Anti-bunched photons emitted by a dc biased Josephson junction

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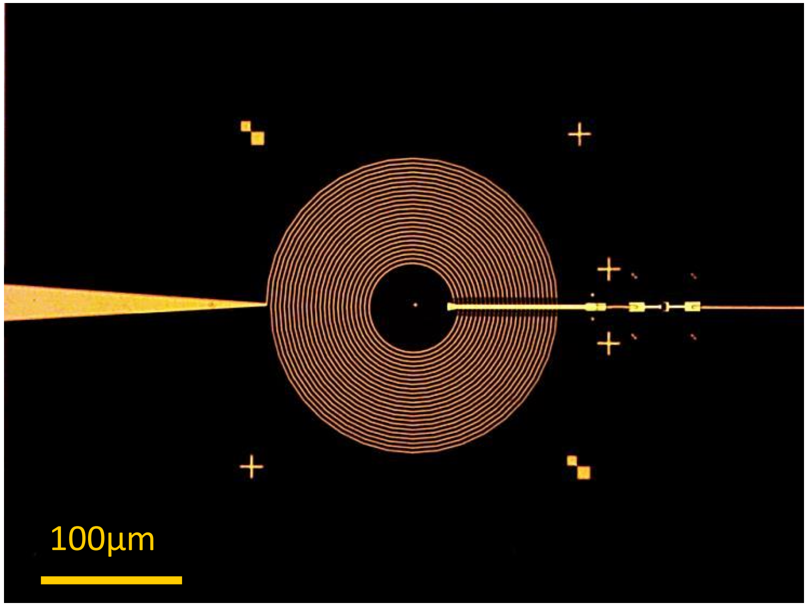
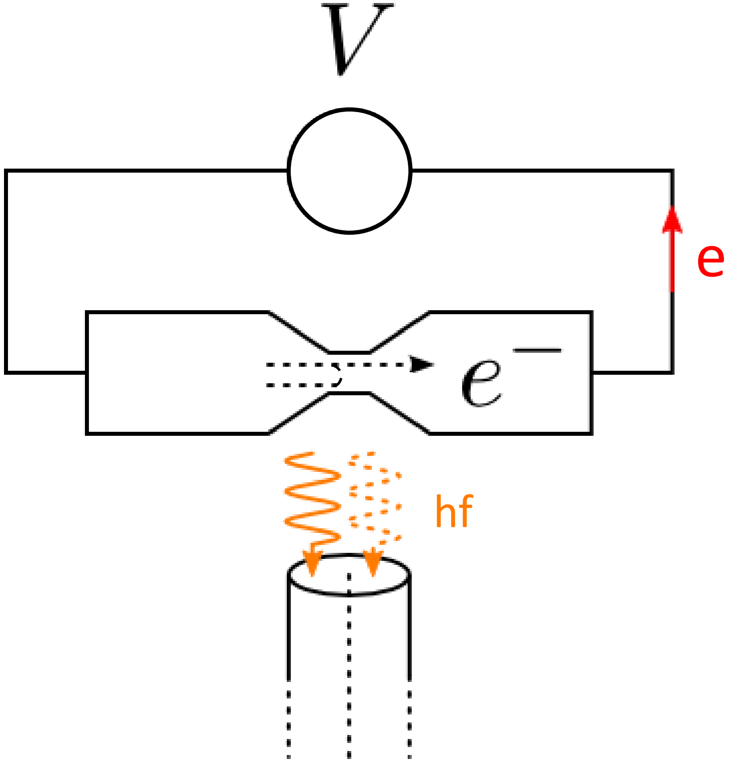
collab.: J. Ankerhold, B. Kubala



Aussois 2016, december 6th

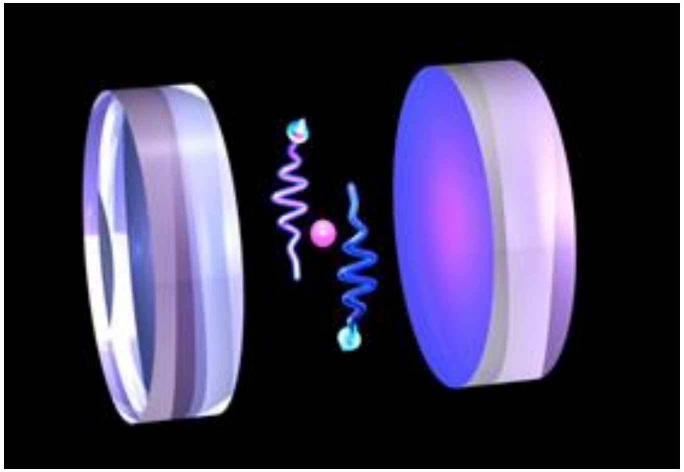
Context: quantum optics of quantum conductors

Quantum conductors



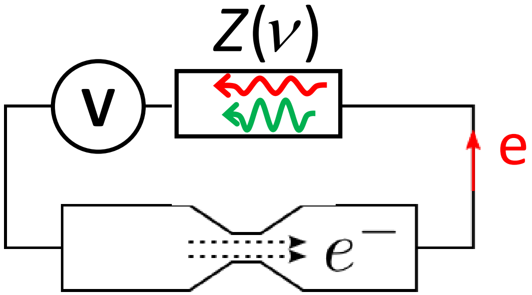
⇒ Many open questions (properties of the emitted radiation, strong feedback of coupling to electromagnetic modes)

Atomic Physics: cavity QED

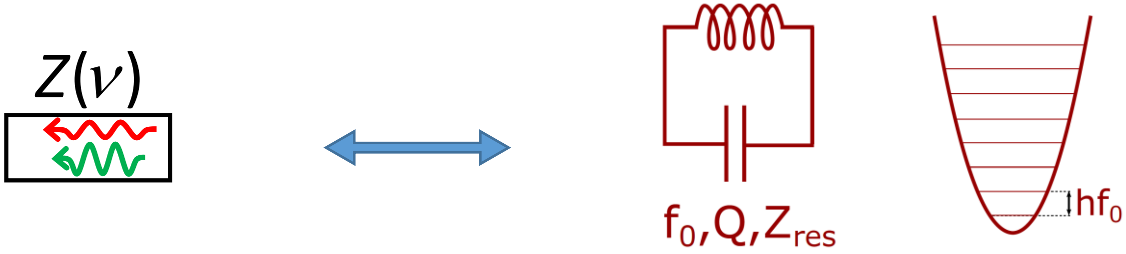


⇒ Excellent understanding (dressed atom formalism...)

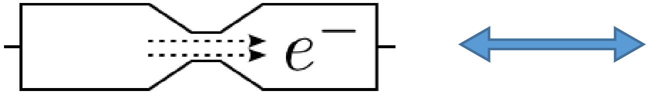
Simplifying the system

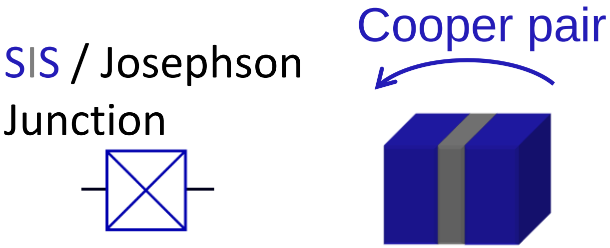


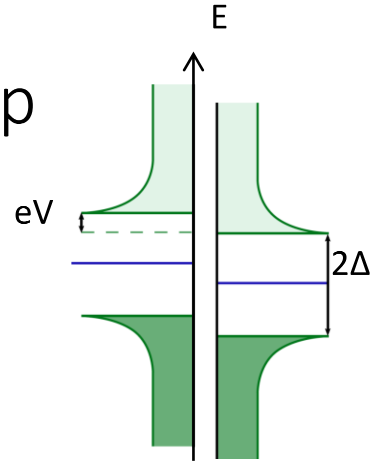
- Environment: single m



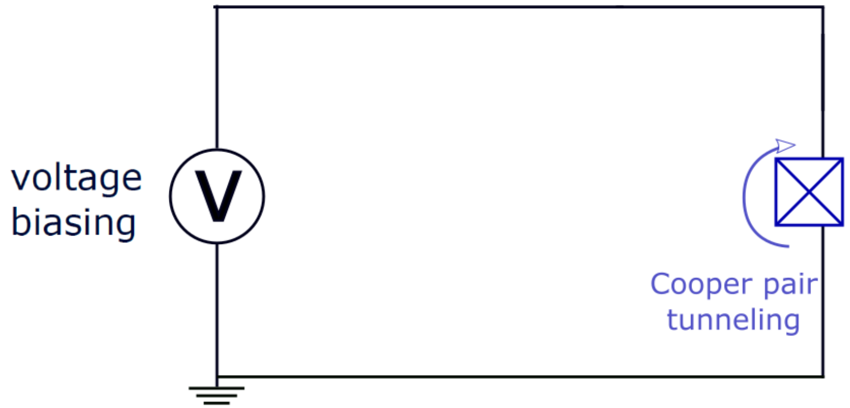
- Josephson junction polarized below the gap voltage 2Δ

