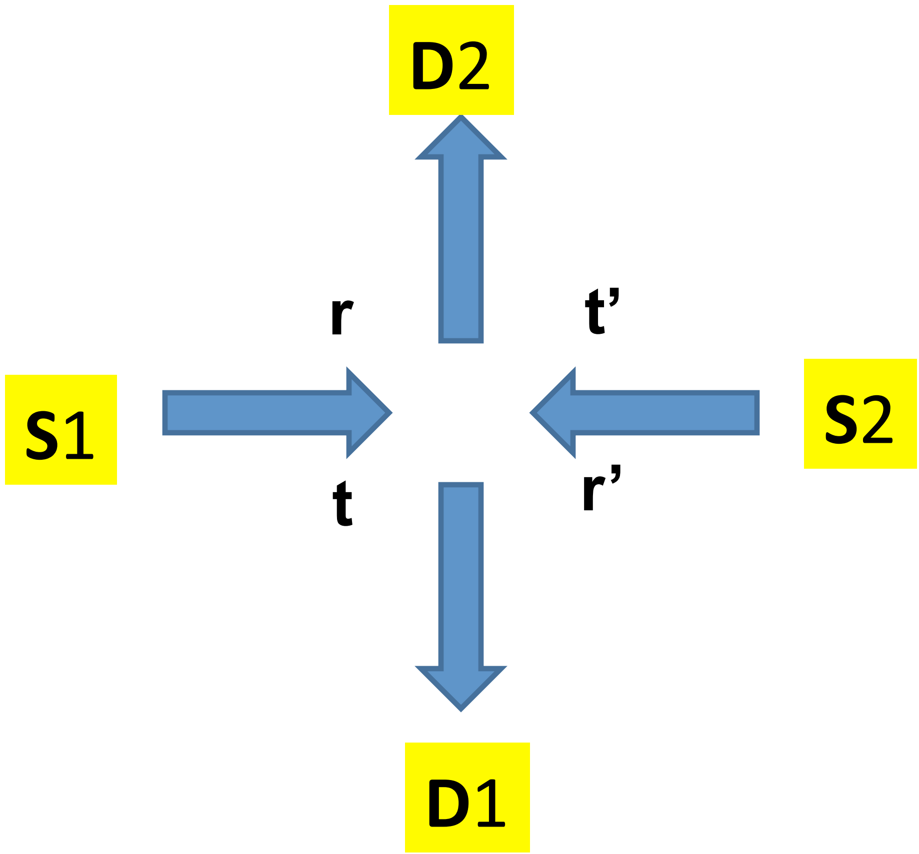
HANBURY BROWN & TWISS SCATTERING



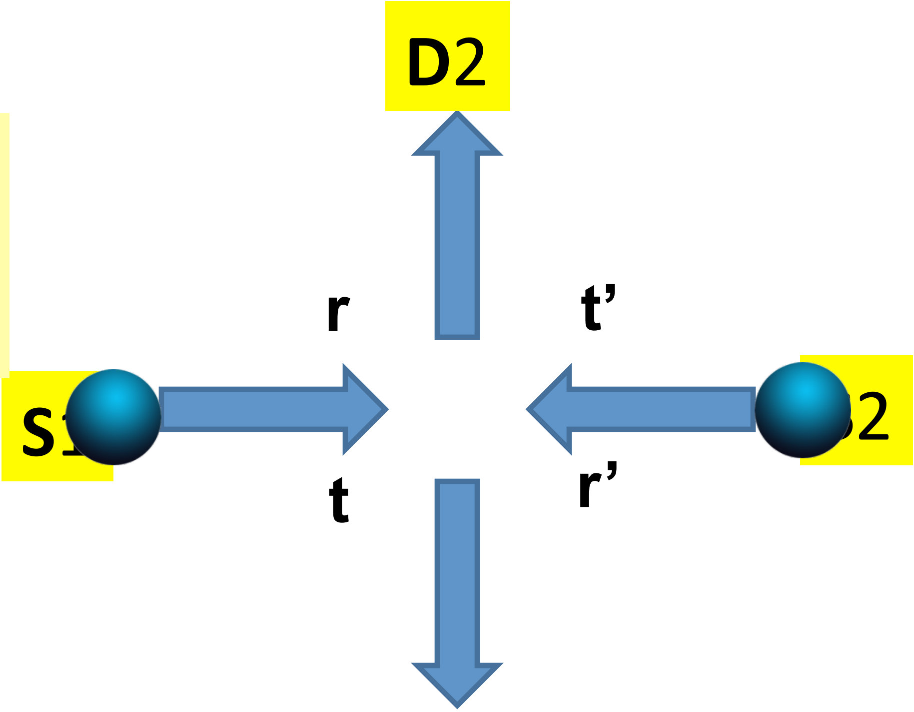
$T = |t|^2$
$R = |r|^2$

Buttiker, Blanter 2000

	P(2,0)	P(1,1)	P(0,2)
Classical	RT	$R^2 + T^2$	RT

Fermions:

$$\begin{pmatrix} b_{D1} \\ b_{D2} \end{pmatrix} = \hat{S} \begin{pmatrix} a_{S1} \\ a_{S2} \end{pmatrix}$$



$T = |t|^2$
$R = |r|^2$

$$\hat{n}_1 = b_{D1}^{\dagger} b_{D1}$$

$$\hat{n}_2 = b_{D2}^{\dagger} b_{D2}$$

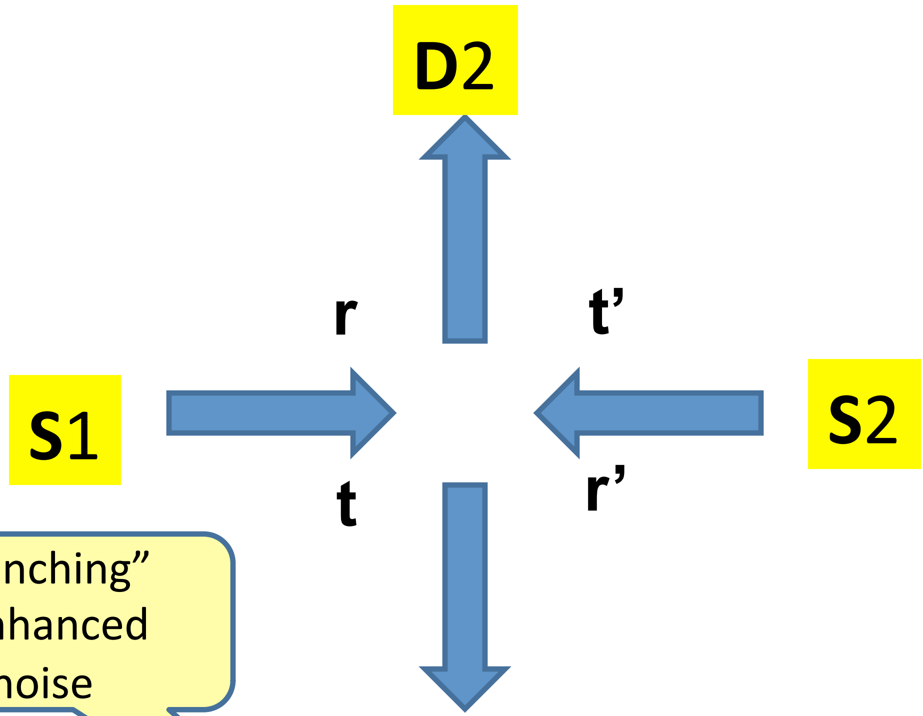
$$P(1,1) = \langle \Psi | \hat{n}_1 \hat{n}_2 | \Psi \rangle = \langle 0 | a_{S2} a_{S1} b_{D1}^{\dagger} b_{D1} b_{D2}^{\dagger} b_{D2} a_{S1}{}^{\dagger} a_{S2}{}^{\dagger} | 0 \rangle$$

$$P(1,1) = (T + R)^2 = 1$$

	P(2,0)	P(1,1)	P(0,2)
Fermions	0	1	0

Buttiker, Blanter

$T = |t|^2$
$R = |r|^2$



"bunching" =enhanced noise

"anti-bunching" =reduced noise

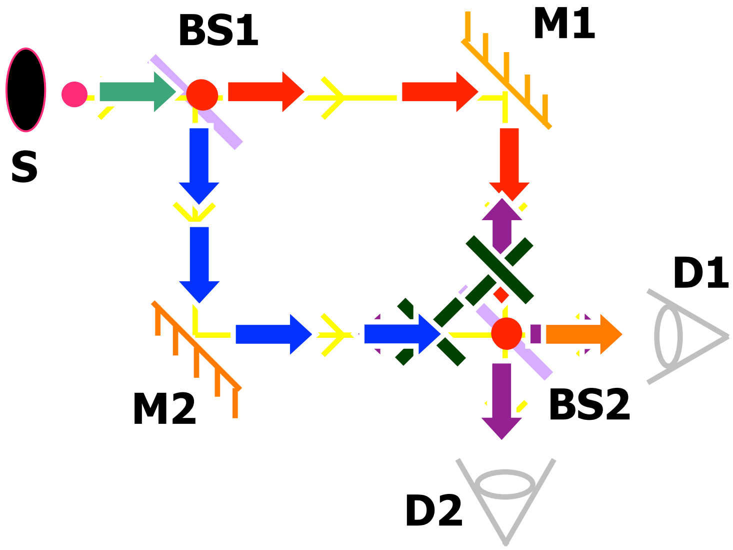
	P(2,0)	P(1,1)	P(0,2)
Classical	RT	$R^2 + T^2$	RT
Bosons	$2RT$	$R^2 + T^2$-$2RT$	$2RT$
Fermions	0	1	0

