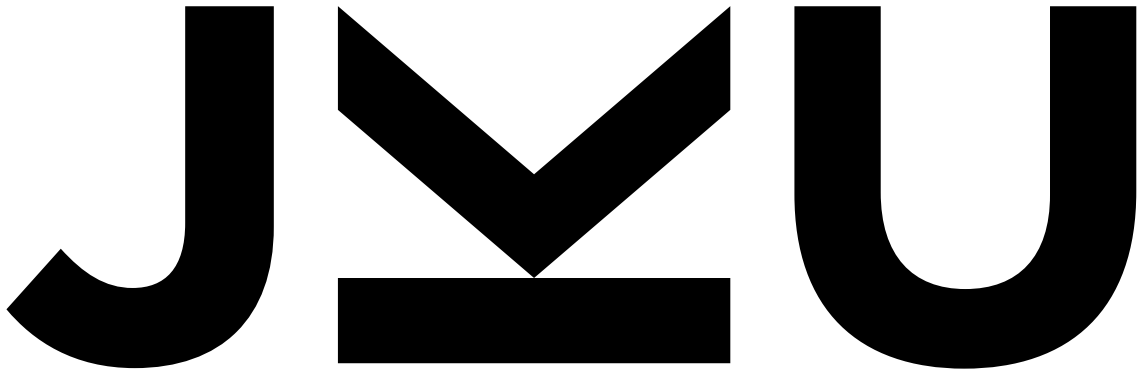


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Superconductors as building blocks for quantum sensors and quantum metrology

Rajdeep Adhikari

Quantum Materials Group
Institute of semiconductor and solid state physics
Johannes Kepler University
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HFP | Institut für Halbleiter- und Festkörperphysik







MAG

Quantum Materials Group

October 2020

Collaborations and funding









































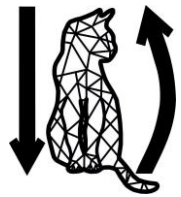














Bridge: USS Enterprise

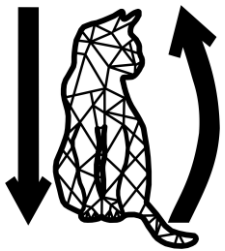


Stardate: 1310.2 (April 23, 2324)

The sensors: Class M planet with humanoid lifeforms, pre-warp civilization

Those sensors must be quantum

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Quantum mechanics

$$E = h\nu$$

$$\Delta x \Delta p \geq \hbar$$

$$H\Psi = E\Psi$$





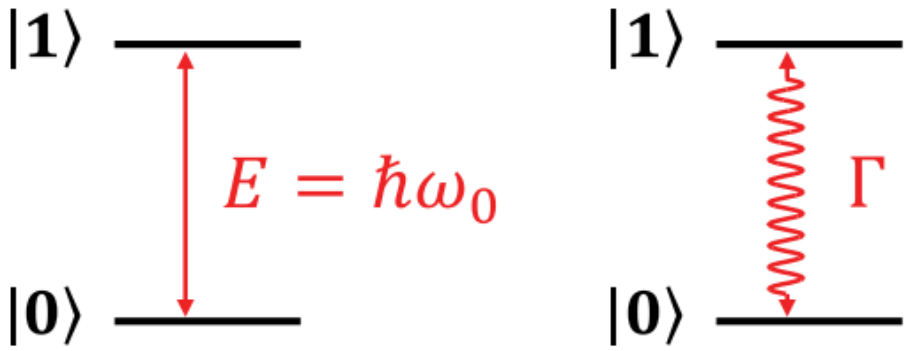
The quantum question

Can we find a promising real-world application of quantum mechanics that exploits its most counterintuitive properties?

Believed to be the promised ones




Belief might be incomplete – we can employ quantum systems for ‘’sensing’’

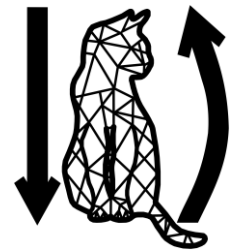


Quantum sensors and sensing

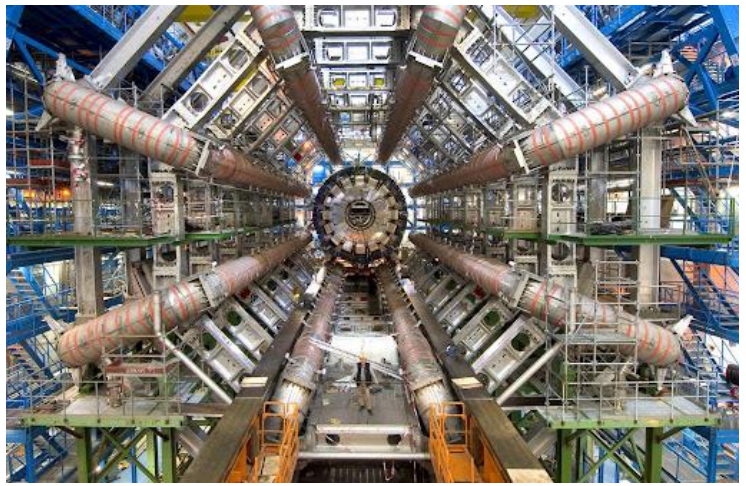
- Capitalize on the central weakness of the quantum systems
- Strong sensitivity to external perturbations

- Quantum coherence
- Quantum entanglement

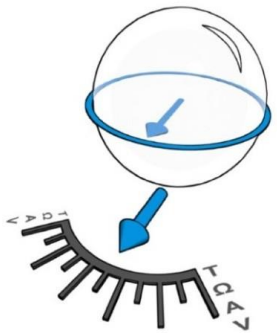
C. L. Degen *et al*. Rev. Mod. Phys. (2017)

