

Breaking Moore's Law

Challenges of quantum transport in nanoscale sensor development for particle physics

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CERN's Quantum Initiative & DRD5 Collaboration

- 7 New Detector R&D Collaborations at CERN
- In particular, DRD5 focuses on «Quantum Sensors»

- Definition: A «quantum sensor» is a device which senses quantum states...

- In particle physics context:
 - Incident radiation deposits energy in device
 - So radiation induces a change in quantum state
 - Read out quantum state for an ultra-precise measurement

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- Meanwhile, Norway has a strong group working on semiconductor radiation trackers

Sensor family → Work Package ↓	clocks & clock networks	superconduct- ing & spin- based sensors	kinetic detectors	atoms / ions / molecules & atom interferometry	opto- mechanical sensors	nano-engineered / low-dimensional / materials
WP1 <i>Atomic, Nuclear and Molecular Systems in traps & beams</i>	X			X	(X)	
WP2 <i>Quantum Materials (0-, 1-, 2-D)</i>		(X)	(X)		X	X
WP3 <i>Quantum super- conducting devices</i>		X				(X)
WP4 <i>Scaled-up massive ensembles (spin-sensitive devices, hybrid devices, mechanical sensors)</i>		X	(X)	X	(X)	X
WP5 <i>Quantum Techniques for Sensing</i>	X	X	X	X	X	
WP6 <i>Capacity expansion</i>	X	X	X	X	X	X