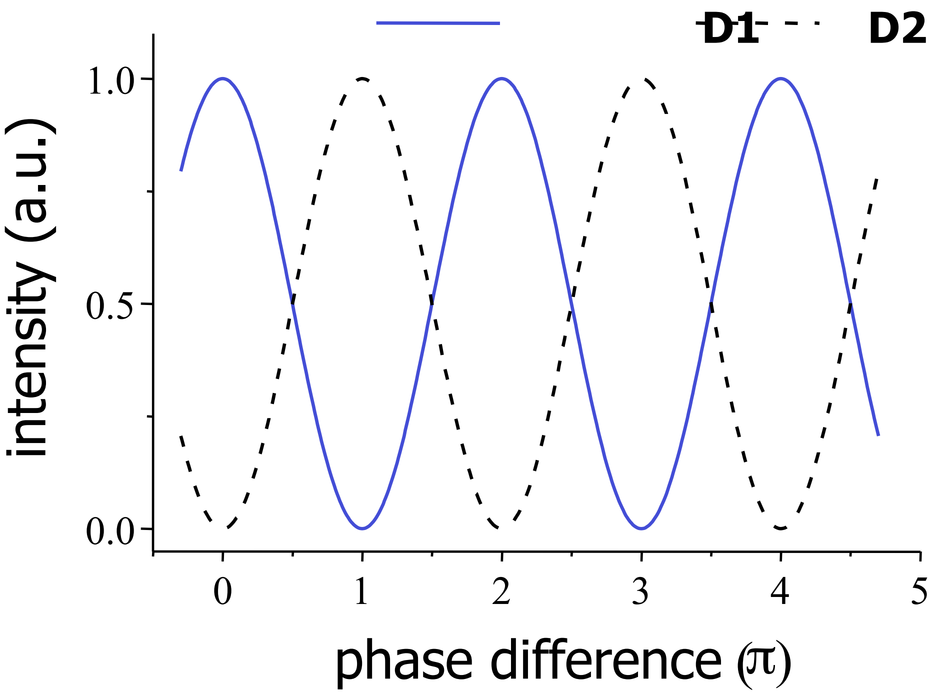
Buttiker, Blanter

	P(2,0)	P(1,1)	P(0,2)
Classical	RT	$R^2 + T^2$	RT
Bosons	$RT(1+J^2)$	$R^2 + T^2 - 2RTJ^2$	$RT(1+J^2)$
Fermions	$RT(1-J^2)$	$R^2 + T^2 + 2RTJ^2$	$RT(1-J^2)$

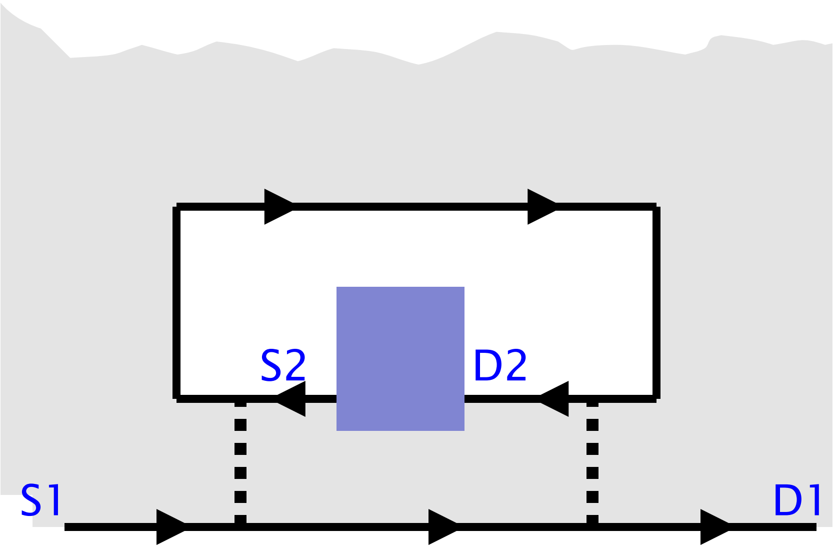
J = overlap between (wavepackets)
of colliding particles

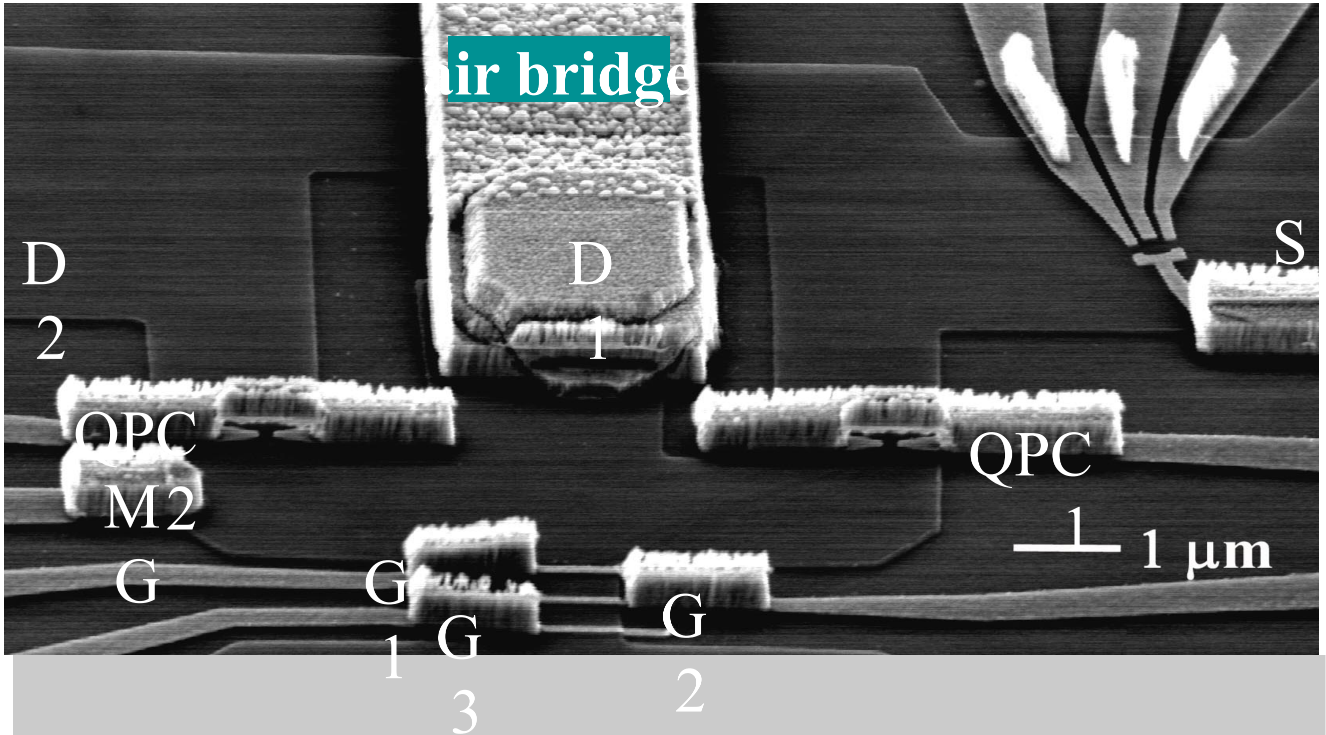
Mach-Zehnder Photonic Interferometer





$$T_{S\to D_2} = \left| t_{BS1} t_{BS2} + r_{BS1} r_{BS2} e^{i\Delta\Phi} \right|^2 = T_0 + T_1 \cos \Delta\Phi$$

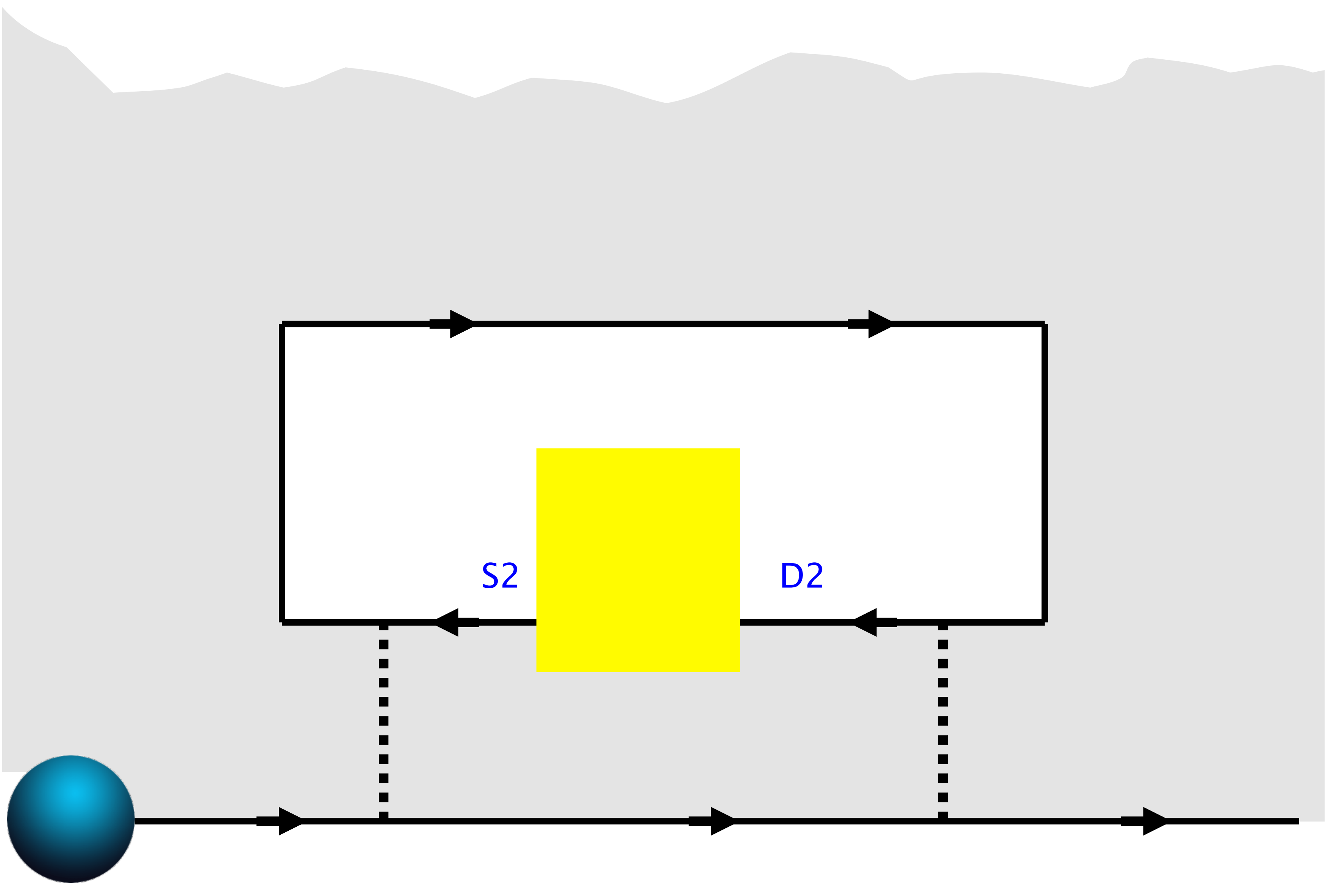


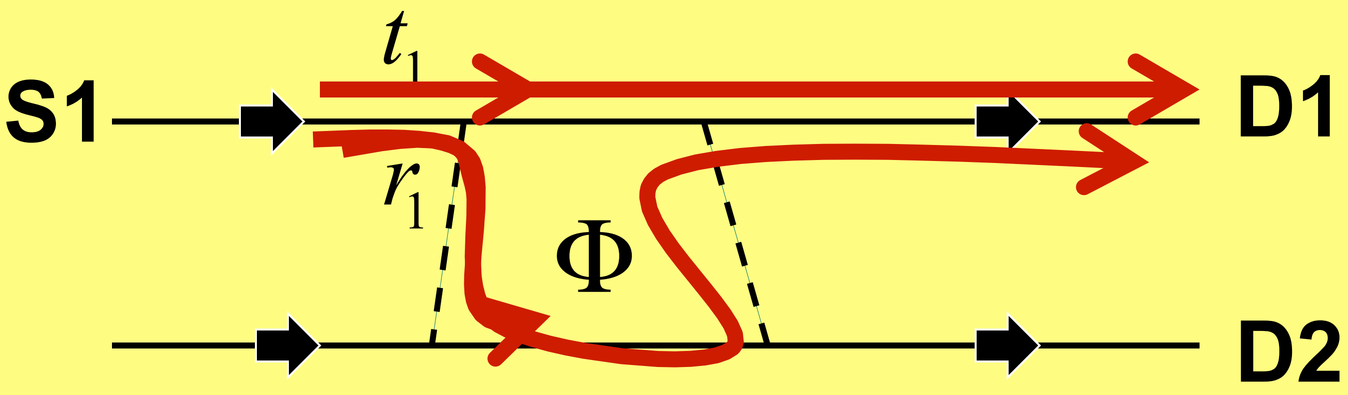


Neder, Heiblum *et al*

DEPHASING THROUGH MEASUREMENT

(which path)

