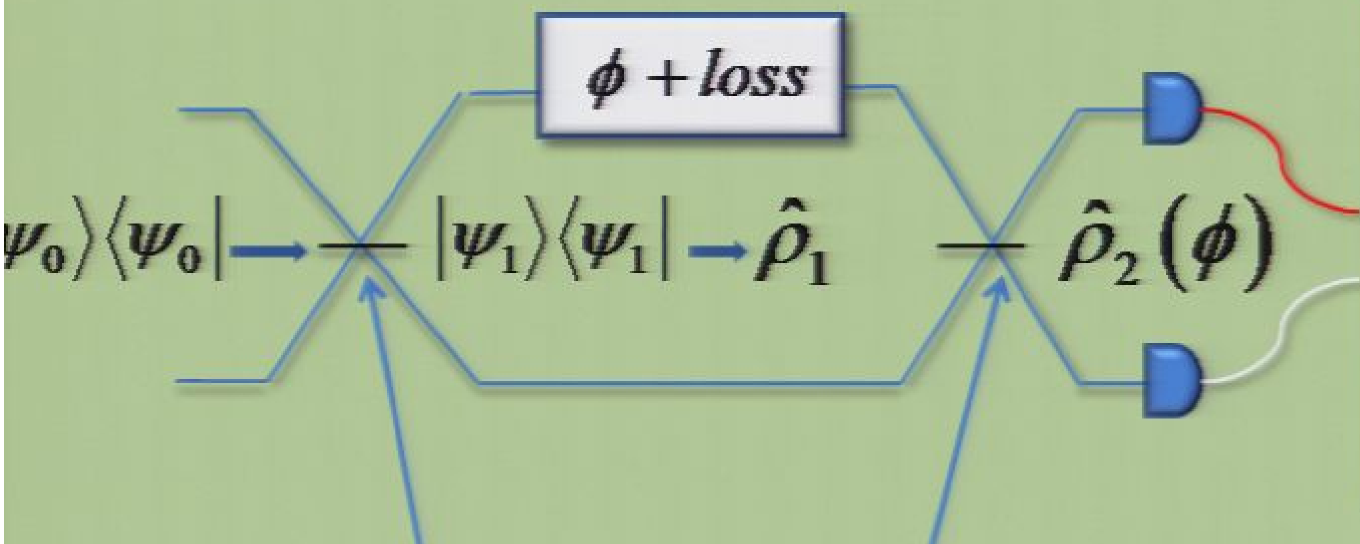

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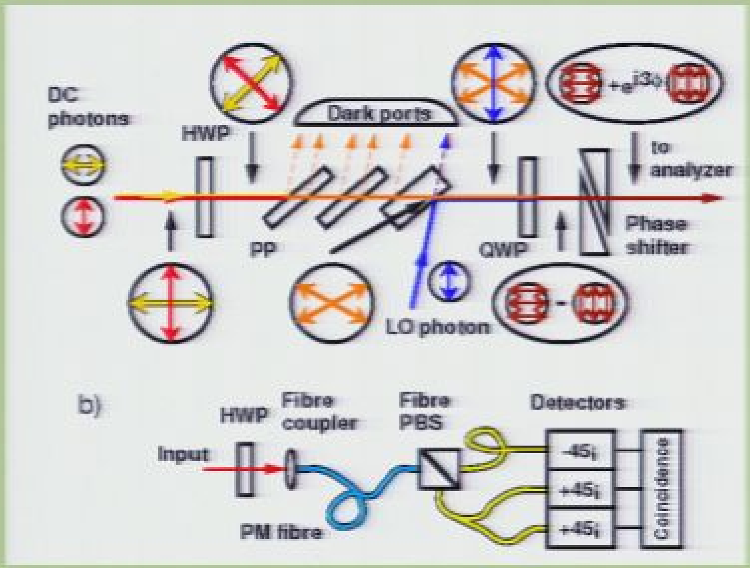
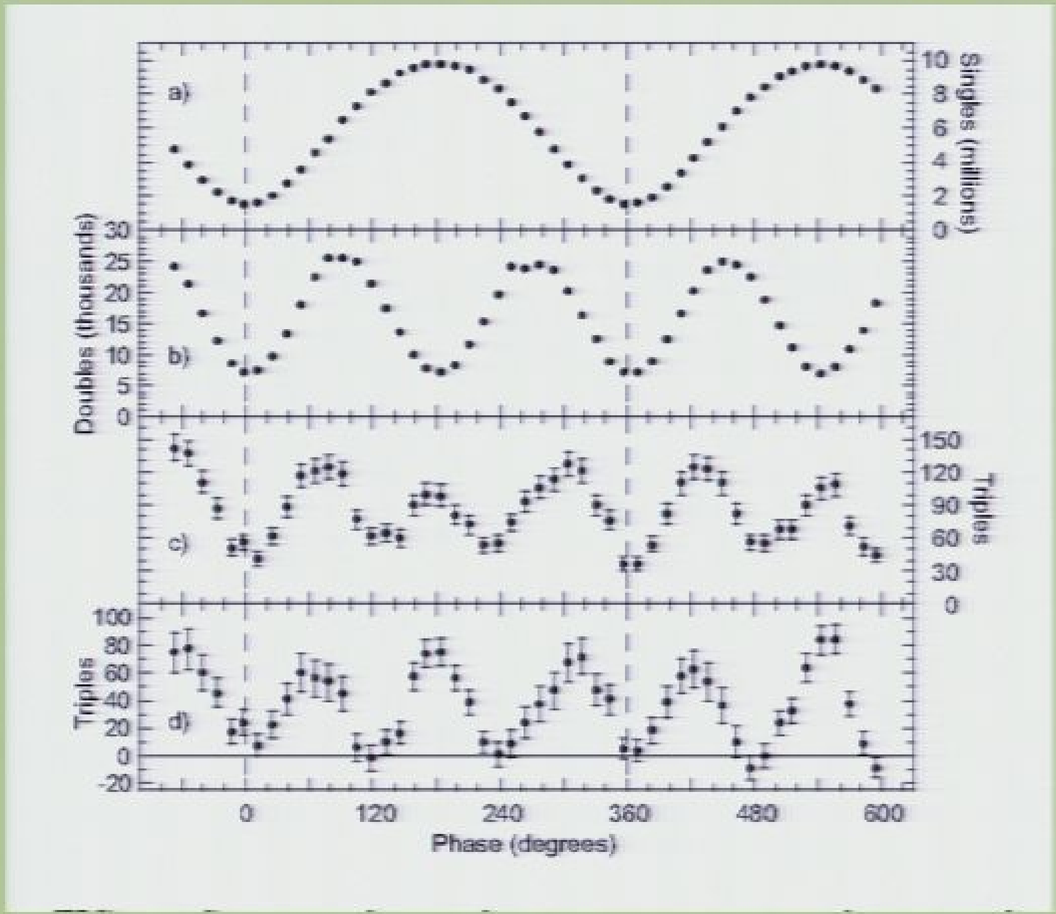
Mitchell, J. S. Lundeen and A. M. Steinberg 2003





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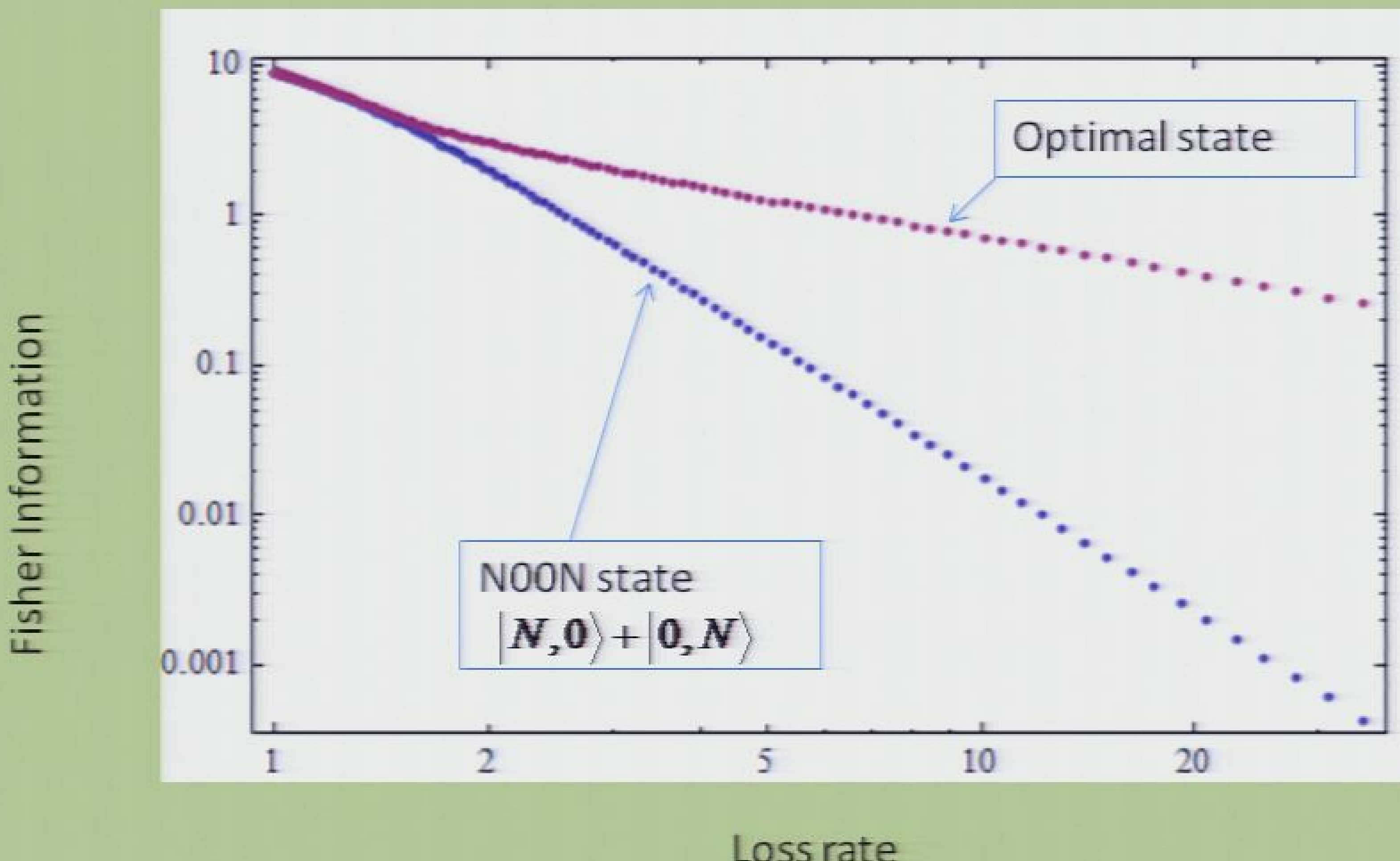

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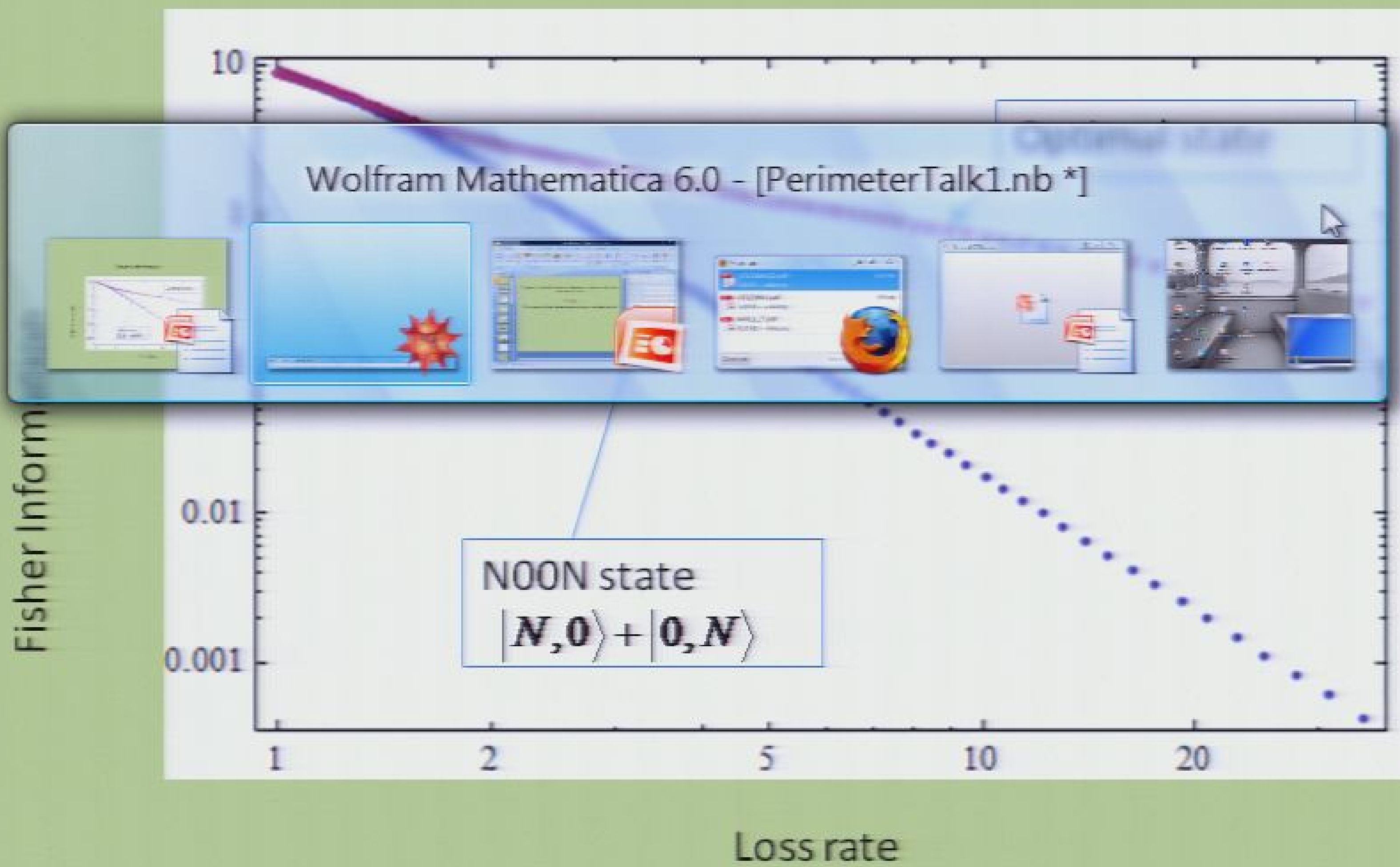

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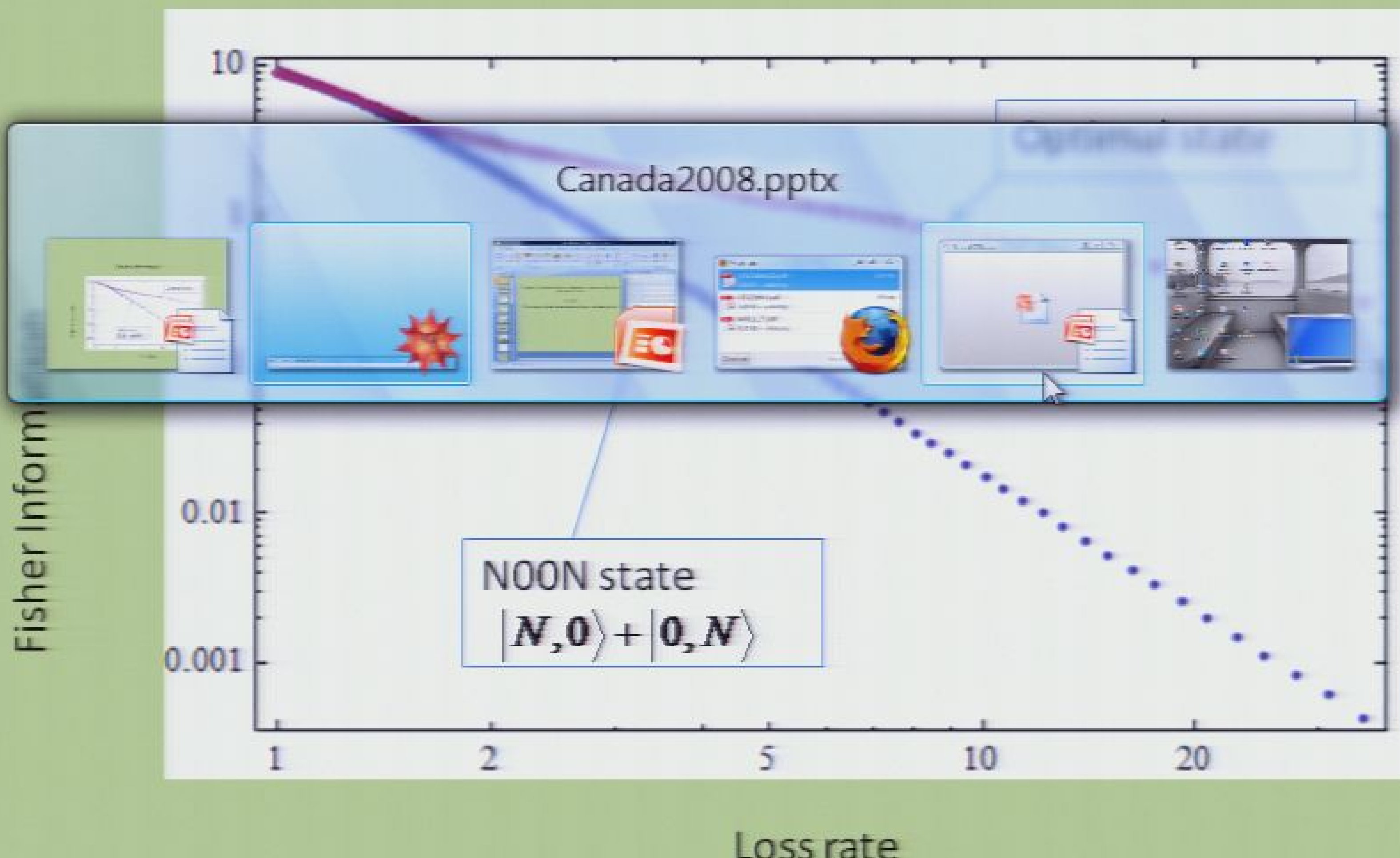

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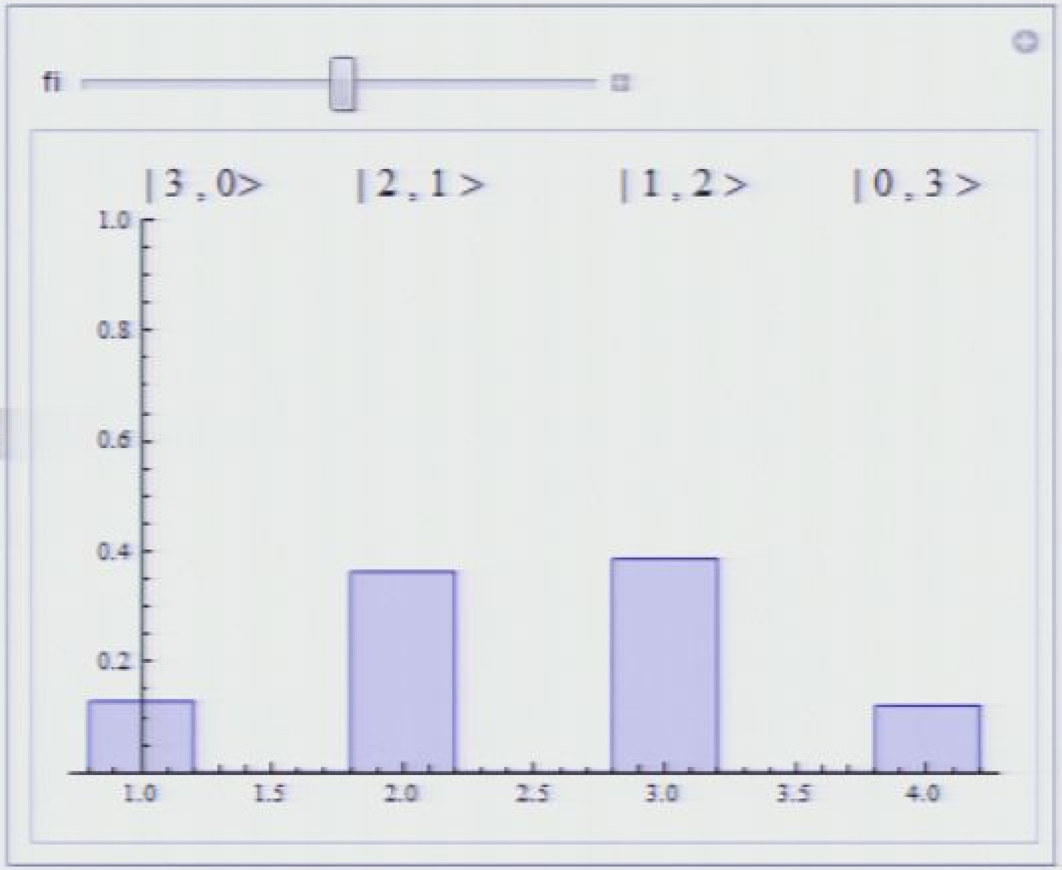
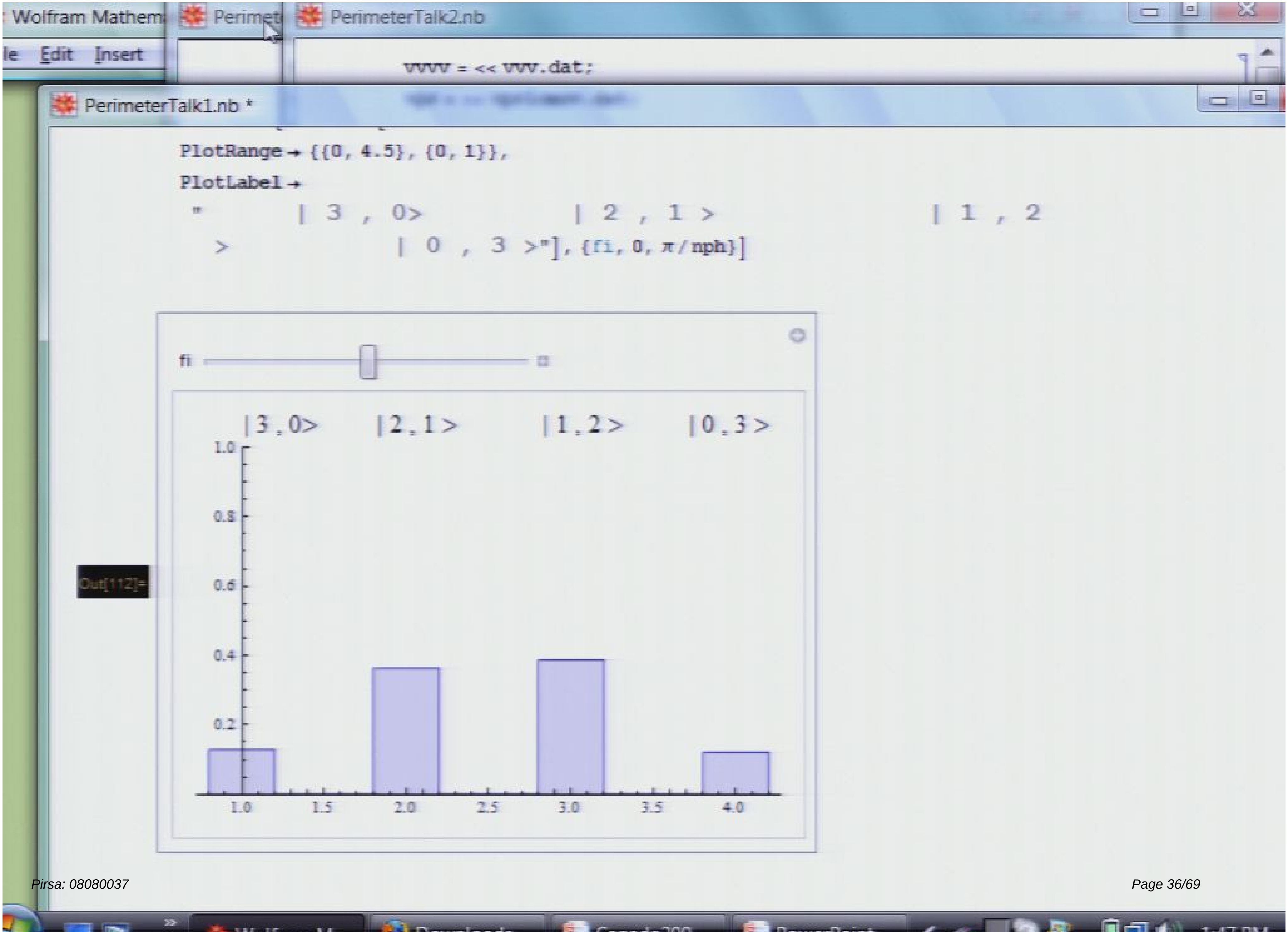
```

Out[112]=



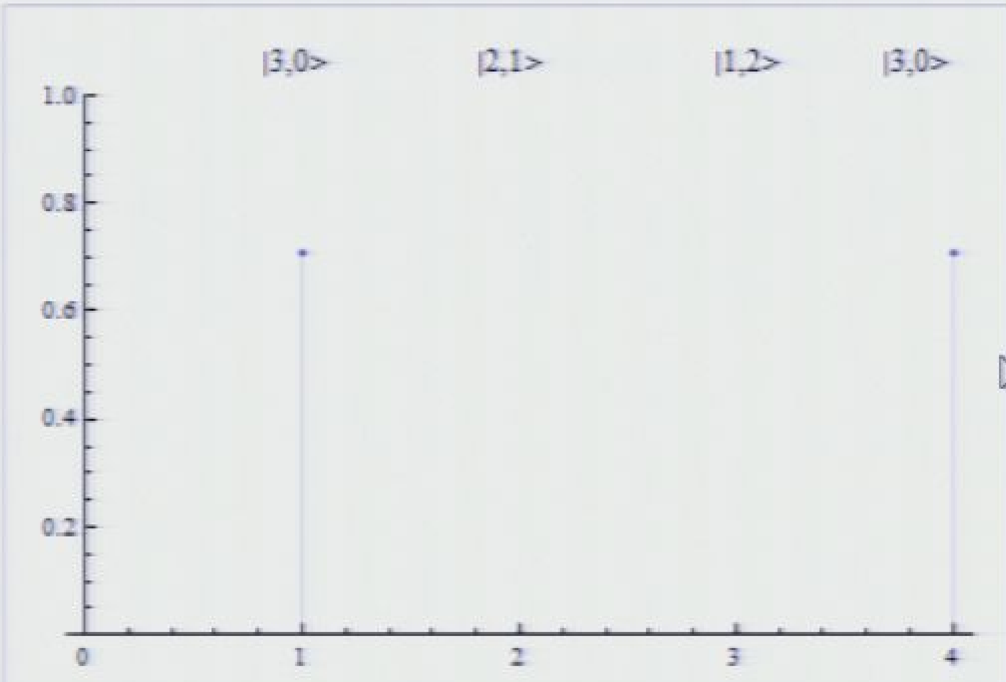

Wolfram Mathem
Perimet
PerimeterTalk2.nb
le Edit Insert
vvvv = << vvv.dat;
PerimeterTalk1.nb *
PlotRange → {{0, 4.5}, {0, 1}},
PlotLabel →
" | 3 , 0> | 2 , 1 > | 1 , 2
