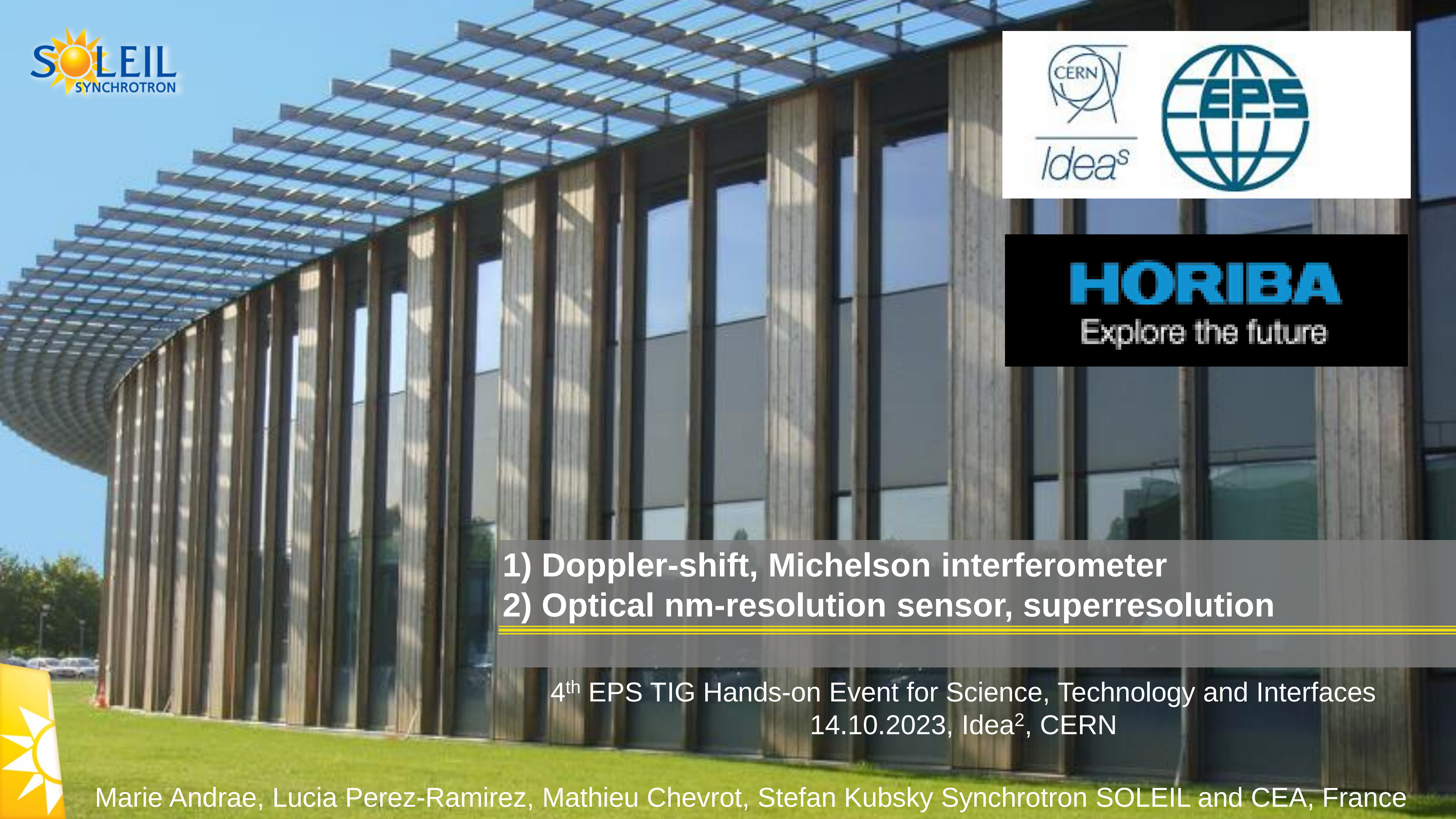


1) Doppler-shift, Michelson interferometer
2) Optical nm-resolution sensor, superresolution

4th EPS TIG Hands-on Event for Science, Technology and Interfaces
14.10.2023, Idea², CERN

Marie Andrae, Lucia Perez-Ramirez, Mathieu Chevrot, Stefan Kubsky Synchrotron SOLEIL and CEA, France

What role played the discoverer of the Doppler effect ?

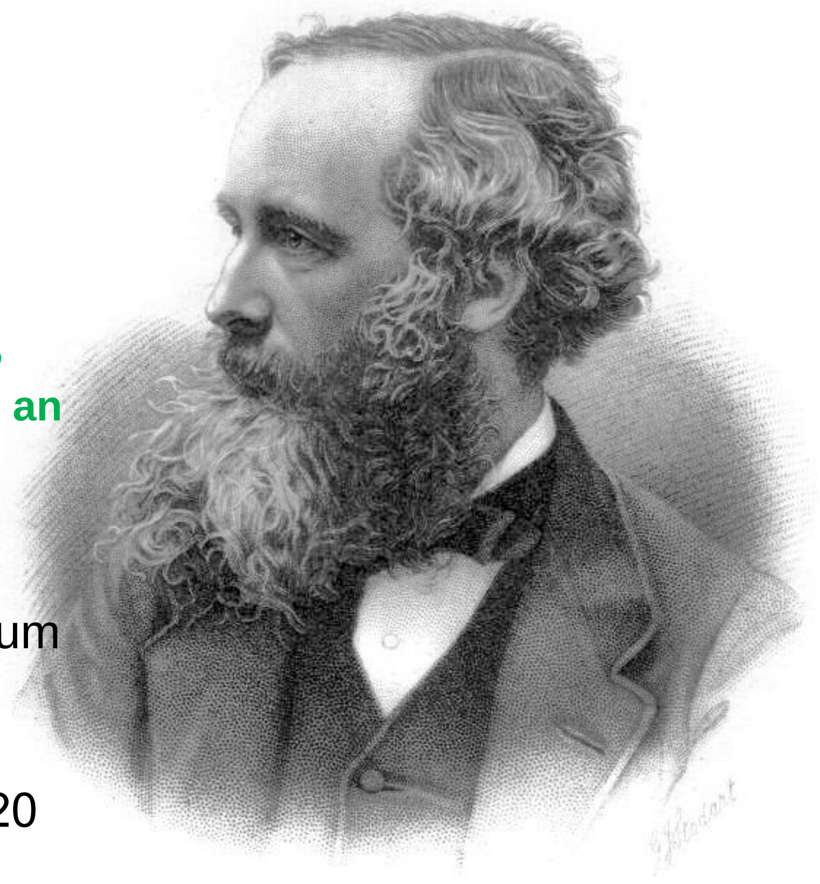
- In 1842, Christian Doppler (1803-53) formulated the hypothesis, that the color observable in starlight stems from a changing distance – wich is not the case.

- However, soon afterwards, thanks to the advent of steam engine powered locomotives, the acoustic Doppler-effect was experimentally verified and named after him.

Where is the connection to **light** and « **modern** » physics ?