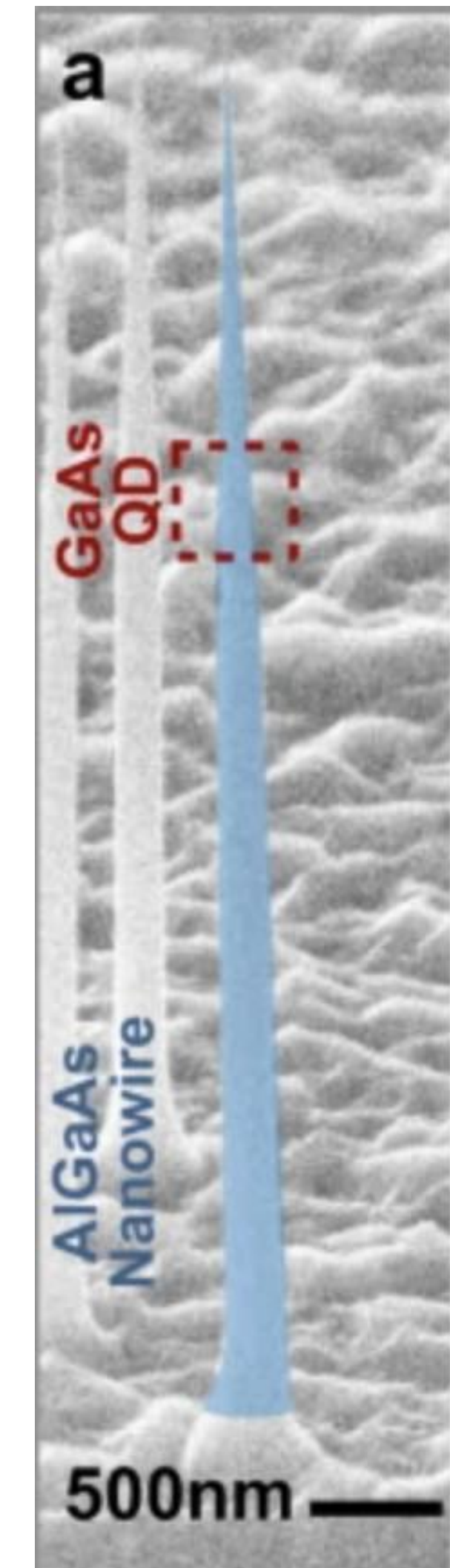
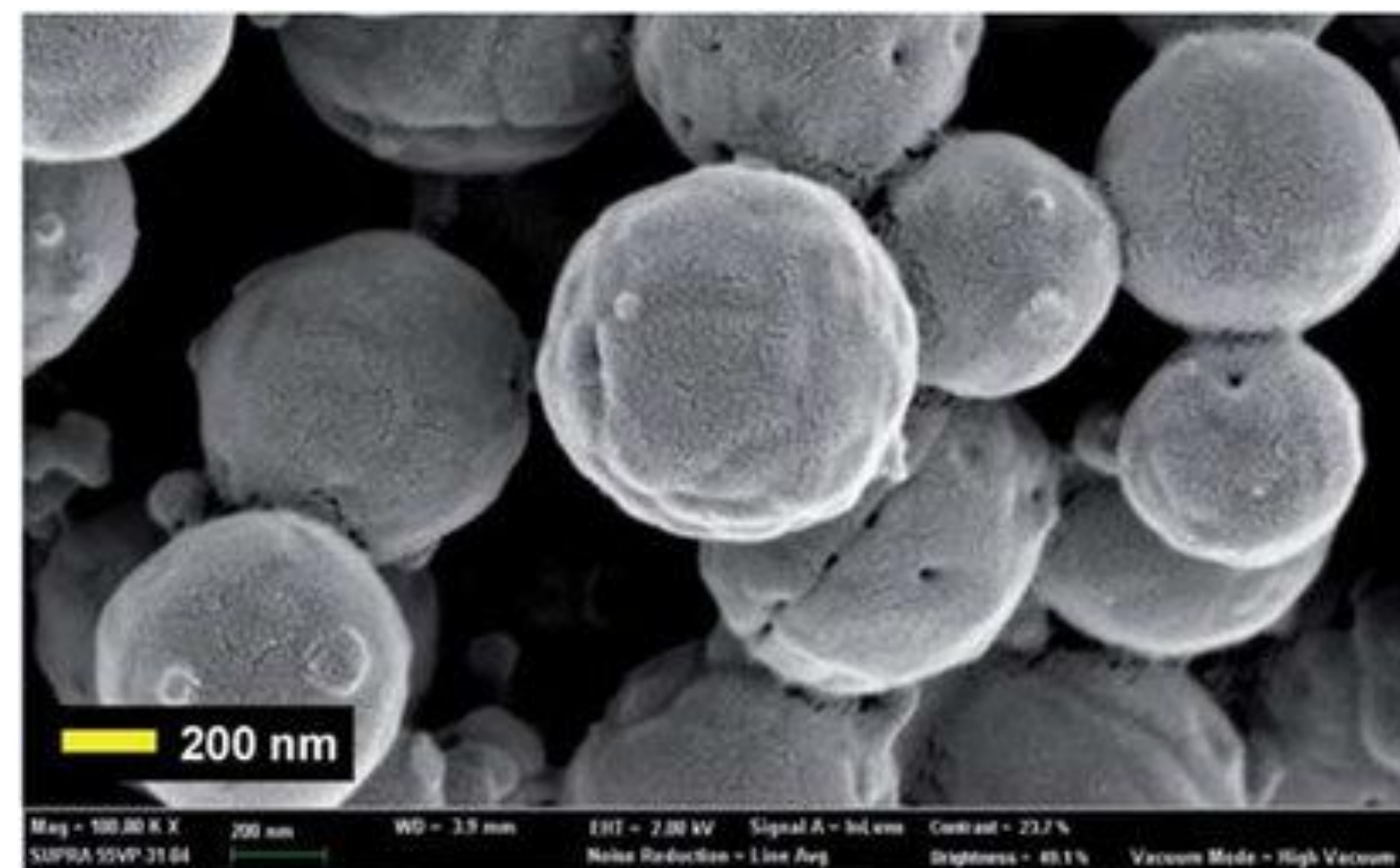
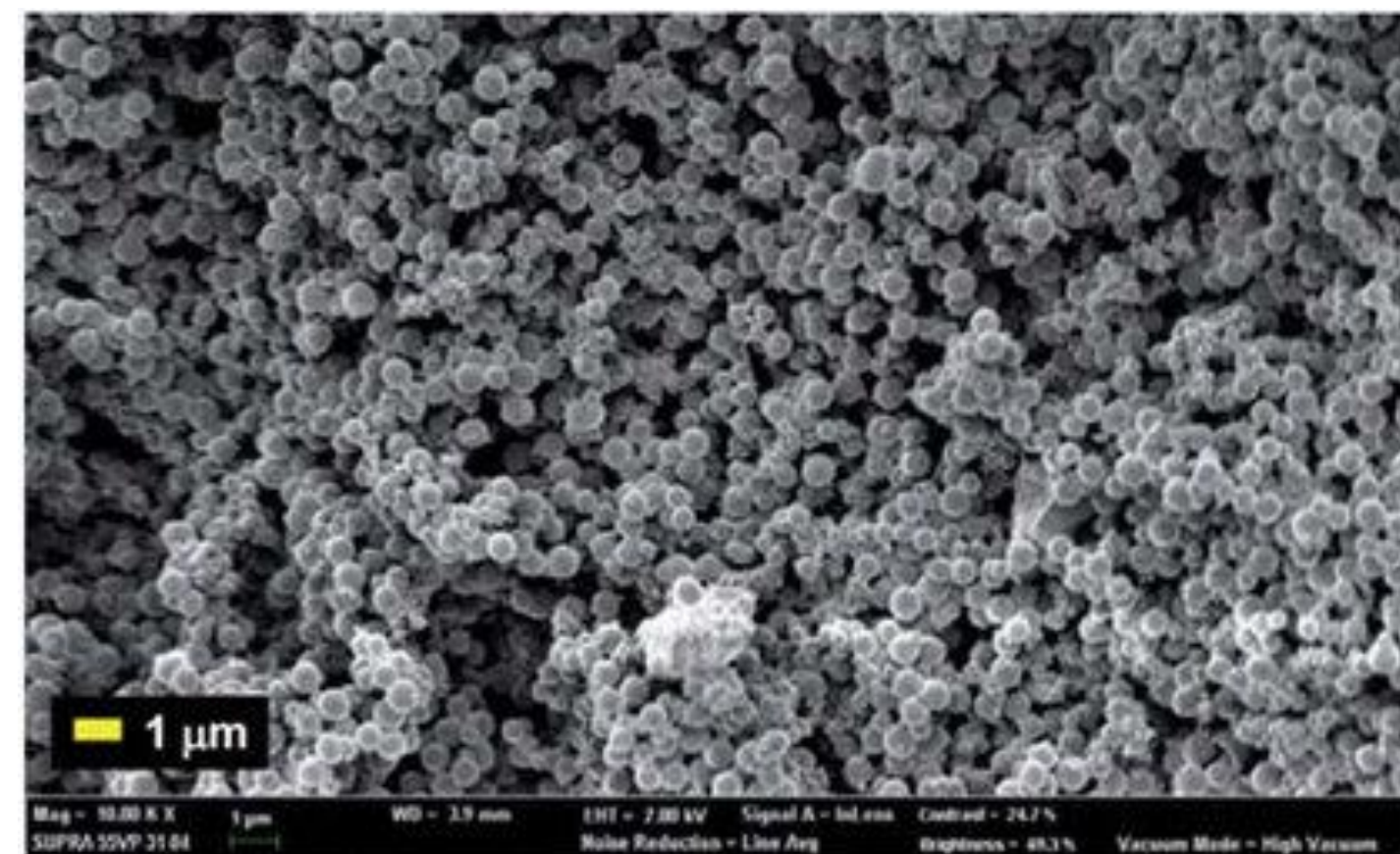
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Semiconductor structures at nanometer scales

- When structures reach the size of : «quantum confinement» occurs
 - The structure impacts the properties of the material itself
 - Can tune the properties to best fit the measurement you want to make
- Depending on how many spatial axes are **not** «quantum confined»
 - 0D: Quantum dots
 - 1D: Nanowires
 - 2D: Nanoplatelets

