Quantum simulation and entanglement engineering in quantum cascade laser frequency combs

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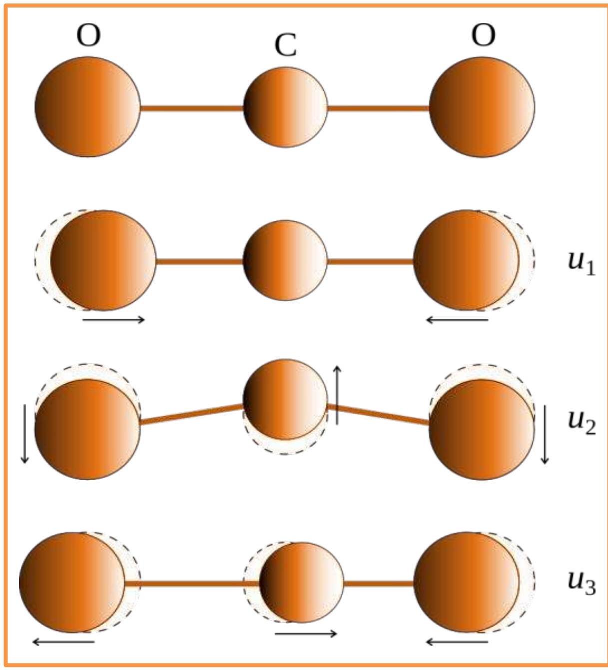
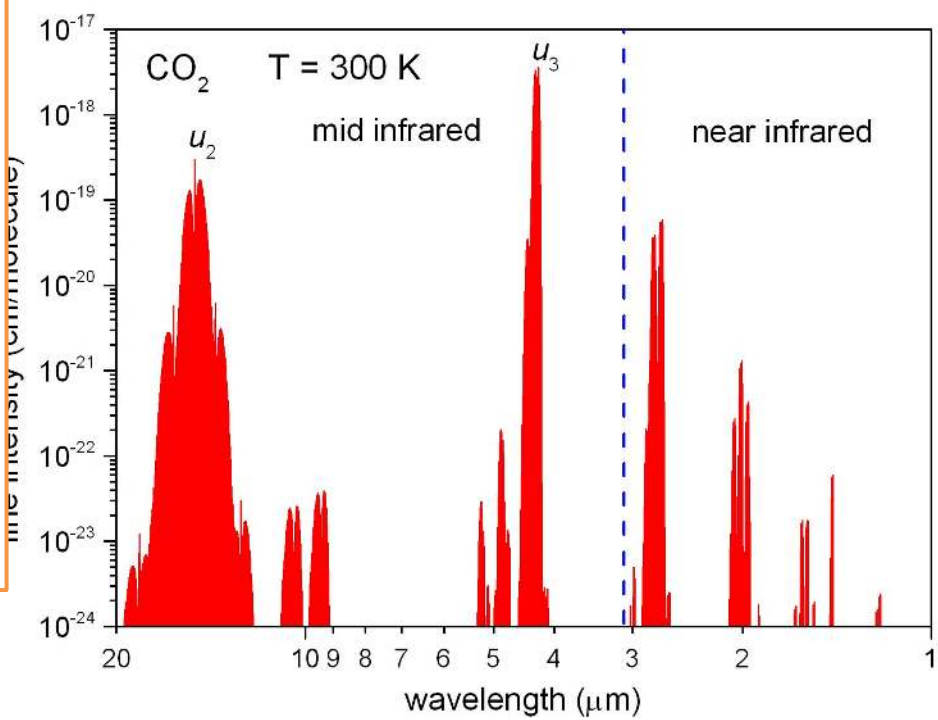
Francesco Minardi

Quantum cascade lasers (QCL)

Molecules have strong absorptions due to ro-vibrational transitions
→ convenient detection in mid-infrared λ > 3 μm





Gas detection → environmental applications, e.g. pollution monitoring (CO_2, CH_4...); security applications (detection of explosives); radiocarbon dating; etc.