James Clerk Maxwell (1831-79) delivered his famous set of equations after a thourough study of the existing knowledge of the time (Faraday, Kelvin, Ampère…) in 1864, concluding:

> **“This velocity is so nearly that of light, that it seems we have strong reason to conclude that light itself (including radiant heat, and other radiations if any) is an electromagnetic disturbance in the form of waves propagated through the electromagnetic field according to electromagnetic laws.”**



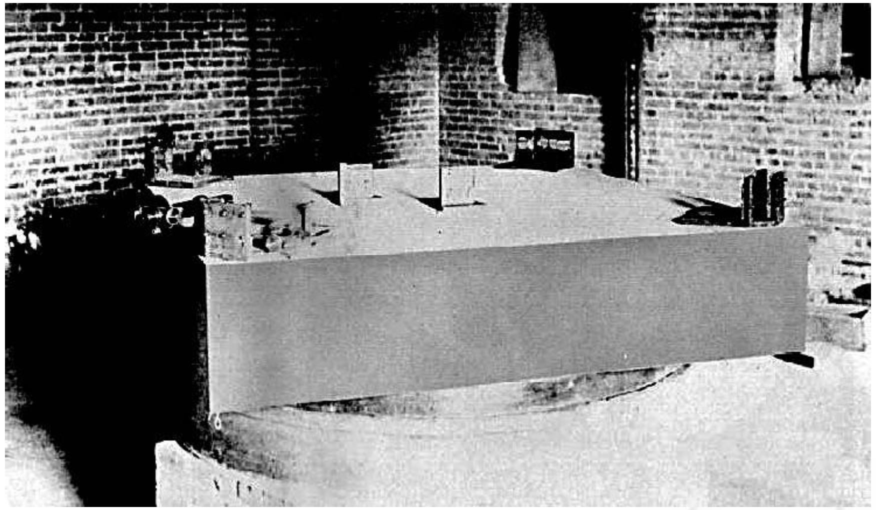
However, Maxwell was of the opinion that electromagnetic waves need a medium to propagate, called « Ether ».

It was an experiment and a theory that proved ethers’ non existence … about 20 and 40 years later, respectively… you know which ?

1) Michelson Interferometer: Doppler shift

What happened during the time when new physics *concepts* arose ?

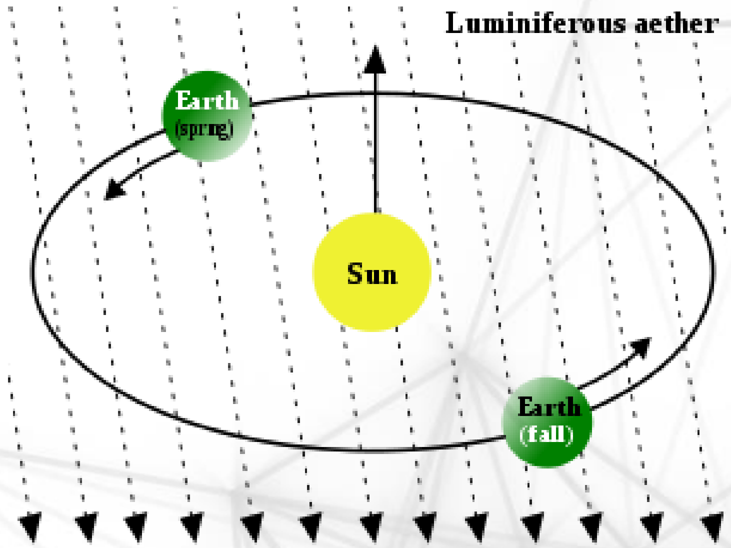
In 1881 in Potsdam, Albert Michelson and in 1887 together with Edward Morley in Cleveland, the « Michelson experiment » prooved the non existence of the Ether ***– against all their hope !***



Predicted: 0,4 fringes of displacement with 11m long arms, using white light !

Since then, the velocity of the sun and the milky way have been taken into account and results yield: 0

-> « most famous failed experiment in history »

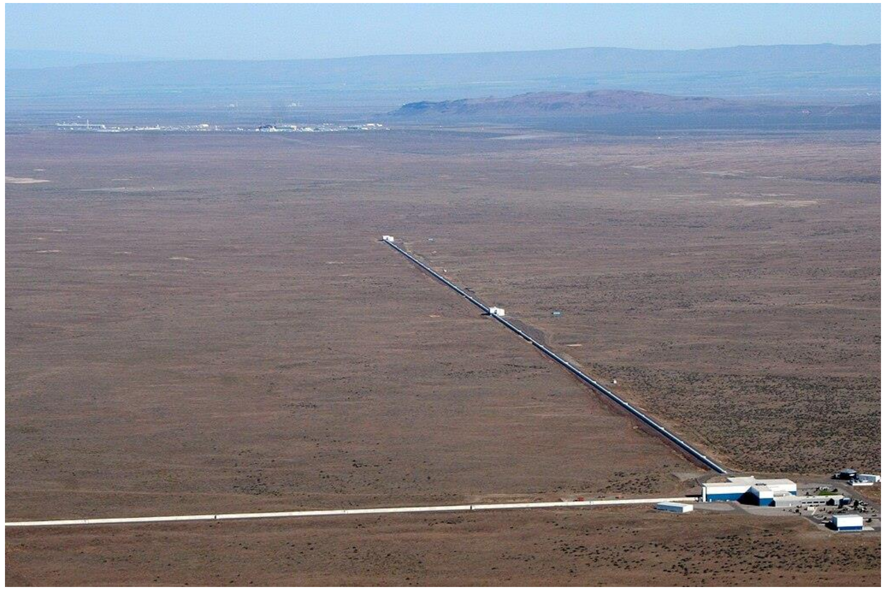


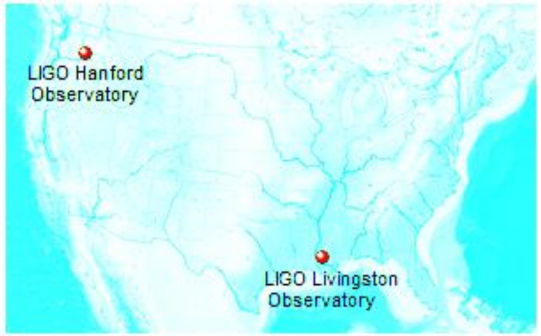
In 1905, Albert Einstein delivered the *special relativity theory*, …

Why is a Michelson Interferometer a iconic piece of instrumentation today ?

