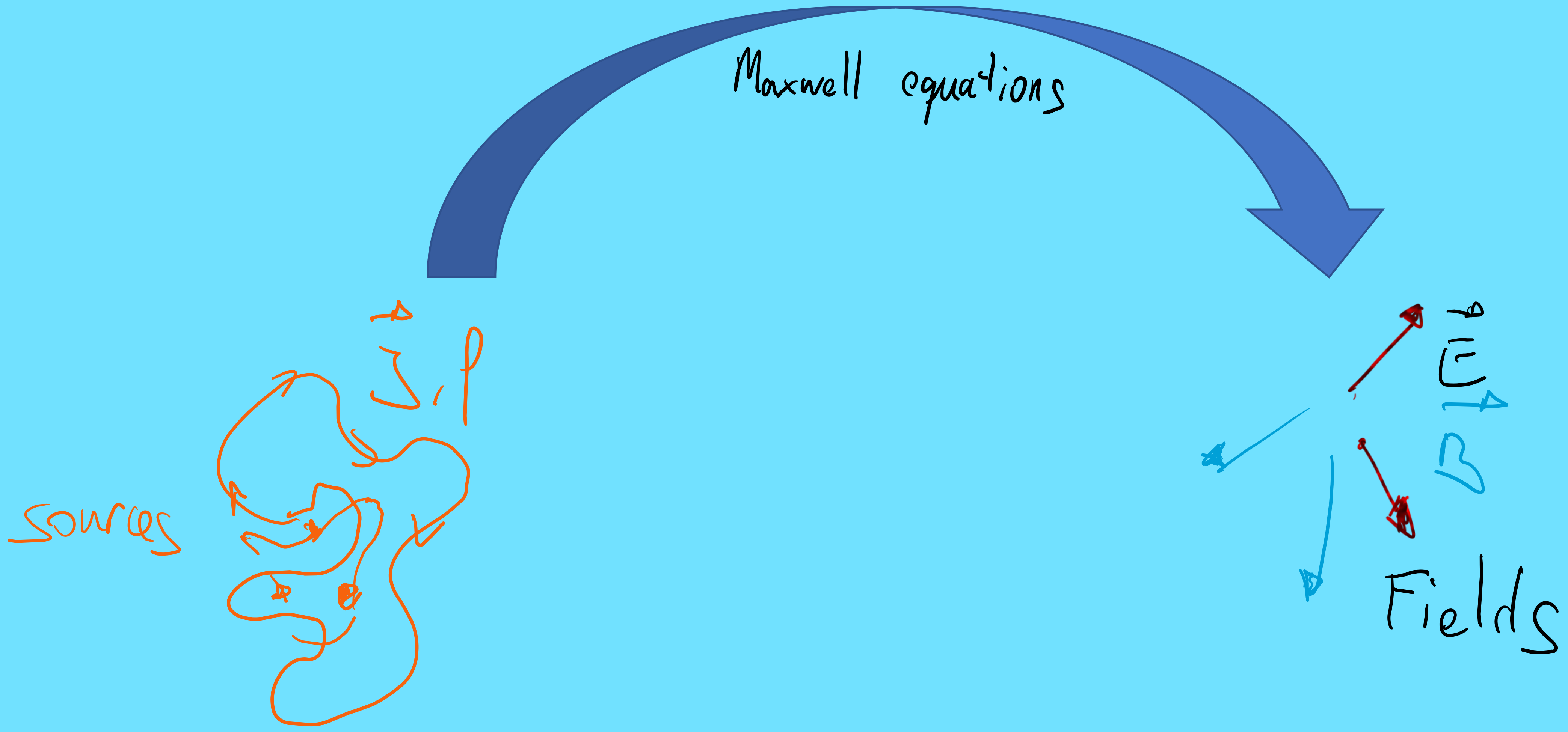
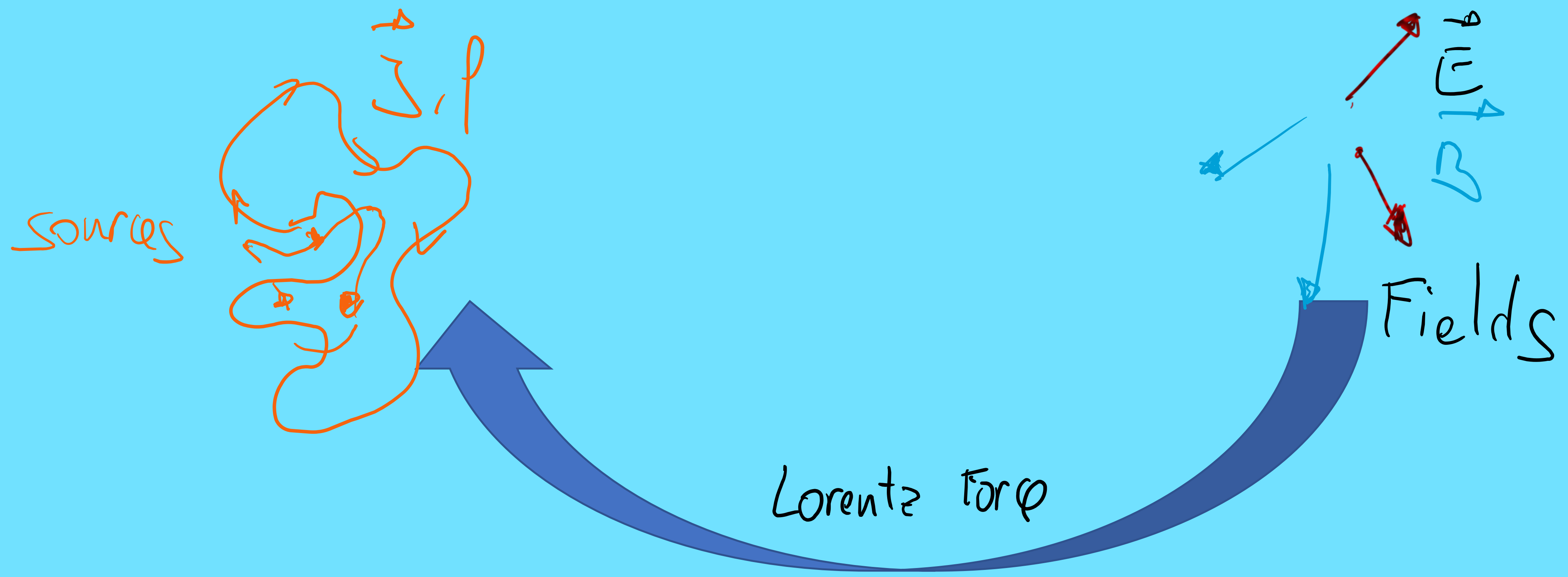
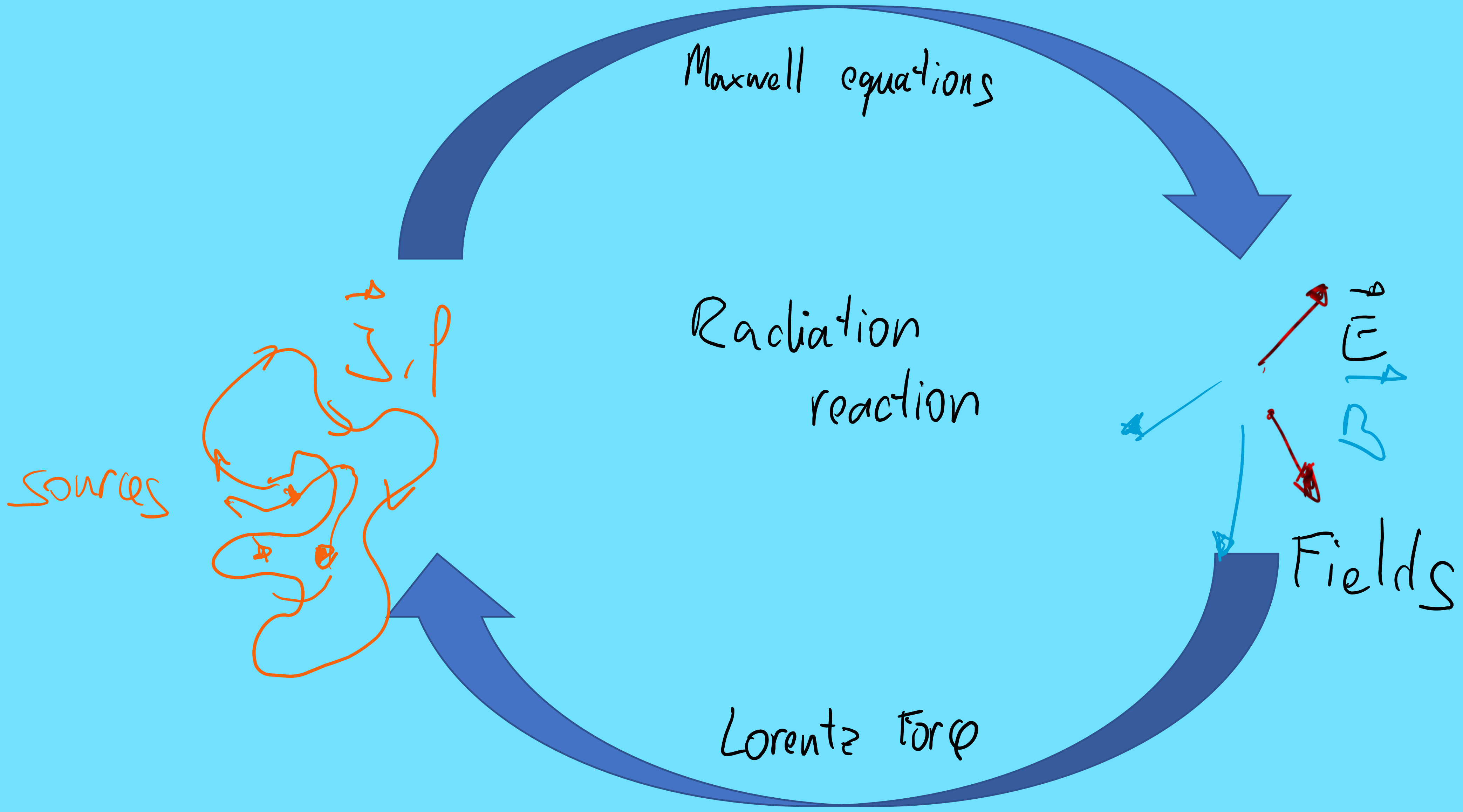
Maxwell’s equations are not causal


Maxwell equations
$\vec{J}, \rho$
Sources
$\vec{E}$
$\vec{B}$
Fields


sources
$\vec{J}, \rho$
$\vec{E}$
$\vec{B}$
Fields
Lorentz force



Maxwell equations
Radiation reaction
$\vec{E}$
$\vec{B}$
Fields
$\vec{j}, \rho$
sources
Lorentz force

Maxwell equations are not causal

- This happens at very small scales: the classical radius of the electron
  - $d \sim 10^{-15}$ m
  - $\tau \sim 10^{-22}$ s
- It leads to “runaway” solutions and also to problems with causality (electron moves before any wave arrives)
- Quantum Eletrodynamics does not seem to solve the problem
- Long standing (and sometimes forgotten) debate still (mostly unsolved)
- Possible solution: set a time scale in Maxwell’s equations

Maxwell equations are not causal

Corrections to formulas:

$\tau \times \omega \sim 10^{-8}$

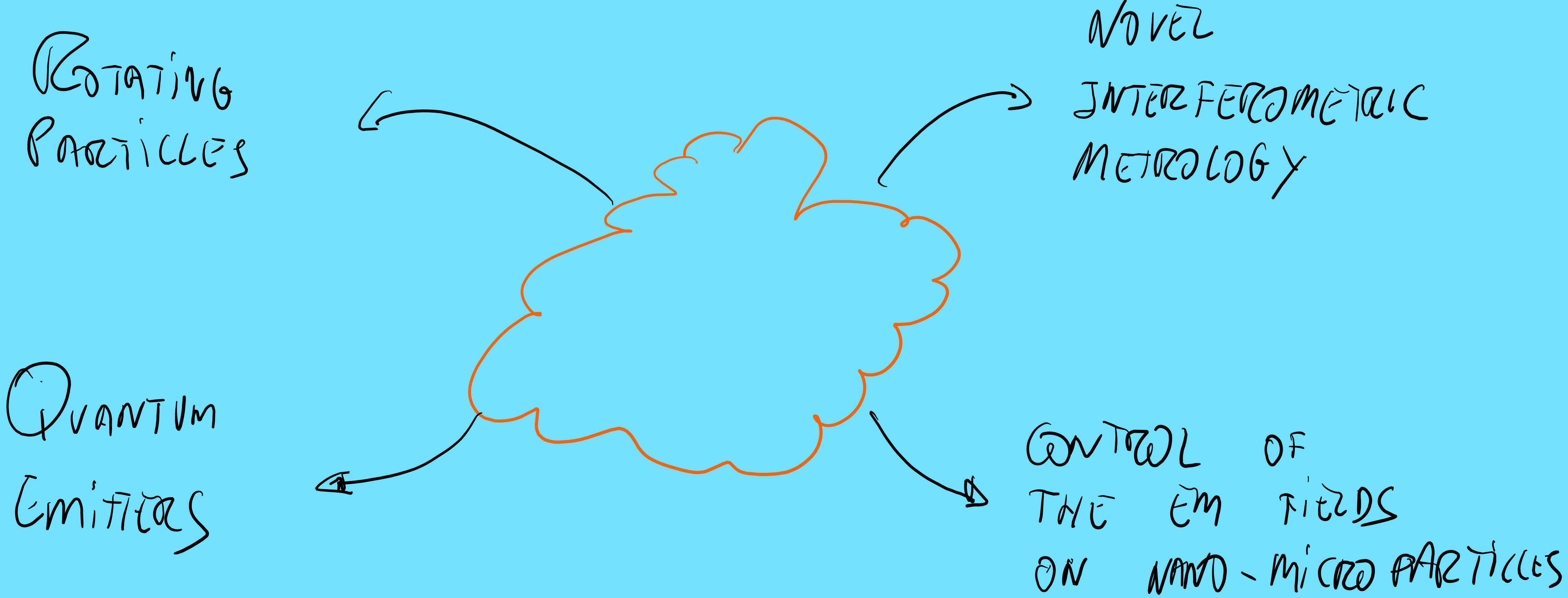
10^{-23}

freq

10^{15}

- For example, one should measure the decrease in the Larmor frequency in the 8th significant digit
- One would need extremely sensitive equipment to measure these effects (no experiment to date has been able to do so)

