Action D.5.5

Single-photon production and manipulation at telecom wavelengths

Progetto di Eccellenza DFA

Frontiere Quantistiche

TIZIANA CESCA

Department of Physics and Astronomy

NanoStructures Group (NSG)

Quantum Frontiers

Action D.5.5: LaTeQ Lab infrastructures (Budget: 200 k€)

OR2: New Materials and Models at the Quantum Frontier

Development of novel quantum materials and devices:

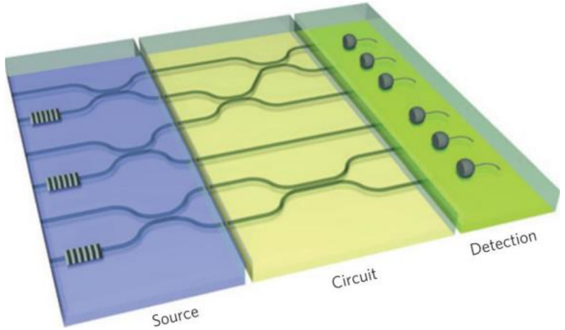
- Single-photon sources
- Novel qubits
- Metasurfaces and metalenses for entangled photons
- Quantum imaging

Applications:

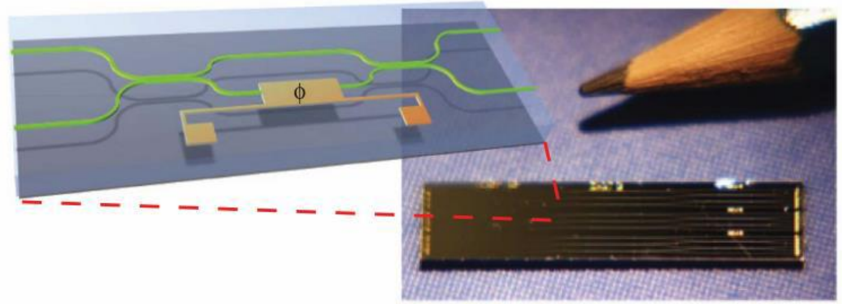
- Quantum Communication, Sensing, Computation

Single-photon sources for Quantum Technologies

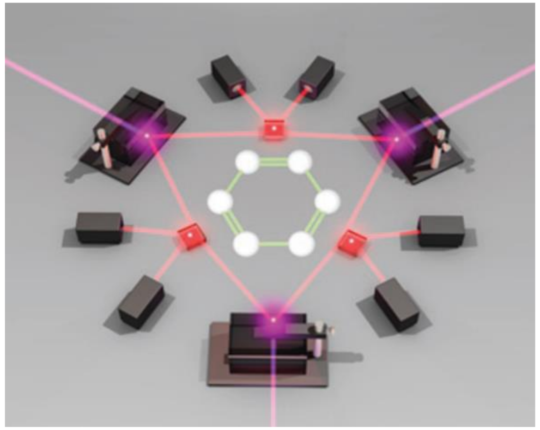
- Quantum cryptography
- Quantum simulation and computation



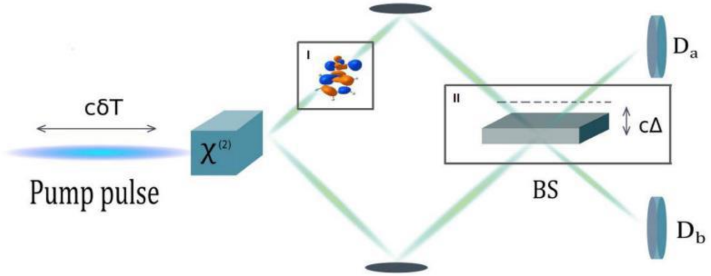
Aspuru Guzik, A. & Walther, P. Photonic quantum simulators. Nature Physics 8, 285 291 (2012)



Ladd, T. D. et al. Quantum computers. Nature 464, 45–53 (2010)



- Quantum Communication and Sensing



Dorfman, K. E., et al.
Hong Ou Mandel interferometry and spectroscopy using entangled photons.
Communications Physics 4, (2021).

Single Photon Counting Confocal Microscope

Time-resolved confocal microscope, equipped with:

- ps laser heads with different operation modes (pulsed, cw, burst) and wavelengths range from UV to IR
- possible coupling with the fs laser (previous PE)
- 3D nanopositioning for sample movement
- Detection subsystem with single photon sensitivity
- SPAD detectors in the NIR range (possible upgrade with a SPAD camera for quantum imaging)
- Time-Correlated Single Photon Counting (TCSPC) with Time-Tagged Time-Resolved mode (TTTR)
- Timing with picosecond resolution up to ms
- Closed-cycle He cryostat for sample cooling

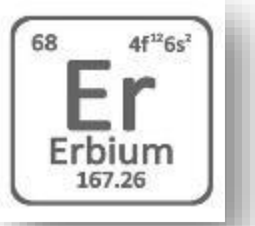
Single Photon Counting Confocal Microscope