2017 Nobel prize in Physics

for Rainer Weiss, Barry C. Barish and Kip S. Thorne
for **“decisive contributions to the LIGO detector and the observation of gravitational waves**“





Hanford

3000kms ~ 10ms

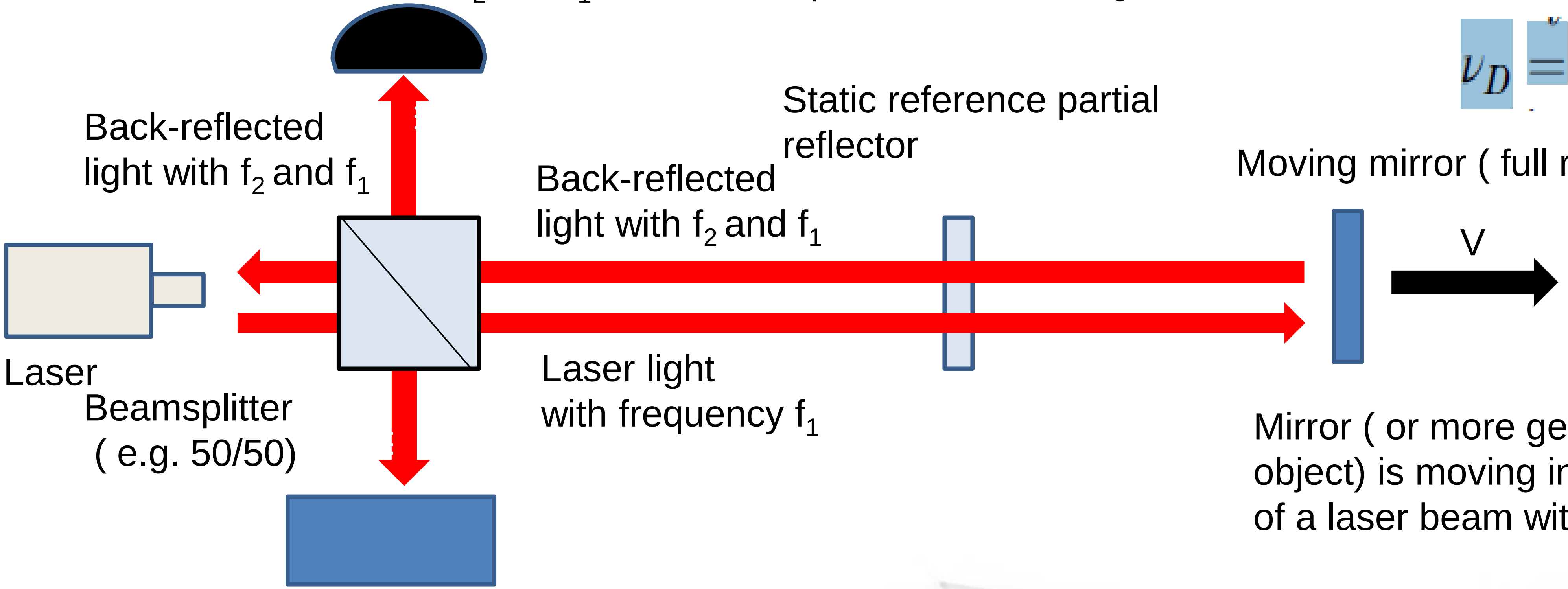
Livingston

1) Michelson Interferometer: Doppler shift

And now ? -> We’re building one in a couple of hours…from scratch and some knowledge:

Photodetector (+ data acqusition, not shown) → yields beat signal of f_2 and f_1 from which speed of the moving mirror can be deduced

$$\nu_D \doteq \nu_0 - 2nV_p\nu_0/c,$$



Mirror (or more general an object) is moving in the direction of a laser beam with speed v

1) Michelson Interferometer: Doppler shift

And now ? -> We're building one in a couple of hours…from scratch and some knowledge:

Tasks for the « Doppler » experiment:

- ✓ Assemble the interferometer (mechanics, optics, detection, electronics, data retrieval, data analysis and interpretation) -> Yeah !
- ✓ How to know about the actual speed of the moving mirror ?
- ✓ Estimate by calculating the interference fringes passing with respect to the Doppler effect (?!)
- ✓ Record interference when one mirror moves ->
- ✓ Develop a clear, educated path to present your findings on Sunday !

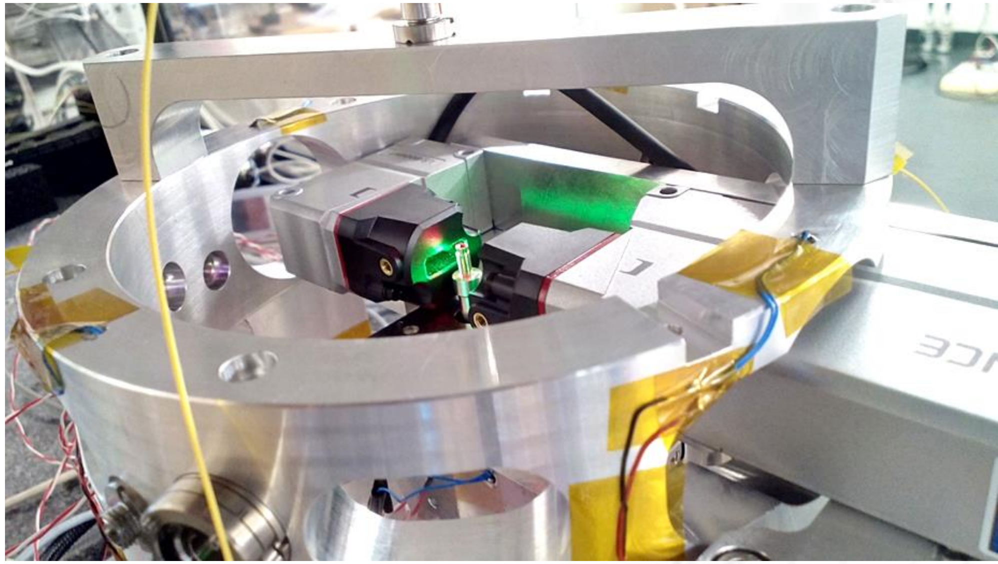
2) Optical nm-resolution sensor, based on superresolution

Why and where would one need nm-resolution ?

Scientific and engineering disciplines dealing with « small » objects (10µm-> sub-nm) need:

Reproducible interaction with the object and a « probe » in an experimental or production situation

