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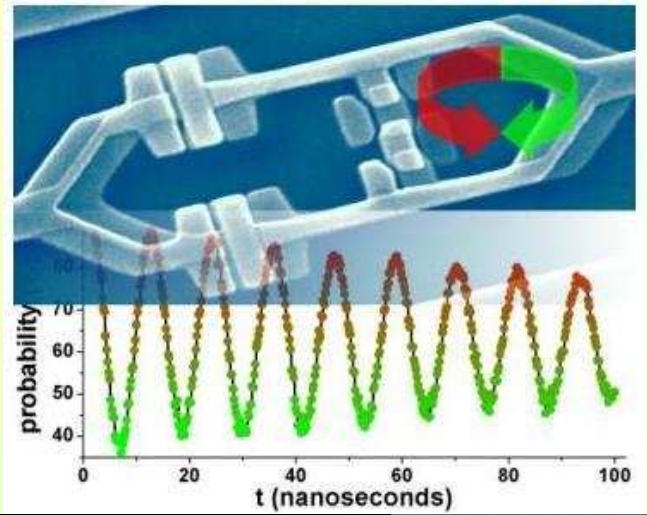
Realistic measurement of non-commuting variables

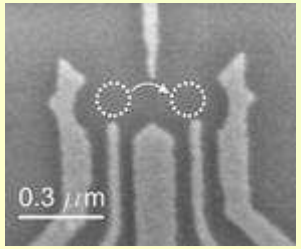
Yuli V. Nazarov

Hongduo Wei

Kavli Institute of Nanoscience Delft

Solid-state-based qubits



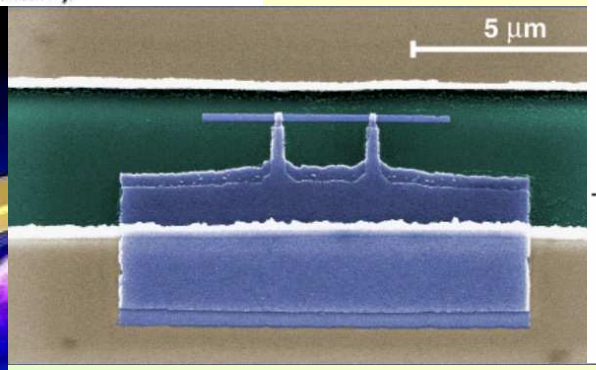


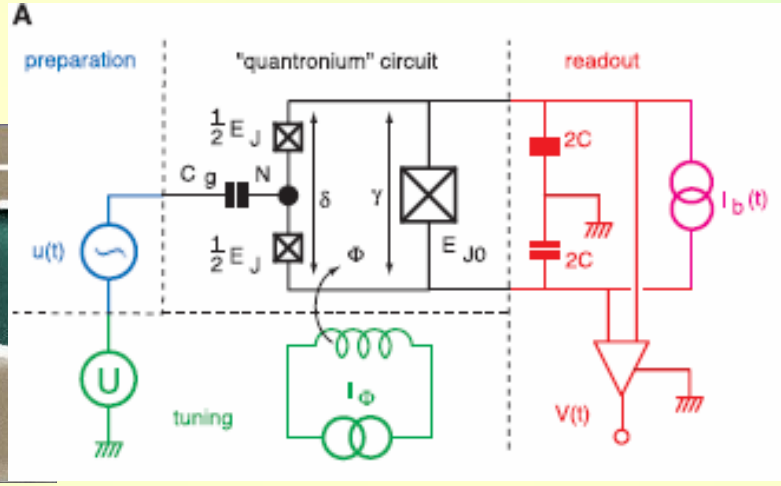
Spin

Charge

Phase

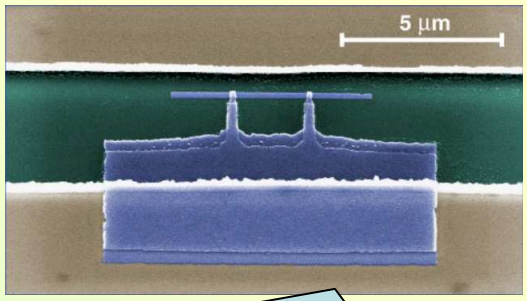
Flux





- Parts of electric circuit

Qubits + amplifiers



input

Feedback:

foe or friend?

output

Outline

- **Preliminary**
  - Misconceptions around quantum measurements
  - ’99-’06 theor. Activities – linear continuous measurement
  - QND experiments on qubits
- **Past**
  - measurement = statistics
  - Theoretical engine to access statistics of realistic measurements
  - Test runs
  - Non-commutimg measurement: quantum monitoring
- **Present**
  - Pumping a qubit
  - Detector with a strobe
- **Future**
  - Pumping entanglement?