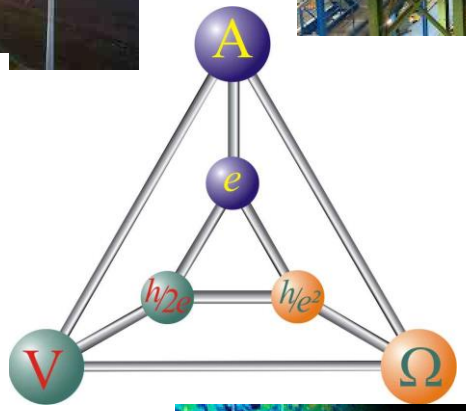


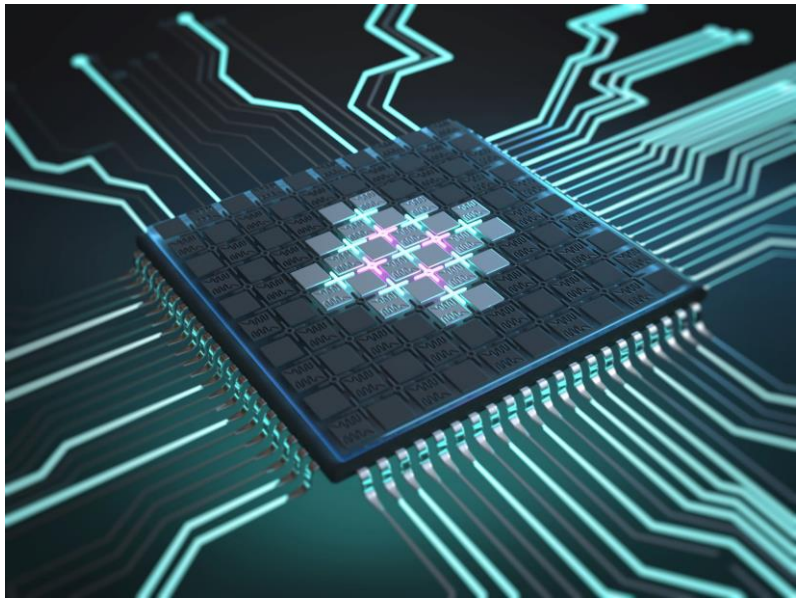


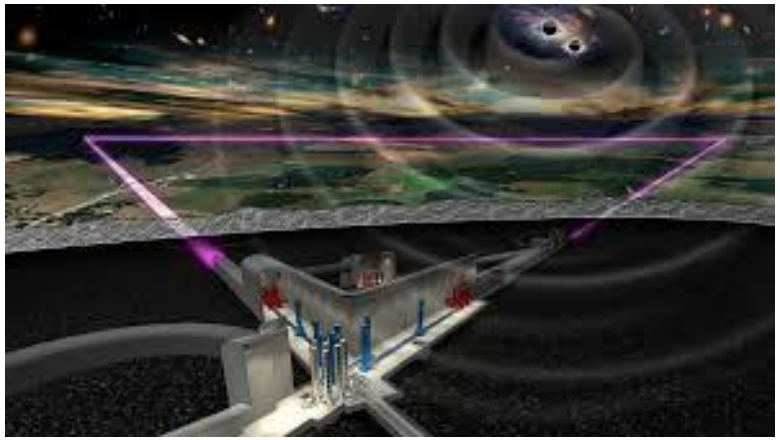


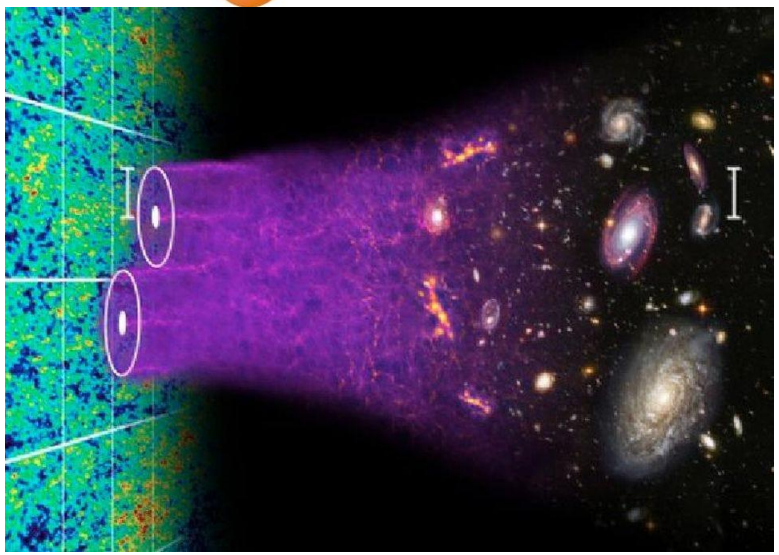





A
e
h/2e
h/e²
V
Ω

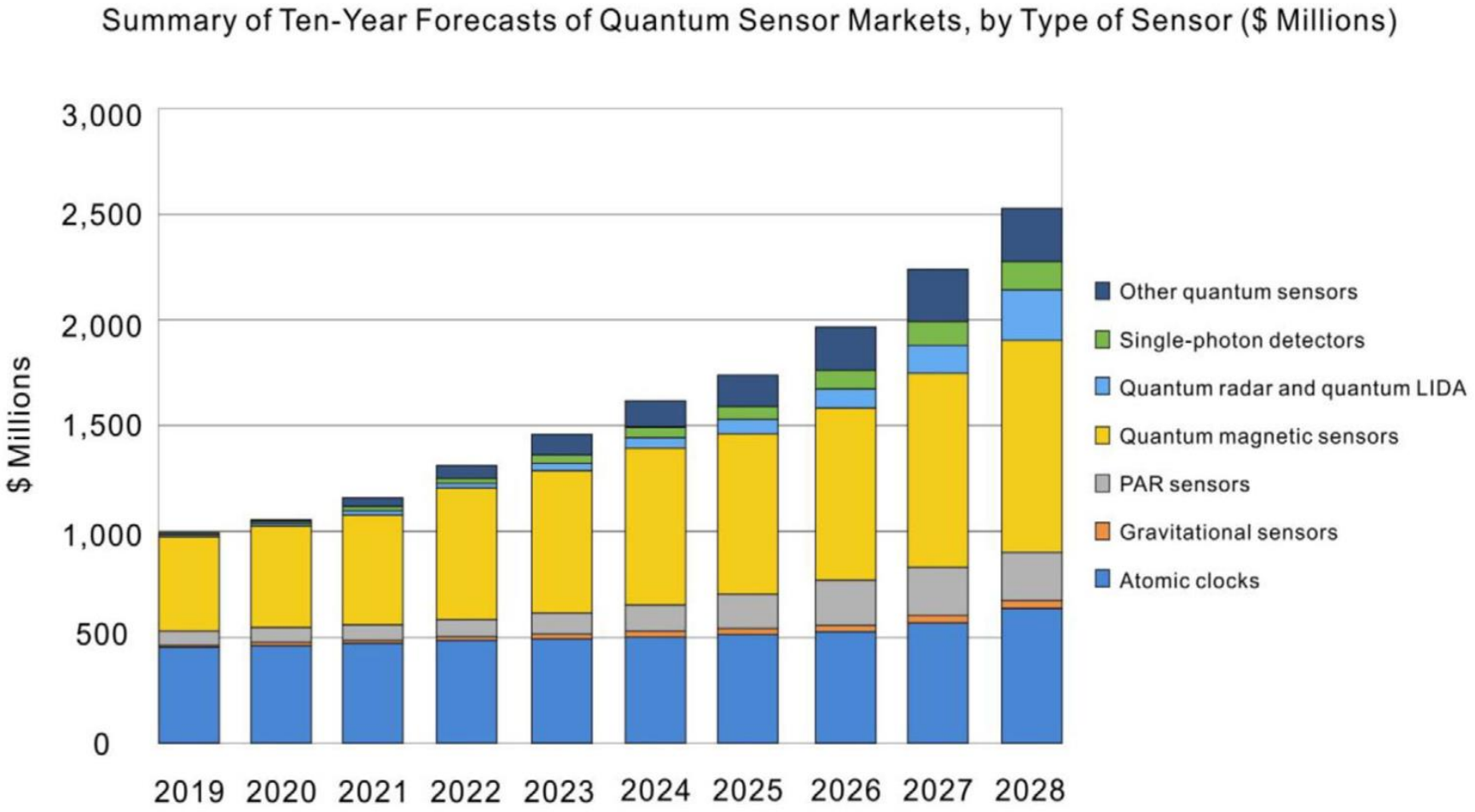




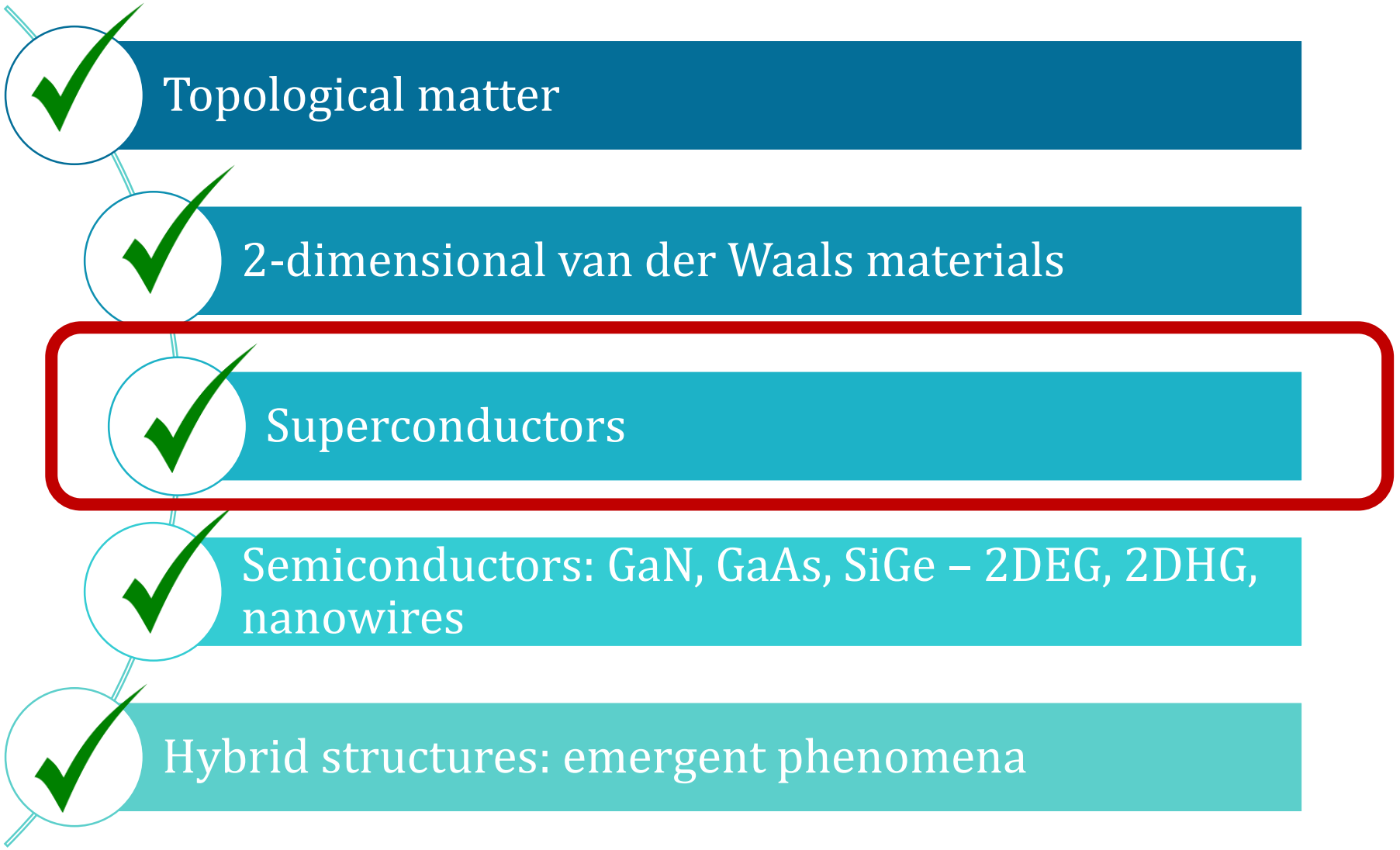


Quantum sensors and sensing

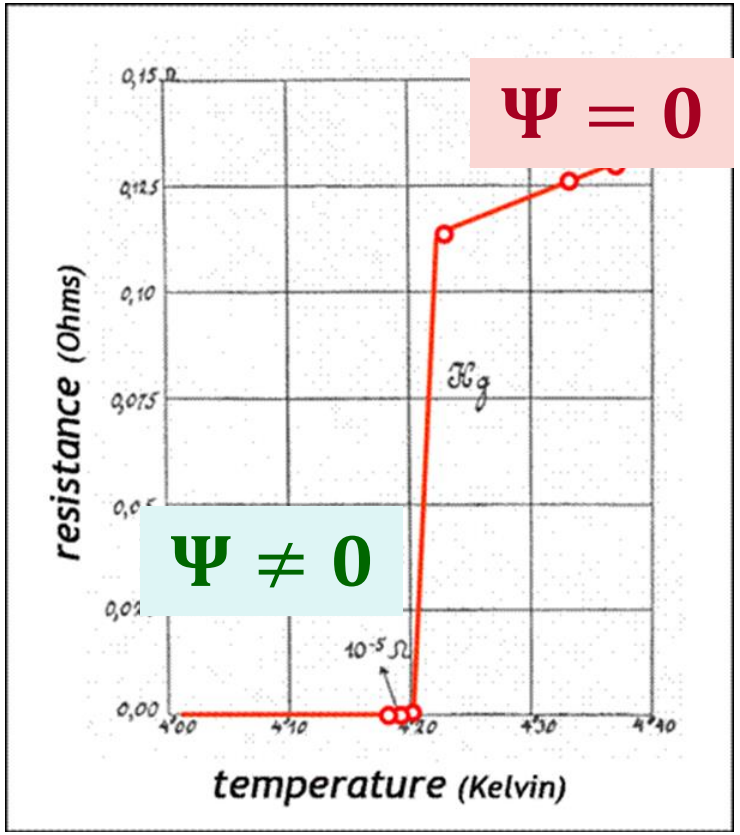
- Energy applications
- High energy physics, dark matter
- Astronomy/astrophysics/gravity