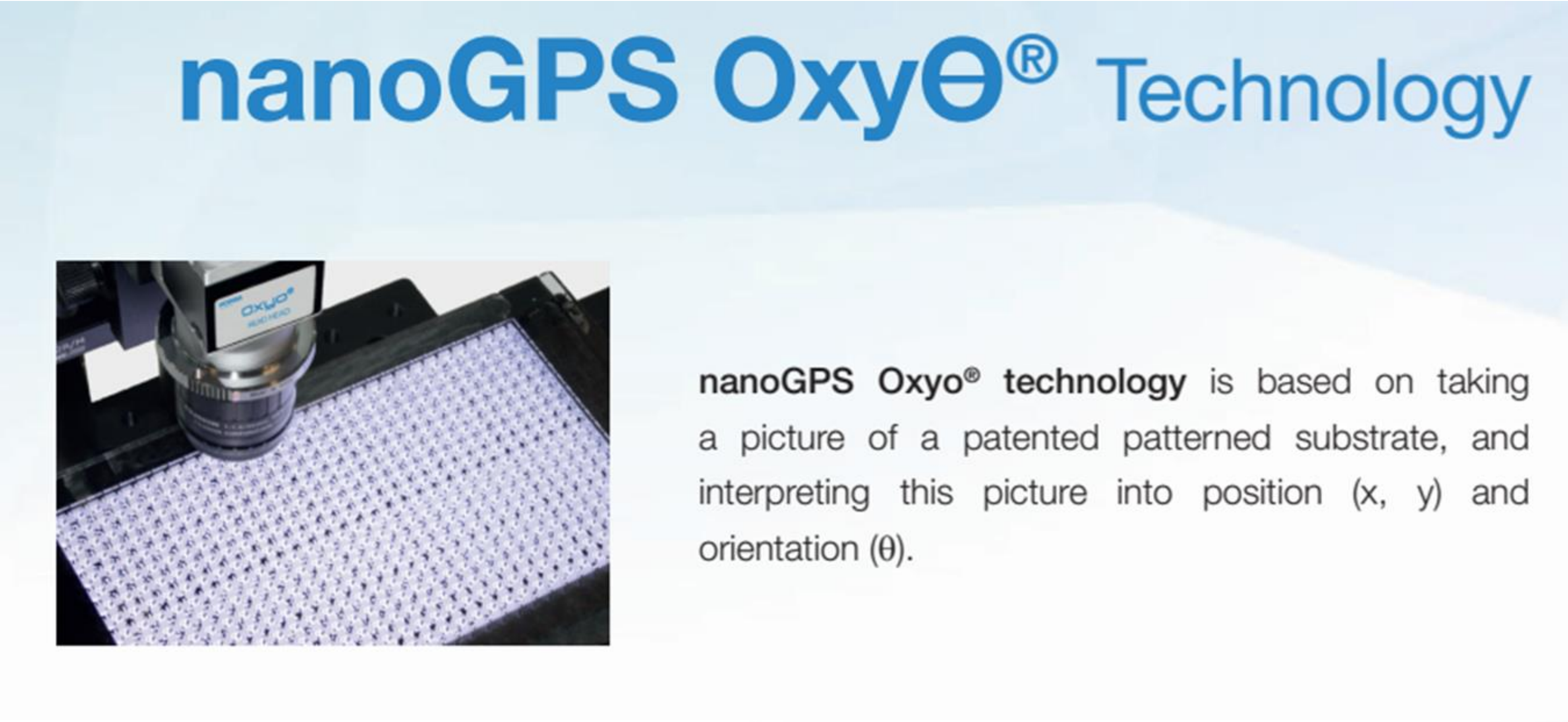
1. Needs to be nm-precise (semiconductor industry is at ~5nm « structure size »)
2. The more dimensions – the better
3. « Absolute » readout - calibration takes time
4. Time resolution (fast)
5. « Rugged » -for use in hostile environments (hot, cold, magnetic field, vacuum)
6. Compact for integration
7. Affordable



2) Optical nm-resolution sensor, based on superresolution

What ?

Horiba's « OXYO » System satisfies the above conditions – Introduction by one of the inventers – Olivier Acher from Horiba



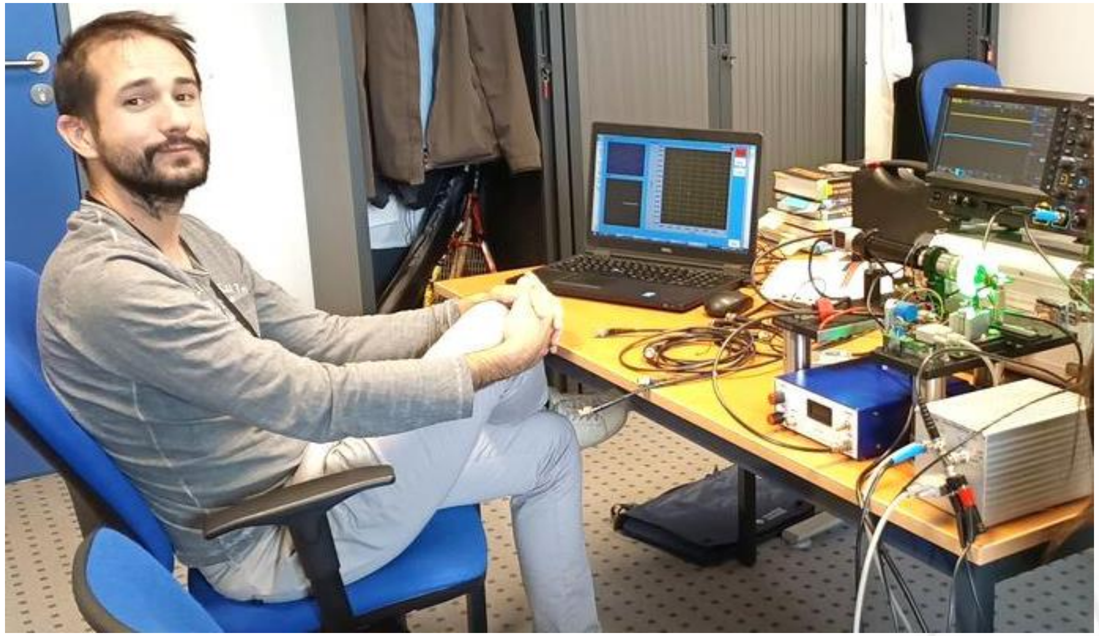
– Identify components of the system, please: What do you see ? What sizes approximately ?

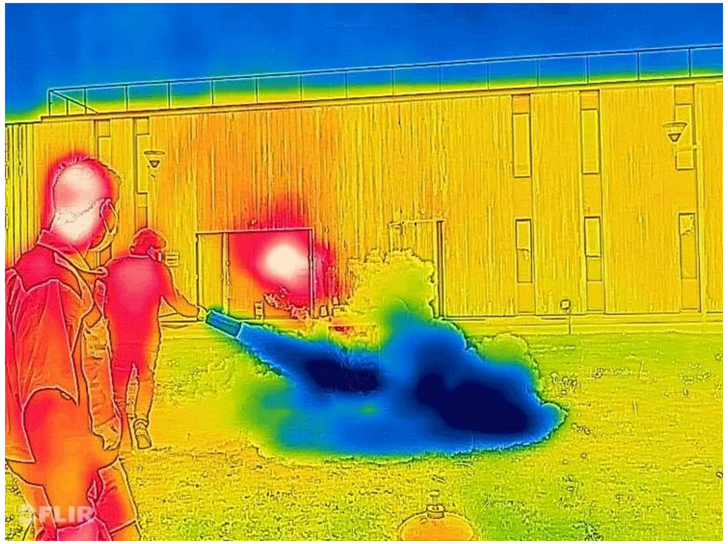
2) Optical nm-resolution sensor, based on superresolution

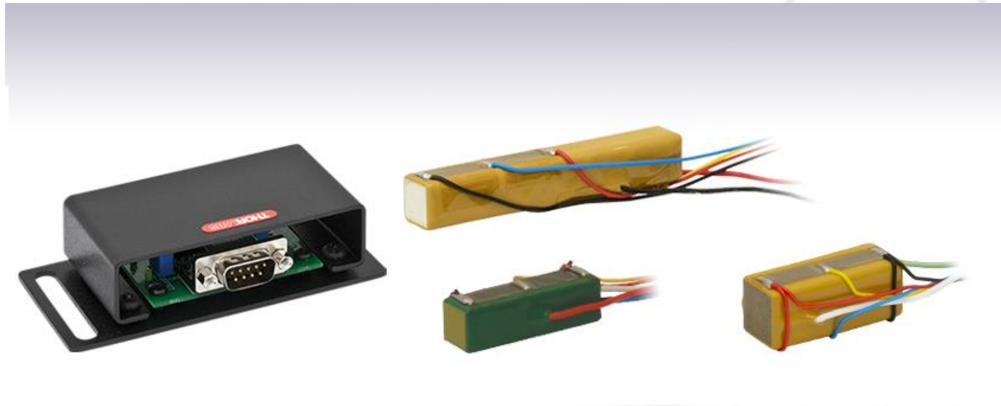
Project: You enter the nanoworld now – and measure : How ?

