Beyond Traditional Quantum Measurement

A game of quantum peek-a-boo with a purpose

PhD research of a CSUF alumni

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CSUF physics department colloquium

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Outline

- Background
  - Quantum Mechanics and Ideal Measurement
  - Real World Measurement
    - Example: Phase Qubit
  - Measurement Reversal
- Where my story begins
  - Explaining experimental results
  - Discovery of new phenomenon
  - Experimental demonstration and verification

- Purpose of this talk
  - Expose to technical jargon and notation
  - Transmit conceptual understanding
  - Share my process of discovery
  - Share my experience with contemporary research

Quantum Mechanics

$$H|\psi\rangle = -i\hbar\frac{\partial}{\partial t}|\psi\rangle$$

Quantum Mechanics =
Schrodinger Equation +
Collapse Postulate

Schrodinger Equation : Normal evolution in time

$$M|\psi\rangle \xrightarrow{\text{yields}} |\varphi_r\rangle \text{ with prob. } P_r = |\langle\psi|\varphi_r\rangle|^2$$

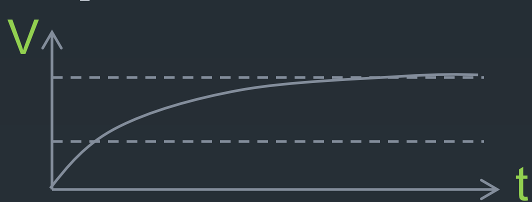
Collapse Postulate : Instantaneous effects of measurement

What Is Left To Discuss?

Real world measurements:

Require Finite Time

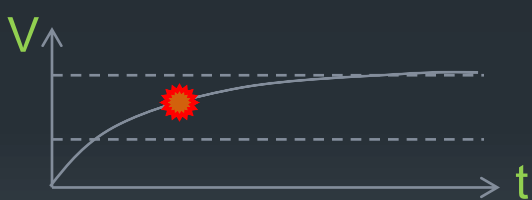
Include Noise

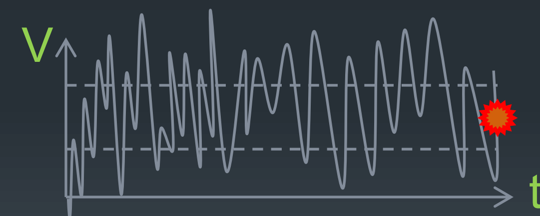


What if:

the process stops part way through?

there is not a clean result?





$$M|\psi\rangle \xrightarrow{\text{yields}} ?\text{ with prob. } P = ?$$

Keywords:
POVM, restricted path integral, quantum trajectories, quantum filtering, quantum jumps, stochastic master equation, etc.

Bayesian Formalism

Bayes' Theorem
(conditional probability)

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Born's Rule

$P(\varphi) = |\langle\psi|\varphi\rangle|^2$ is the probability that the system is in state $|\varphi\rangle$