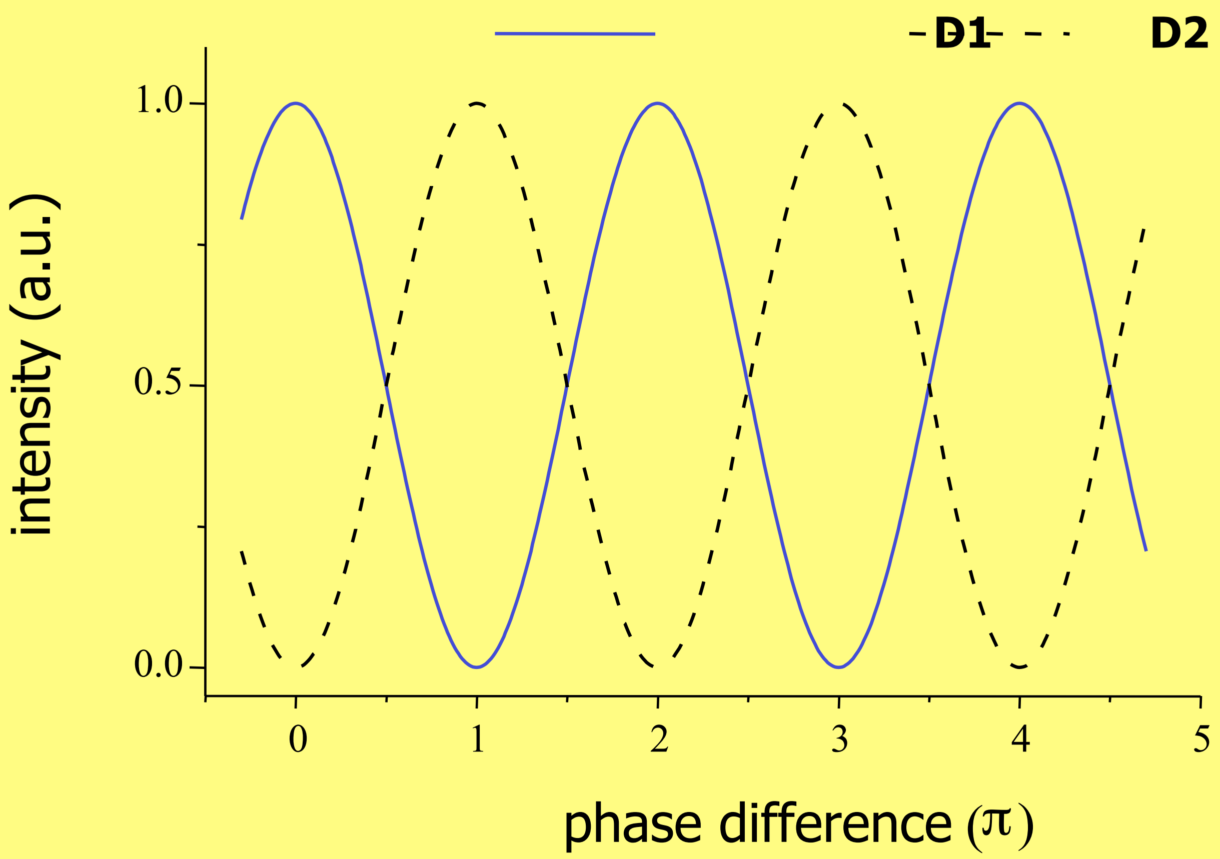

S2
D2



$$\psi_{D1} = t_1 t_2 e^{i2\pi\Phi/\Phi_0} + r_1 r_2$$

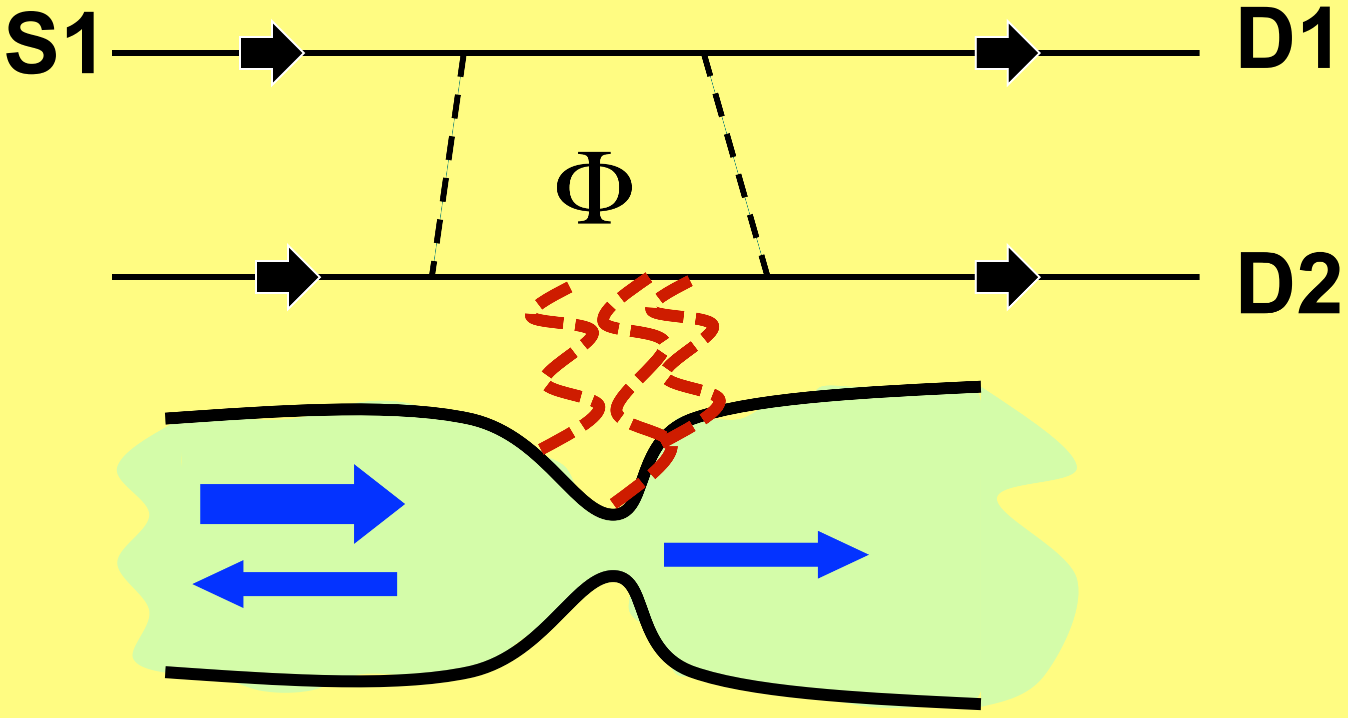
$$|t_1|, |t_2|, |r_1|, |r_2| = 1/\sqrt{2}$$

$$P_{D2} = \frac{1}{2} + \frac{1}{2}\cos(2\pi\Phi/\Phi_0) \Rightarrow visibility = 1$$



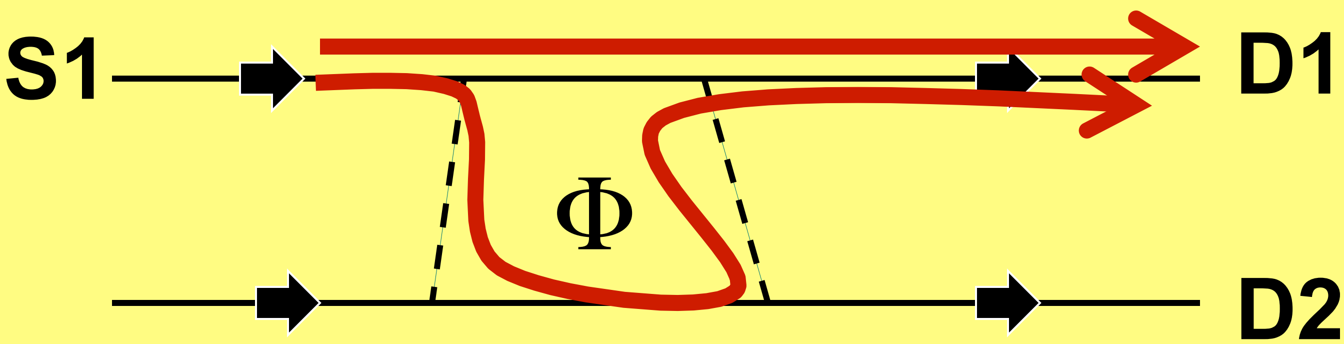
D1
D2
1.0
0.5
0.0
0
1
2
3
4
5
intensity (a.u.)
phase difference (π)

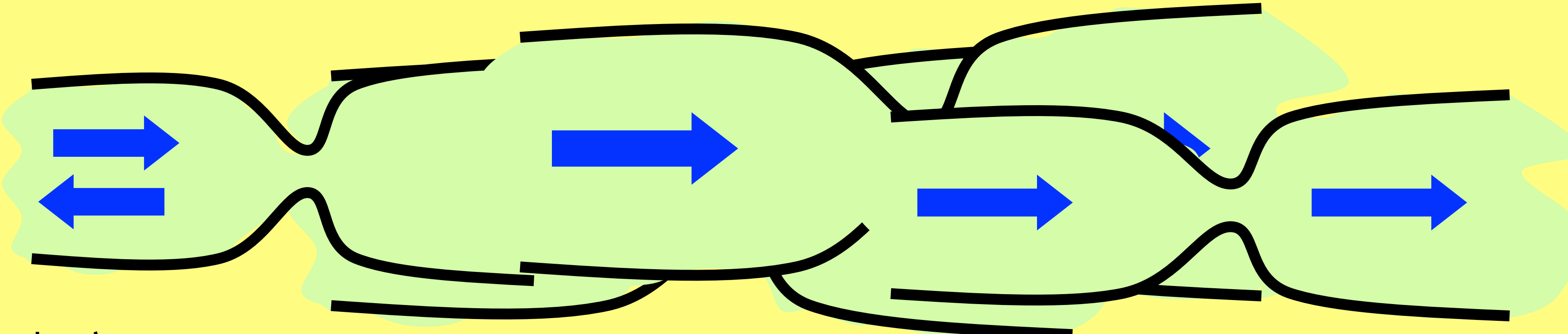
now, adding a detector



STRONG MEASUREMENT

STRONG MEASUREMENT





$|\downarrow\rangle_{system} \otimes |r\rangle_{detector}$ $|\uparrow\rangle_{system} + e^{i2\pi\Phi/\Phi_0} \otimes |\uparrow\rangle_{system} \otimes |t\rangle_{detector}$

