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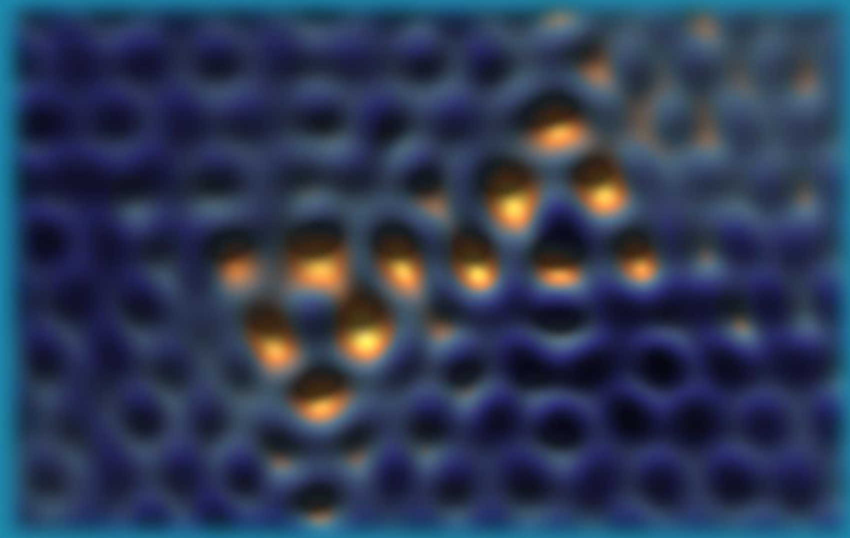
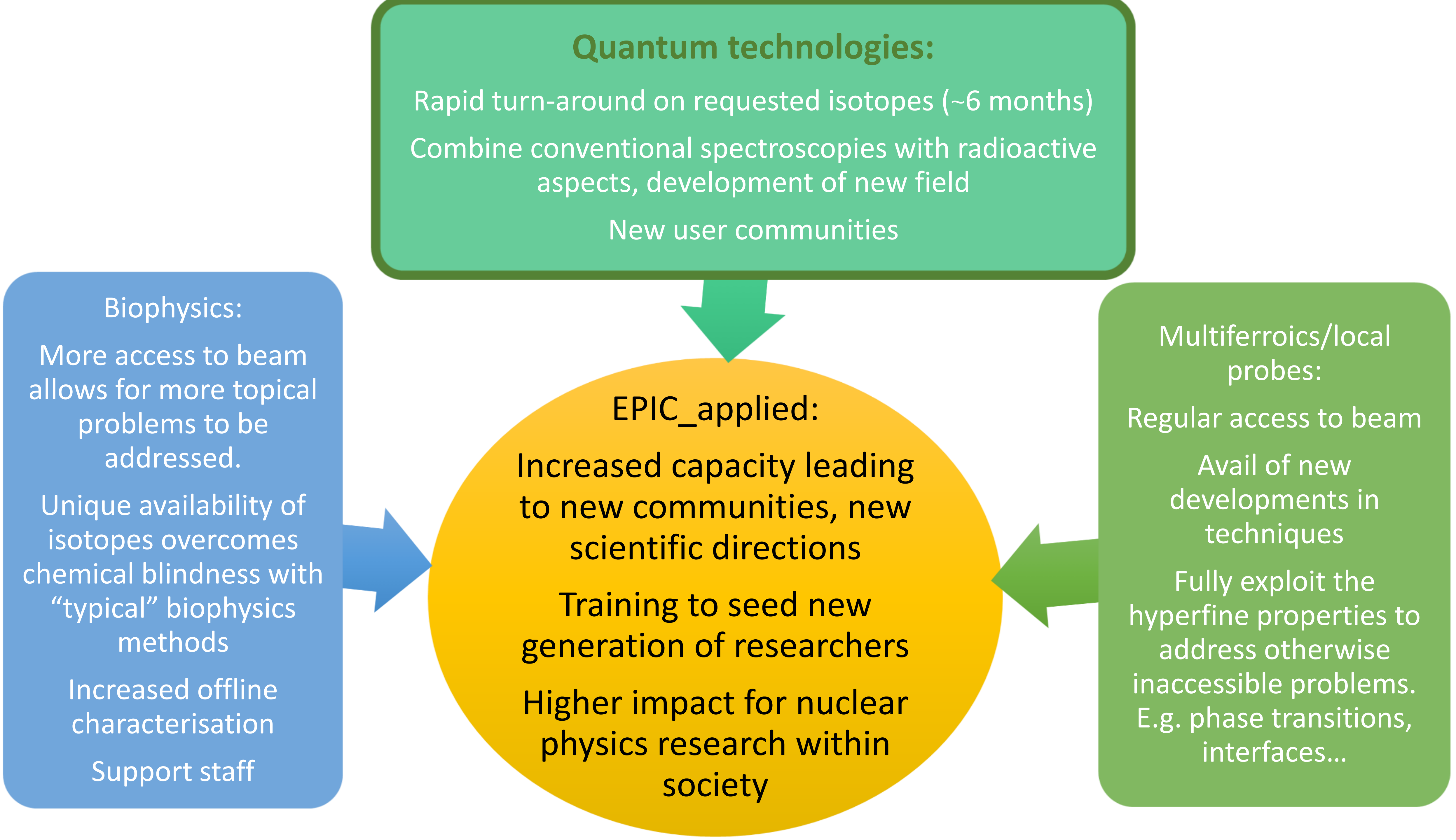
Quantum materials research with radioactive probes



Lino M.C. Pereira

KU Leuven, Quantum Solid State Physics section

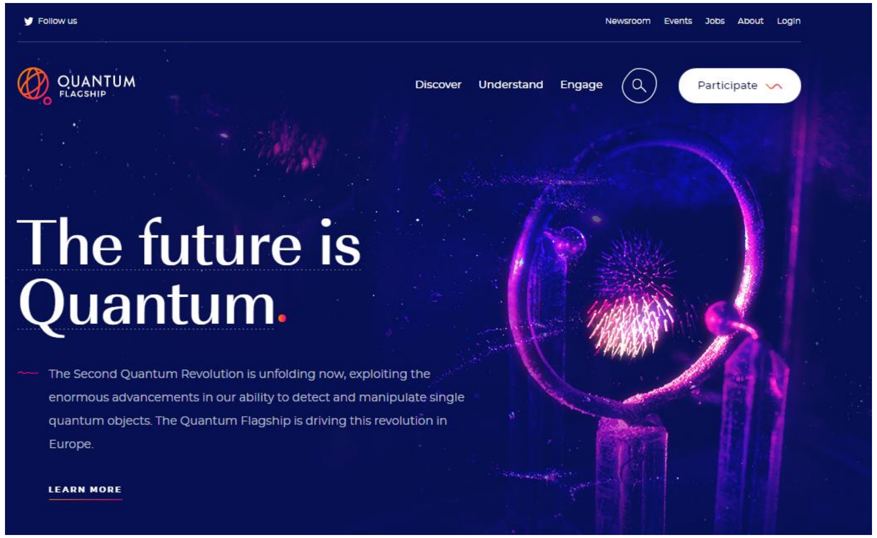


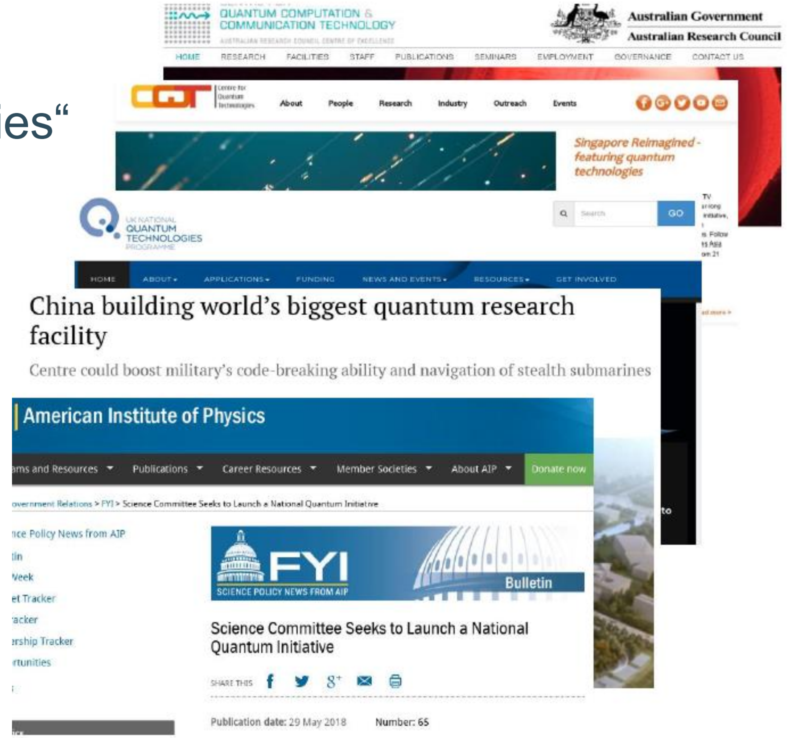
Quantum technologies:
Rapid turn-around on requested isotopes (~6 months)
Combine conventional spectroscopies with radioactive aspects, development of new field
New user communities
Biophysics:
More access to beam allows for more topical problems to be addressed.
Unique availability of isotopes overcomes chemical blindness with "typical" biophysics methods
Increased offline characterisation
Support staff
EPIC_applied:
Increased capacity leading to new communities, new scientific directions
Training to seed new generation of researchers
Higher impact for nuclear physics research within society
Multiferroics/local probes:
Regular access to beam
Avail of new developments in techniques
Fully exploit the hyperfine properties to address otherwise inaccessible problems. E.g. phase transitions, interfaces...

quantum technologies

- to exploit the non-classical properties of quantum systems for practical applications
- emerging trend in research programs worldwide
- European Union - The Quantum Flagship http://qt.eu

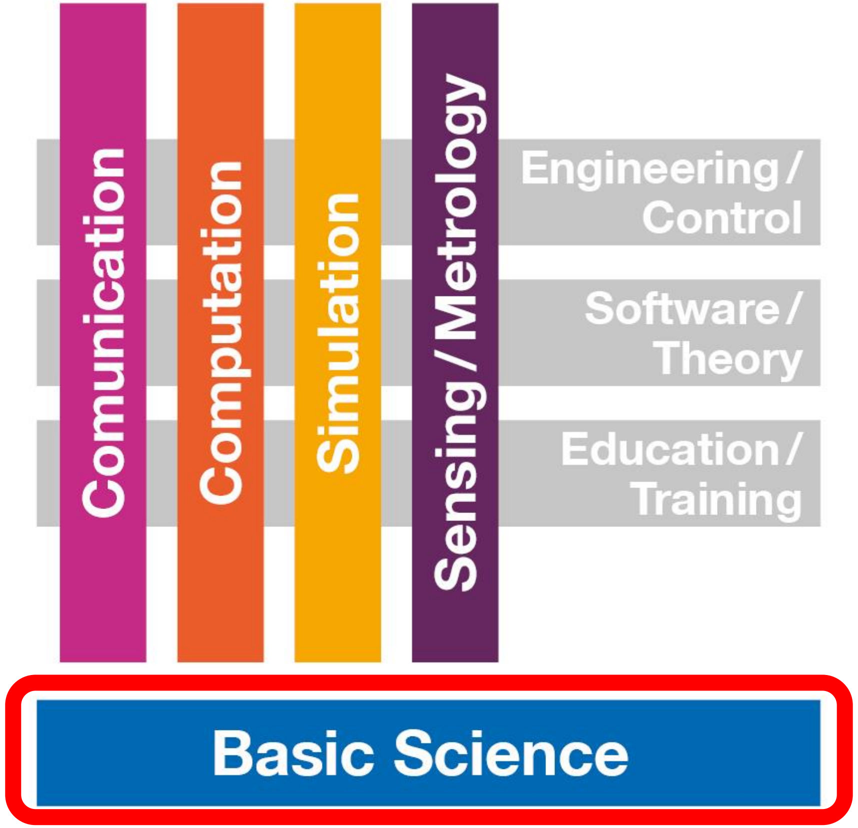
  "to kick-start a competitive European Industry in Quantum Technologies“