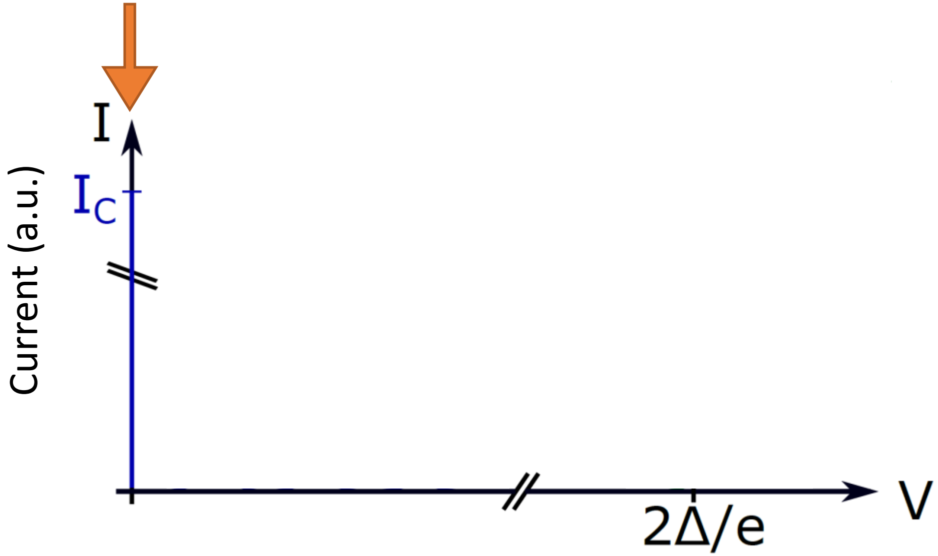


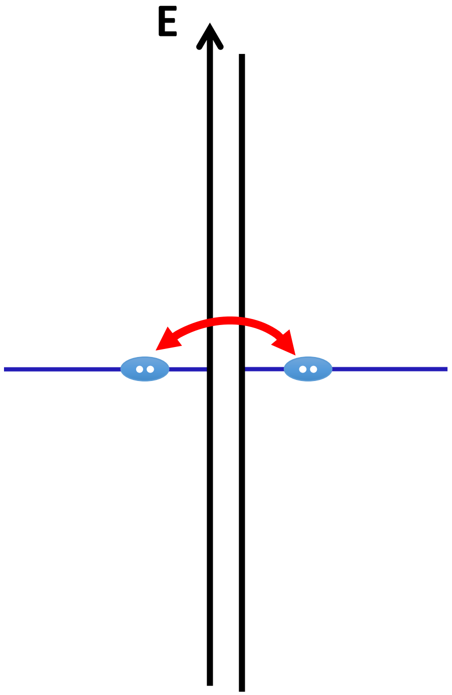




Circuit

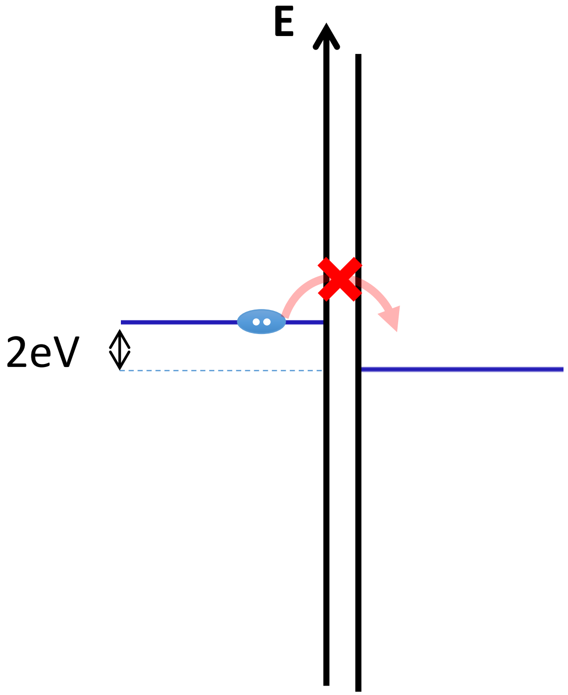

voltage biasing
V
Cooper pair tunneling

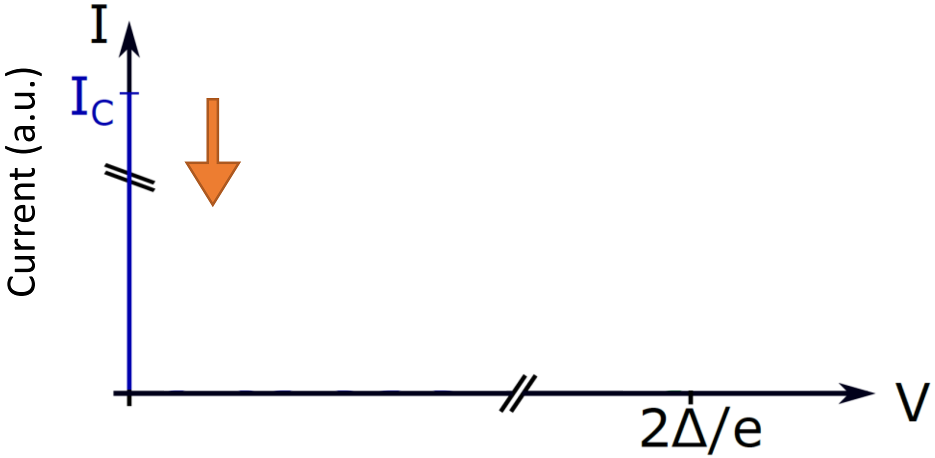

I
I_C
Current (a.u.)
V
2Δ/e


E

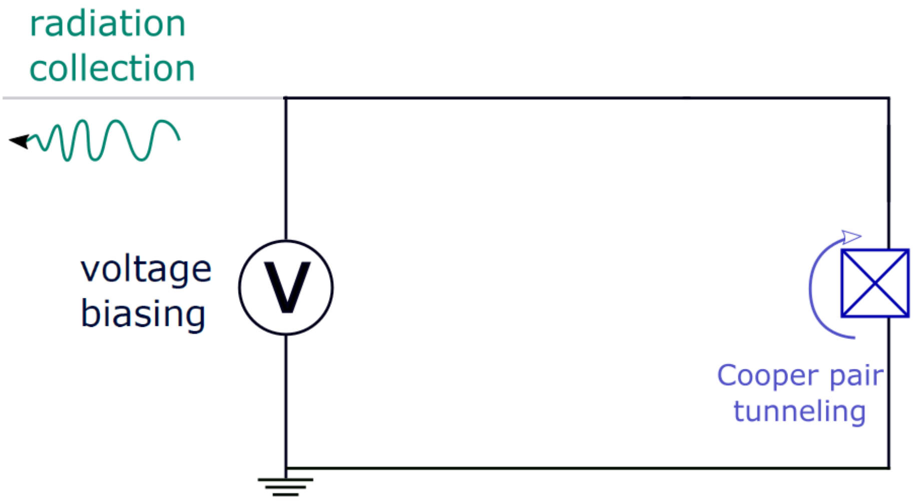
Circuit

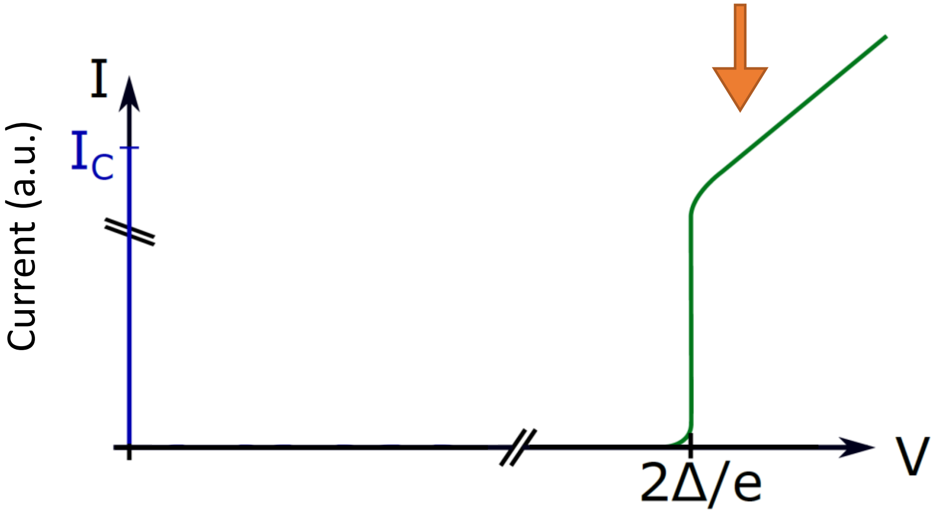

voltage biasing
V
Cooper pair tunneling

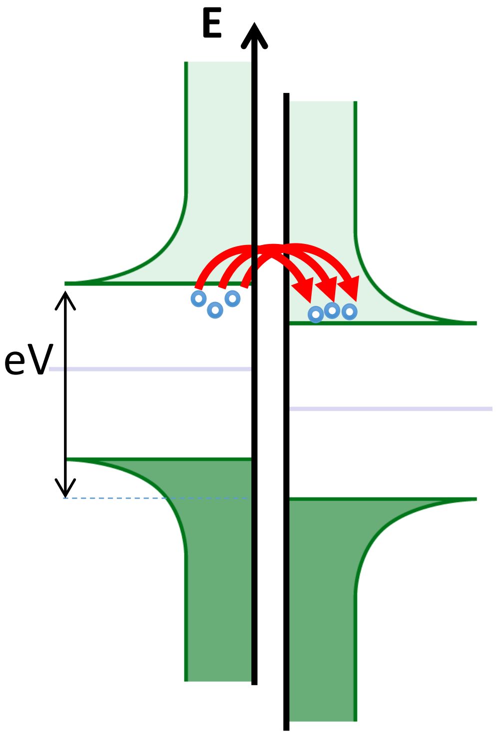

E
2eV


I
I_C
Current (a.u.)
V
$2\Delta/e$

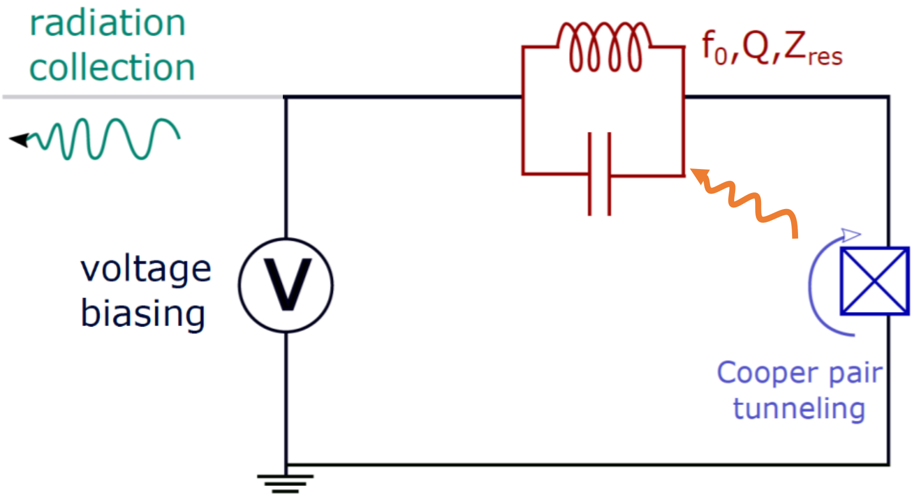
Circuit

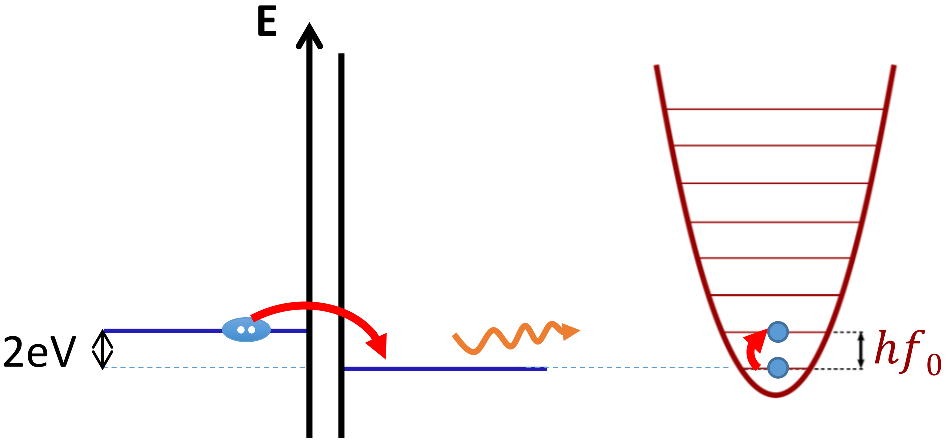

radiation
collection
voltage
biasing
V
Cooper pair
tunneling

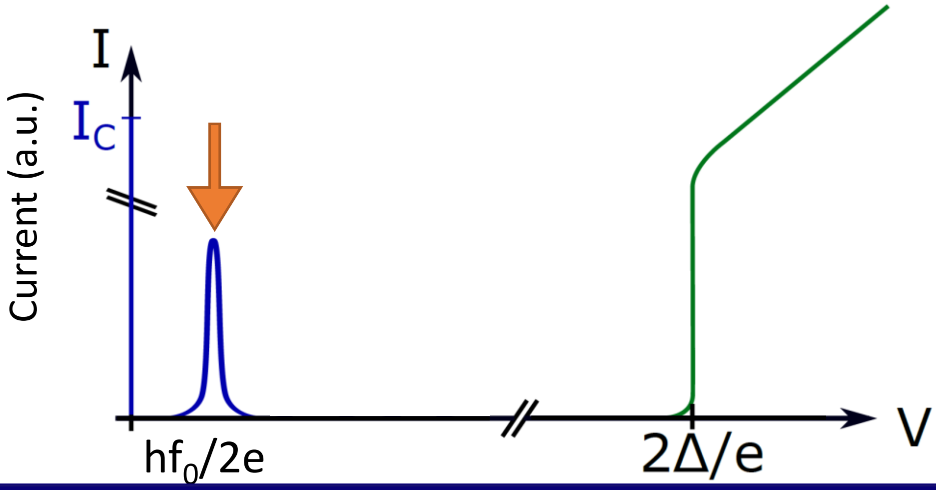

I
I_C
Current (a.u.)
V
2Δ/e


E
eV

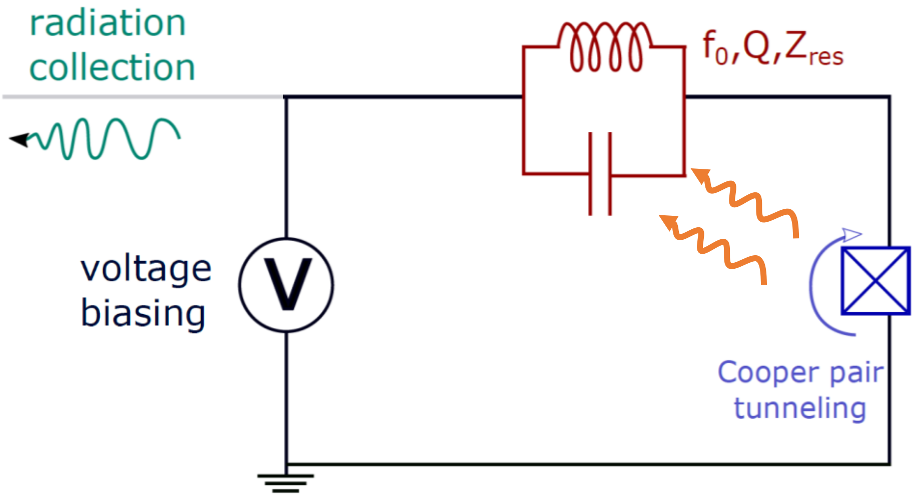
Circuit