> | 0 , 3 >"], {fi, 0, π/nph}]
fi
Out[112]=
|3,0> |2,1> |1,2> |0,3>
1.0
0.8
0.6
0.4
0.2
1.0 1.5 2.0 2.5 3.0 3.5 4.0

PerimeterTalk3.nb

```
vr >> vr.dat;
vvr = << vr.dat;
Manipulate[ListPlot[Abs[vvr[[m, n, 2]]], PlotRange → {0, 1},
  Filling → Bottom,
  PlotLabel →
   "                         |3,0>
     |2,1>                        |1,2>                  |3,0>"],
 {n, 1, 156, 1}, {m, 1, 11, 1}]
```

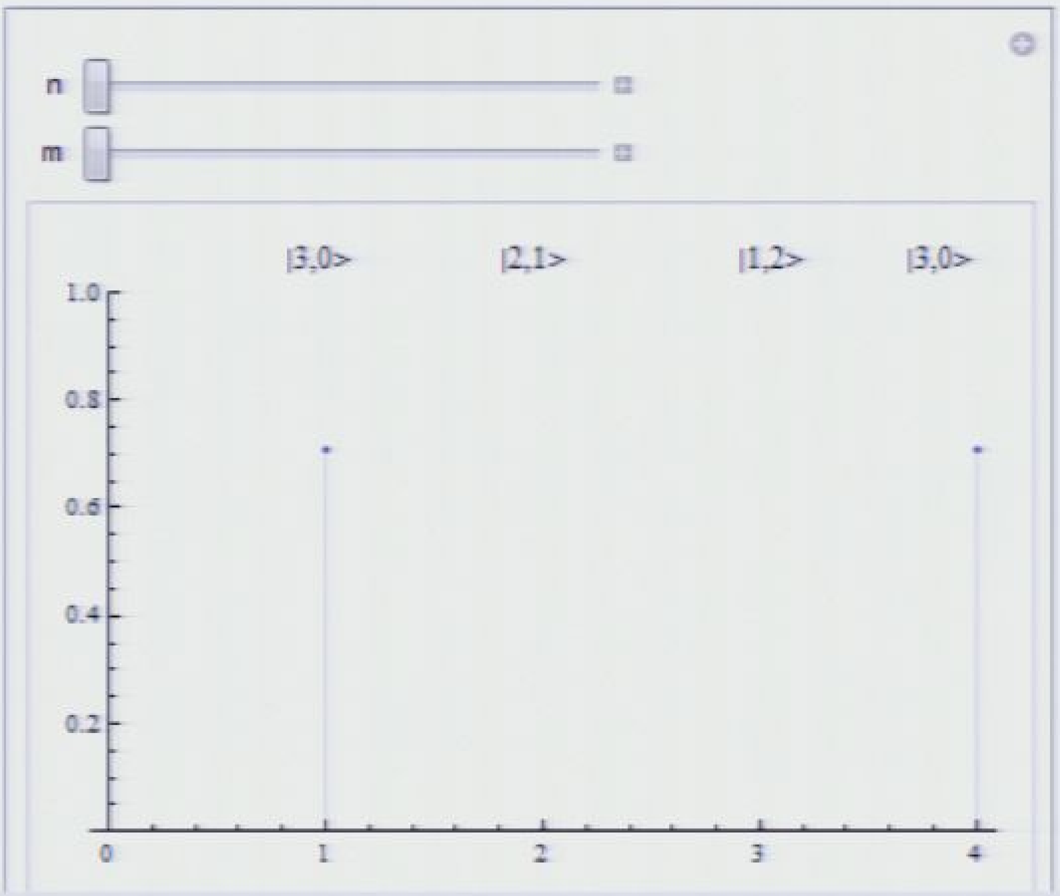
n

m

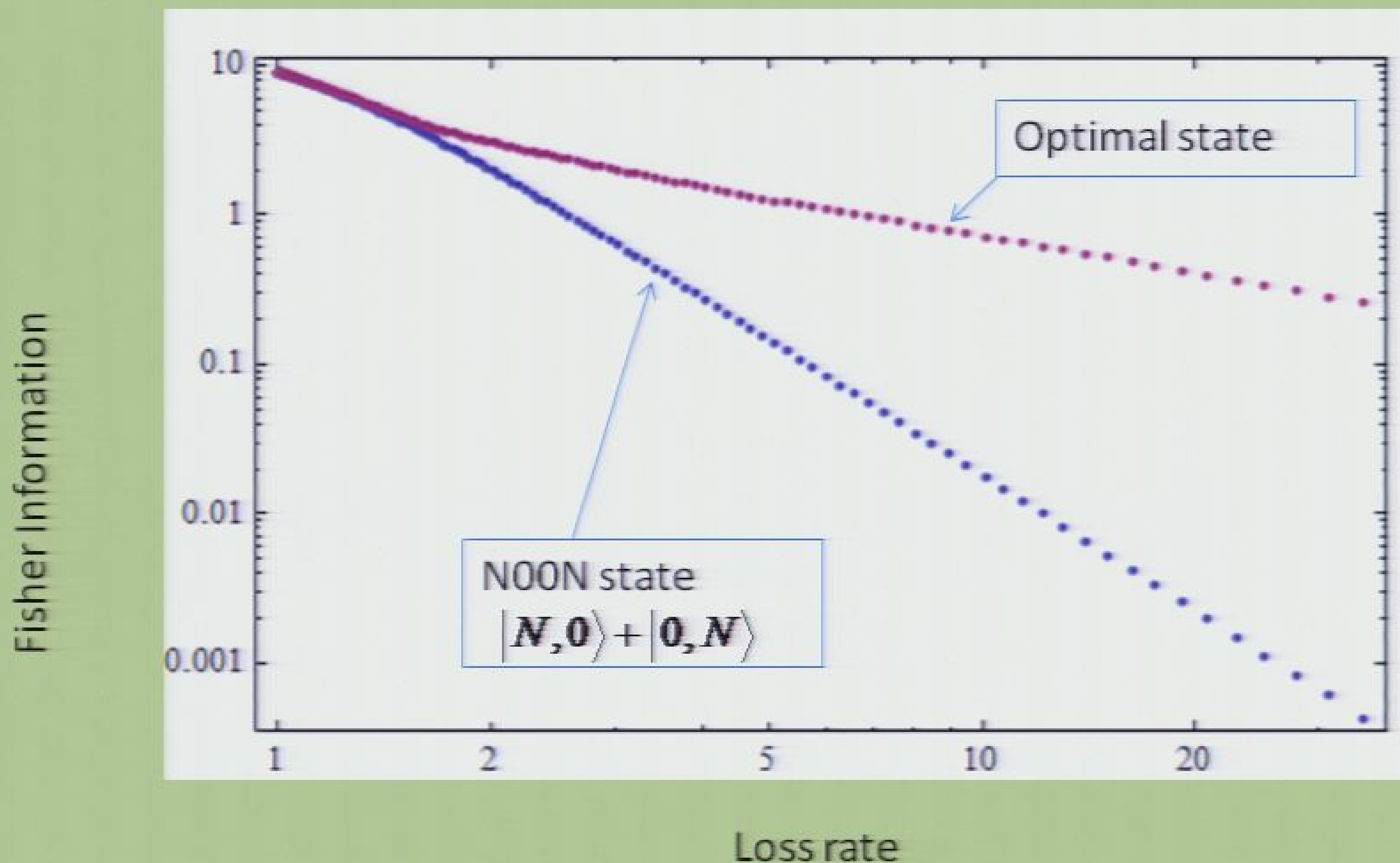


PerimeterTalk3.nb

```
vr >> vr.dat;
vvr = << vr.dat;
Manipulate[ListPlot[Abs[vvr[[m, n, 2]]], PlotRange → {0, 1},
  Filling → Bottom,
  PlotLabel →
   "                          |3,0>
     |2,1>                          |1,2>                |3,0>"],
 {n, 1, 156, 1}, {m, 1, 11, 1}]
```

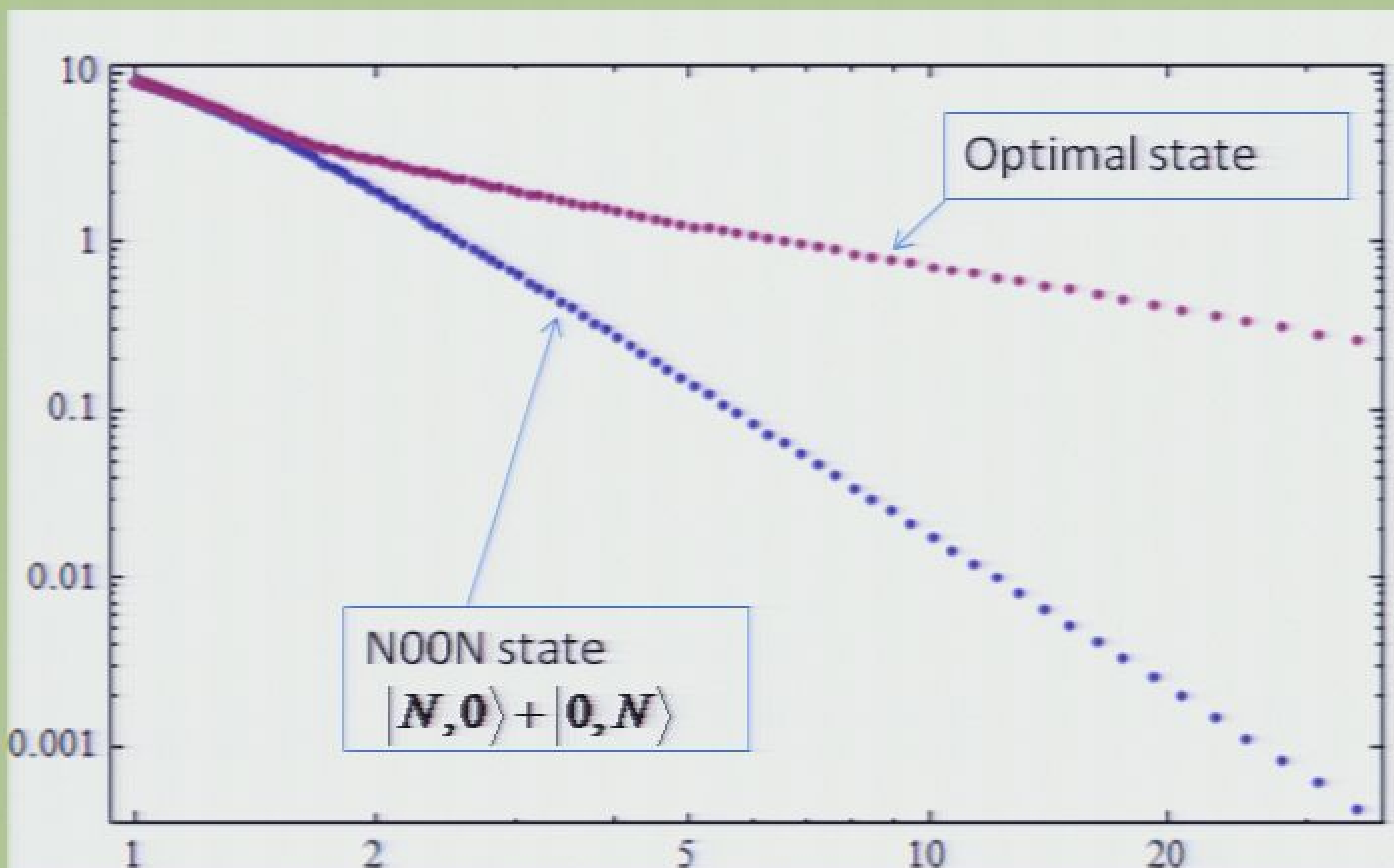


Fisher Information



What is the Optimal State ψ_1 ?