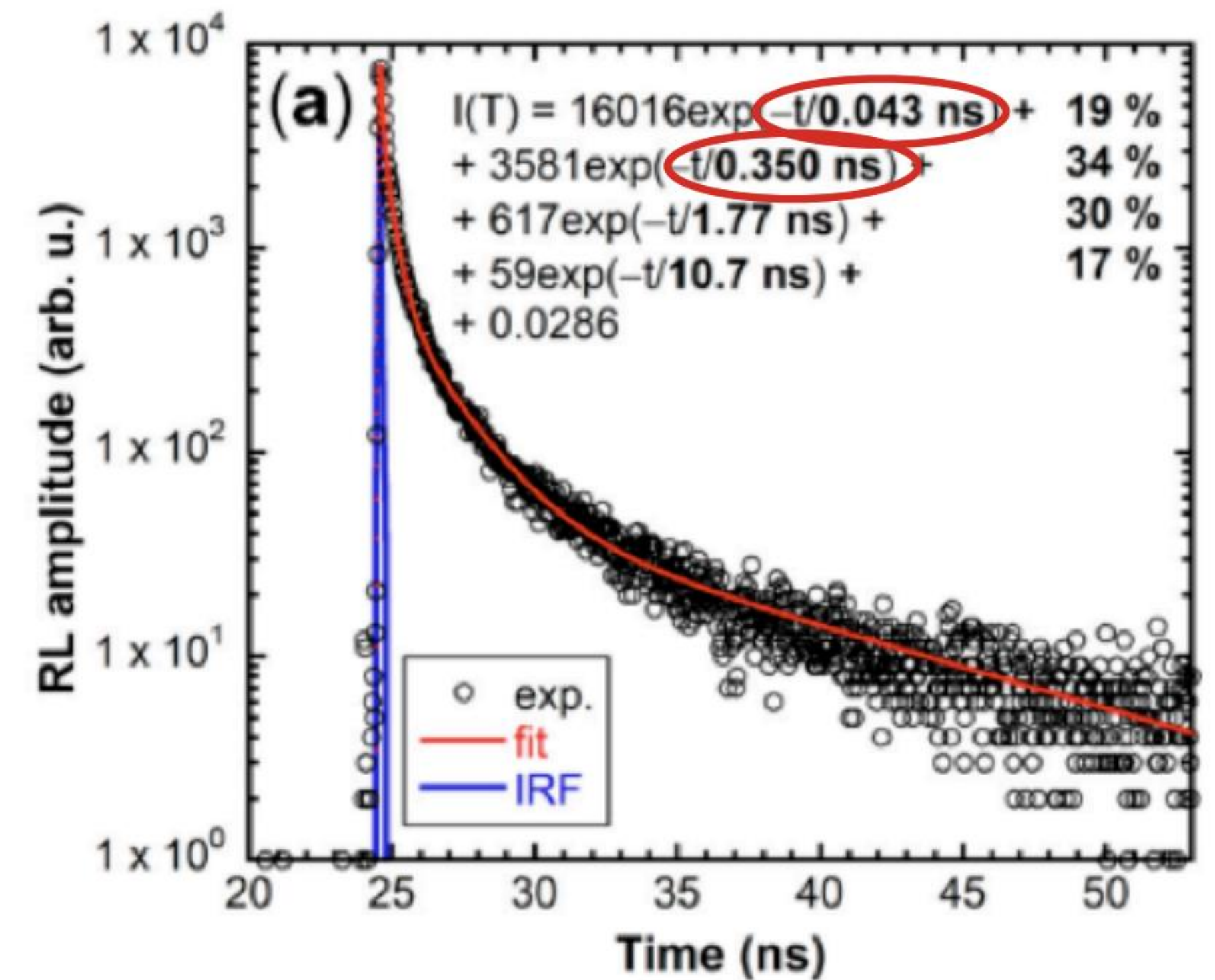
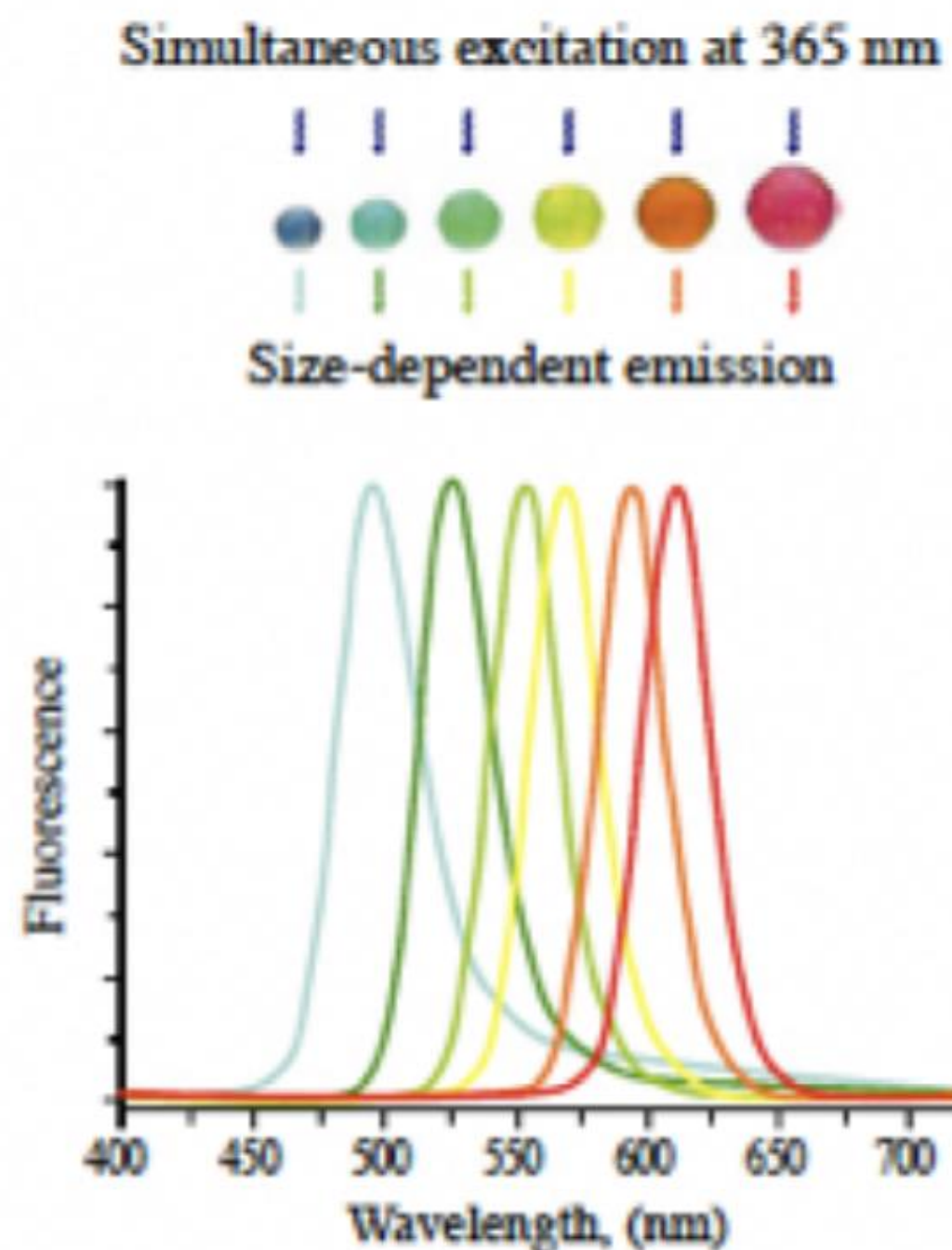