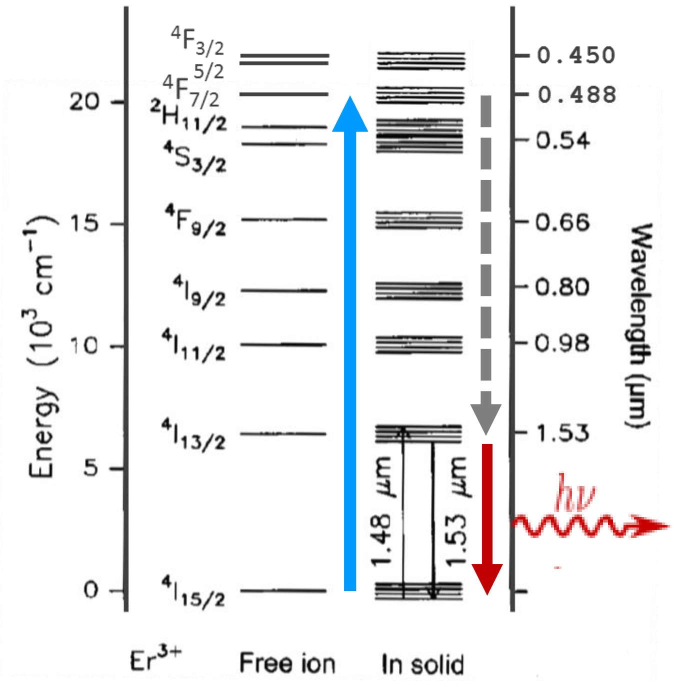
The microscope can be used for several applications, as:

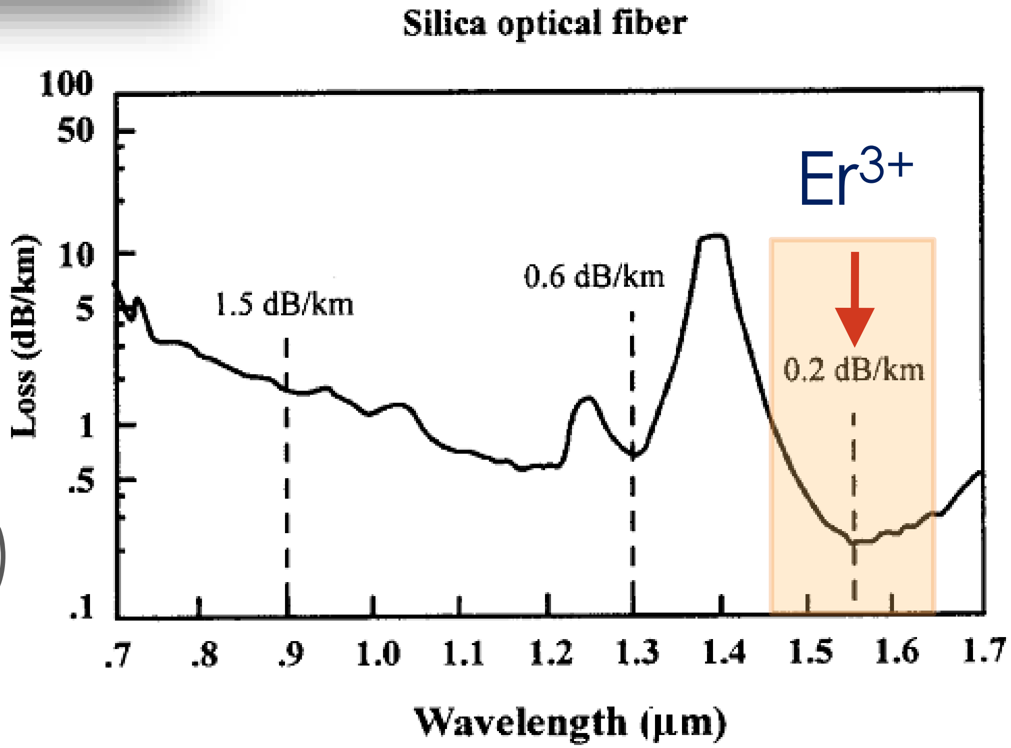
- Time-Resolved Photoluminescence (TRPL)
- Fluorescence Lifetime Imaging (FLIM)
- Phosphorescence Lifetime Imaging (PLIM)
- Photoluminescence Correlation Spectroscopy (FCS)
- Photoluminescence Lifetime Correlation Spectroscopy (FLCS)
- Single-molecule Detection (SMD)
- Coincidence correlation / Photon Antibunching (g(2)(t))
- Molecule Blinking
- Carrier Diffusion Measurements
- With upgrade: Quantum Imaging

Er:SiO_2 for telecom

T. Cesca,
B. Kalinic,
G. Mattei
(NSG)







- resonant excitation
- low excitation cross-section ($\sigma_{exc} \sim 10^{-21} \div 10^{-20}$ cm^2)
- long PL lifetime: $\tau_{em} \sim 14$ ms
- Mixed ED + MD (50:50)

LDOS Engineering

T. Cesca,
B. Kalinic,
G. Mattei
(NSG)

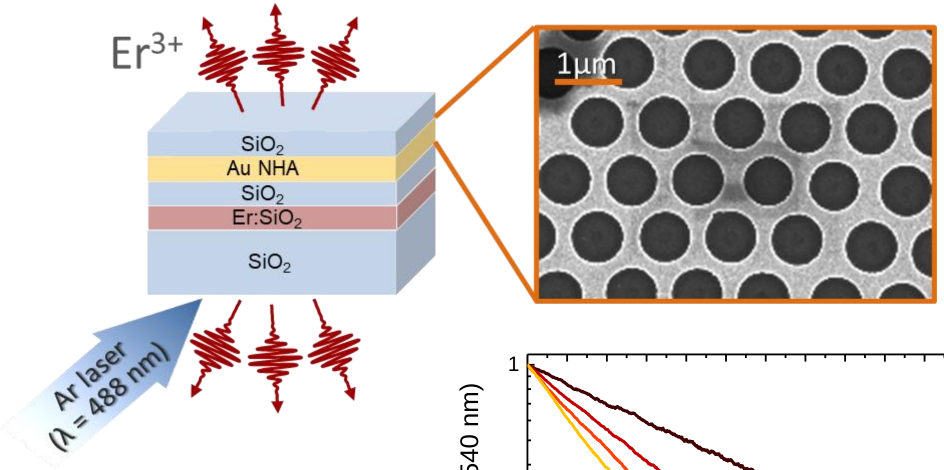
Er^{3+}@ telecom wavelengths (1.5 μm)