Fisher Information

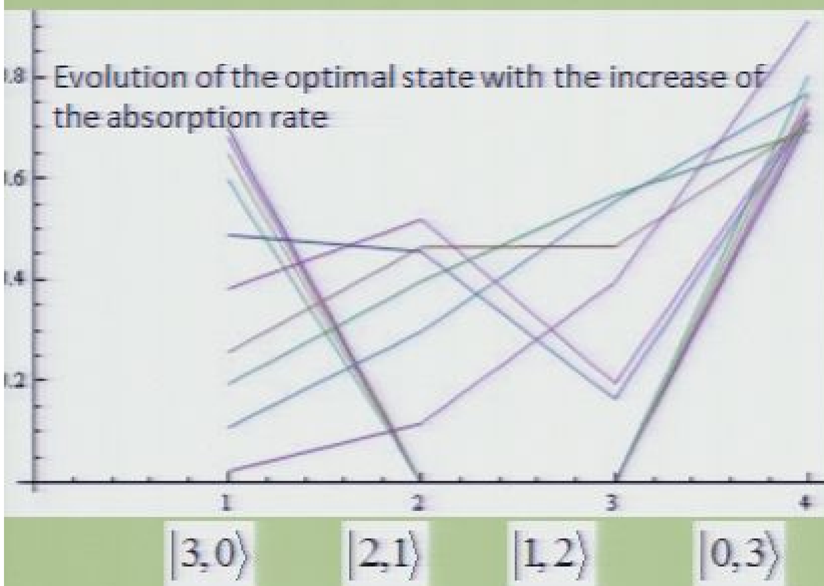


Fisher Information

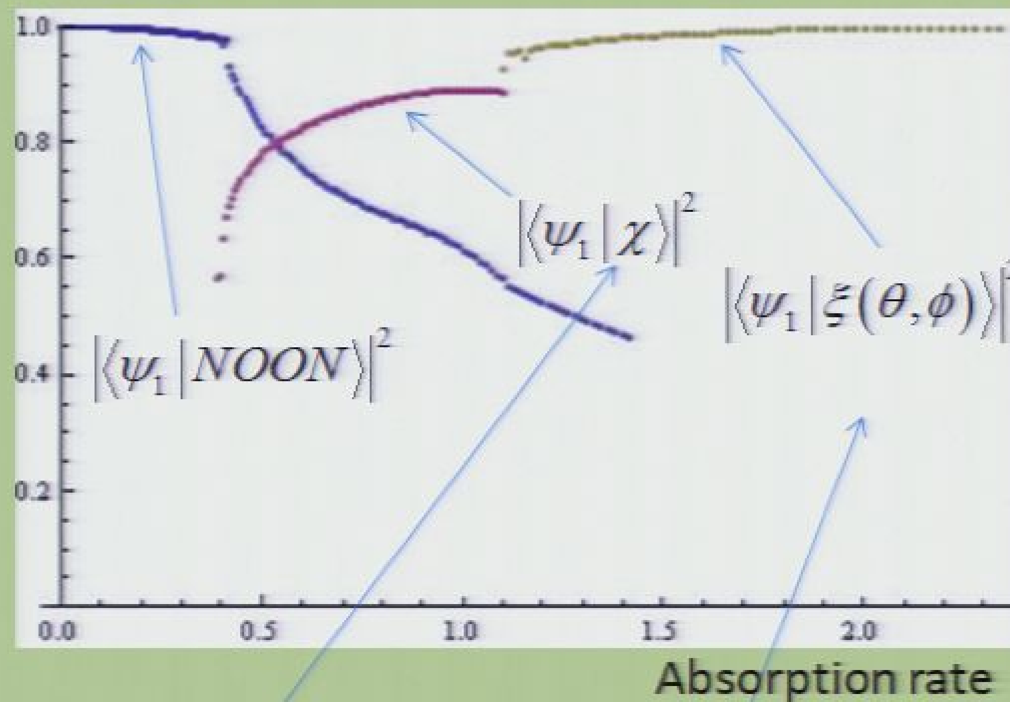
Loss rate

What is the Optimal State ψ_1 ?

Absorption rate



Structure of the optimal state

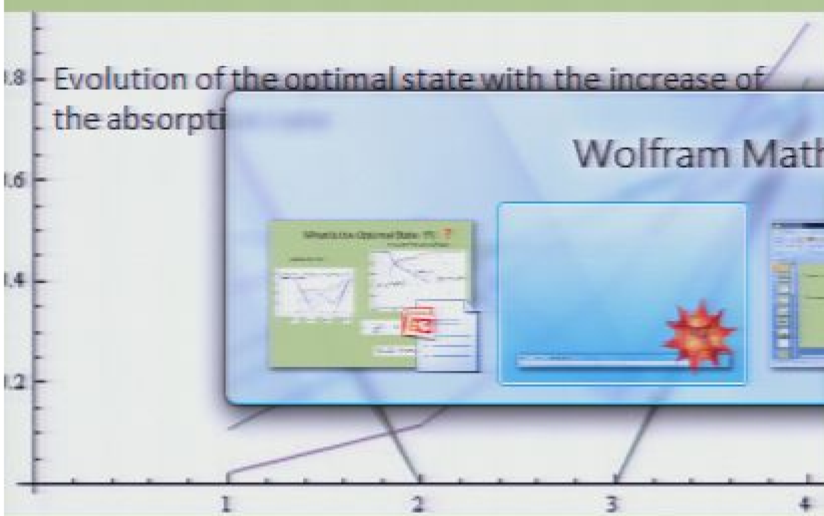


$$\chi = \frac{1}{\sqrt{2}}\left(|N-1,1\rangle + |0,N\rangle\right)$$

$$|\xi(\theta,\phi)\rangle = Generalized\ Coherent\ State$$

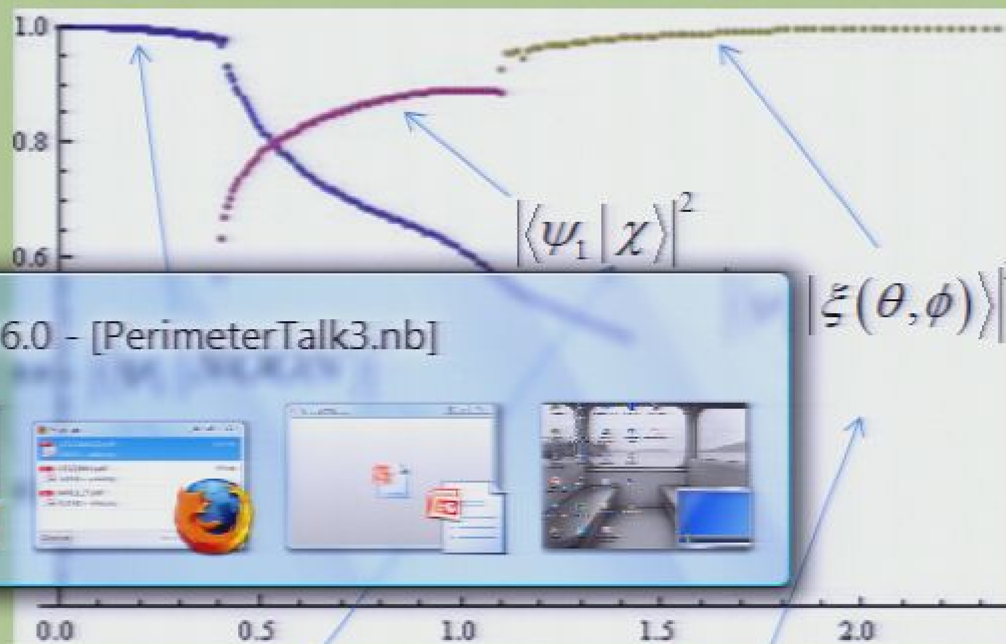
What is the Optimal State ψ_1 ?

Absorption rate



$|3,0\rangle$ $|2,1\rangle$ $|1,2\rangle$ $|0,3\rangle$

Structure of the optimal state



$|\langle\psi_1|\chi\rangle|^2$

$|\xi(\theta,\phi)\rangle|^2$

Absorption rate

$$\chi = \frac{1}{\sqrt{2}}\left(|N-1,1\rangle + |0,N\rangle\right)$$

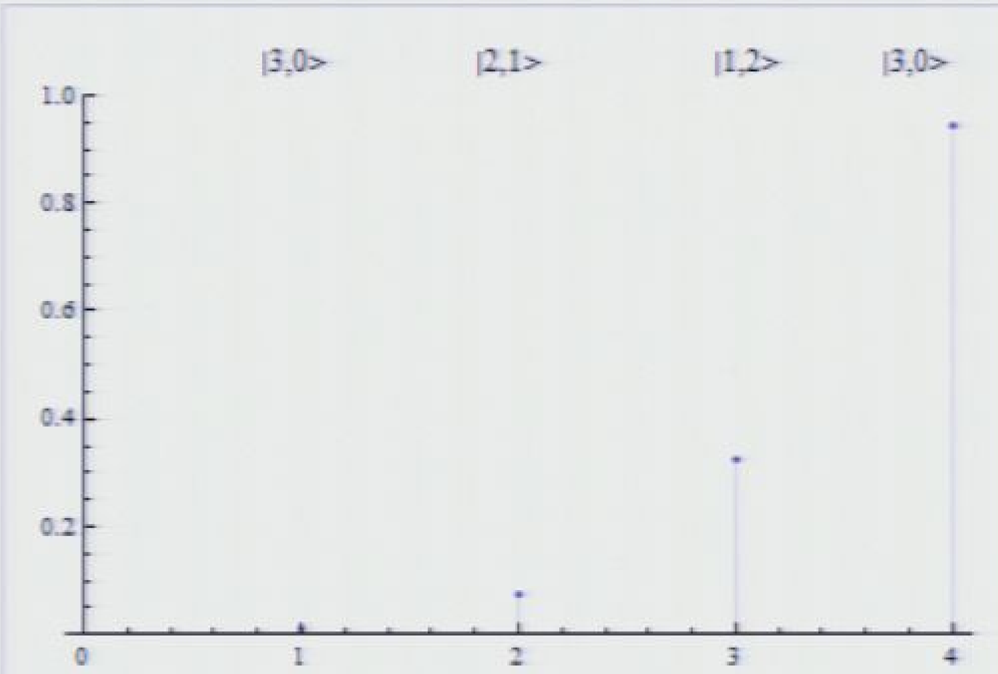
$$|\xi(\theta,\phi)\rangle = Generalized\ Coherent\ State$$

PerimeterTalk3.nb

```
vr >> vr.dat;
vvr = << vr.dat;
Manipulate[ListPlot[Abs[vvr[[m, n, 2]]], PlotRange → {0, 1},
  Filling → Bottom,
  PlotLabel →
   "                    |3,0>
     |2,1>                    |1,2>                |3,0>"],
 {n, 1, 156, 1}, {m, 1, 11, 1}]
```

n

m



100%

PerimeterTalk3.nb

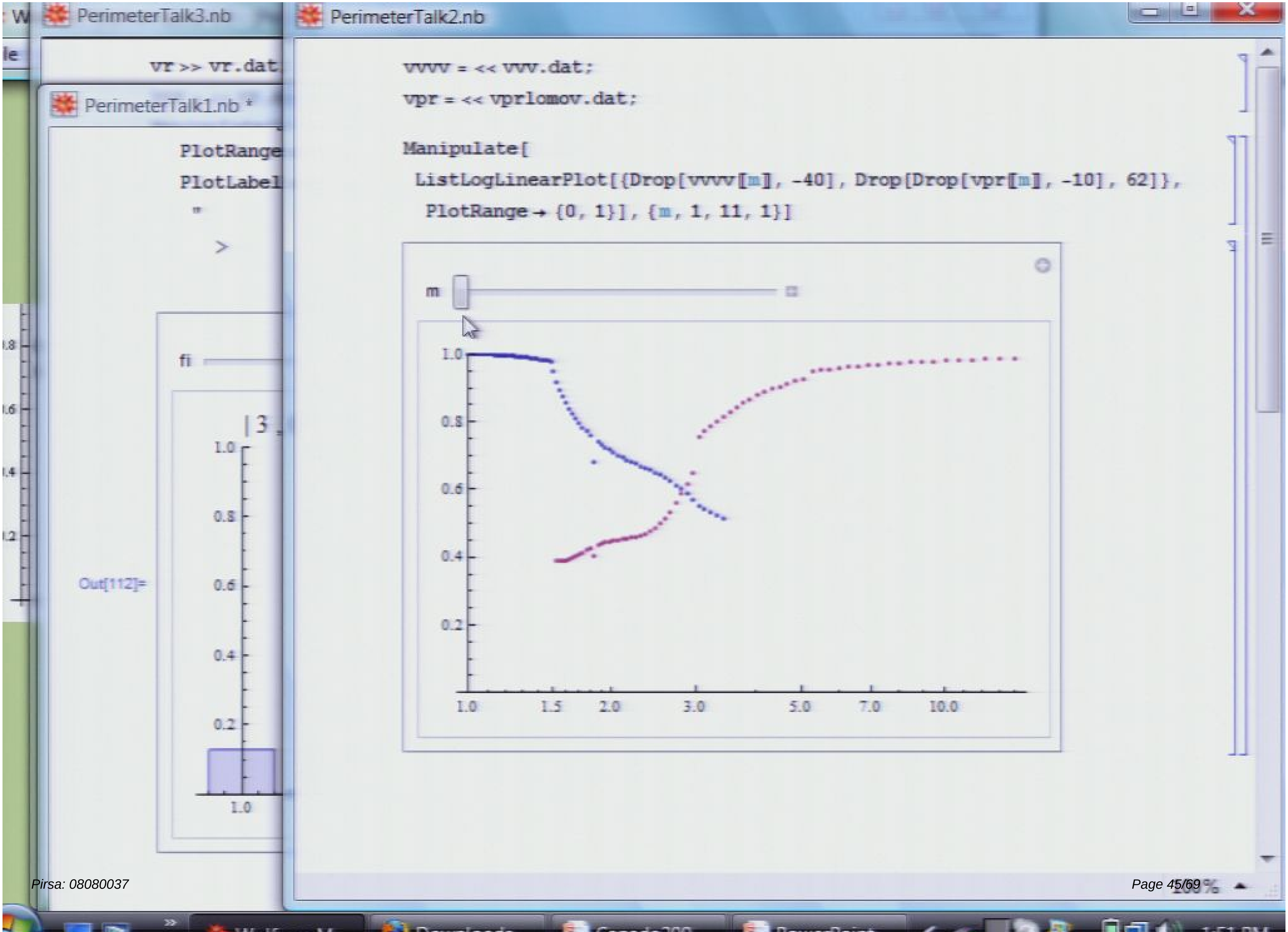
```
vr >> vr.dat;
```

PerimeterTalk1.nb *

```
PlotRange → {{0, 4.5}, {0, 1}},