D.V. Averin

M. Buttiker

A.A. Clerk

S.M. Girvin

A.N. Jordan

A.N. Korotkov

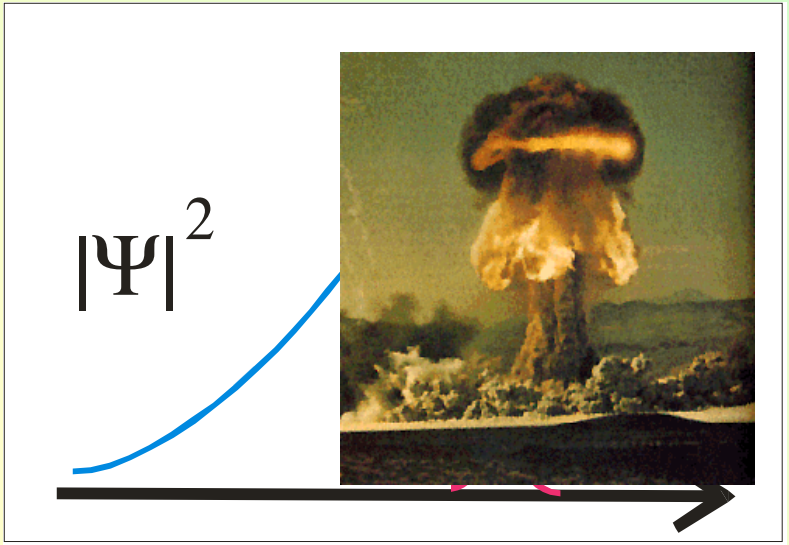
Y. Makhlin

G. Schon

A. Shnirman

A.D. Stone

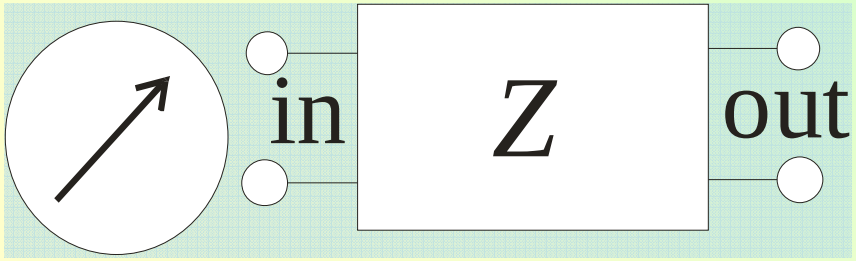
Quantum measurement vs. measurement of smth. quantum



- **Quantum measurement**
  - No measurement! Information transfer
  - Projective: wave function collapses
  - Is it realistic?
- **The collapse does not matter if**
  - Particle decay
  - Scattering
  - Quantum optics
- **It matters if the quantum system persists**
  - Measurement time
  - Decoherence time
  - Relaxation time
- **QND definition: repetitive measurements give the same result**
- **Implicated: each measurement is projective**

Linear measurement

- (almost) Any measurement – linear measurement
- Any detector –linear amplifier



- Gain(s) $a_{12}, a_{21}=0$, impedances (zero reverse gain condition)
- Output noise S_{oo}, noise of inp.variable S_{ii} noise correlations S_{io}
- Quantum restrictions

$$S_{oo}S_{ii} \geq S_{oi}^2 + \hbar^2 a_{12}{}^2 / 4 \Rightarrow$$

dimensionless

$$C_{||} \geq 1$$

classicity

- Acquisition rate $\Gamma_{ac} = \frac{a_{12}^2}{S_{oo}}$
- NOT faster than decoherence rate $\Gamma_{\phi} = \frac{2S_{ii}}{\hbar^2} = 2C_{||}\Gamma_{ac}$