L. Leandro *et al*
«Resonant excitation of
nanowire quantum dots»
(2020) *npj Quantum
Information*
<https://doi.org/10.1038/s41534-020-00323-9>

N. Ngafwan *et al* «Study on novel fluorescent carbon nano materials in food analysis» (2021), Food Science and Technology, DOI: 10.1590/fst.37821

Example: Quantum dot scintillation

- Scintillation in quantum dot has impeccable timing resolution
- Also more radiation hard than one would expect...
- Emission wavelength can be tuned by quantum dot size



K. Decka et al., Scintillation Response Enhancement in Nanocrystalline Lead Halide Perovskite Thin Films on Scintillating Wafers. *Nanomaterials* 2022, 12, 14.
<https://doi.org/10.3390/nano12010014>

- Clear benefits of using nano engineered structures for both high and low energy physics!
- Actual development of devices requires quantum transport simulations...

Why Quantum Transport Simulations?

Scaling simulations down to nanoscale

- Problems with quantum mechanical effects!
 - Compressive strain in materials
 - Tensile strain in materials
 - Electron-phonon coupling and others...
 - Discrete Impurities

However, these problems can «*kind of*» be remedied in semiclassical simulations...

We do we need «Quantum Transport»?

- Need full quantum mechanical picture for:
 - Superpositions
 - Entanglement

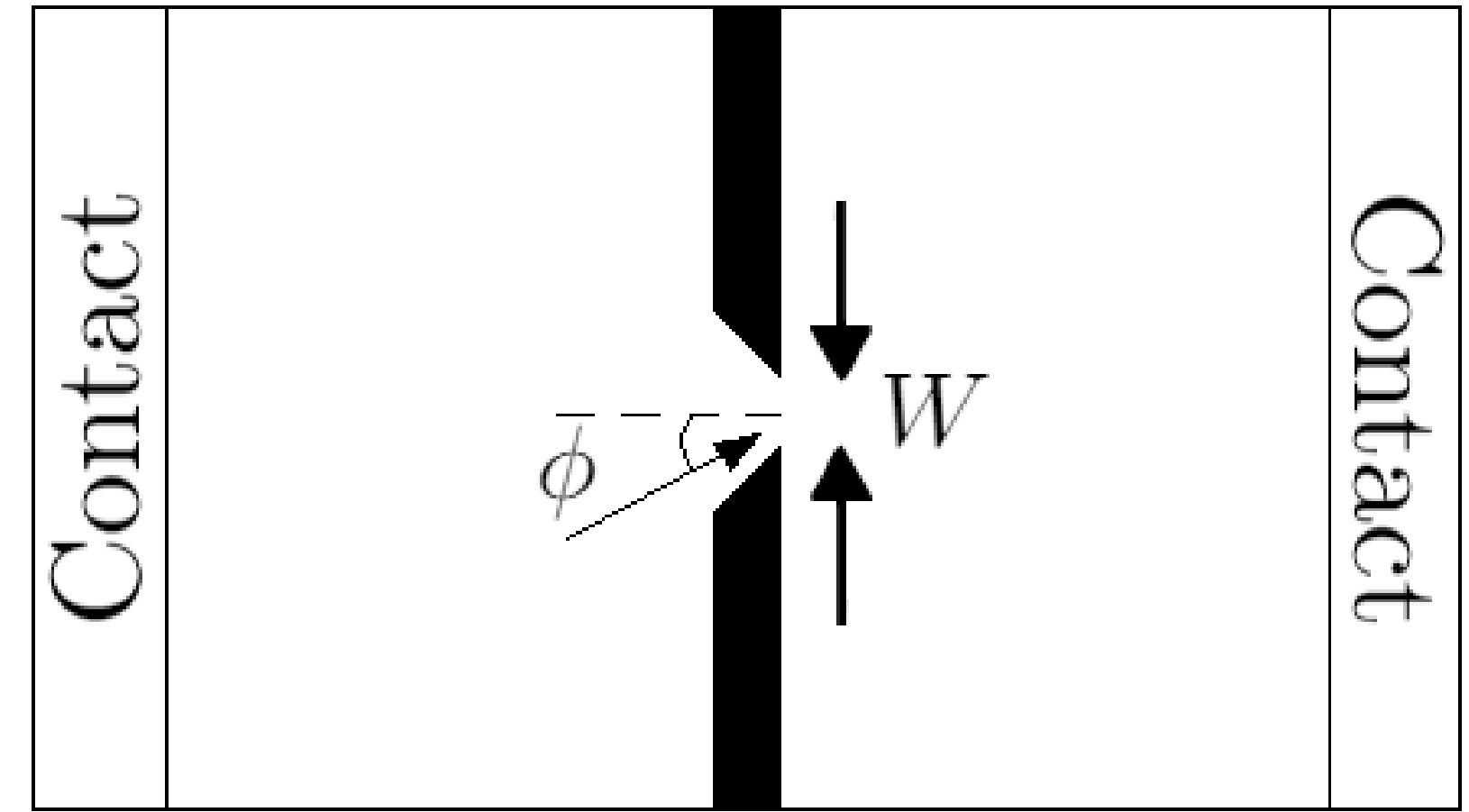
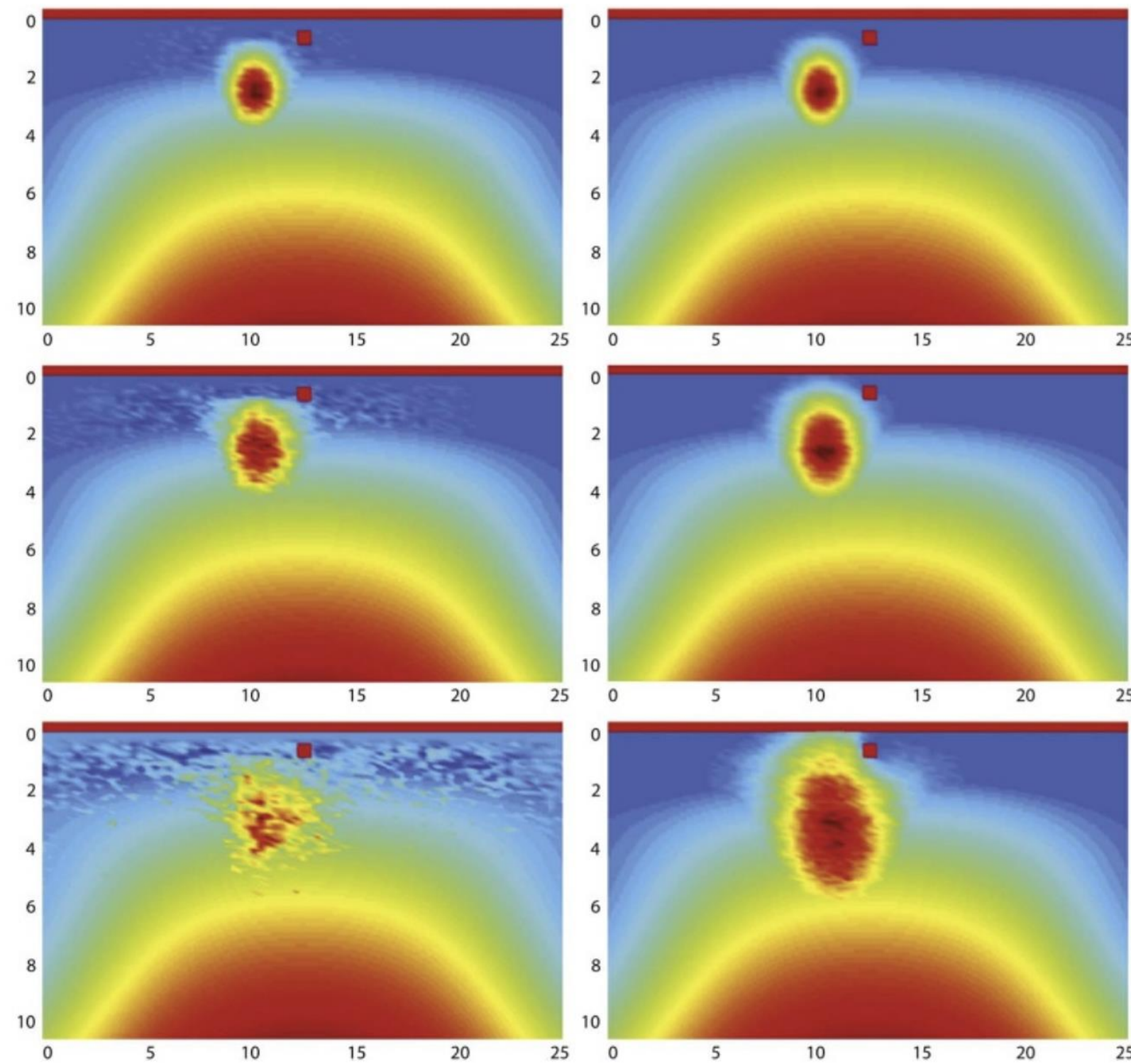


Illustration of a quantum point contact, taken from https://en.wikipedia.org/wiki/Quantum_point_contact



Decoherence of electron wave packet due to impurity.
Quantum Transport (Left) and Semiclassical Transport (Right)

- Can simulate things such as
 - Interferometry with quantum point contacts (QPC)
 - Interference caused by impurities
 - Quantum tunneling
 - Others?