PlotLabel →
 "     | 3 , 0>        | 2 , 1 >             | 1 , 2
  >          | 0 , 3 >"], {fi, 0, π / nph}]
```

Out[112]=

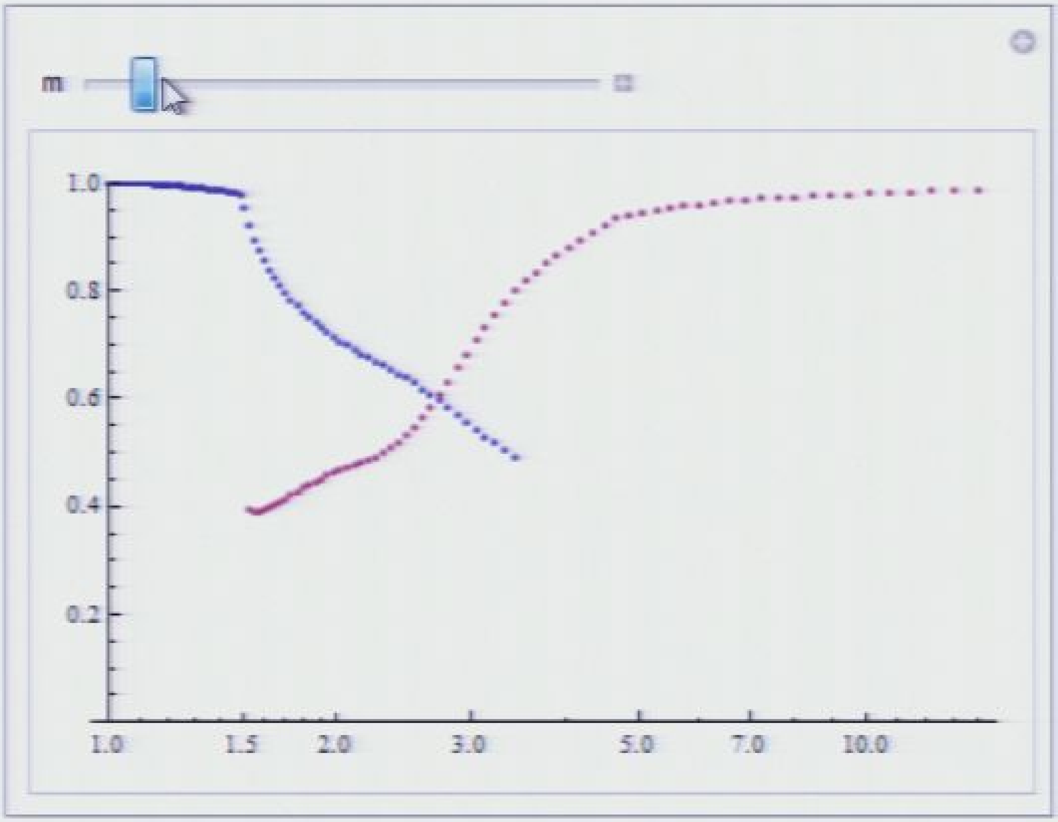
fi

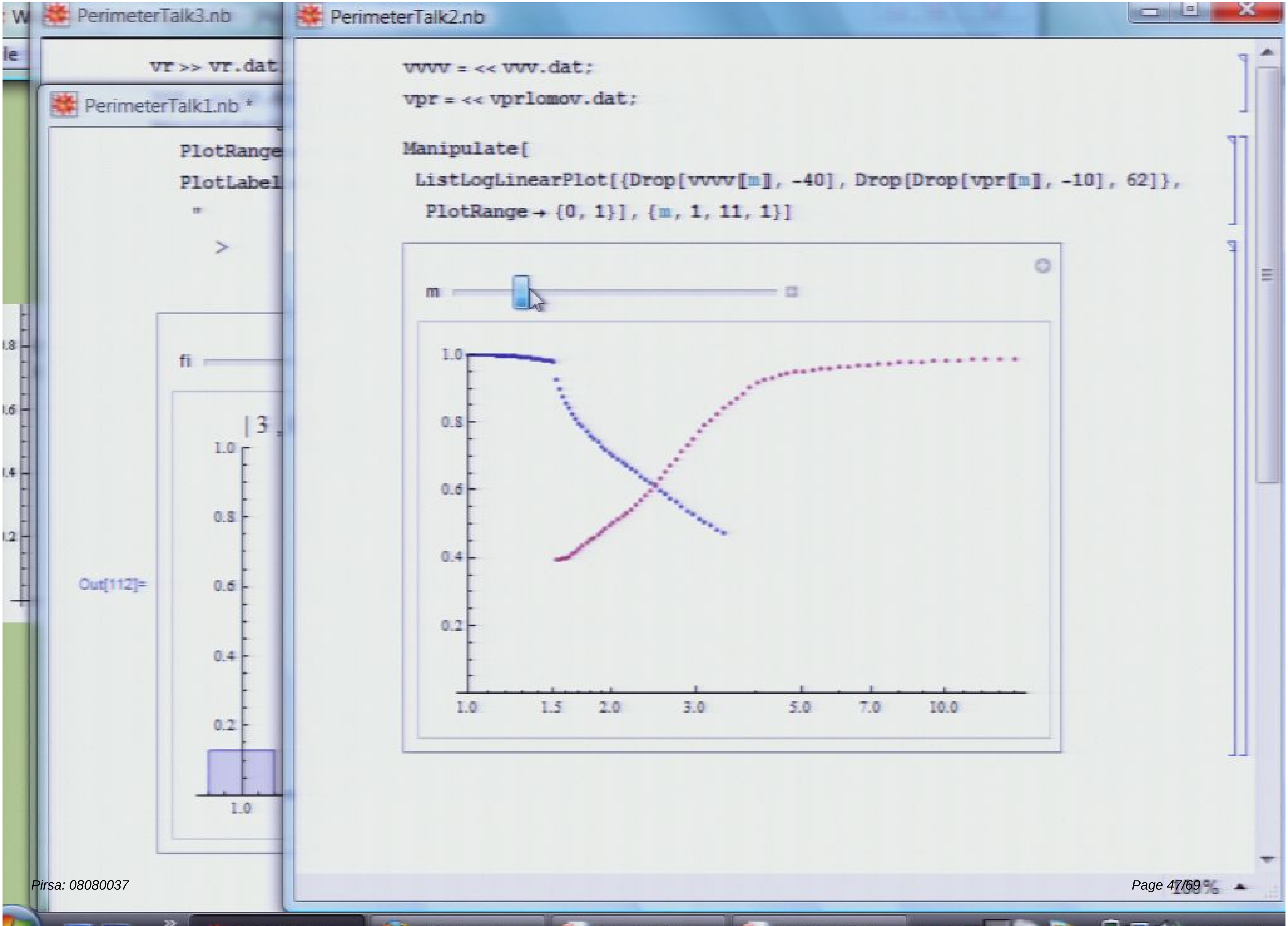

PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
1.0
0.8
0.6
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0
PlotRange
PlotLabel
fi
Out[112]=

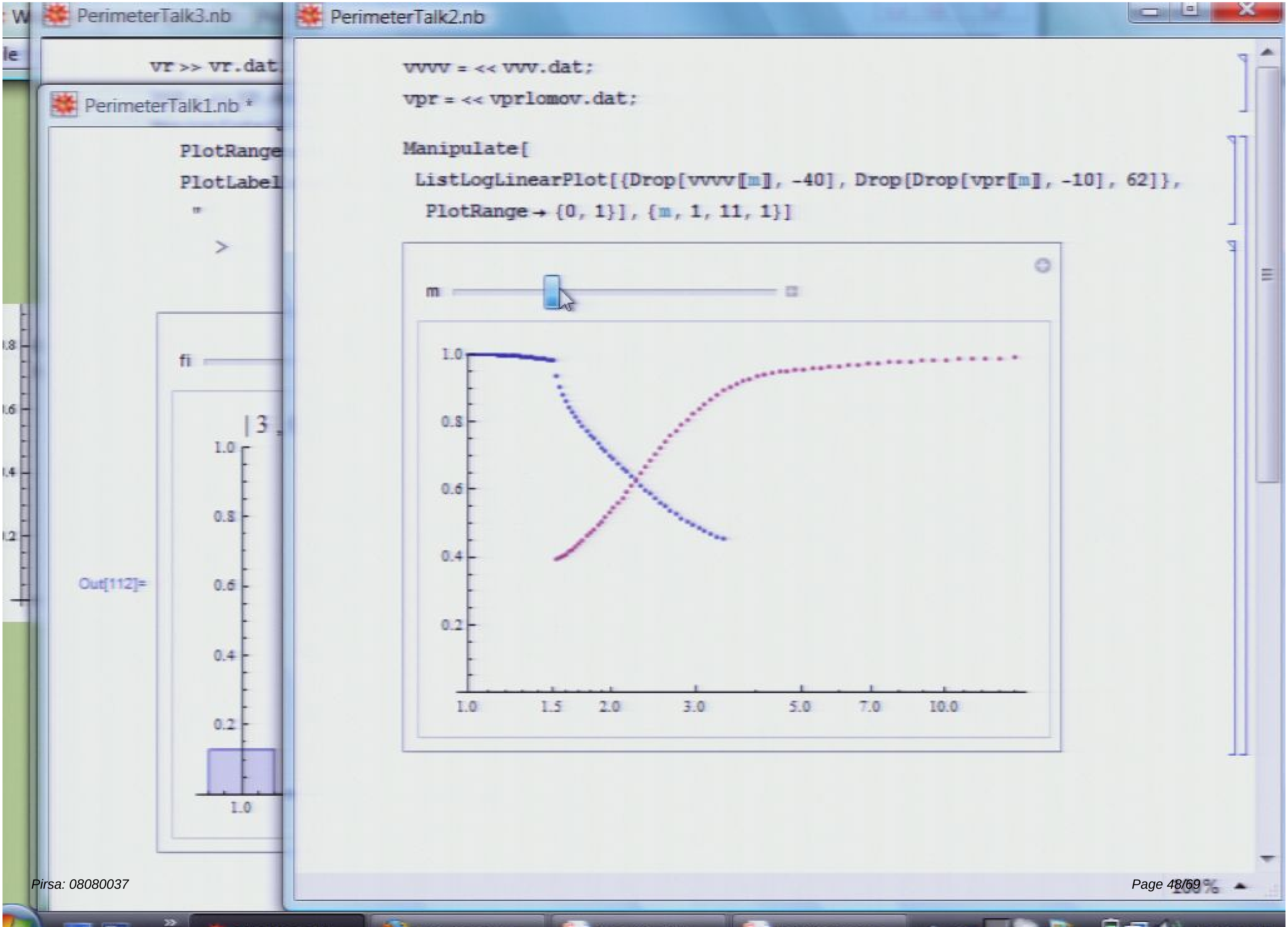
PerimeterTalk2.nb

```
vvvv = << vvv.dat;
vpr = << vprlomov.dat;

Manipulate[
 ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
  PlotRange → {0, 1}], {m, 1, 11, 1}]
```

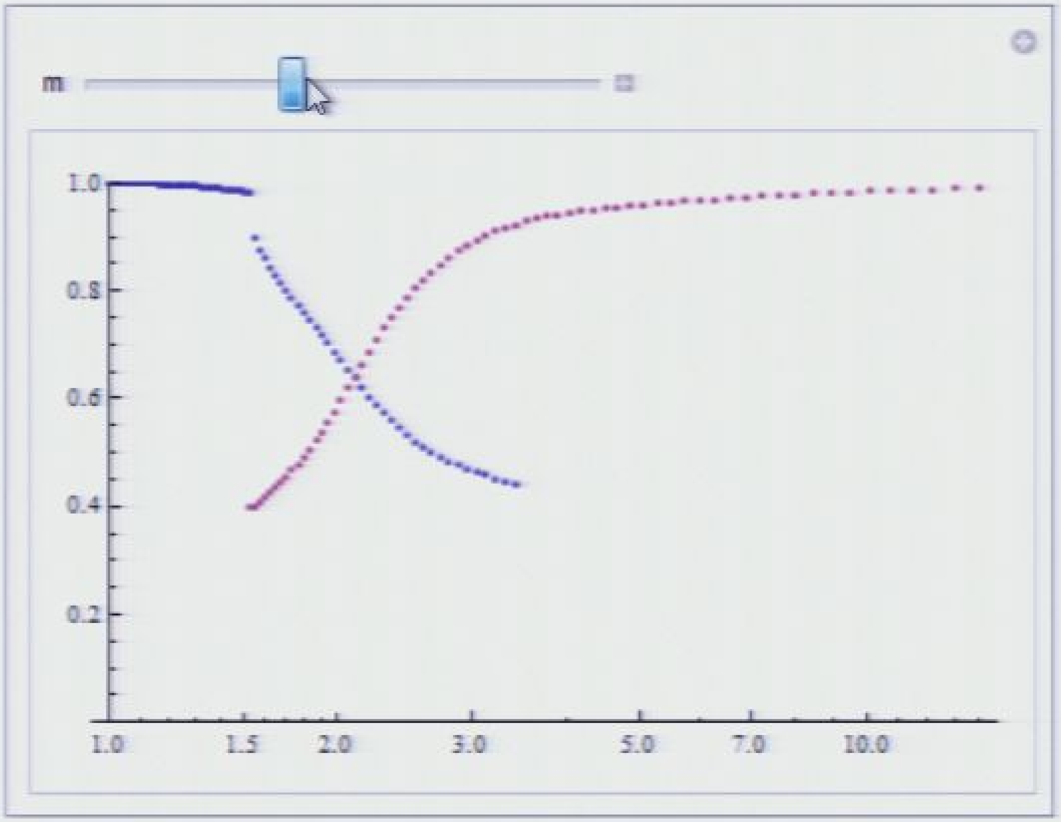


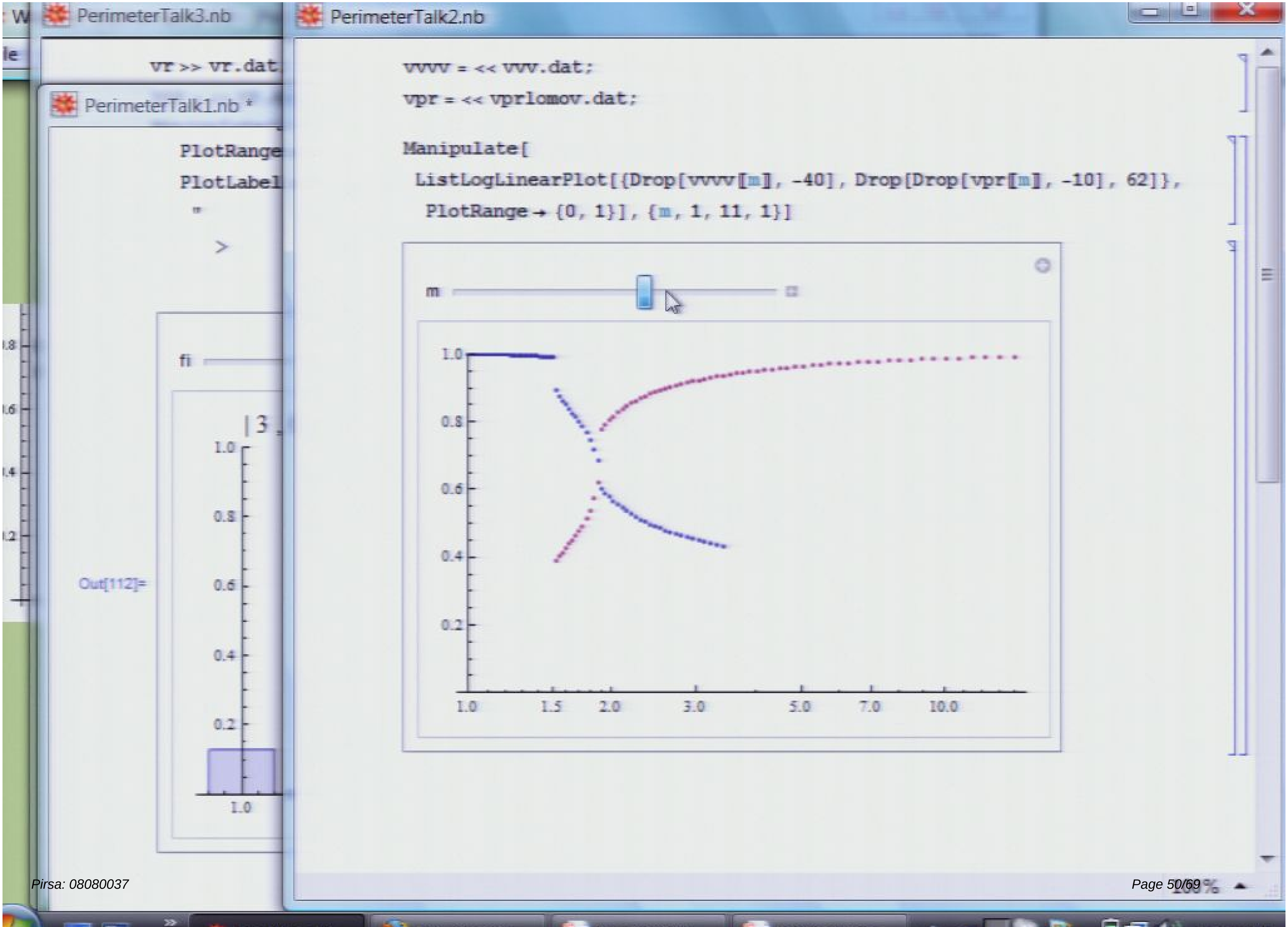

PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
PlotRange
PlotLabel
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
fi
Out[112]=
1.0
0.8
0.6
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0

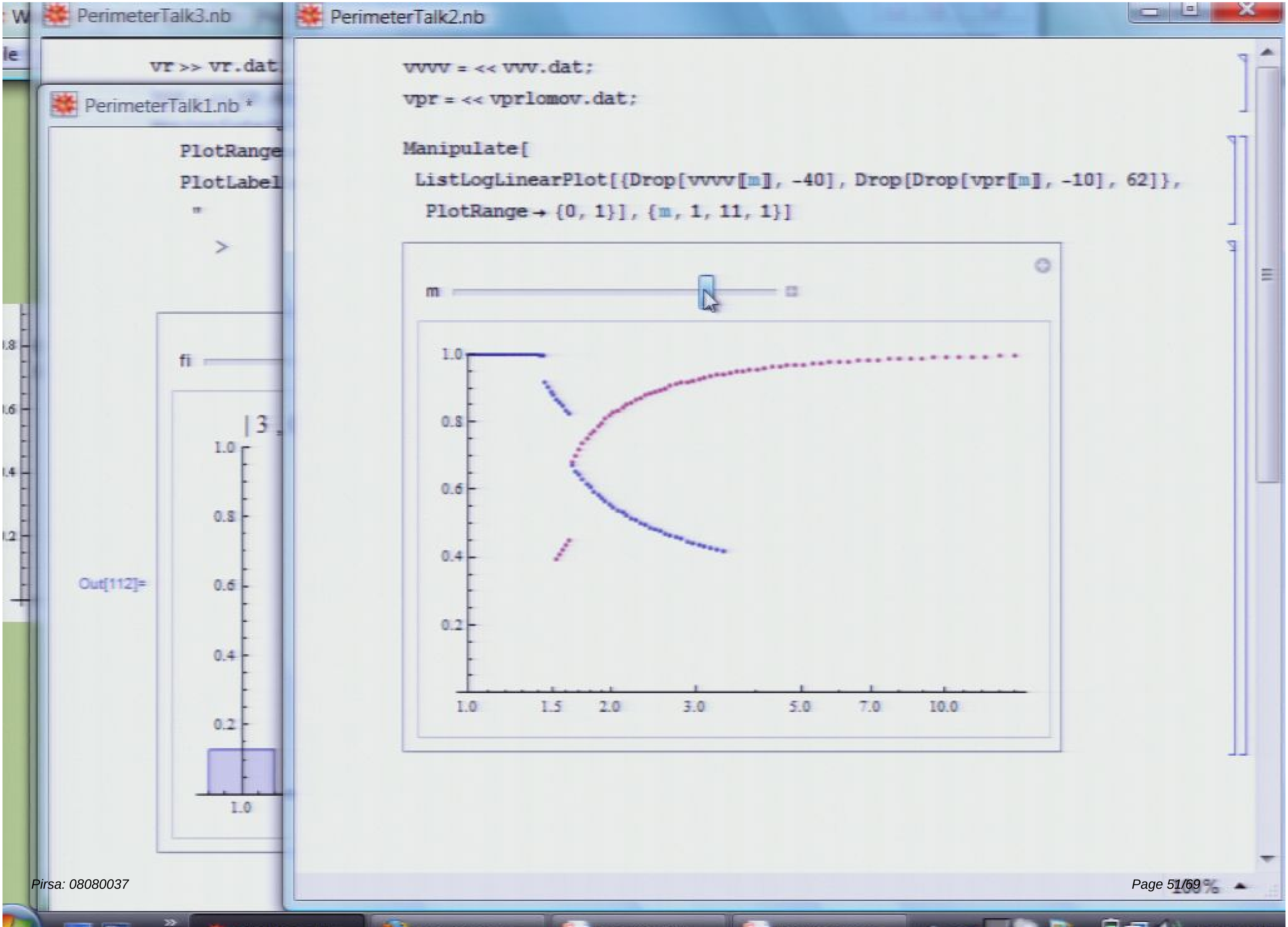

PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
PlotRange
PlotLabel
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
Out[112]=
fi
1.0
0.8
0.6
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0

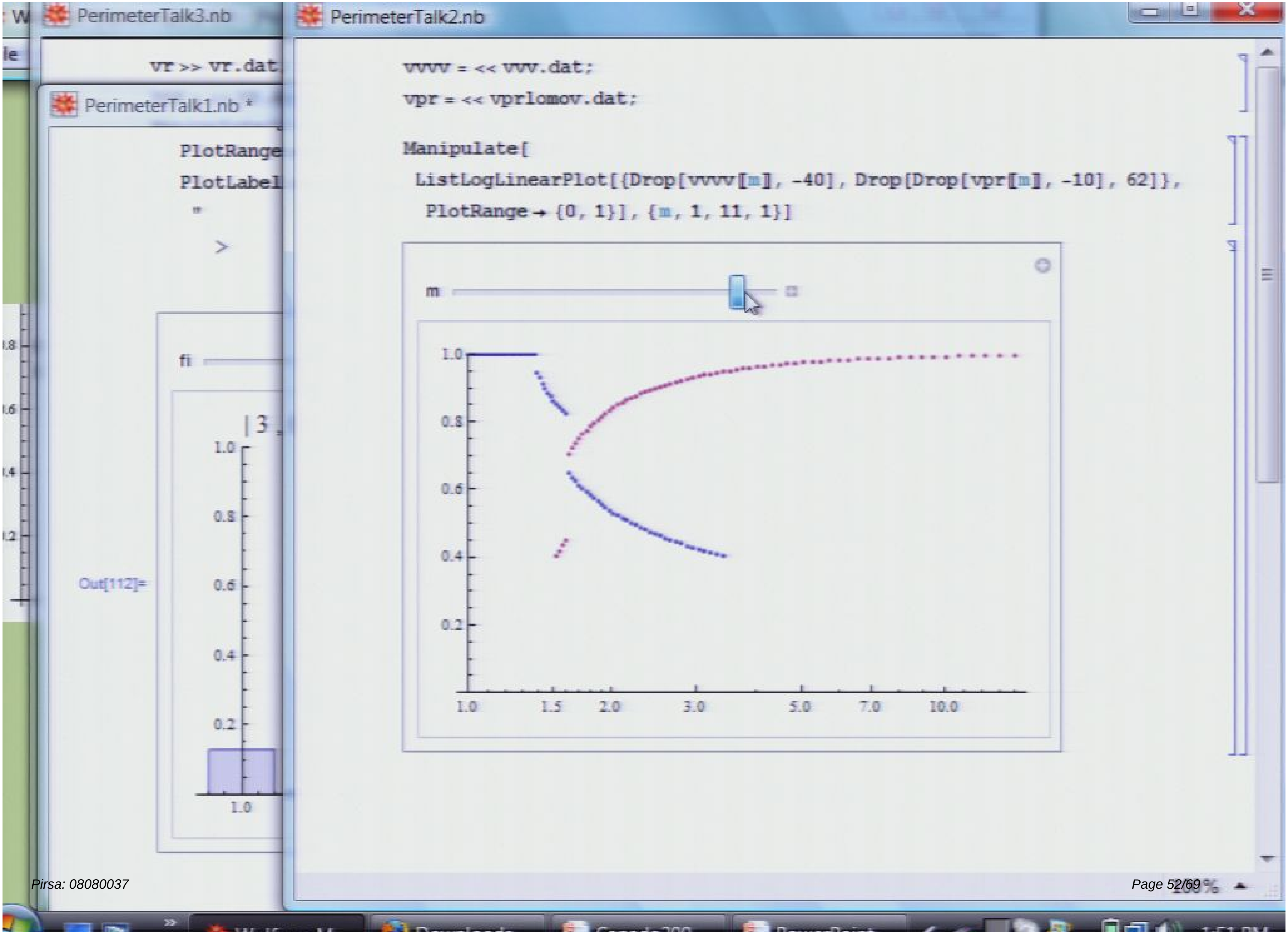
```
vvvv = << vvv.dat;
vpr = << vprlomov.dat;

Manipulate[
 ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
  PlotRange → {0, 1}], {m, 1, 11, 1}]
```




PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
1.0
0.8
0.6
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0
Out[112]=

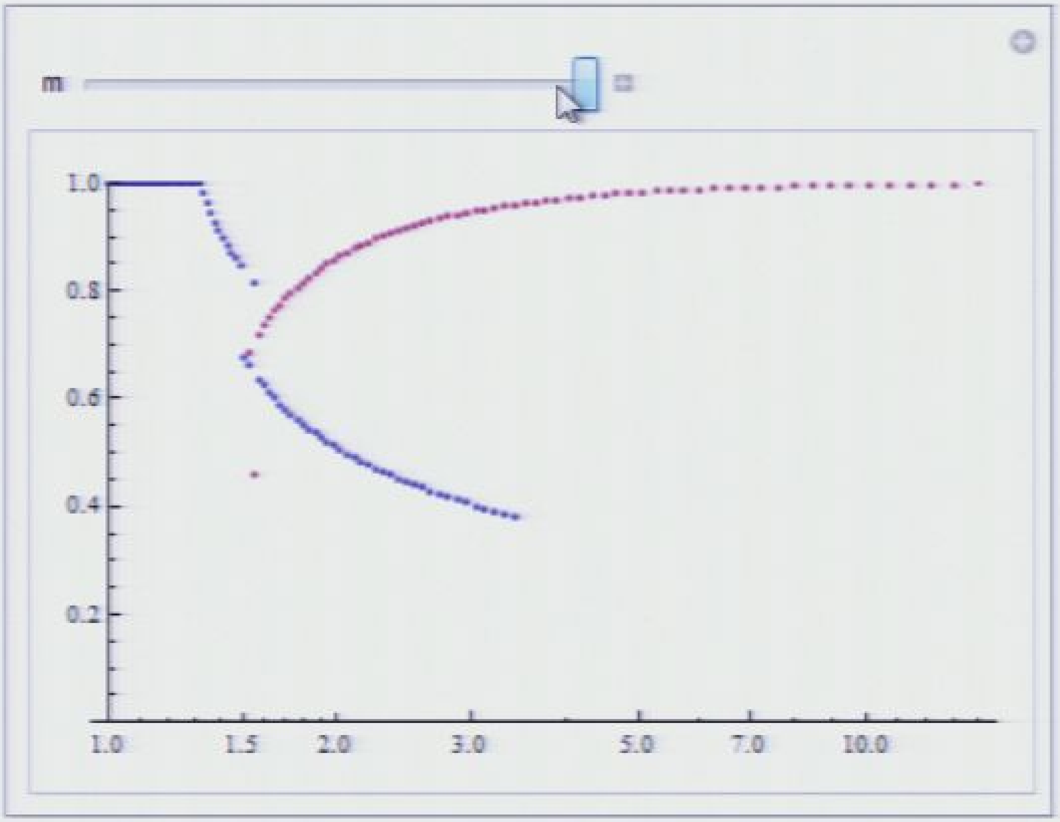

PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
Out[112]=
PlotRange
PlotLabel
fi

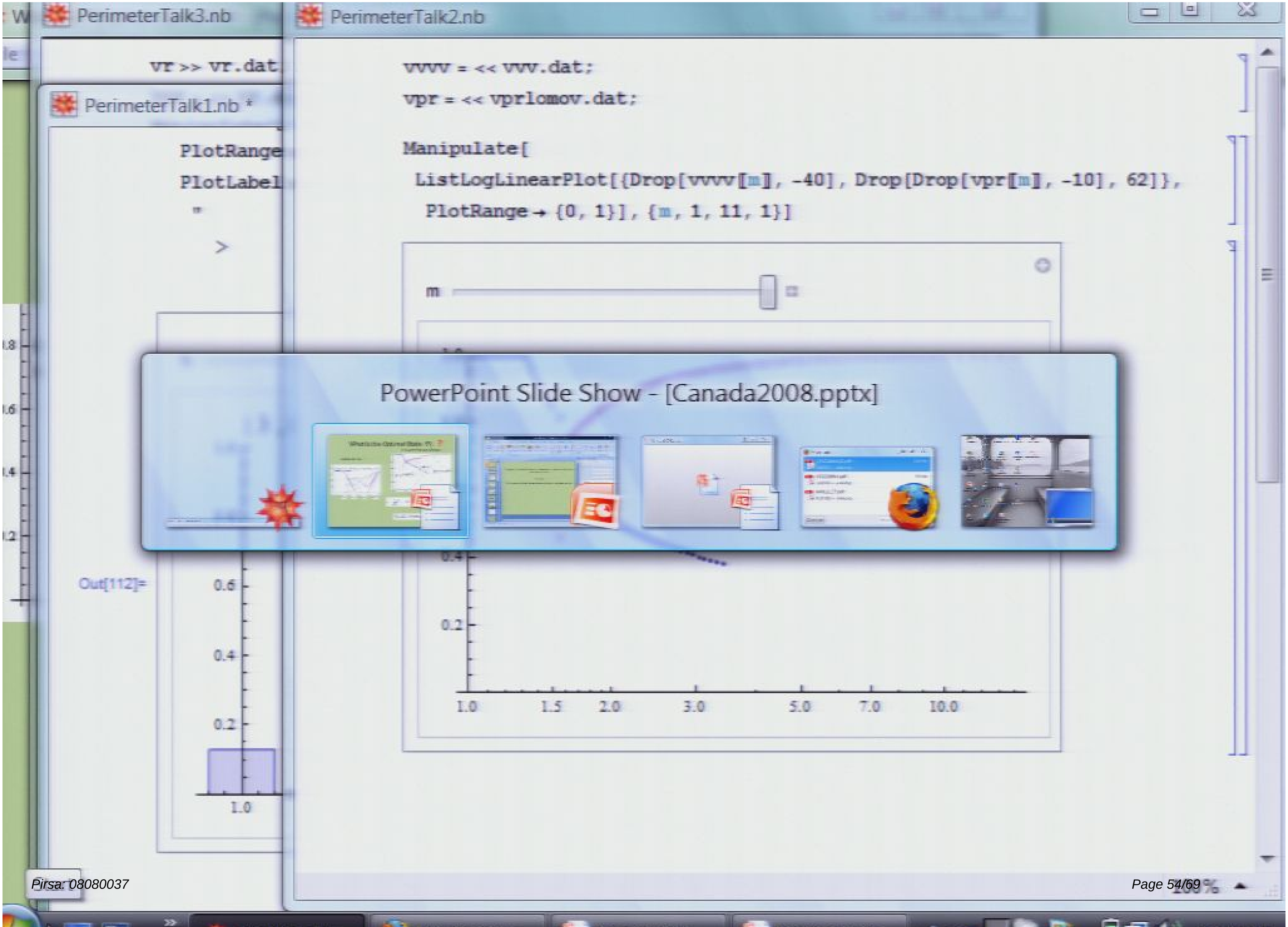

PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
PlotRange
PlotLabel
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
fi
Out[112]=
1.0
0.8
0.6
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0

PerimeterTalk2.nb

```
vvvv = << vvv.dat;
vpr = << vprlomov.dat;

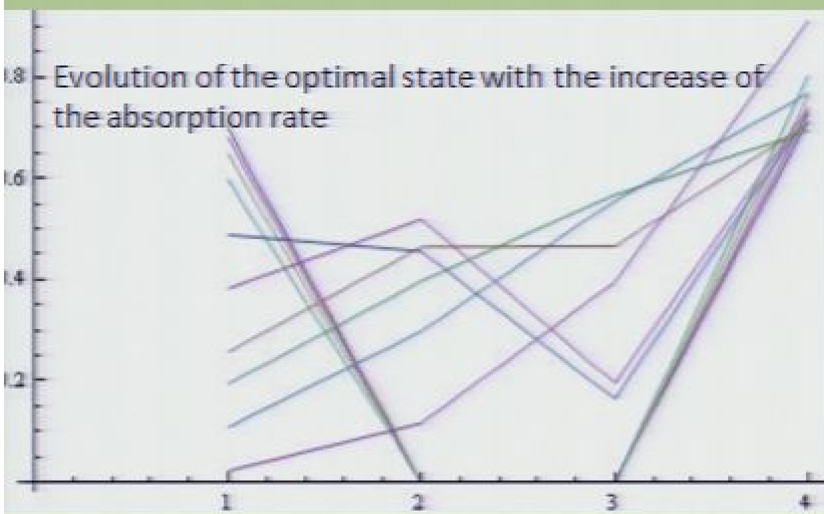
Manipulate[
 ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
  PlotRange → {0, 1}], {m, 1, 11, 1}]
```




PerimeterTalk3.nb
PerimeterTalk2.nb
PerimeterTalk1.nb *
vr >> vr.dat
PlotRange
PlotLabel
vvvv = << vvv.dat;
vpr = << vprlomov.dat;
Manipulate[
ListLogLinearPlot[{Drop[vvvv[[m]], -40], Drop[Drop[vpr[[m]], -10], 62]},
PlotRange → {0, 1}], {m, 1, 11, 1}]
m
PowerPoint Slide Show - [Canada2008.pptx]
Out[112]=
0.6
0.4
0.2
1.0
0.4
0.2
1.0
1.5
2.0
3.0
5.0
7.0
10.0

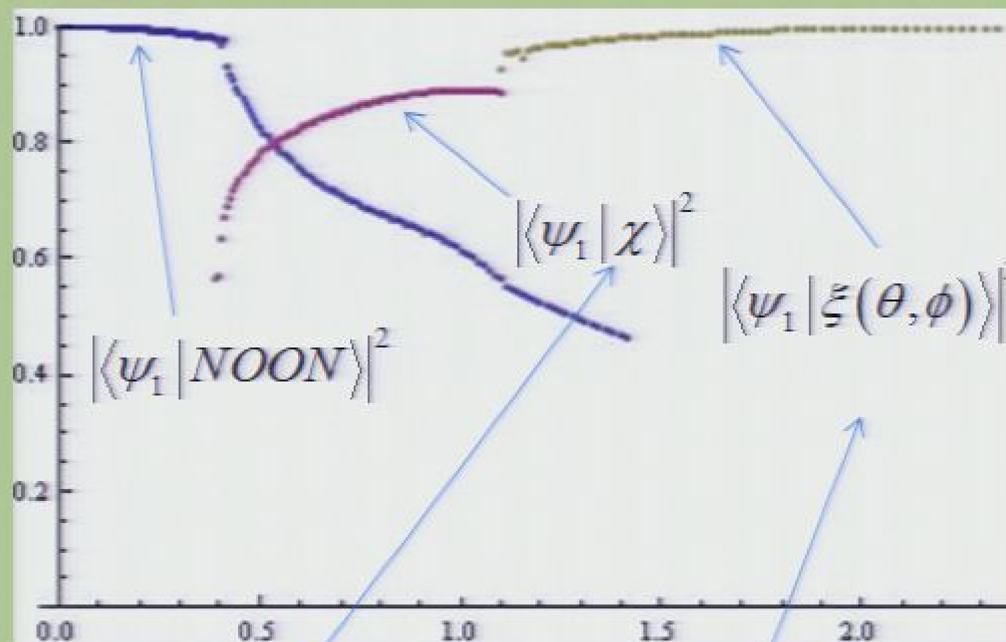
What is the Optimal State ψ_1 ?