- Bio imaging



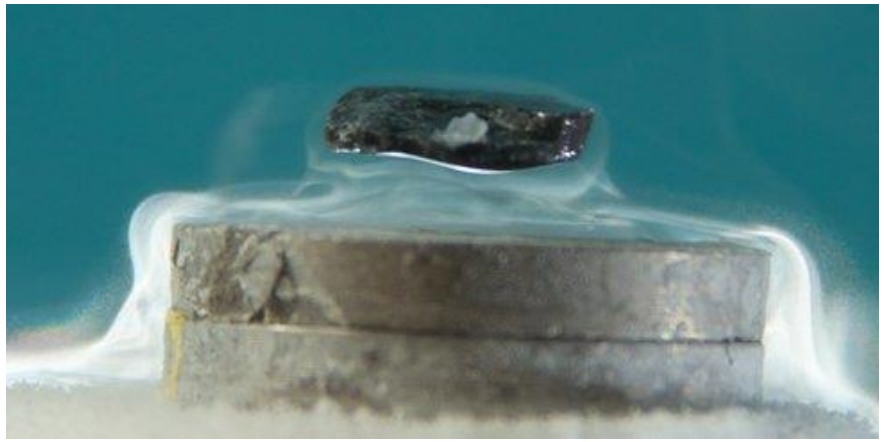
The quantum materials



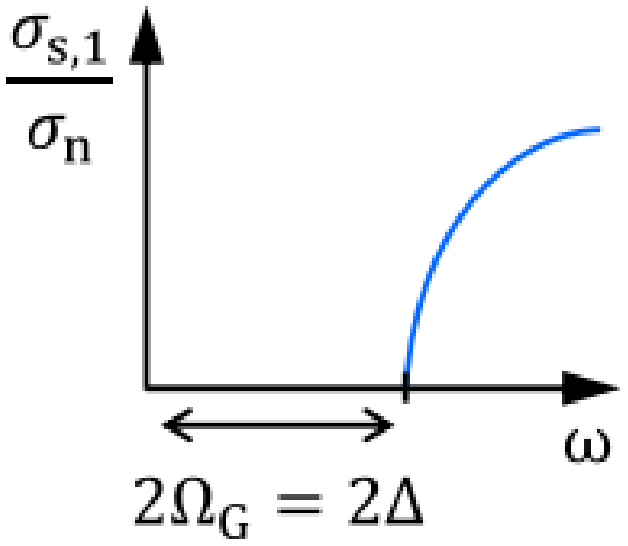
Superconductivity: The phenomenon



Zero resistivity



Perfect diamagnet



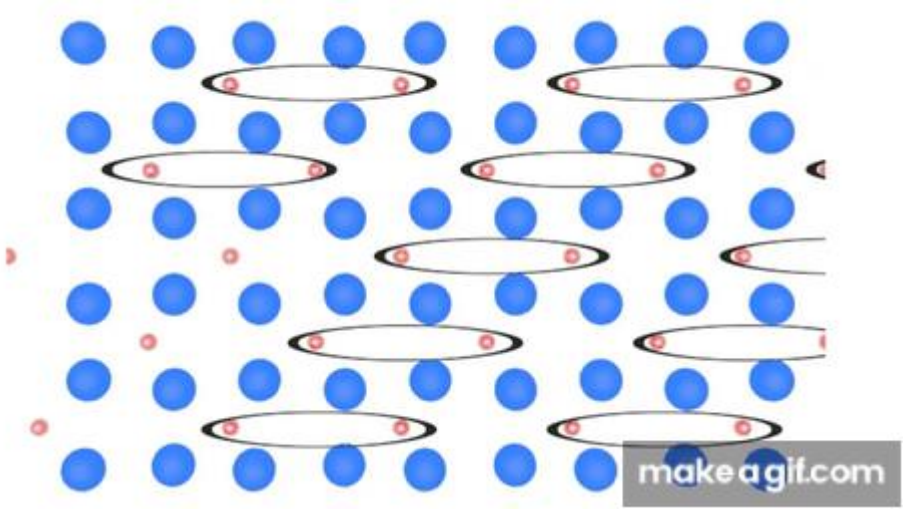
Energy gap

Order parameter Ψ

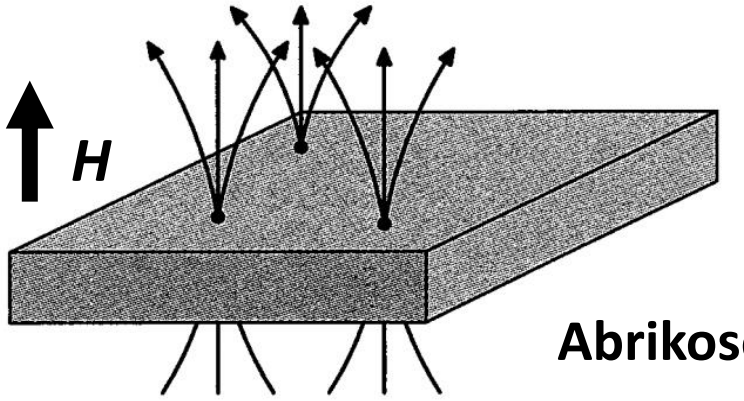
- Thermodynamic phase transition
- Electron-phonon interaction: Cooper pairs
- Coherent state