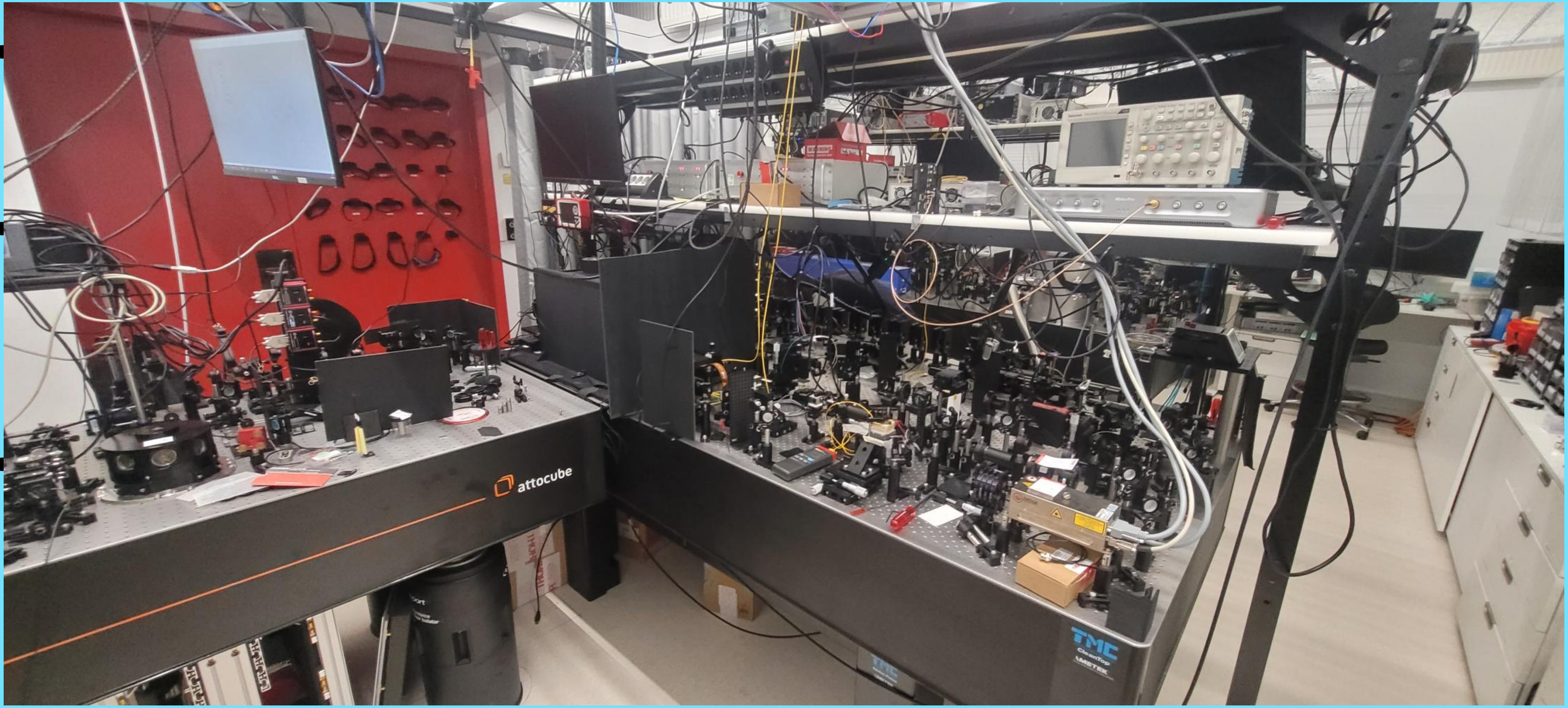
Wishlist


ROTATING PARTICLES
NOVEL INTERFEROMETRIC METROLOGY
QUANTUM EMITTERS
CONTROL OF THE EM FIELDS ON NANO-MICRO PARTICLES

Quantum Nanophotonics Lab
(and how we contribute to Particle Physics)

Gabriel Molina Terriza
Ikerbasque Research Professor
Materials Physics Center

Laboratory



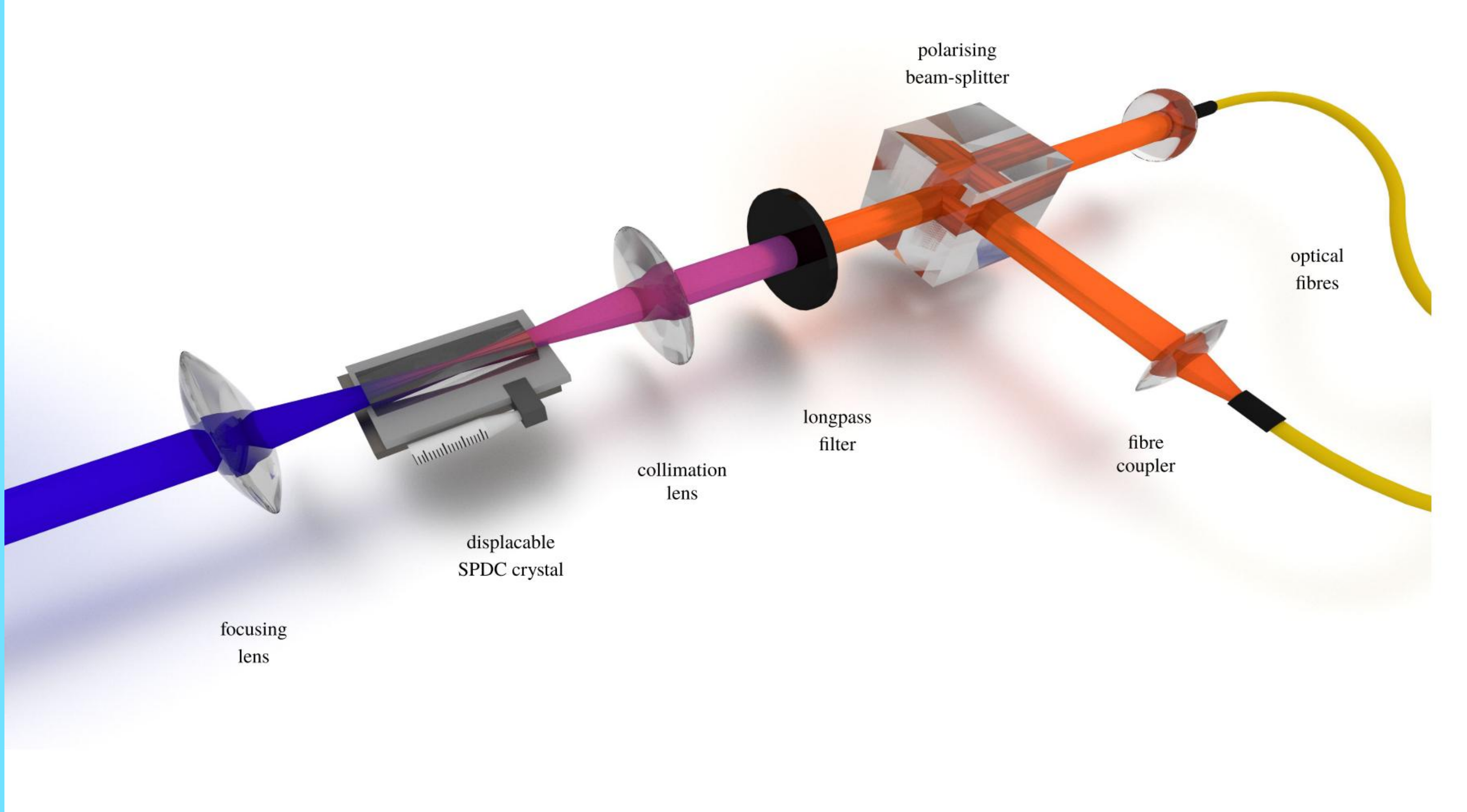
Topics we cover at the Quantum Nanophotonics Laboratory

1. Quantum and classical photonics

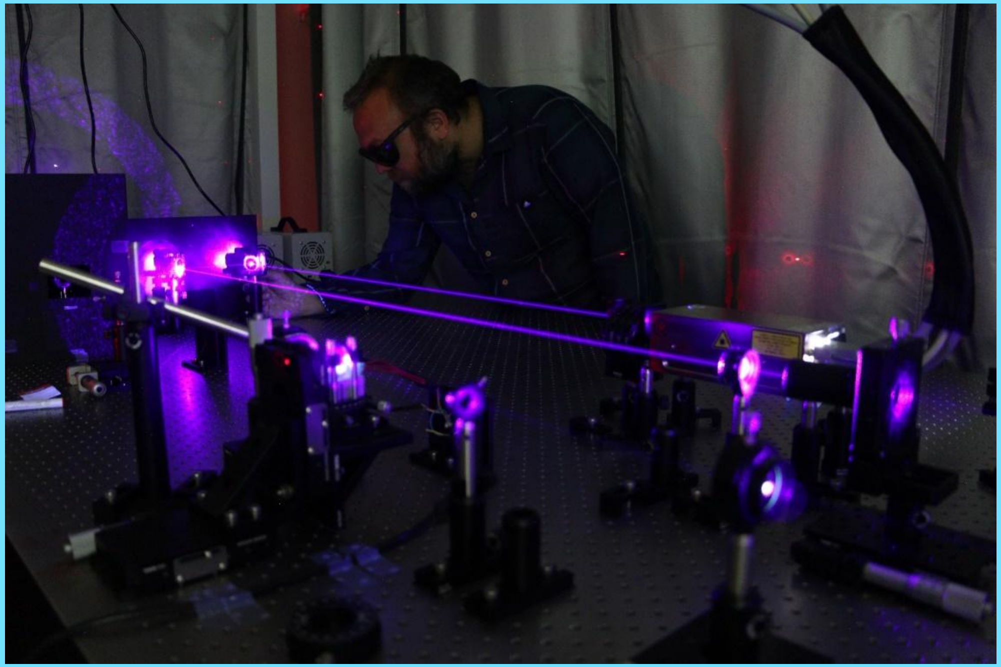
2. Optical forces: trapping and levitation

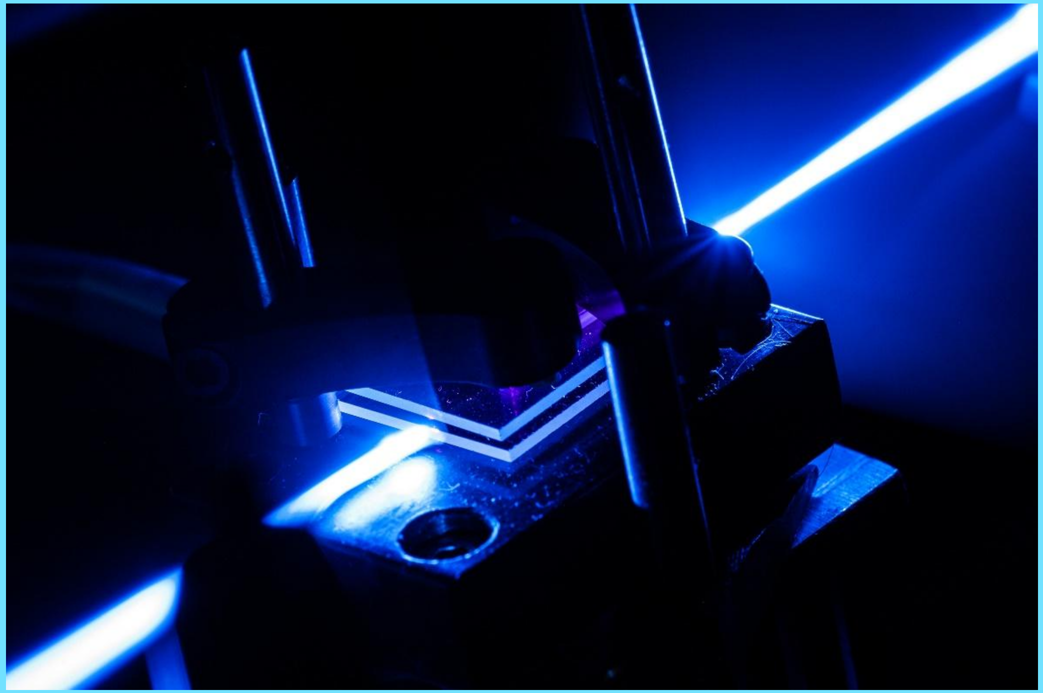
3. Control of the electronic and nuclear spin of Nitrogen Vacancy centers in diamond