Absorption rate



$|3,0\rangle$ $|2,1\rangle$ $|1,2\rangle$ $|0,3\rangle$

Structure of the optimal state

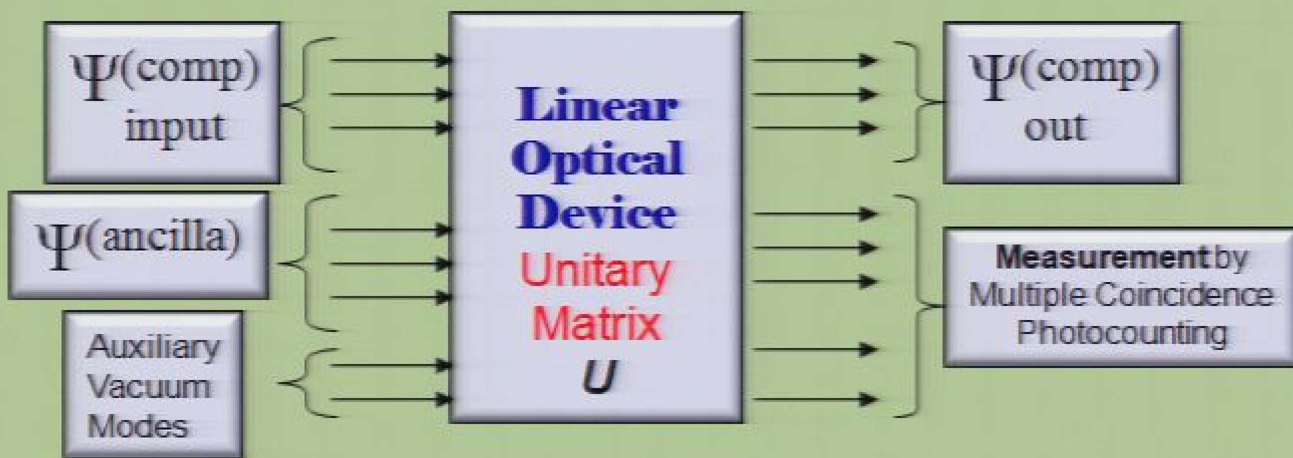


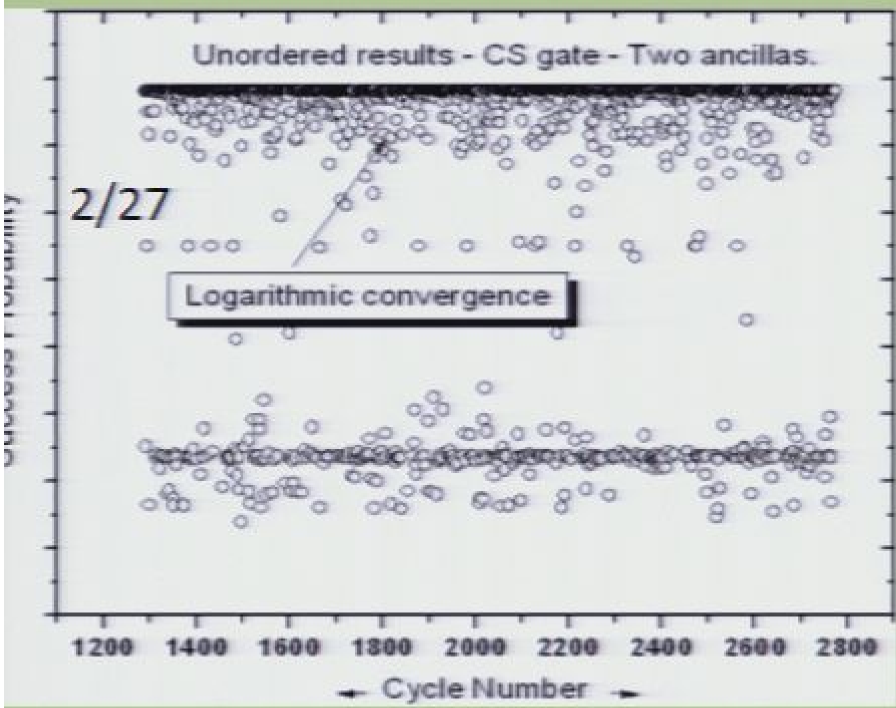
Absorption rate

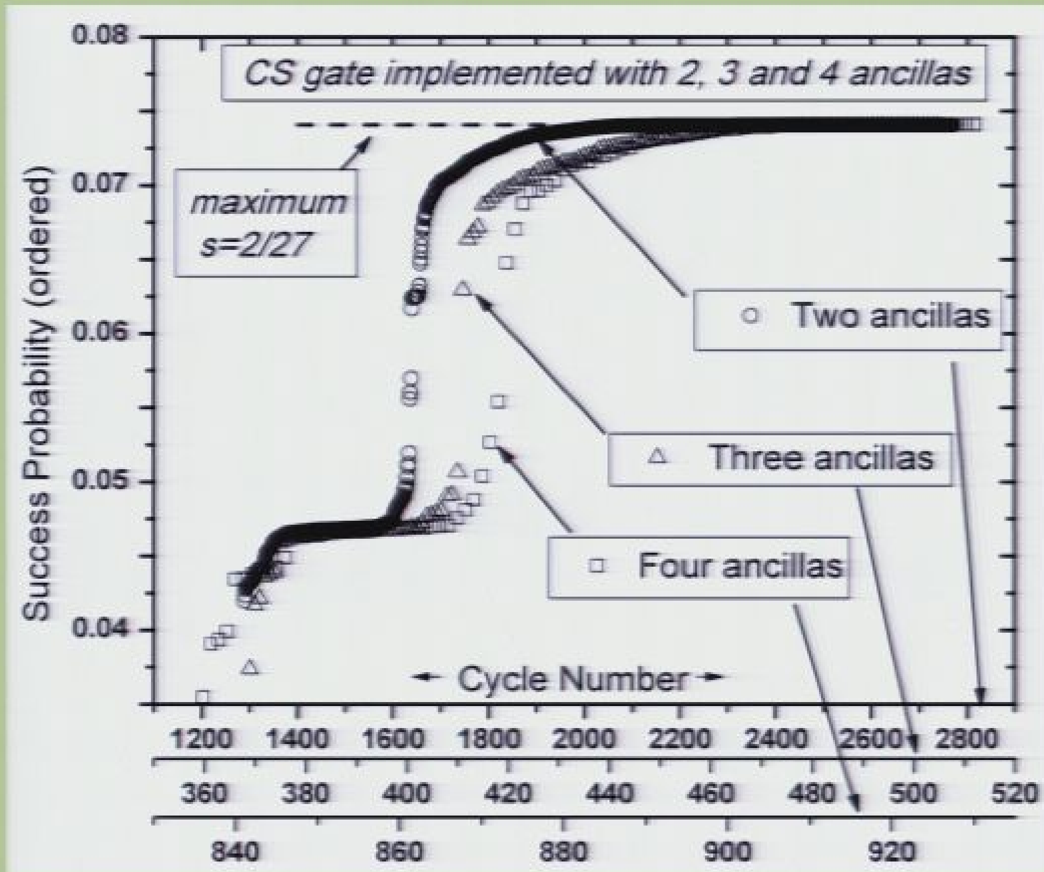
$$\chi = \frac{1}{\sqrt{2}}\left(|N-1,1\rangle + |0,N\rangle\right)$$

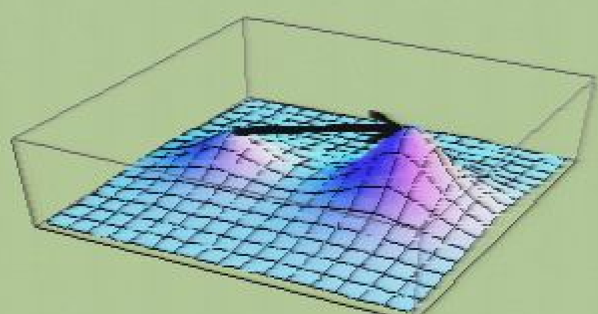
$$|\xi(\theta,\phi)\rangle = Generalized\ Coherent\ State$$

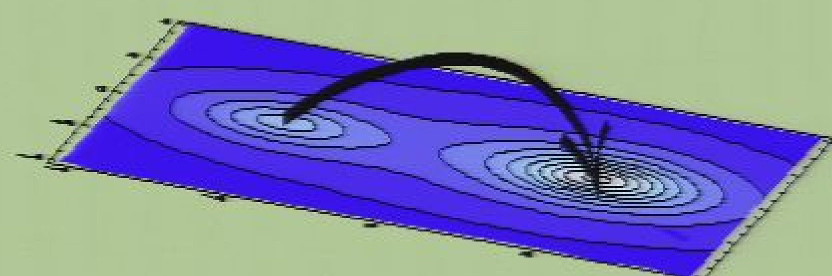
Optimization of Success Probabilities of Quantum Photonic Gates

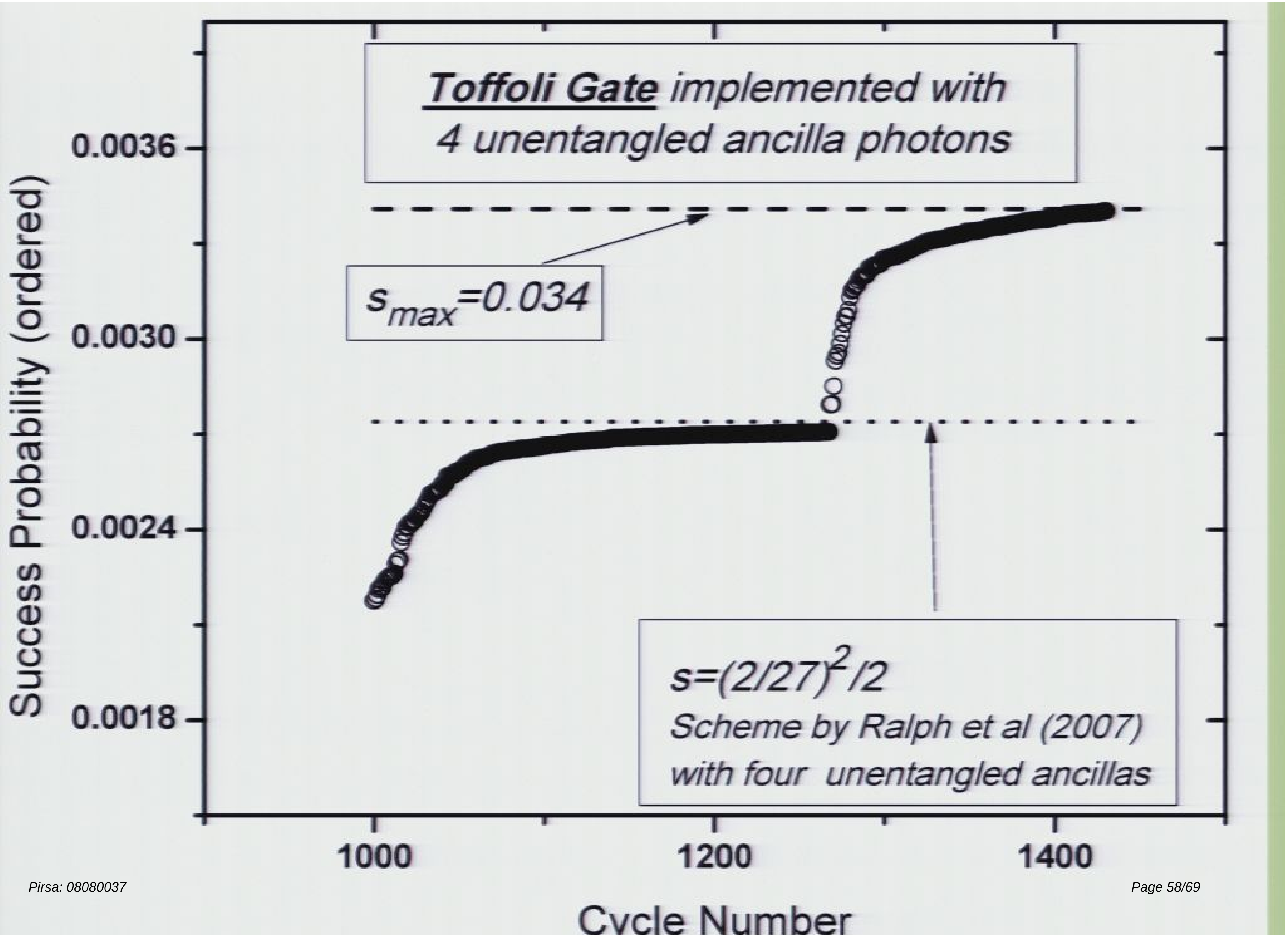



Unordered results - CS gate - Two ancillas.