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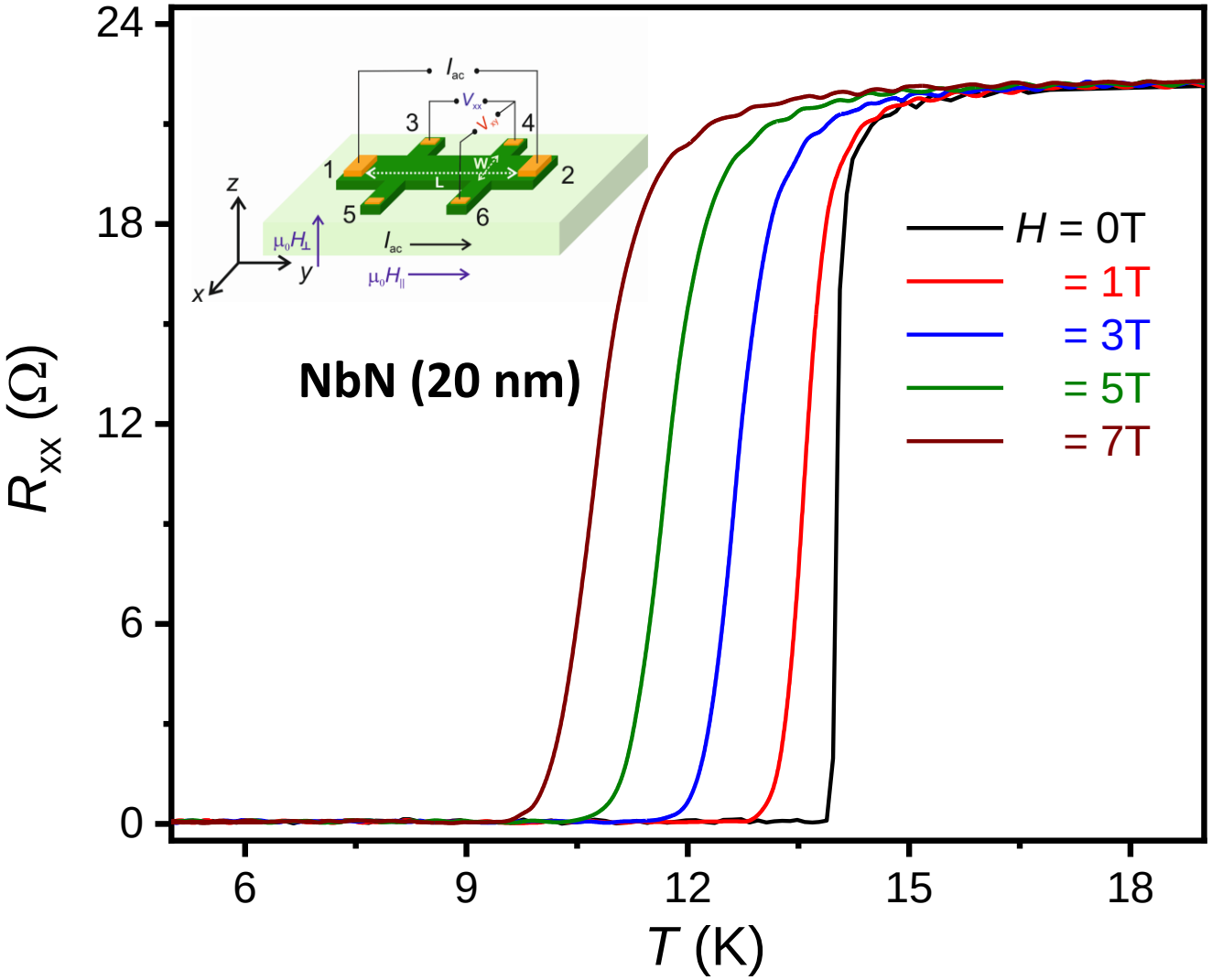
Superconductivity: The mechanism



Cooper pairs

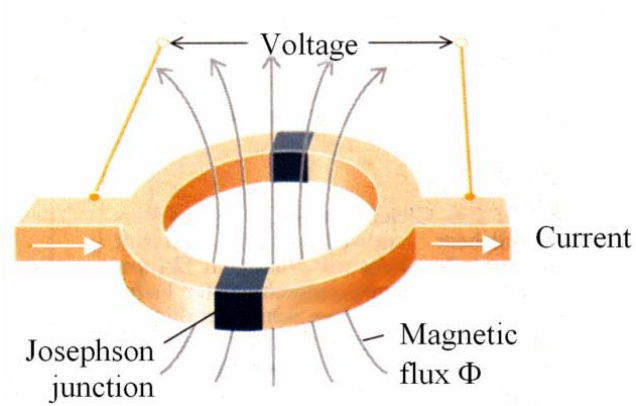


Abrikosov vortices



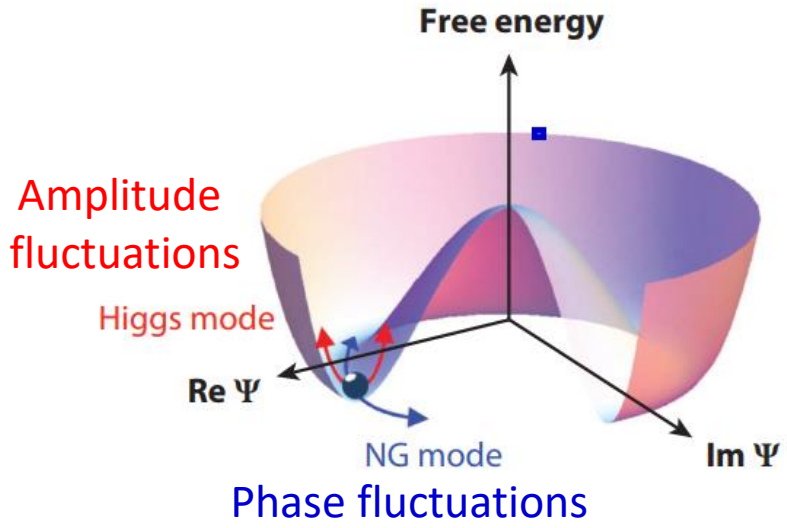
R. Adhikari *et al*. Nanomaterials (2022)

Superconductivity: A few more facts

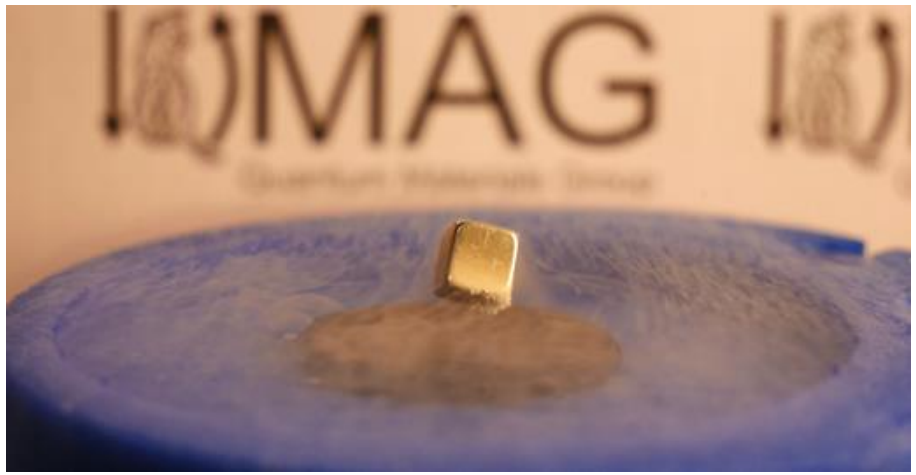


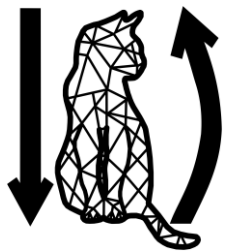
Josephson effect: tunnelling of Cooper pairs

- Josephson effect: Cooper pairs can tunnel across an insulator
- Anderson-Higgs mechanism: Emergence of massive photons
- Higgs bosons in superconductors – observed before LHC
- Gapless superconductivity: a topological effect
- Quantum phase slips: tunelling of vortices



Higgs mechanism massive bosons





Superconducting quantum sensors: Fabrication and characterization

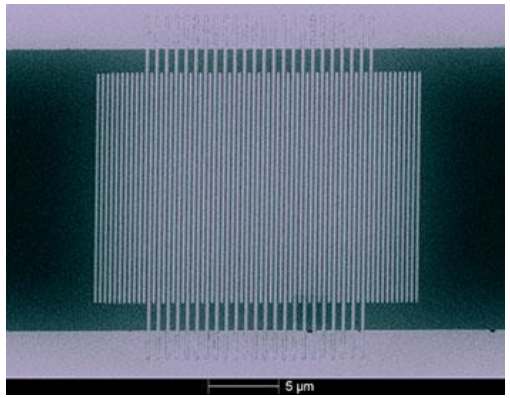


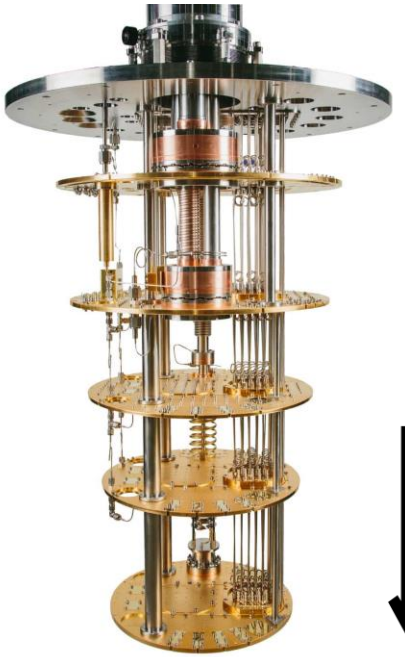


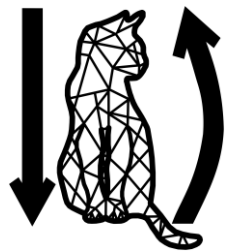




LIT OIC, QMag, JKU







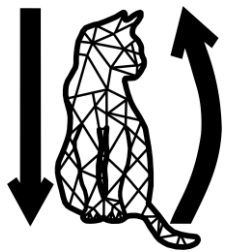
Quantum sensing: Principle

“Quantum sensors” capitalize on the central weakness of quantum systems, their strong sensitivity to external disturbances.