Entangled photons



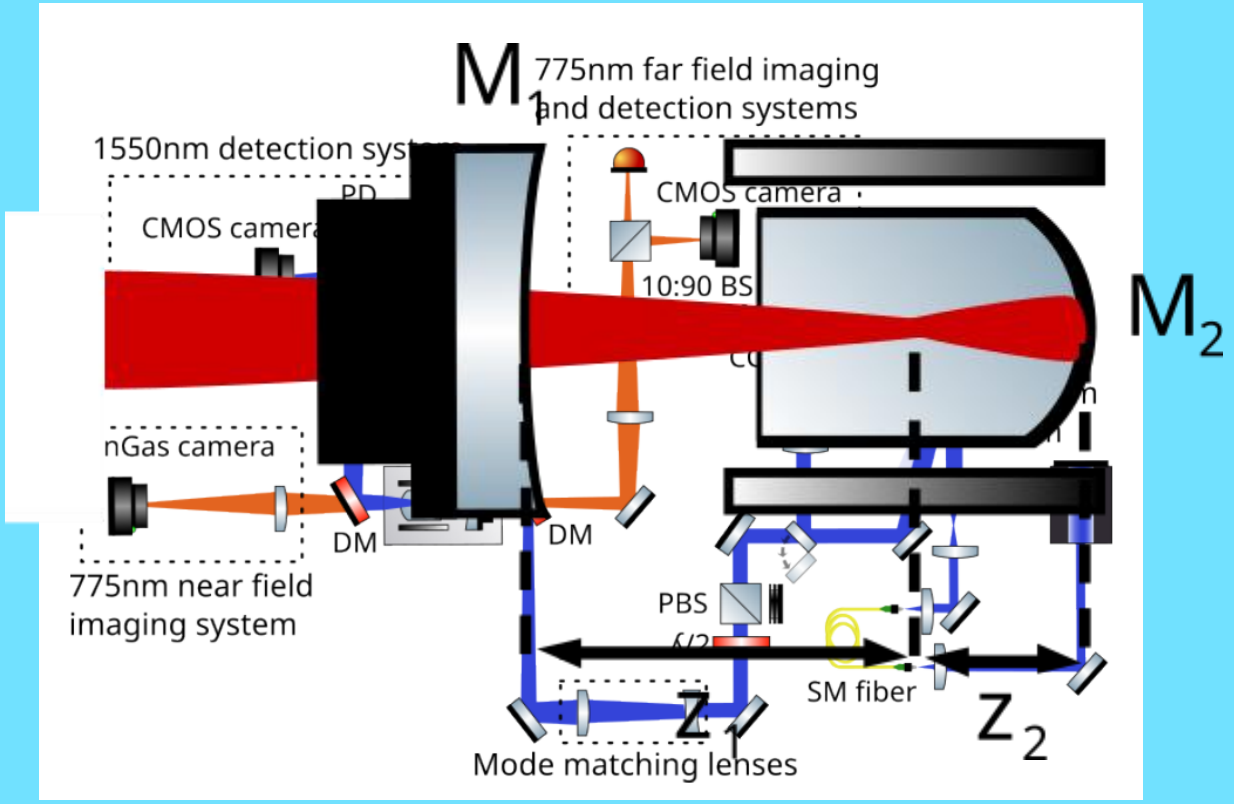
Entangled photons at QNanoLab: Quantum communications and sensing

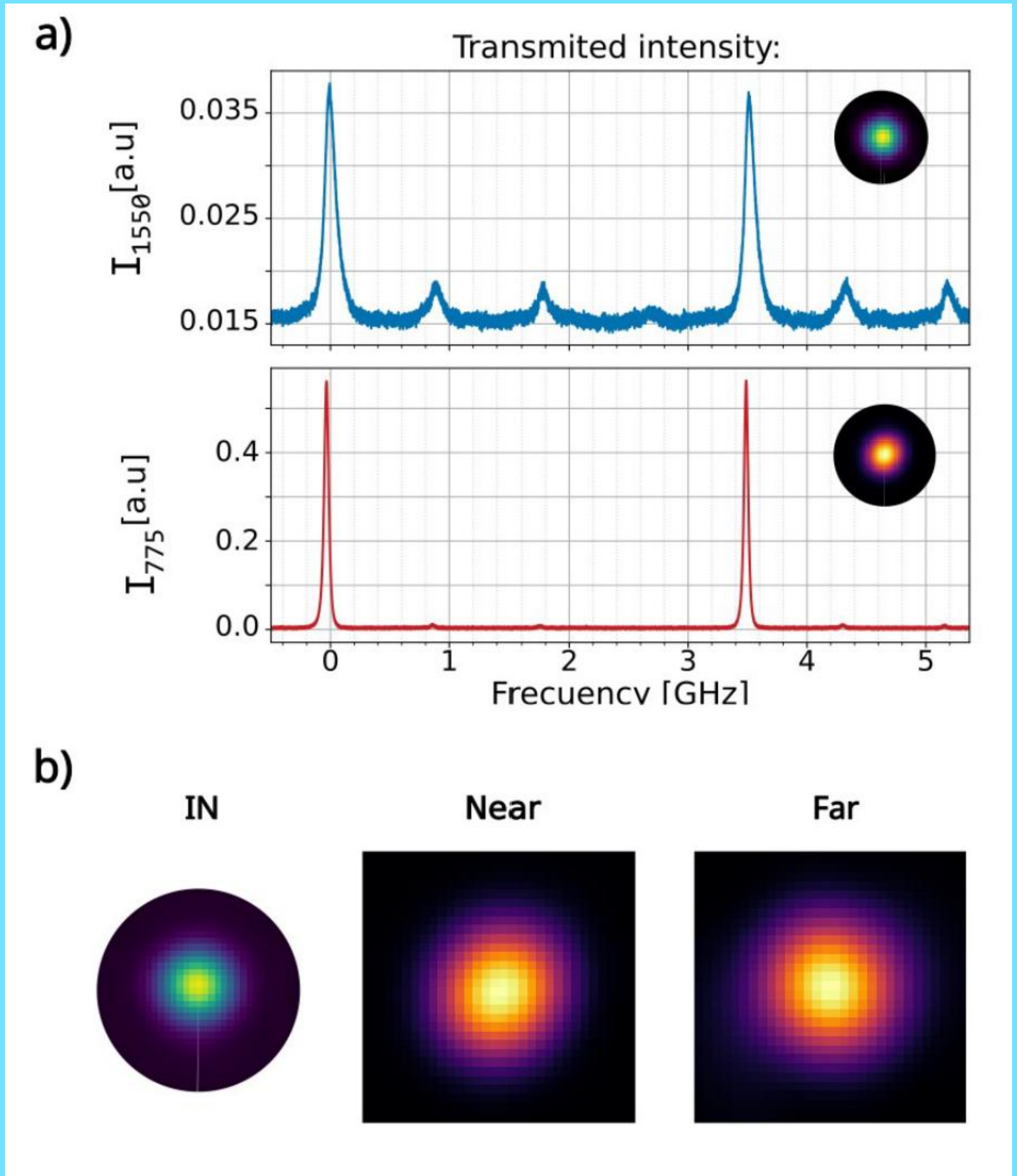




Entangled photons

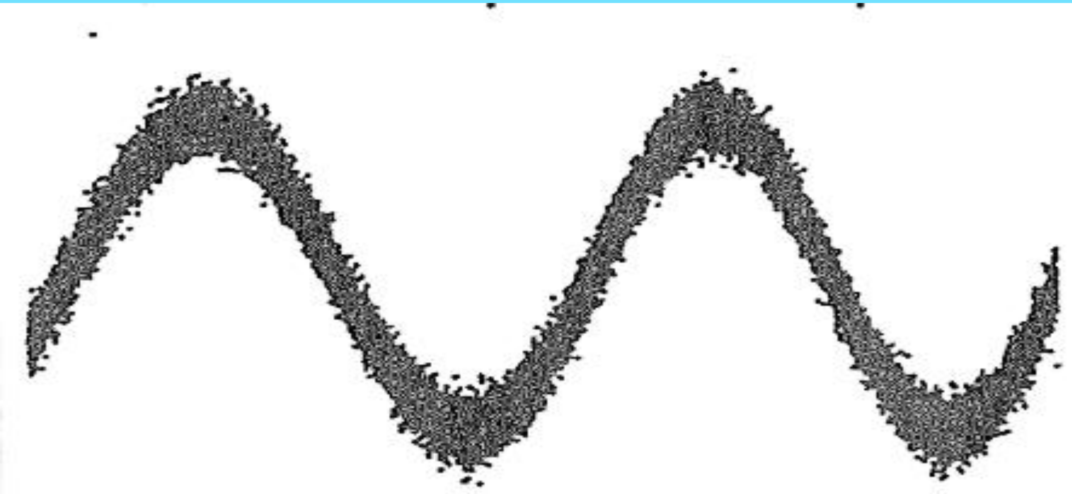
Quantum squeezing



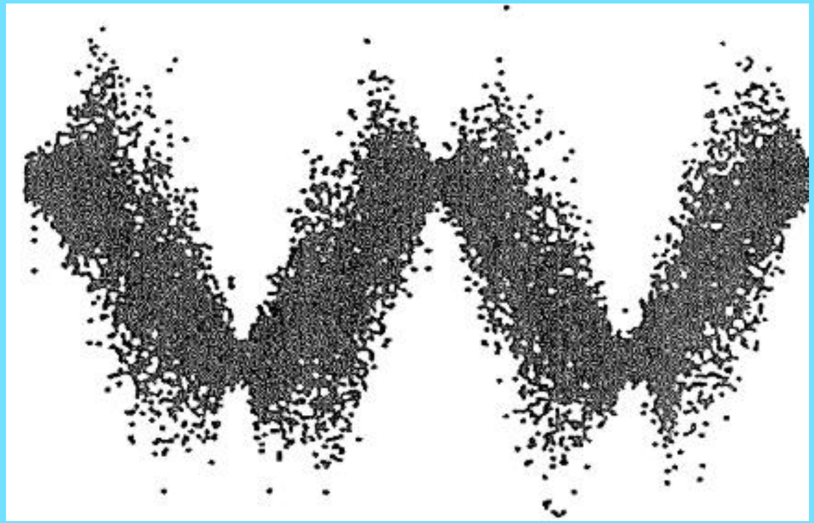


Shot noise limits some measurements

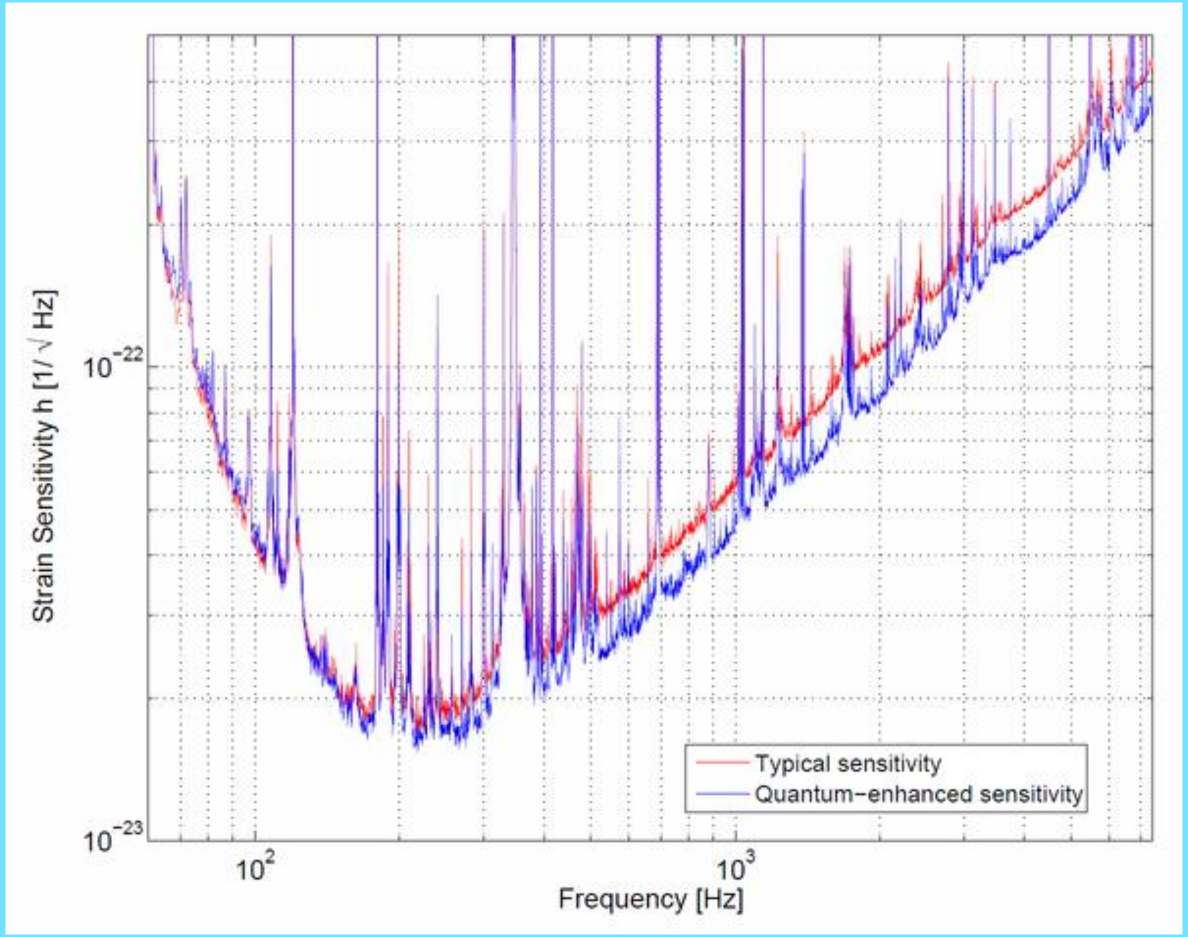
- In very sensitive applications the shot noise of the light that it is used for measuring is the main source of noise