- Construct an OXYO position readout system
- Move the fiducial with nm-fine precision, record, analyse and present the trajectory
- Compare the OXYO-based measurement to classical strain gauge measurement
- Make observations on measurement errors and uncertainties (thermal drift, vibration) estimate their impact
- Present the results (~20 mins presentation on sunday)

Optical nm-resolution sensor, based on superresolution

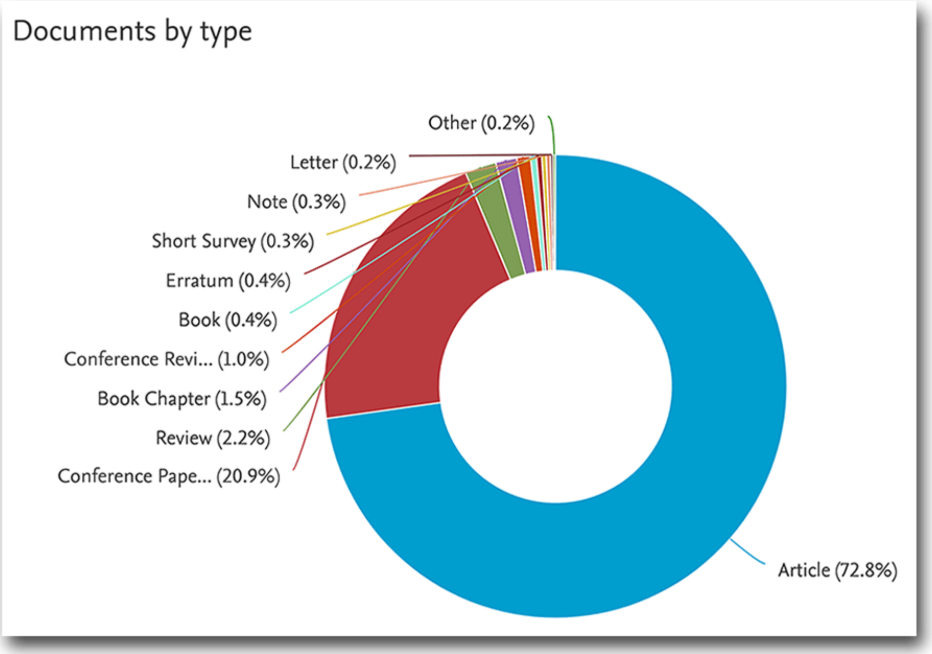


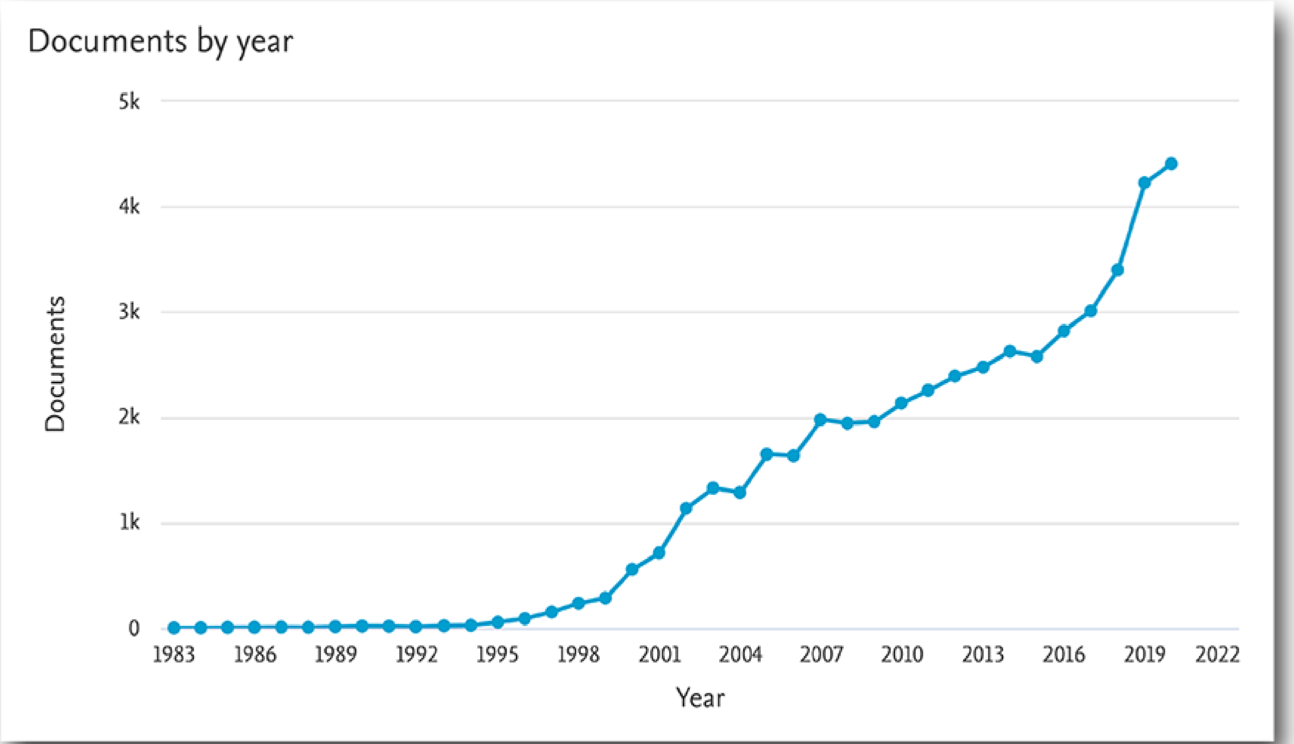




Please ask for help when you're unsure on how to proceed !