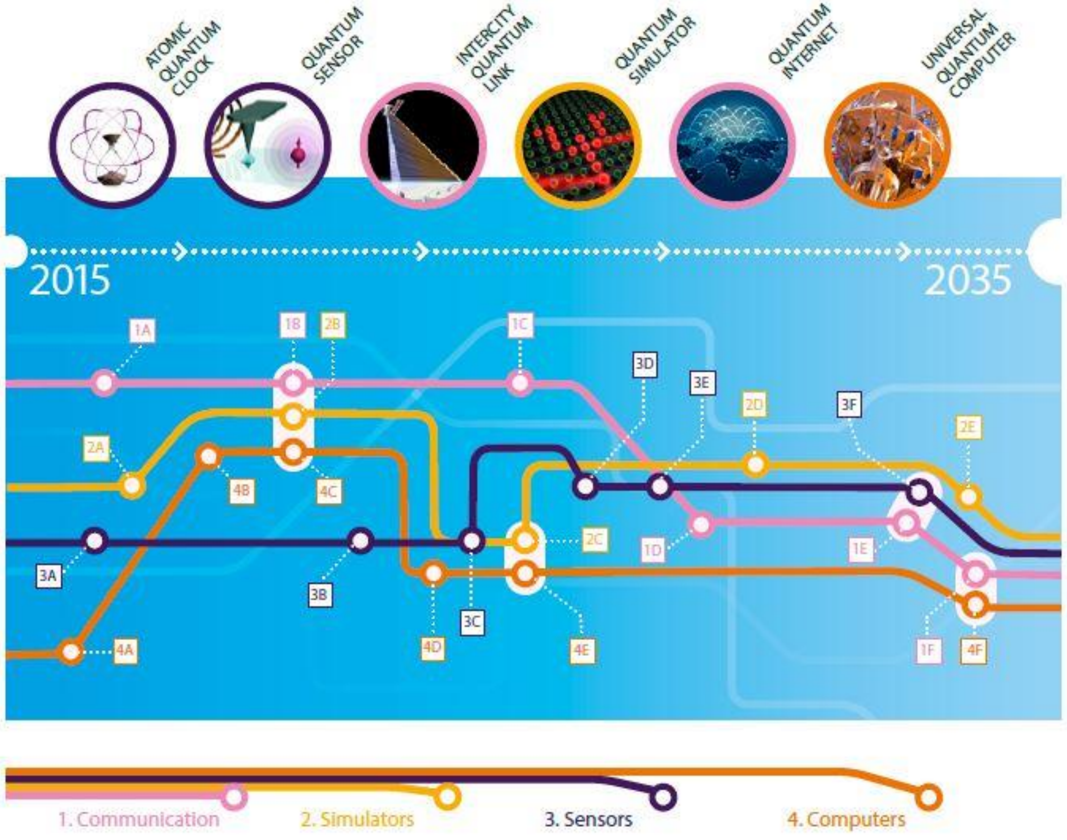


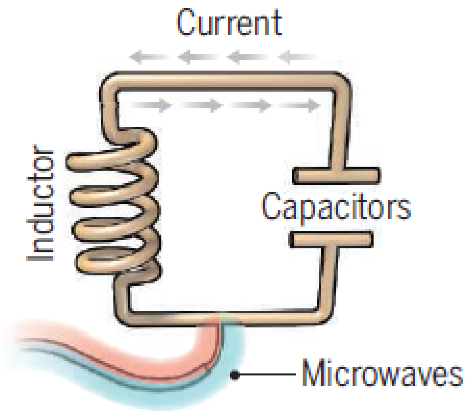


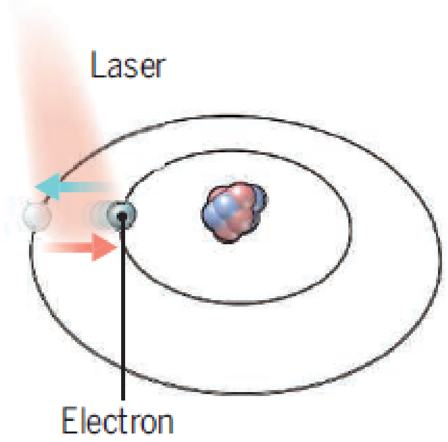
quantum technologies

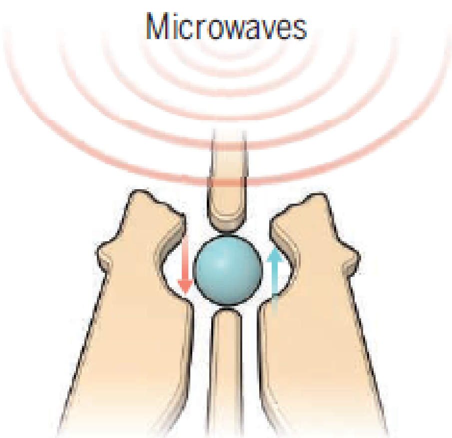
the Quantum Flagship framework and timeline

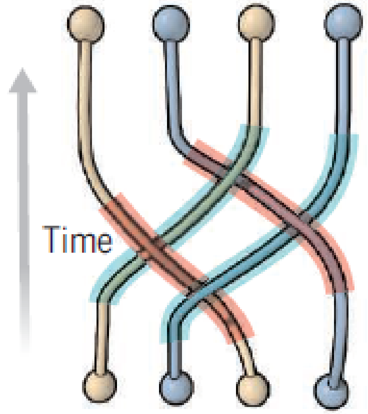


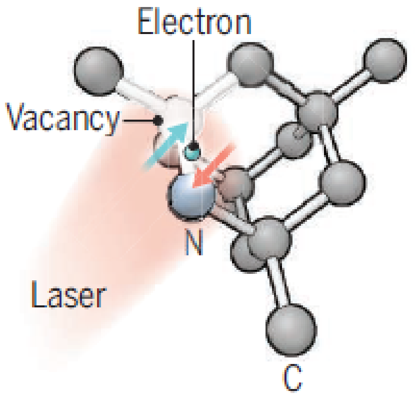






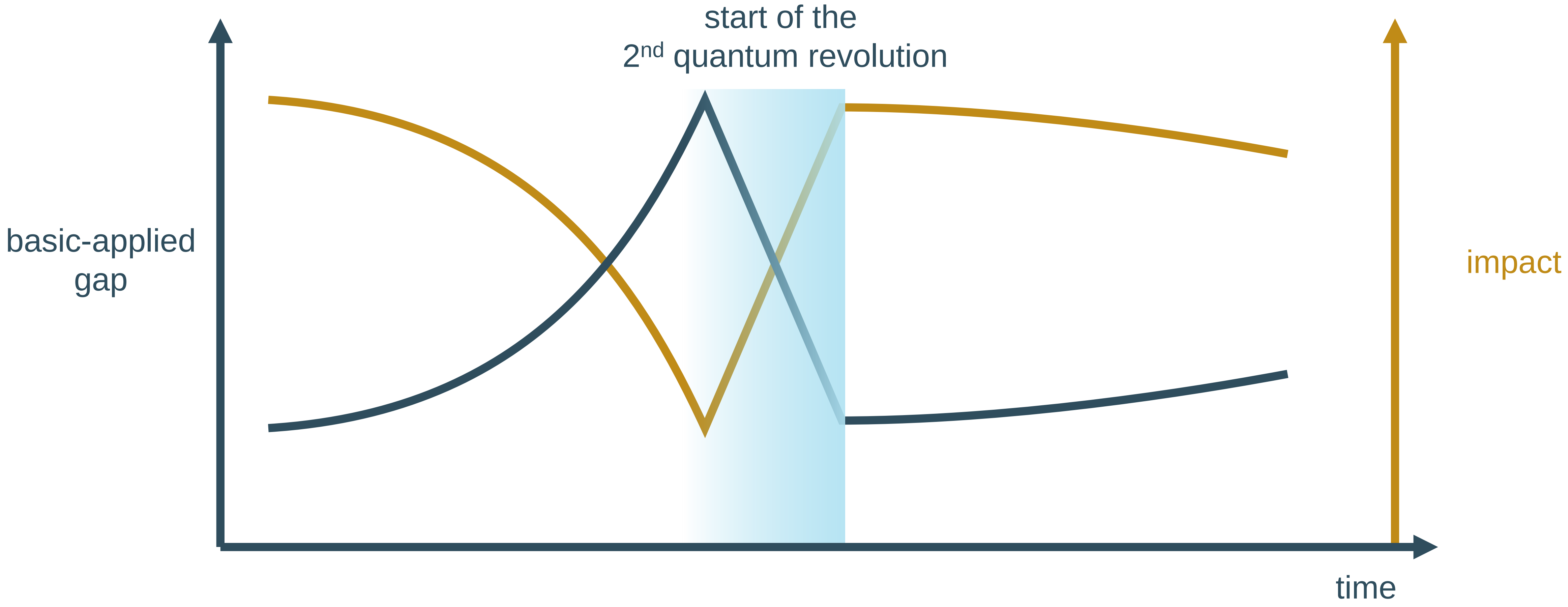






	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies

basic *vs.* applied solid-state physics



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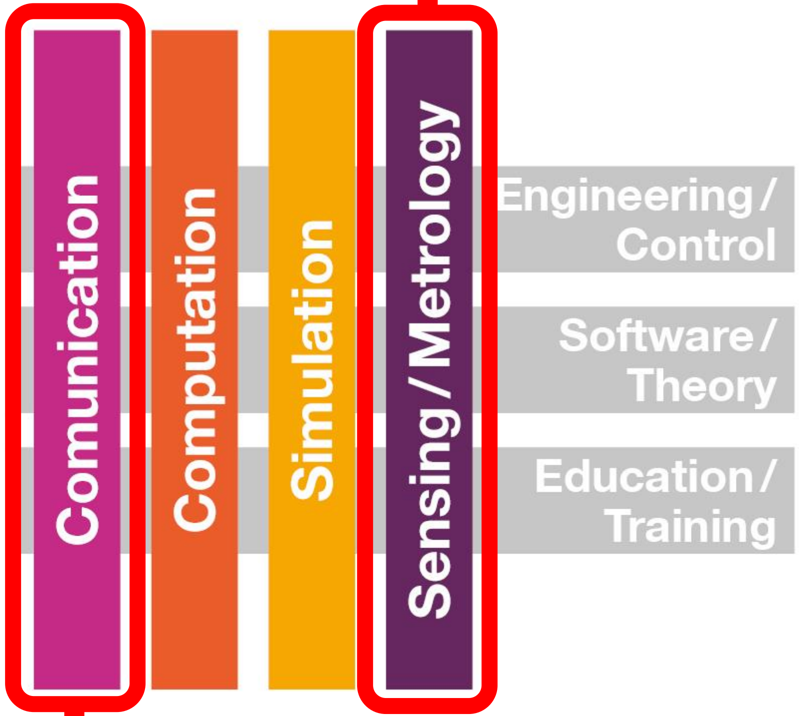
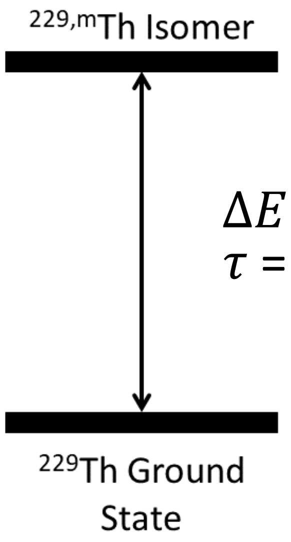
quantum technologies: SSP@ISOLDE