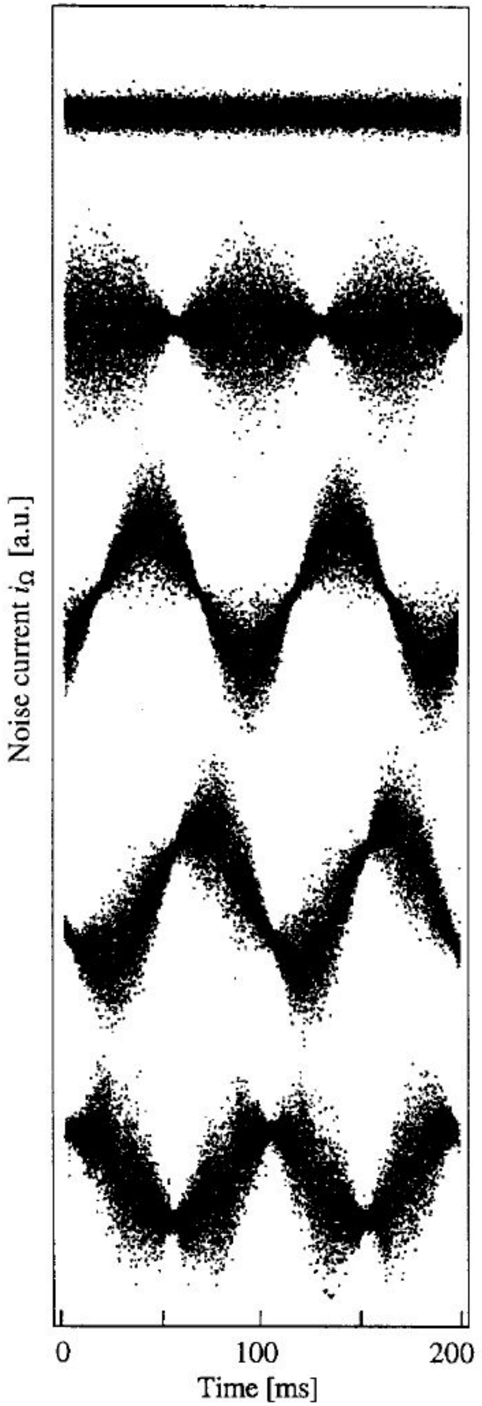


Quantum squeezing provides a (partial) solution



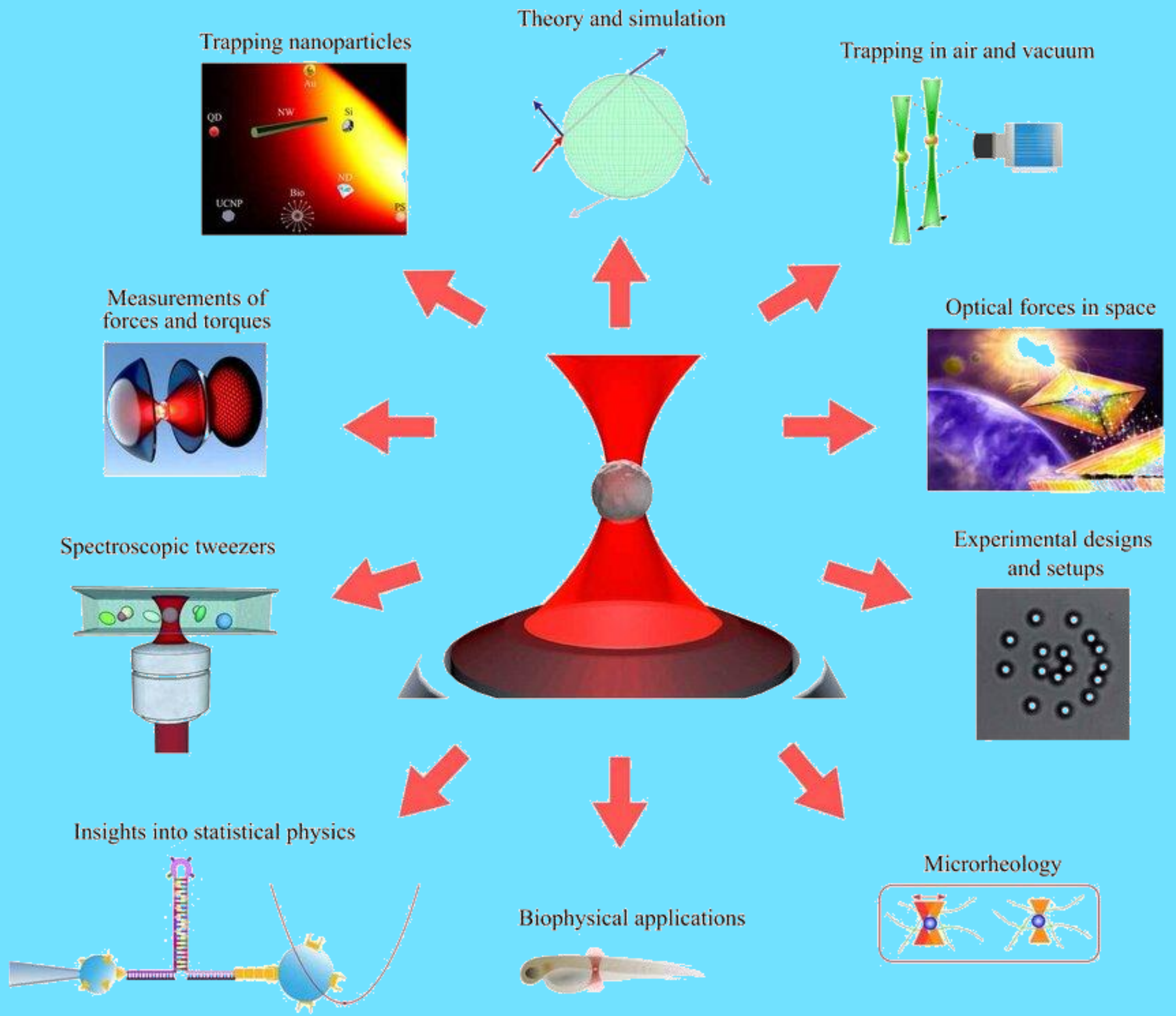
Quantum squeezing is already helping to detect gravitational waves

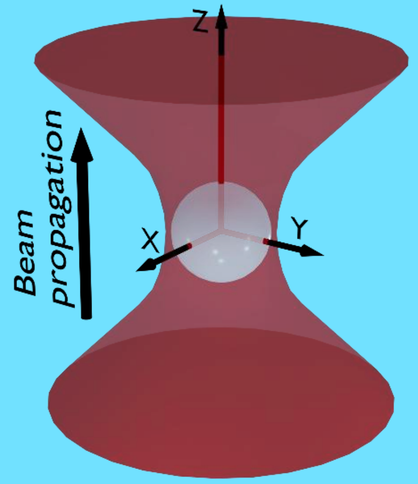


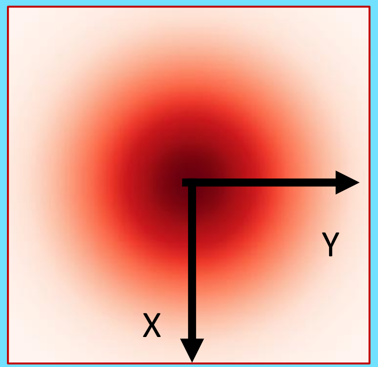


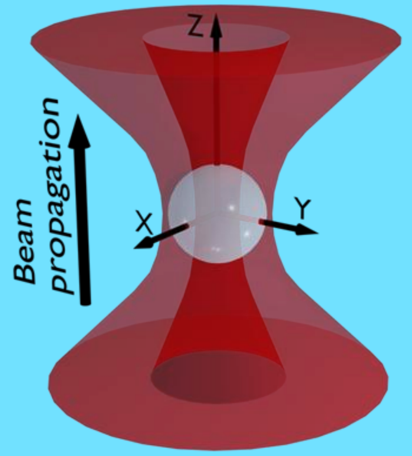
Optical levitation

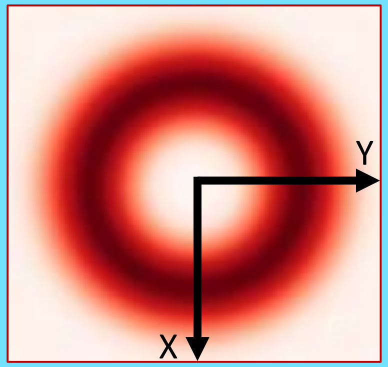
You can trap and manipulate particles with **optical forces**