2/27
Logarithmic convergence
1200 1400 1600 1800 2000 2200 2400 2600 2800
Cycle Number

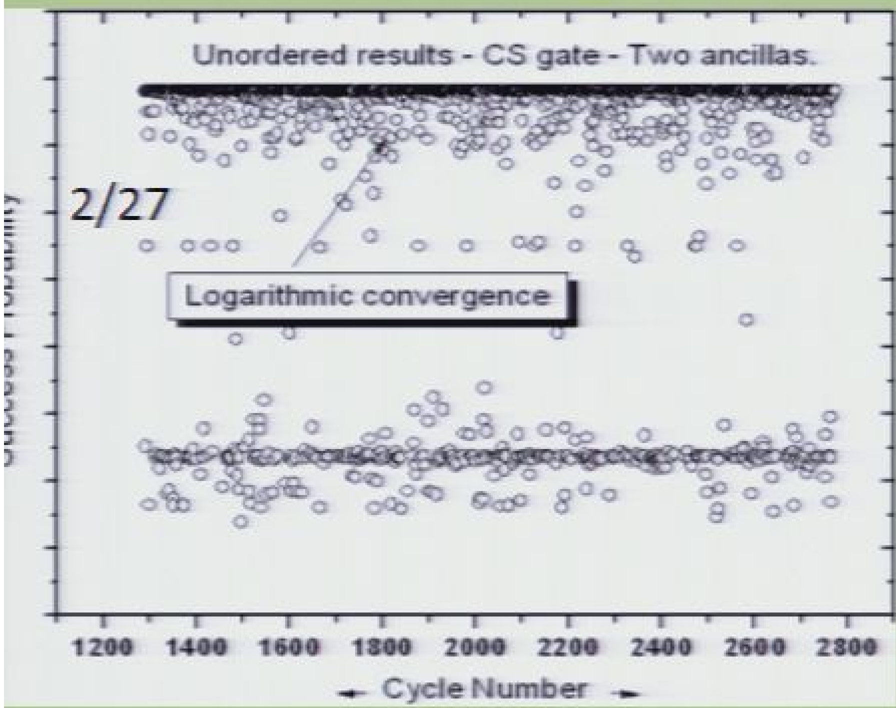

CS gate implemented with 2, 3 and 4 ancillas
maximum
s=2/27
Two ancillas
Three ancillas
Four ancillas
Success Probability (ordered)
0.08
0.07
0.06
0.05
0.04
Cycle Number
1200 1400 1600 1800 2000 2200 2400 2600 2800
360 380 400 420 440 460 480 500 520
840 860 880 900 920

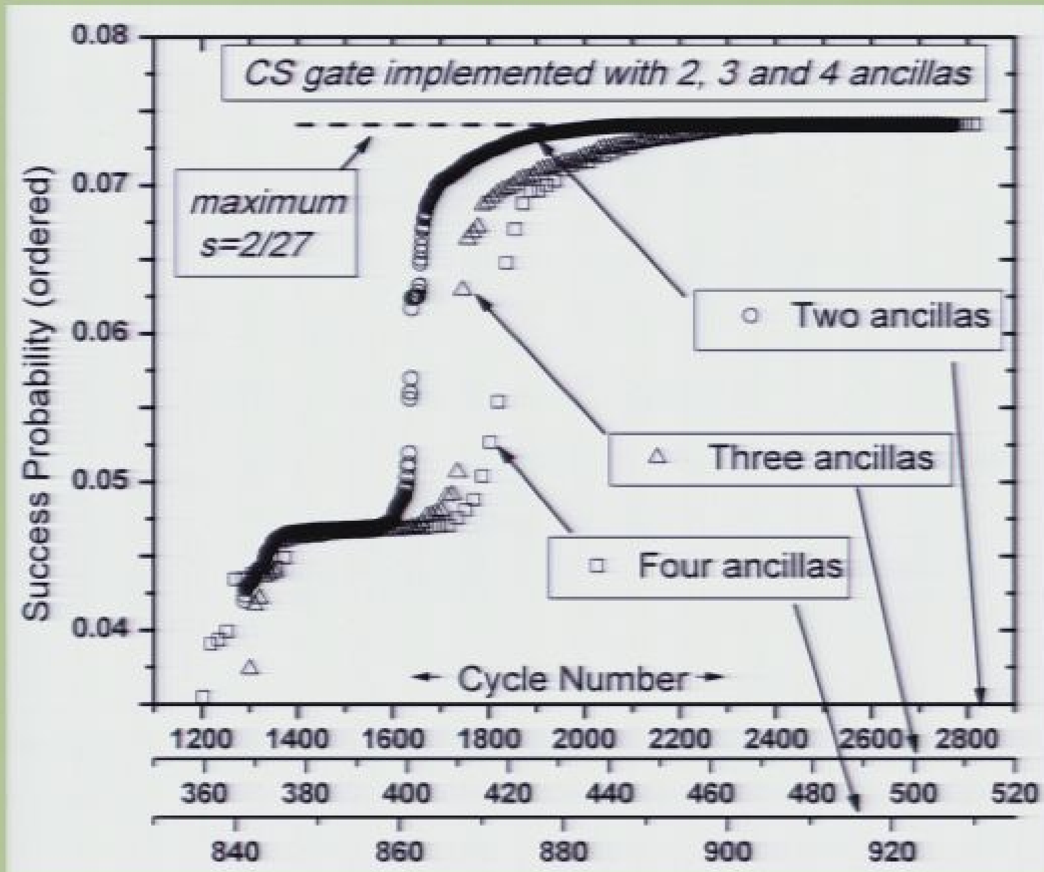


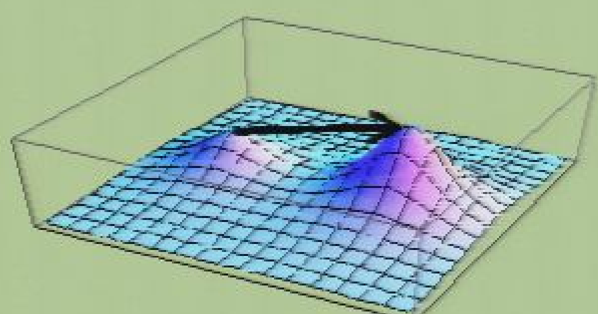


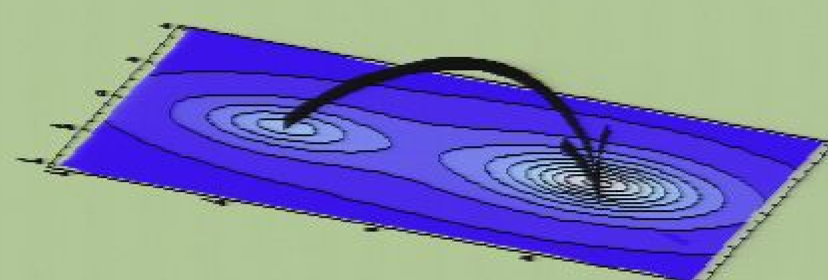


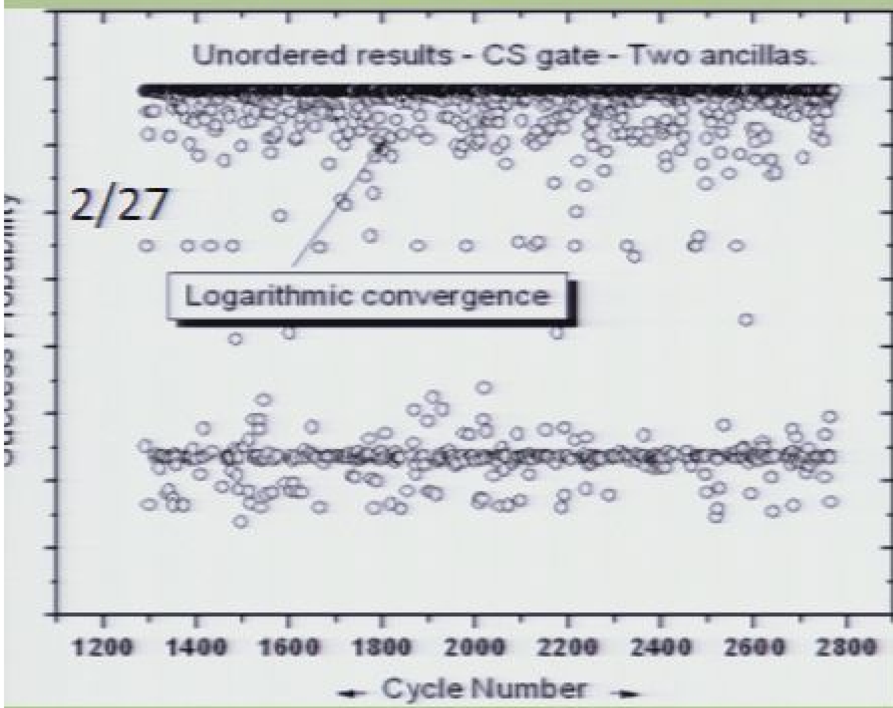
Toffoli Gate implemented with
4 unentangled ancilla photons
s_max=0.034
s=(2/27)^2/2
Scheme by Ralph et al (2007)
with four unentangled ancillas
Success Probability (ordered)
0.0036
0.0030
0.0024
0.0018
1000
1200
1400
Cycle Number

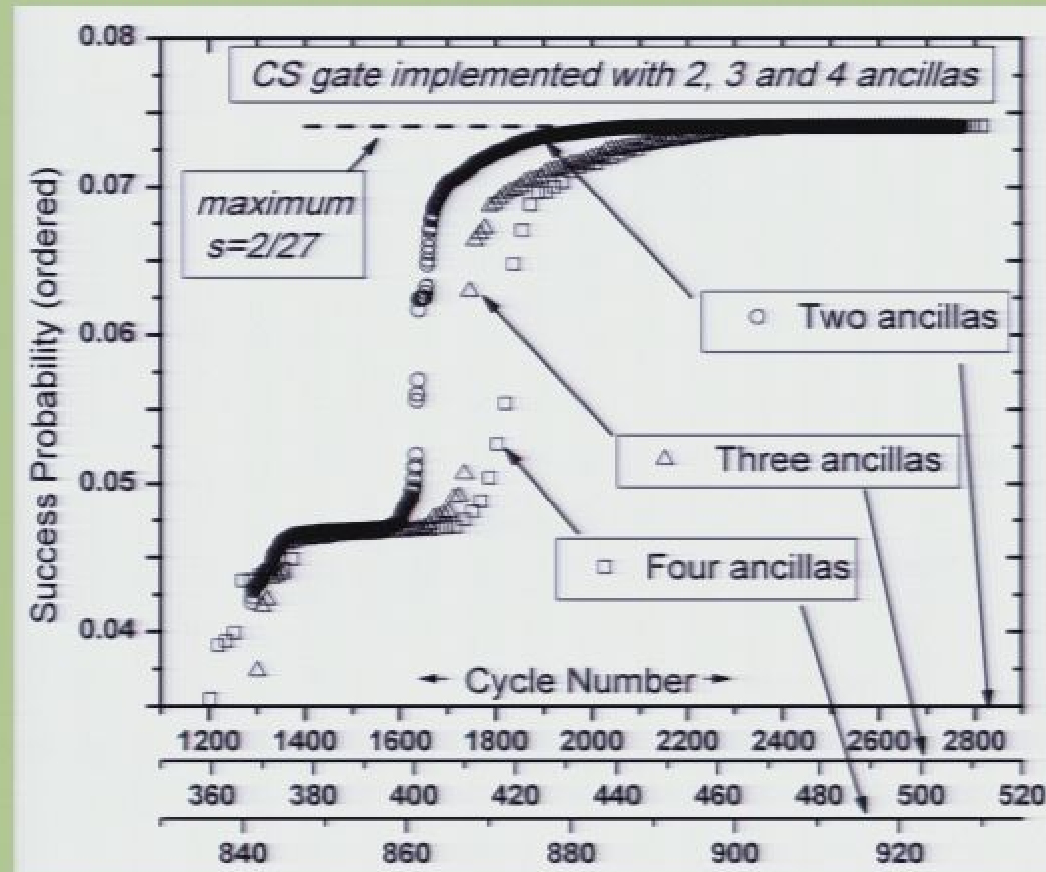

Unordered results - CS gate - Two ancillas.
2/27
Logarithmic convergence
1200 1400 1600 1800 2000 2200 2400 2600 2800
Cycle Number

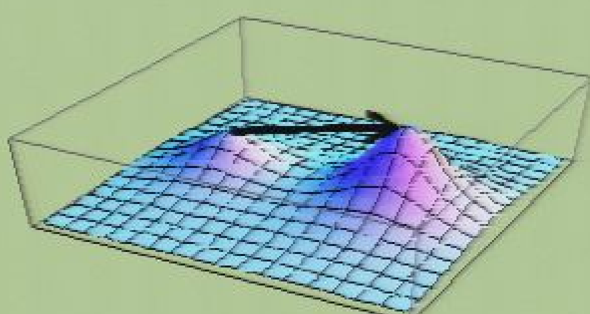

CS gate implemented with 2, 3 and 4 ancillas
maximum
s=2/27
Two ancillas
Three ancillas
Four ancillas
Success Probability (ordered)
0.08
0.07
0.06
0.05
0.04
Cycle Number
1200 1400 1600 1800 2000 2200 2400 2600 2800
360 380 400 420 440 460 480 500 520
840 860 880 900 920

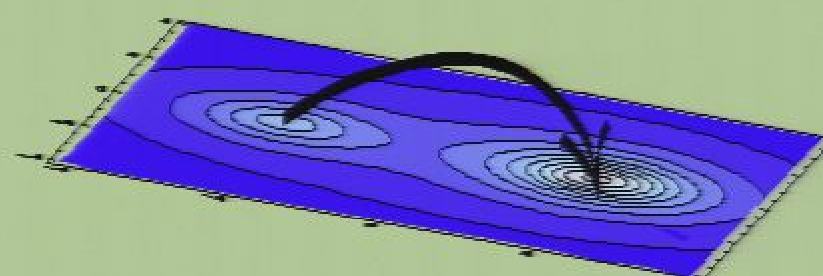


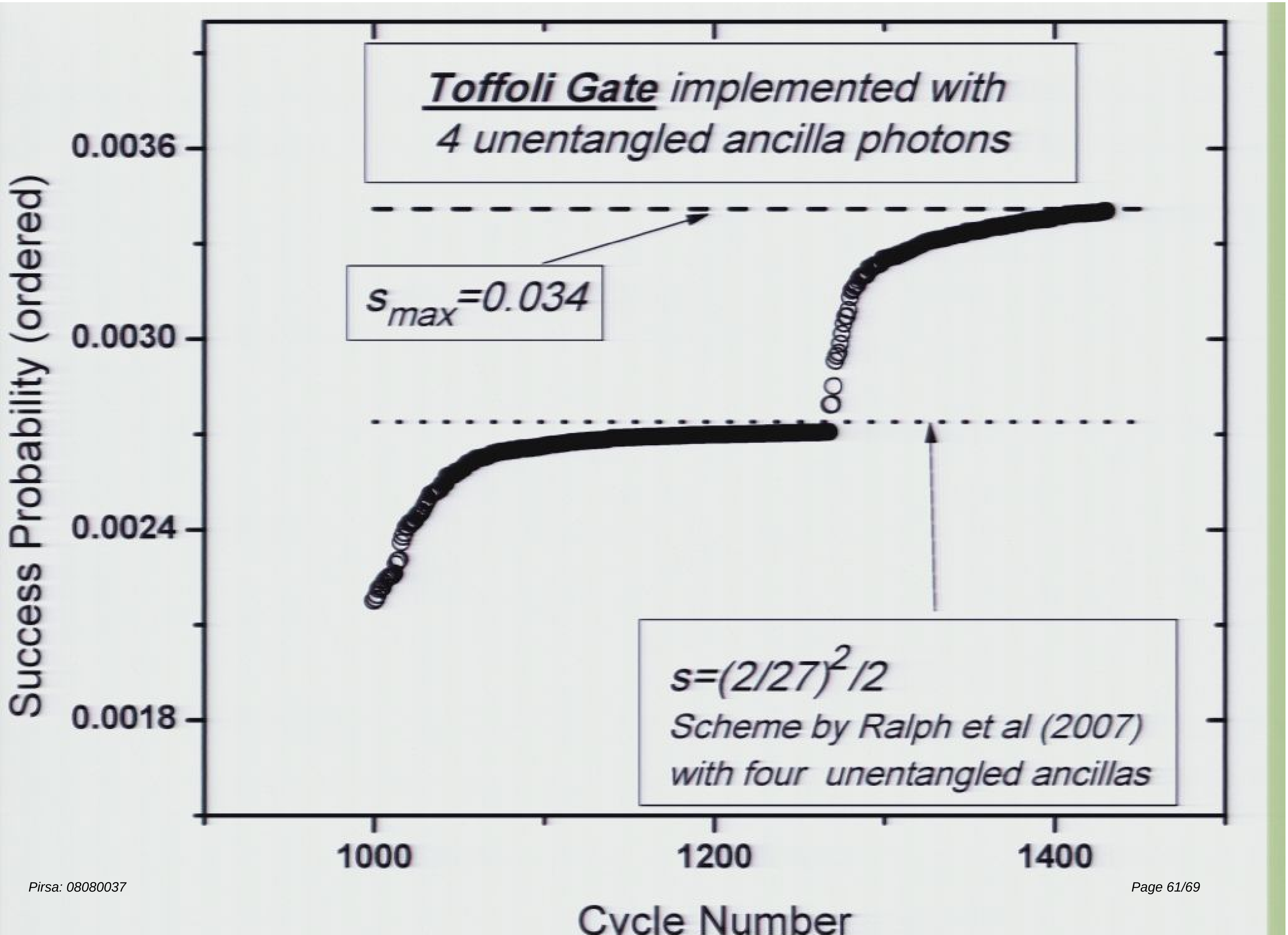



Unordered results - CS gate - Two ancillas.