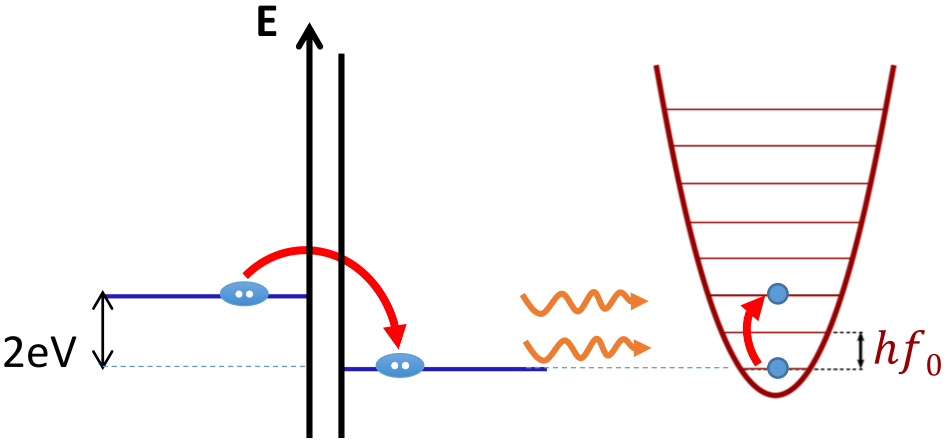

radiation
collection
f_0,Q,Z_{res}
voltage
biasing
V
Cooper pair
tunneling

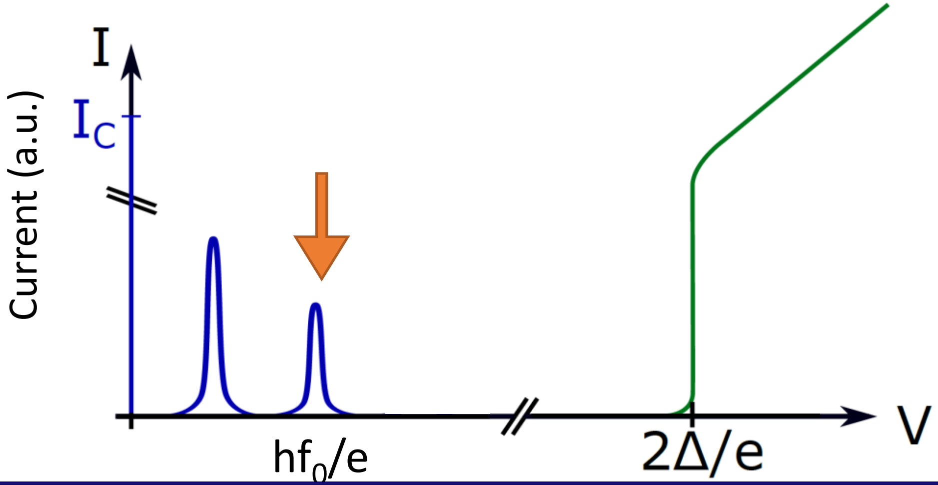

E
2eV
hf_0


I
I_C
Current (a.u.)
$hf_0/2e$
$2\Delta/e$
V

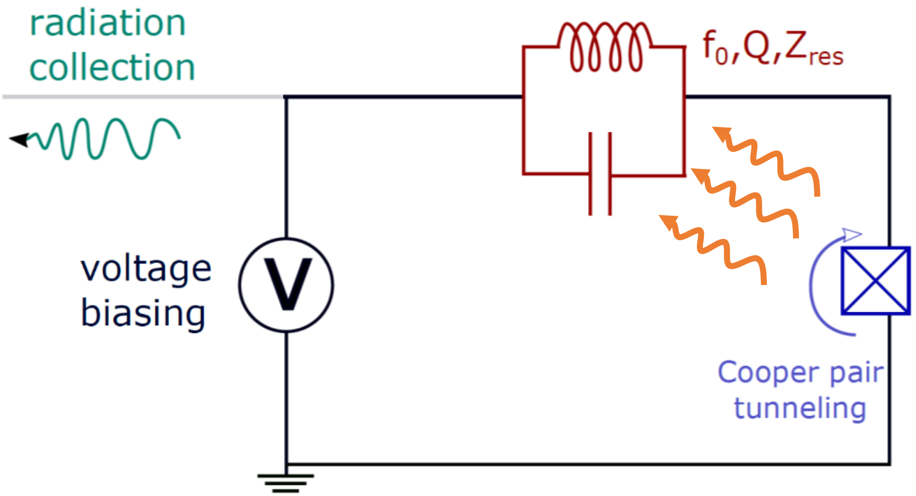
Circuit

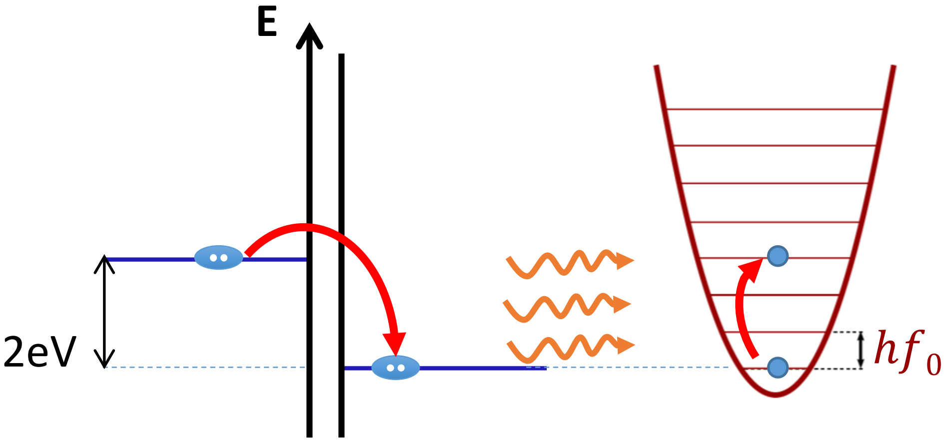

radiation collection
f_0,Q,Z_{res}
voltage biasing
V
Cooper pair tunneling

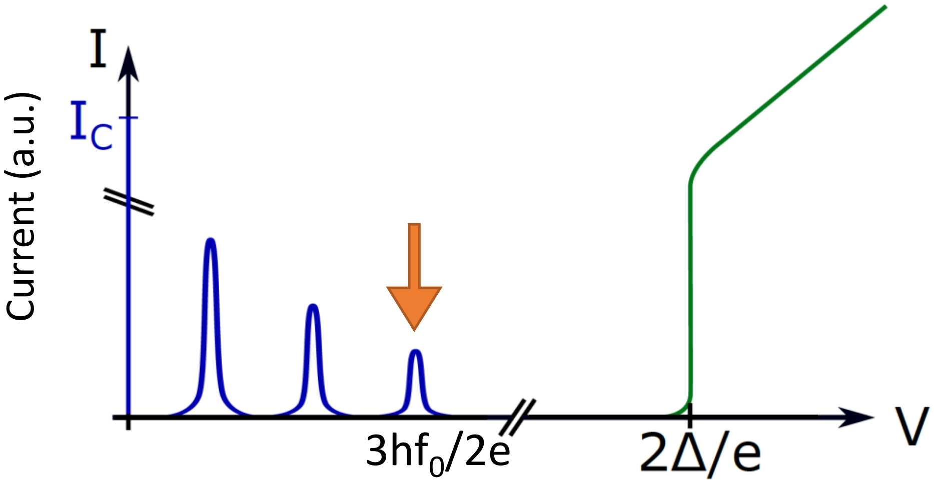

E
2eV
hf_0


I
I_C
Current (a.u.)
hf_0/e
$2\Delta/e$
V

dc current only if photons can be absorbed







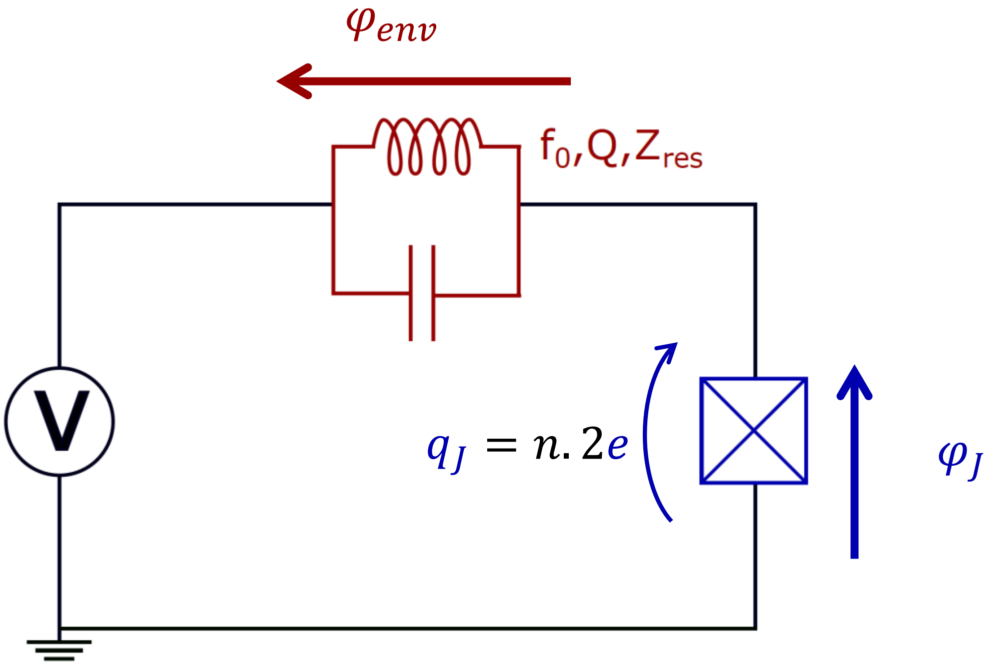
$$\boxed{2eV = khf_0}$$

Emission rates ?

Hamiltonian of the system

$$H = \underbrace{hf_0\,(a^\dagger a + 1/2)}_{\text{Resonator}} - \underbrace{E_J.\,cos(\varphi_J)}_{\text{CP tunneling}}$$