Quantum non-demolition measurement

- **Definition: repetitive measurements give the same result**
- **Implicated: each measurement is projective**

$$H = H_{qubit} + H_{coupling} + H_{\det ector}$$

- **Qubit Ham. and Coupling commute**

$$H_{qubit} = h\hat{\sigma}_z$$

$$H_{coupling} = \hat{\sigma}_z \hat{i}; \quad \hat{i} - \text{input variable}$$

- **Fluctuations of *i* = *decoherence***

Hamiltonians (1 qu. + 1 det.)

$$H = H_{qubit} + H_{coupling} + \sum_k \hbar\omega_k \hat{b}_k^+ \hat{b}_k$$

$$H_{qubit} = h\,\hat{\sigma}_z, \quad H_{coupling} = -\hat{\sigma}_z \hat{i}.$$

$$\hat{i} = \sum_k i_k \hat{b}_k + h.c.; \quad \hat{o} = \sum_k o_k \hat{b}_k + h.c.;$$

Scrambled to:

correlators – noises

$$S_{oi}(t,t') = \left\langle \hat{o}(t)\hat{i}(t') \right\rangle$$

τ - duration of the measurement

$$To\,compute: Statistics\ of\ outcomes: \hat{p} = \frac{\int_{t_1}^{t_1+\tau} \hat{o}(t)dt}{\tau}$$

Features of our engine

- *Note:* any realistic measurement – the distribution of the outputs
- *Purpose:* to evaluate the distribution
- *Design:* generating function (χ) of the dist. from an extended Bloch equation for quasi-density matrix $\rho(\chi)$

$$\frac{\partial\hat{\rho}}{\partial t} = i[\hat{H},\hat{\rho}] - i\chi[\hat{\sigma}_z,\hat{\rho}]_+ - \Gamma(\hat{\rho} - \frac{1}{2}Tr(\hat{\rho})) - \chi^2\hat{\rho}/2$$

- *Scalability*: many qubits, many detectors, many measurements
- *Restrictions:* white noise, no-delay feedback

Details of (quasi) density matrix

- *Normal density matrix*: in space of spin(X)outcome(p) $\hat{\rho}(p_1, p_2)$
- *quasi-density matrix*: Fourier of diagonal

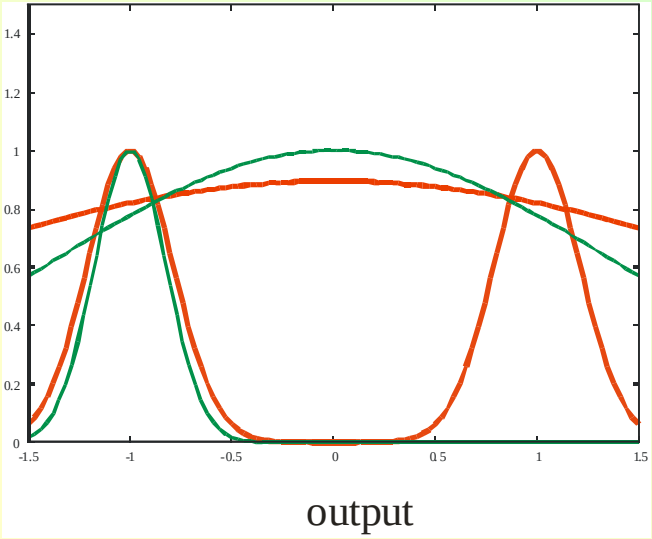
$$\hat{\rho}(\chi) = \int dp\, e^{-ip\chi}\, \hat{\rho}(p_1, p_2)$$

- *Godsend*: diagonal/non-diagonal decouple

QND measurement

- Confirmed
  - projective
  - repetitive
  - undoable(?)