two present examples

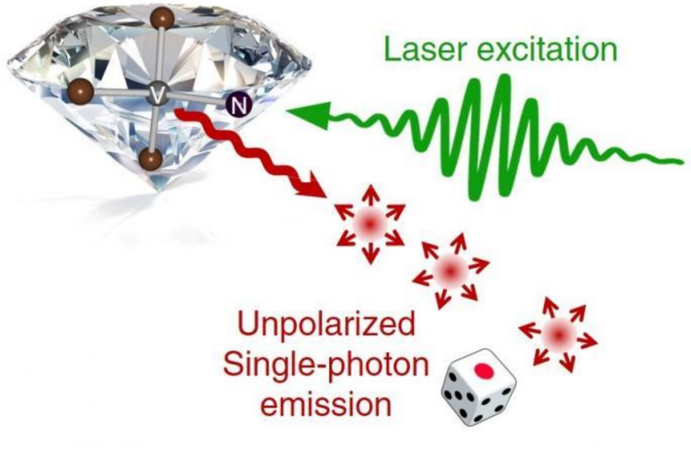
^{229}Th nuclear clock



single-photon emitters (color centers) in diamond



ΔE = 8.28 (0.17) eV
$\tau = 10^3 - 10^4\ s$



diamond color centers

many color centers - “known” or proposed

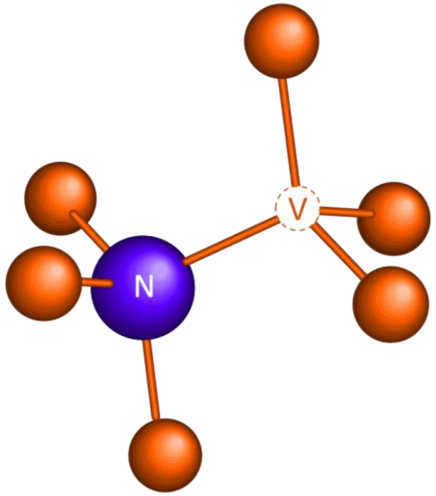
- different impurity elements and defect configurations
- **which color centers are suitable and can be fabricated?**

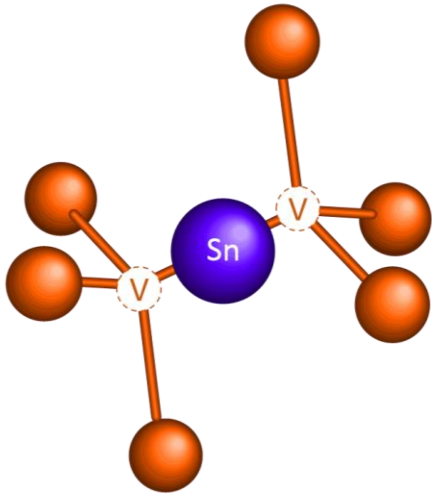
color center production and optimization

- suitable defects should be fabricated by reproducible and scalable methods
    - **ion implantation** currently most promising technique

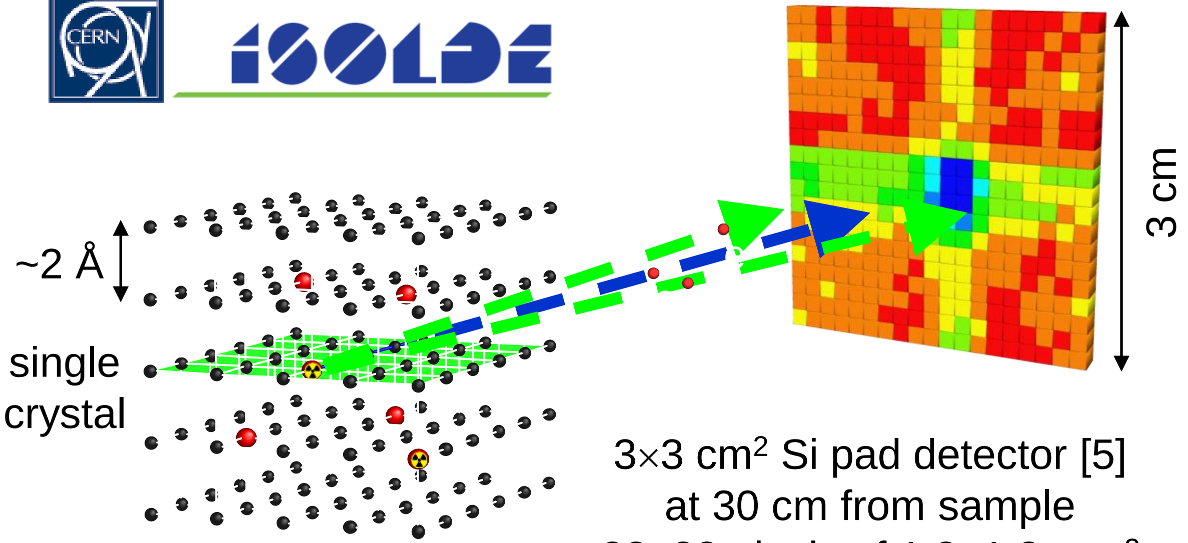
understanding quantum emitters

- **defect structure** and photonic quantum properties
    - **identification** typically indirectly inferred from spectroscopic analysis
    - **emission channeling** lattice location experiments are uniquely suited



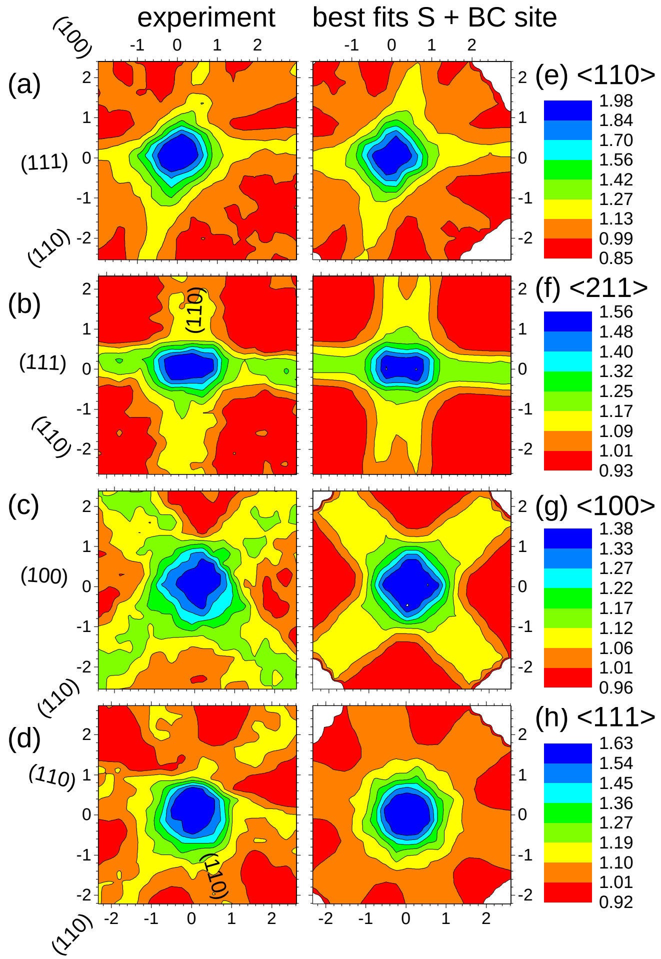


Emission Channeling with Short-Lived Isotopes (EC-SLI)



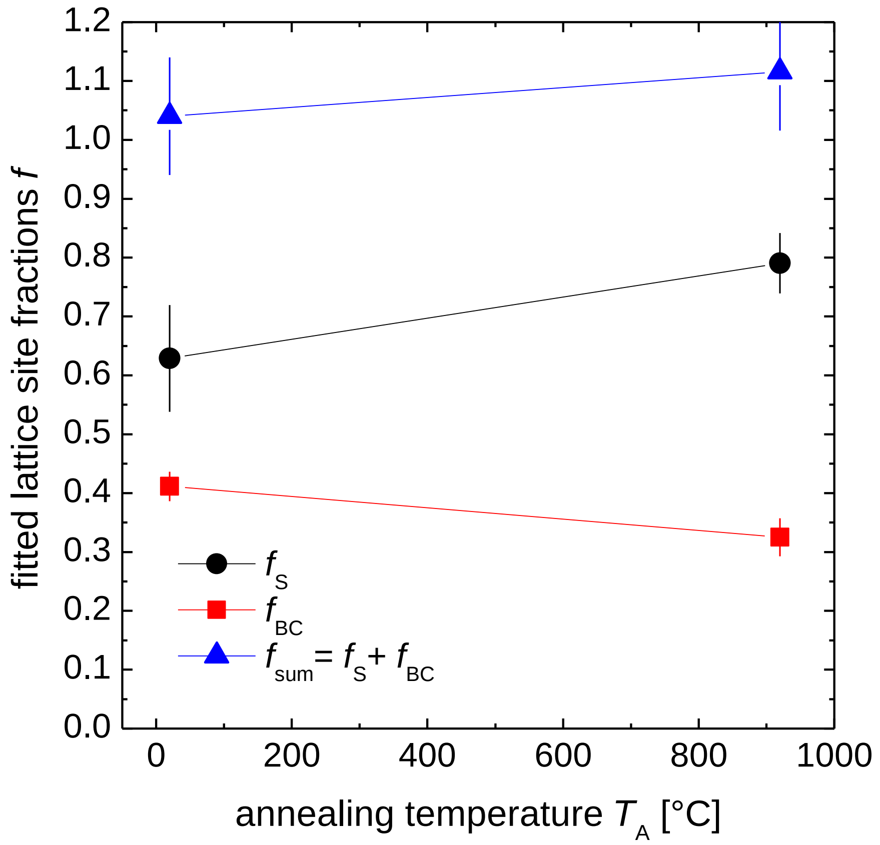
3×3 cm² Si pad detector [5]
at 30 cm from sample
22×22 pixels of 1.3×1.3 mm²

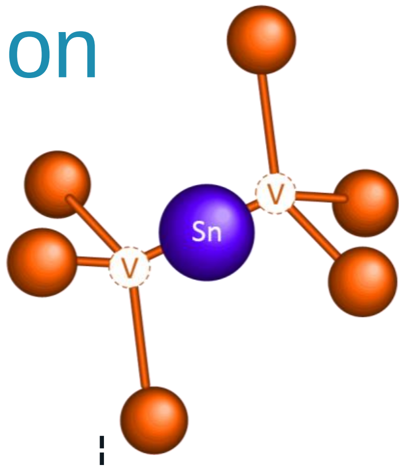
combined with radiotracer PL @ISOLDE
for **unambiguous** correlation
between **structure** and **photonics**