- **Why ?**
  - Ultimate computation speed
  - Optimization as a problem class is a key application: financial trading, defense, logistics, cryptography and communication
  - Research on QCs is a globally active field[2]
  - Textbooks are scarce[3]





Quantum Computing

- **How ?**

  – Many physical objects exist, fulfilling the requirements for qubits inside a QC[4], each having advantages and disadvantages, research for appropriate systems is ongoing

  – Key problems for implementation[5]:
    - Physically scalable to increase the number of qubits
    - Qubits that can be initialized to arbitrary values
    - Quantum gates that are faster than decoherence time (typ. between ns and s)
    - Universal gate set
    - Qubits that can be read easily

  – Qubits are very sensitive to their environment. This can also *inversely* be exploited as a feature: **Quantum sensing**

[4] see e.g. https://en.wikipedia.org/wiki/Quantum_computing
[5] DiVincenzo, David P. (13 April 2000). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783. arXiv:quant-ph/0002077. Bibcode:2000ForPh..48..771D. doi:10.1002/1521-3978(200009)48:9/11<771::AID-PROP771>3.0.CO;2-E.

Quantum Technologies - Pillars

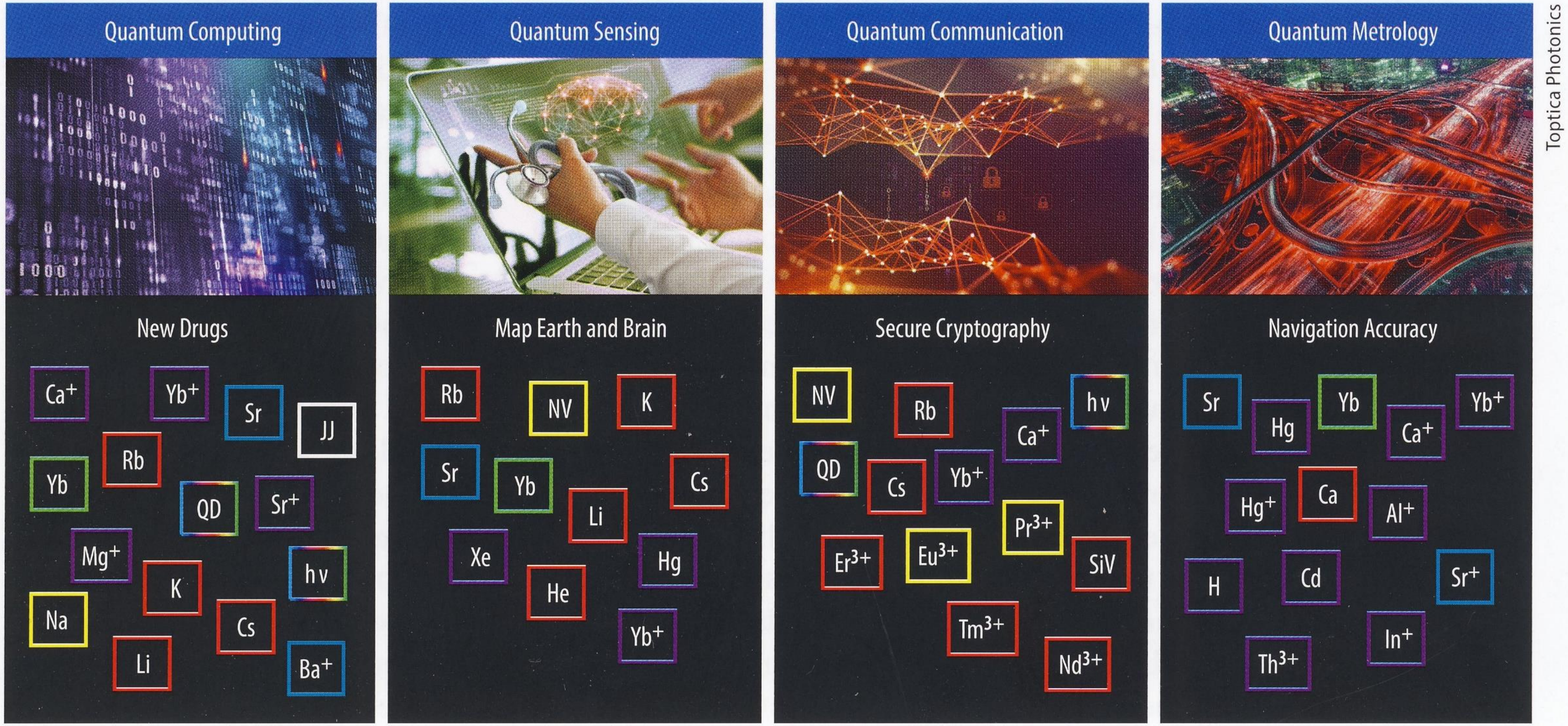
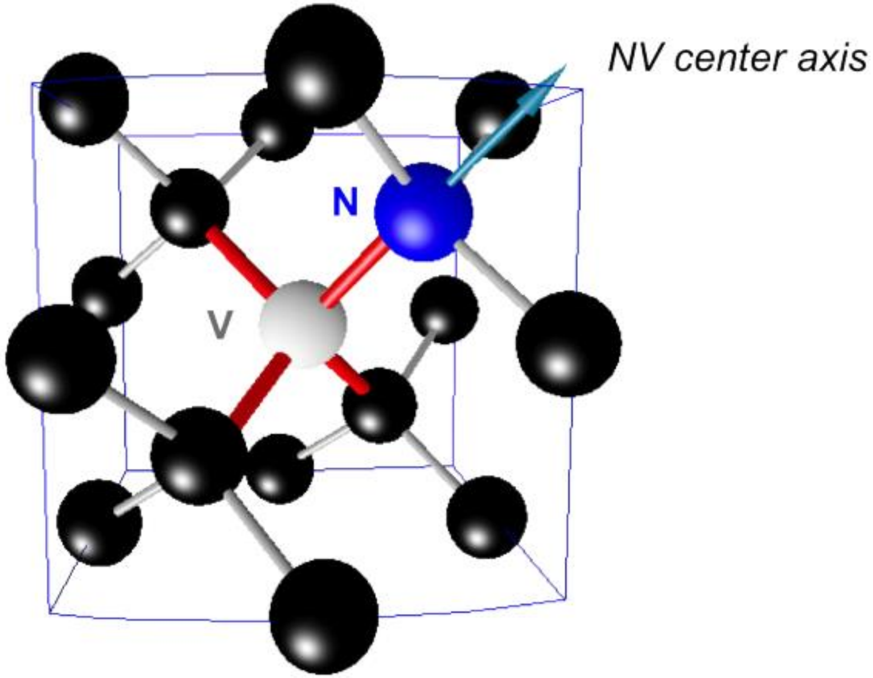


Fig. 1 Four pillars of quantum technologies (top) and a potential application result (below each image). There is a great variety of quantum systems used to implement different applications of quantum technologies. Species of atoms, ions and other quantum systems are shown in the square boxes. The more commonly used elements are at the top, the more exotic ones at the bottom.

