

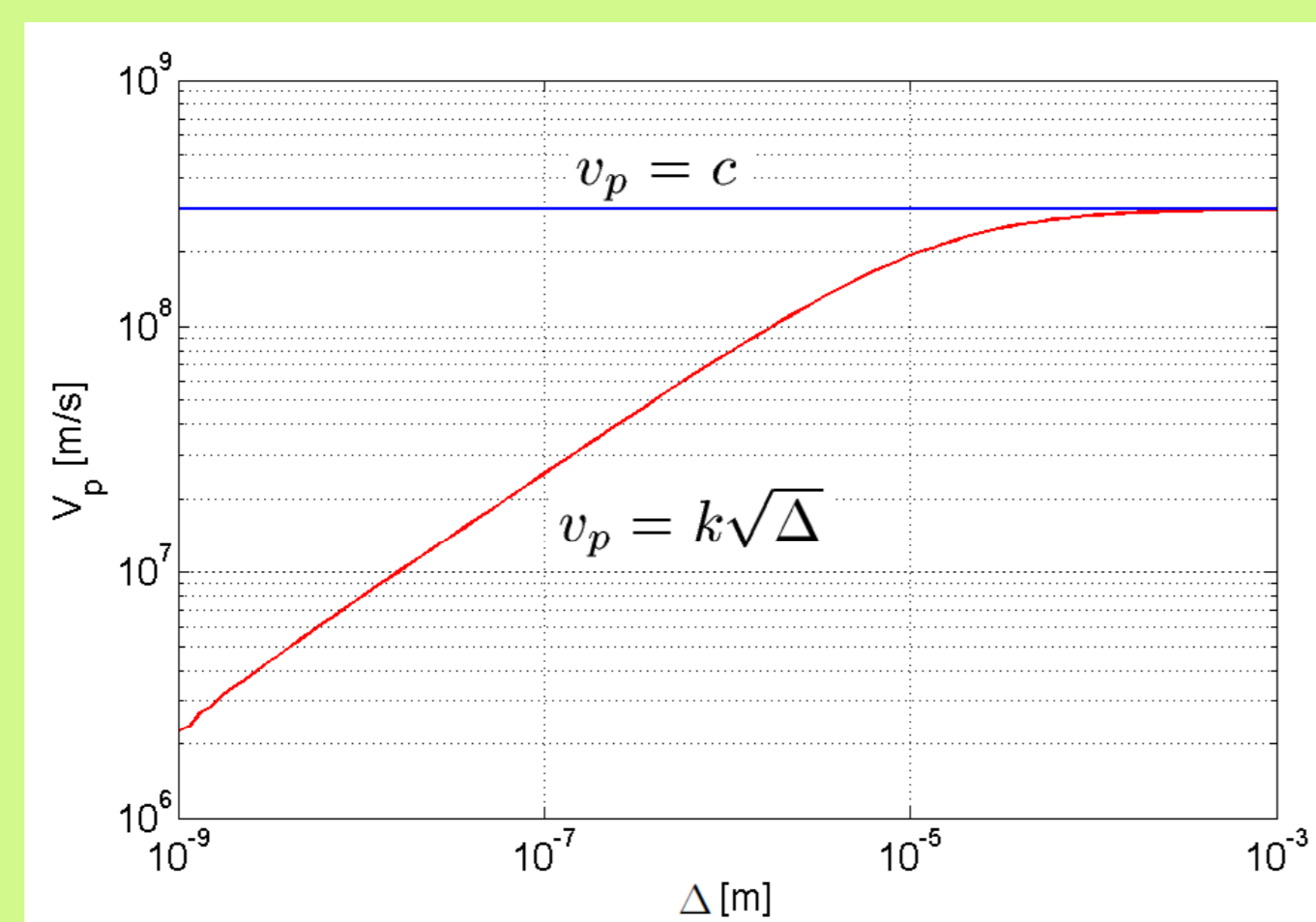
## Network scalability

- How does the channel capacity scale when the network dimensions shrink into the nanoscale?
- We consider the scalability of the capacity of a point-to-point link, where both transmitter and receiver are in the nanoscale
- The scale parameters are:
  - $\Delta$ : nanodevice size
  - $d$ : transmission distance
- We want to study the scalability when  $\Delta \rightarrow 0$ ,  $d \rightarrow 0$