Fermi's golden rule

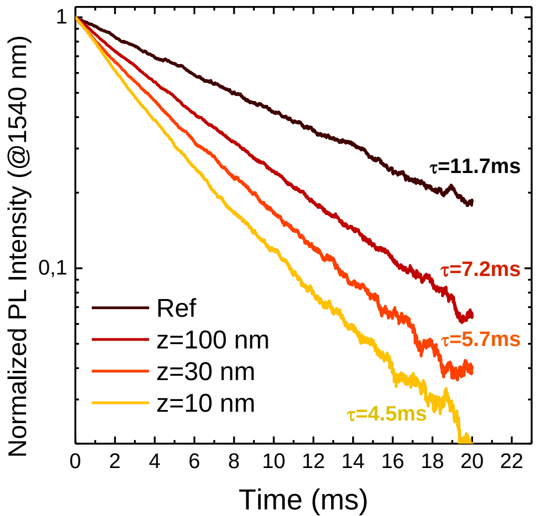
$$\Gamma_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f$$

Transition decay rate — Interaction matrix element — LDOS

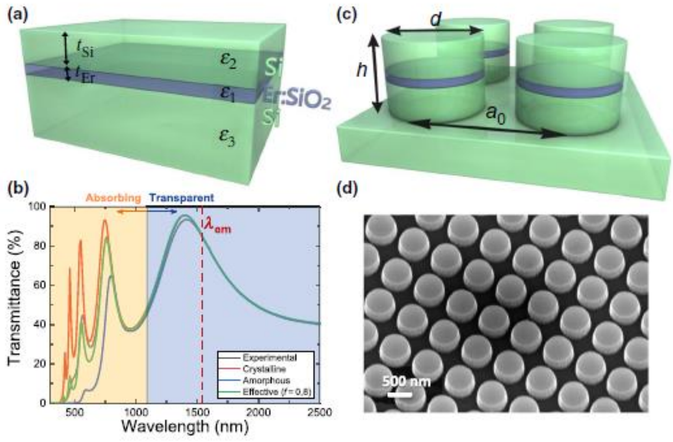
B. Kalinic, T. Cesca et al., "*Controlling the emission rate of Er^{3+} ions by dielectric coupling with thin films*"
J. Phys. Chem. C 119, 6728 (**2015**)