$$[\varphi, q] = i\hbar$$



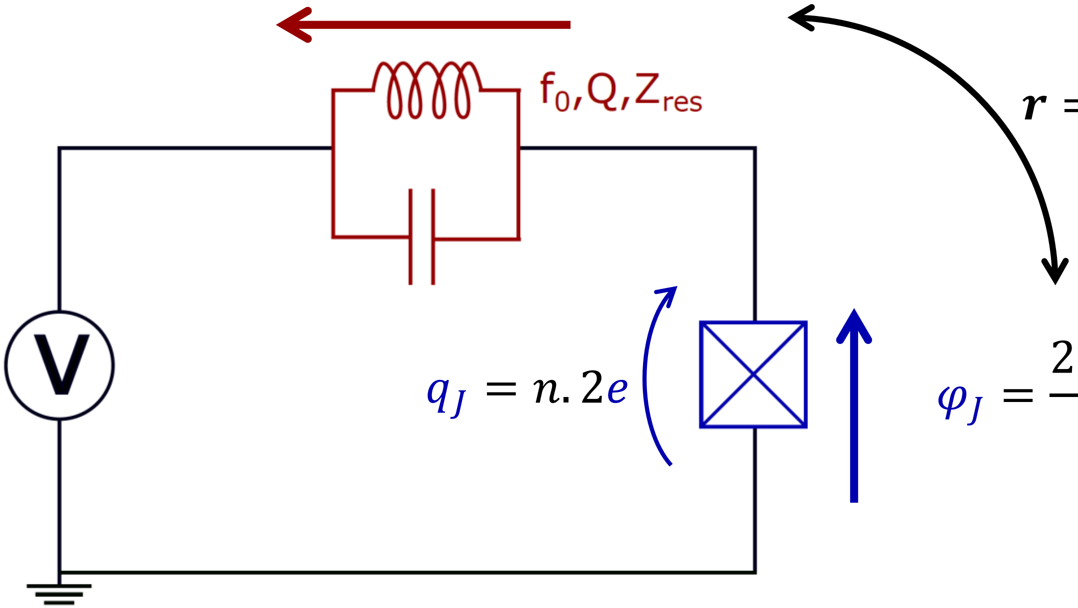
D. Averin, Y. Nazarov, and A. Odintsov, Physica B 165-166, 945 (1990)
Ingold & Nazarov, arxiv:0508728 (1992)

Hamiltonian of the system

$$H = \underbrace{hf_0\,(a^\dagger a + 1/2)}_{\text{Resonator}} - \underbrace{\frac{E_J}{2}\left(e^{i\varphi_J} + e^{-i\varphi_J}\right)}_{\text{CP tunneling}}$$

$$[\varphi, q] = i\hbar$$

$$\varphi_{env} = \sqrt{\boldsymbol{r}}\,(a^\dagger + a)$$



$$\boldsymbol{r} = \pi\frac{Z_{res}}{R_Q};\; Z_{res} = \sqrt{\frac{L}{C}}$$

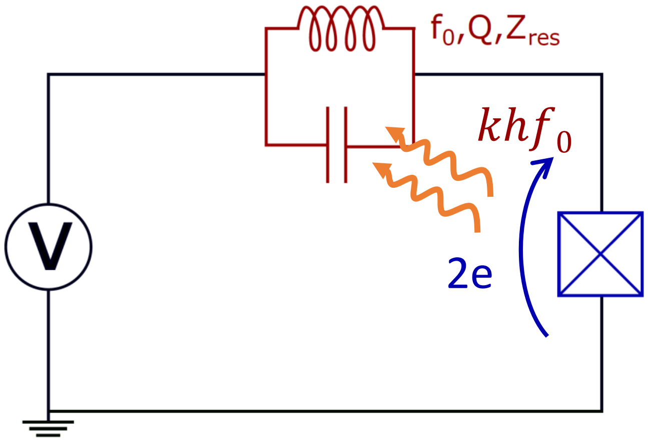
$$q_J = n.2e$$

$$\varphi_J = \frac{2eV}{\hbar}t + \varphi_{env}$$

D. Averin, Y. Nazarov, and A. Odintsov, Physica B 165-166, 945 (1990)

Ingold & Nazarov, arxiv:0508728 (1992)