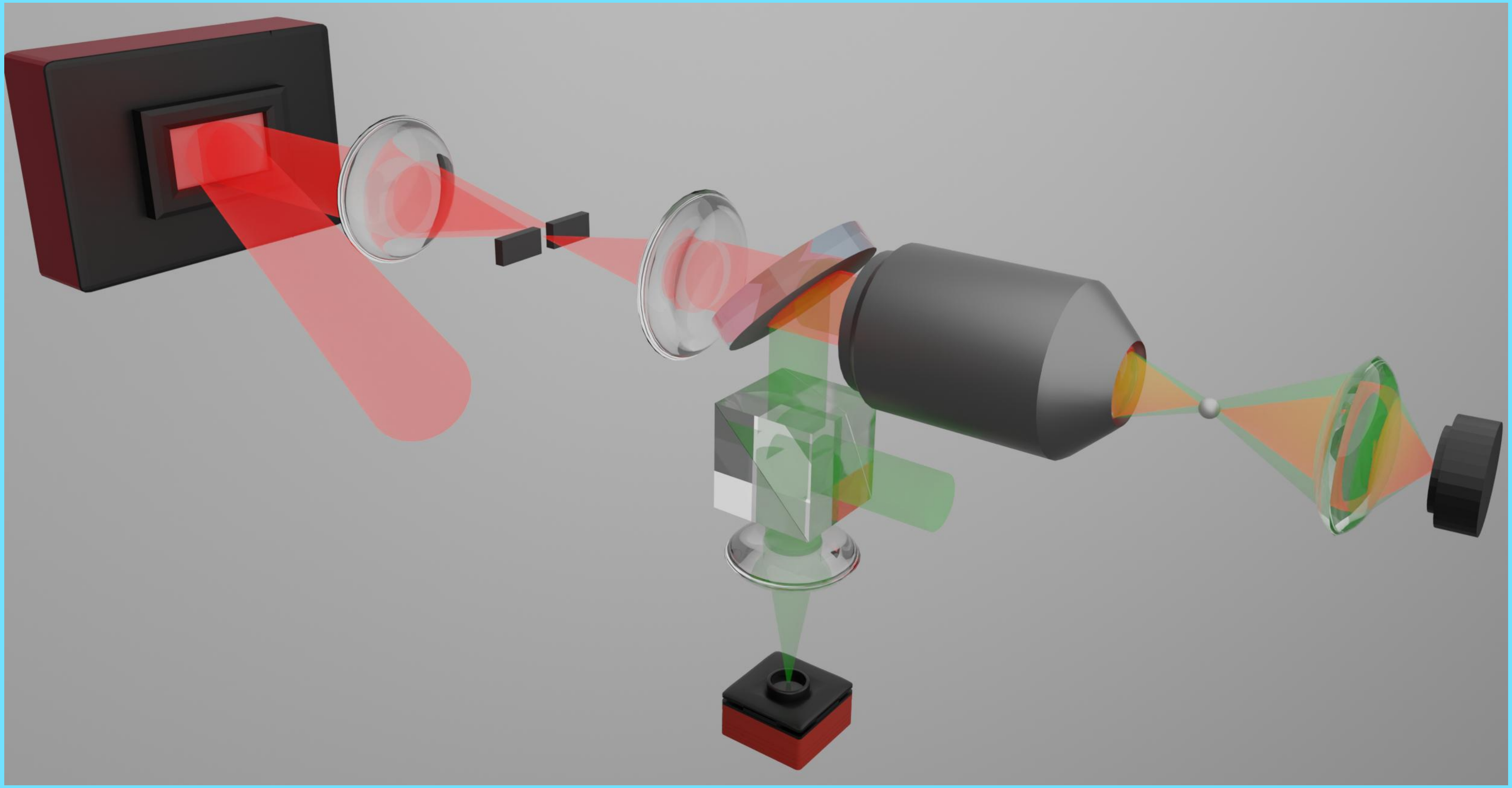

Z
Beam propagation
X
Y

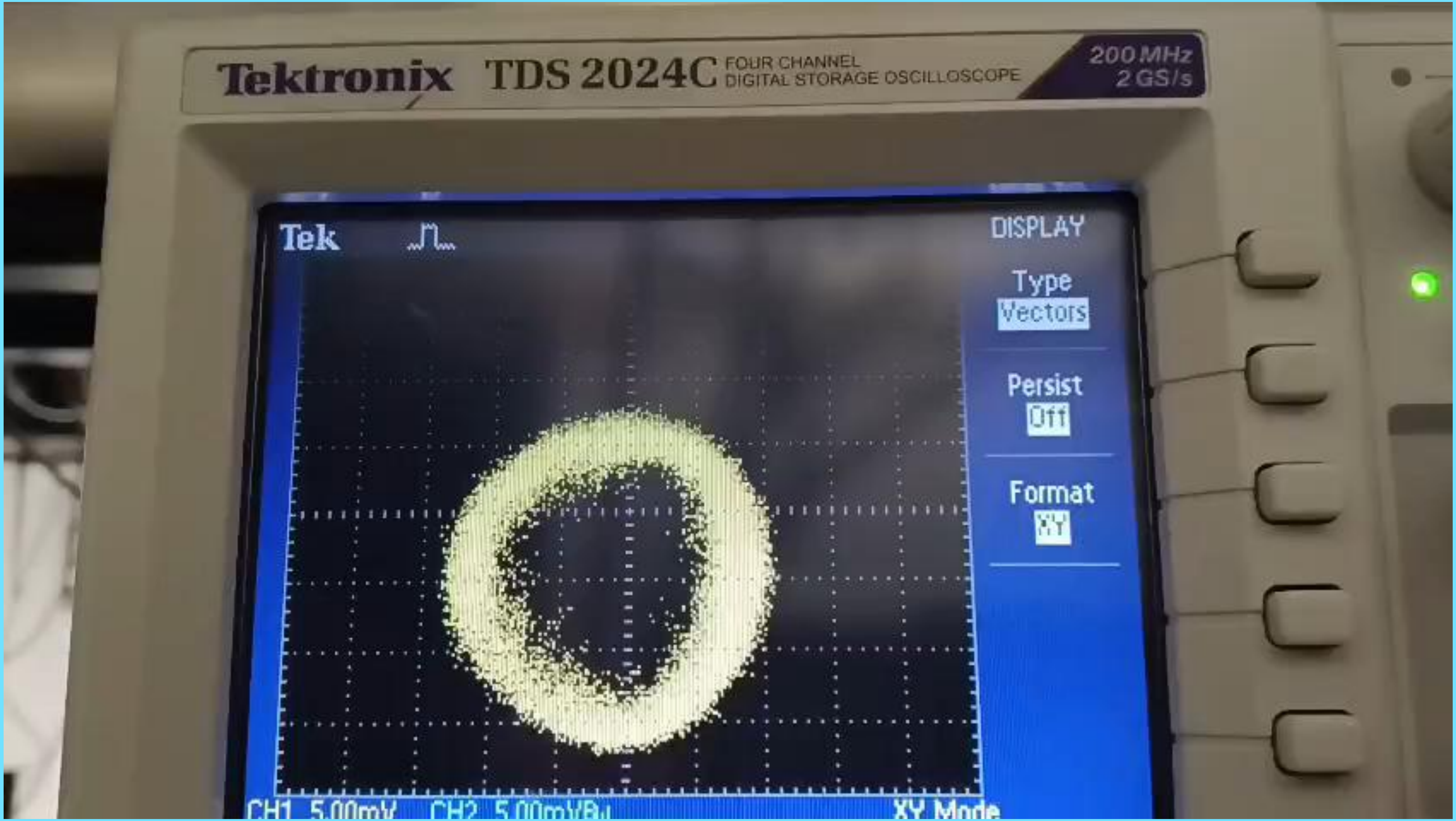

Y
X

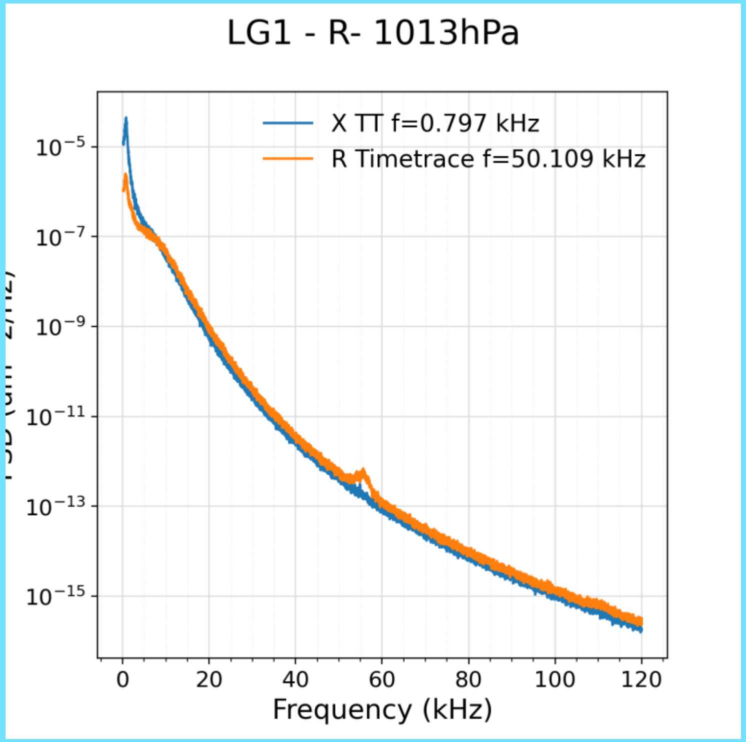

Z
Beam propagation
X
Y

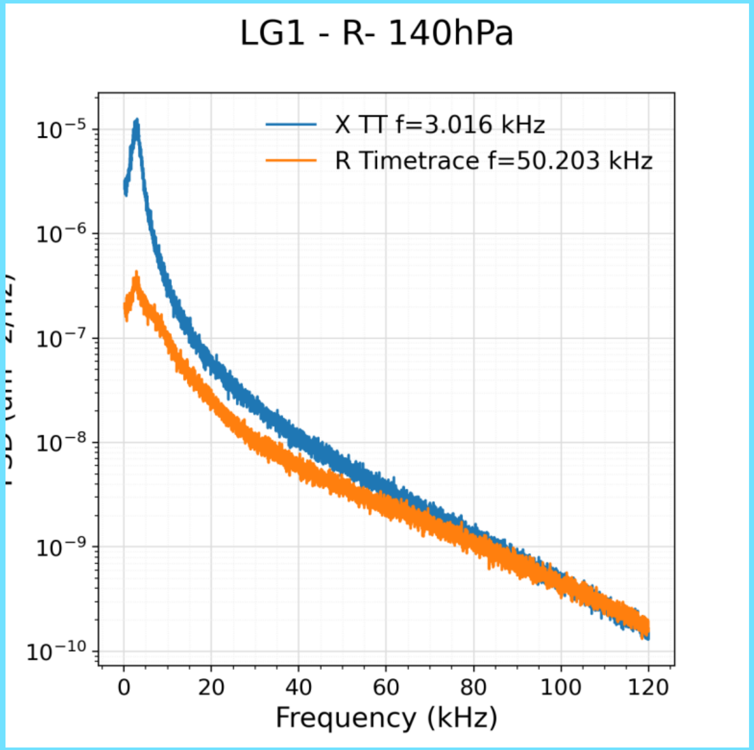

Y
X

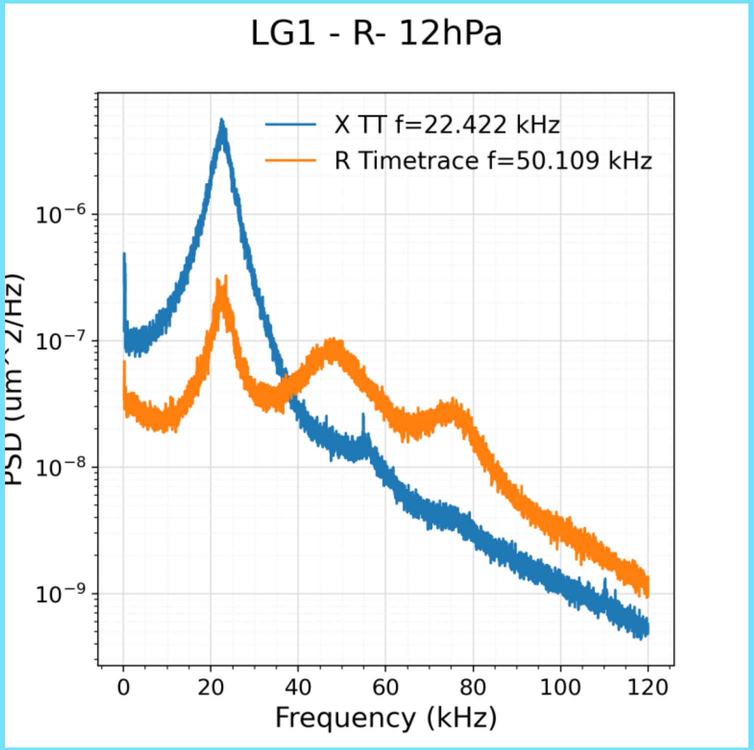
Levitation Experiments




Tektronix TDS 2024C FOUR CHANNEL DIGITAL STORAGE OSCILLOSCOPE
200 MHz 2 GS/s
Tek
DISPLAY
Type
Vectors
Persist
Off
Format
XY
XY Mode


LG1 - R- 1013hPa
X TT f=0.797 kHz
R Timetrace f=50.109 kHz
Frequency (kHz)


LG1 - R- 140hPa
X TT f=3.016 kHz
R Timetrace f=50.203 kHz
Frequency (kHz)


LG1 - R- 12hPa
X TT f=22.422 kHz
R Timetrace f=50.109 kHz
PSD (um^2/Hz)
Frequency (kHz)

Moore and Garasci

arxiv.org/pdf/2008.13197

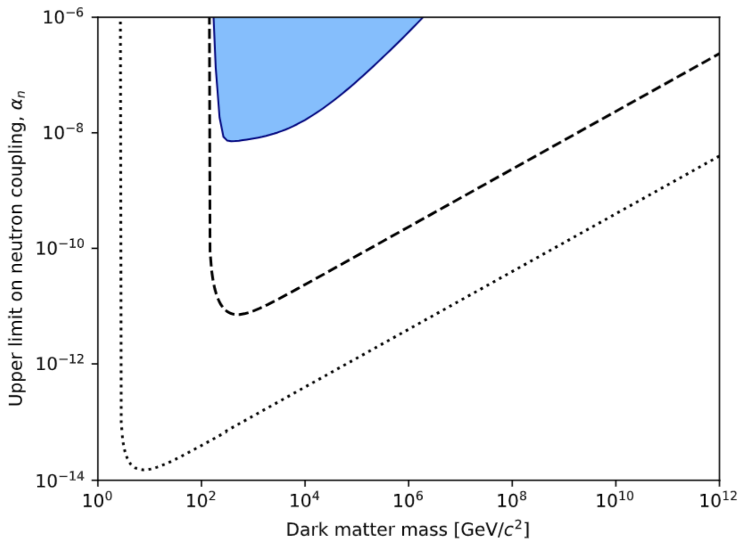


Figure 8. Background free sensitivity projections to a dark matter candidate interacting with neutrons through a long-range force, assuming a massless mediator. Existing constraints from an initial demonstration of such a search (with a few ng-days exposure) are shown by the blue filled region [82]. Substantial improvement over the initial search is possible with longer exposures and larger arrays of spheres. Projections for the sensitivity of a 100 element array of spheres with 1 yr exposure at the current sensitivity (dashed) and at the SQL (dotted) are also shown.

Moore and Garasci

arxiv.org/pdf/2008.13197

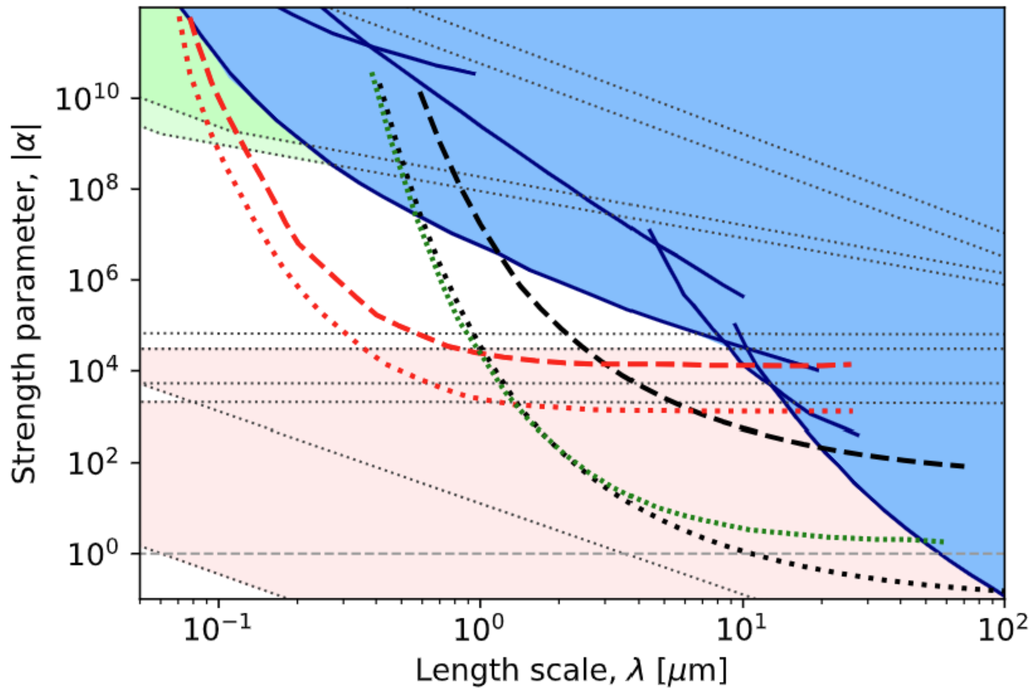


Figure 4. Background free sensitivity projections to deviations from Newton's law for example optically levitated masses. Existing limits are denoted by the blue region [10, 49, 86], with examples of specific theoretical predictions for such deviations

Eur. Phys. J. C (2024) 84:596
https://doi.org/10.1140/epjc/s10052-024-12943-y

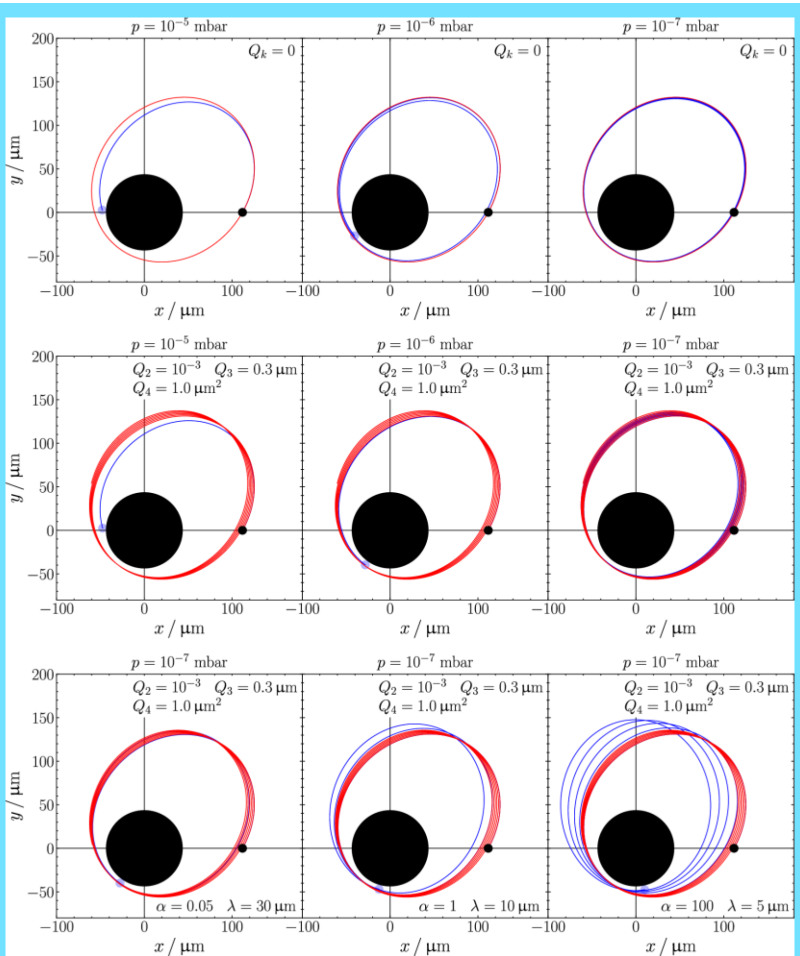
THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Theoretical Physics