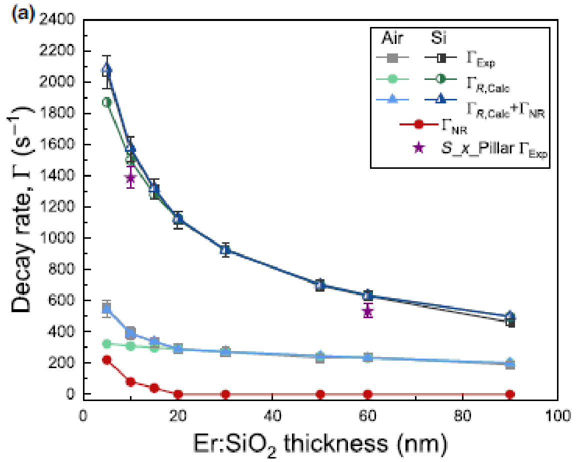


Plasmonic nanohole arrays



All-dielectric nanocavities





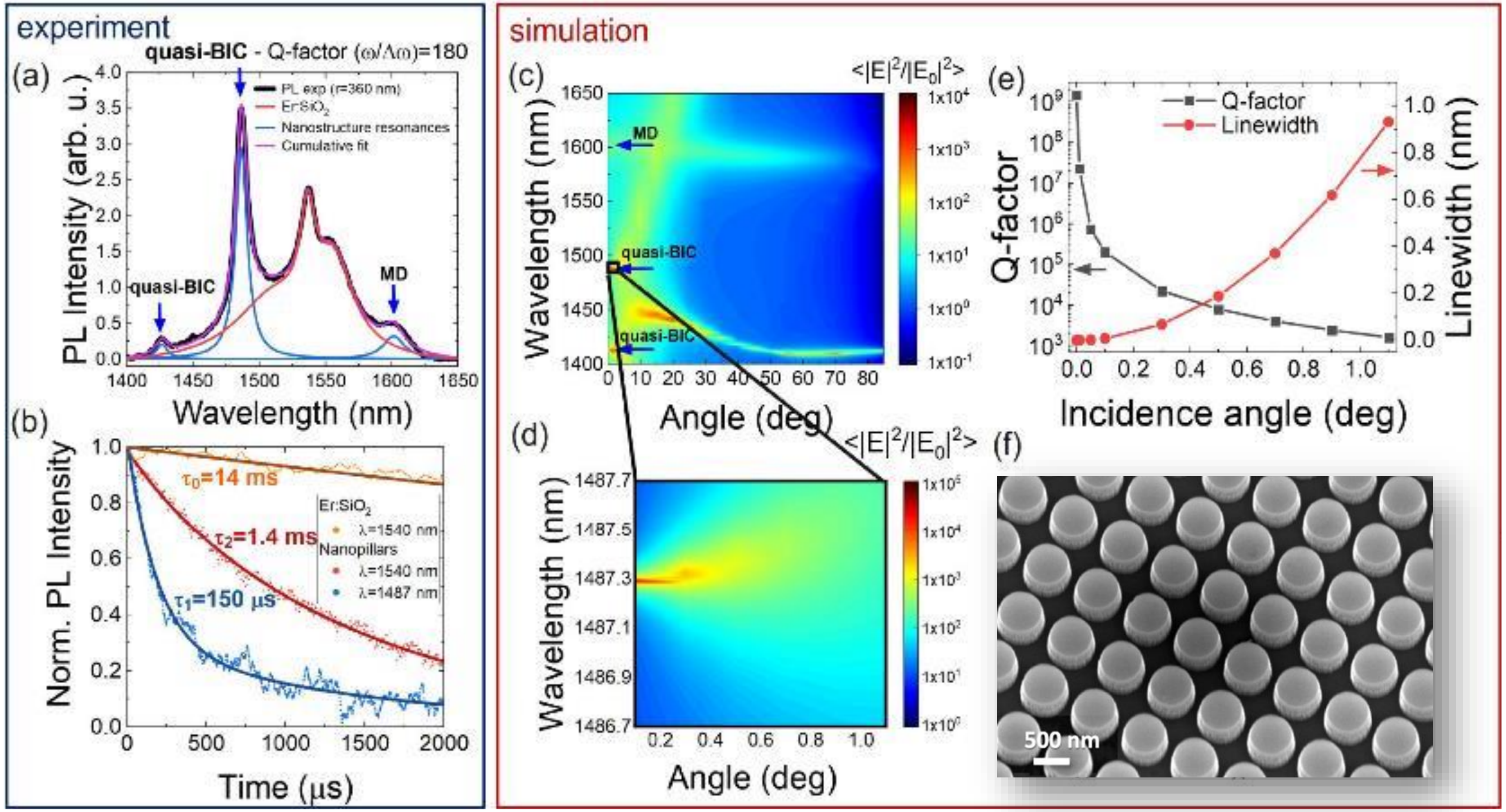
B. Kalinic, T. Cesca et al., "*All-Dielectric Silicon Nanoslots for Er^{3+} Photoluminescence Enhancement*"
Phys. Rev. Applied 14, 014086 (**2020**)

LDOS Engineering

T. Cesca,
B. Kalinic,
G. Mattei
(NSG)

Er^{3+}@ telecom wavelengths (1.5 μm)

High Q-factor nanocavities



Bound States in the Continuum (**BIC**) Modes

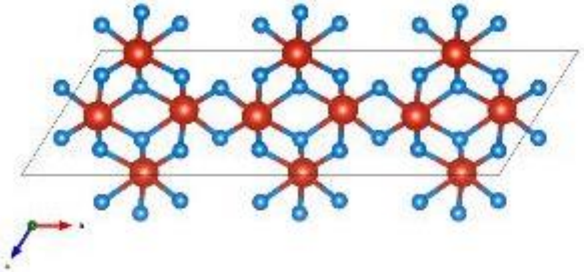
- 10^9 Q-factor
- Sub-nm linewidth
- High Purcell factors

B. Kalinic, et al, *Quasi-BIC Modes in All-Dielectric Slotted Nanoantennas for Enhanced Er^{3+} Emission*, ACS Photonics, 10, 534 (**2023**)

Active Control of Er emission
Phase-change Materials

T. Cesca,
B. Kalinic,
G. Mattei
(NSG)

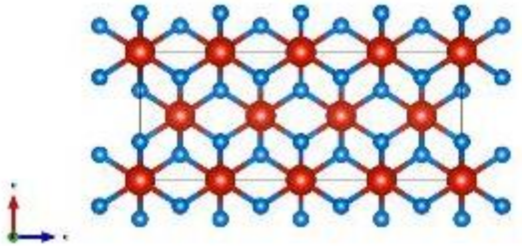
Semiconducting-to-Metal Transition (SMT) in VO_2



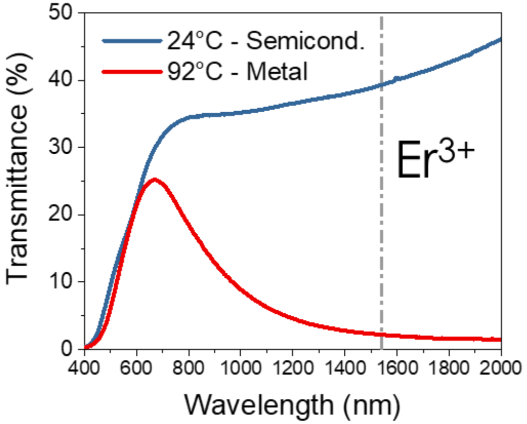
(a)M1 - VO_2 (RT)
Semiconducting Phase
(monoclinic)