Cooper pair and photon rates



$$H = hf_0\,(a^\dagger a + 1/2) - \frac{E_J}{2}\left(e^{i\varphi_J} + e^{-i\varphi_J}\right)$$

$$\boldsymbol{r} = \pi\frac{Z_{res}}{R_Q}$$

<u>Emission rates (from empty resonator):</u>

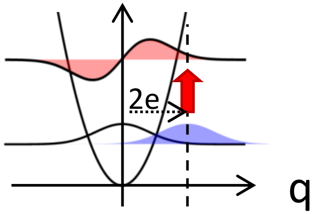
$$\Gamma^{ph}(2eV = khf_0) = k.\,\Gamma^{2e}(2eV = khf_0)$$

$$\Gamma^{2e}(2eV) = \frac{\pi E_J^2}{2\hbar}\sum_k \left|\langle k|e^{-2i\varphi_J}|0\rangle\right|^2 \delta(2eV - khf_0)$$

$$= \frac{\pi E_J^2}{2\hbar}\sum_k e^{-\boldsymbol{r}}\frac{\boldsymbol{r}^k}{k!}\delta(2eV - khf_0)$$

→ k photons / Cooper pair

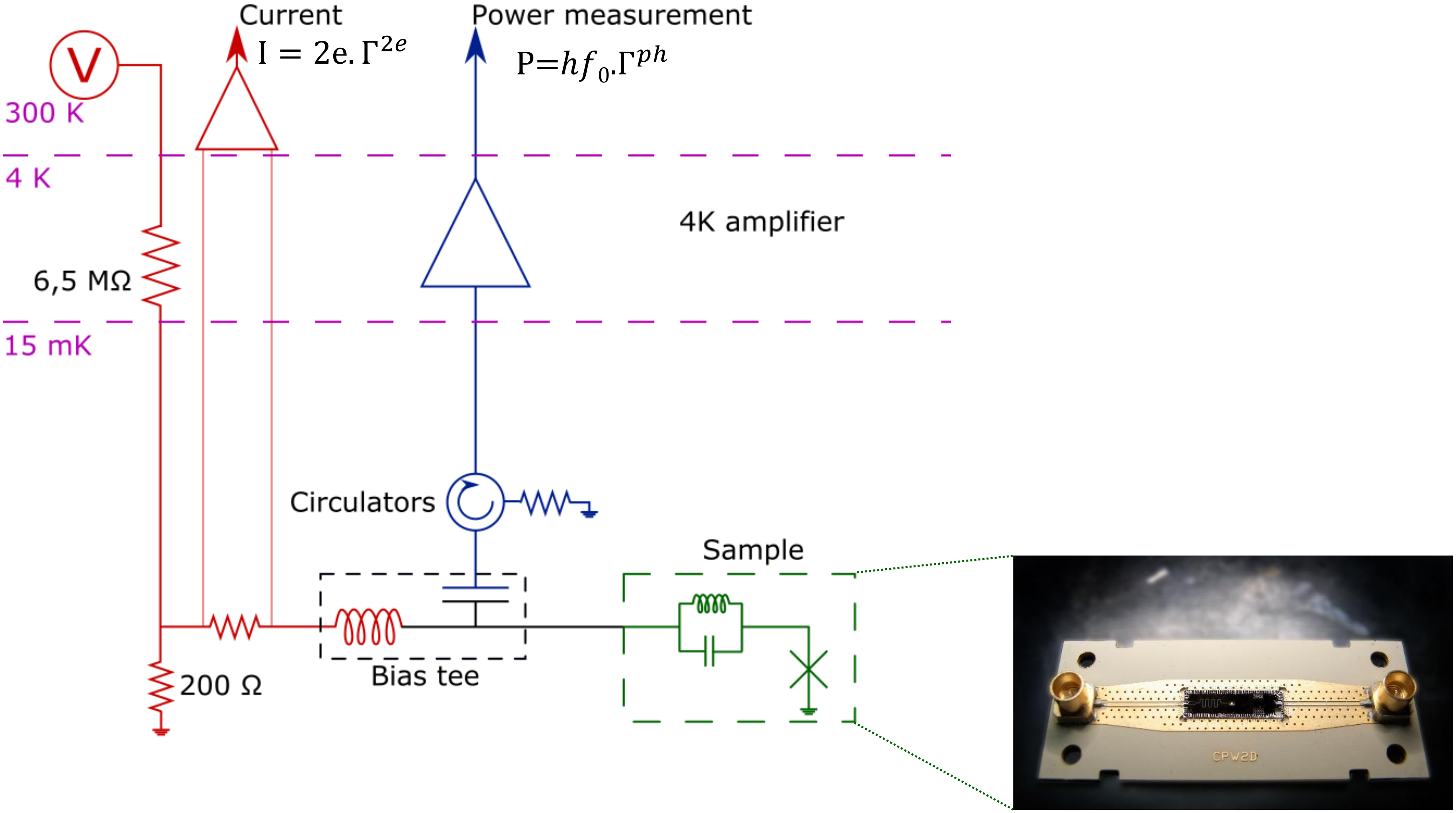
→ Γ ∝



→ Large $\boldsymbol{r}$ favors multiphoton processes

D. Averin, Y. Nazarov, and A. Odintsov, Physica B 165-166, 945 (1990)
H. Pothier, PhD dissertation (1991)

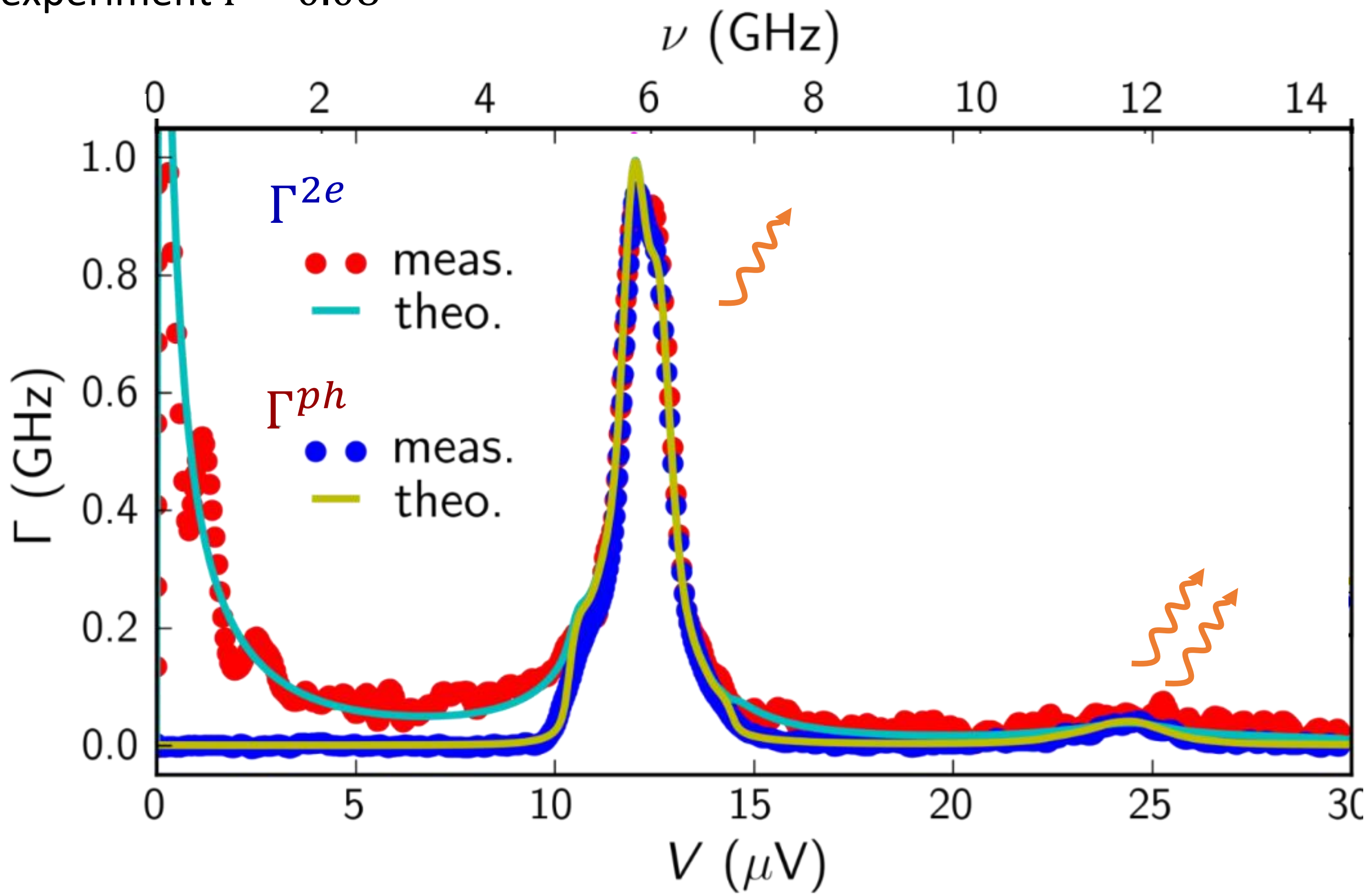
Measurement setup



Hofheinz *et al.*, PRL **106**, 217005 (2011)