Quantum Cascade Lasers

Coherent sources in mid-infrared to THz region

λ = 3 - 300 μm,

ν = 1- 100 THz, E = 4 - 400 meV

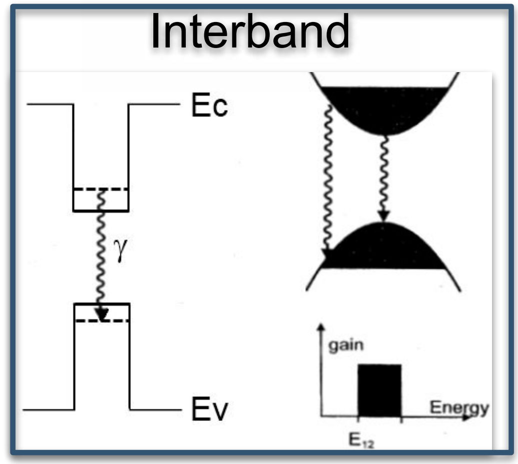
Semiconductor lasers based on *inter-subbands transitions*

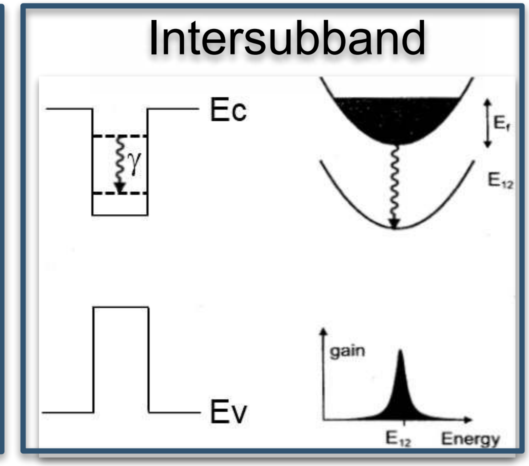
- λ adjustable by band-structure engineering

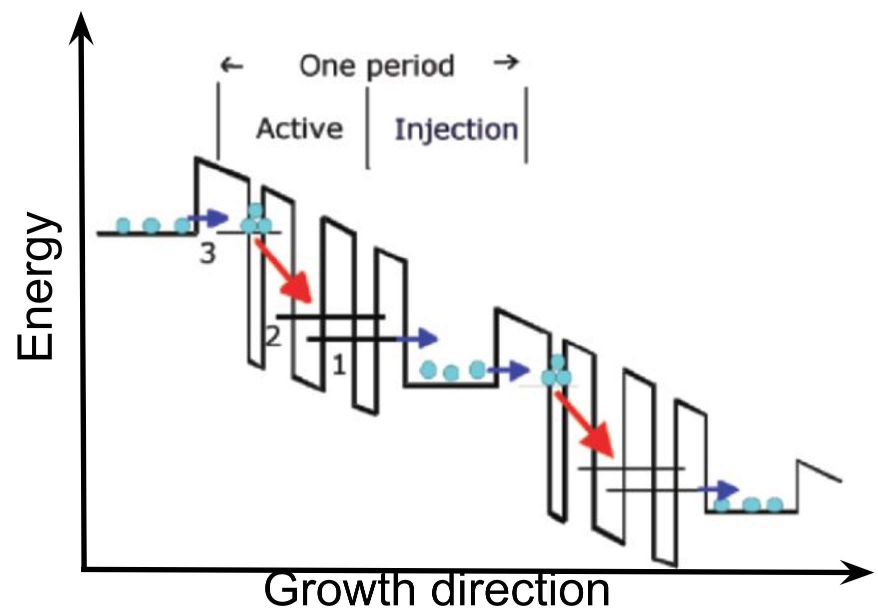
Periodic heterostructures

Each carrier ⟶ multiple photons in a “cascade” of successive stimulated emissions