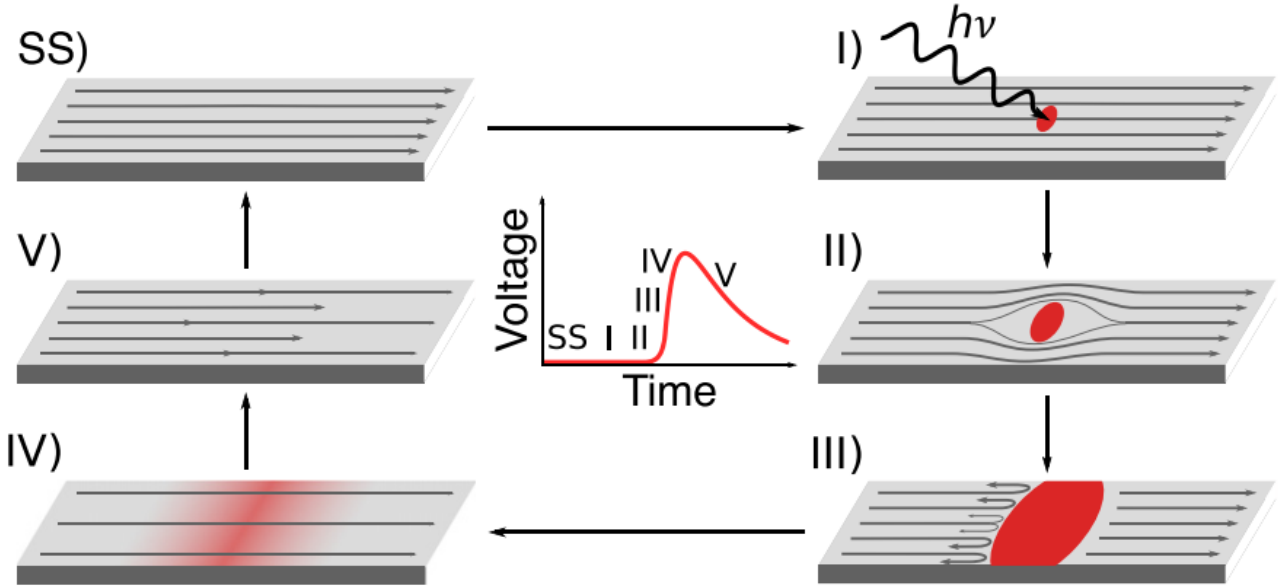
Superconducting quantum sensors

- Josephson effect: SQUID
- Superconductor-insulator-superconductor (SIS)
- Superconducting nanowire single photon detectors (SNSPD)
- Transition edge sensors (TES)
- Hot electron bolometers (HEB)

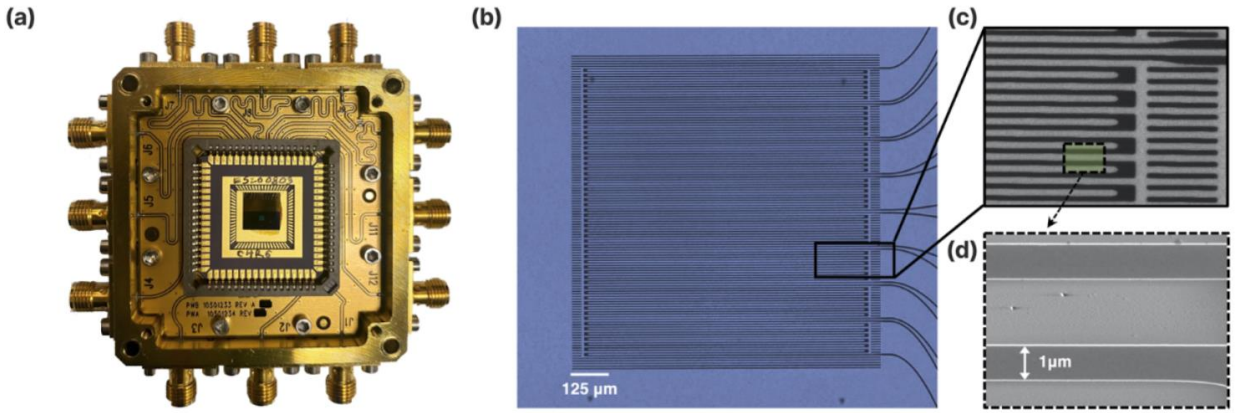
C. L. Degen *et al*. Rev. Mod. Phys. (2017)
R. Kaltenbeck *et al*. Expt. Astronomy (2021)
I. Esmaeilzadeh *et al*. Appl. Phys. Lett. (2021)



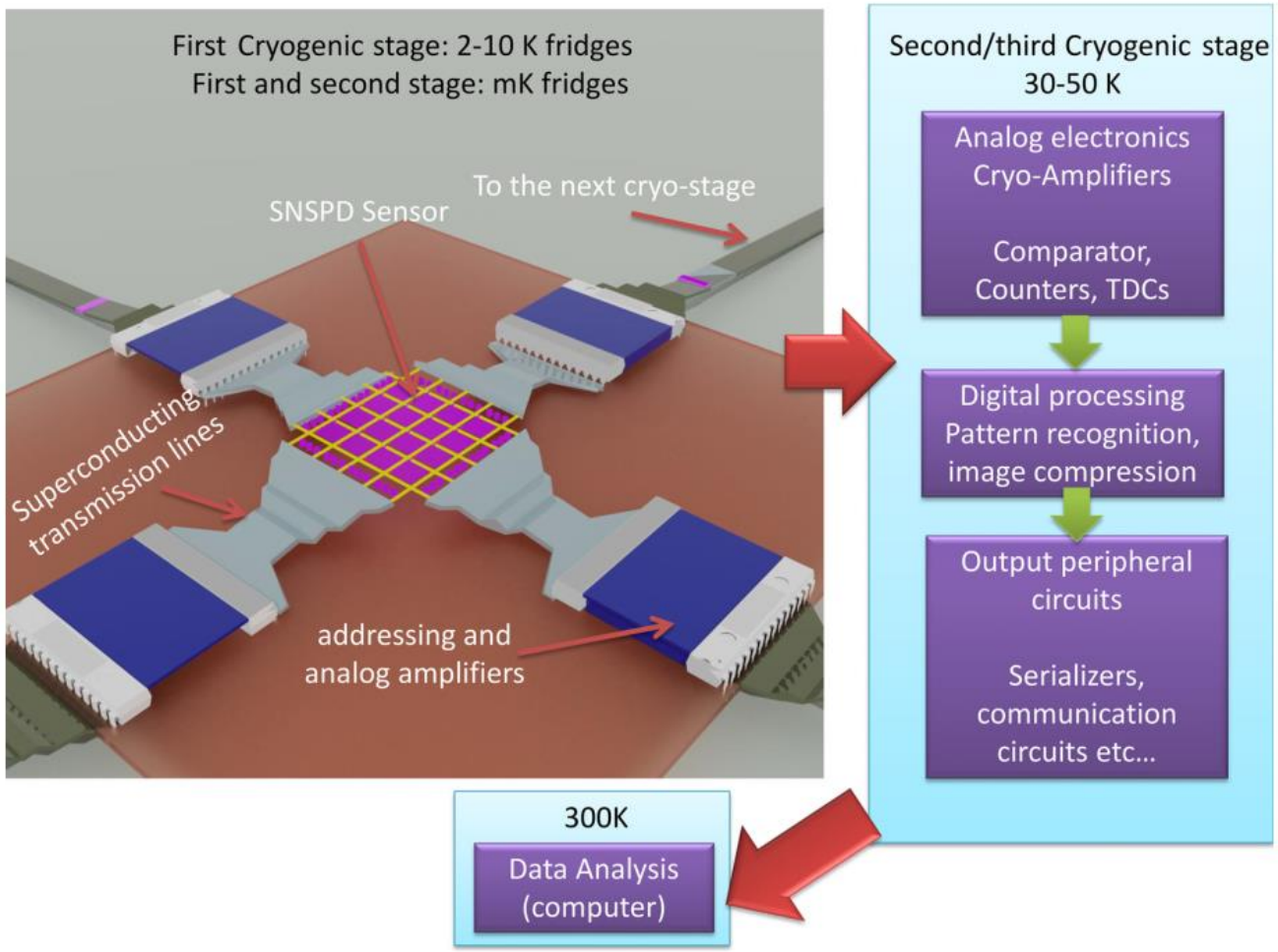
Pair breaking sensors – SNSPD



- Width: (50-100) nm
- Thickness: (5-10) nm
- Meandering structures
- X-ray to mid-IR