  (Korotkov,Jordan)
- Lots of quantitative details

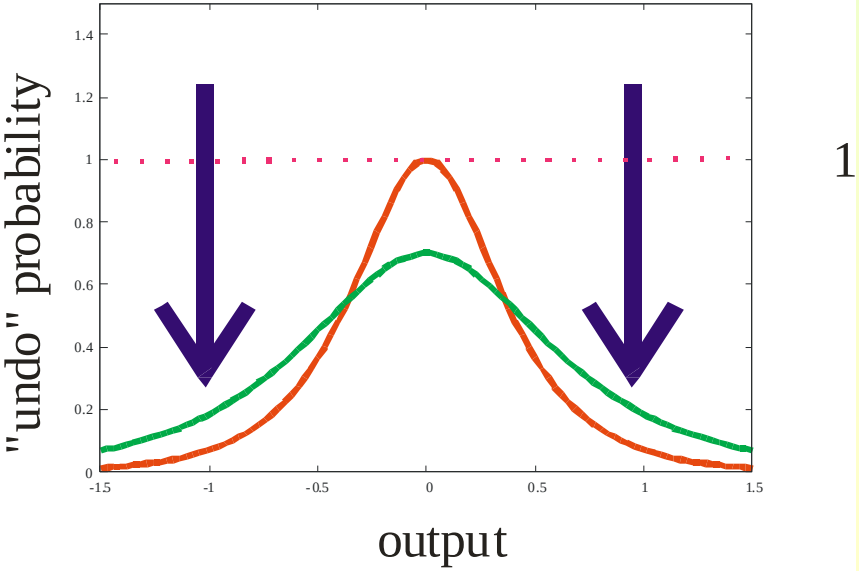


First

Second

Ideal

Realistic



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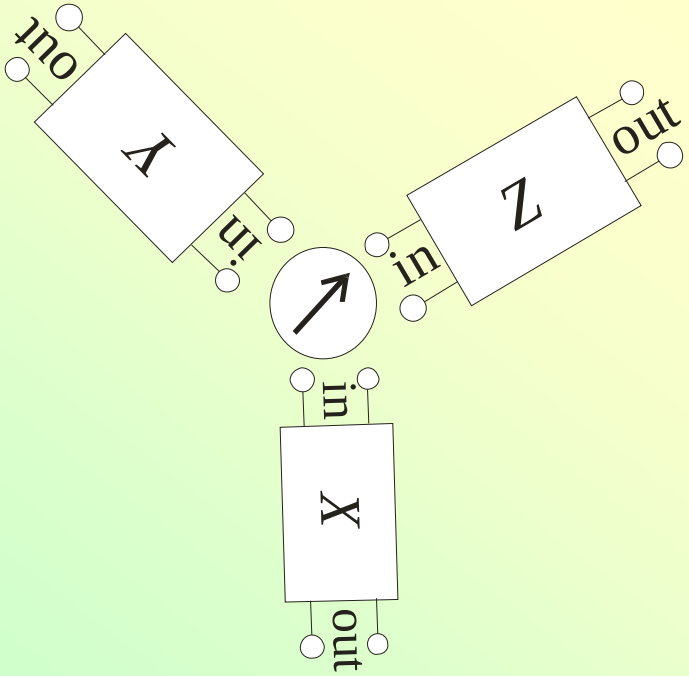
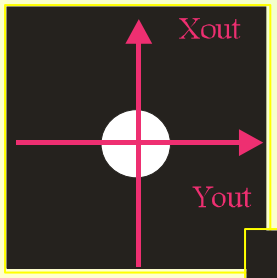
Forbidden measurement

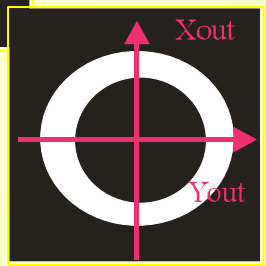
- Quantum measurement of non-commuting variables=nonsense=forbidden
- Forbidden = not good for you
- No reason not to try



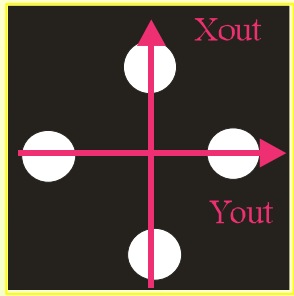
Can you guess the result?

A.