J. Faist et al., Science **264**, 553 (1994)



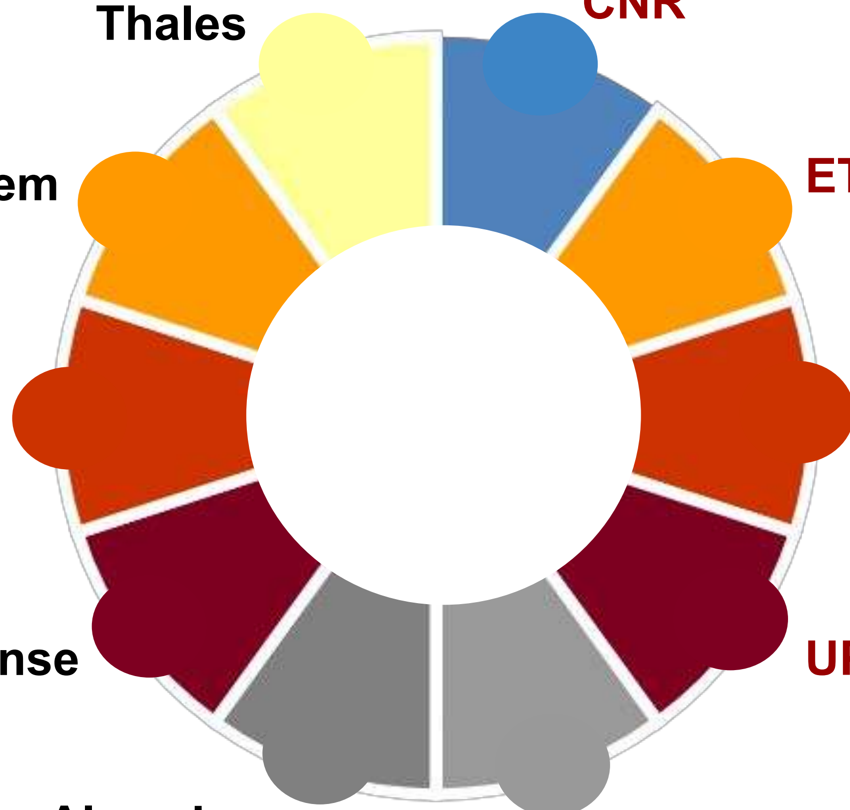




Consortium

5 private companies

5 academic/research institutions



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Alpes Lasers Fabricate new-generation quantum cascade laser frequency combs (QCL-combs) with non-classical emission

ppqSense Develop & fabricate ultralow-noise current drivers for new-generation QCL-combs operation