Current vs Power measurements

First experiment $r = 0.08$

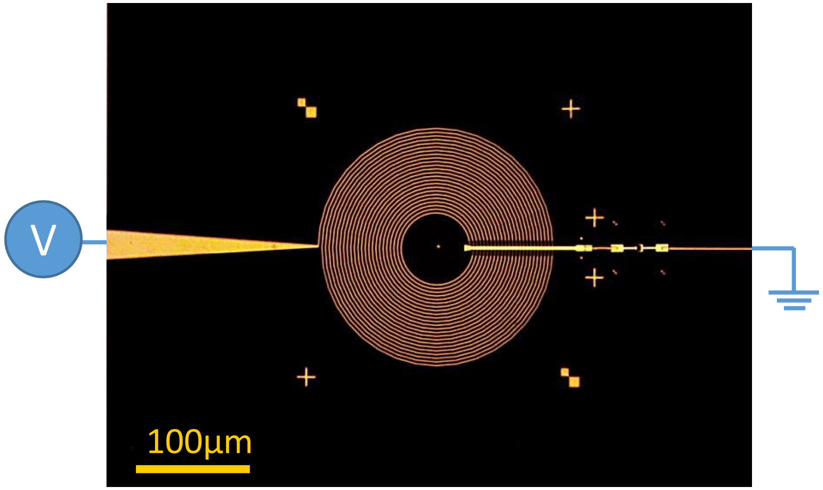


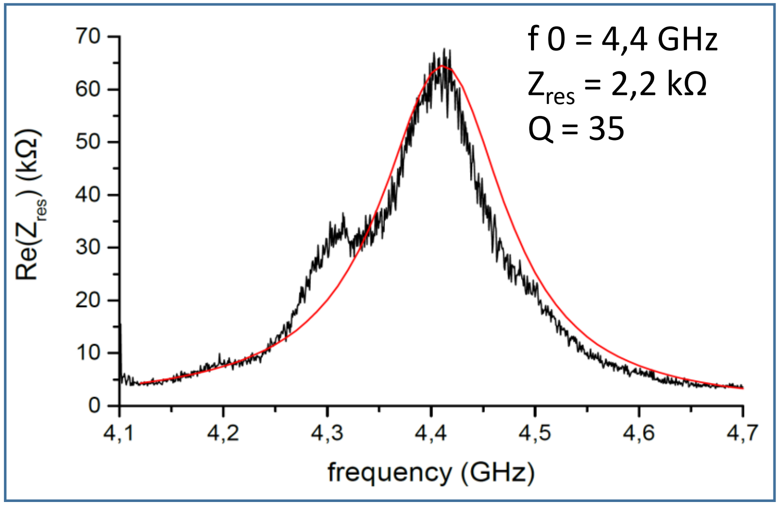
Cooper pair and photon mean rates match!

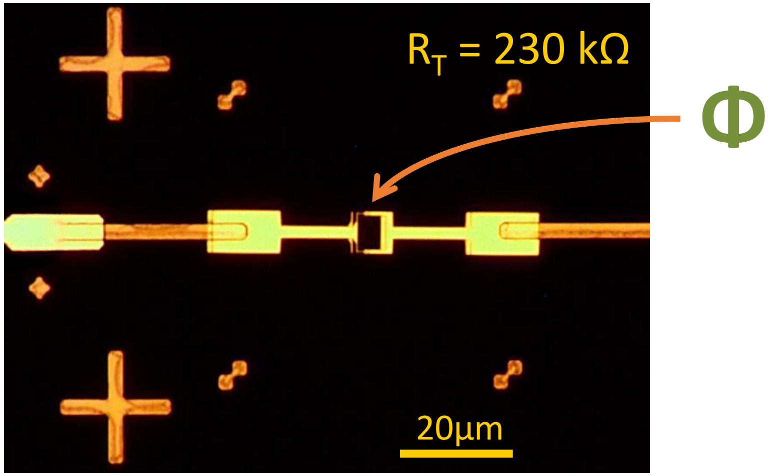
Hofheinz *et al.*, PRL **106**, 217005 (2011)

High impedance resonator

$$\omega_0 = \frac{1}{\sqrt{L\,C}} \in [4;8]\,GHz \text{ and } Z_{res} = \sqrt{\frac{L}{C}} \approx 2\text{k}\Omega \rightarrow \begin{cases} \text{High inductance : } L\sim 60\text{ nH} \\ \text{Low capacitance : } C\sim 15\text{ fF} \end{cases}$$







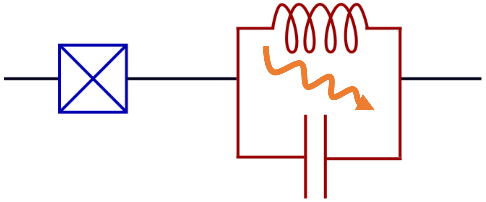
$$E_J(\Phi) = E_J^0 \left|\cos(\pi\,\Phi/\Phi_0)\right|$$

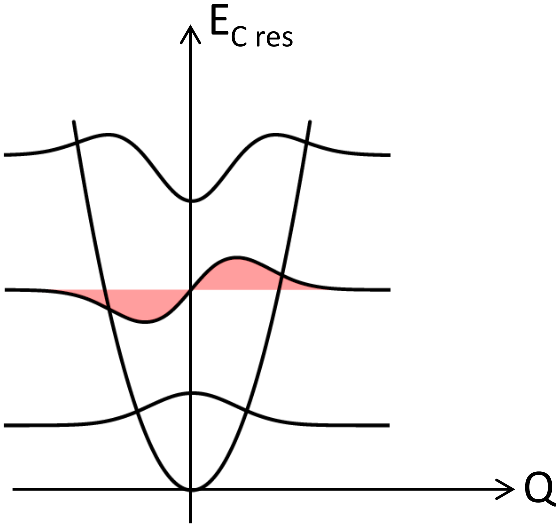
Large coupling achieved : r=1.1

Resonator back-action?

$$\boxed{\Gamma^{2e}(2eV = hf_0) \propto \left|\langle n+1| e^{-2i\varphi_J} |n\rangle\right|^2}$$

successive tunnel events



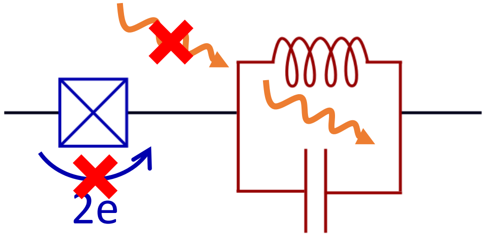


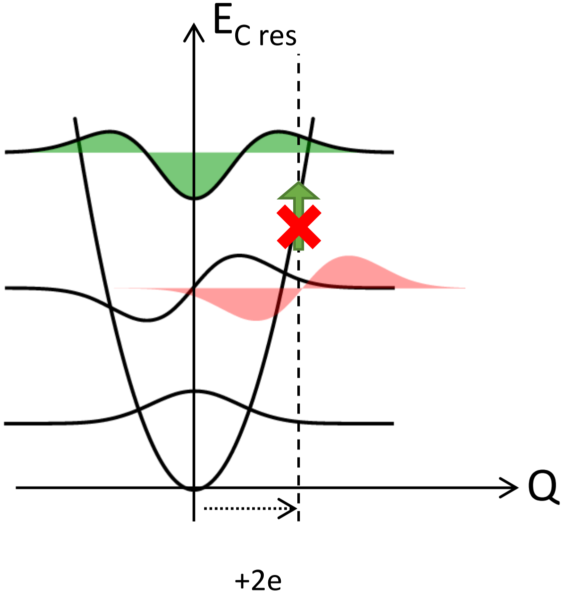
V. Gramich *et al*, Phys.Rev.Lett. **111**, 247002, **2013**

Anti-bunching

$$\boxed{\Gamma^{2e}(2eV = hf_0) \propto \left|\langle 2|e^{-2i\varphi_J}|1\rangle\right|^2 = 0 \text{ for r=2}}$$

successive tunnel events

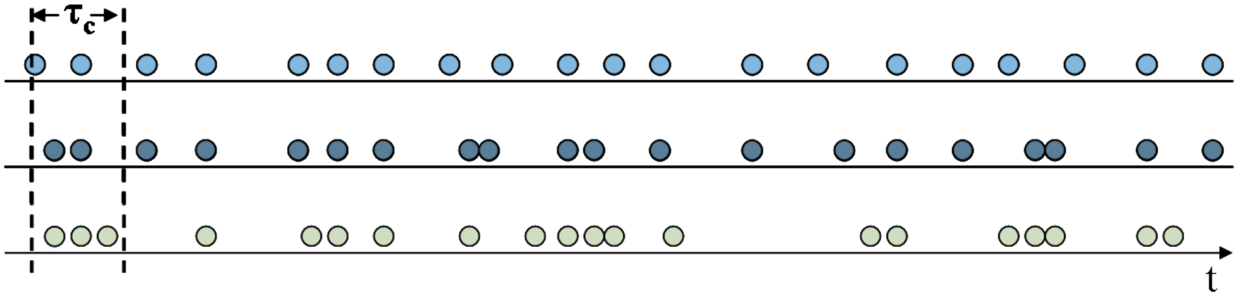




CP can’t tunnel when 1 photon in the resonator !