I. Esmaeilzadeh *et al*. Appl. Phys. Lett. (2021)

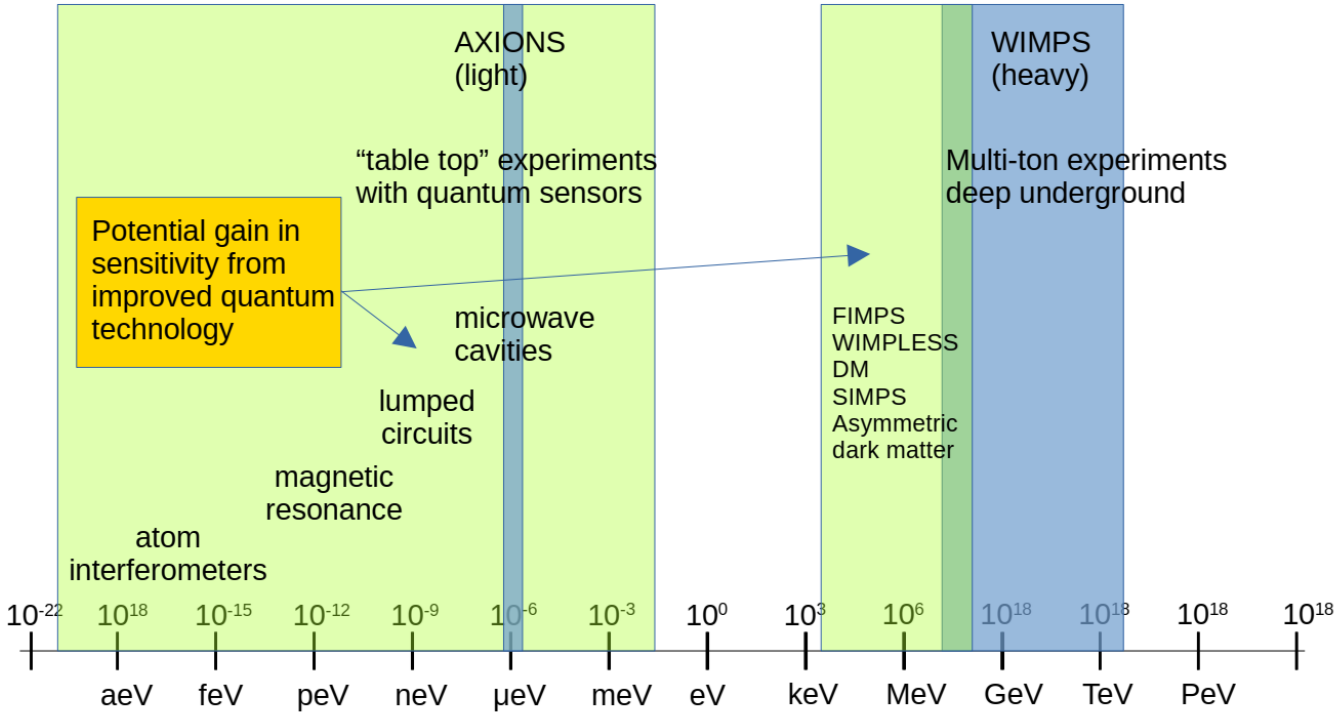


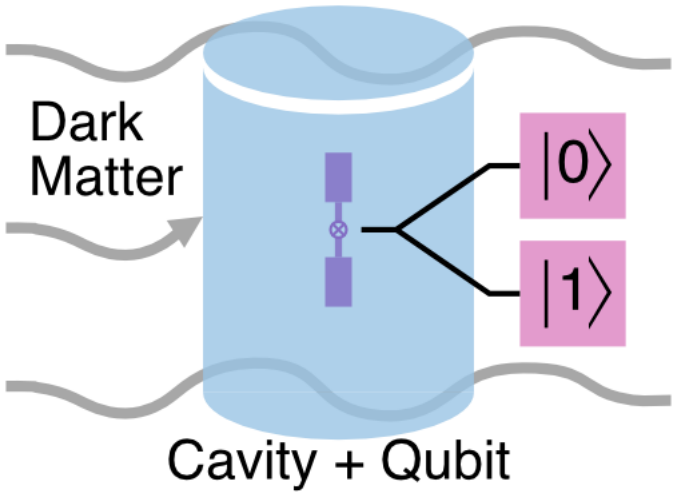
- Quantum optics,
- LIDAR, Imaging, Weather
- Exoplanet search
- Terrestrial and space telescopes
- Deep space communication
- Dark matter search
- Positron emission tomography
- Biomedical imaging

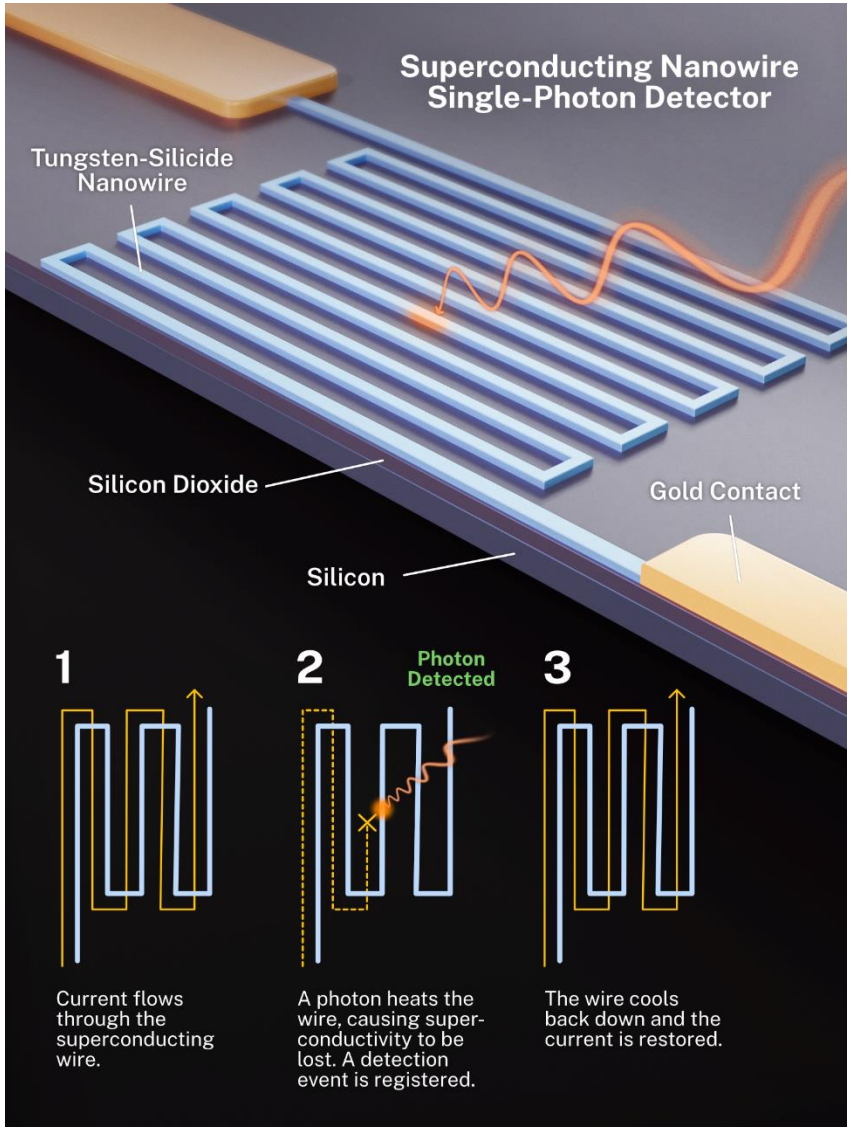
SNSPD: 5-folds improved performance over photodiodes !!

I. Esmaeilzadeh *et al*. Appl. Phys. Lett. (2021)

Superconducting quantum sensors as dark matter detector



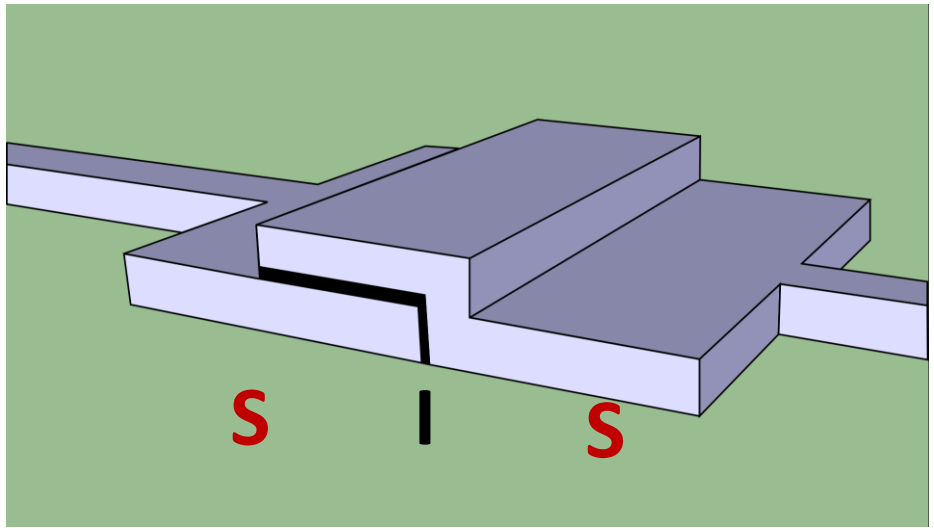


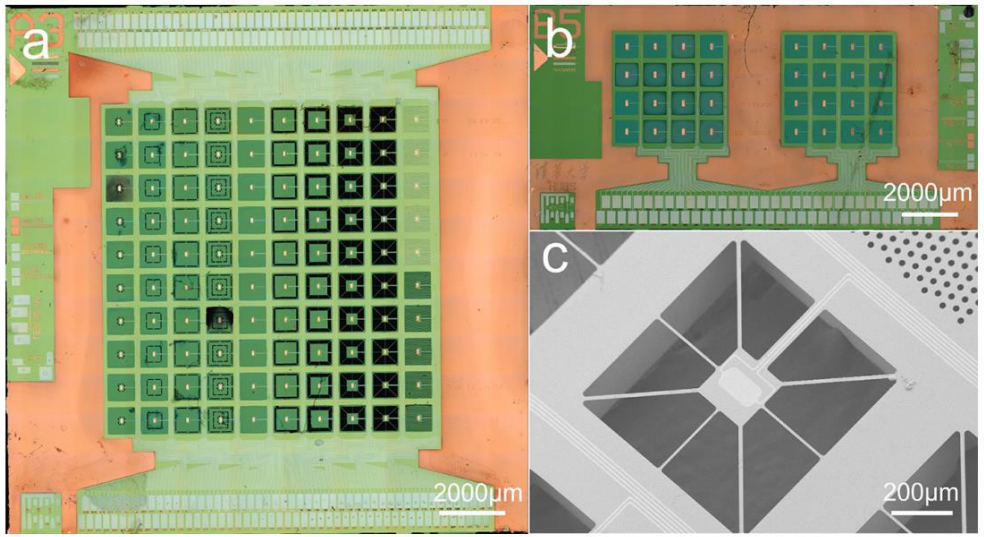


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S. Golwala *et al*. Annu. Rev. Nucl. Part. Sci (2022)