Towards a realistic setup for a dynamical measurement of deviations from Newton's $1/r^2$ law: the impact of air viscosity

J. Baeza-Ballesteros[1,2,a], A. Donini[1,2], G. Molina-Terriza[3,4,5], F. Monrabal[3,4], A. Simón[3,6]



Moore and Garasci

arxiv.org/pdf/2008.13197

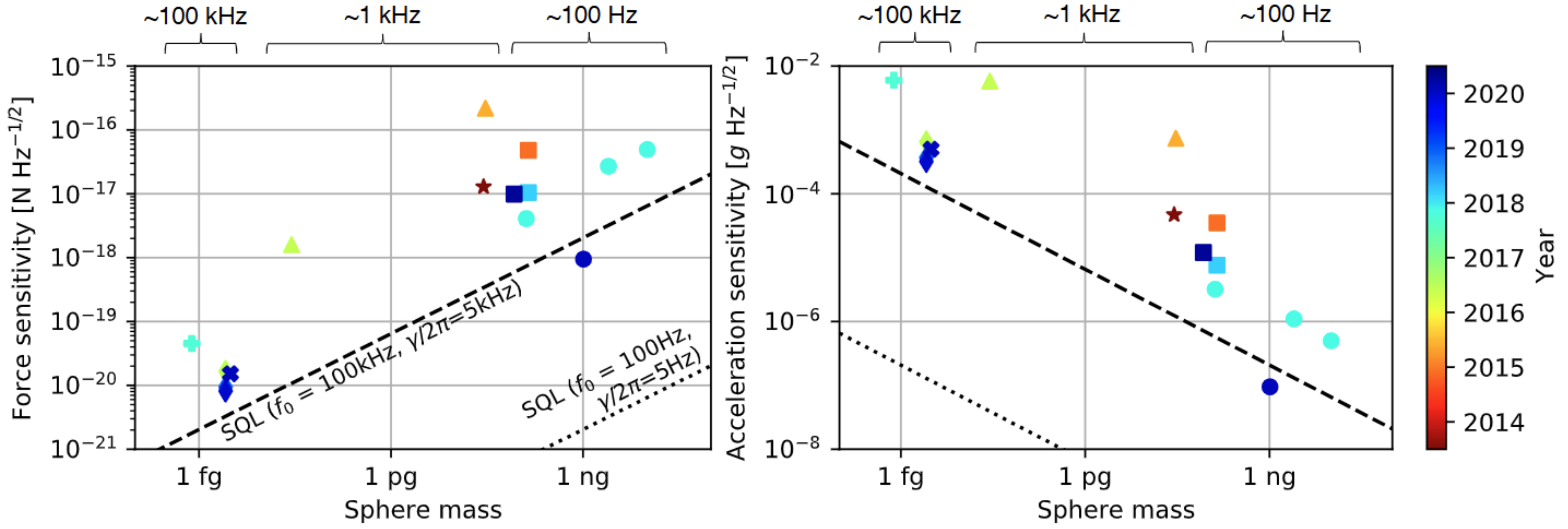
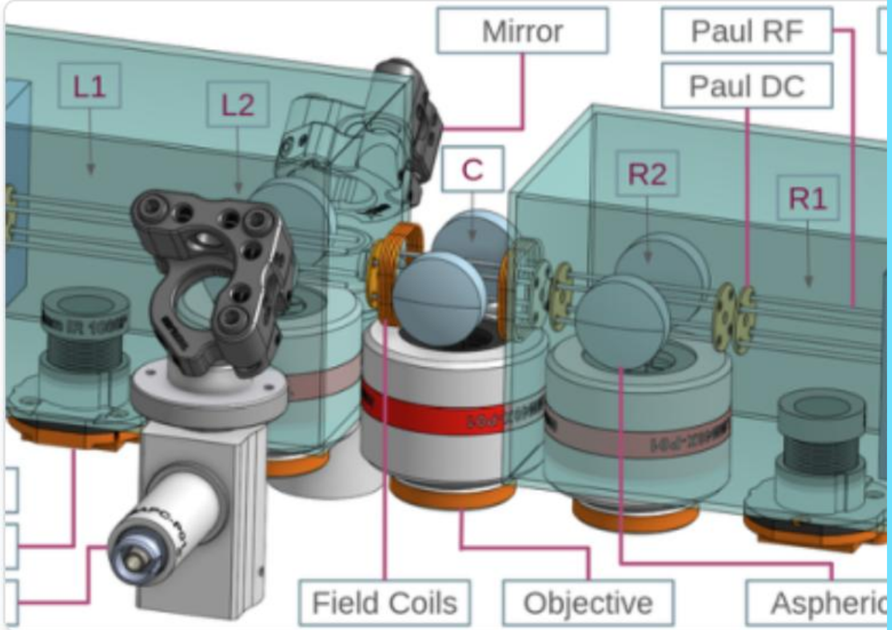


Figure 2. Compilation of measured force and acceleration sensitivities for optically levitated masses range between ∼ 1 fg to ∼10 ng from a variety of groups: ETH Zurich

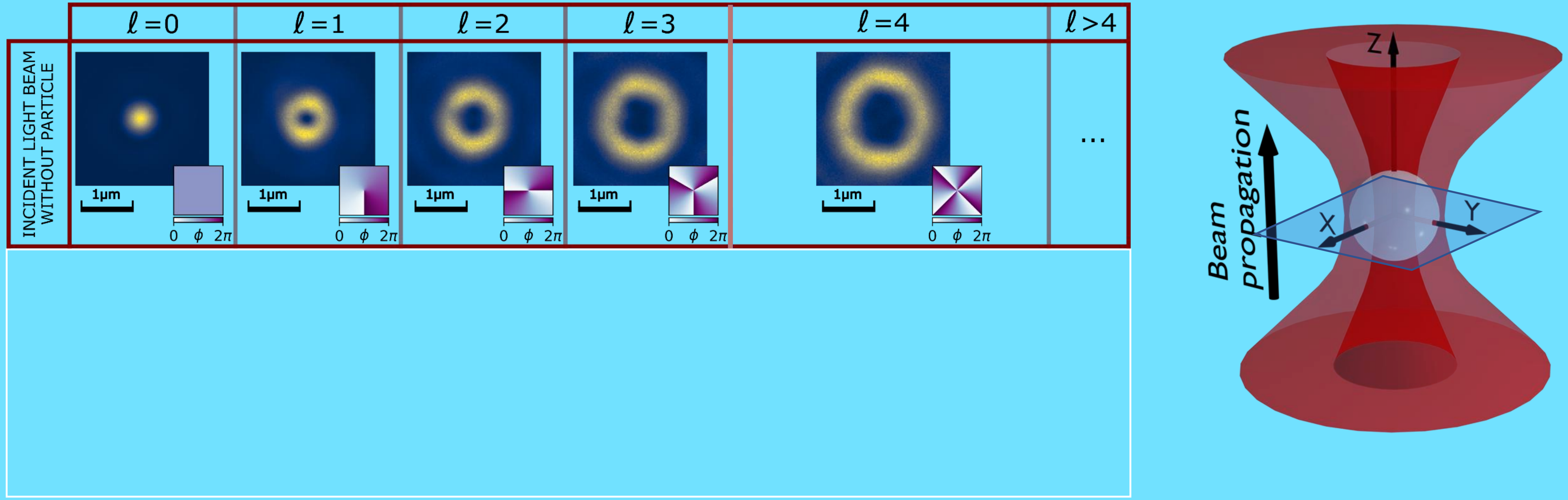
LEVITAS - Levitodynamics Experiments in Vacuum Interaction and Thermal Atmospheric Sensing



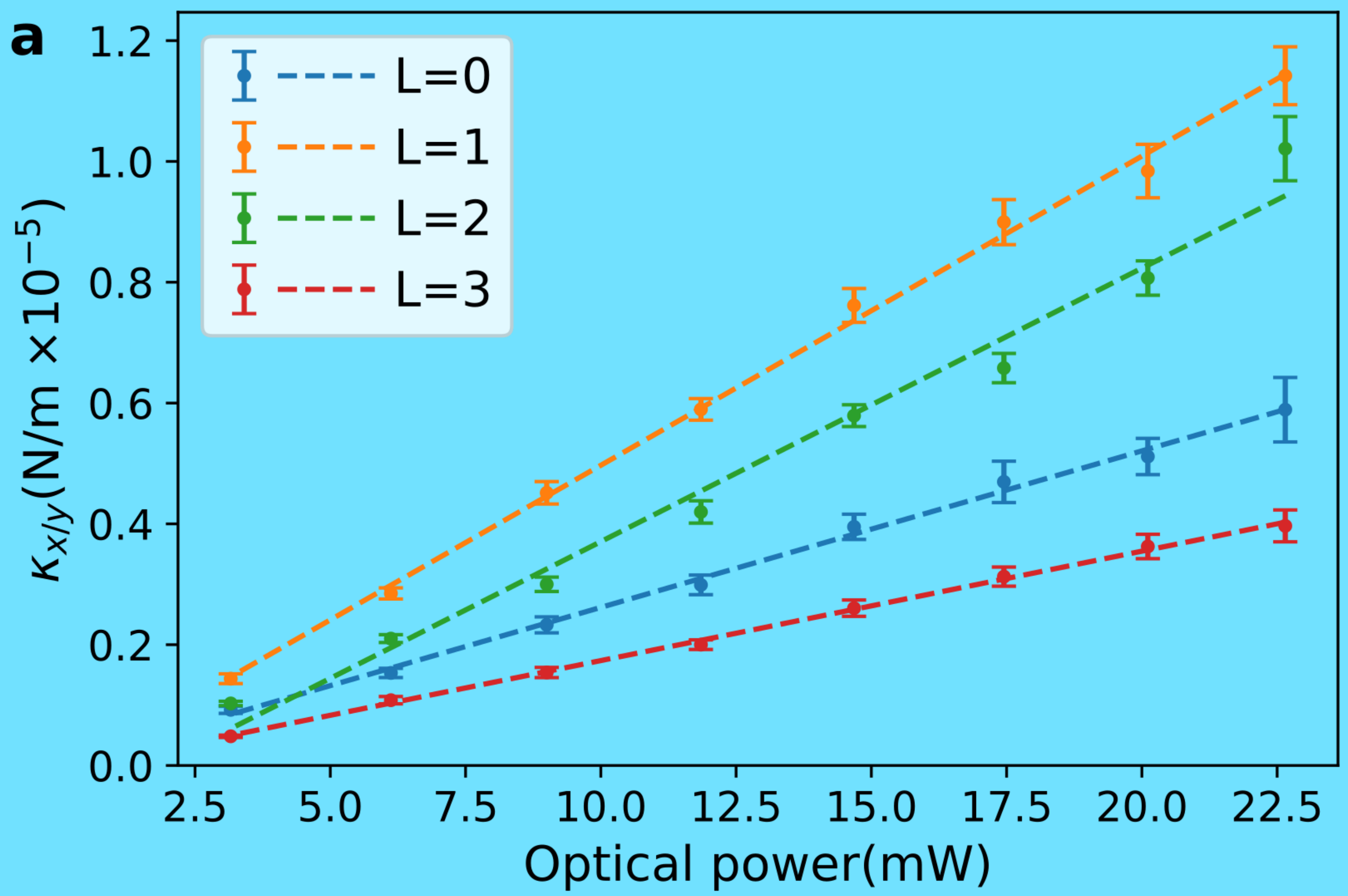
Programme Reference	Status	Country	Start Date	End Date
IPD-0545	Closed	United Kingdom	2024	2025