$|\downarrow\rangle_{system} \otimes |r\rangle_{detector}$ $|t\rangle_{detector}$

$$P_{D1} = const \Rightarrow visibility = 0$$

“DEPHASING”

(loss of coherent interference pattern due to “which path” detection)

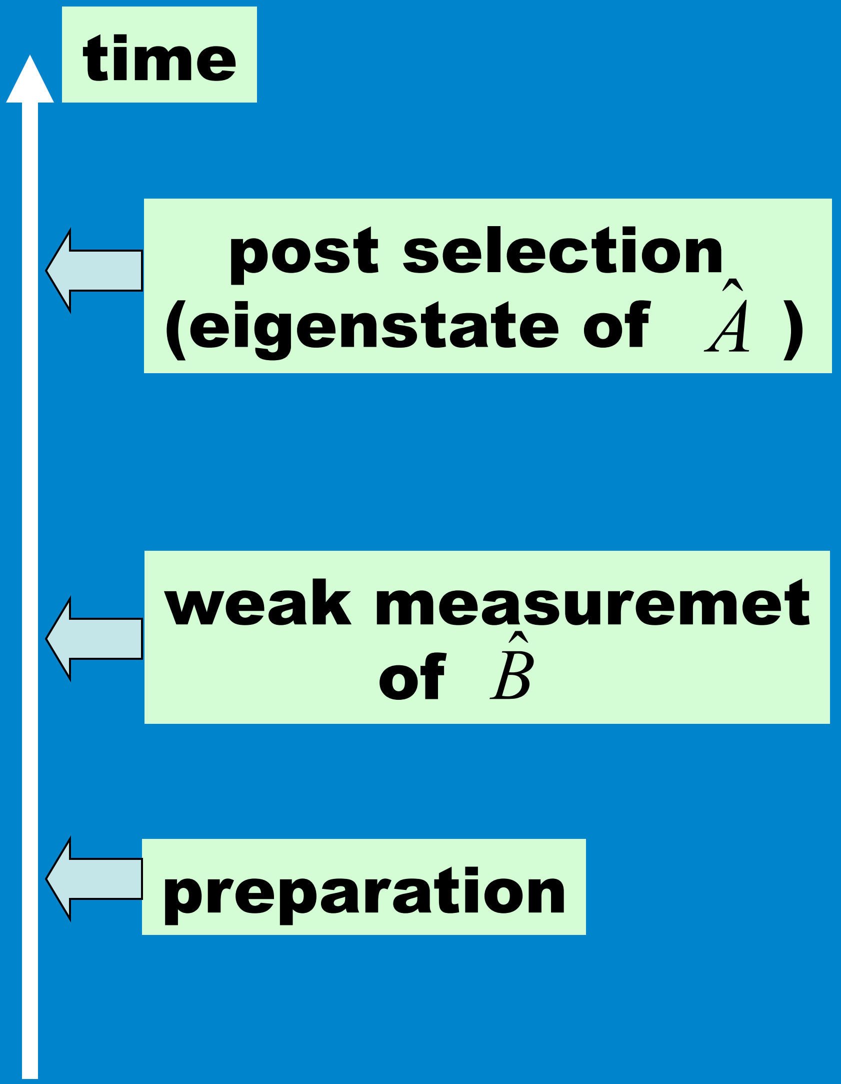
QUANTUM ERASURE

(Weisz, Heiblum, YG, et al Science 2014)

IV COMPOSITE MEASUREMENT PROTOCOLS: weak value protocol and beyond

WEAK VALUE : Aharonov, Albert, Vaidman, 1988

$$[\hat{A}, \hat{B}] \neq 0$$



$$\langle \hat{B} \rangle = \langle \Psi_{in} | \hat{B} | \Psi_{in} \rangle =$$

$$\sum_{\Psi_n^A} \langle \Psi_{in} | \Psi_n^A \rangle \cdot \langle \Psi_n^A | \hat{B} | \Psi_{in} \rangle =$$

$$\frac{\langle \Psi_n^A | \Psi_{in} \rangle}{\langle \Psi_n^A | \Psi_{in} \rangle} \bullet \Rightarrow \sum_{\Psi_n^A} | \langle \Psi_n^A | \Psi_{in} \rangle |^2 \cdot \langle \Psi_n^A | \hat{B} | \Psi_{in} \rangle / \langle \Psi_n^A | \Psi_{in} \rangle$$

weak disturbance

$$= \sum_{\Psi_n^A} P(|\Psi_{fin}\rangle = |\Psi_n^A\rangle \,|\, \Psi_{in}) \cdot \langle \Psi_n^A | \hat{B} | \Psi_{in} \rangle / \langle \Psi_n^A | \Psi_{in} \rangle$$

$$ {}_{\Psi_0^A}\langle \hat{B} \rangle_{\text{weak}} = P(|\Psi_{fin}\rangle = |\Psi_0^A\rangle |\Psi_{in}) \cdot \frac{\langle \Psi_0^A | \hat{B} | \Psi_{in} \rangle}{\langle \Psi_0^A | \Psi_{in} \rangle} $$

select (post-select) Ψ_0^A

(only "successful" measurements of $\hat{B}$

$$ \langle \hat{B} \rangle = \sum_{\Psi_n^A} P(|\Psi_{fin}\rangle = |\Psi_n^A\rangle |\Psi_{in}) \cdot \frac{\langle \Psi_n^A | \hat{B} | \Psi_{in} \rangle}{\langle \Psi_n^A | \Psi_{in} \rangle} $$

$$ {}_{\Psi_{final}}\langle \hat{B} \rangle_{\text{weak}} = \frac{\langle \Psi_{final} | \hat{B} | \Psi_{in} \rangle}{\langle \Psi_{final} | \Psi_{in} \rangle} $$

same expression through microscopic system-detector analysis

example: Spin 1/2

time

$$\left| S_x = +\frac{1}{2} \right\rangle$$

post selection (eigenvalue of $\hat{A}$)

measuring $\frac{(\hat{S}_x + \hat{S}_z)}{\sqrt{2}}$

weak measuremet of $\hat{B}$

$$\left| S_z = +\frac{1}{2} \right\rangle$$

preparation

example: Spin 1/2

$$\left\langle \hat{B} \right\rangle_{weak} = \frac{\left\langle \Psi^0_{fin} \,|\, \hat{B} \,|\, \Psi_{in} \right\rangle}{\left\langle \Psi^0_{fin} \,|\, \Psi_{in} \right\rangle}$$

$$\frac{\left\langle S_x = +\frac{1}{2} \,|\, [\frac{(\hat{\mathrm{S}}_{\mathrm{x}} + \hat{\mathrm{S}}_{\mathrm{z}})}{\sqrt{2}}] \,|\, S_z = +\frac{1}{2} \right\rangle}{\left\langle S_x = +\frac{1}{2} \,|\, S_z = +\frac{1}{2} \right\rangle} =$$

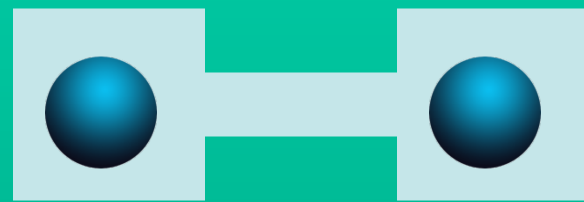
example: Spin 1/2

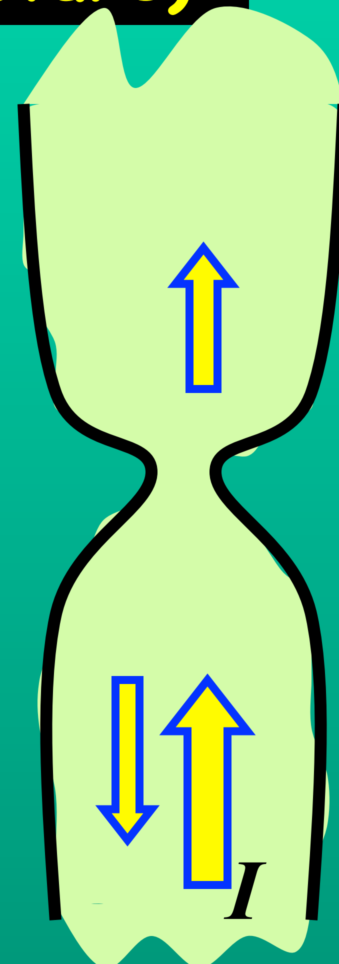
$$\frac{\left\langle S_x=+\frac{1}{2}\,|\,[\frac{(\hat{S}_x+\hat{S}_z)}{\sqrt{2}}]\,|\,S_z=+\frac{1}{2}\right\rangle}{\left\langle S_x=+\frac{1}{2}\,|\,S_z=+\frac{1}{2}\right\rangle}=$$

$$\frac{1}{2}g\frac{1}{\sqrt{2}}\frac{\left\langle S_x=+\frac{1}{2}\,|\,S_z=+\frac{1}{2}\right\rangle}{\left\langle S_x=+\frac{1}{2}\,|\,S_z=+\frac{1}{2}\right\rangle}+\frac{1}{2}g\frac{1}{\sqrt{2}}\frac{\left\langle S_x=+\frac{1}{2}\,|\,S_z=+\frac{1}{2}\right\rangle}{\left\langle S_x=+\frac{1}{2}\,|\,S_z=+\frac{1}{2}\right\rangle}=\frac{1}{\sqrt{2}}=$$