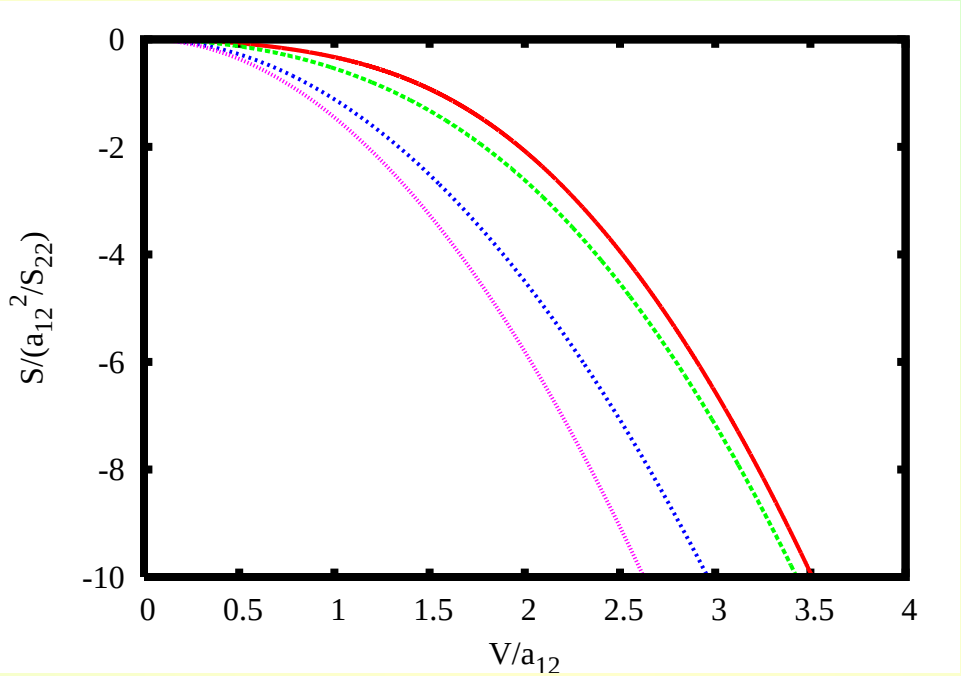
B.



C.

Distribution of outputs

- Spherically-symmetric
- Centered at zero
- Additional noise
- Non-gaussian shape
- Large outputs preffered



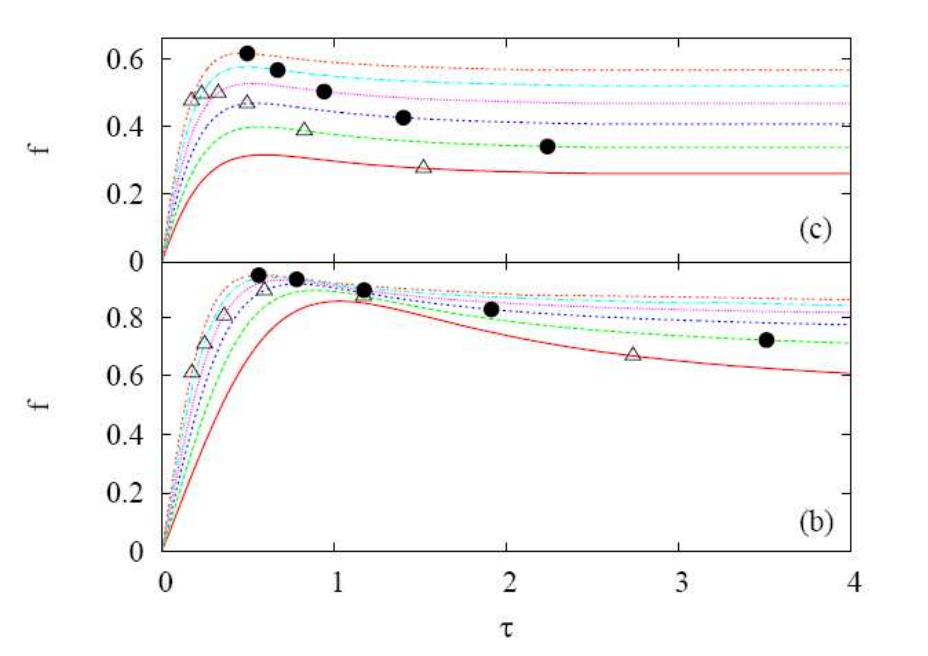
Ideal monitoring of the wave function

- We can know more than measure
- One-shot measurement in three directions: impossible
- Ideal monitoring in three directions: possible
- Wait for and look at big outputs