From Physics' Best April 2022, p9

Quantum Sensing with NV- centers in Diamond

- NV- centers in Diamond are point defects within the diamond crystal lattice (fcc). One nitrogen atom N is on a lattice position and one adjacent lattice–site is vacant V[6] :

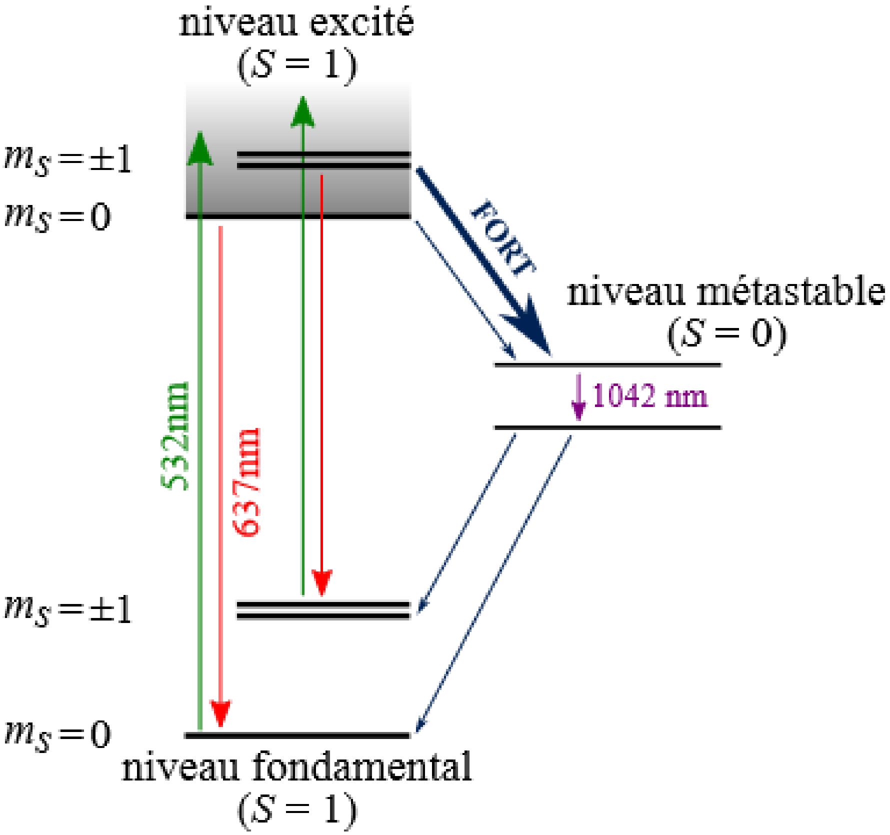


- Two charge states can exist: NV^0 and NV^-. NV^-, has one more electron, the total configuration has a spin of S=1. The NV^- centers are discussed here.

[6] from Margarita Lesik. Engineering of NV color centers in diamond for their applications in quantum information and magnetometry. Quantum Physics [quant-ph]. École normale supérieure de Cachan - ENS Cachan, 2015. English. ffNNT : 2015DENS0008ff. fftel-01158995, https://tel.archives-ouvertes.fr/tel-01158995 and refs therein. Thanks to Prof. J.-F. Roch.

Quantum Sensing with NV- centers in Diamond

- NV- centers' electronic structure[7]



1. Optical pumping from the S=1 ground state triplet populates the excited state.
2. Relaxation occurs optically at 637nm or non radiatively via S=0
3. Optically allowed transitons are spin-conserving, therefore the metastable level is dark.
4. Pump cycling can achieve population of the m_s=0 states, which could be exploited to initialise a quantum state for use within a QC.
5. External magn. Field (=Zeeman splitting on m_s=+-1) does not affect zero spin levels

n.b. : The energy levels and transition-probabilities are furthermore influenced by electrical fields, crystal strain and temperature. Transition energies between these many more levels lie in the Microwave region and permit to prepare and read electrically a population configuration of the NV- center: towards a QC @RT.

[7] From LoicToraille: Utilisation de centres NV comme capteurs de champs magnétiques à haute pression dans des cellules à enclumes de diamant. Physique [physics]. Université Paris Saclay (COmUE), 2019. Français. NNT: 2019SACLN056. tel-02429177v2; https://tel.archives-ouvertes.fr/tel-02429177v2

NV- centers in Diamond: how to make them ?

- Different paths to obtain NV- centers in diamond, from [6]:

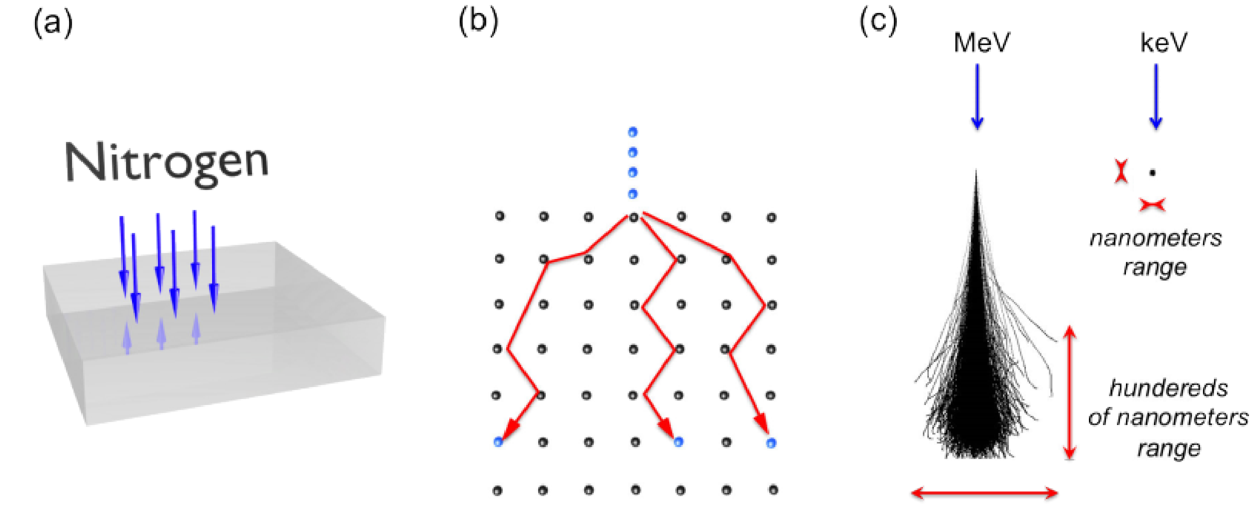


Figure 1.8: (a) Schematic representation of the nitrogen implantation experiment. (b) Ions straggling due to collisions and repulsions. (b) Example of the nitrogen ions penetrating tracks in the diamond sample using SRIM simulation.