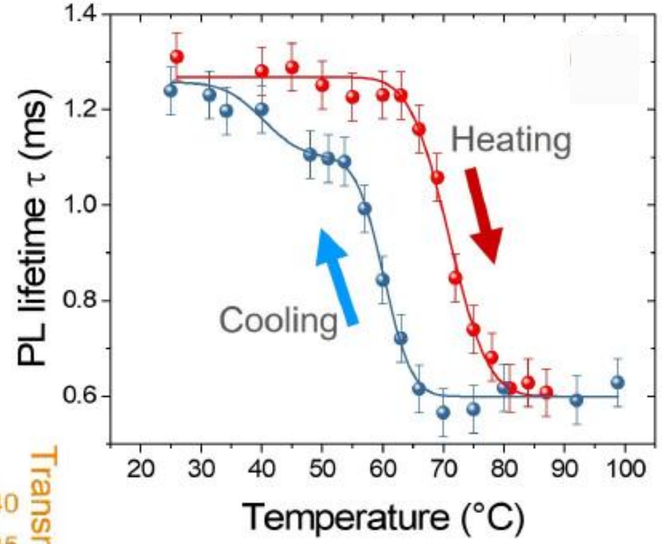
SMT
T ~ 68 °C

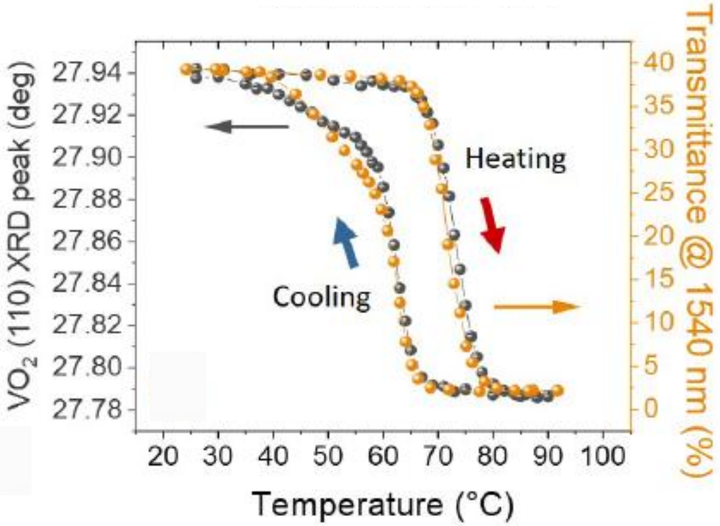
T



(b) R - VO_2
Metallic Phase
(tetragonal – rutile)



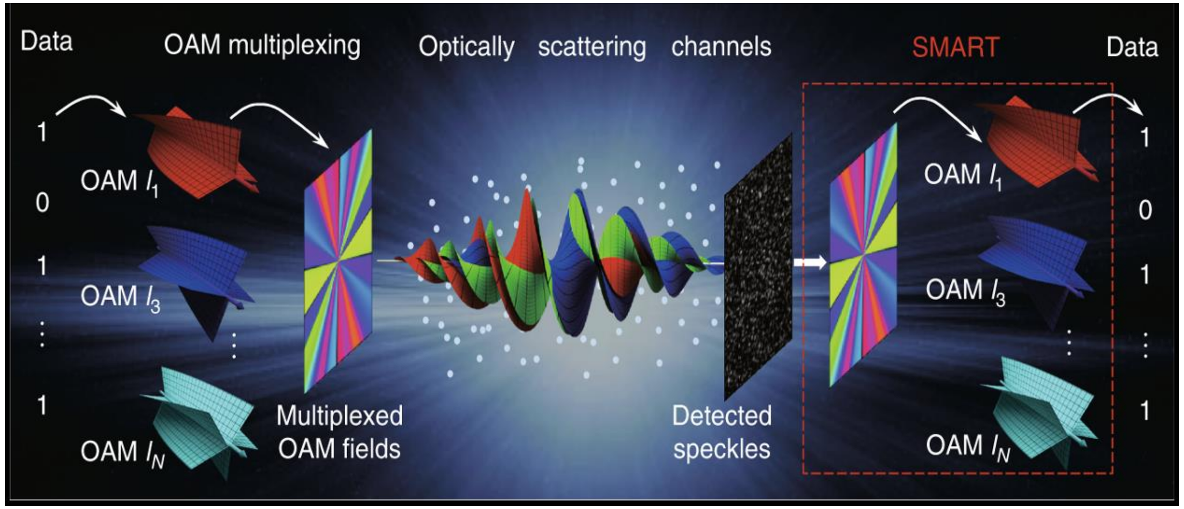


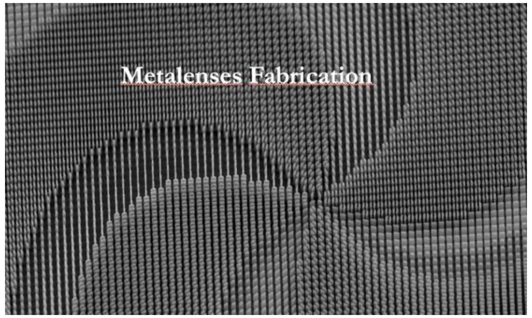


B. Kalinic, T. Cesca et al., *"Active modulation of the Er^{3+} emission lifetime by VO_2 phase-change thin films"* ACS Photonics (**2023**)