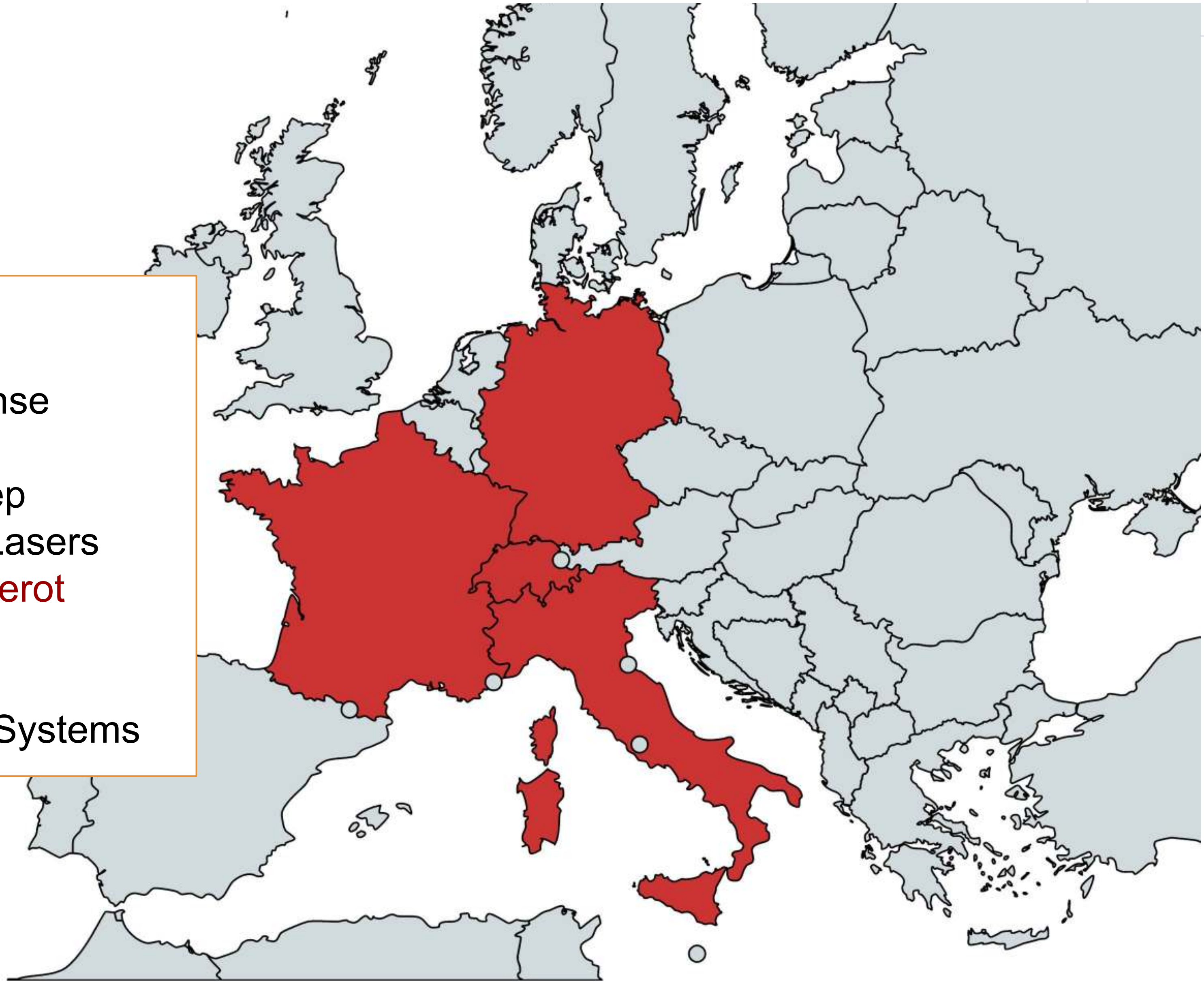
Menlo Systems Develop & fabricate difference-frequency-generated mid-infrared frequency comb for QCL-combs characterization