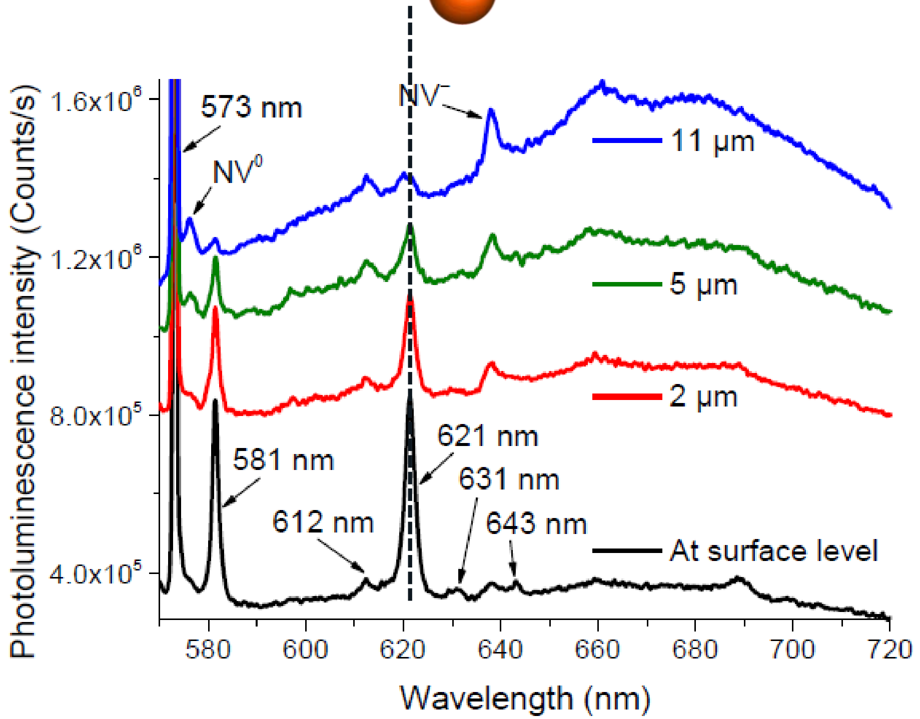


^{121}Sn-vacancy: identification and quantification

Emission channeling + Photoluminescence







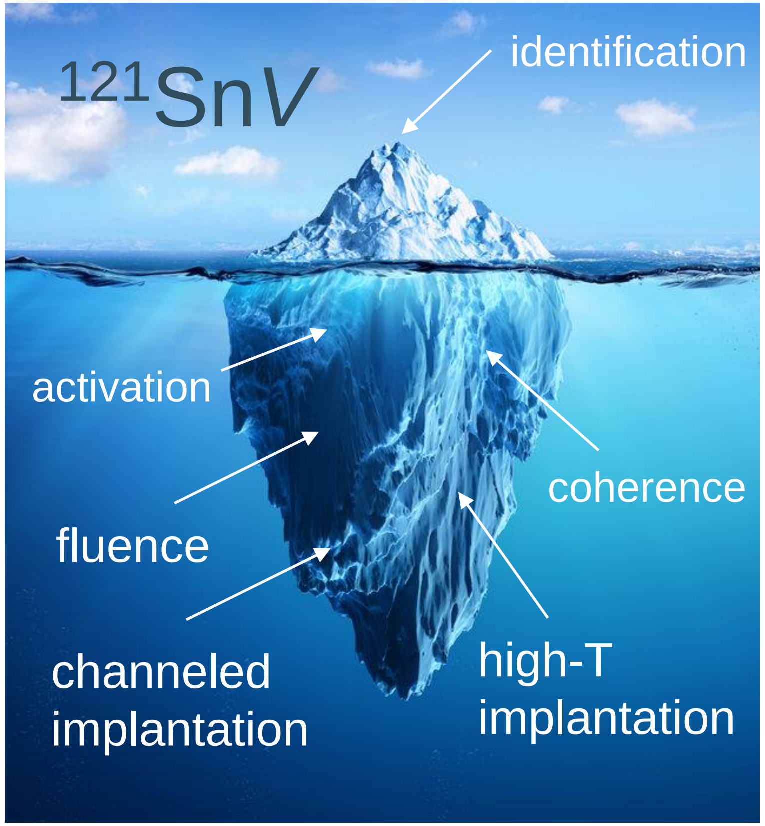
^{121}Sn-vacancy: the tip of the iceberg

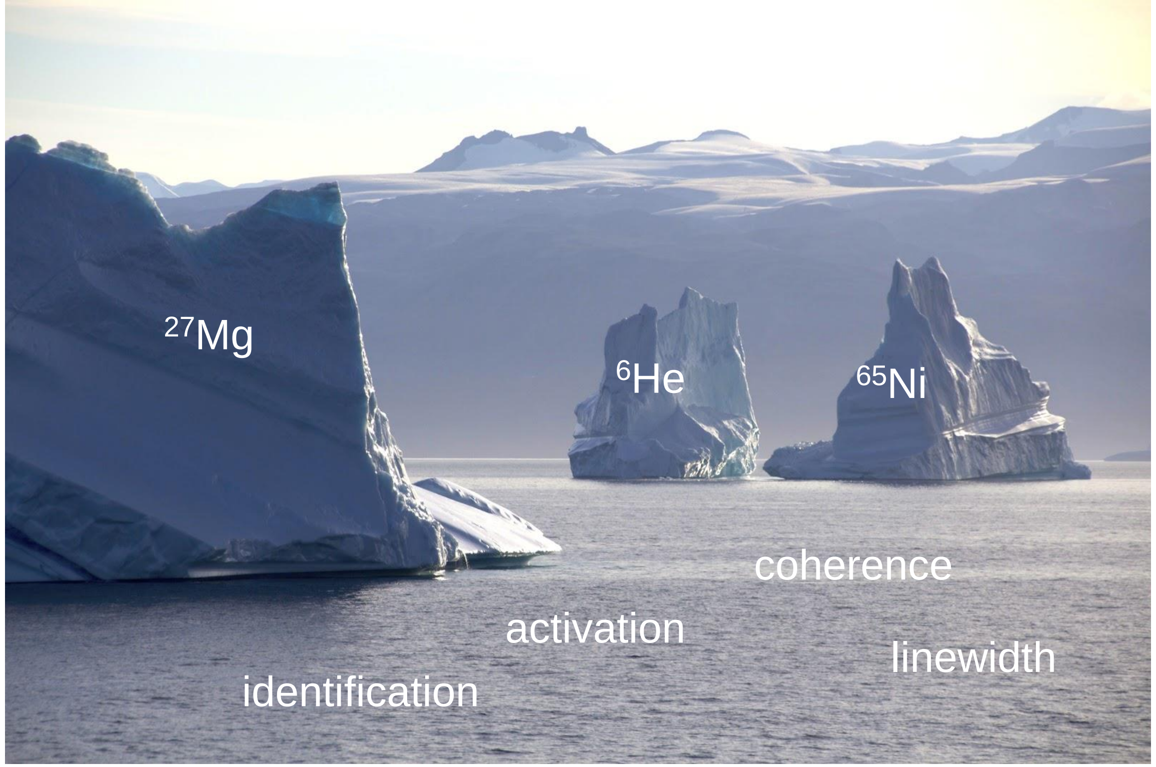
Physical Review Letters **125**, 045301 (2020)

Direct structural identification and quantification of the split-vacancy configuration for implanted Sn in diamond

U. Wahl, J. G. Correia, R. Villarreal, E. Bourgeois, M. Gulka, M. Nesládek, A. Vantomme, and L. M. C. Pereira

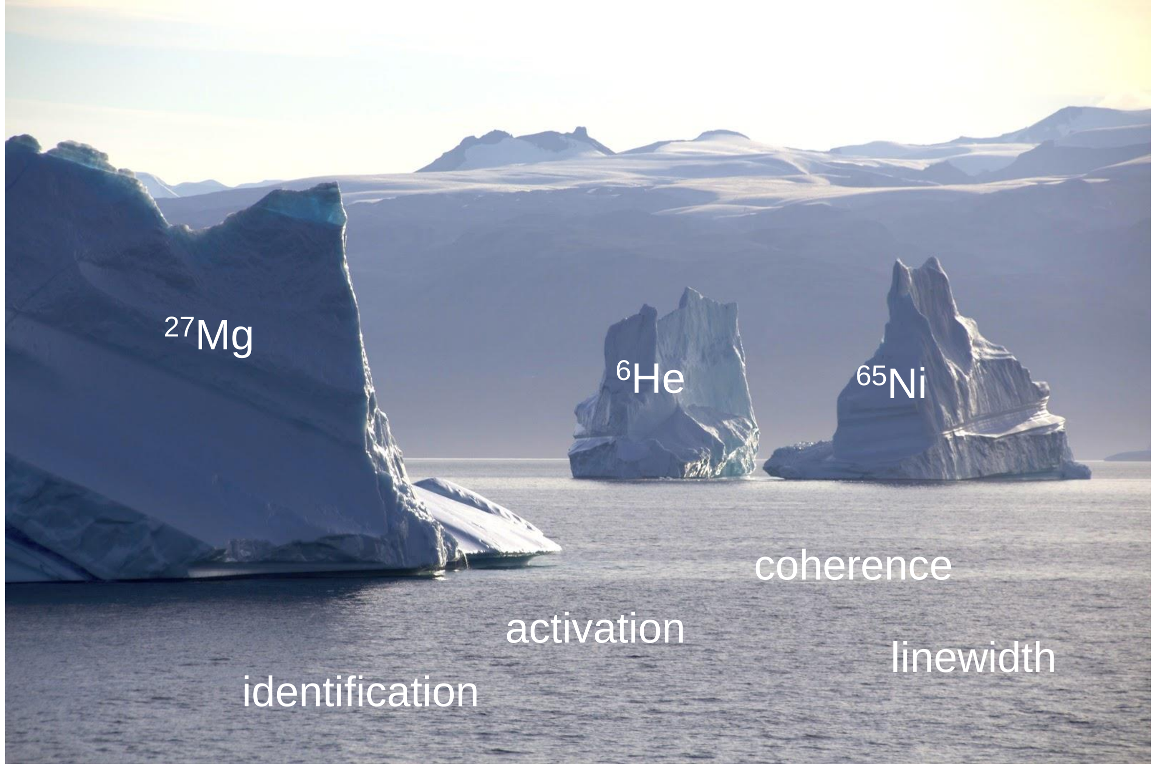
INTC-P-562: *Quantum color centers in diamond studied by emission channeling with short-lived isotopes (EC-SLI) and radiotracer photoluminescence*



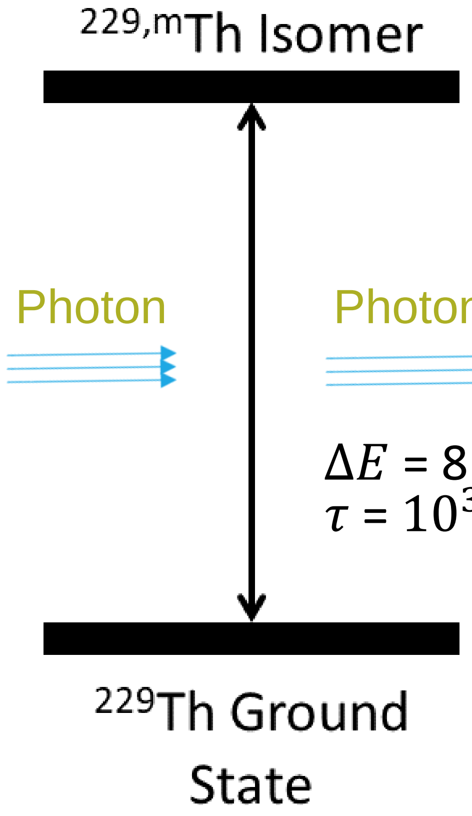


INTC-P-562: *Quantum color centers in diamond studied by emission channeling with short-lived isotopes (EC-SLI) and radiotracer photoluminescence*

- determine lattice location of ion implanted impurities = **structure** of color centers in diamond using **emission channeling**
- and correlate with the **optical properties** of the centers - **radiotracer photoluminescence**
- only experimental approach capable of doing so directly
- **perfect match between the needs of the field and the unique strengths of our approach**
  - doping by ion implantation ✓
  - low fluence ✓
  - direct and unambiguous defect structure ✓
  - direct and unambiguous correlation between defect structure and optical signature ✓