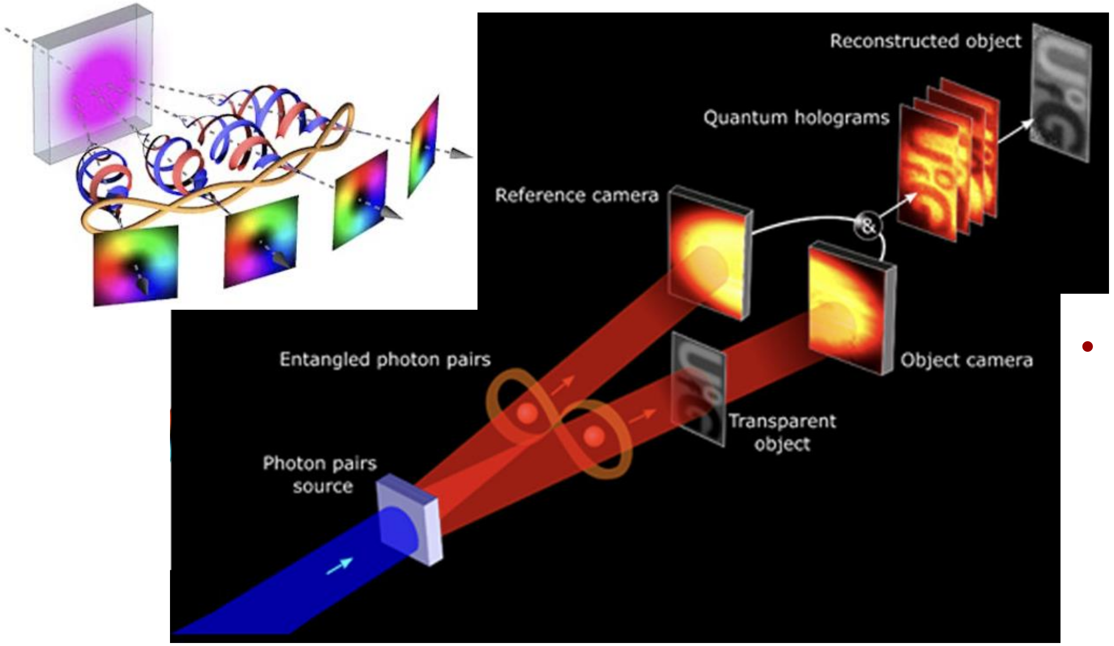
Multistate quantum entanglement

F. Romanato, G. Ruffato

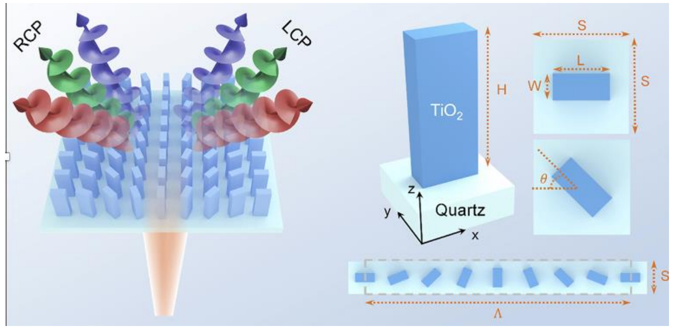




- Meta-lens can generate entangled photons for secure quantum communication QKD
- Multistate entanglement will be determined by using the optical setup for entangled photon detection
- Entangled photon microscopy will be developed using ghost photons



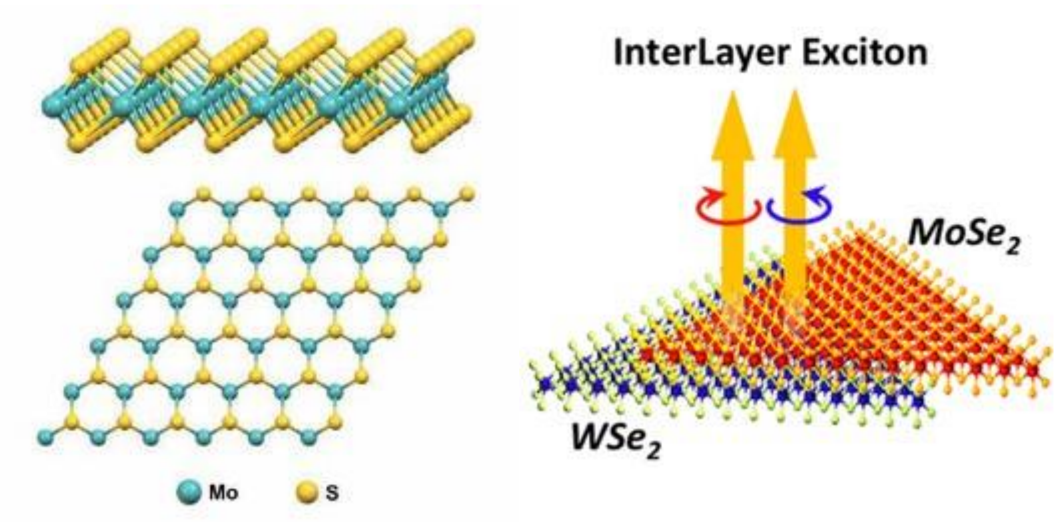
- Meta-atoms made of Si/glass or TiO_2 can be deposited by sputtering and nanostructured using metal evaporation