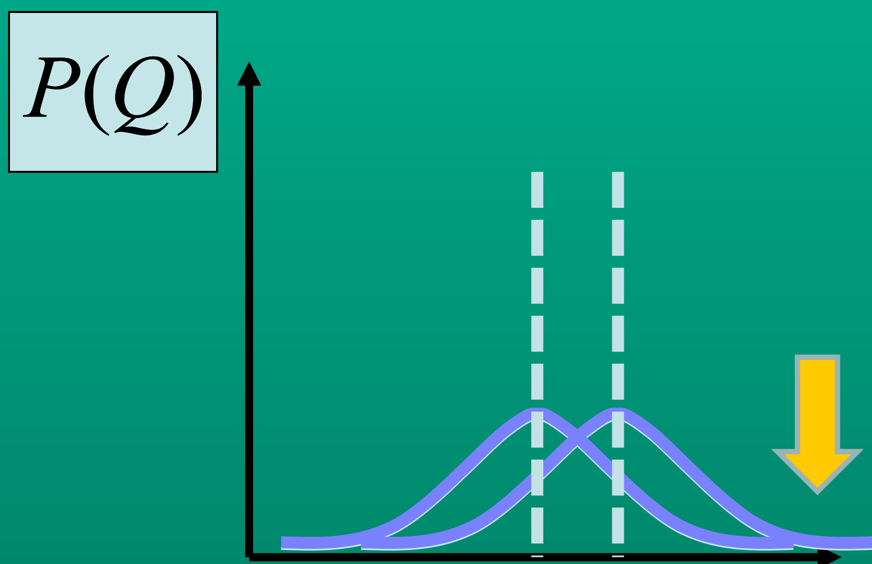
$$\frac{\sqrt{2}}{2}\Rightarrow \text{outside } [-\frac{1}{2},+\frac{1}{2}] \quad !!!$$

HOW CAN IT BE? (physical picture)





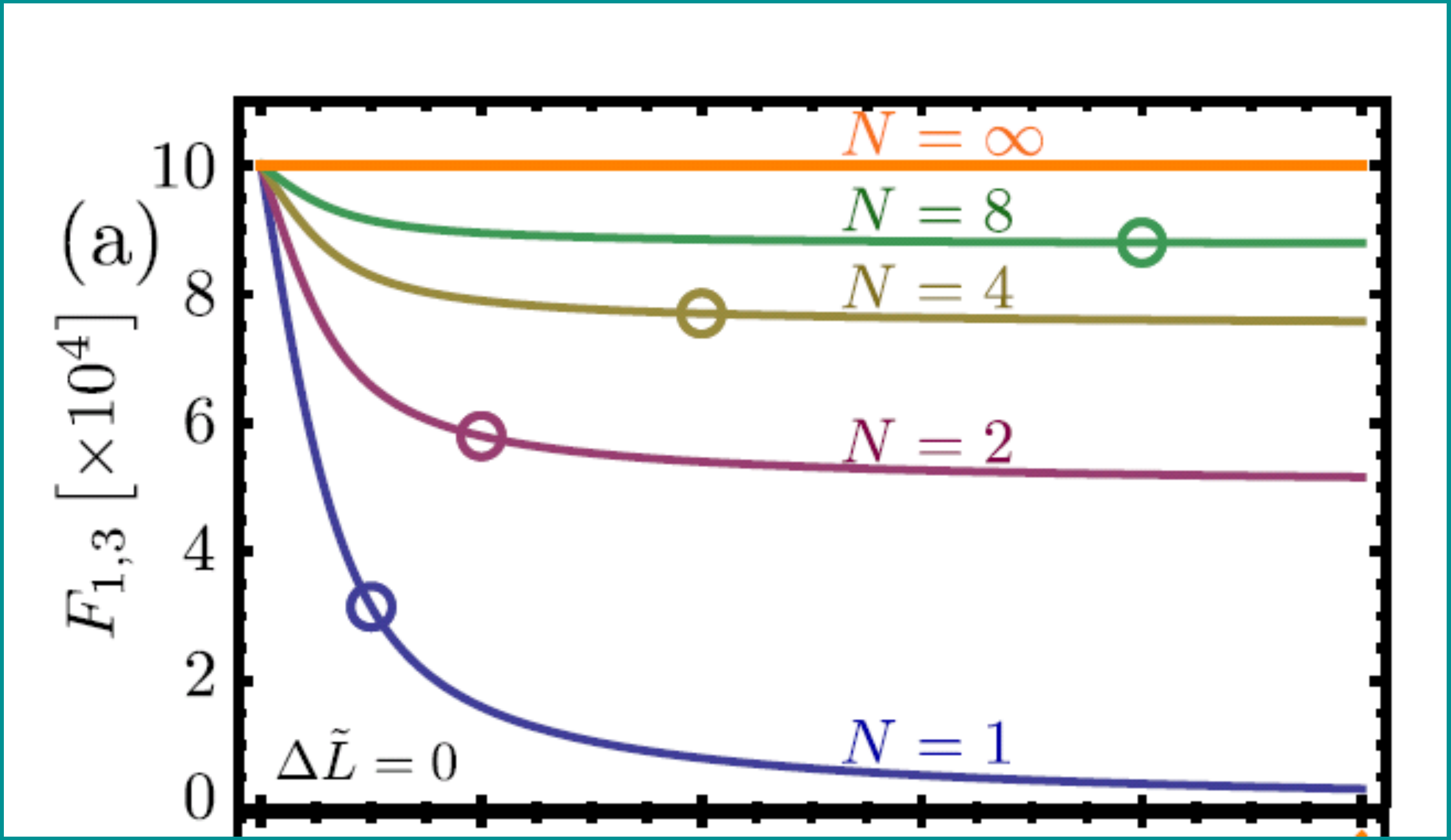
Quantum Point Contact



$$Q = \int_{\Delta t} I \cdot dt$$

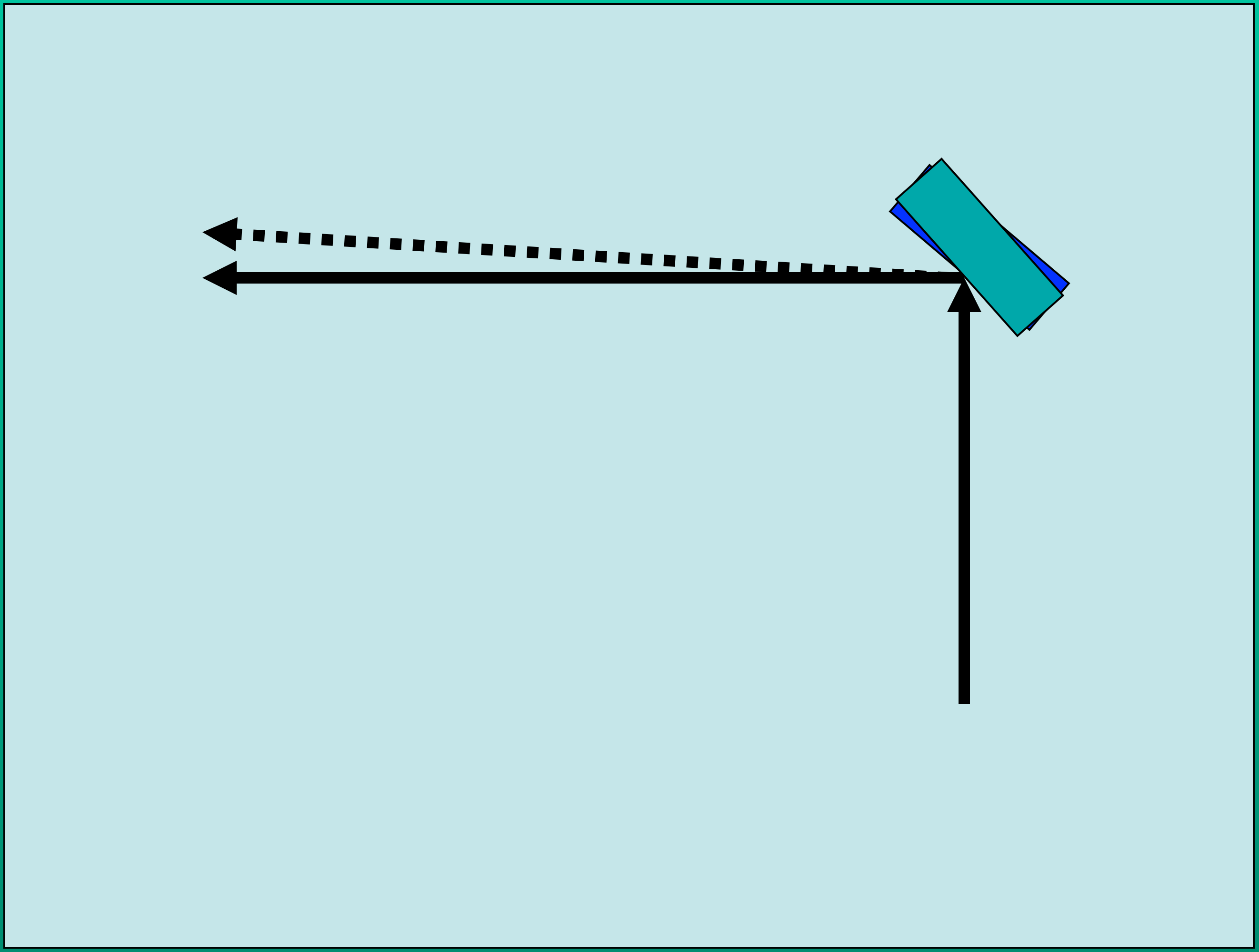
WHAT ARE WEAK VALUES GOOD FOR?

- **EXOTIC EXPECTATION VALUES**
  (> largest eigenvalue; total spin=negative; complex)
  Romito, YG, Blanter PRL 2008, Shpitalnik, Romito, YG, PRL 2008, Williams, Jordan PRL 2008.
- **ULTRA SENSITIVE AMPLIFICATION**
  Dixon et al, PRL 2009; Hosten Kwiat Science 2009
- **QUANTUM STATE DISCRIMINATION**
  Zilberberg, Romito, Starling, Howland, Howell, YG PRL 2013
- **OBSERVATION OF VIRTUAL STATES**
  cotunneling: Romito, YG , 2015
- **QUANTUM ERASURE**
  Weiss, Heiblum, YG et al Science 2014, YG & Romito
- **NON-LOCAL EFFECTS**
  "Elitzur-Vaidman Box" Zilberberg, Romito,YG,PRB 2016
- **TOPOLOGICAL EXCITATIONS ….**