IRsweep Develop mid-infrared spectrometers based on new-generation QCL-combs

Thales Develop of LIDAR systems based on new-generation QCL-combs

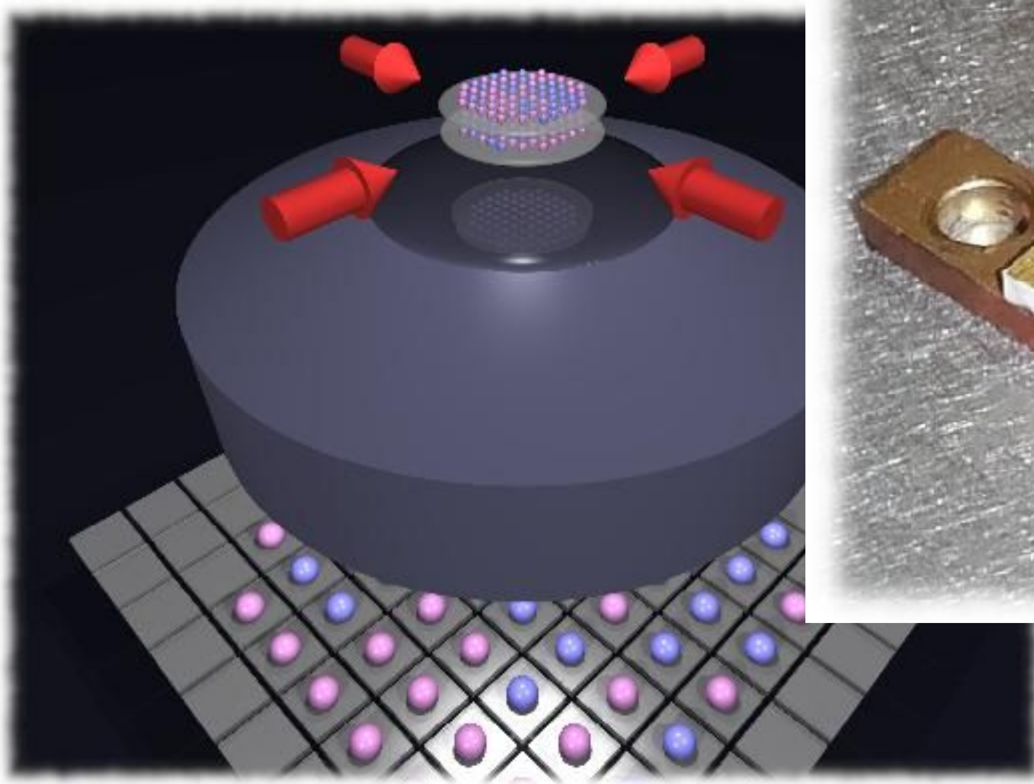
Consortium

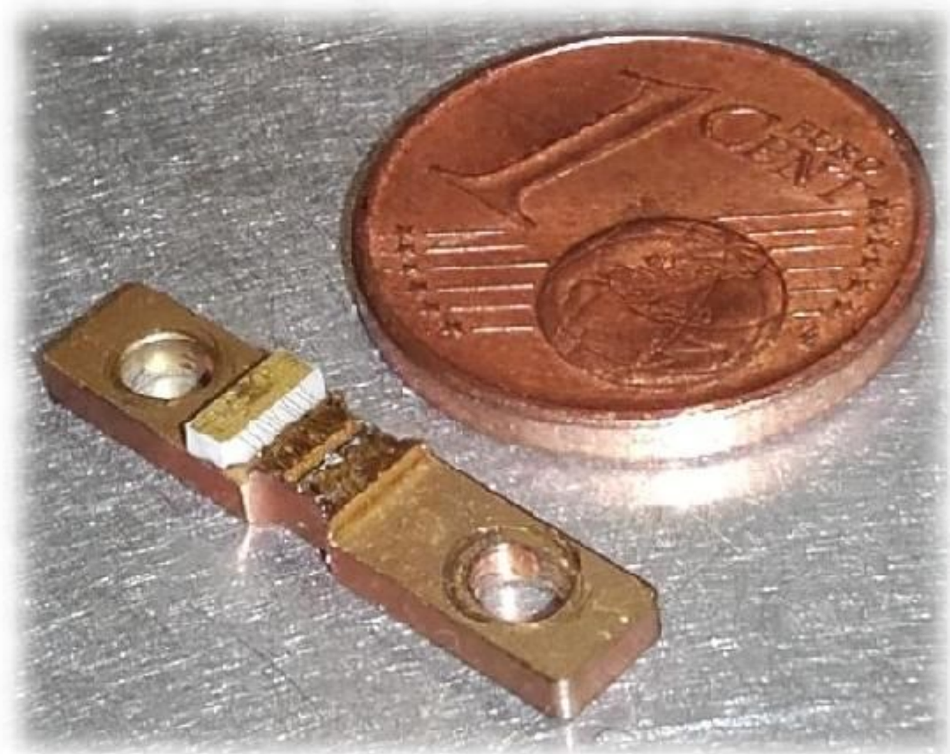
IT: CNR
ASI
ppqSense
CH: ETH
IRsweep
Alpes Lasers
FR: UP Diderot
Thales
DE: TUM
Menlo Systems



Focus

The main goal of the project is to realize 2 quantum simulator platforms able to simulate some **key properties** of quantum cascade laser (QCL) and QCL frequency combs (QCL-combs)