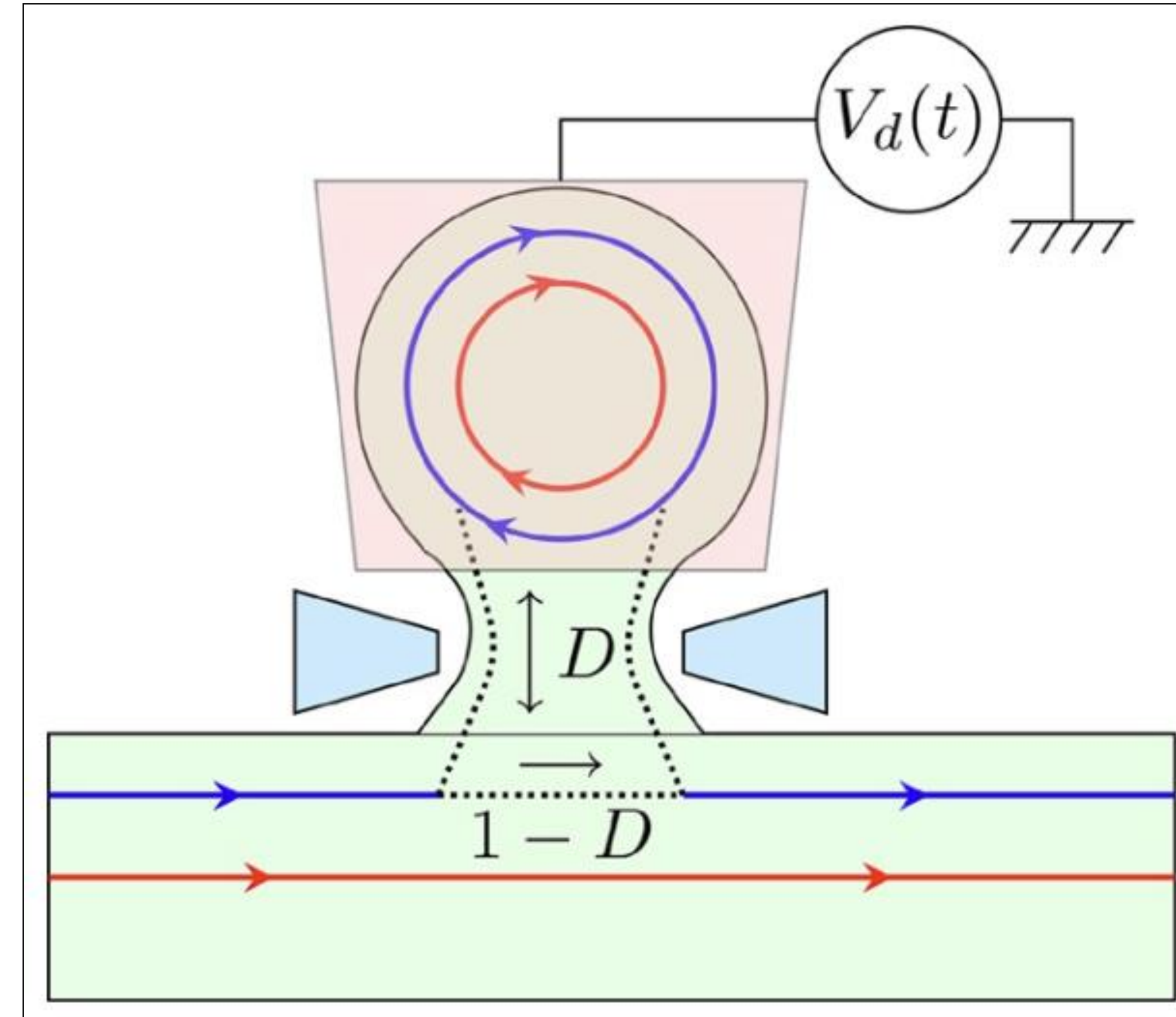
Example: Mesoscopic capacitor

Used as a single-electron emitter

- Quantum dots coupled to (electronic) chiral edge states via a quantum point contact
 - For particle tracking... similar to pixel detectors
- Incident radiation creates electron-hole pairs in QD
- Tunnel through QPC within some time-frame
- Couples to highly coherent chiral edge state
 - Chiral edge state can be read out as a current
- Read out current

Benefits:

- Very high spatial resolution ($\sim$ nm)
- Radiation hard
- Potentially extremely sensitive (high S/N ratio)
- High temporal resolution (?)