Zilberberg, Romito, YG, 2016

AMPLIFICATION



AMPLIFICATION

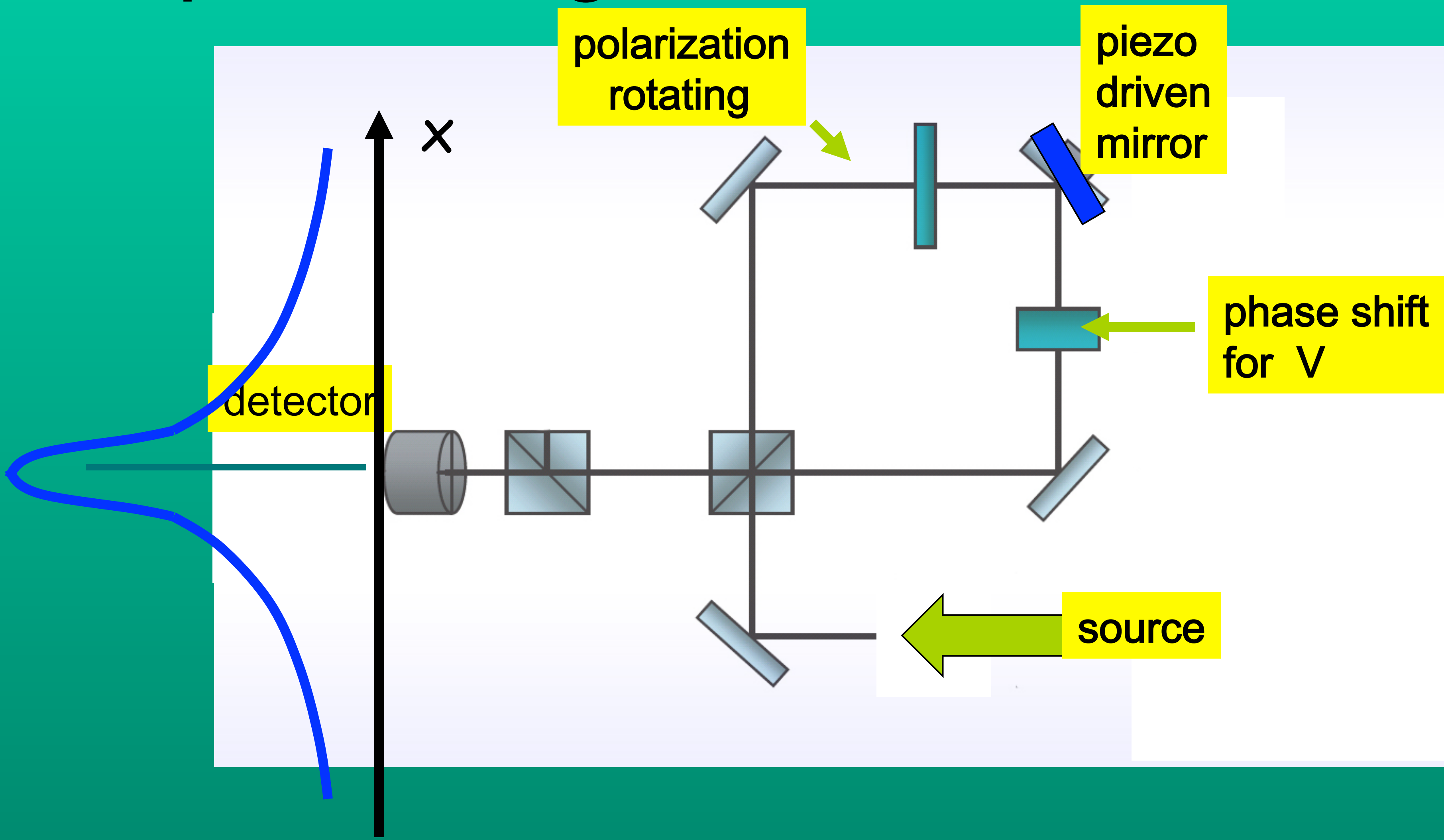
Measured 560 frad of mirror deflection

deflection $< 2\mu$

Dixon et al, PRL 2009

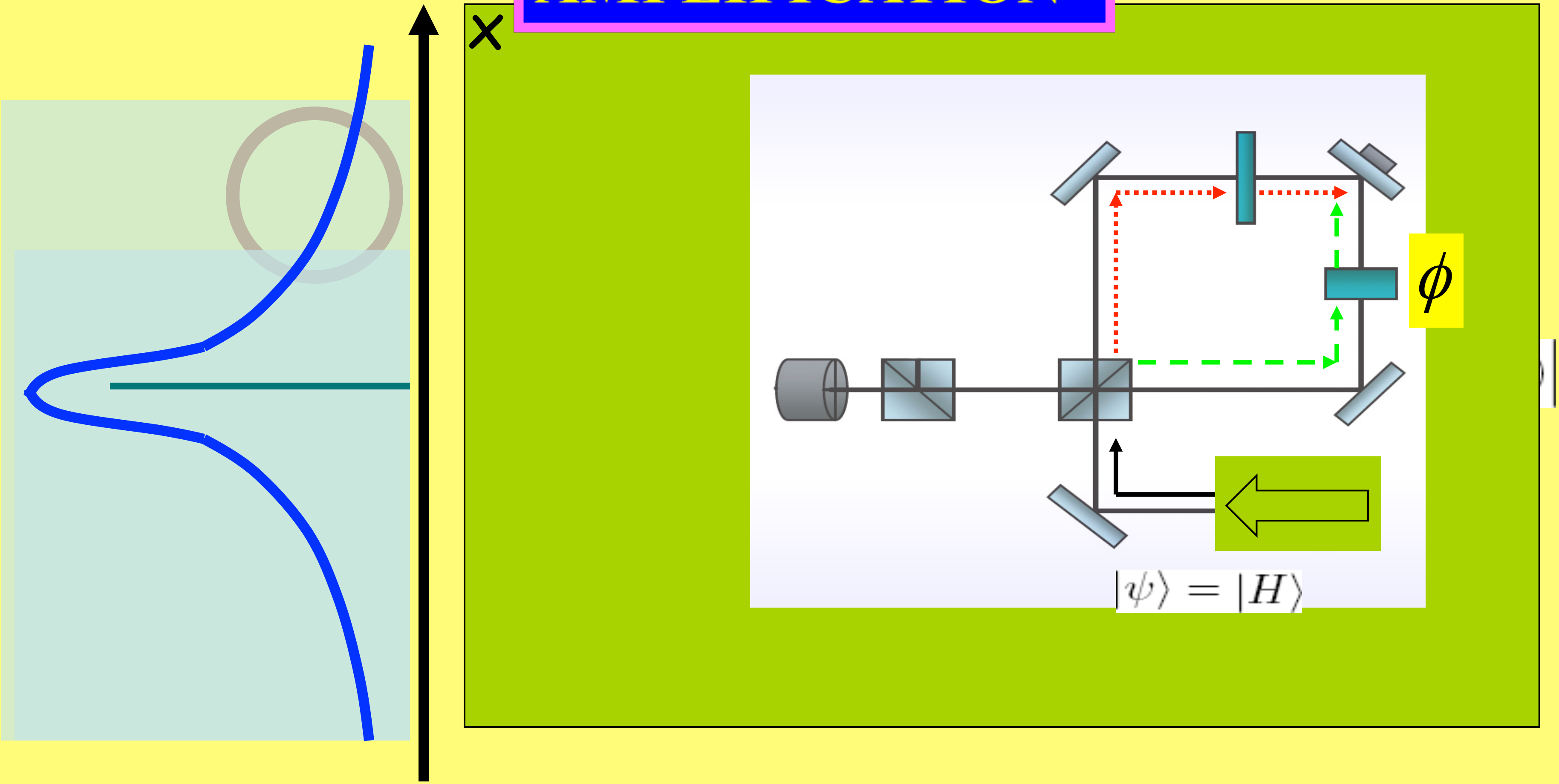
AMPLIFICATION

optical Sagnac interferometer



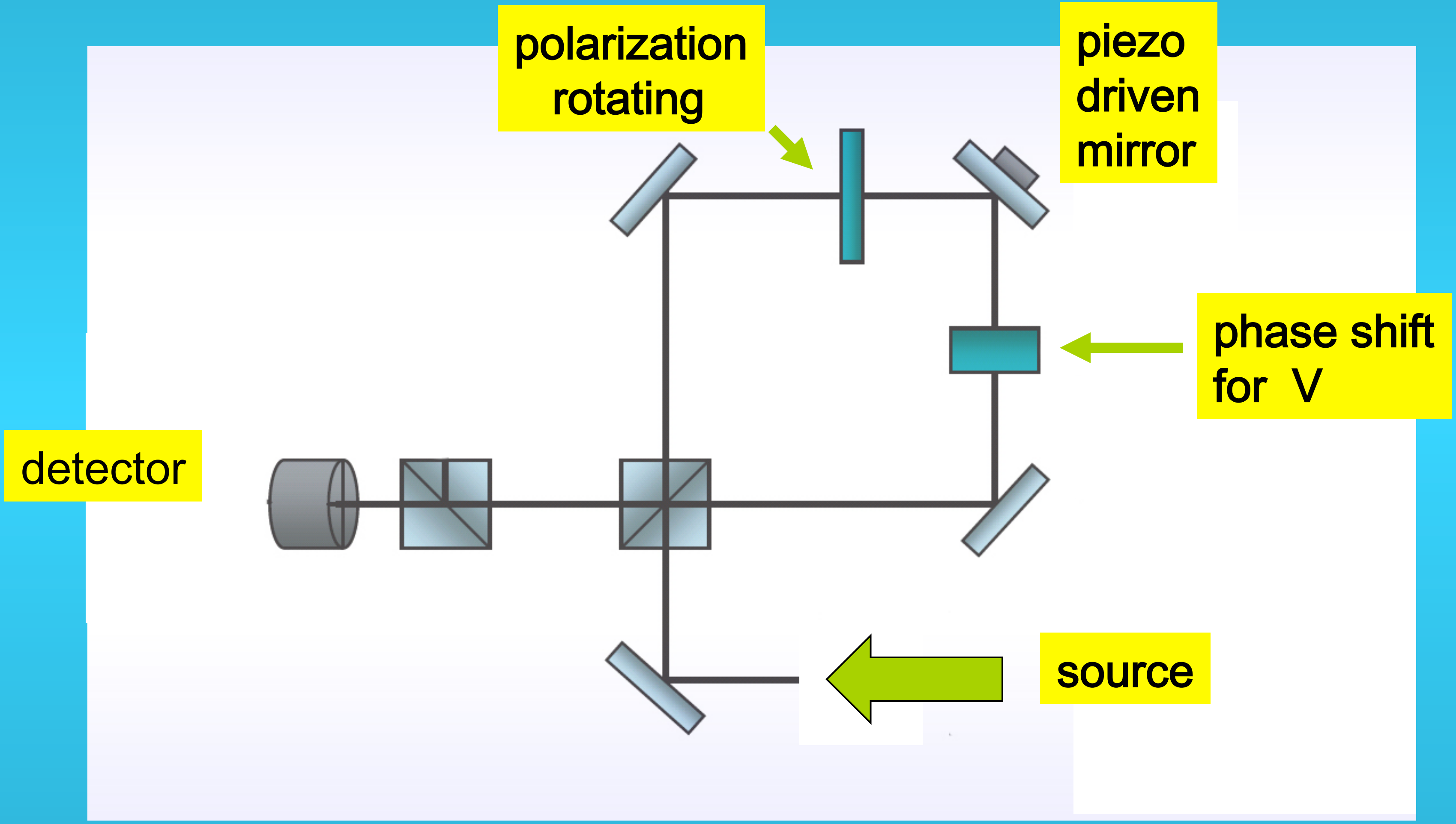
Dixon et al PRL 2009

AMPLIFICATION



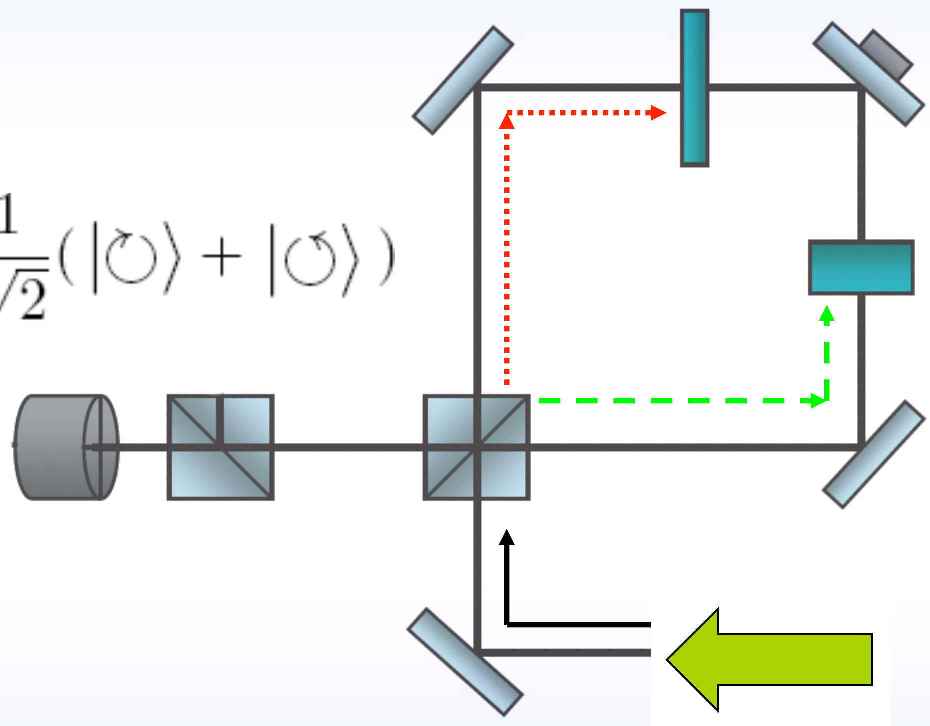
Zilberberg, Romito, YG, PRL 2011

optical Sagnac interferometer



optical Sagnac –ultra sensitivity

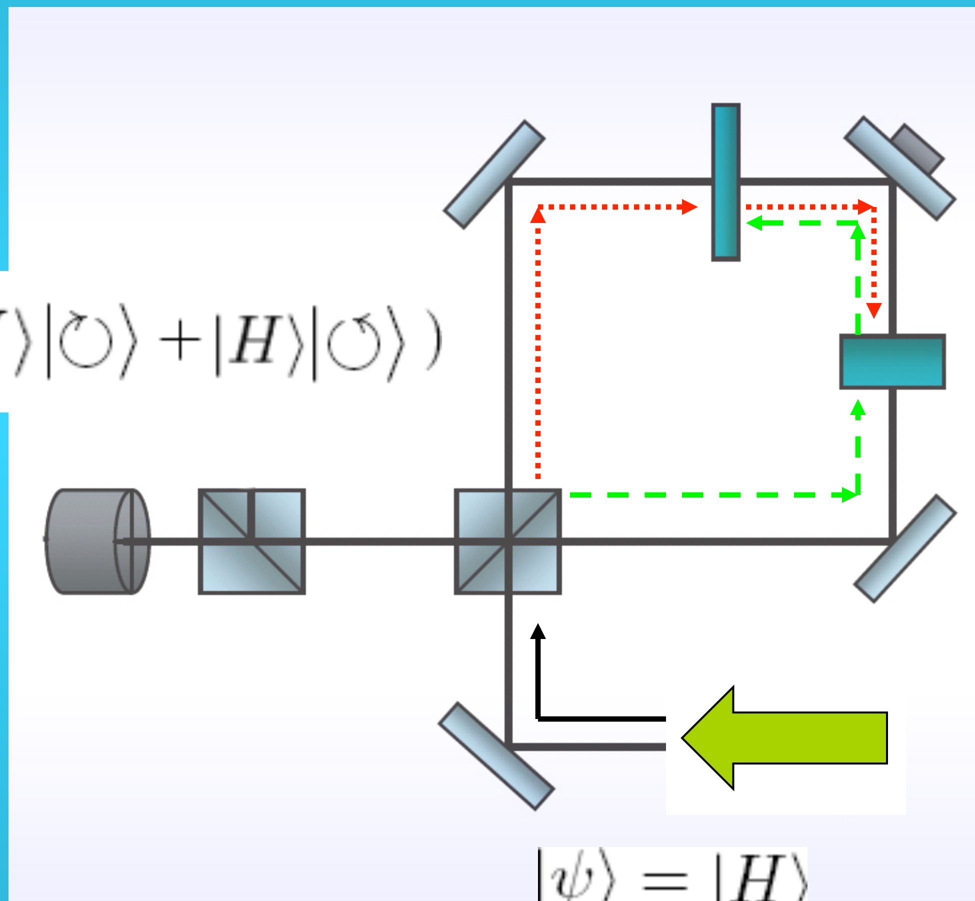
$$|\psi\rangle = |H\rangle \times \frac{1}{\sqrt{2}}\left(|\circlearrowright\rangle + |\circlearrowleft\rangle\right)$$



$$|\psi\rangle = |H\rangle$$

optical Sagnac –ultra sensitivity