V. Gramich *et al*, Phys.Rev.Lett. **111**, 247002, **2013**

Photon statistics



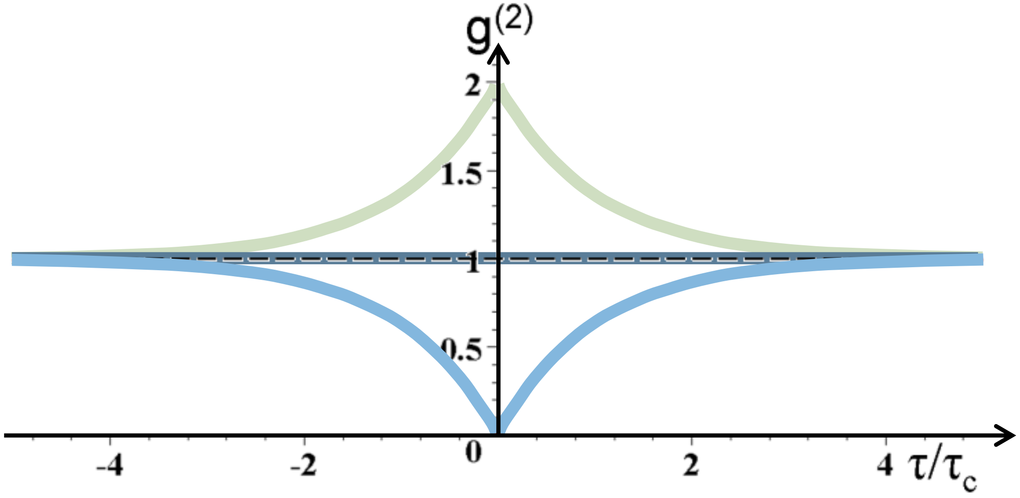
Anti-bunched

non correlated

Bunched photons

Statistic of photon emission: $g^{(2)}$ function

$$g^{(2)}(\tau) = \frac{\langle a^\dagger(t) a^\dagger(t+\tau) a(t+\tau) a(t) \rangle}{\langle a^\dagger a \rangle^2}$$



τ_c, averaged photon lifetime in the resonator

Theoretical predictions:

$$\boxed{g^{(2)}(0) = \left(1 - \frac{\boldsymbol{r}}{2}\right)^2}$$

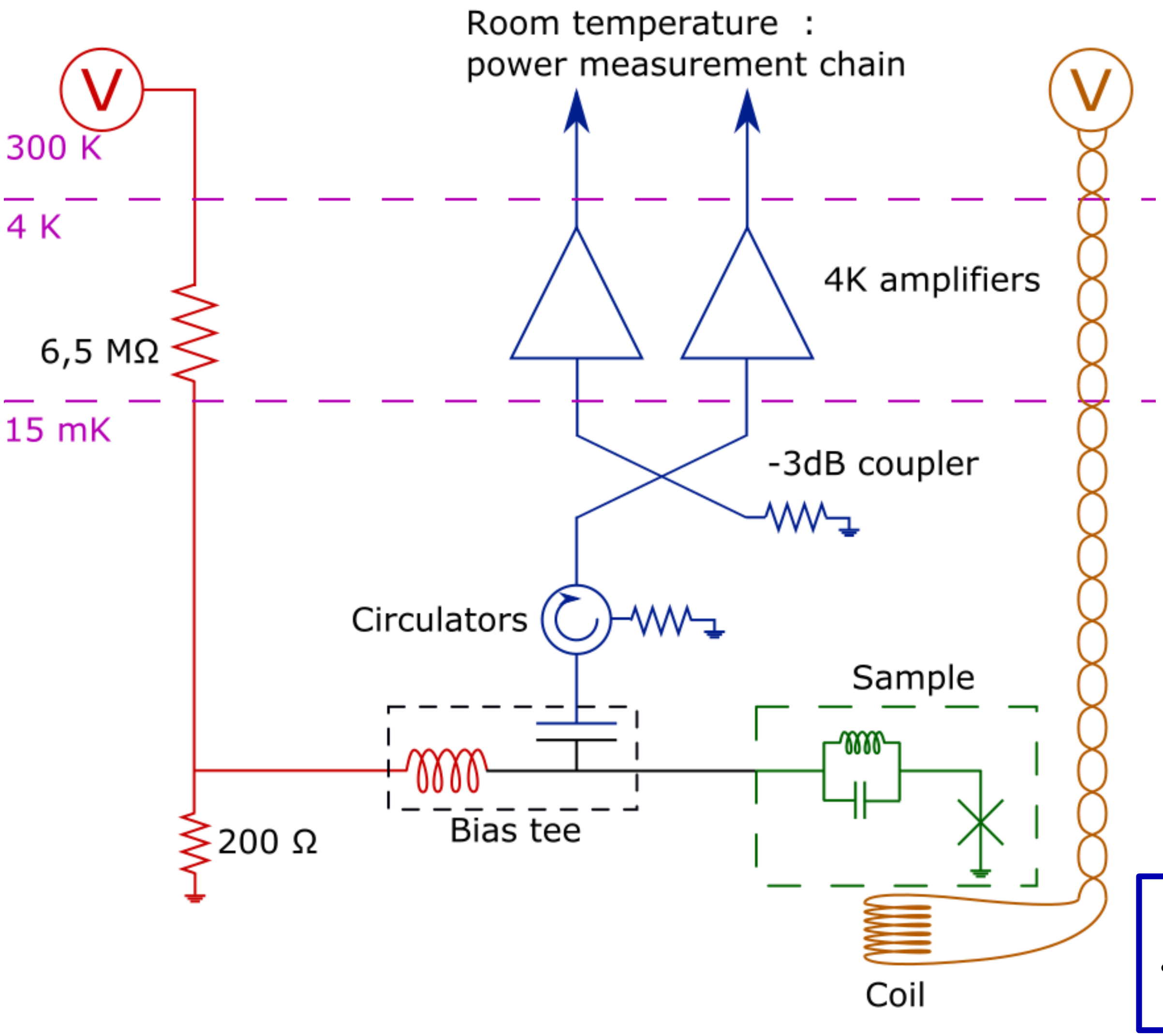
our sample: r = 1.1 → $g^{(2)}(0) \approx 0.22$

V. Gramich *et al*, Phys.Rev.Lett. **111**, 247002, **2013**

Measurement :

$$\boxed{g^{(2)}(\tau) = 1 + \frac{\langle \delta P(t) \delta P(t+\tau) \rangle}{P^2}}$$

HBT measurement setup



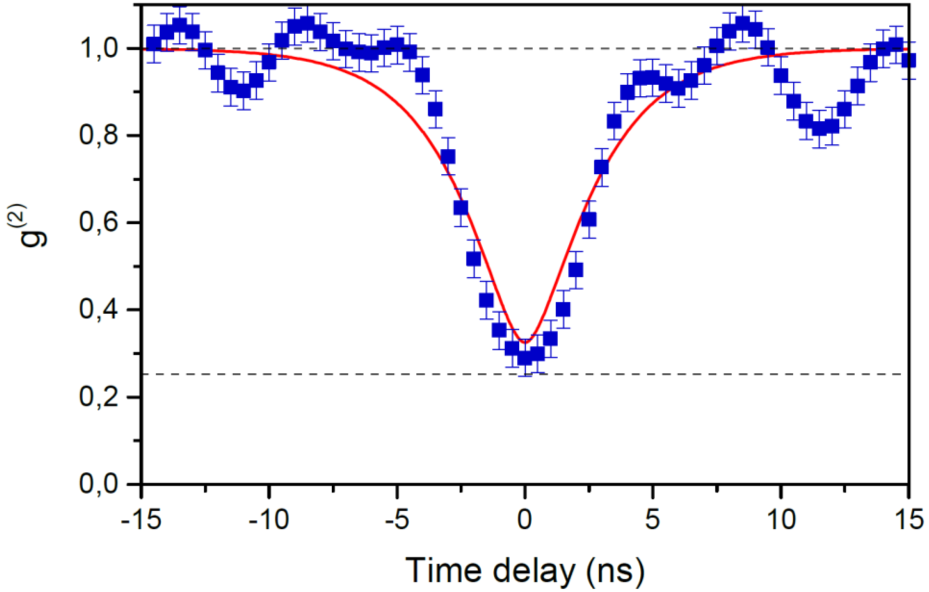
$$g^{(2)}(\tau) = 1 + \frac{\langle \delta P(t) \delta P(t+\tau) \rangle}{P^2}$$

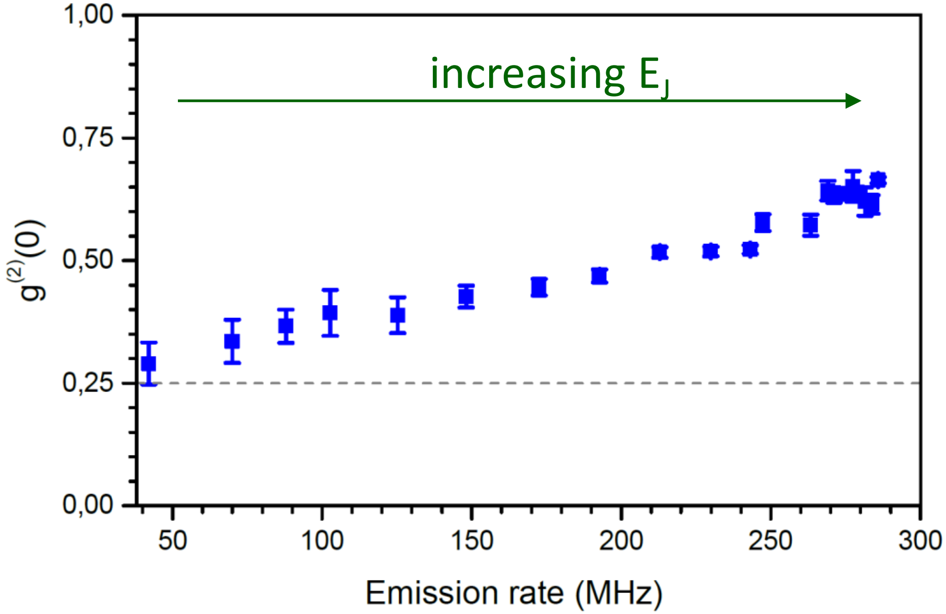
Second order correlator results $g^{(2)}(\tau)$