$$P(\varphi|r) = \frac{P(r|\varphi)P(\varphi)}{P(r)}$$

Collapse Postulate is a Special Case
$P(\varphi_r|r) = 1$

Representing a Qubit State

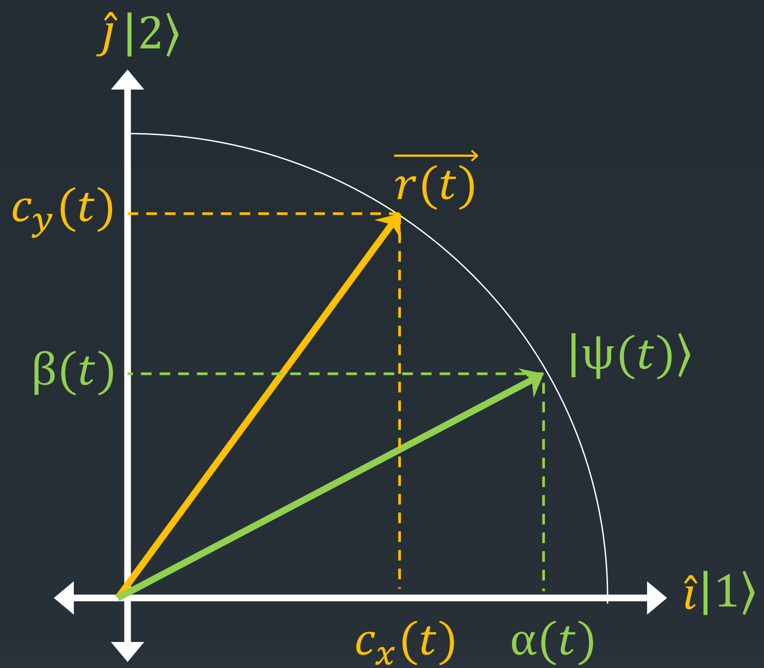
Vector decomposition in Euclidean space

$$\overrightarrow{r(t)} = c_x(t)\,\hat{\imath} + c_y(t)\,\hat{\jmath}$$

State representation using fixed basis

$$|\psi(t)\rangle = \alpha(t)|1\rangle + \beta(t)|2\rangle$$

Slight technical difference:
$\alpha(t)$ and $\beta(t)$ are complex numbers



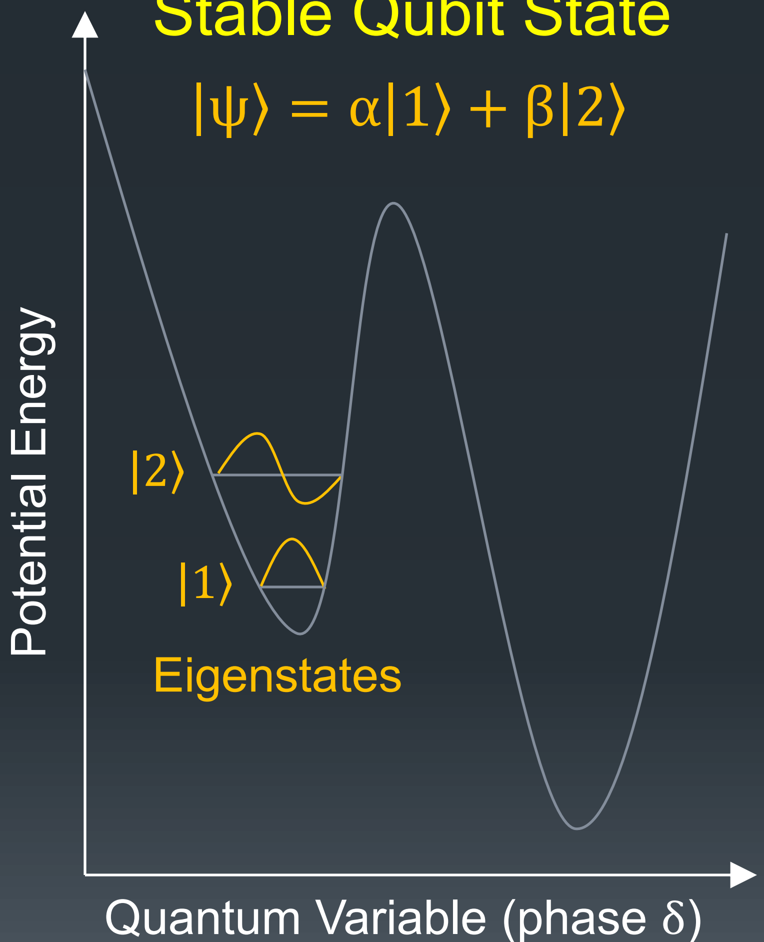
Usually time dependence is implied

$$|\psi\rangle = \alpha|1\rangle + \beta|2\rangle$$

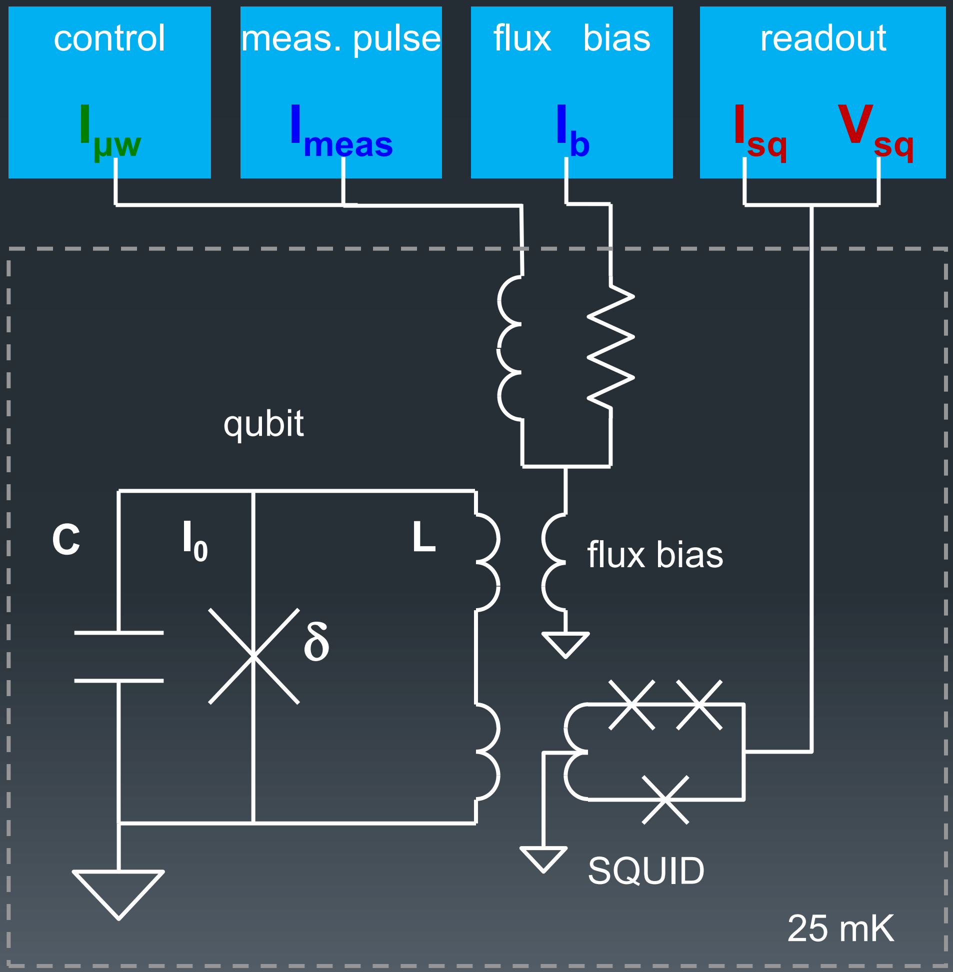
Example: Phase Qubit

Stable Qubit State

$|\psi\rangle = \alpha|1\rangle + \beta|2\rangle$



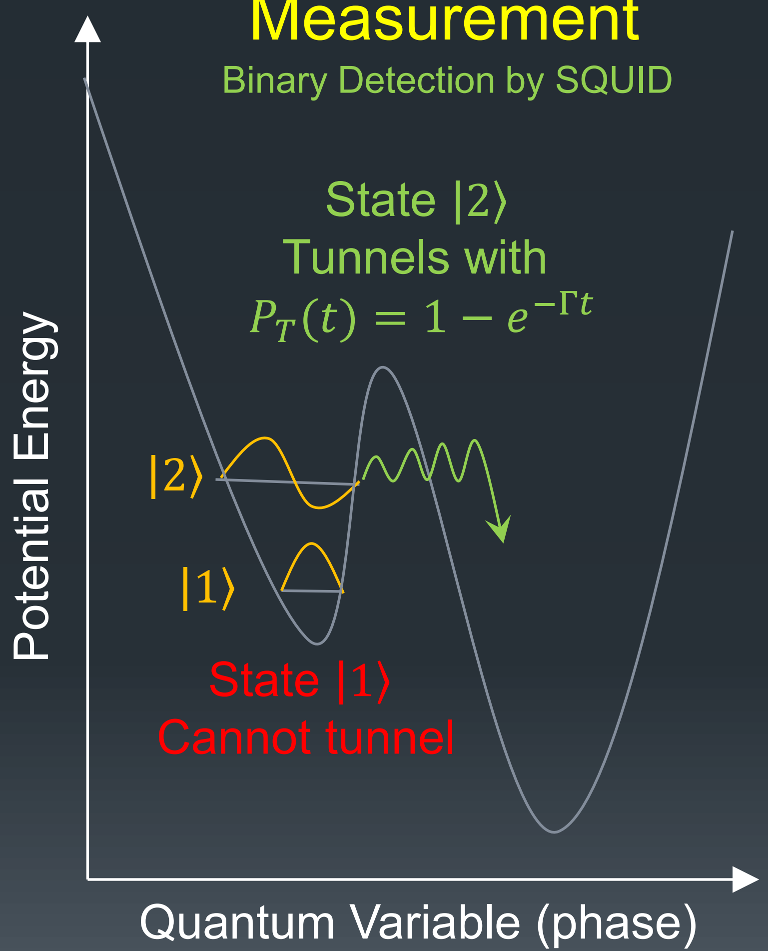
Phase Qubit Circuit



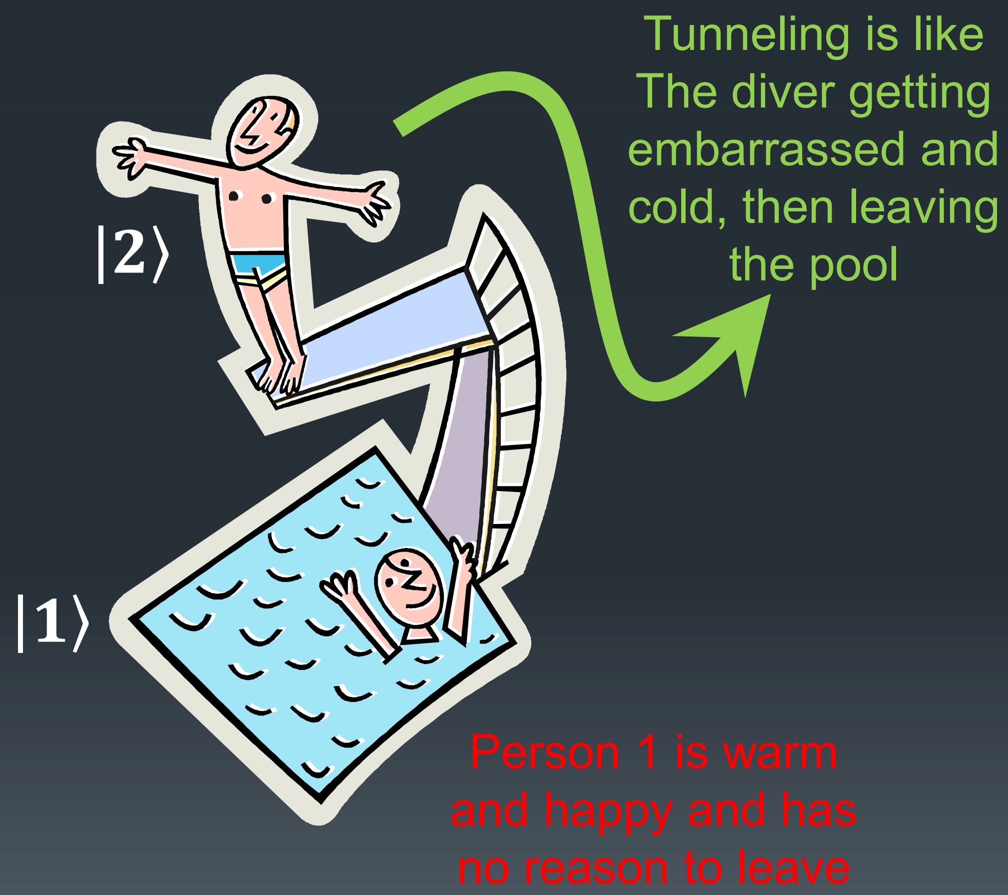
Example: Phase Qubit

Measurement

Binary Detection by SQUID



Really Bad Analogy



Example: Phase Qubit

Classical Interpretation

When tunneling is detected:
Qubit was in state $|2\rangle$ and
it is now destroyed