## Quantum effects

When using CNT/GNR-based antennae to radiate electromagnetic waves in the nanoscale, there appear quantum effects due to the ballistic transport of electrons in graphene:

- Macro-scale behavior:  $v_p = c$
- Quantum behavior:  $v_p = k\sqrt{\Delta}$



- We study whether these effects actually benefit or harm communication

## Nano-EM channel capacity

The capacity of a frequency-selective communication channel can be obtained using the Shannon-Hartley theorem:

$$C = \max_{S(f): \int S(f) df \leq S_T} \int_0^B \log_2 \left( 1 + \frac{S(f)}{A(f)N_0} \right) df$$

We assume the following expressions for the radiated power spectral density and the channel attenuation:

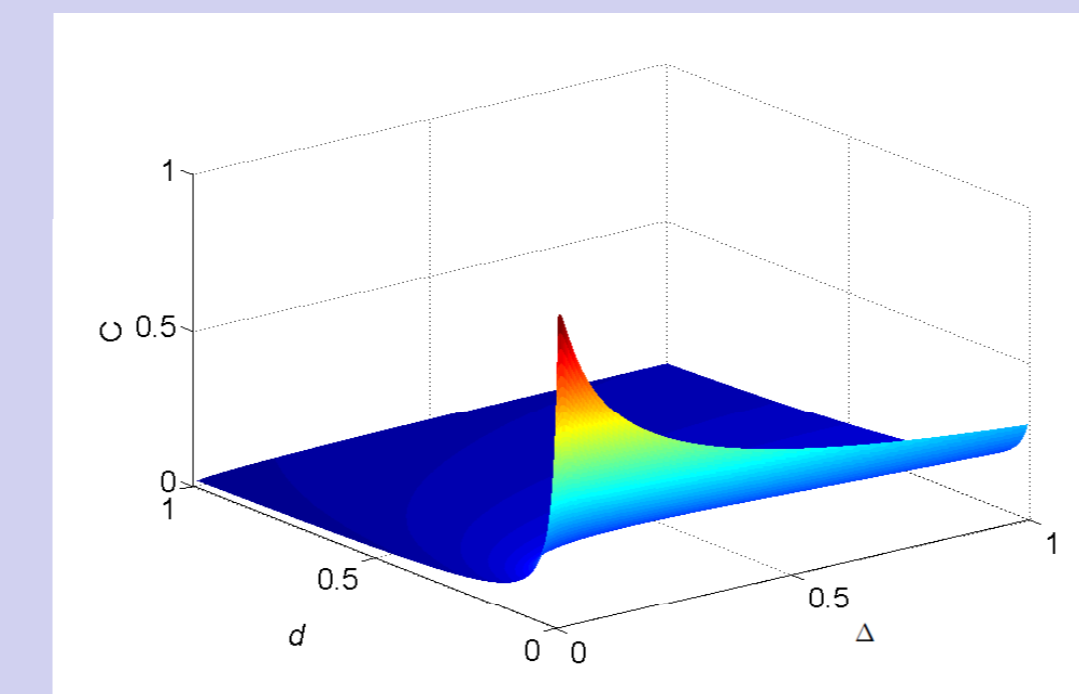
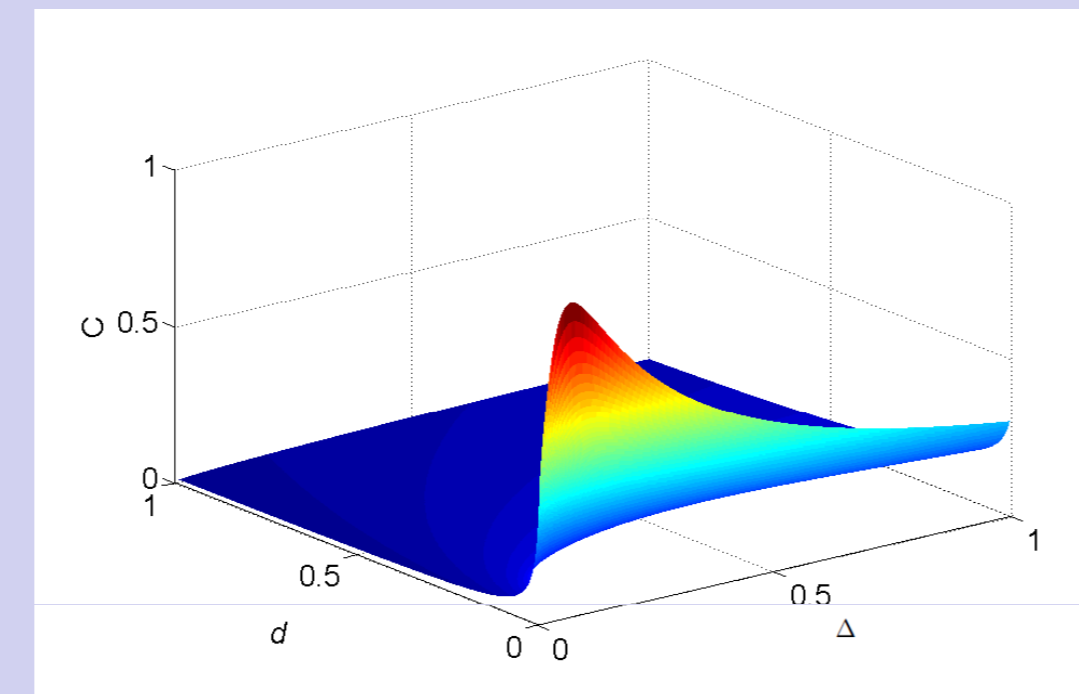
- Spectrally-flat radiated power  $S(f) = \frac{S_T}{B}$