- Anti-bunched photon emission

- Time scale of correlations : photon lifetime in the cavity

- The correlation decreases with mean population of the resonator

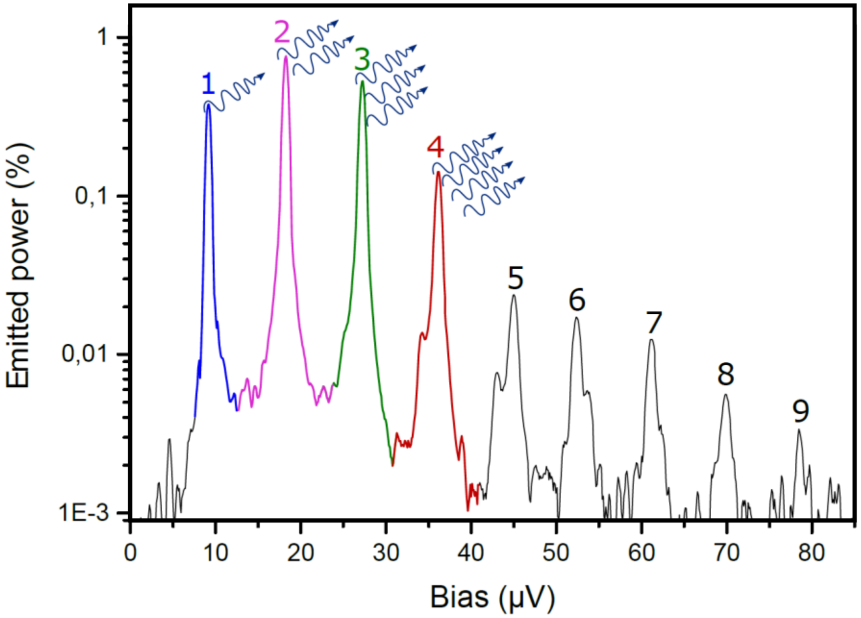


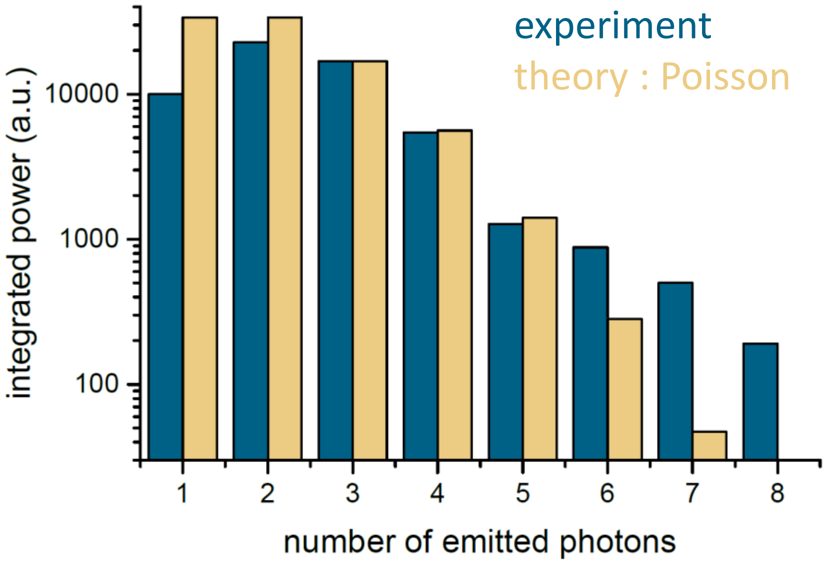


Multiple photon emission

- We can now observe up to 9-photon processes :

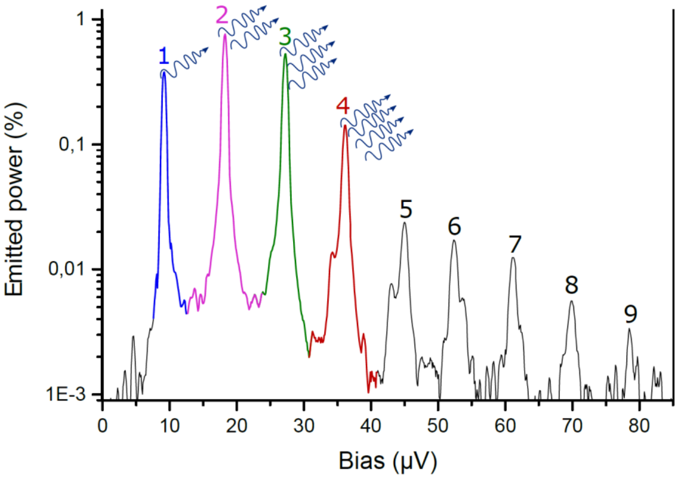
$$\boxed{\Gamma^{ph}(2eV = khf_0) = E_J^2 \frac{\boldsymbol{r}^k}{(k-1)!}}$$



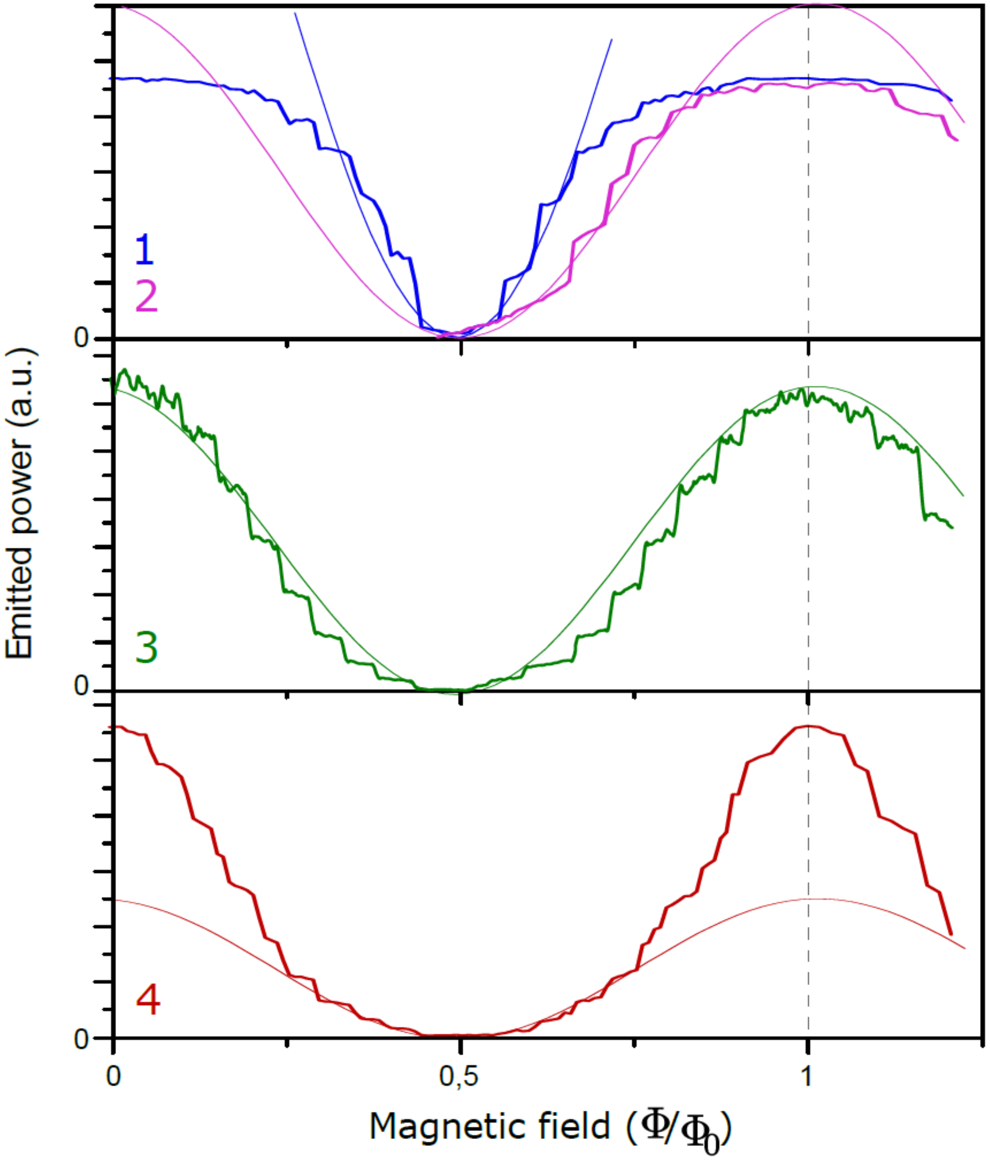


Does the emission follow theoretical predictions ?

Multiple photon emission



$$\Gamma^{ph} \propto E_J^2 \cos^2(\Phi)$$



Conclusion and perspectives

Summary

dc-biased Josephson junction:

simple, compact and bright source of non-classical photons

What's next ?

- Higher coupling : perfect single photon source ?
- Transition to parametric resonance (photon pair bursts)
- Probe for other quantum devices ?

Thanks : Marc Westig, Iouri Moukharski, Denis Vion, Philippe Joyez, Carles Altimiras, Patrice Roche, Daniel Estève

Thanks !