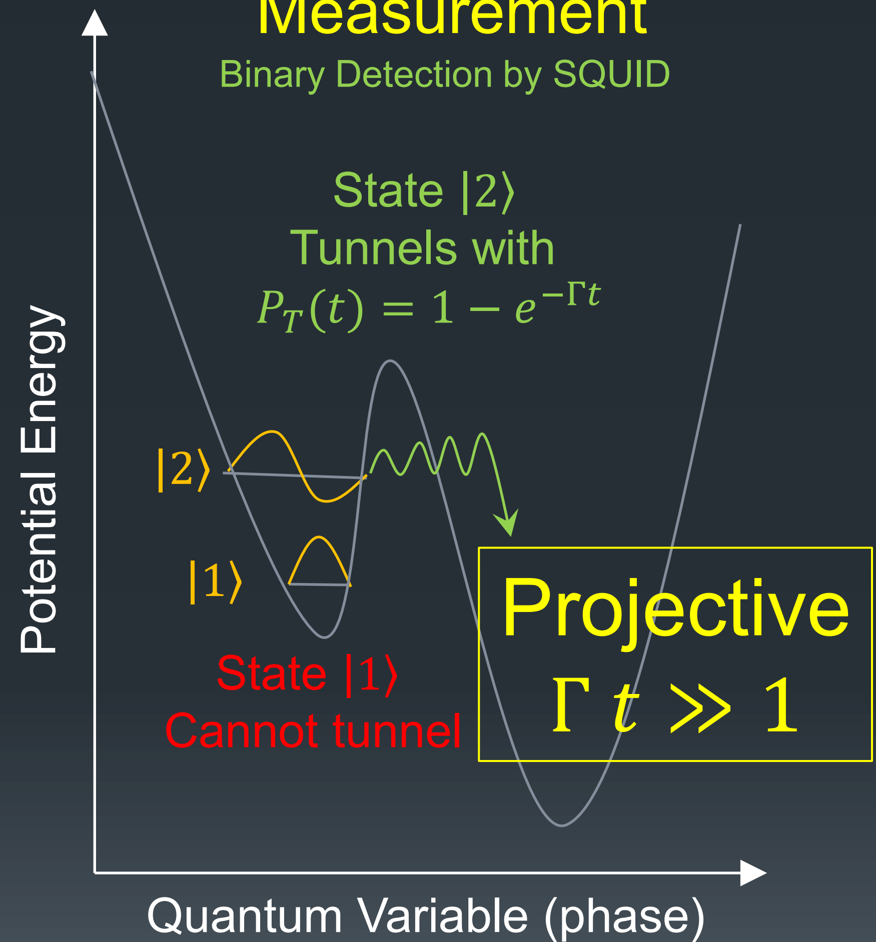
Destructive

When tunneling is **NOT** detected:
Qubit was in state $|1\rangle$ and
it is now in state $|1\rangle$

Collapse

Measurement

Binary Detection by SQUID



Example: Phase Qubit

Classical Interpretation

When tunneling is detected:

Qubit was in state $|2\rangle$ and
it is now destroyed

SAME

Destructive

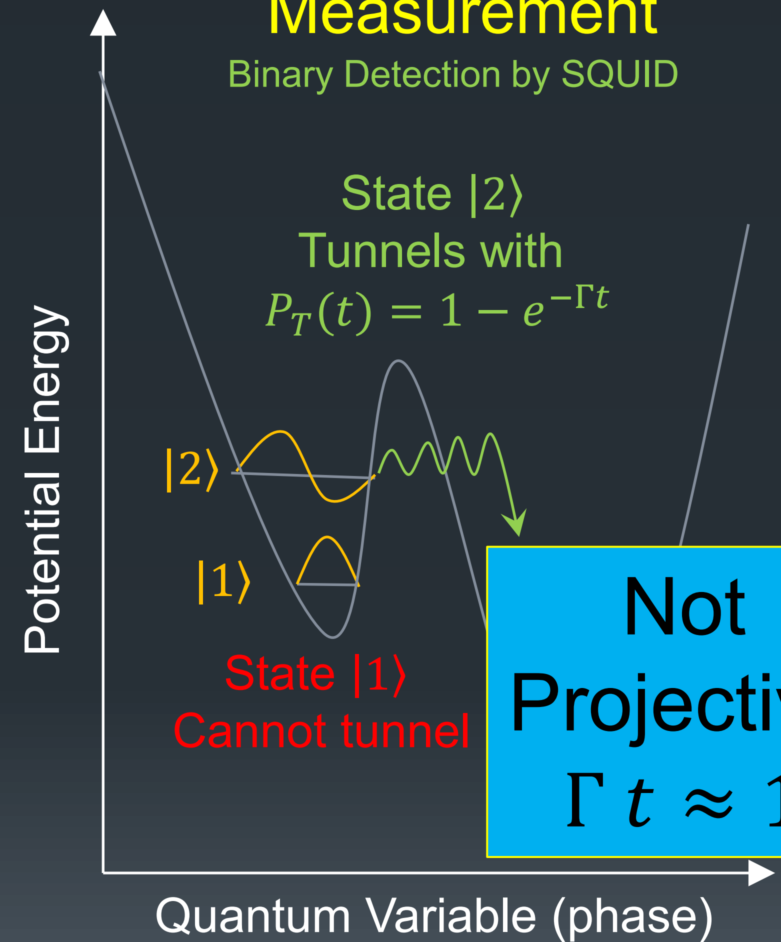
When tunneling is **NOT** detected:

Qubit was in state $|1\rangle$ and
it is now in state $|1\rangle$
OR
Qubit was in state $|2\rangle$, but
did not have the chance to tunnel and
it is now in state $|2\rangle$

Weak Measurement

Weak Measurement

Binary Detection by SQUID



Not Projective
$\Gamma t \approx 1$

Bayes' Theorem

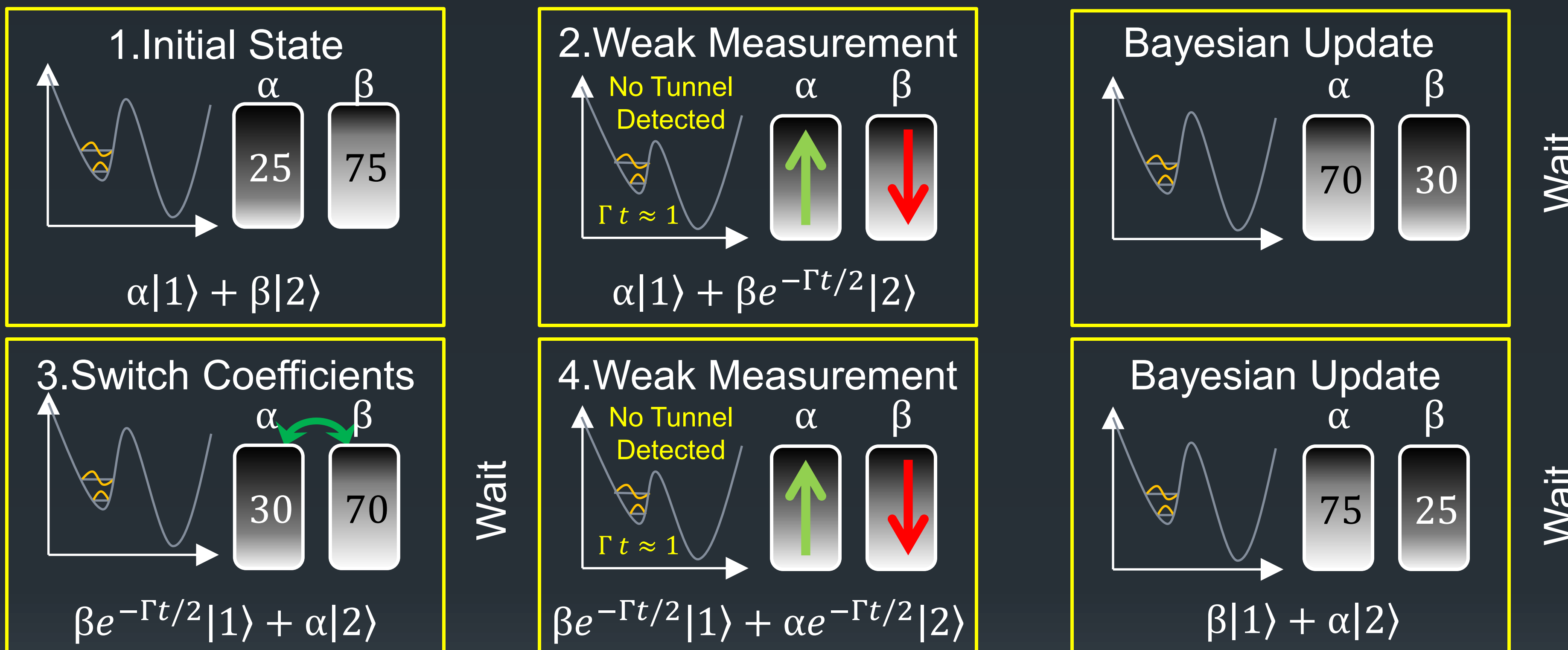
$$P(2) \rightarrow \frac{|\beta|^2 e^{-\Gamma t}}{|\alpha|^2 + |\beta|^2 e^{-\Gamma t}}$$