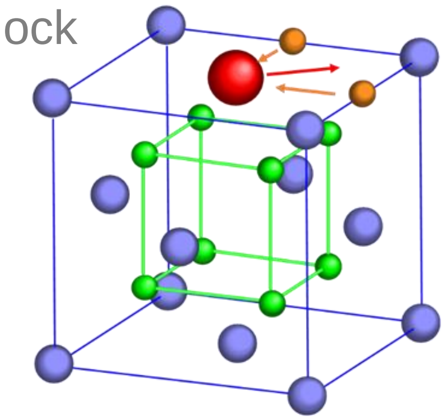


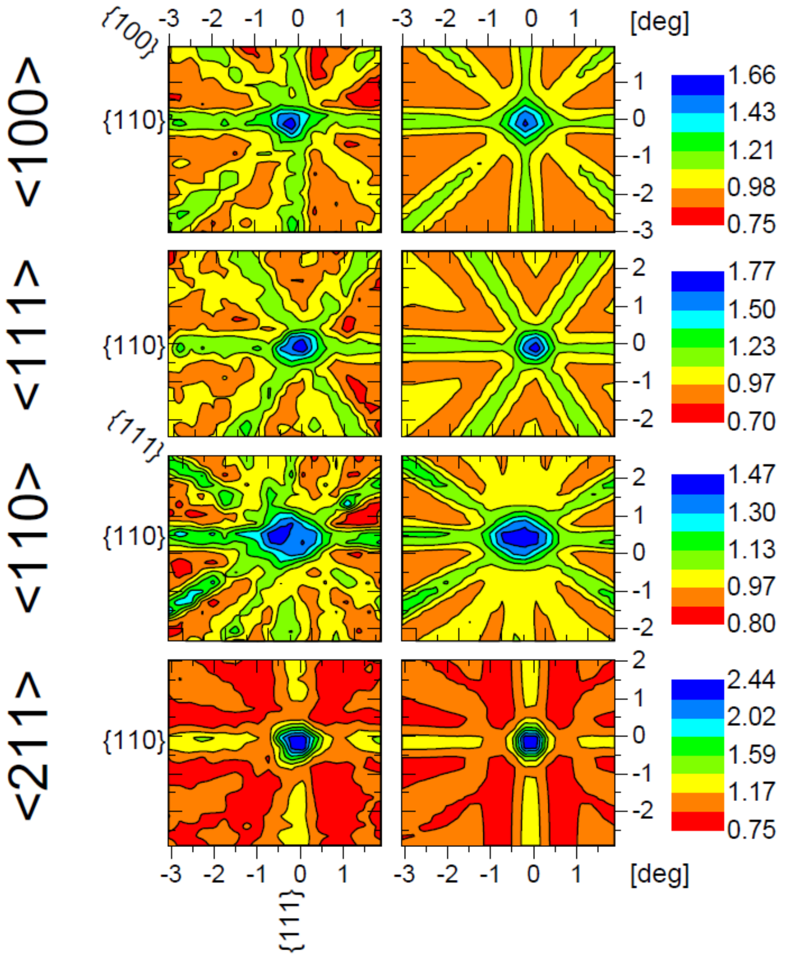
INTC-P-548:
Study of the radiative decay of the low-energy isomer in ^{229}Th



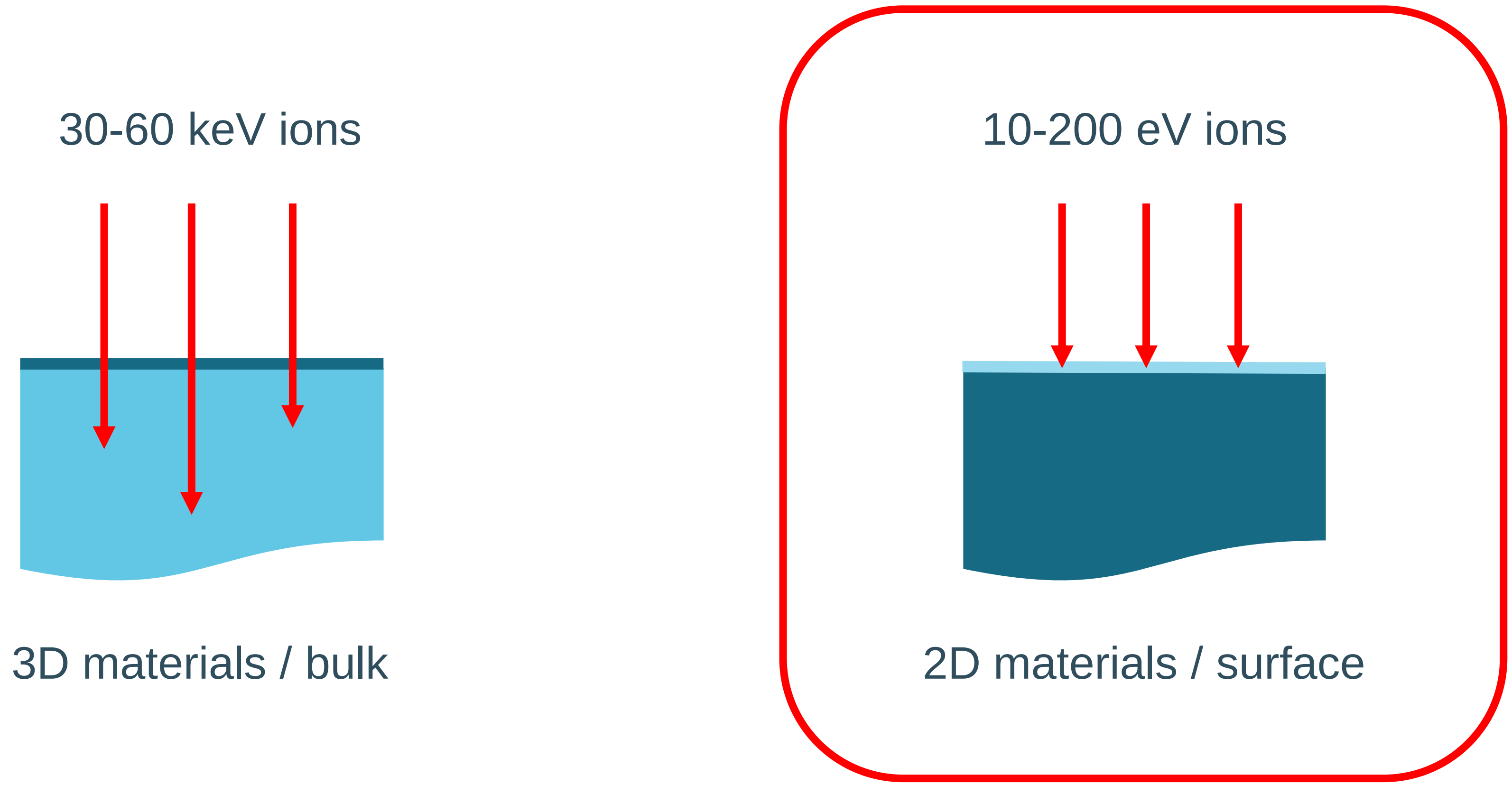
ΔE = 8.28 (0.17) eV
$\tau = 10^3 - 10^4\ s$

- CaF_2 crystal
  - 12 eV band gap (> isomer energy)
- Th^{4+}
  - Block IC
  - Spectroscopy
  - Nuclear clock

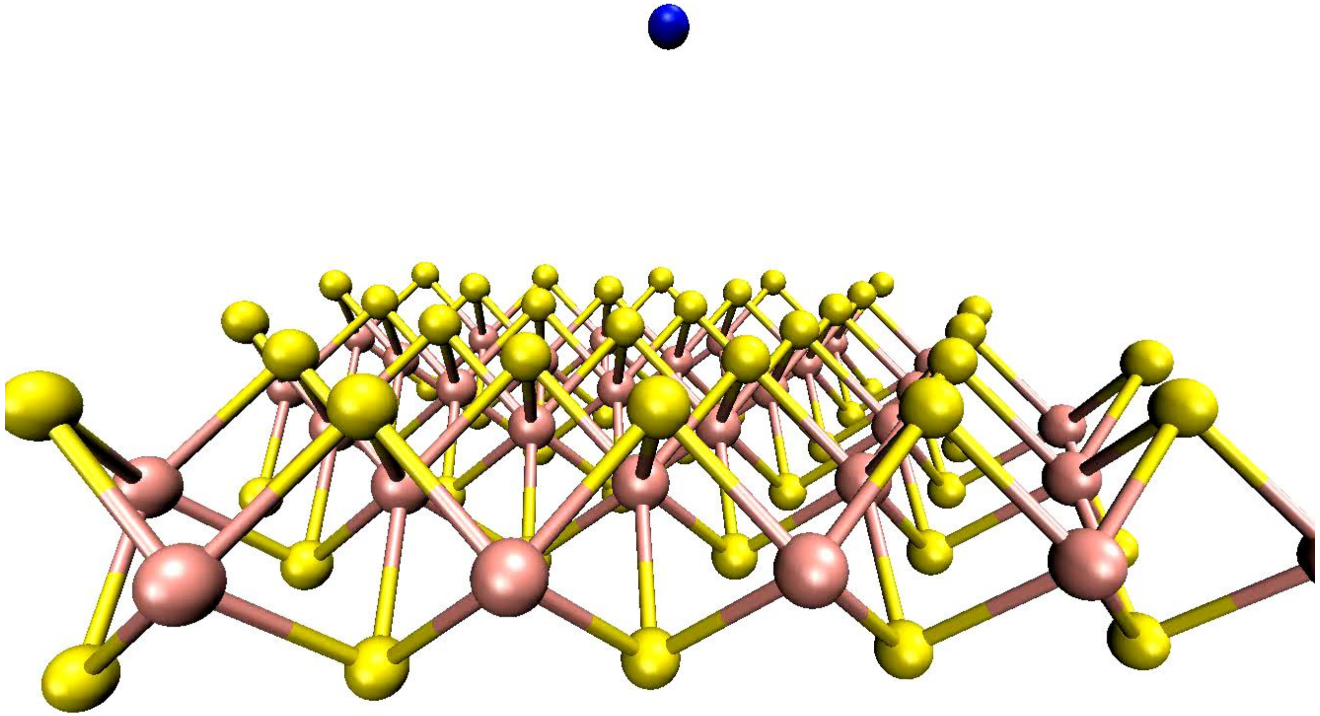




going 2D: ultra-low energy ion implantation



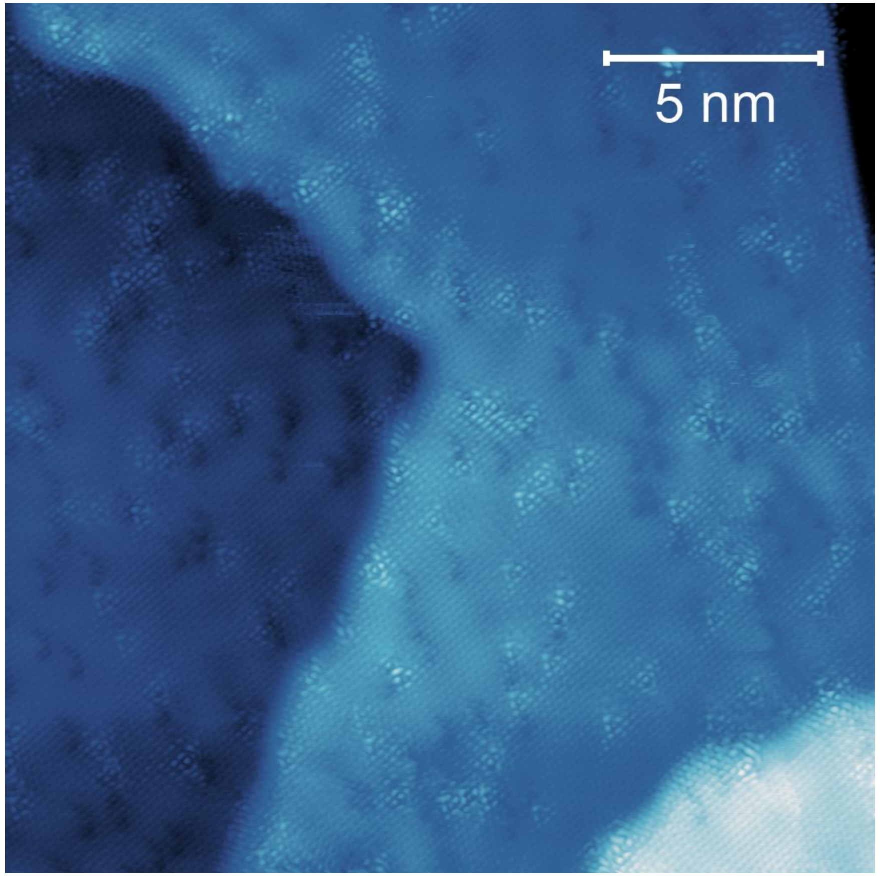
ultra-low energy ion implantation (~ 10-200 eV)