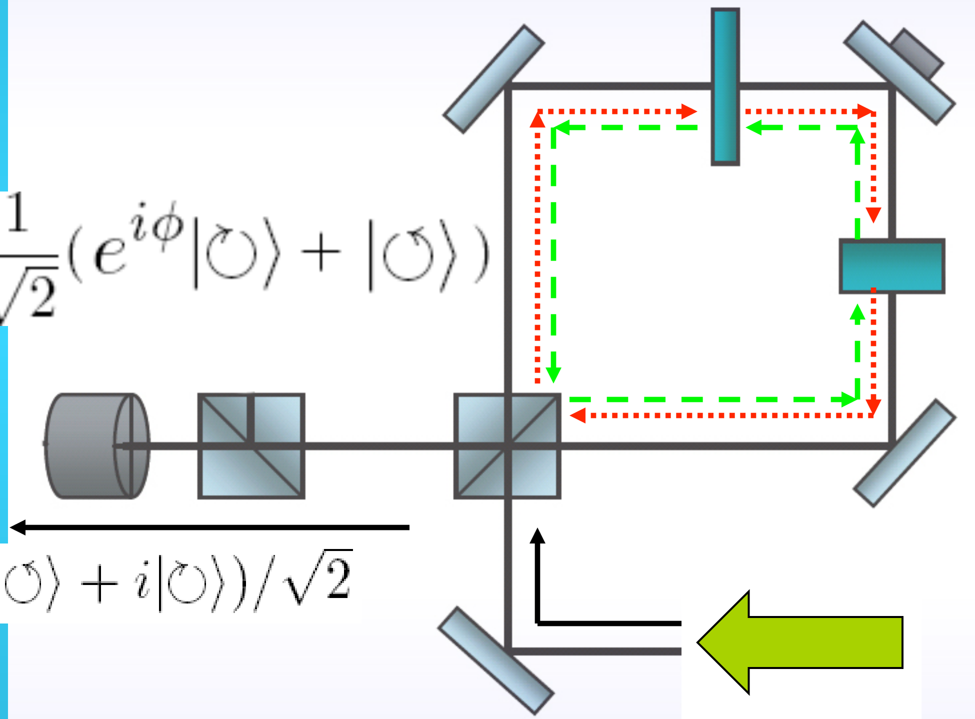
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|V\rangle|\circlearrowright\rangle + |H\rangle|\circlearrowleft\rangle \right)$$



$$|\psi\rangle = |H\rangle$$

optical Sagnac –ultra sensitivity

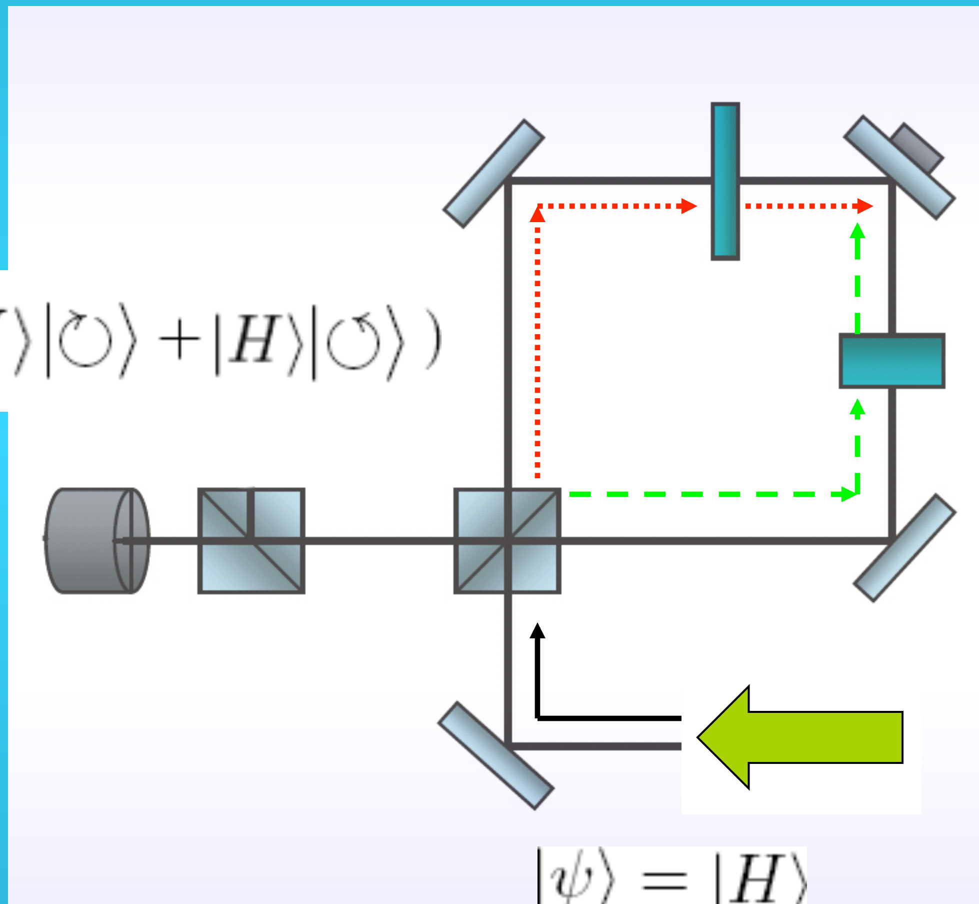
$$|\psi\rangle = |V\rangle \times \frac{1}{\sqrt{2}}(e^{i\phi}|\circlearrowright\rangle + |\circlearrowleft\rangle)$$



$$|\psi_f\rangle = (|\circlearrowleft\rangle + i|\circlearrowright\rangle)/\sqrt{2}$$

$$|\psi\rangle = |H\rangle$$

optical Sagnac –ultra sensitivity



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|V\rangle|\circlearrowright\rangle + |H\rangle|\circlearrowleft\rangle \right)$$