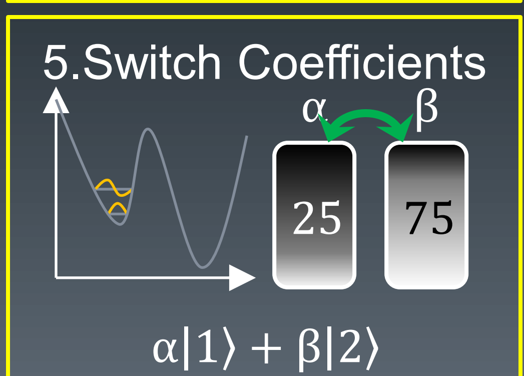
Born's Rule

$$\beta \rightarrow \frac{\beta e^{-\Gamma t/2}}{\sqrt{|\alpha|^2 + |\beta|^2 e^{-\Gamma t}}}$$

$M|\psi\rangle \xrightarrow{\text{yields}} |\widetilde{\psi}\rangle$ with prob. $P = |\alpha|^2 + |\beta|^2 e^{-\Gamma t}$

Weak Measurement Reversal





Concept: Independent of Measurement Strength

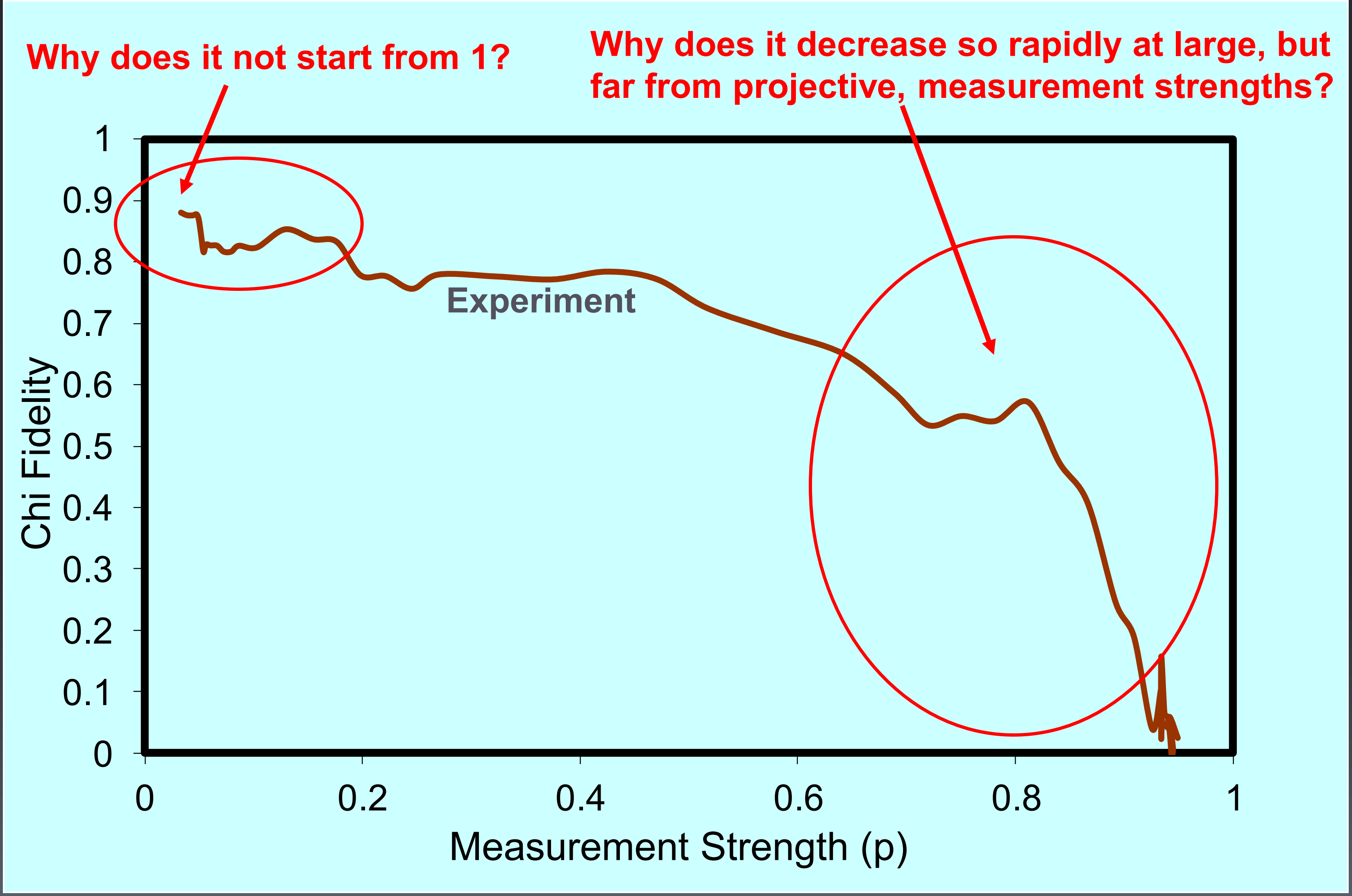
Partially extract real information about state

Probabilistically get contradictory information

Best description = nothing changed

Numbers are qualitative, α and β are complex

Why Isn't Life Simple?



N. Katz et al., Phys. Rev. Lett. 101, 200401 (2008)

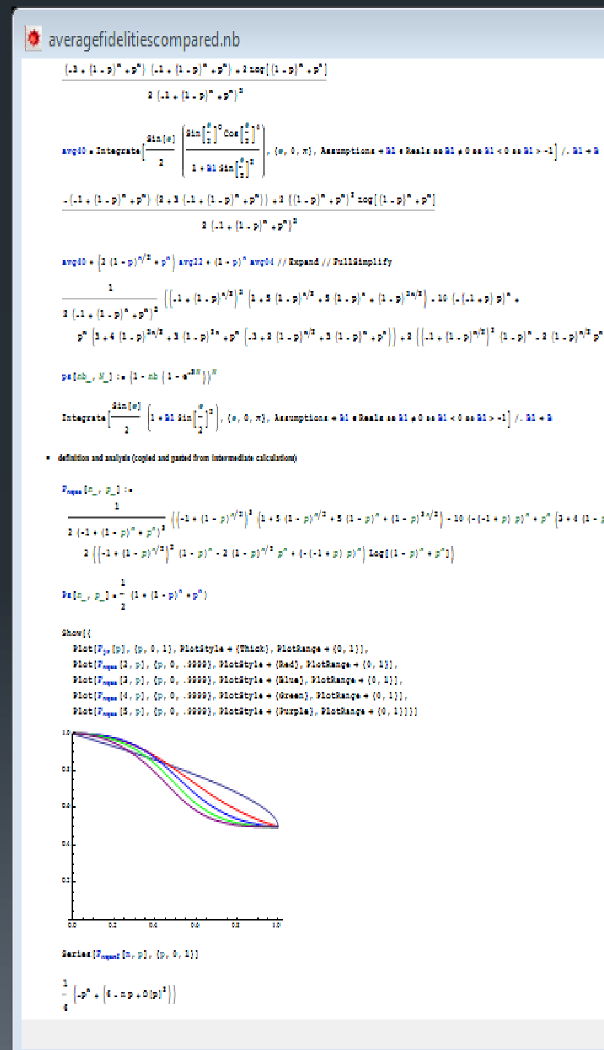
Simulate!