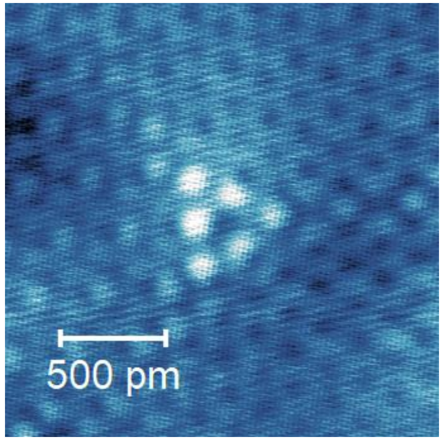


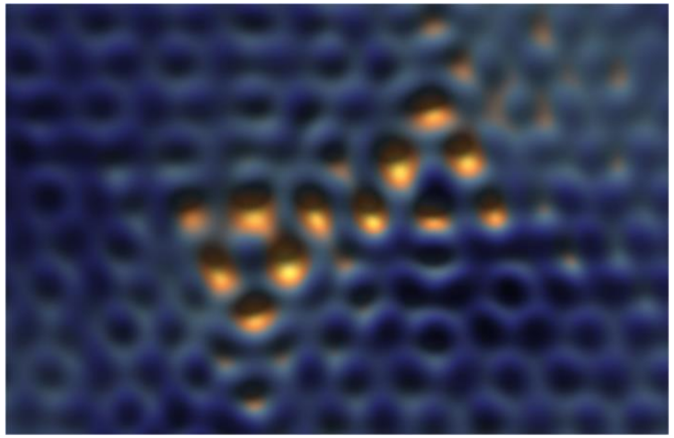
- any element of the periodic table
- control ion energy → configuration
- control number of implanted ions
- reproducible
- scalable
- area-selective

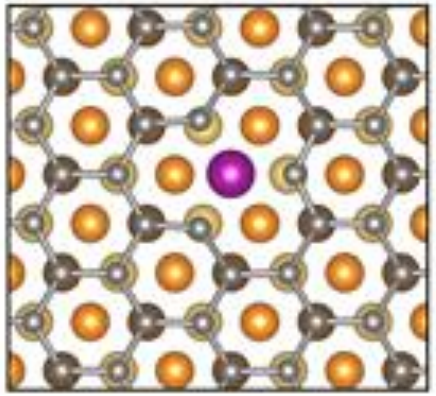
ultra-low energy ion implantation (~ 5-200 eV)

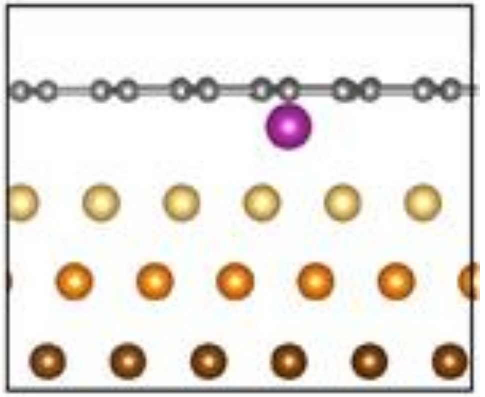
substitutional dopants in 2D materials



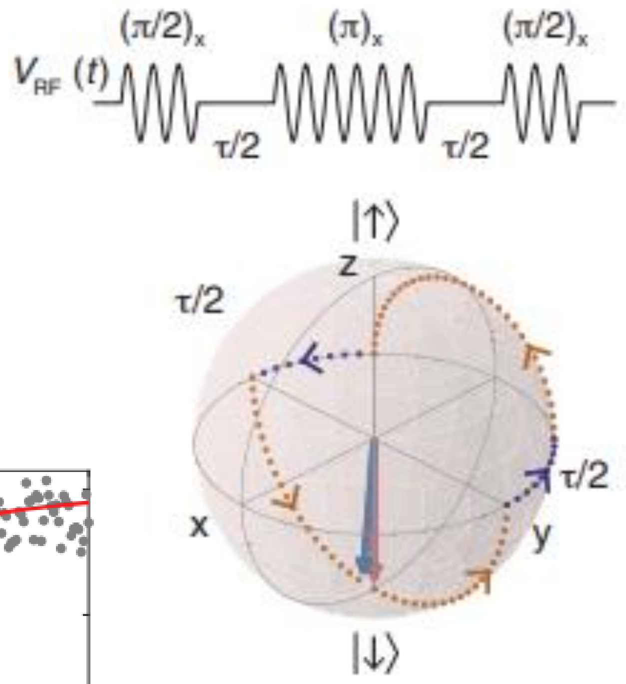


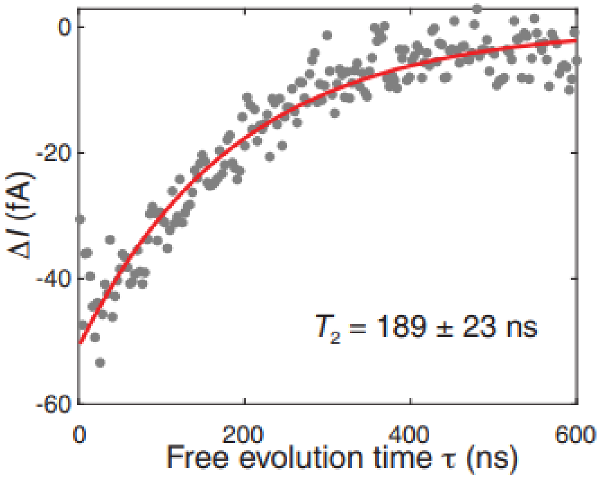


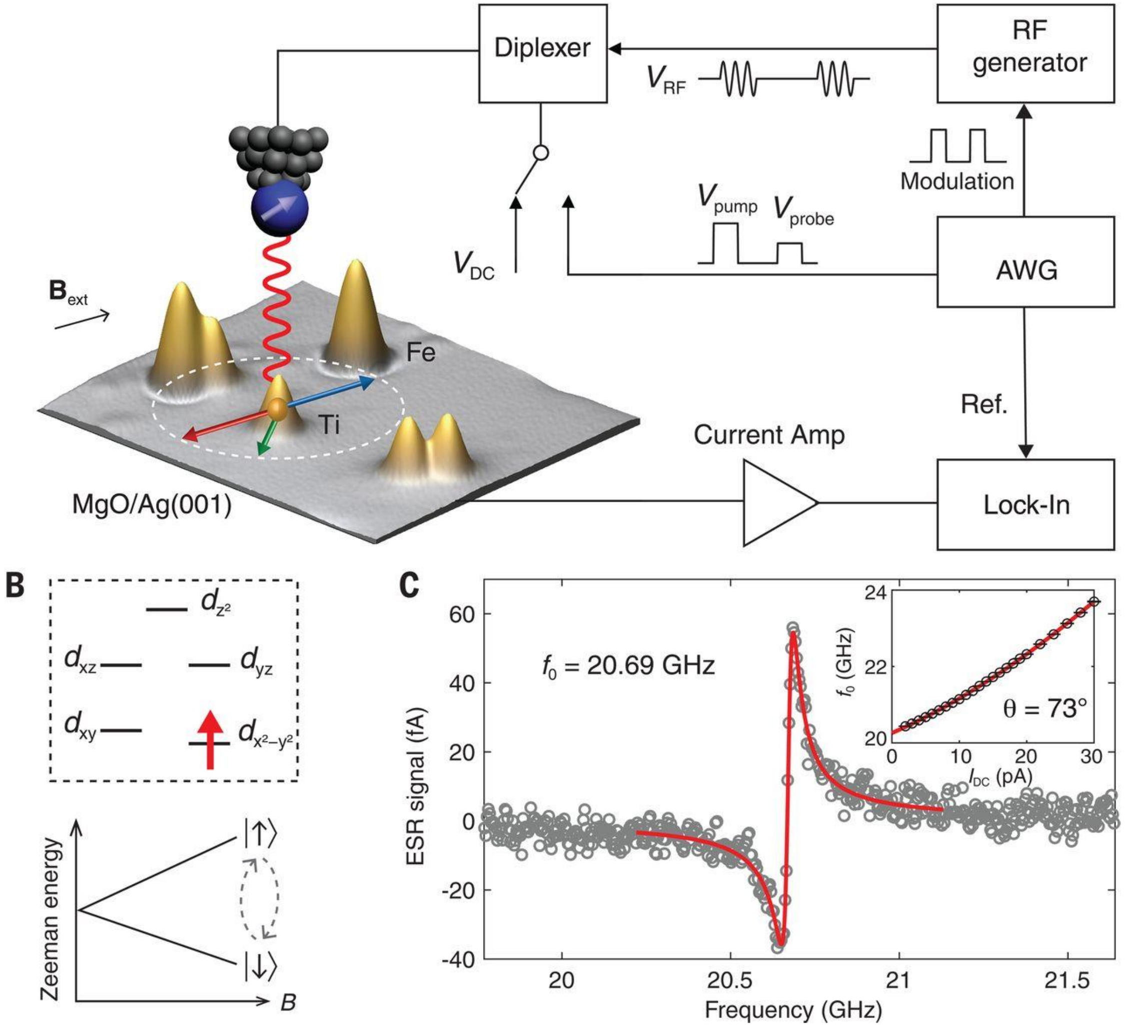




Coherent spin manipulation of individual atoms on a surface







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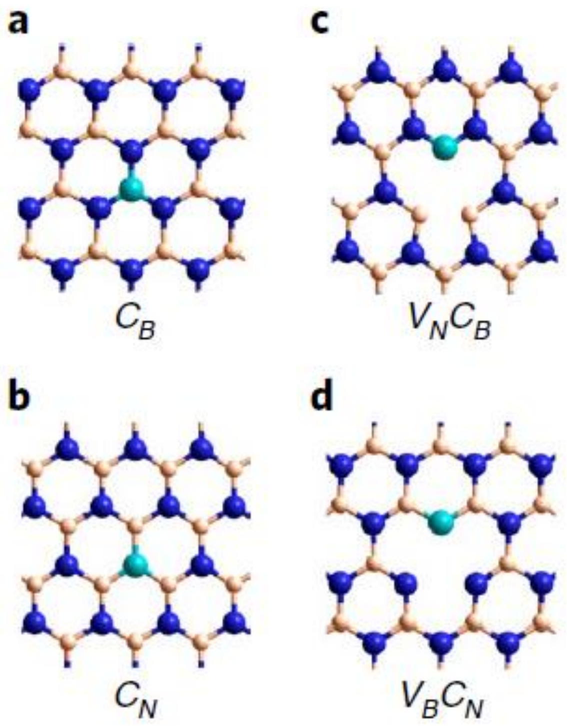
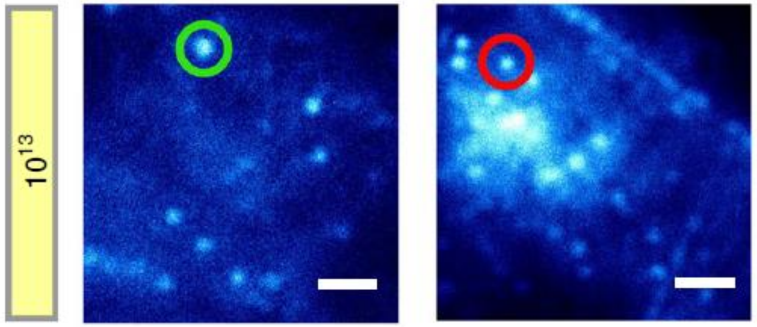
Identifying carbon as the source of visible single-photon emission from hexagonal boron nitride