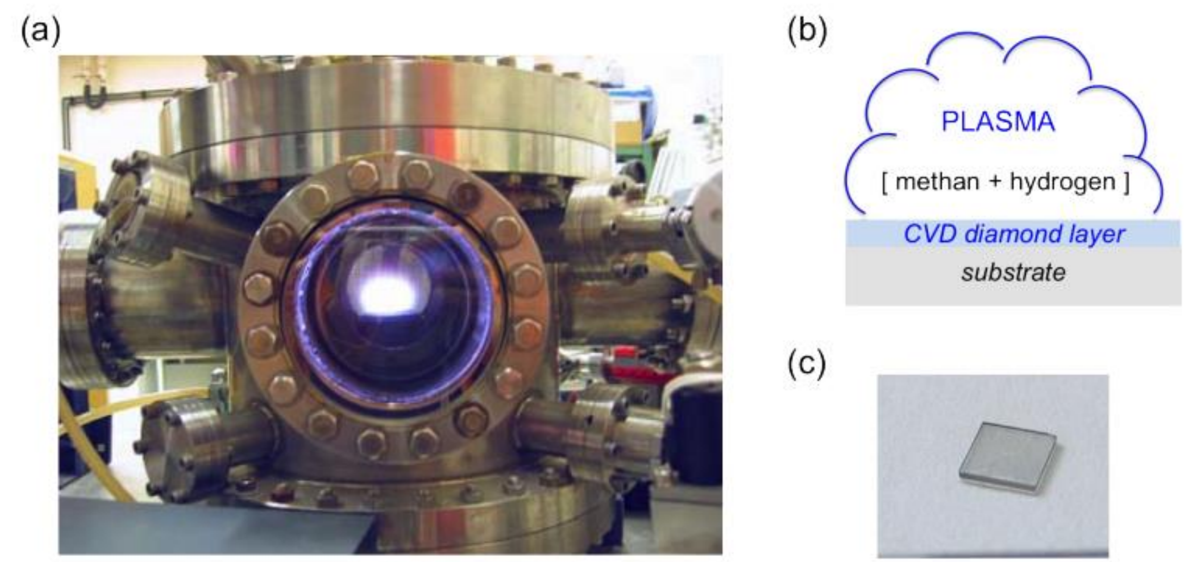
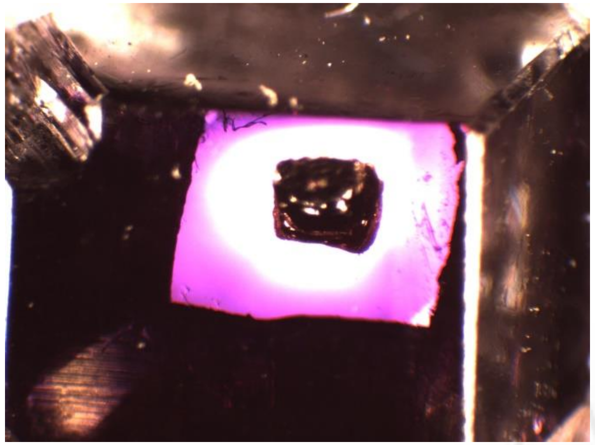


Figure 1.12: (a) Image of a CVD growth reactor used for the deposition of high purity diamond crystal. (b) Schematic representation of the CVD layer deposition process. (c) Image of a standard ultrapure diamond sample.

Spin coherence time is one of the key parameters for quantum computation, surface proximity (<2nm) makes NV- centers spins more fragile to external perturbations. At RT, 2ms have already been reported.

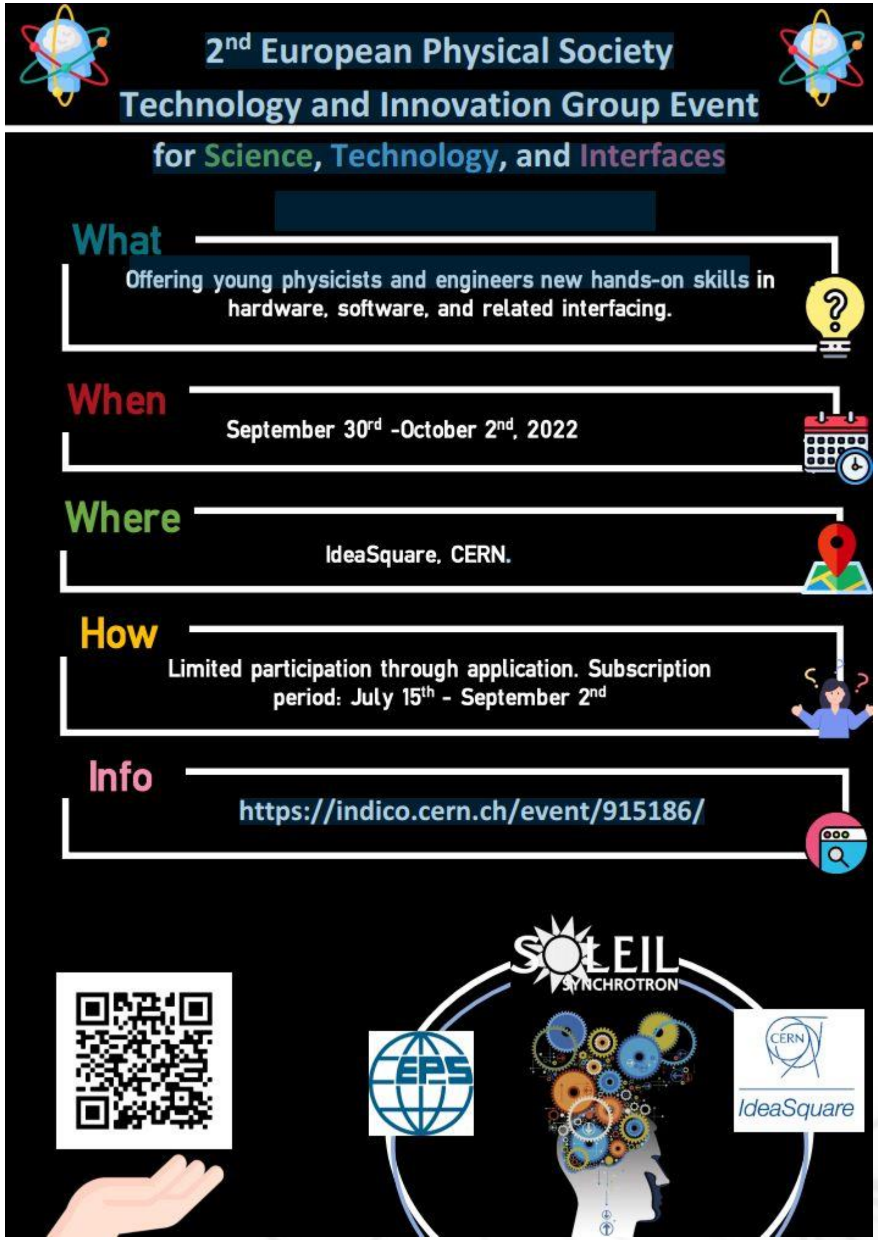
Hands-on quantum magnetometer



- Quantum magnetometer: exploit PL influenced by external magnetic field
- Experimental requirements (your part):
  - Need NV- centers in diamond (by Quantum Technologies, Leipzig)
  - Green light source (532nm)
  - Optical excitation setup
  - Optical read-out concept (consider spectral range versus readout speed)
  - Detector(s)
  - Magnet to produce magnetic field
  - PC and software -> data acquisition and interpretation
  - Ion implantation simulation to obtain NV-Centers
  - Presentation of results

Want More hands-on experience ?

Apply and come to CERN:



More insight into NV- centers in diamond from NATURE[8]:

https://www.youtube.com/watch?v=VCT0wDLyvSs

[8] Link: thanks to Mathieu Chevrot !