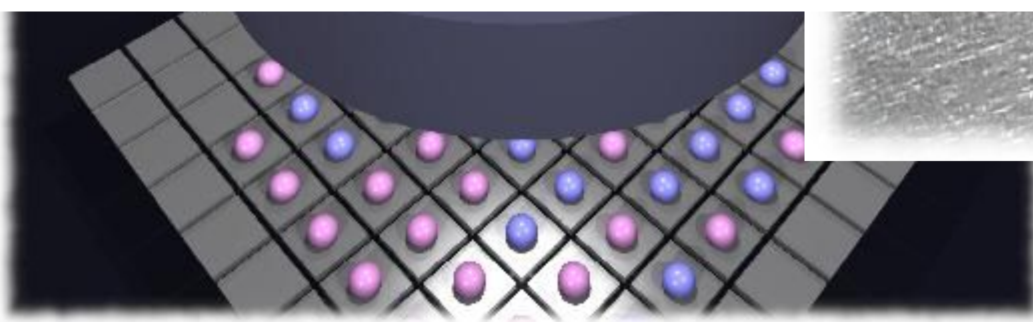
Focus

The main goal is to realize 2 quantum simulator platforms able to simulate some **key properties** of quantum cascade laser (QCL) and QCL frequency combs (QCL-combs)

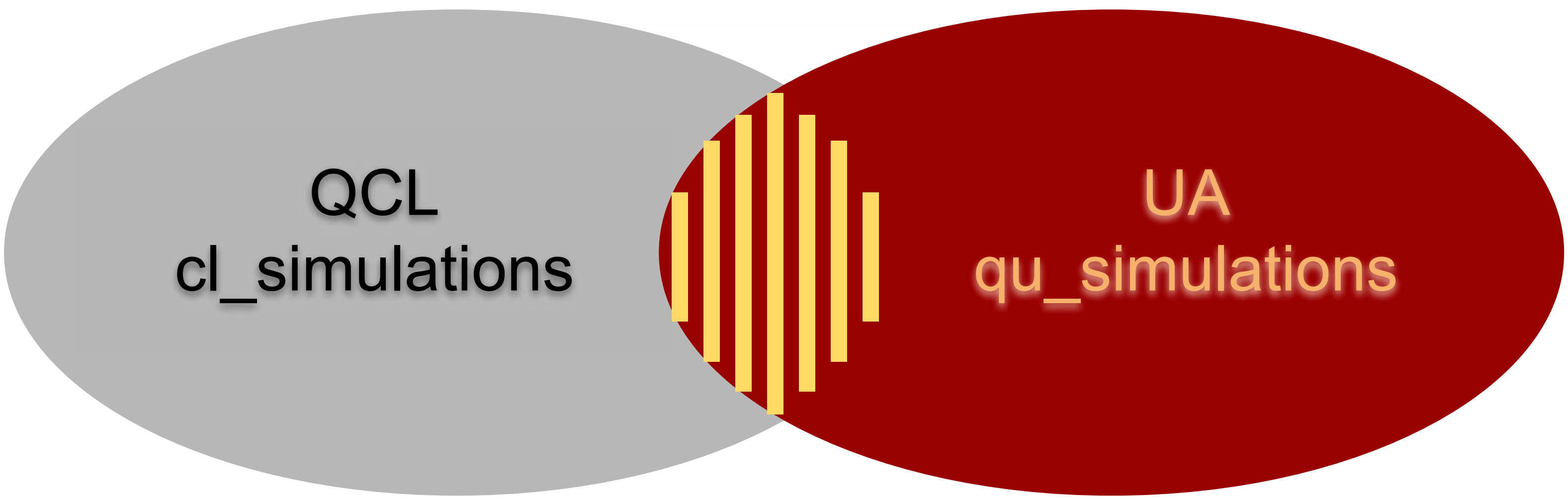
Very specific analog simulator with very specific tasks:

- transport of carriers (electrons) in QCL heterostructures
- non classical correlations between longitudinal modes ("teeth") of QCL frequency combs

In addition, improving Quantum Cascade Detectors and Quantum Well Infrared Detectors operation