2D Crystals as single-photon sources

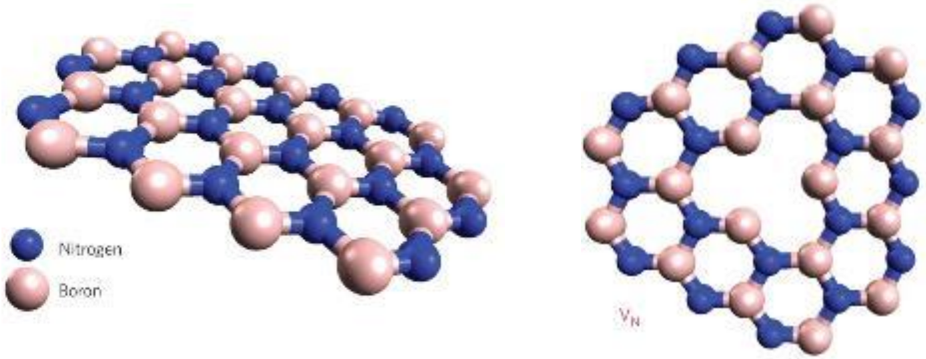
M. Merano

Trapped excitons in monolayer TMDC and heterostructures



When light is emitted from a source embedded in a solid-state device, most of the emission gets trapped within the solid itself yielding poor emission efficiency. This is an obstacle for the realization of quantum optics devices. To avoid this trapping, an easy solution is to use light sources embedded in 2D materials.

Among the different methods for 2D growth, sputtering is getting attention due to its simplicity, reliability, large area growth possibility and repeatability.



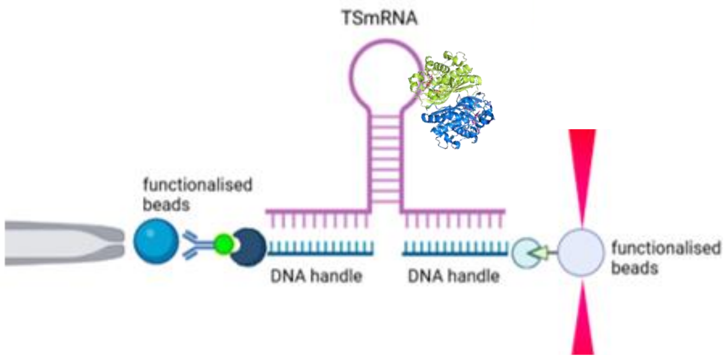
Nitrogen Vacancy in monolayer BN

Quantum-enhanced single-molecule studies

D. Ferraro,
A. Zaltron
(LAFSI)

NOW @ DFA

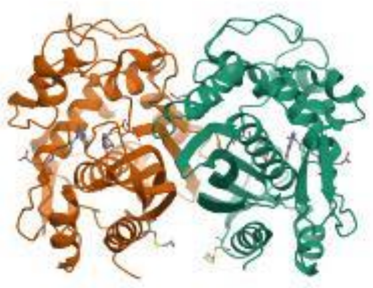
Single-Molecule Force Spectroscopy by Optical Tweezers



ENERGY of molecular interactions characterization

Current studies:

- DNA binding with peptide targets
- Interaction of proteins with DNA/RNA molecules (Thymidylate Synthase: chemioterapic application)



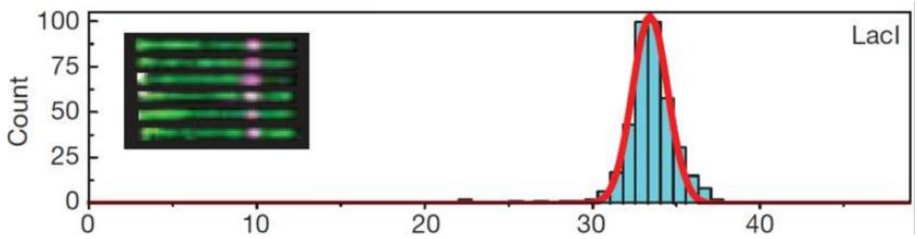
However, the info on molecular arrangements or binding sites ***are only inferred***

Quantum-enhanced single-molecule studies

D. Ferraro,
A. Zaltron
(LAFSI)

FUTURE @ DFA

Single-Molecule Quantum Microscopy will allow IMAGING molecular interactions, e.g.: via quantum coherence analysis, quantum-dots labeling or Raman nanospectroscopy.