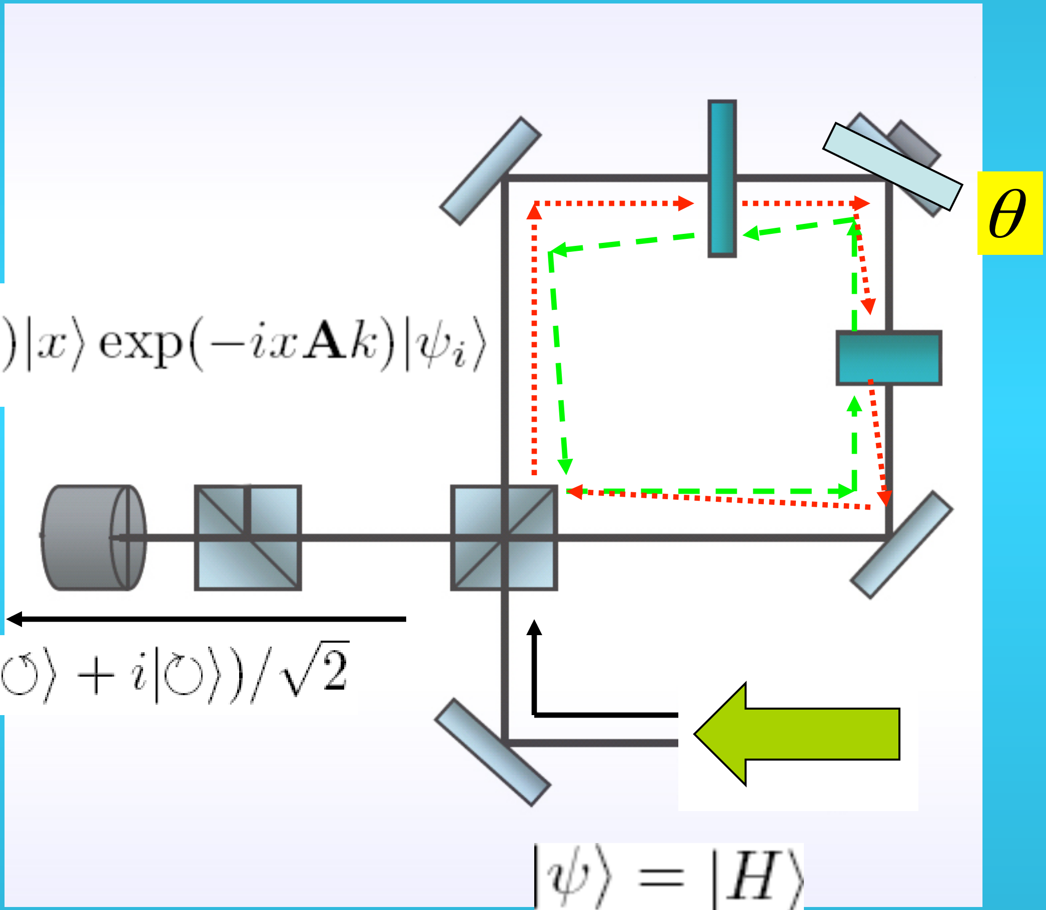
$$|\psi\rangle = |H\rangle$$

$$e^{i\lambda pA} \to e^{ikxA}$$

$$\lambda \to k \propto \theta \qquad p \to x$$

$$\mathbf{A} = |\circlearrowright\rangle\langle\circlearrowright| - |\circlearrowleft\rangle\langle\circlearrowleft|$$

$$|\Psi\rangle = \int dx \psi(x)|x\rangle \exp(-ix\mathbf{A}k)|\psi_i\rangle$$

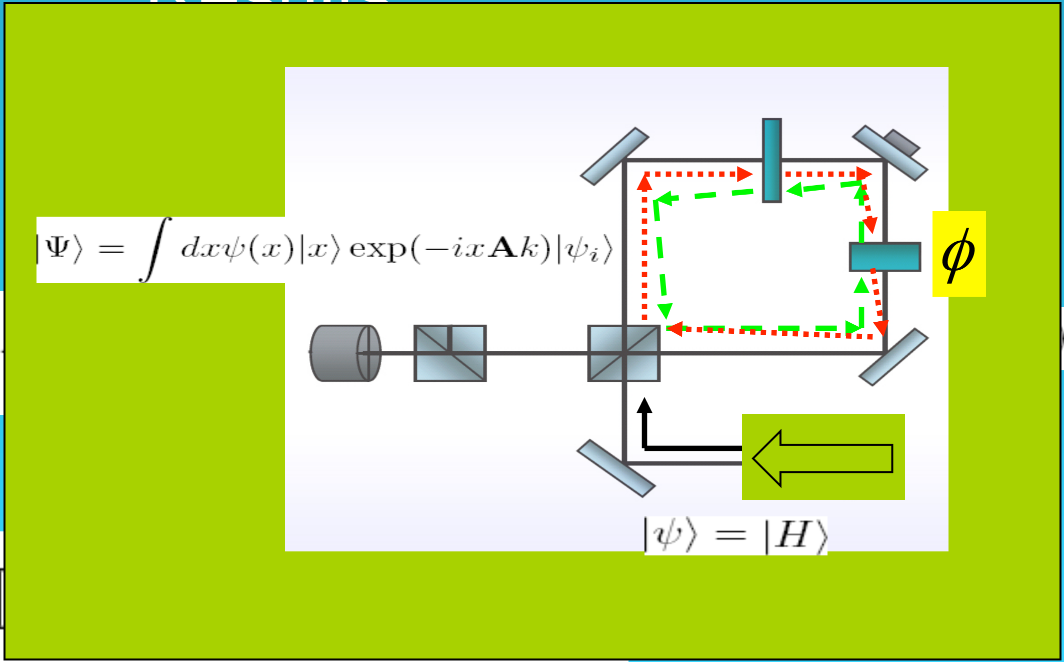


$$|\psi_f\rangle = (|\circlearrowleft\rangle + i|\circlearrowright\rangle)/\sqrt{2}$$

$$|\psi\rangle = |H\rangle$$

Results

$$|\Psi\rangle = \int dx\psi(x)|x\rangle \exp($$

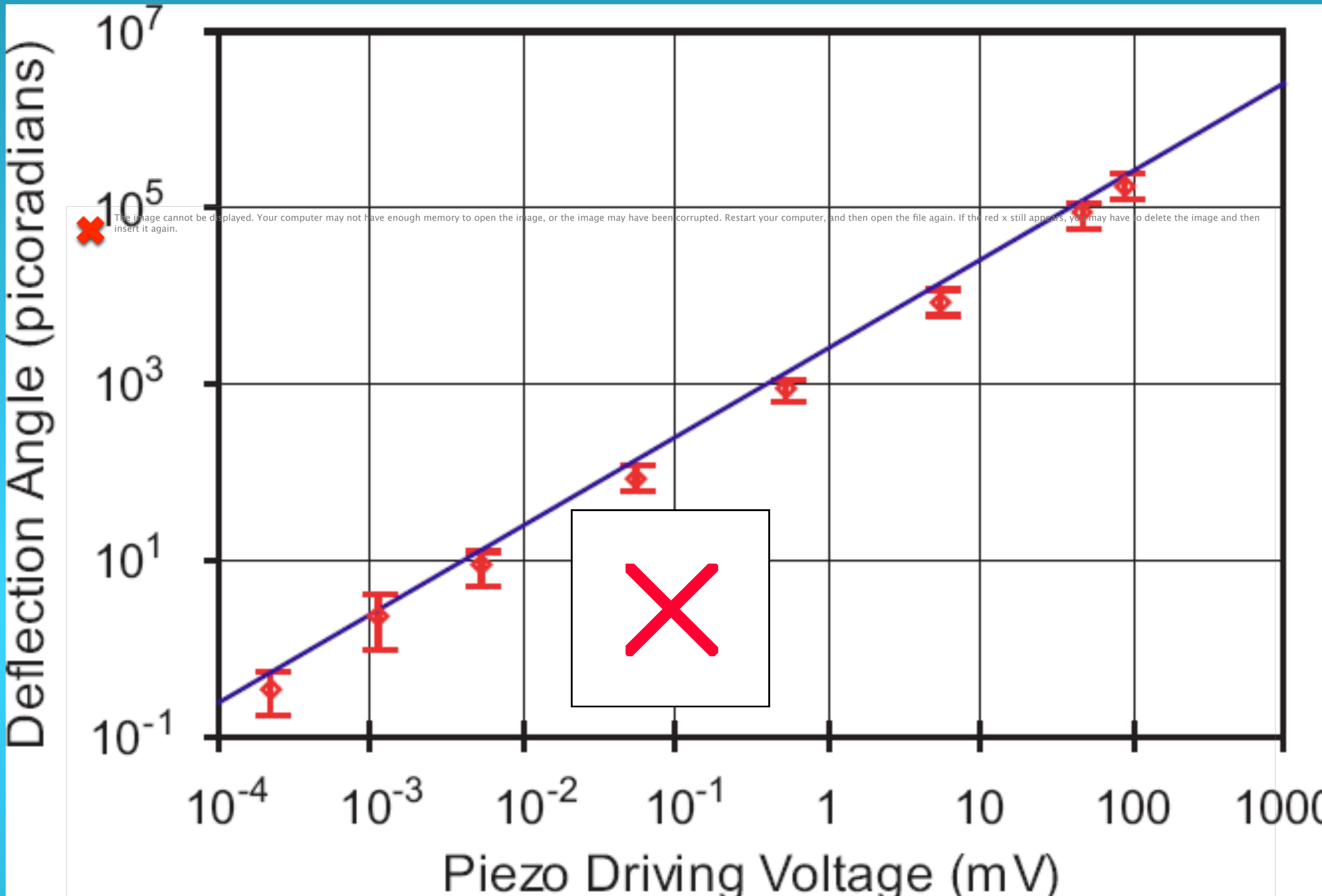


$$\langle\psi_f|\Psi\rangle = \int dx\psi(x)|x\rangle[$$

$$\langle\psi_f|\Psi\rangle = \langle\psi_f|\psi_i\rangle \int dx\psi(x)|x\rangle \exp(-ixA_w k)$$

$$A_w = \frac{\langle\psi_f|\mathbf{A}|\psi_i\rangle}{\langle\psi_f|\psi_i\rangle} = -i\cot(\phi/2) \approx -2i/\phi$$

Results



- WV amplification factors of over 100
- Measured 560 frad of mirror deflection which is caused by 20 fm of piezo travel.