Coding Simulator

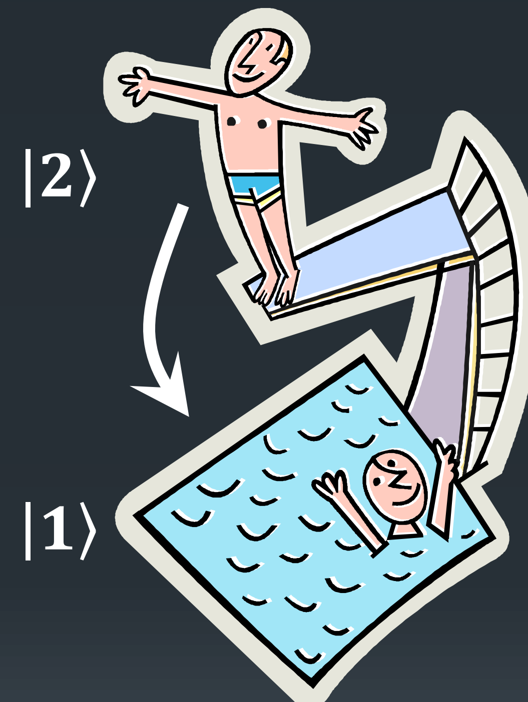
Process

Prepare, wait,
Measurement, wait
Switch, wait
Measurement, wait
Switch

Simulator Code



Really Bad Analogy

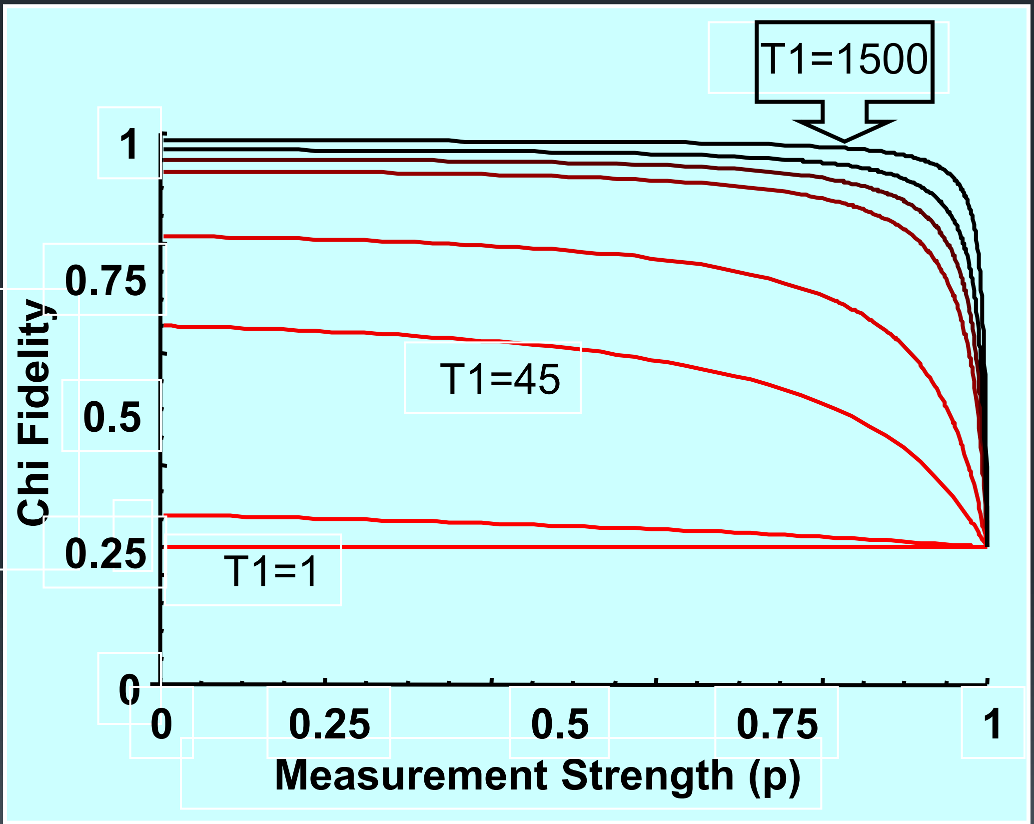


Relaxation

Diver gets tired from being nervous and dives into pool

Assume a Spherical Cow

The Effect of Relaxation (T1) on Fidelity



Duration of Process = **44** ns

T1(ns)= 1, 10, 45, 100, 300, **450**, 700, 1500

F(p=0)

$$\frac{1}{4}\left(1+e^{-t/T_1}+2e^{-t/T_2}\right)$$

Duration of Process = t

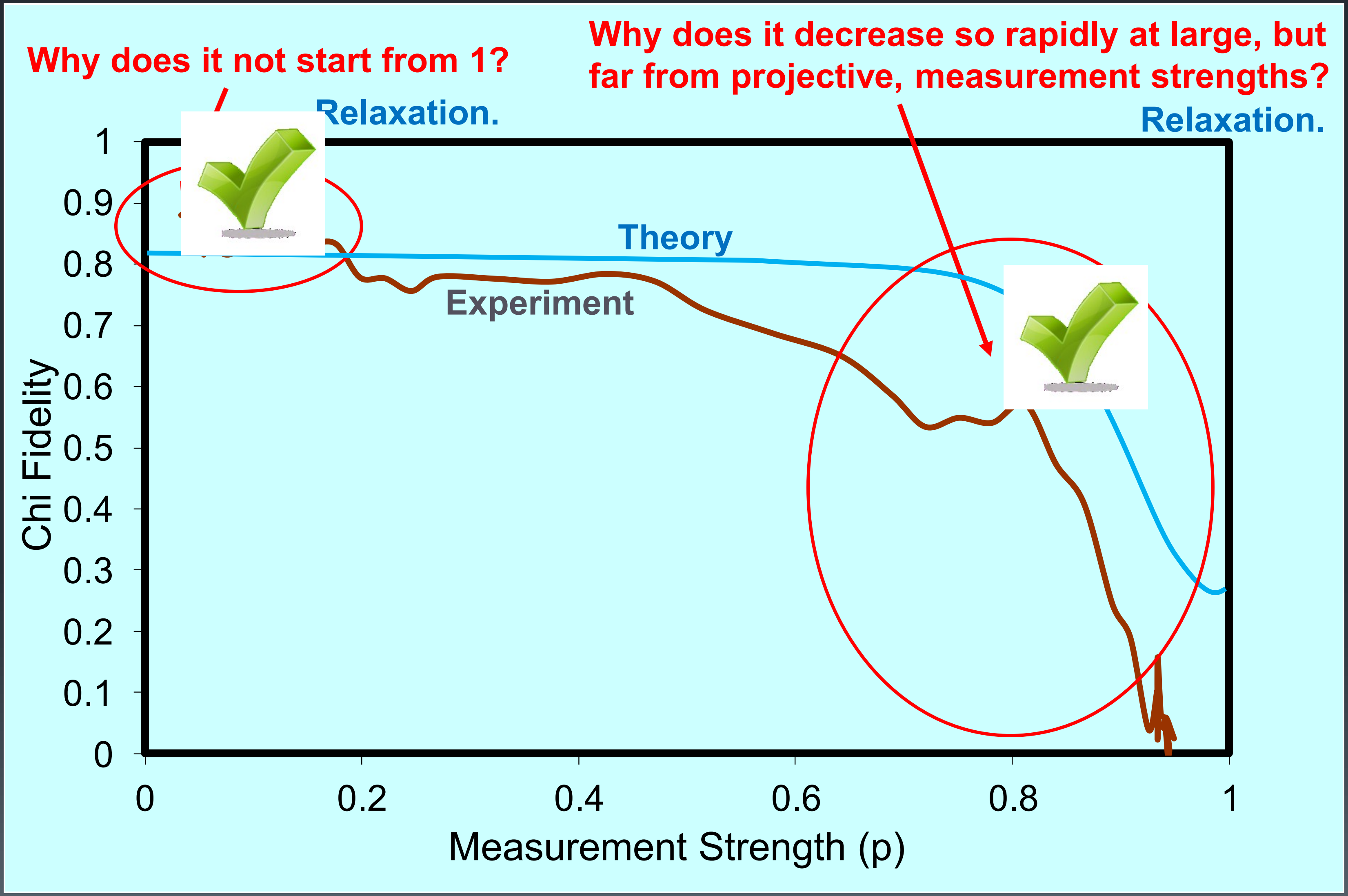
Universal Scaling of F(p near 1)