Datum	Measurement	Output Assesment	Action
08:00	1	typical	skip
08:01	2	typical	skip
08:02	3	**Big: fidelity 90%**	Write down: sz =0; sx = 0.4; sy=0.9
08:03	4	typical	skip
08:04	5	typical	skip
08:04	6	typical	skip

Fidelity and duration

- Waiting time exponentially long?
  - need numerical estimation



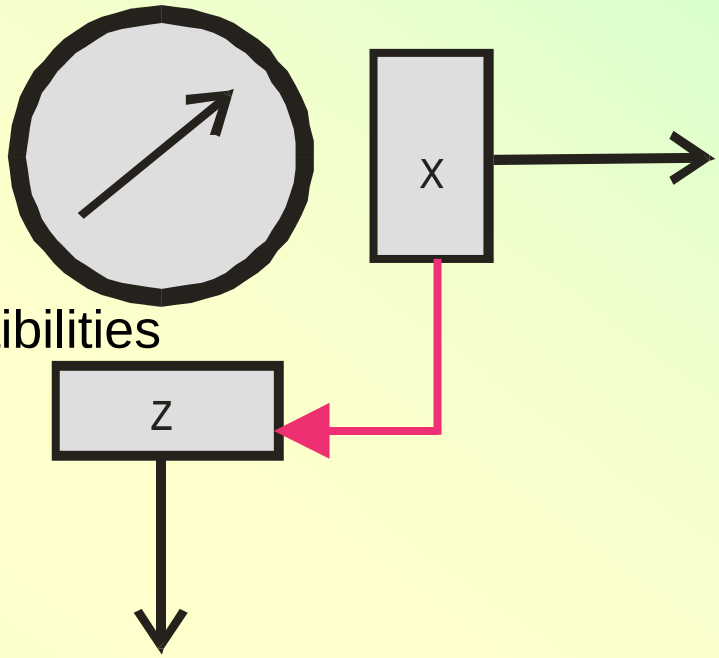
- Optimistic conclusion
  - 10 % relevant, fidelity 95 % => t = 7 t_{dec}

Relation to quantum infomation goodies

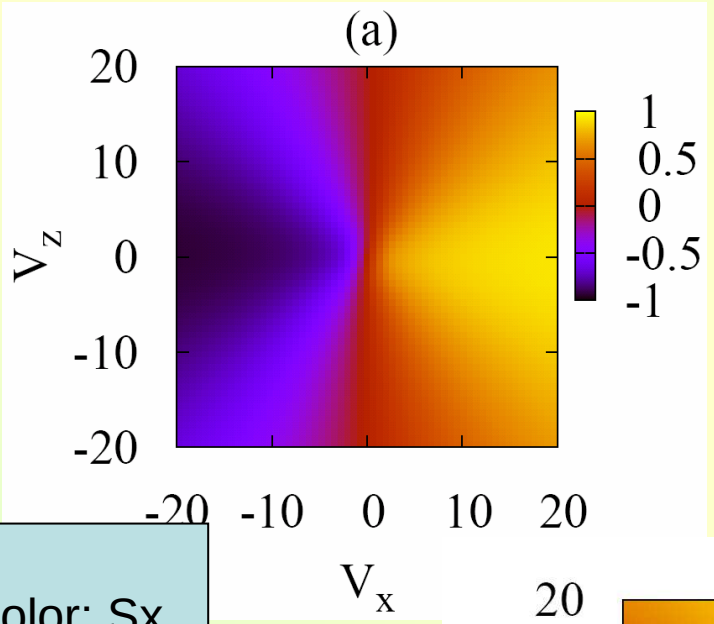
- Entanglement as a resource
  - distillation algorithms (Bennett, 1998)
  - purification algorithms (Nakazato, 2003)
  - quantum error correction
- Implementation?
  - not specific for photons
  - we provide one
  - more qubits, detectors, feedbacks ...