- Free-space propagation loss  $A(f) = \left( \frac{4\pi df}{c} \right)^2$

## Scalability of channel capacity

The channel capacity scales differently whether we consider or not the quantum phenomena:

$$C_{nq} = \Theta \left( \frac{1}{\Delta} \log \left( 1 + \frac{\Delta^3}{d^2} \right) + \frac{\sqrt{\Delta}}{d} \arctan \left( \frac{d}{\Delta^{3/2}} \right) \right) \quad C_q = \Theta \left( \frac{1}{\sqrt{\Delta}} \log \left( 1 + \frac{\Delta^{3/2}}{d^2} \right) + \frac{\sqrt[4]{\Delta}}{d} \arctan \left( \frac{d}{\Delta^{3/4}} \right) \right)$$



## Capacity limits in the nanoscale

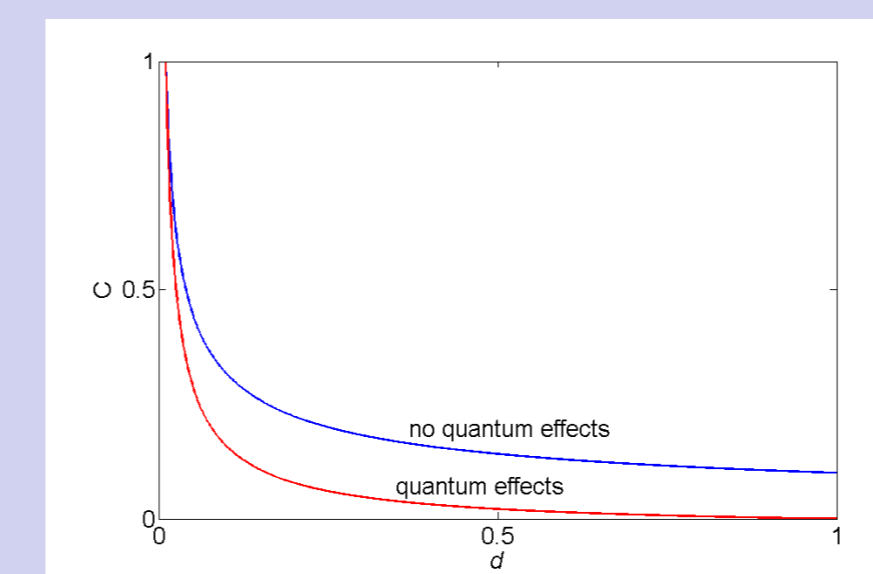
The expressions above do not have a unique limit when  $\Delta \rightarrow 0$ ,  $d \rightarrow 0$