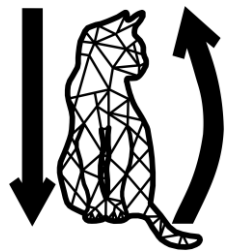
Superconductor-insulator-superconductor sensors



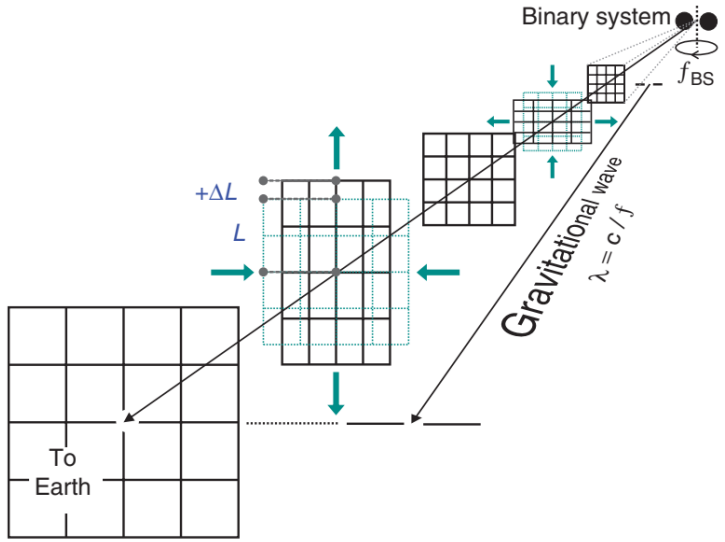


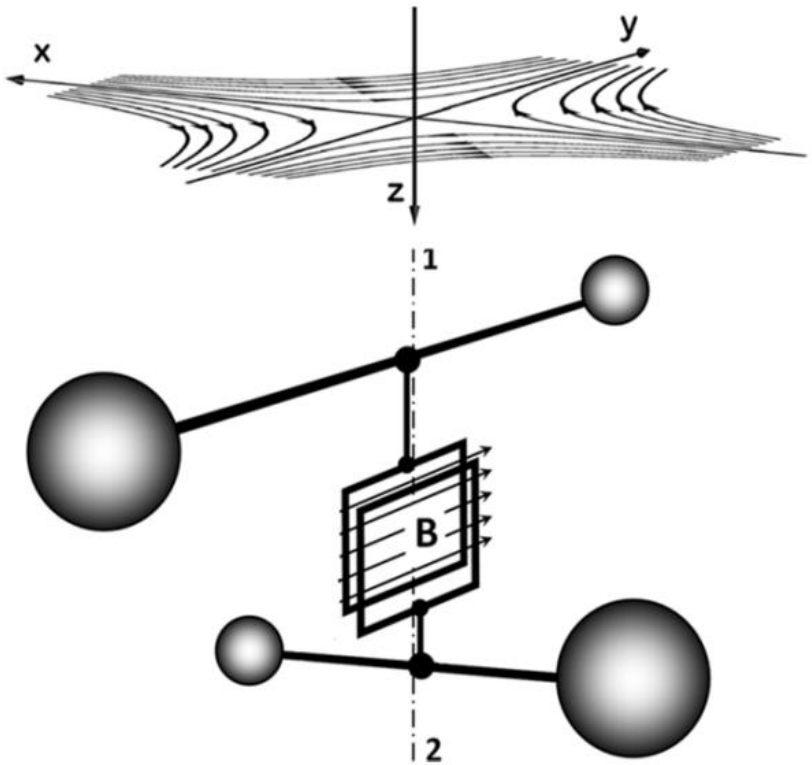
- Tunelling of quasiparticles
- Transition edge sensors
- Hot electron bolometers
- Kinetic inductance detectors
- μm to sub-mm
- Temperature and polarization maps of CMBR
- Axion searcher – DM research
- Mass $\leq$ 1 meV difficult for colliders
- Space telescopes

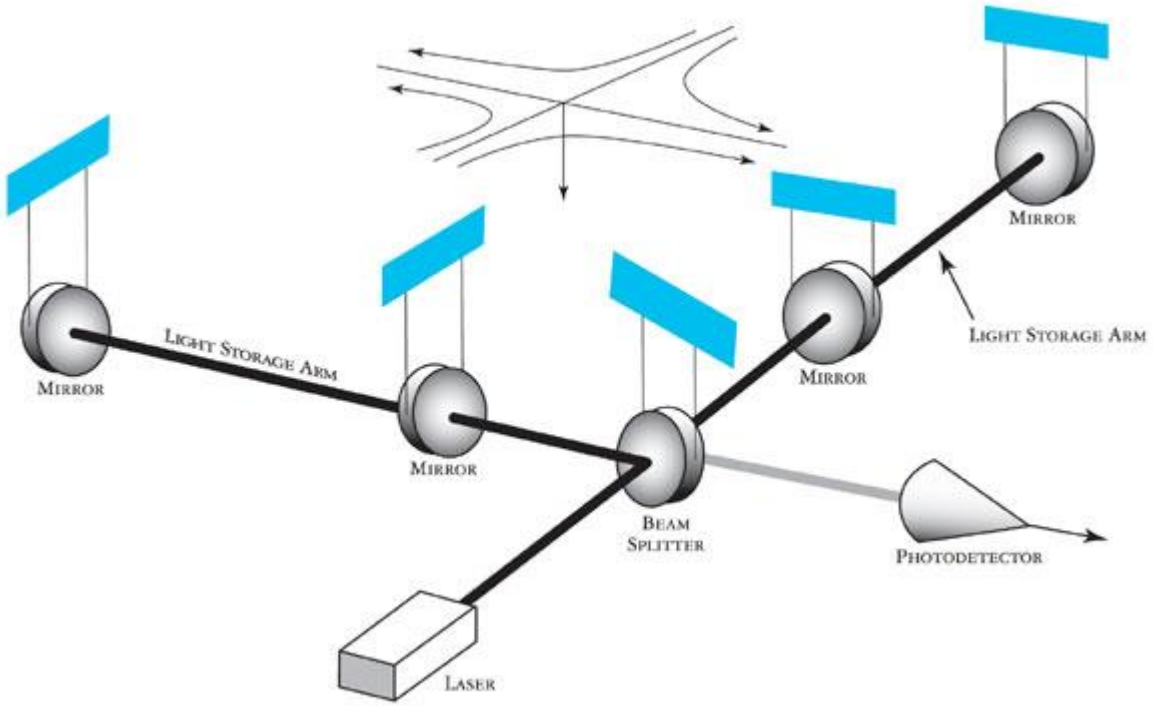
S. Wang *et al*. Superconductivity (2022)



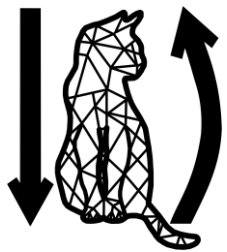
Superconducting quantum sensors for gravity