Pumping qubit: idea

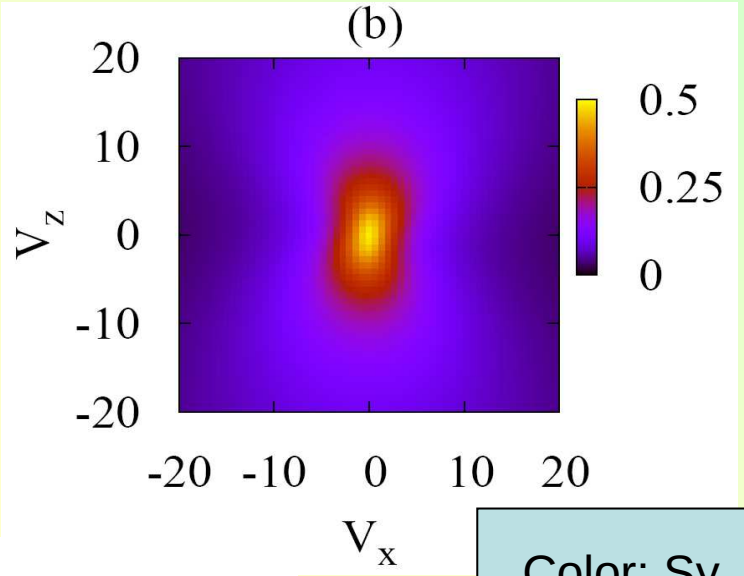
- **Feedback? Feedback!**
  - get output =>send to input
  - and do not listen back
- **Equlibrium-Non equilibrium**
  - listen - not listen
  - in our engine: asymmetric succeptibilities
- **Why pumping?**
  - nuclear spin pumping
- **Challenge**
  - touch x,z, polarize in y
  - improve polarization with quantum monitoring of x,z



Pumping qubit: results



Color: Sx



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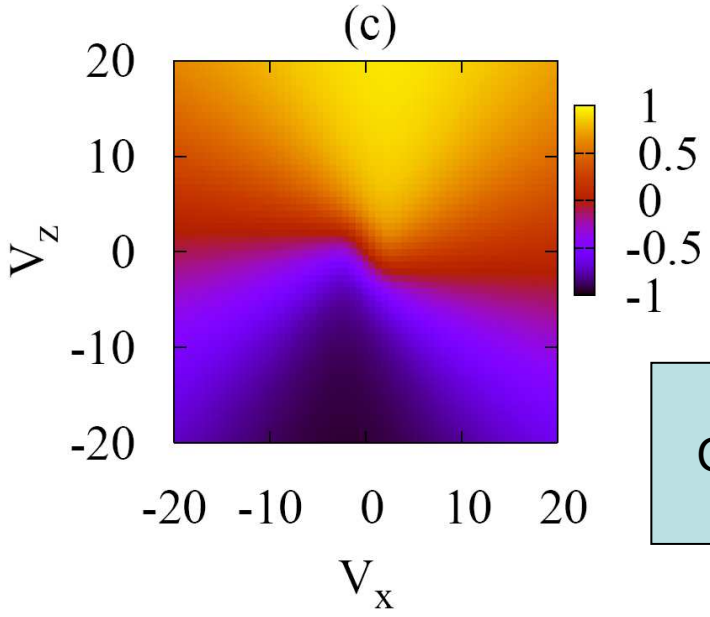
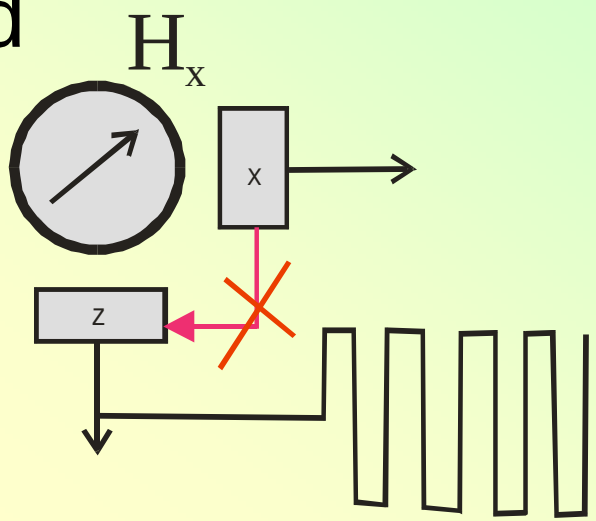