In order to find the limit expressions, we need to do an assumption on the relationship between  $\Delta$  and  $d$ . There are 3 interesting cases:

When  $\Delta = \Theta(d)$ , in the limit  $d \rightarrow 0$  the capacity increases at a higher rate when considering the quantum effects:

$$C_{nq} = \Theta \left( \frac{1}{\sqrt{d}} \right)$$

$$C_q = \Theta \left( \frac{-\log d}{\sqrt{d}} \right)$$



When  $\Delta = \Theta(1)$ , the capacity increases at the same rate whether we include quantum effects or not:

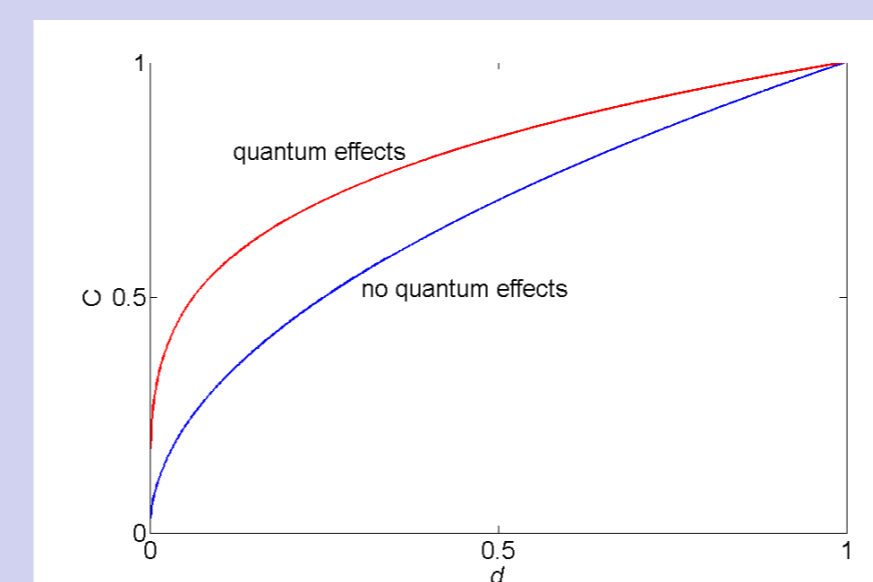
$$C_{nq} = \Theta(-\log d)$$

$$C_q = \Theta(-\log d)$$

When  $d = \Theta(1)$ , the capacity decreases at a higher rate when we include quantum phenomena:

$$C_{nq} = \Theta(\sqrt{\Delta})$$

$$C_q = \Theta(\sqrt[4]{\Delta})$$

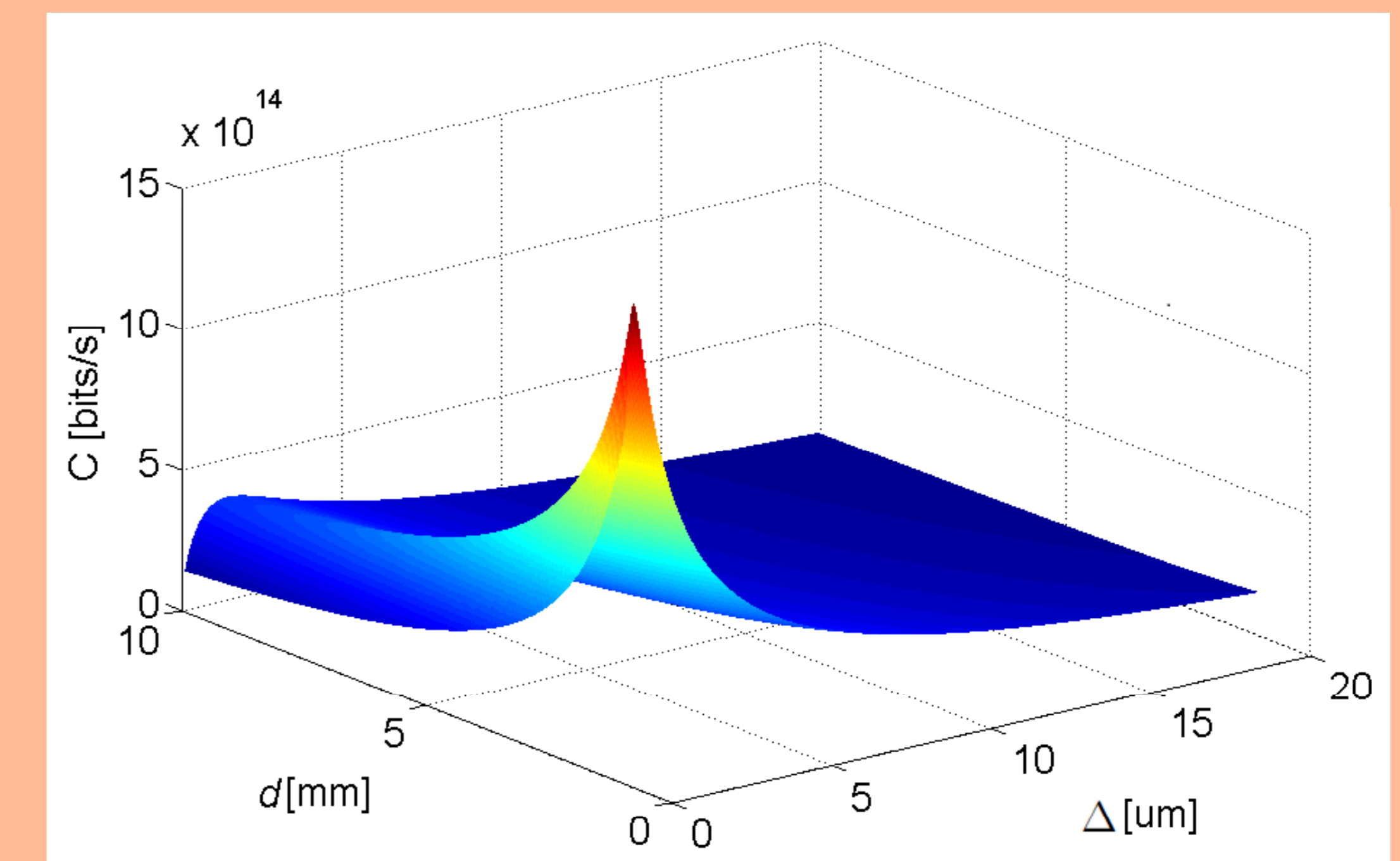


## Numerical results

In order to obtain quantitative results of the channel capacity, we give realistic values to the parameters of the capacity expression:

- $\Delta$  from 100 nm to 20  $\mu\text{m}$
- $d$  from 1 to 10 mm

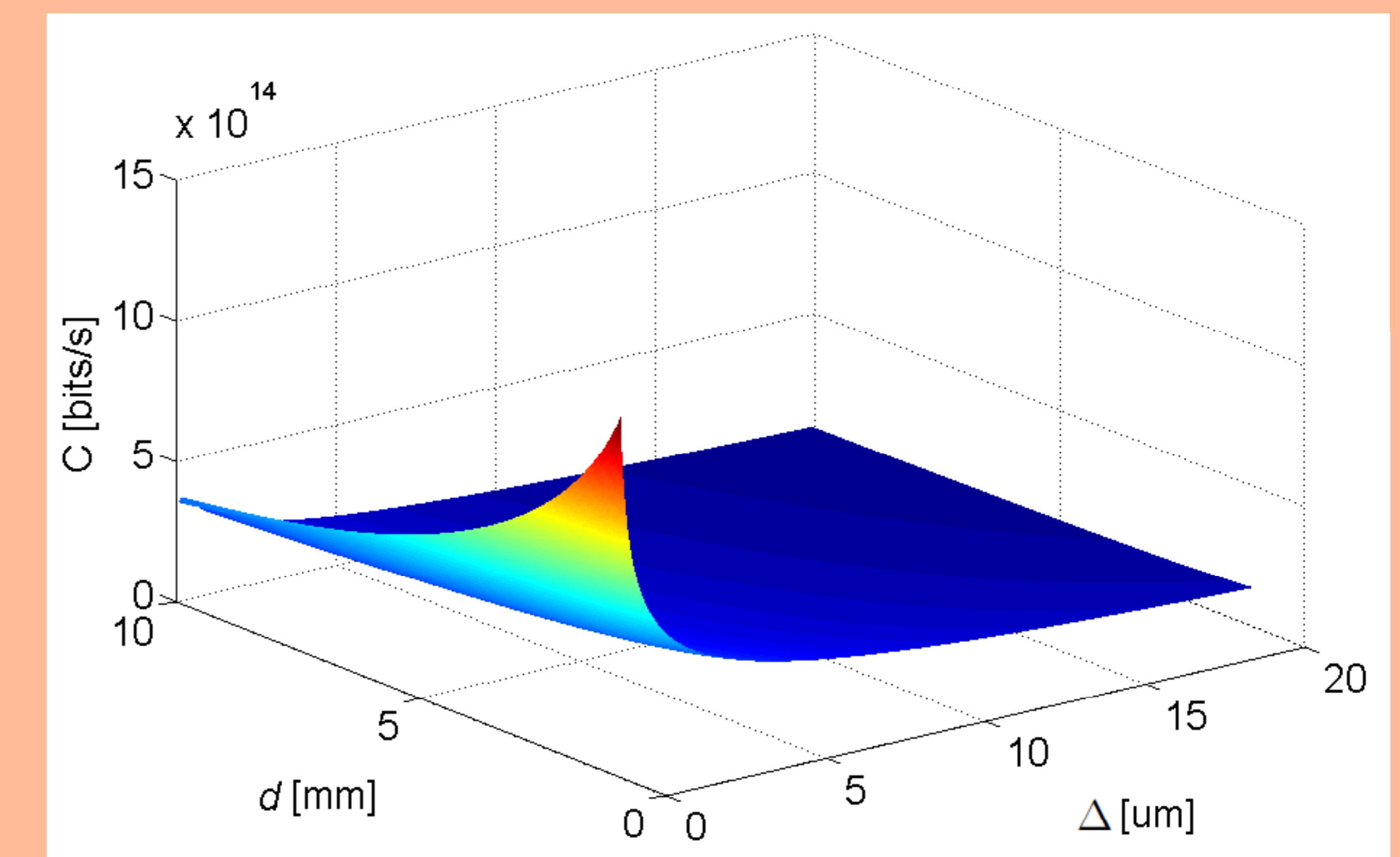
Without quantum effects



Without quantum effects:

- High channel capacity
- Capacity tends to 0 when  $\Delta \rightarrow 0$
- There is an optimal antenna size

With quantum effects



With quantum effects:

- Lower channel capacity
- Capacity tends to  $\infty$  when  $\Delta \rightarrow 0$ : there is no peak in capacity
- The smaller the antenna, the better!