Related Content

Programme: FutureEO **Prime Contractor:** UNIV WARWICK

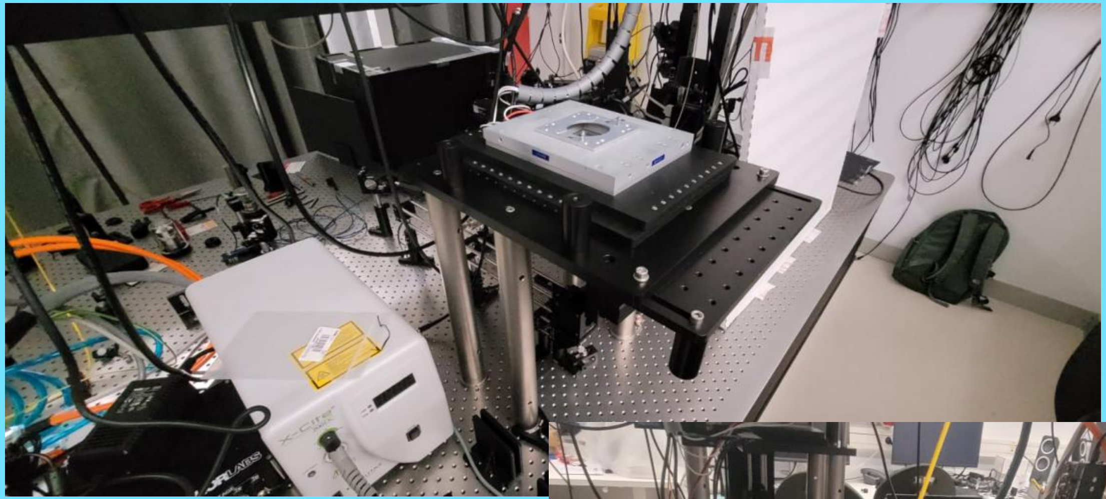


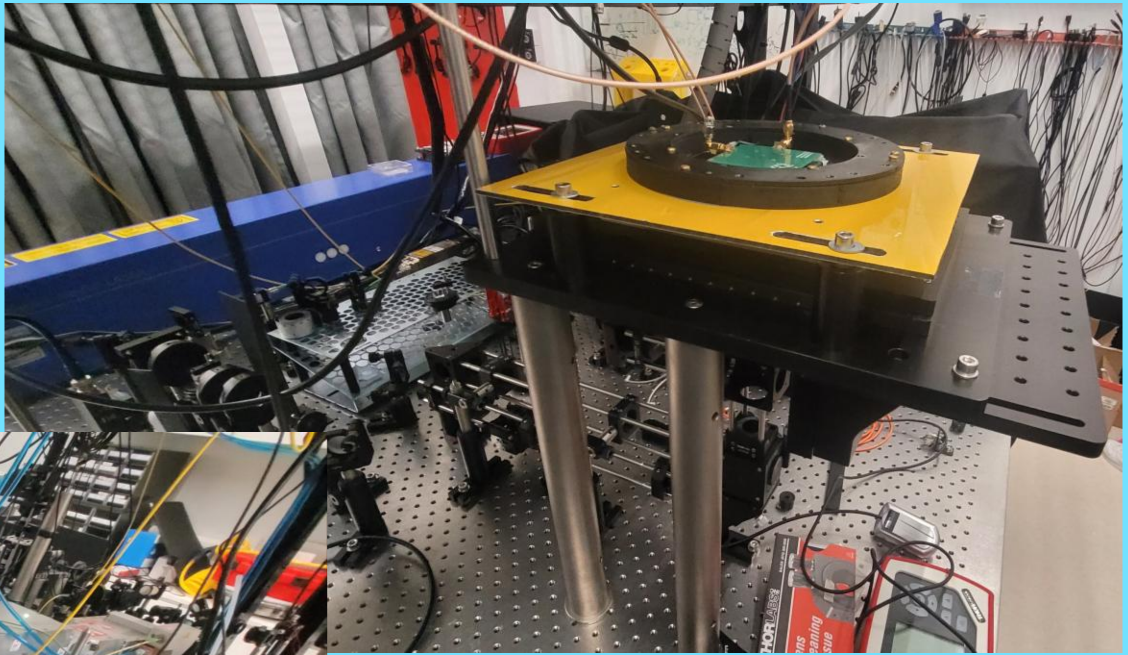
ℓ=0
ℓ=1
ℓ=2
ℓ=3
ℓ=4
ℓ>4
INCIDENT LIGHT BEAM WITHOUT PARTICLE
1μm
0 ϕ 2π
...
Z
X
Y
Beam propagation

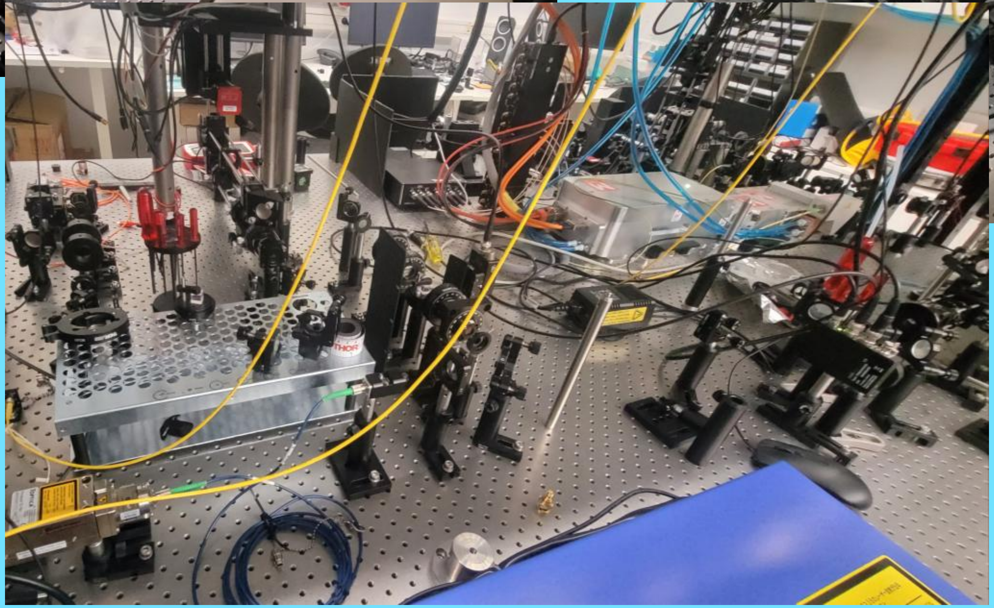


a
L=0
L=1
L=2
L=3
$\kappa_{x/y}$(N/m ×10^{-5})
0.0
0.2
0.4
0.6
0.8
1.0
1.2
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
Optical power(mW)