Taken from B. Roussel et al (2017),
<https://doi.org/10.1002/pssb.201600621>

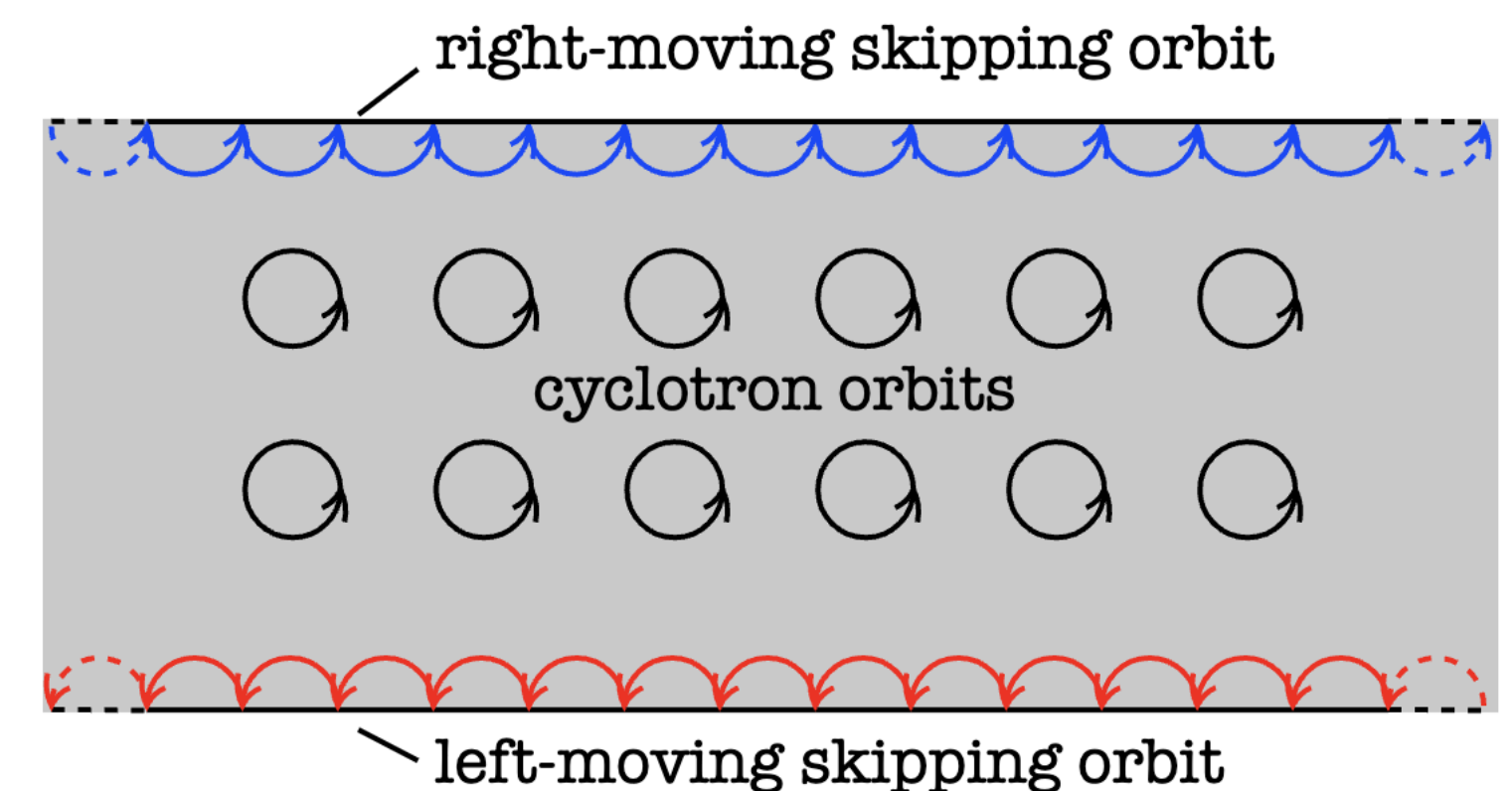
Requires a fully quantum mechanical simulation!

Thank you for listening! 😊

Extra spice

Chiral edge states

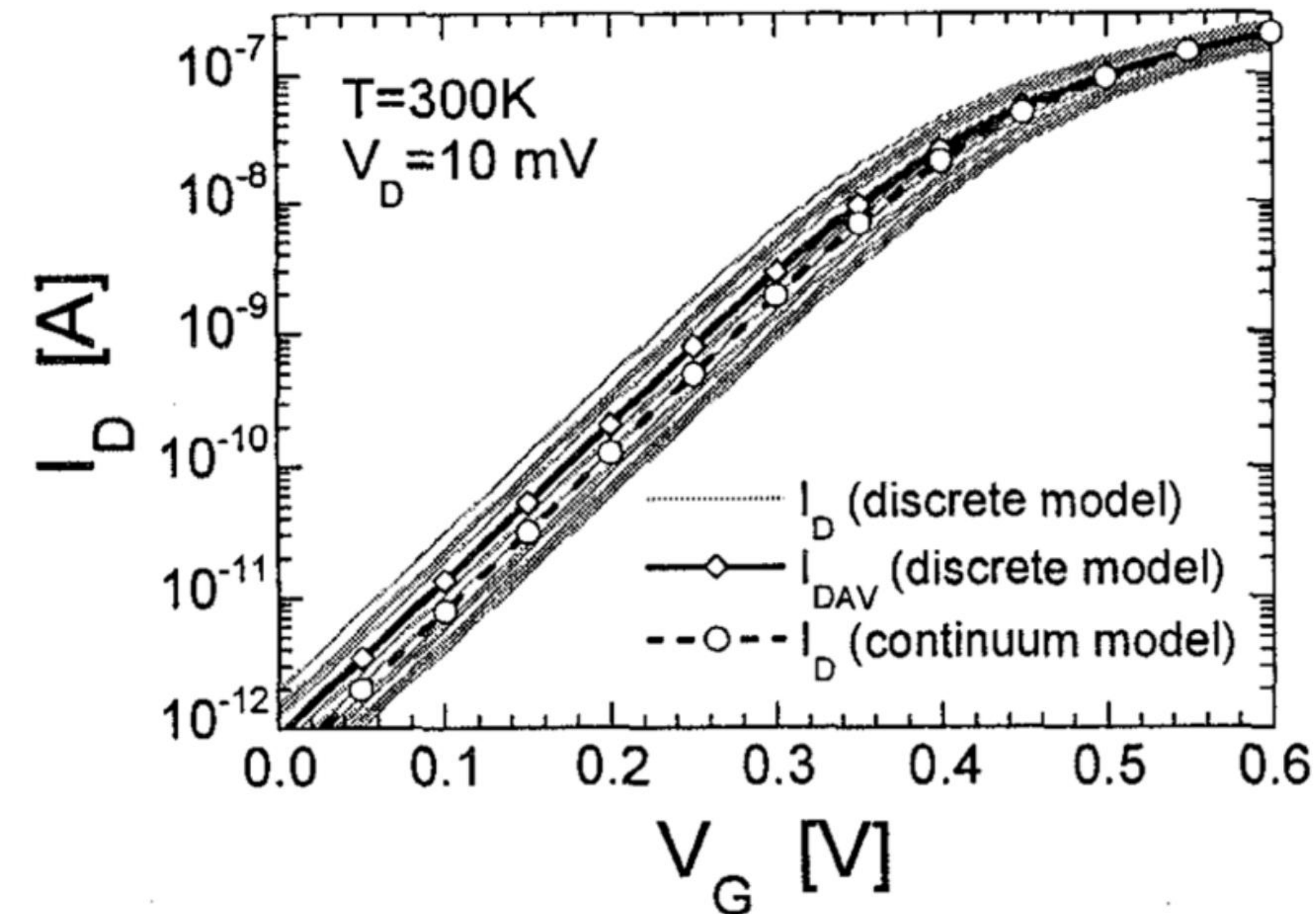
- A material under a strong enough magnetic field exhibits the Quantum Hall effect
- In addition: electronic states which travel along your material with quantised energy levels
 - These are called chiral edge states