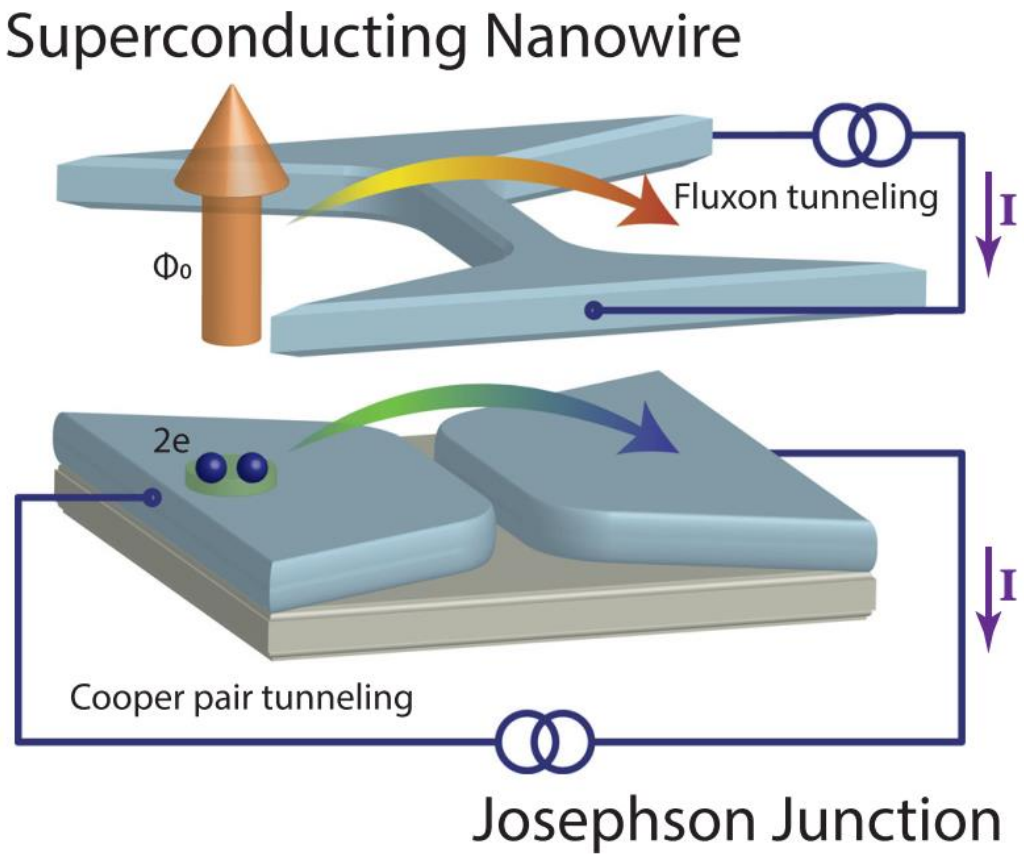


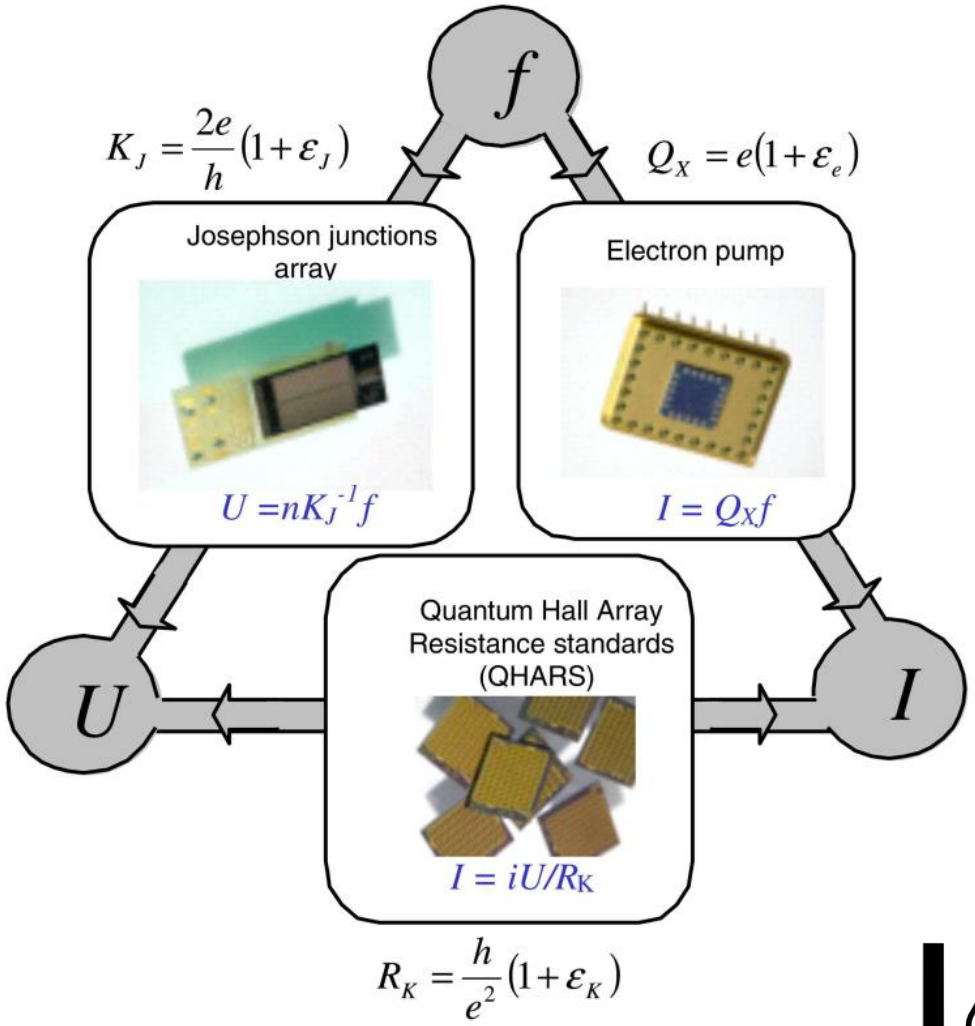


A. Gulian *et al*. Phys. Rev. Res. (2021)



Superconducting quantum sensors: quantum metrology





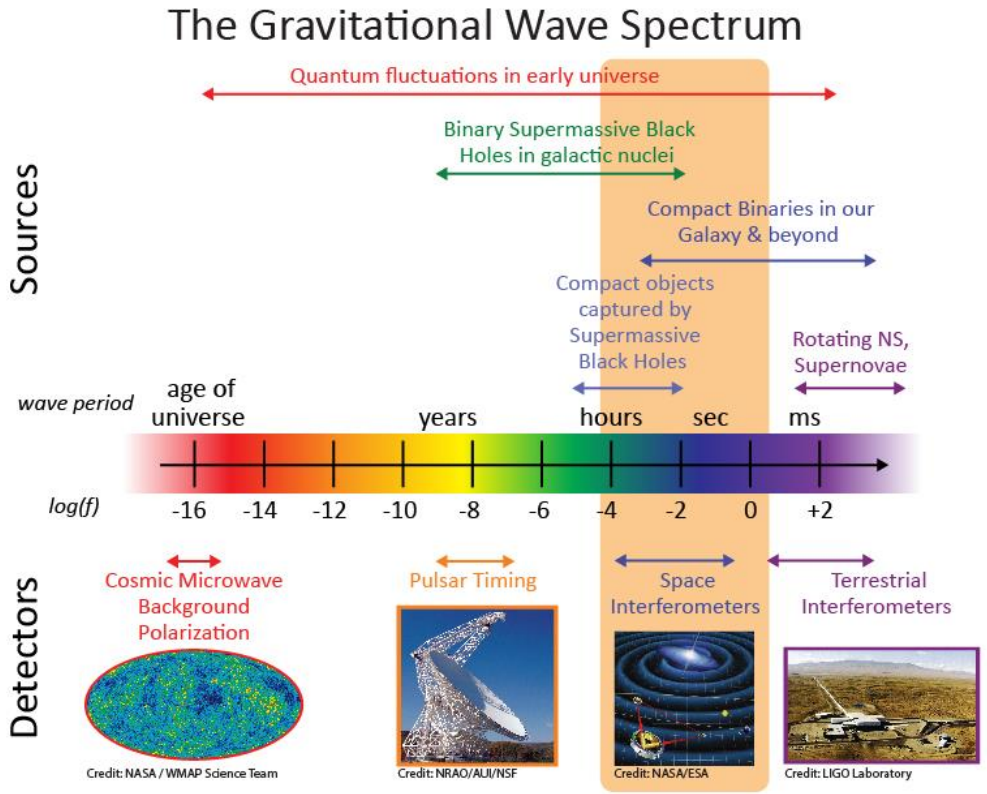
K. Arutyunov *et al*. Commun. Phys. (2021)

Future space missions with superconducting quantum sensors

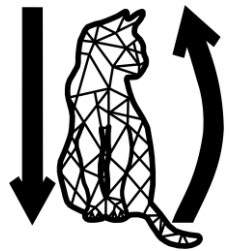
- Hot Universe Baryon Surveyor (HUBS)
- Atacama Large Millimeter/submillimeter Array (ALMA)
- Athena X-ray observatory
- GUSTO high-altitude balloon mission
- Laser Interferometer Space Antenna (LISA)







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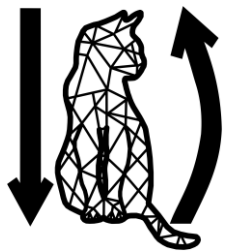


The importance of industry-academia collaboration

- Quantum sensors roadmap: Over a few billion dollar industry over the next (10-15) years
- Investments: bulk share from governments
- Space industry, health, defence – government-industry partnerships
- Close cooperation of academic research, industry based R&D : realization of next generation of hybrid cryo sensor prototypes

Success in quantum technology

- ✓ **Sustainable earth**
- ✓ **Civilizational progress**
- ✓ **Exploration of the final frontier – SPACE!!**




"....to boldly go where no one has gone before!"