Quantum magnetic sensing with diamond





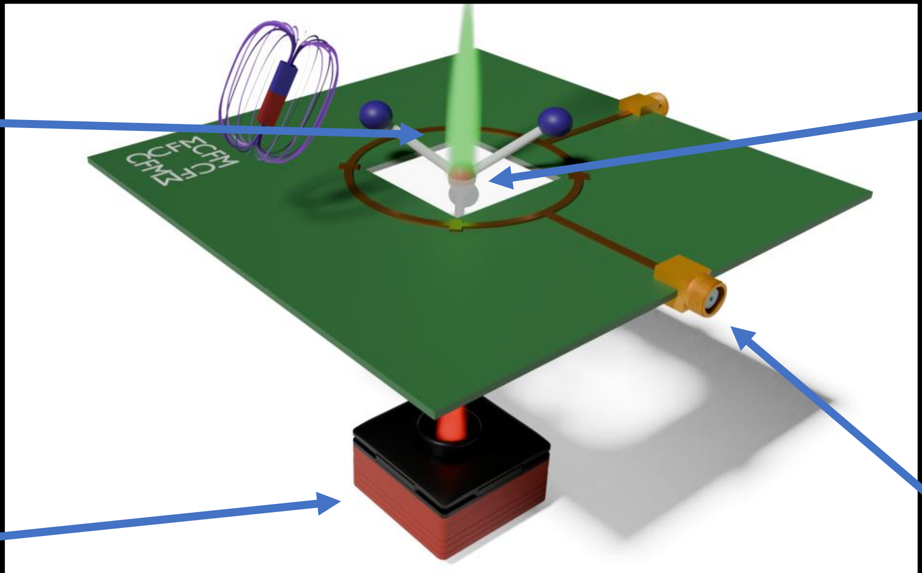


NV-Center Working Principles

QUANTUM SENSOR RECIPE

LASER

Diamond

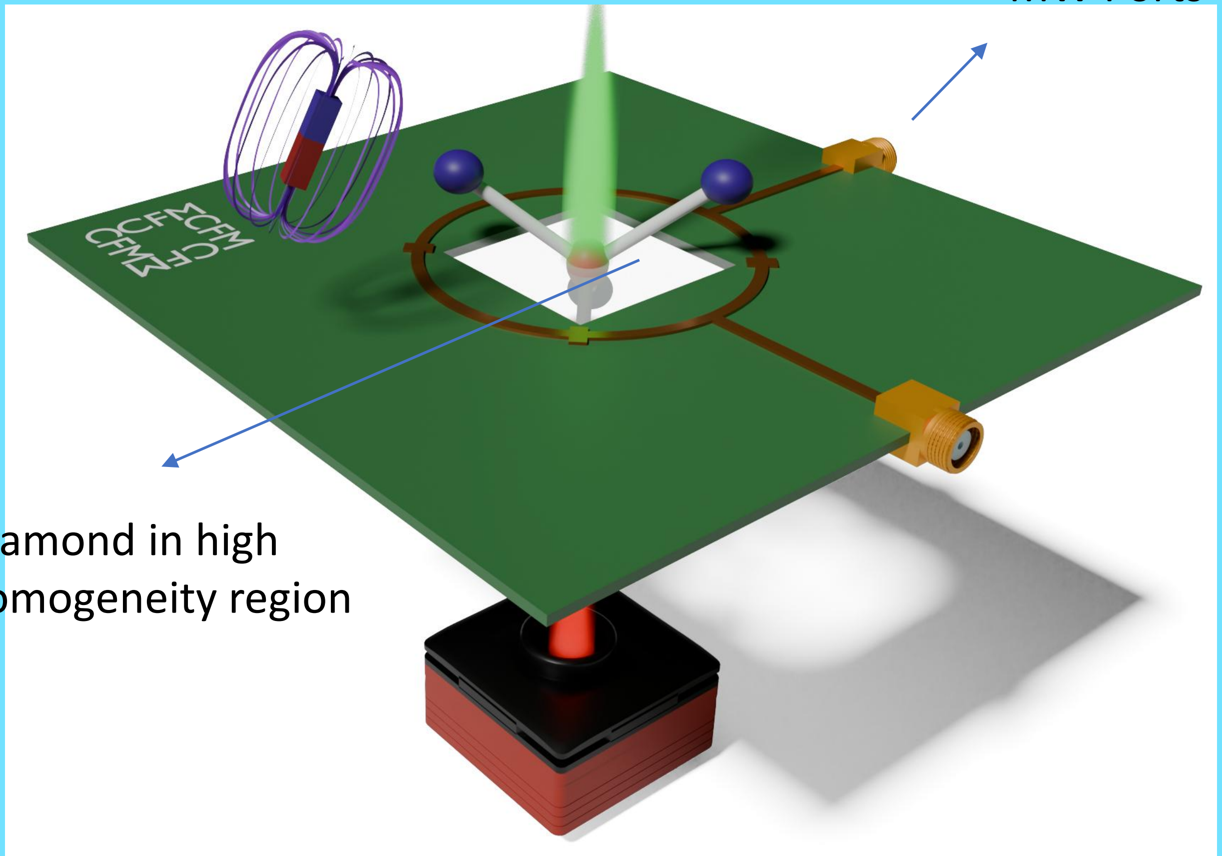


Collection system

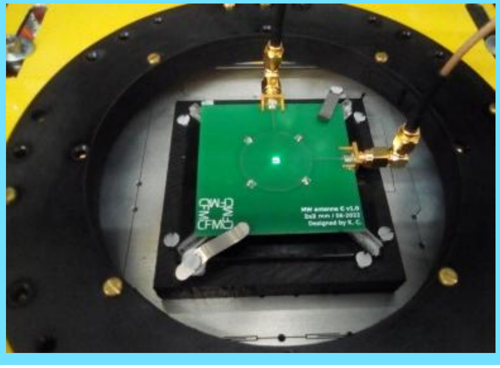
Microwave delivery

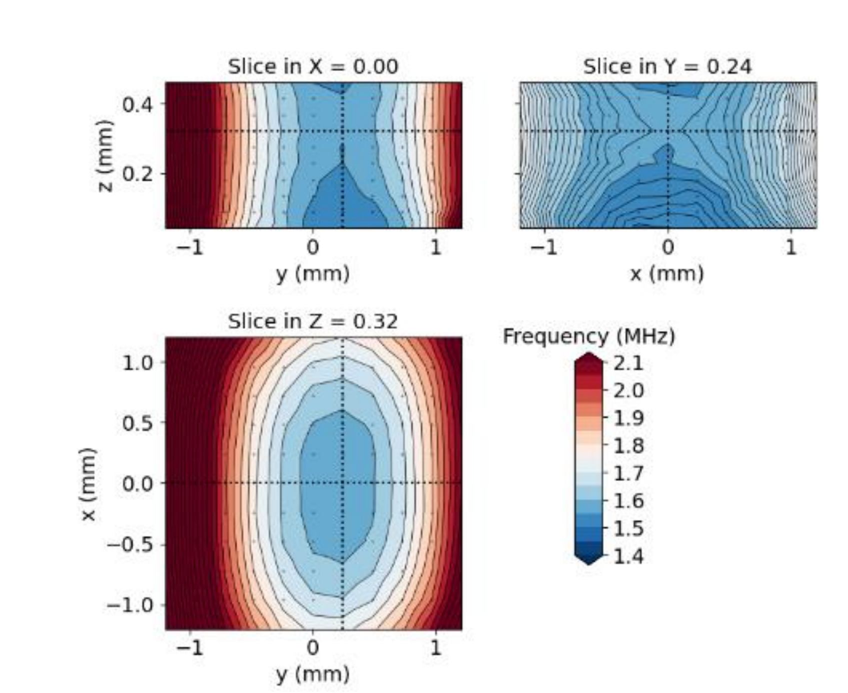
Antenna for Bias Free Magnetometry

MW Ports



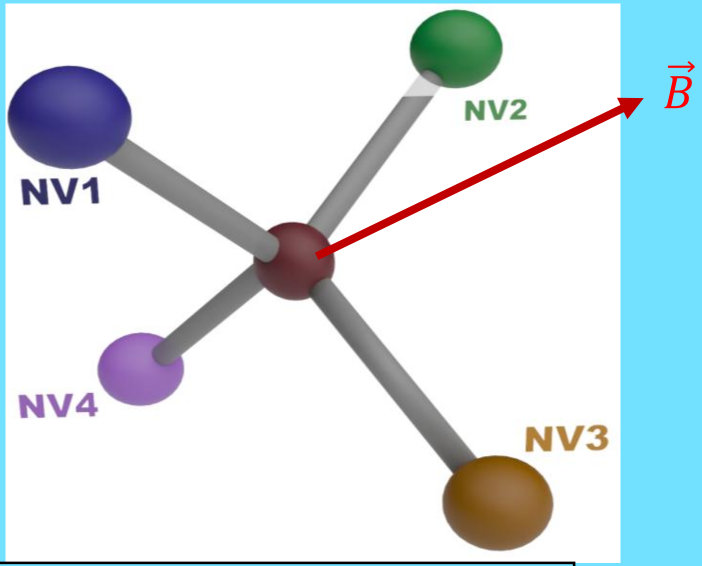
Diamond in high homogeneity region





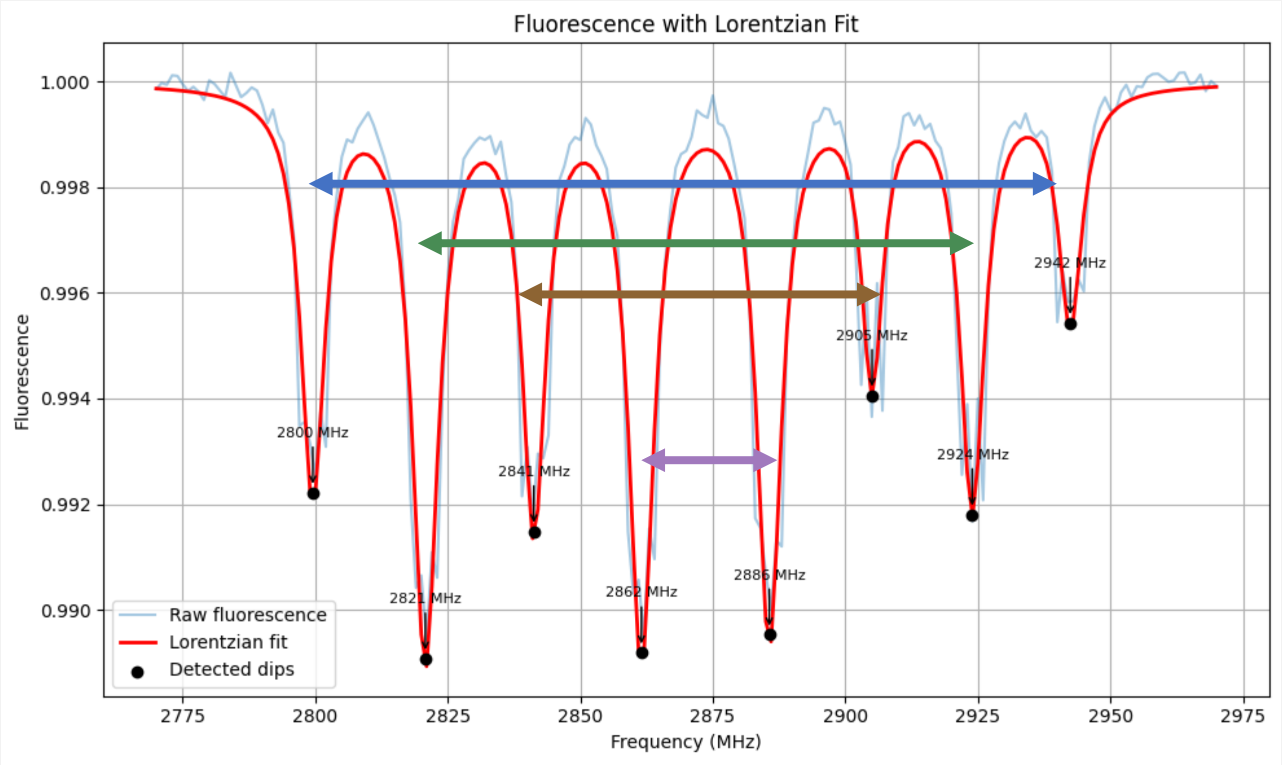
Pellicer-Guridi et. al. Versatile quadrature antenna for precise control of large electron spin ensembles in diamond. *Advanced Quantum Technologies*, *8*(3)

Common Magnetometry Limitations



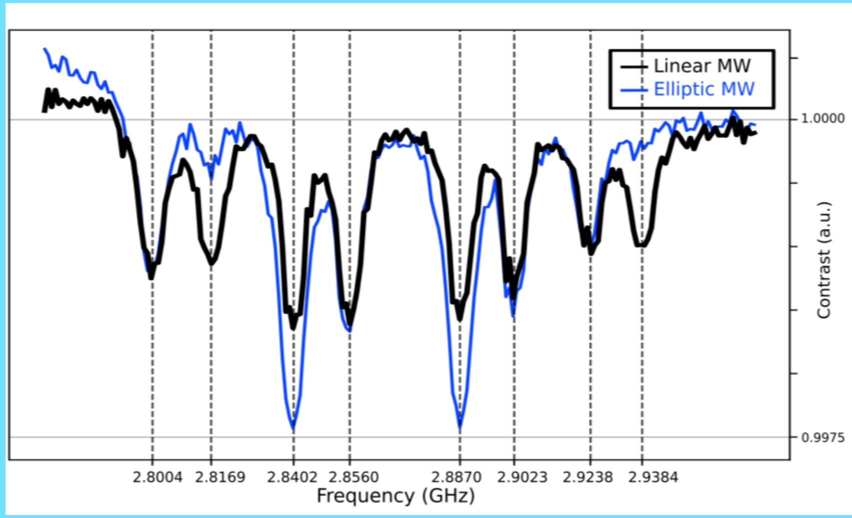
$$\begin{pmatrix} B_z^1 \\ B_z^2 \\ B_z^3 \\ B_z^4 \end{pmatrix} = \begin{pmatrix} -\frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ \frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ 0 & \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} \\ 0 & -\frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} B_x \\ B_y \\ B_z \end{pmatrix}$$

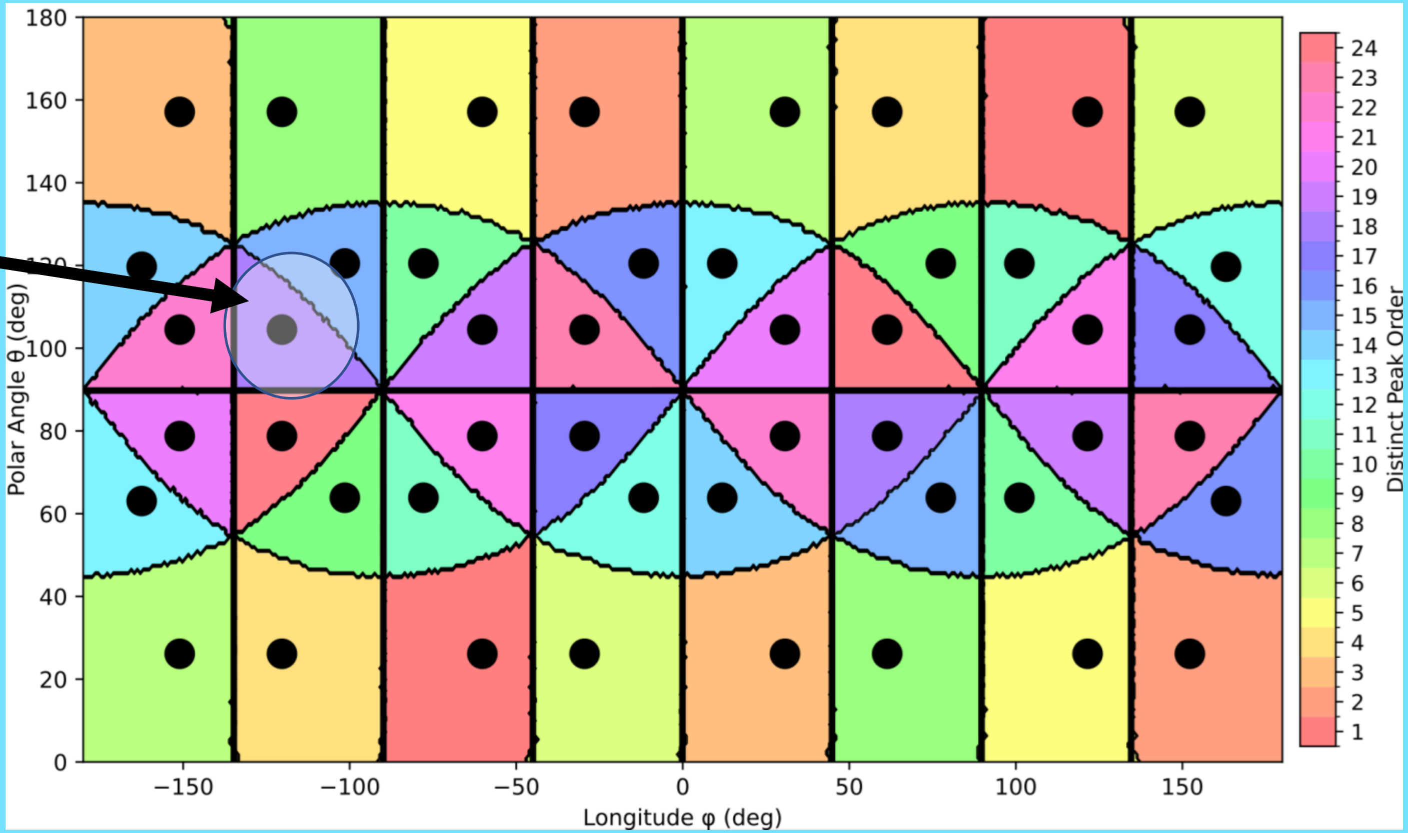
Linearly polarized MW



Limitations

- **Single ESR:**
  - No information on axis producing peaks.
  - 48 posible solutions.
  - Typical magnetometry is limited to a single coloured area.





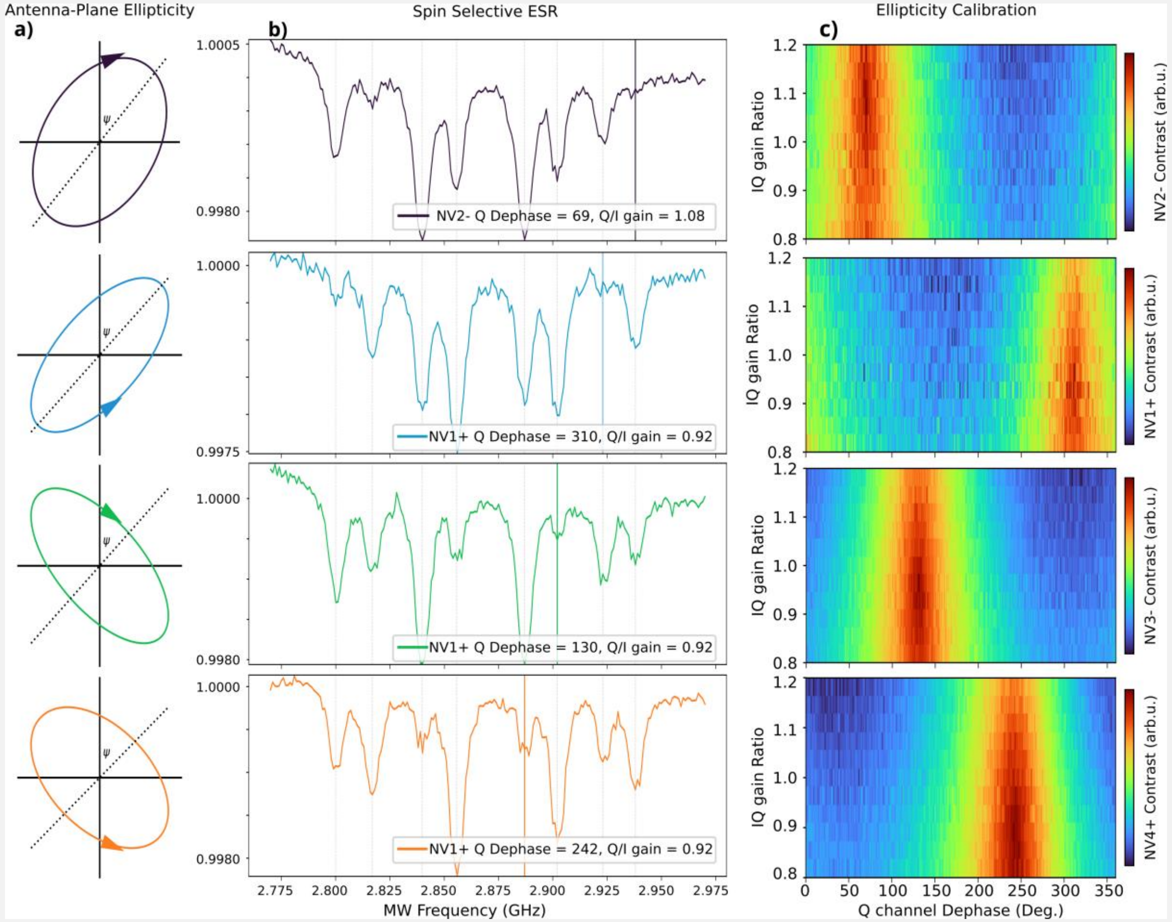
Solution: Elliptically polarized MW

Proof of concept for vector magnetometry protocol

- Individual MW configurations optimal for each cristal axis found in agreement with theoretical predictions.

- The spectrum response to each polarized microwave pulse reveals the axis orientation of each peak.

- Independent of **B.**



Mongelos-Martinez, A., Francis, J. T., Bertero-DiTella, J., Giedke, G., Molina-Terriza, G., & Pellicer-Guridi, R. (2026). Unconditional full vector magnetometry using spin selectivity in Nitrogen Vacancy centers in diamond. *arXiv preprint arXiv:2602.12090*.

With our protocol you can measure:

1. The full vector magnetic field with a bulk diamond sample
2. The orientation of a single NV center with respect to a given external magnetic field