$$F_\chi=\frac{1}{4}\left(1+\frac{1}{1+\frac{1}{x}}+\frac{2}{1+\frac{1}{2x}}\right)$$

where $x=\dfrac{1-p}{1-e^{-t_3/T_1}}$

t_3 = the amount of time between the Pi rotation and the second measurement

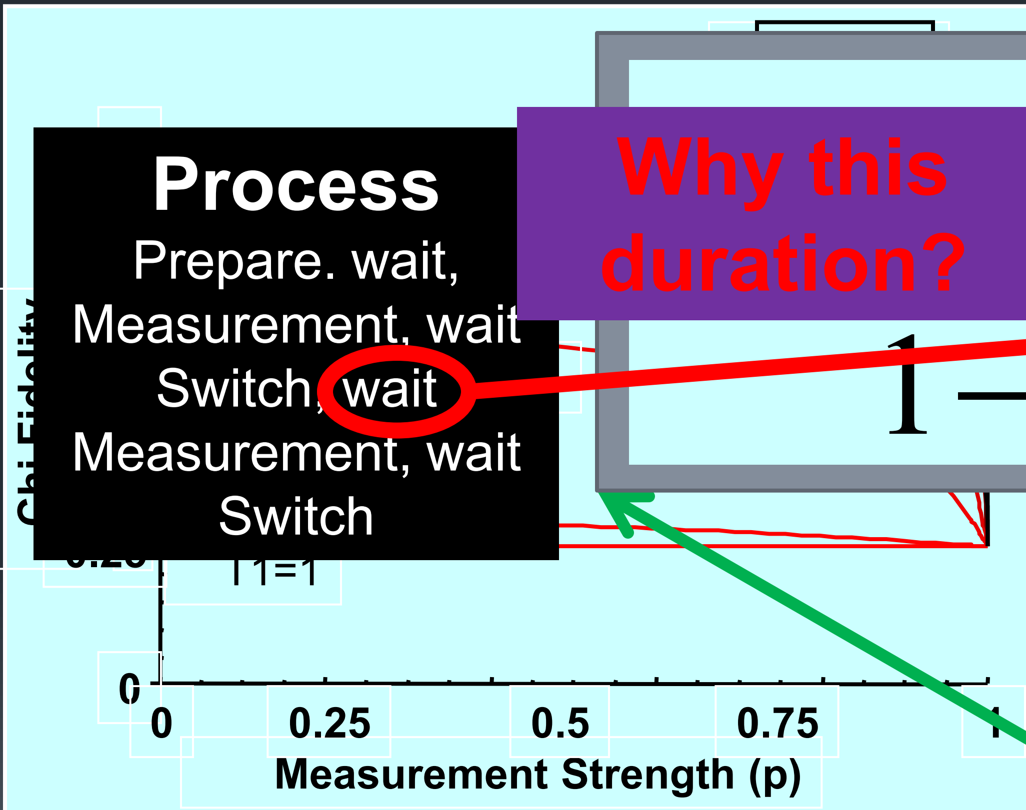
Simple Answer: Relaxation



N. Katz et al., Phys. Rev. Lett. 101, 200401 (2008)

But, wait… I Don't Get It

The Effect of Relaxation (T1) on Fidelity



Process

Prepare. wait,
Measurement, wait
Switch, wait
Measurement, wait
Switch

Why this duration?

$$\frac{1-p}{1-e^{-t_3/T_1}}$$

Duration of Process = **44** ns

T1(ns)= 1, 10, 45, 100, 300, **450**, 700, 1500

F(p=0)

$$\ldots 2e^{-t/T_2}\Big)$$

…cess = t

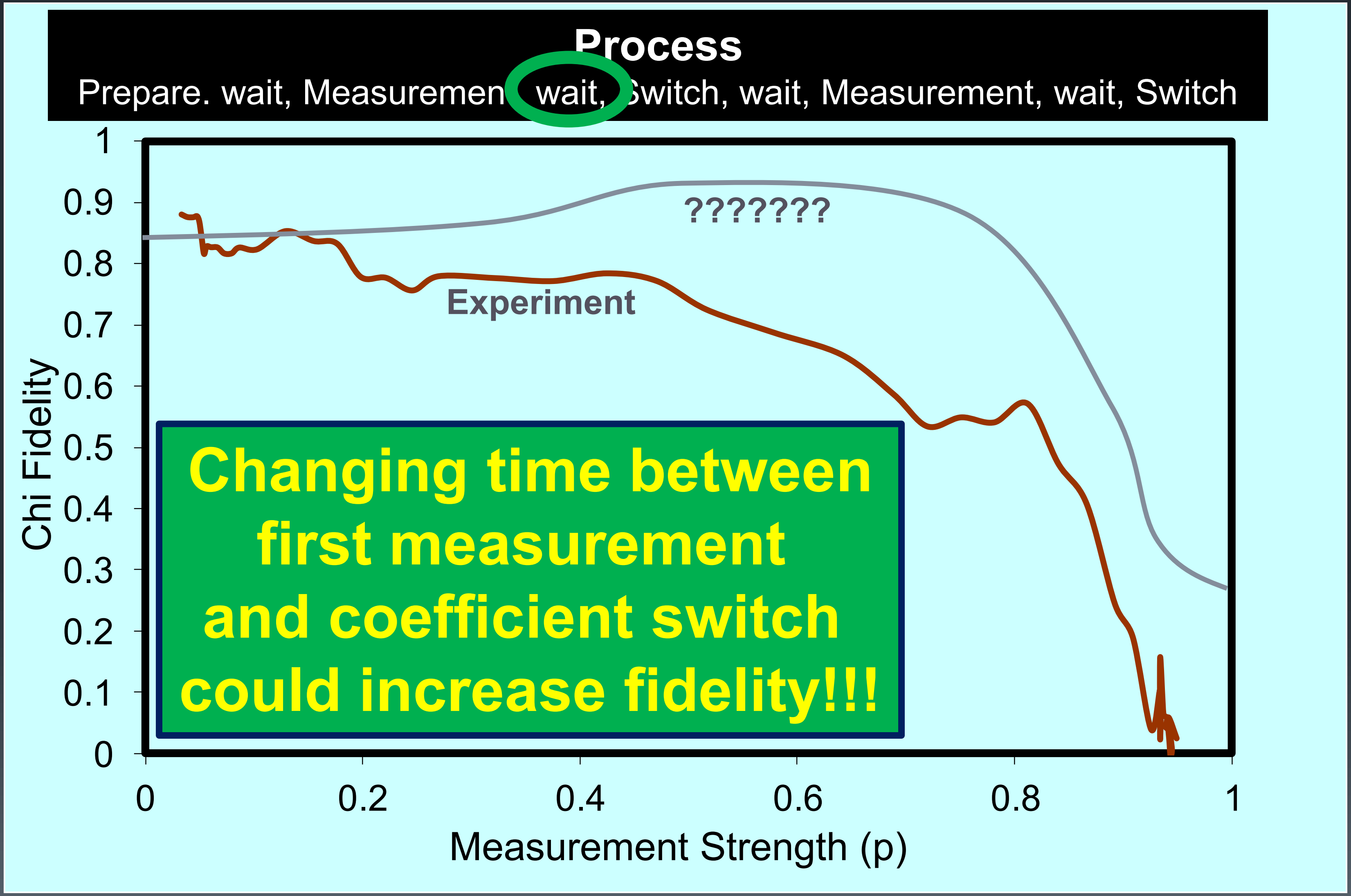
…f F(p near 1)