Taken from
https://topocondmat.org/w3_pump_QHE/QHEedgestates.html

Discrete impurities

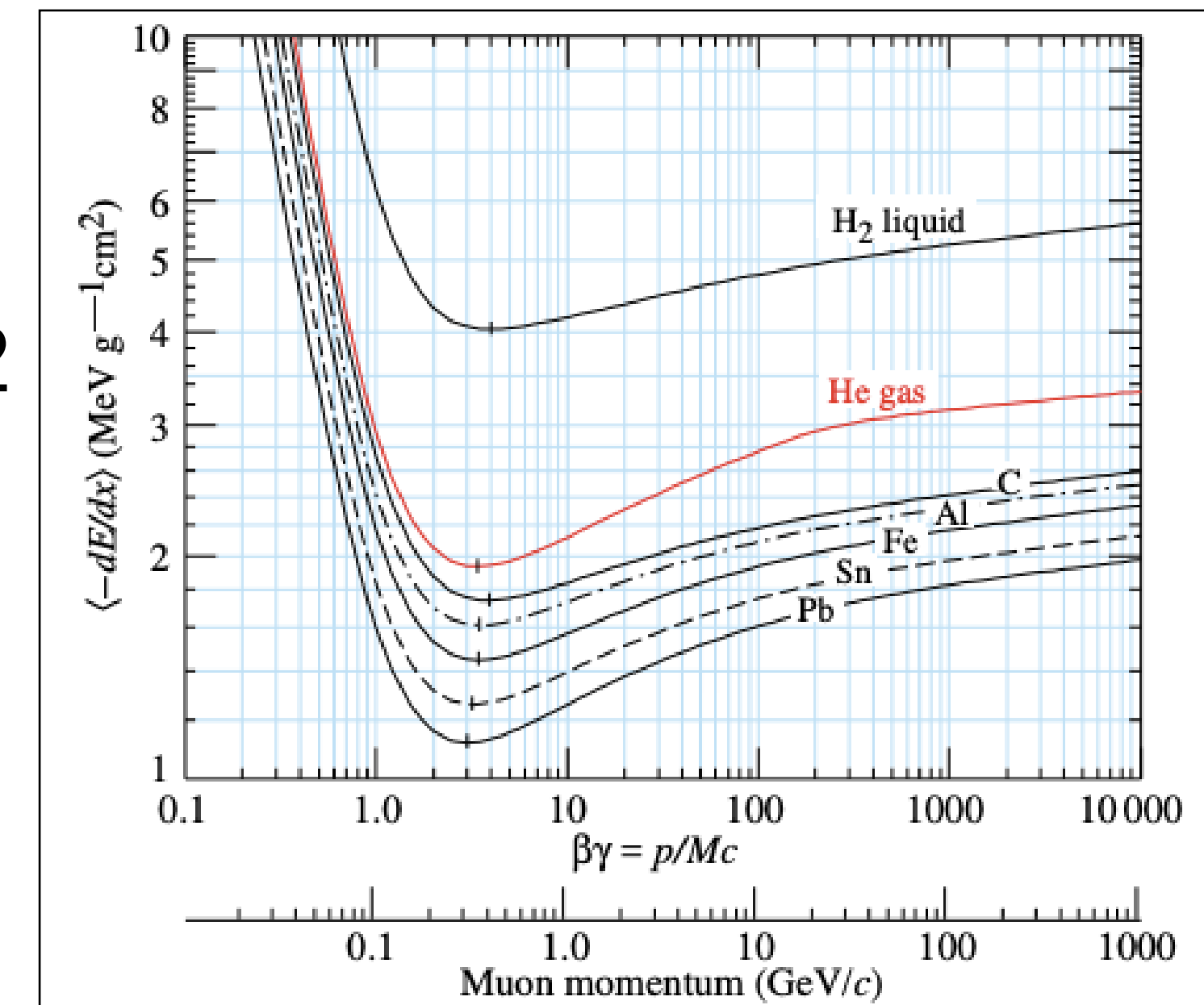
- Doping concentration of $1e20 \text{ cm}^{-3}$ is the same as 0.1nm^{-3}
- In a 10nm sized Quantum Dot: You have ONE impurity
- Uncertainty in doping concentration
- Placement of impurity



Taken from: David K Ferry et al 2022 Semicond. Sci. Technol. 37 043001

What would the current be?

- Using e.g mesoscopic capacitors with nanometer sized QDs...
- $-dE/dx$ of 1GeV/c muons is around 1-2 MeV per gram per cm^2 in various solids
- So ``at worst'', on average 2.26eV is released per nanometer
- Energy required to create electron-hole pair in Si: $\sim 3.6\text{eV}$
- In conclusion: Only a few electron-hole pairs are created from incident radiation through nanometer-scale trackers
- **TINY current! (picoampere?)**



Taken from Particle Data Group «Passage of Particles Through Matter». Last updated August 2019

Interesting problems for HEP

- Can electron interferometry be used for read-out electronics?
- Can it be directly used in front-end?
- What kind of new types of sensors can be made with interferometric techniques?
 - Inspiration from atom interferometry and quantum optics
 - GW detection? Probably not since the coherence is kept for microns, not kilometers
 - Reduce shot-noise? A radiating particle would disturb the superposition
 - Mesoscopic capacitors? A QD coupled to edge channels via a quantum point contact allows to perform interferometry directly on signals generated by incident radiation