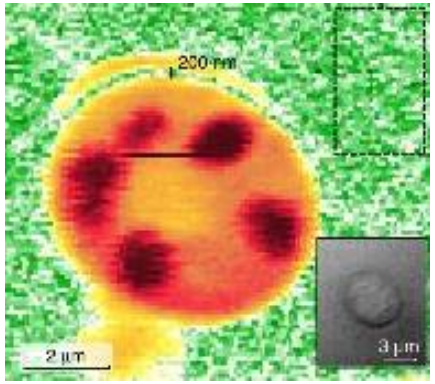


Localization of the binding site of RNA polymerase to λ-DNA

Nature, 2010

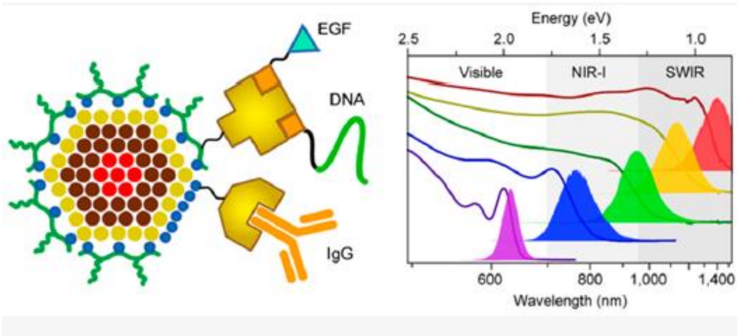
Quantum-enhanced nonlinear microscopy

Nature, 2021



Short wave infrared QD for single-molecule imaging

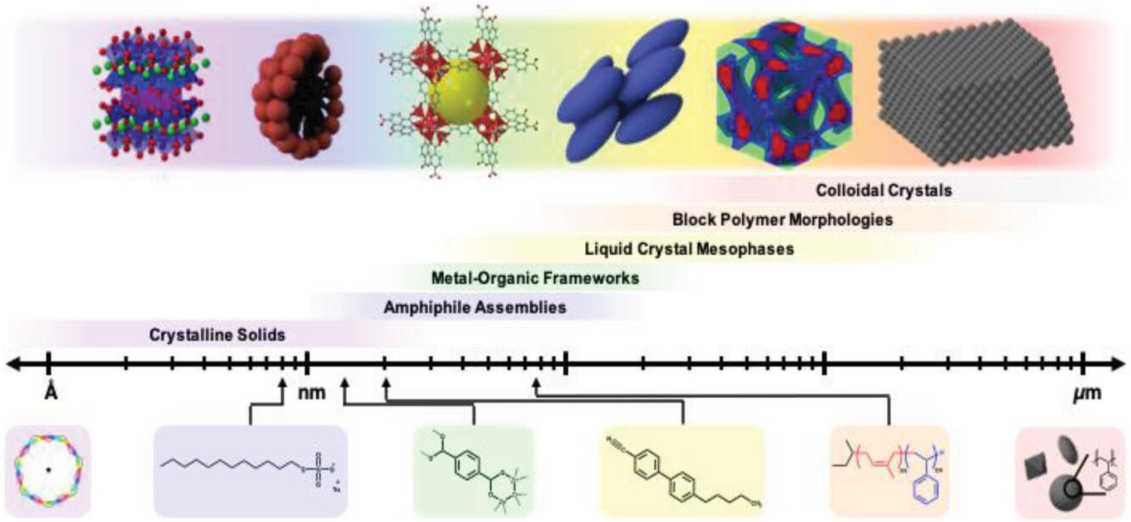
JACS, 2020



Soft-Matter-Enabled Quantum Materials

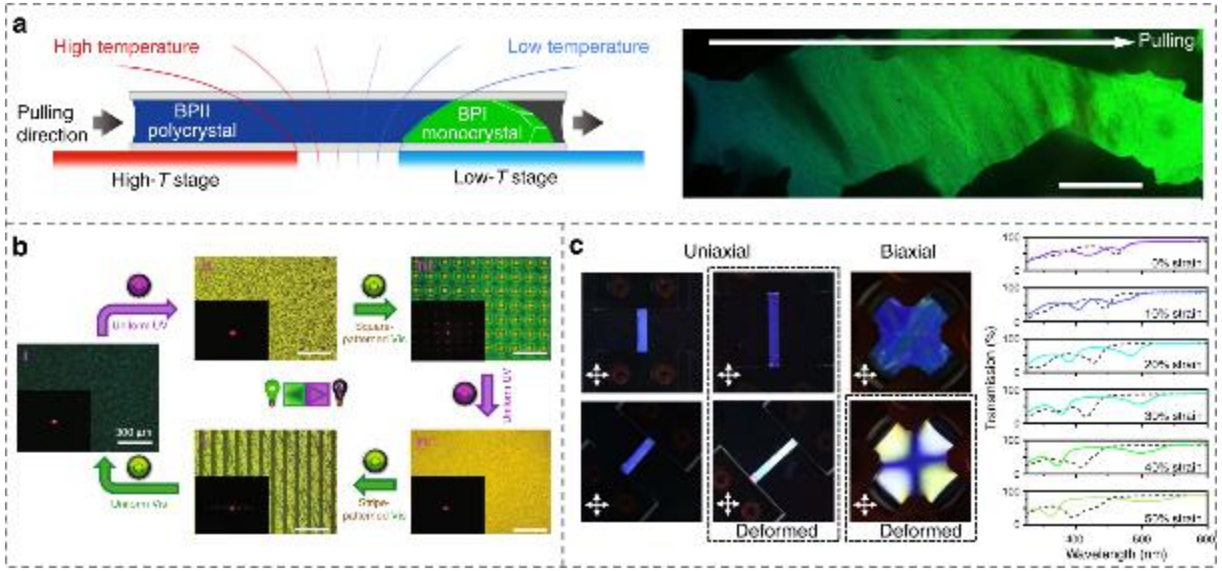
M. Pierno
G. Mistura
(LAFSI)

Convergence of hard and soft condensed matter science: soft matter provides a wealth of systems with additional degrees of freedom for controlling structure over a wide range of length scales



Advanced Materials 2022

Liquid crystals based topological photonics



LIGHT 2022, PNAS 2021

The use of soft building blocks allows for reconfigurable systems that exploit the interplay between topological states of light and the underlying responsive medium

…in summary: Action D.5.5 @ LaTeQ

- The proposed system is versatile and can be used for different quantum materials characterizations.
- Future upgrades con be considered to extend the range of applications.
- Together with the nanofabrication systems that will be acquired within the project (see next presentation by G. Mattei) it will allow to set-up **a shared facility for the synthesis and advanced characterization of materials and devices for quantum optics.**

Single photon counting confocal microscope