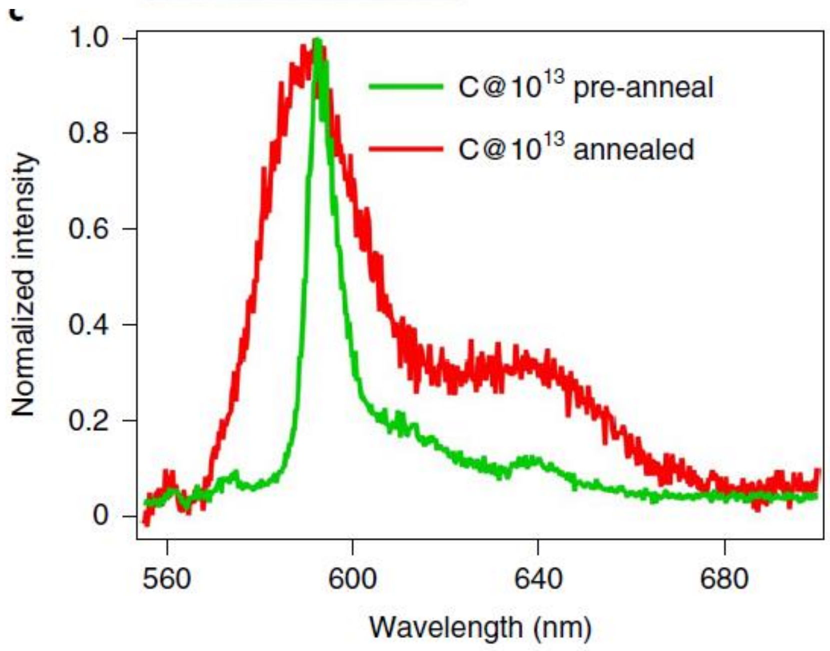
"Computational analysis of the simplest 12 carbon-containing defect species suggest the negatively charged $V_BC_N^-$ defect as a viable candidate"

ASPIC
+
Radiotracer PL

@ISOLDE
would provide direct identification

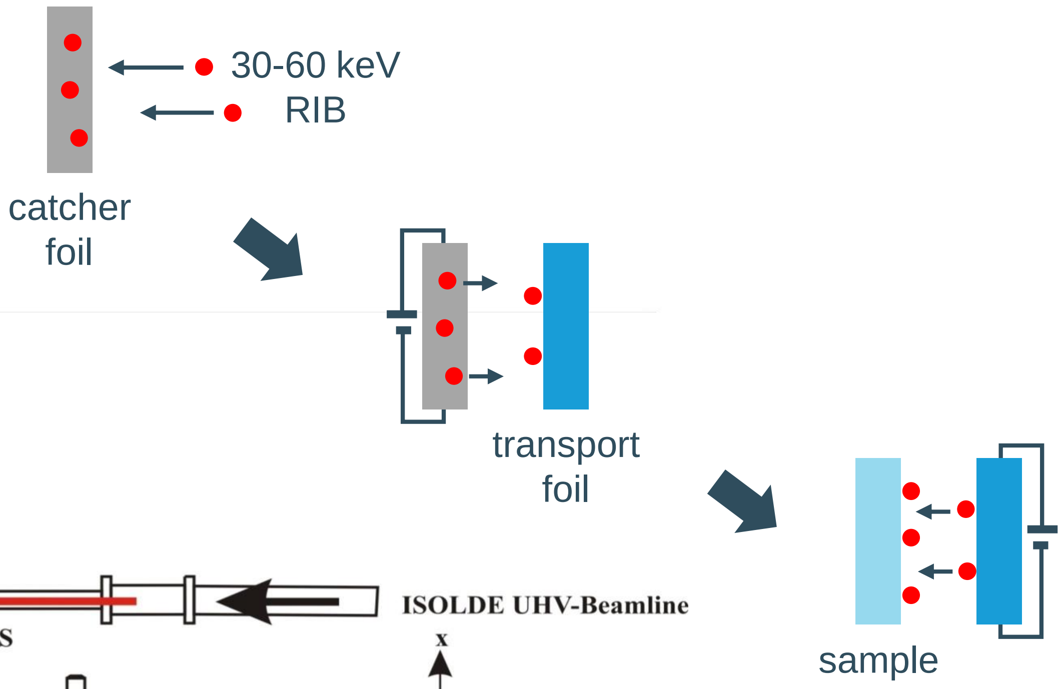


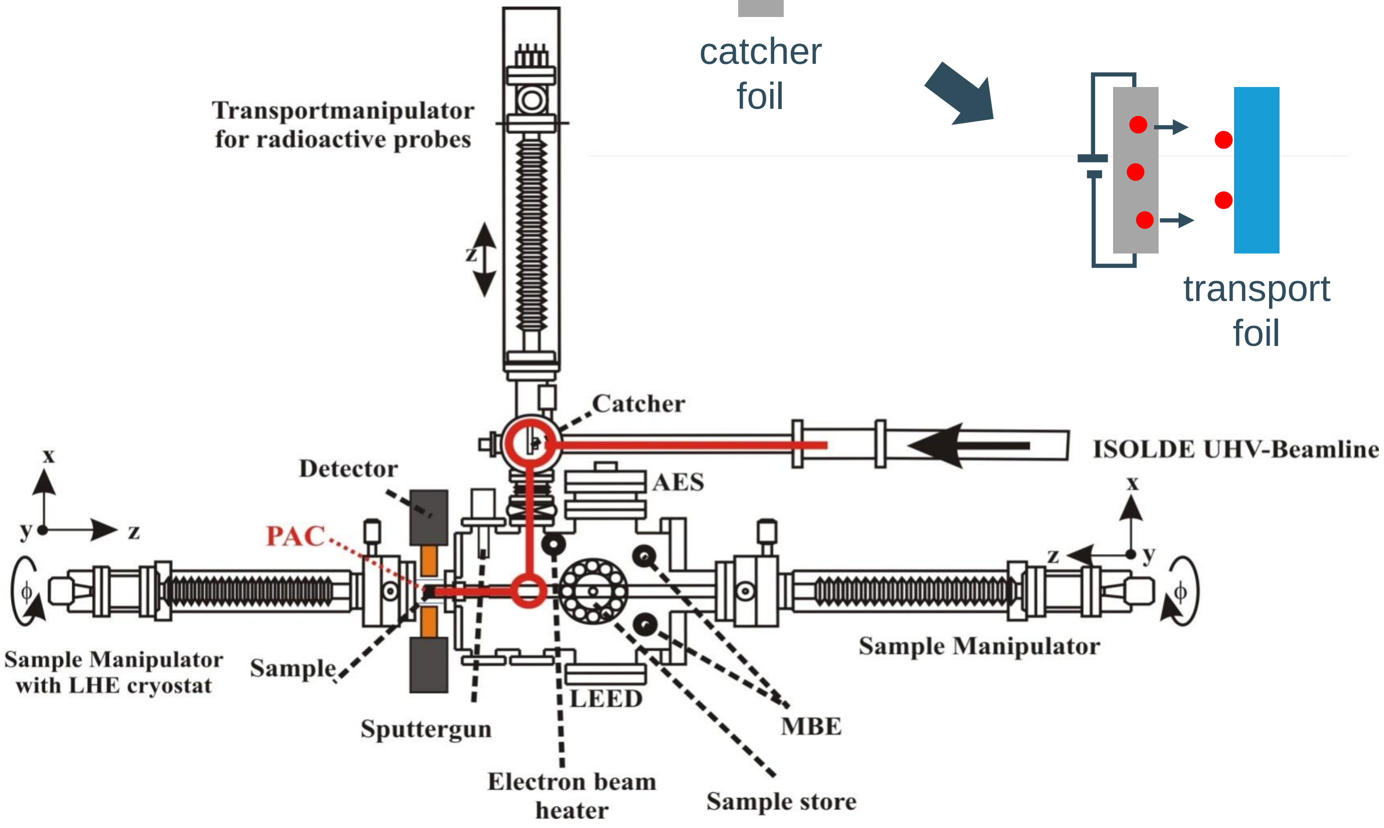




ASPIC: *Apparatus for Surface Physics and Interfaces at CERN*

before…





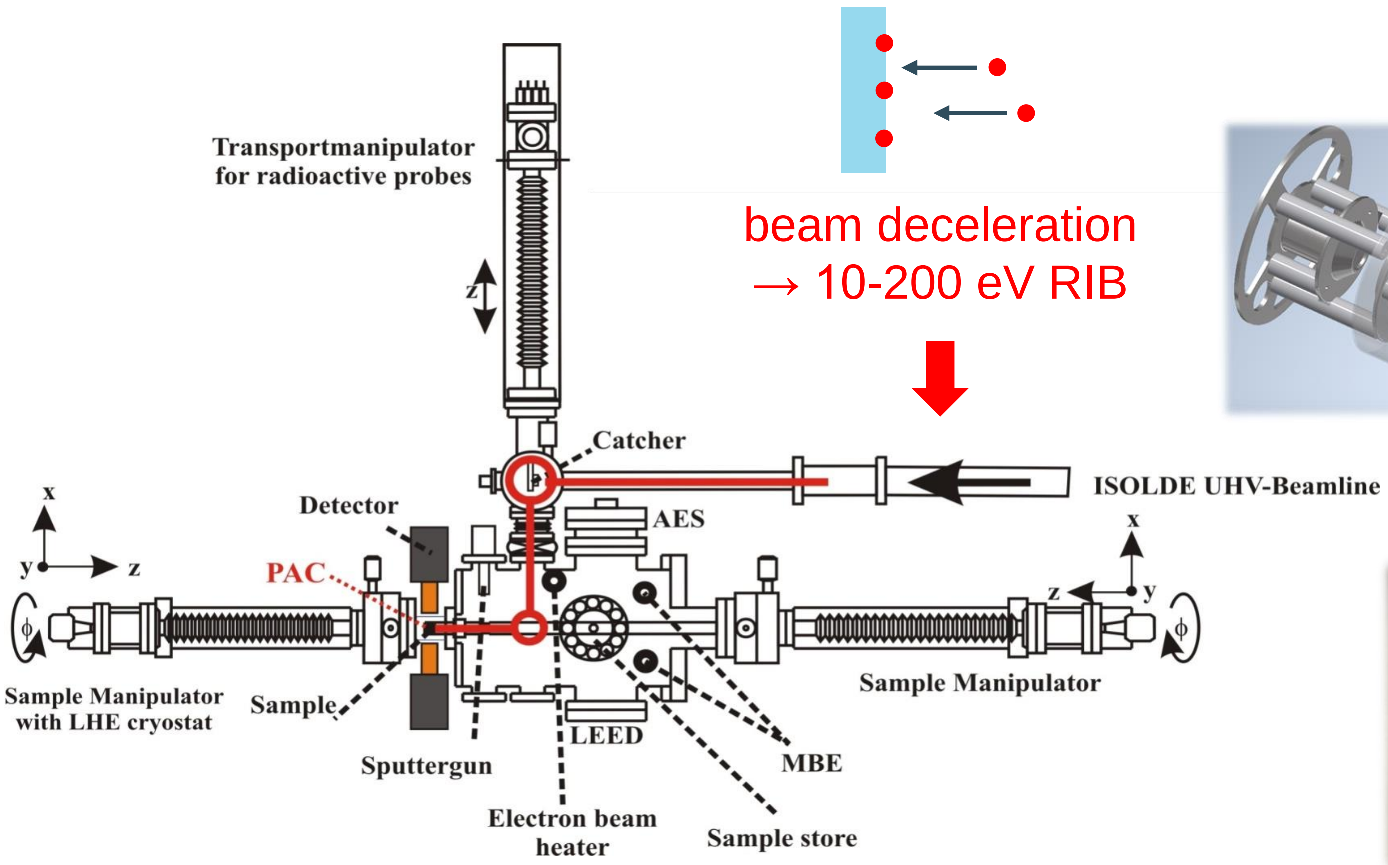
ASPIC: ***A****pparatus for* ***S****urface* ***P****hysics and* ***I****nterfaces at* ***C****ERN*