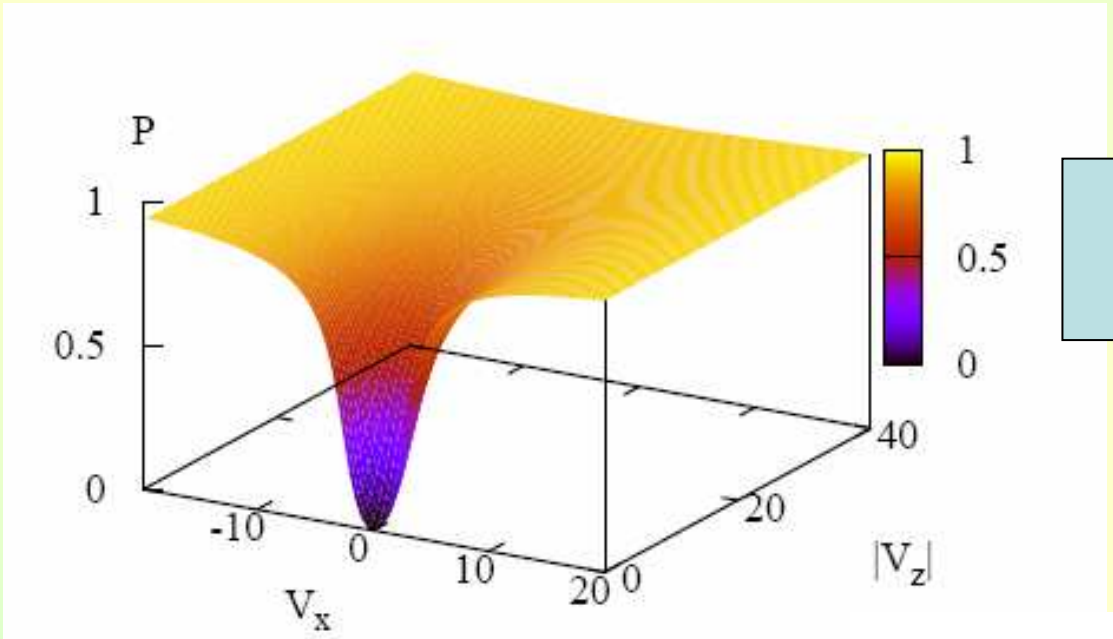
Color: Sz

~~Pumping~~ with a strobe: idea

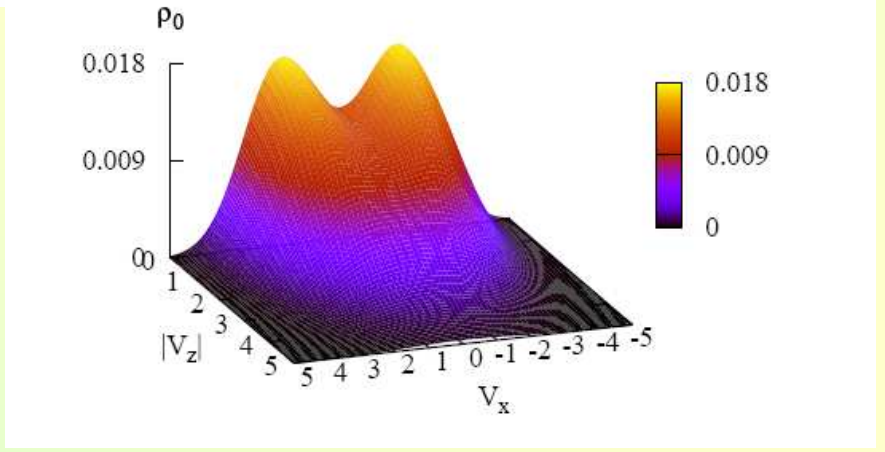
- Orientation in x direction: bad
- Bad=rotation about x axis
- To compensate: Measure at the rot. frequency(strobe)
- Does not help pumping...
- Saves number of detectors!
  - was: three detectors=three variables
  - now: two detectors=two variables



Detector with a strobe: results



Color: fideliity



Future

- Clear up (some theory)
- Feedback? Feedback!
  - one qubit: monitoring=purification
  - two qubits: entanglement distillation
  - Entanglement at large distances
  - Checked with statistics
- Back to reality
  - feedback with delay