$$F_x=\frac{1}{4}\left(1+\frac{1}{1+\frac{1}{x}}+\frac{2}{1+\frac{1}{2x}}\right)$$

where $x=\dfrac{1-p}{1-e^{-t_3/T_1}}$

t_3 = the amount of time between the Pi rotation and the second measurement

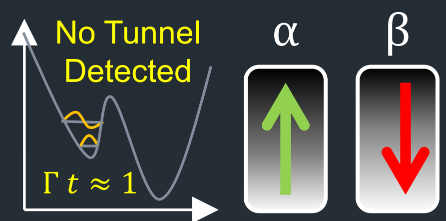
When in Doubt, Turn Knobs



N. Katz et al., Phys. Rev. Lett. 101, 200401 (2008)

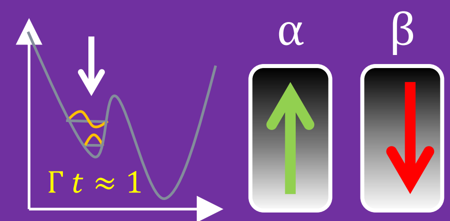
Relaxation Suppression by WMR

1.Weak Measurement

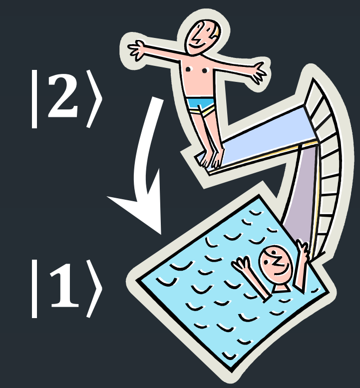


$\alpha|1\rangle + \beta e^{-\Gamma t/2}|2\rangle$

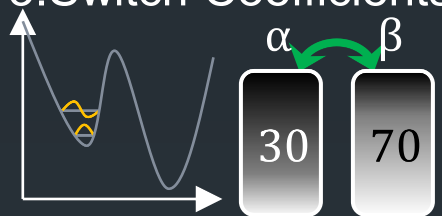
2.Relaxation



$\alpha|1\rangle + \beta e^{-\Gamma t/2} e^{-t/T1}|2\rangle$



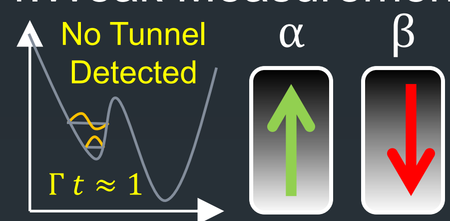
3.Switch Coefficients



$\beta e^{-\Omega t/2}|1\rangle + \alpha|2\rangle$

Wait

4.Weak Measurement



$\beta e^{-\Omega t/2}|1\rangle + \alpha e^{-Kt/2}|2\rangle$

$\alpha|1\rangle + \beta e^{-\Gamma t/2} e^{-t/T1}|2\rangle$
$\equiv \alpha|1\rangle + \beta e^{-\Omega t/2}|2\rangle$

$K \rightarrow \Omega = \Gamma + 1/T1$

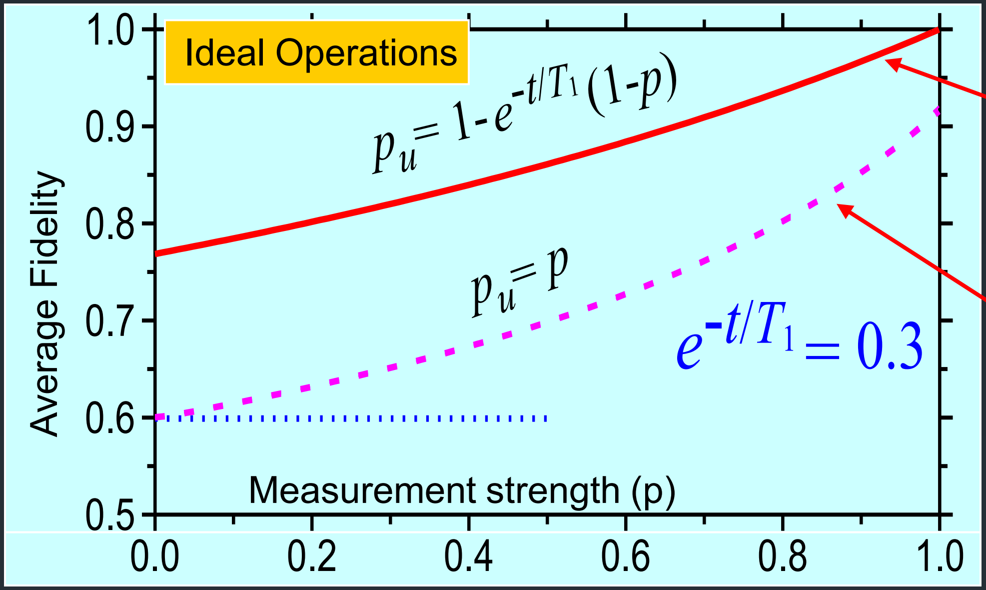
5.Switch Coefficients

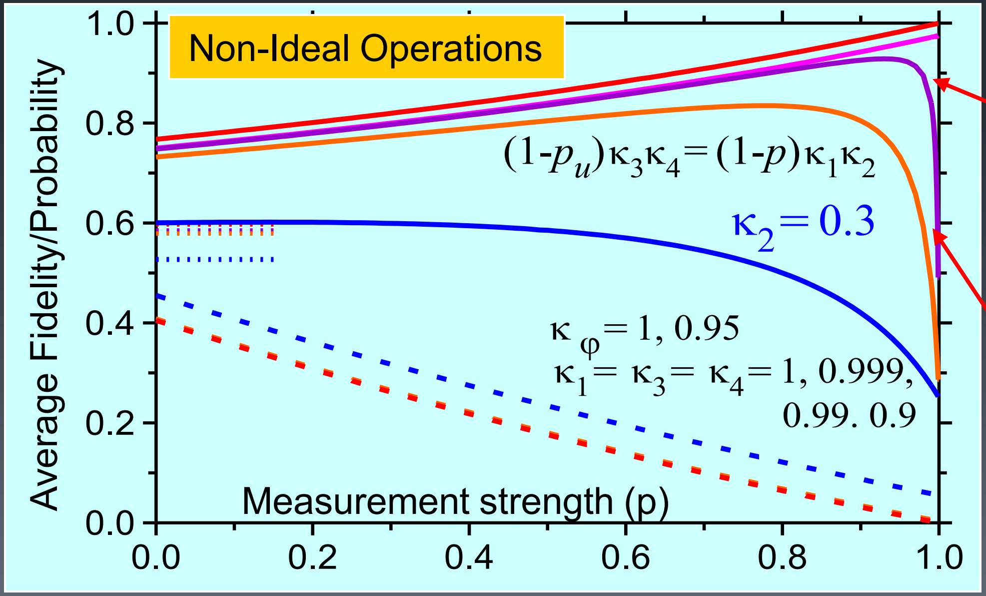
$\alpha|1\rangle + \beta|2\rangle$

Concept: Preferentially Select No Relaxation
Decrease Likelihood of being in $|2\rangle$
Relaxation Naturally Suppressed
Reverse Measurement and Relaxation