2/27
Logarithmic convergence
1200 1400 1600 1800 2000 2200 2400 2600 2800
Cycle Number

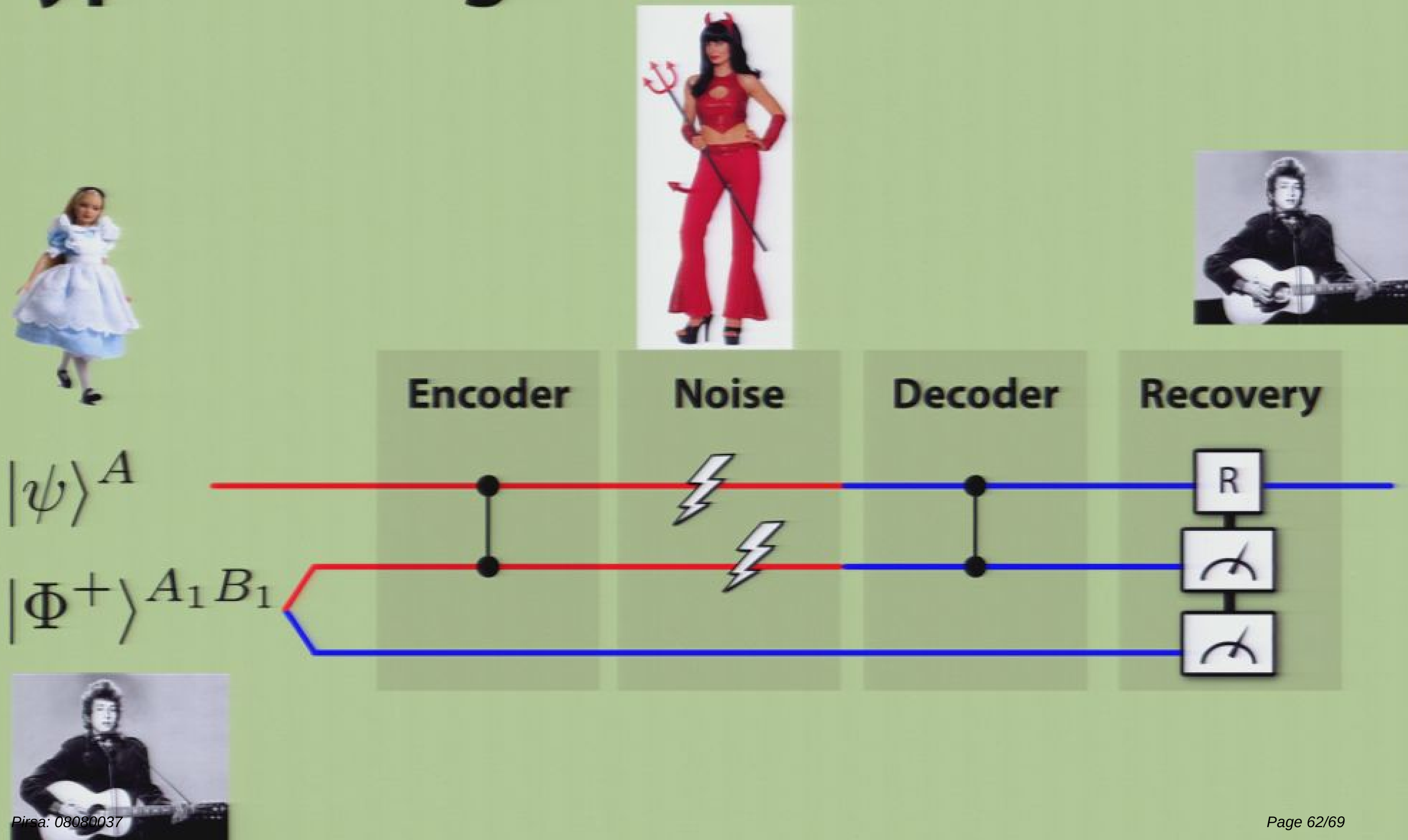

CS gate implemented with 2, 3 and 4 ancillas
maximum
s=2/27
Two ancillas
Three ancillas
Four ancillas
Success Probability (ordered)
0.08
0.07
0.06
0.05
0.04
Cycle Number
1200 1400 1600 1800 2000 2200 2400 2600 2800
360 380 400 420 440 460 480 500 520
840 860 880 900 920






Toffoli Gate implemented with
4 unentangled ancilla photons
s_max=0.034
s=(2/27)^2/2
Scheme by Ralph et al (2007)
with four unentangled ancillas
Success Probability (ordered)
0.0036
0.0030
0.0024
0.0018
1000
1200
1400
Cycle Number

Operation of the Hyperentanglement–Assisted Code



M. M. Wilde and D. B. Uskov, arXiv:0807.4906 (2008)

Error Syndrome Table

Error	Recovery	Syndrome
I	I	Φ^+
X^A	X	Φ^-
X^{A_1}	Z	Ψ^+
$X^A X^{A_1}$	ZX	Ψ^-

Syndrome table reduces to **superdense coding**!

M. M. Wilde and D. B. Uskov, arXiv:0807.4906 (2008)

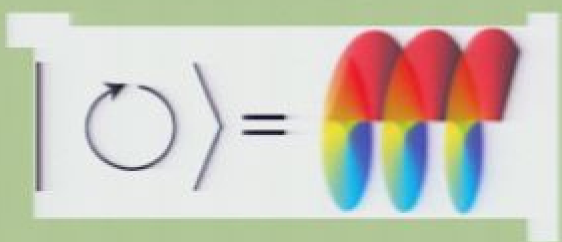
Hyperentanglement

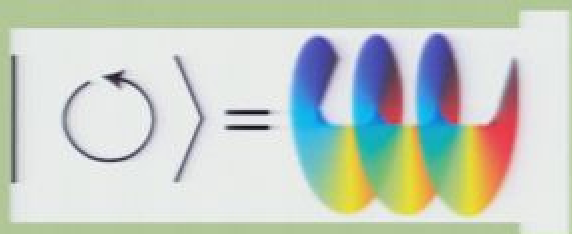
A **hyperentangled** state is simultaneously entangled in

polarization and **orbital angular momentum**

$$\frac{1}{2}\left(|HH\rangle^{AB}+|VV\rangle^{AB}\right)\otimes\left(|\circlearrowleft\circlearrowright\rangle^{AB}+|\circlearrowright\circlearrowleft\rangle^{AB}\right)$$

where





J.T. Barreiro, T.-C. Wei, and P.G. Kwiat, Nature Physics 4, 282 (2008)

Encoding and Decoding Circuit

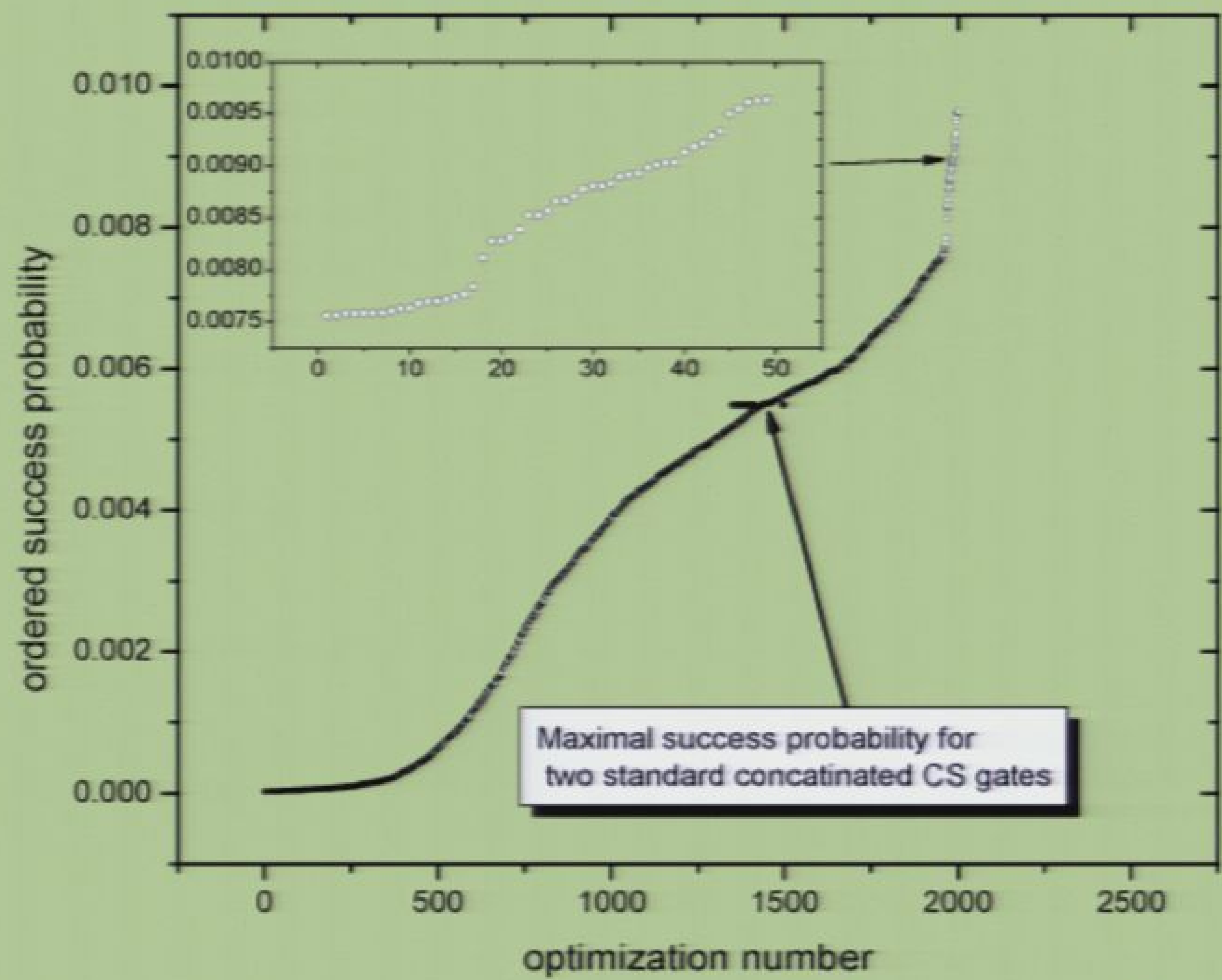
Transform the following basis states

$$\left|V\right\rangle^{A}\left|V\circlearrowleft\right\rangle^{A_1}\rightarrow-\left|V\right\rangle^{A}\left|V\circlearrowleft\right\rangle^{A_1},$$
$$\left|V\right\rangle^{A}\left|V\circlearrowright\right\rangle^{A_1}\rightarrow-\left|V\right\rangle^{A}\left|V\circlearrowright\right\rangle^{A_1}.$$

and leave the others **alone**!

M. M. Wilde and D. B. Uskov, arXiv:0807.4906 (2008)

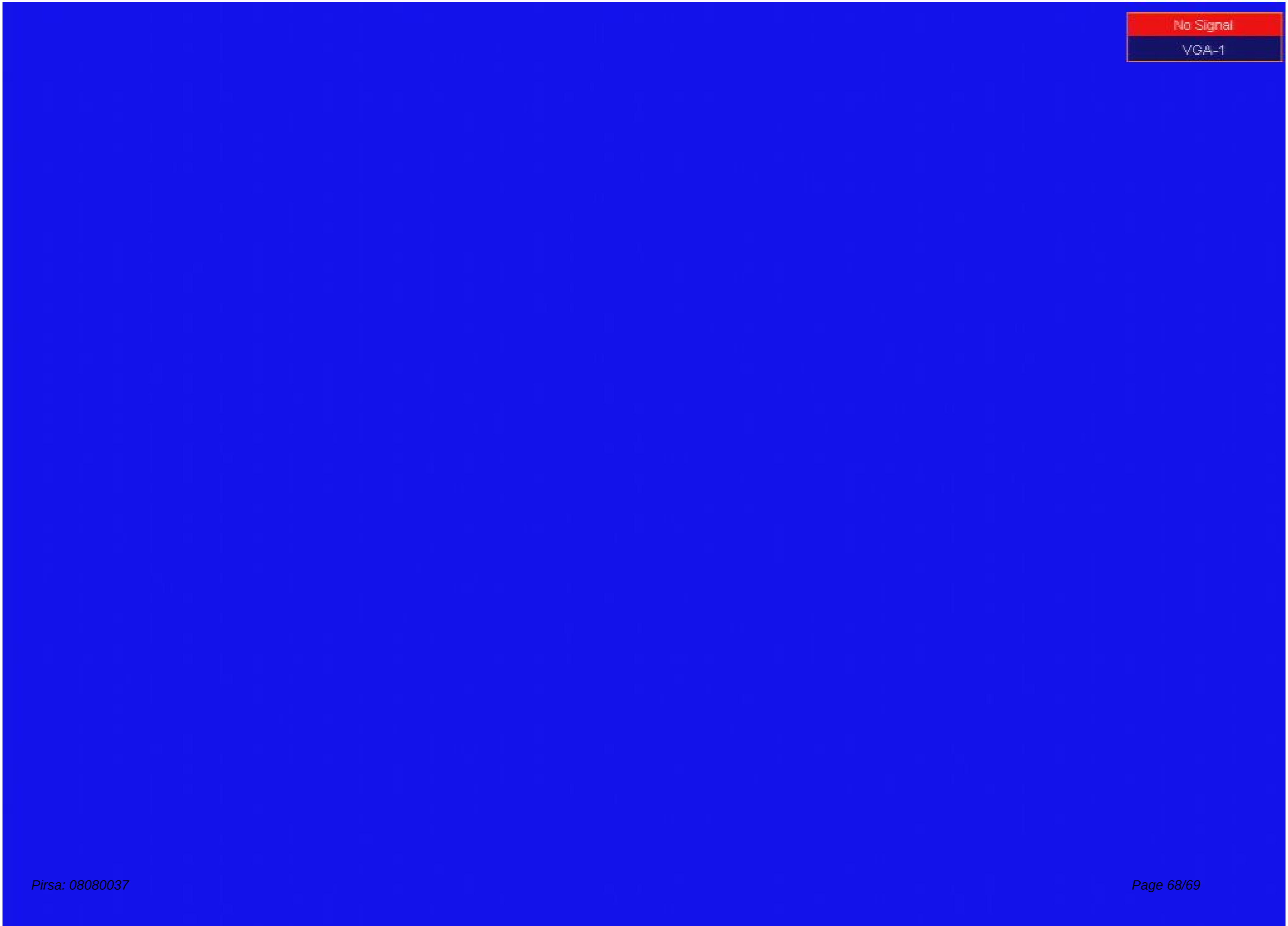
Gate Optimization

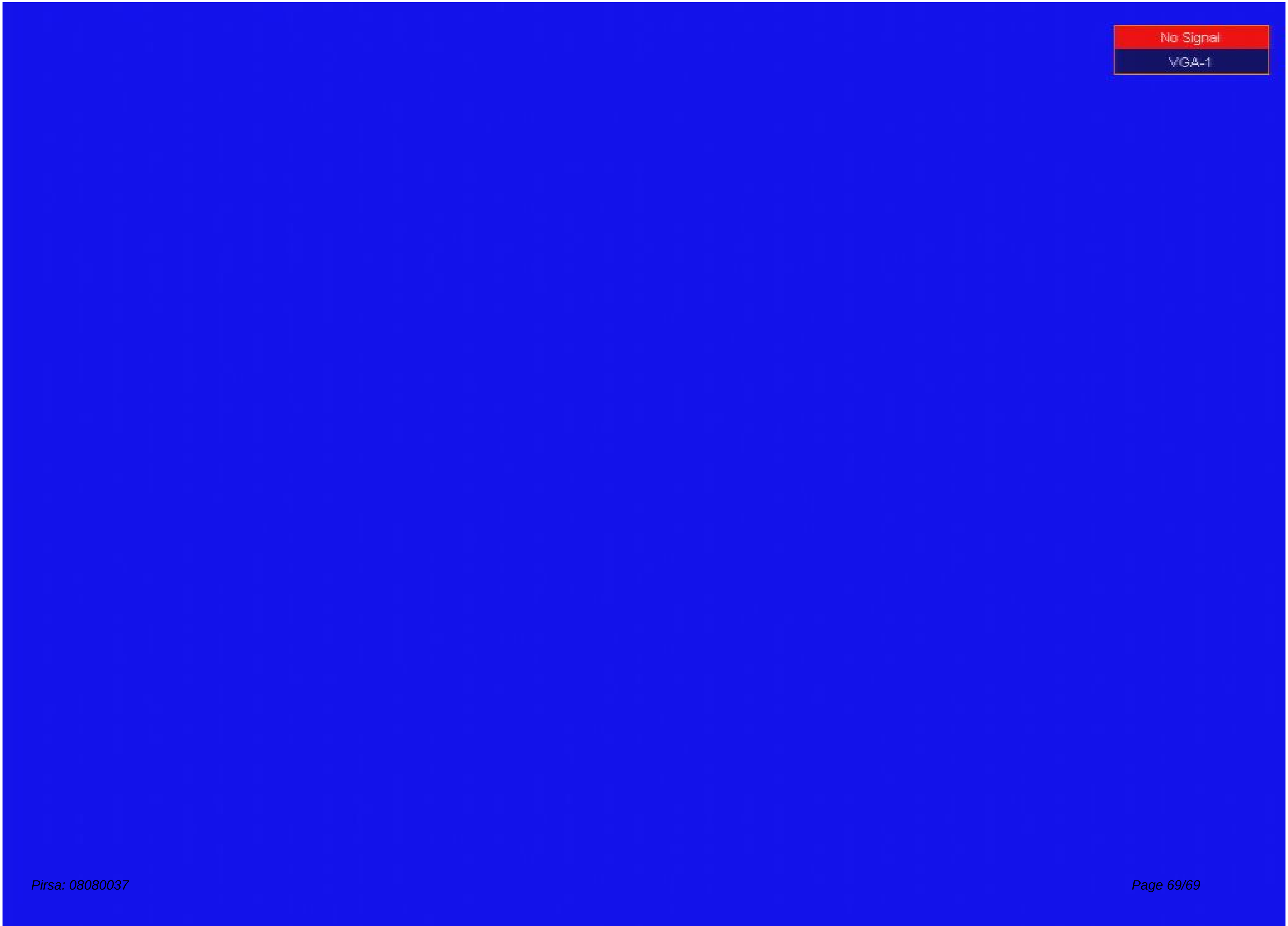


Gate requires only **3 ancilla modes** and has success probability of **0.0096**

M. M. Wilde and D. B. Uskov, arXiv:0807.4906 (2008)

End of slide show, click to exit.


No Signal
VGA-1


No Signal
VGA-1