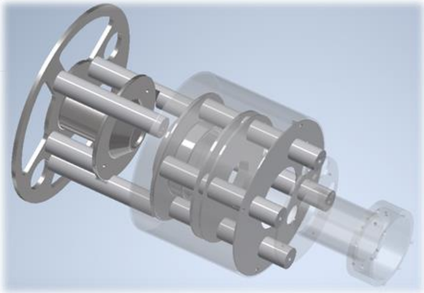
near future…

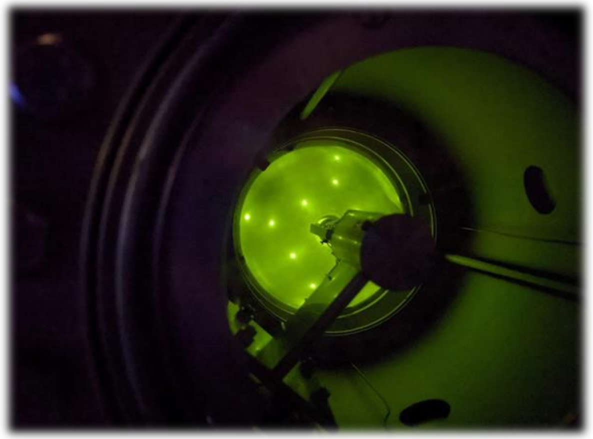
ongoing upgrade funded by
BMBF (Germany)
and FWO (Belgium)

sample – **direct doping** of 2D materials

beam deceleration
→ 10-200 eV RIB

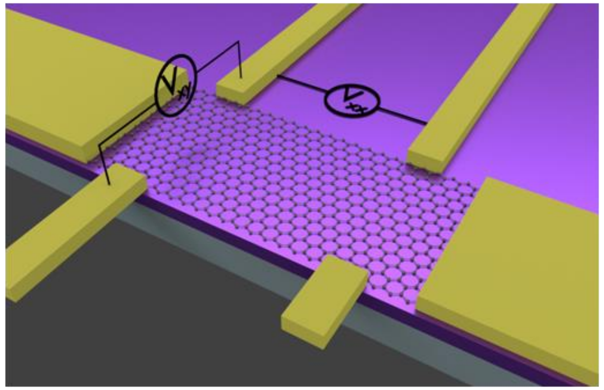


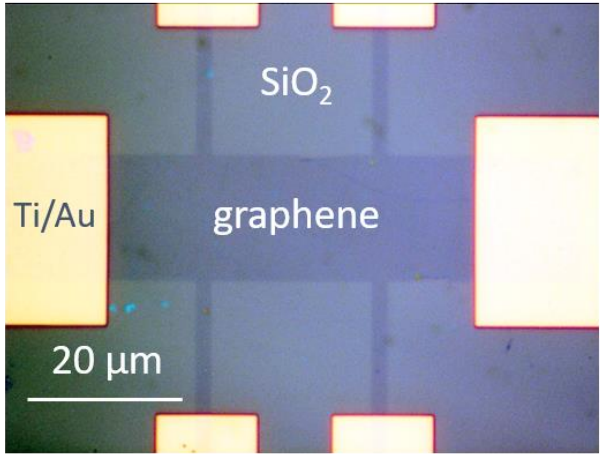


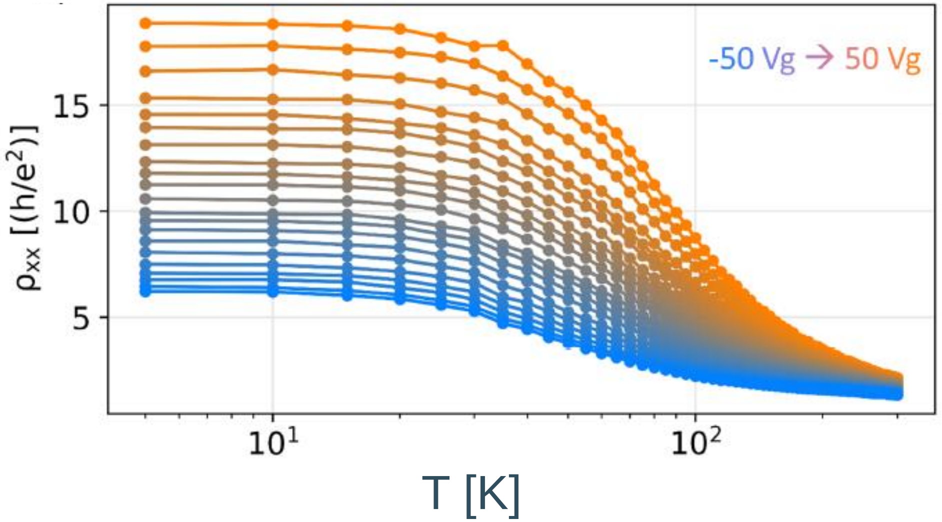


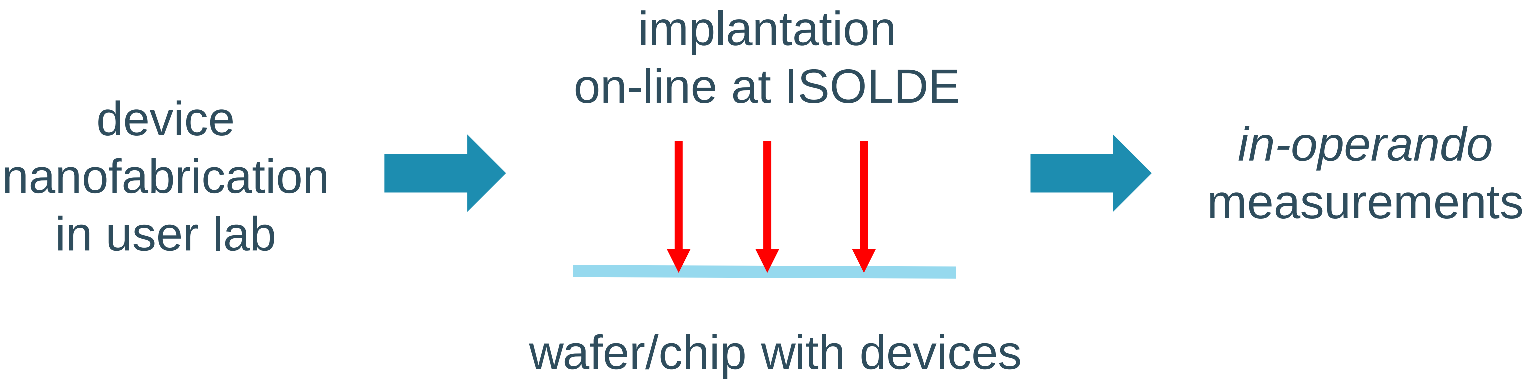
What else?

RIB + quantum devices (*in-operando*)









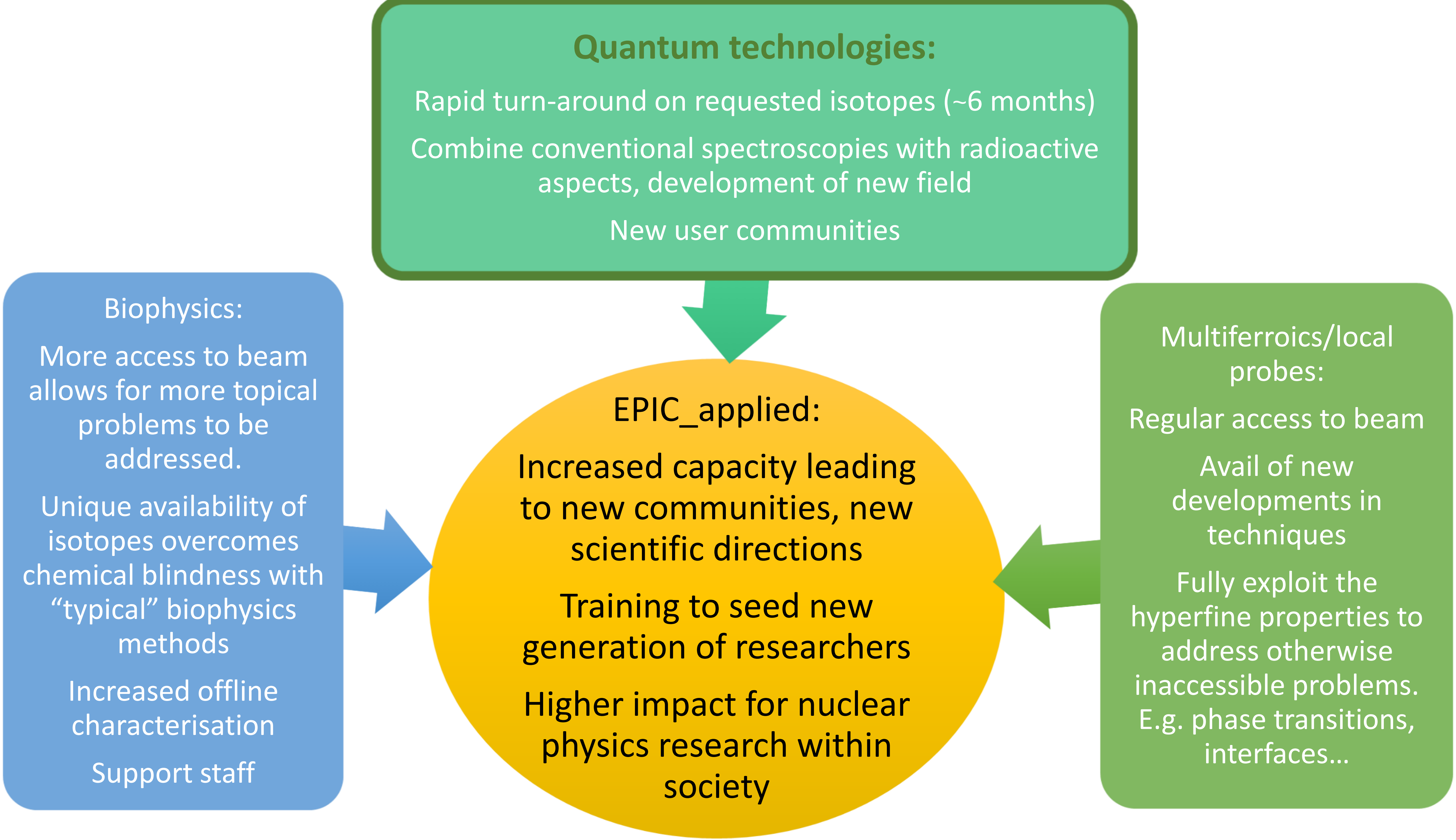
- properties changing over time
  (half-life → unambiguous correlation)
- device operation + nuclear technique
  (gate bias, current injection etc. changes probed properties → *in-operando*)

needs / dreams

- new ISOLDE hall dedicated to low energy physics
  - dedicated target(s) and ion source(s) for
    - fast turn-around (~6 months) from proposal acceptance to beam time allocation
    - **guaranteed** – critical for research in these topics – sustainable research programs
  - extended on-line floor space for new setups (ASPIC…)
  - extended off-line lab space for (PL lab, quantum devices lab…)
- on-site staff/scientists
  - to maintain on-line and off-line labs
  - to run offline experiments continuously throughout the year
  - to support/bridge the access of new non-RIB users (PL, devices, …):
    - new users, high-profile, high impact…

funding

- National programs
  - IRI in Flanders/Belgium
  - BMBF in Germany
  - …
- CERN?
  - Quantum initiative?
  - Societal impact! (basic-applied gap)
- European programs
  - Quantum Flagship?
  - …


Quantum technologies:
Rapid turn-around on requested isotopes (~6 months)
Combine conventional spectroscopies with radioactive aspects, development of new field
New user communities
Biophysics:
More access to beam allows for more topical problems to be addressed.
Unique availability of isotopes overcomes chemical blindness with “typical” biophysics methods
Increased offline characterisation
Support staff
EPIC_applied:
Increased capacity leading to new communities, new scientific directions
Training to seed new generation of researchers
Higher impact for nuclear physics research within society
Multiferroics/local probes:
Regular access to beam
Avail of new developments in techniques
Fully exploit the hyperfine properties to address otherwise inaccessible problems. E.g. phase transitions, interfaces…