Numbers are qualitative, α and β are complex

Published New Protocol





-Wise choice of uncollapsing measurement strength will return a state that is arbitrarily close to the initial state

- Even a bad choice of uncollapsing strength will yield an improvement over pure relaxaed state

-Ideal operations with relaxation <u>and dephasing during the error period</u>, the ideally returned state is only slightly degraded

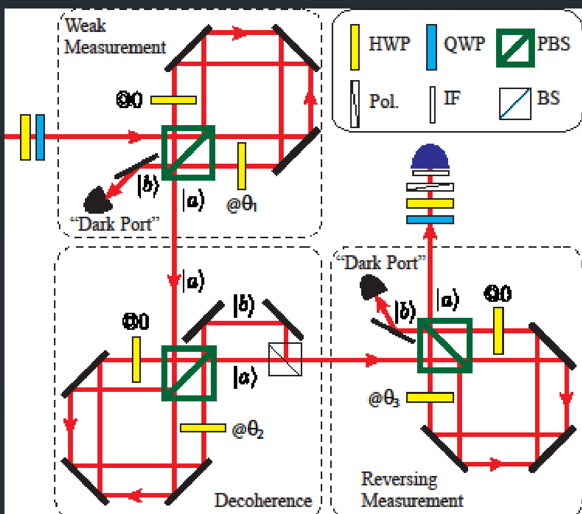
- Improvement is still realizable in the presence of considerable <u>decoherence during the operations</u>, although perfect restoration is no longer achievable

K and K., Phys. Rev. A 81, 040103(R) (2010)

Life Goes On…

Experiment in Optics Express

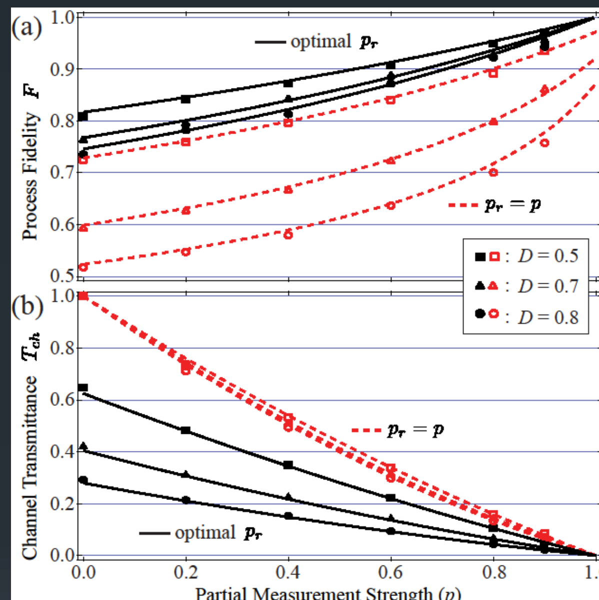
Optical Circuit



Weak Measurement realized with Polarization Beam Splitter, Half Wave Plate, and Dark Port

Relaxation realized with similar components,
except no dark port

Results



Nearly exact match to theory!!!

Jong-Chan Lee, Youn-Chang Jeong, Yong-Su Kim, and Yoon-Ho Kim, "Experimental demonstration of decoherence suppression via quantum measurement reversal," Opt. Express **19**, 16309-16316 (2011)

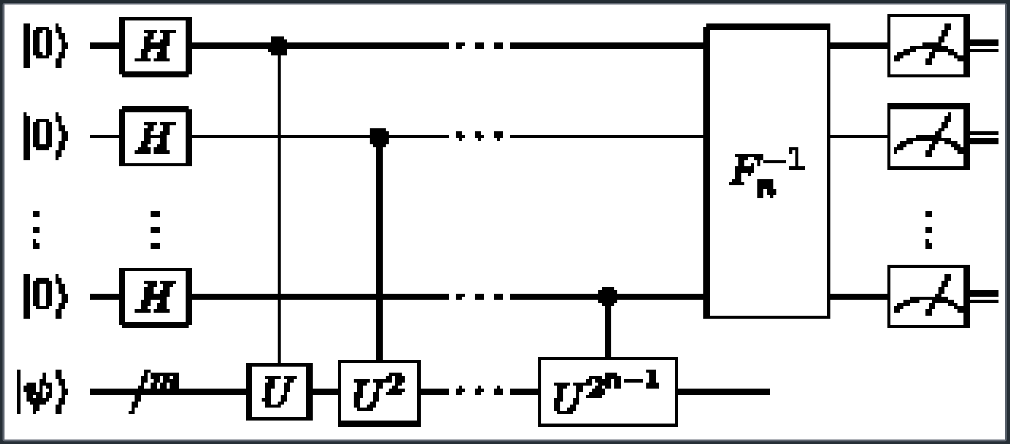
Happy Grad Student

Eventually, everything seems to work out or fizzle away.

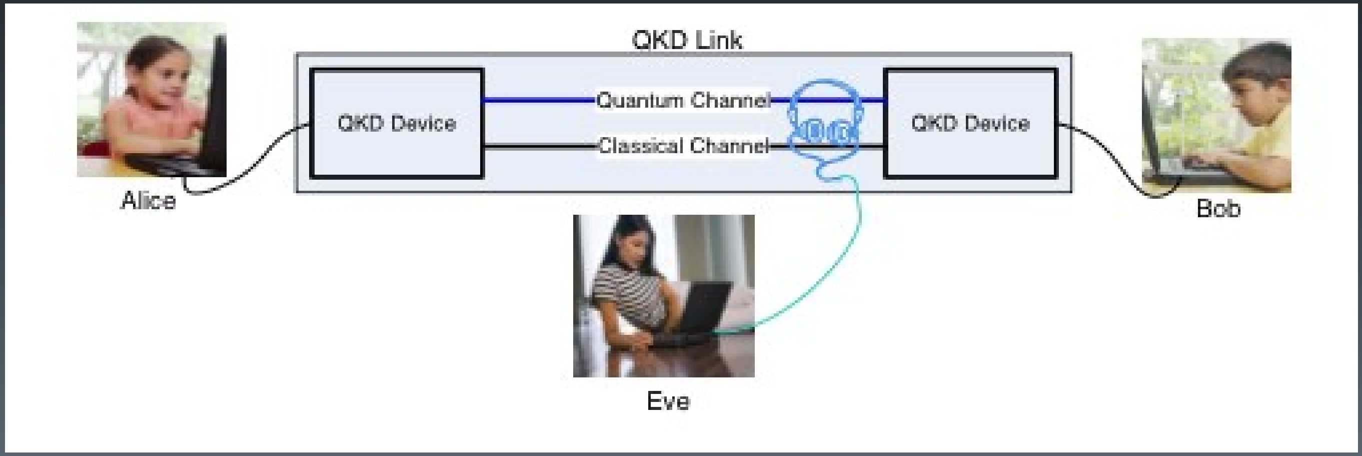
This was a good moment

Applications

Protect a qubit during use in a quantum computer



Protect information from relaxation during distribution of quantum cryptographic key



Conclusions

Weak measurement is consistent with the interpretation that the wave function is a reflection of our best information

New information creates a continuous change if we acknowledge and adapt to it

Weak measurements are reversible, but there is a probability of failure

Even mundane tasks can lead to discoveries

Unexpectedly, weak measurement reversal has a purpose as a decoherence suppression technique for relaxation (Quantum Error Correction)

YES WE CAN!

(Get into graduate school, work really hard, give up our social lives, find an advisor, struggle to catch up with a progressing field, figure out that we do not like the field, find a new advisor, learn jargon, program code, and **fake it until we make it**)