Simulation approach



Two Ultracold Atoms experimental platforms

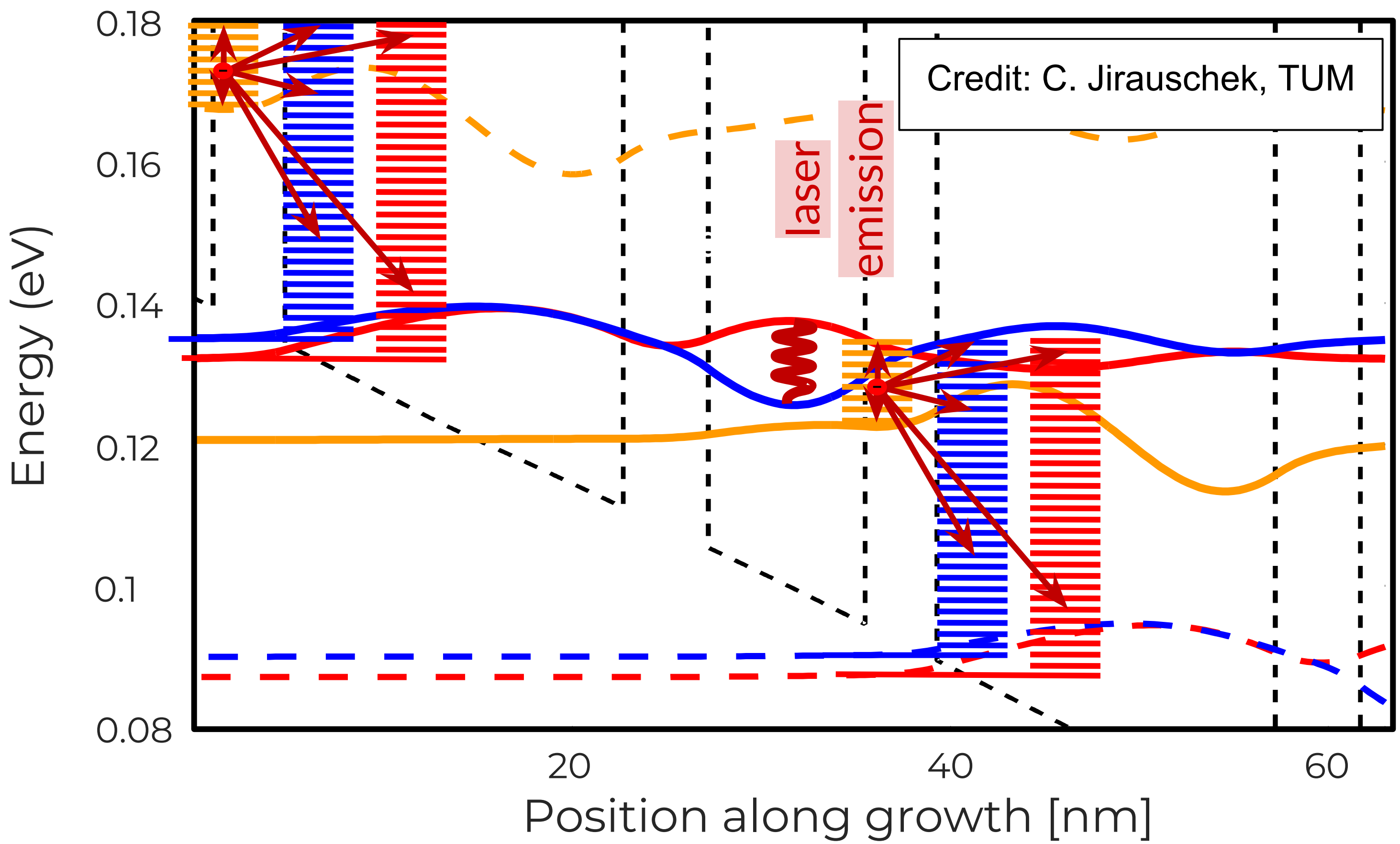
(1) fermions in a tailored super-lattice

(2) array of Bose-Einstein condensates with evenly spaced momenta

QCL carrier transport

Classical numerical simulations (C. Jirauscheck, TUM)

Transport via Boltzmann equation: phonons, interfaces roughness, alloy disorder, impurities…



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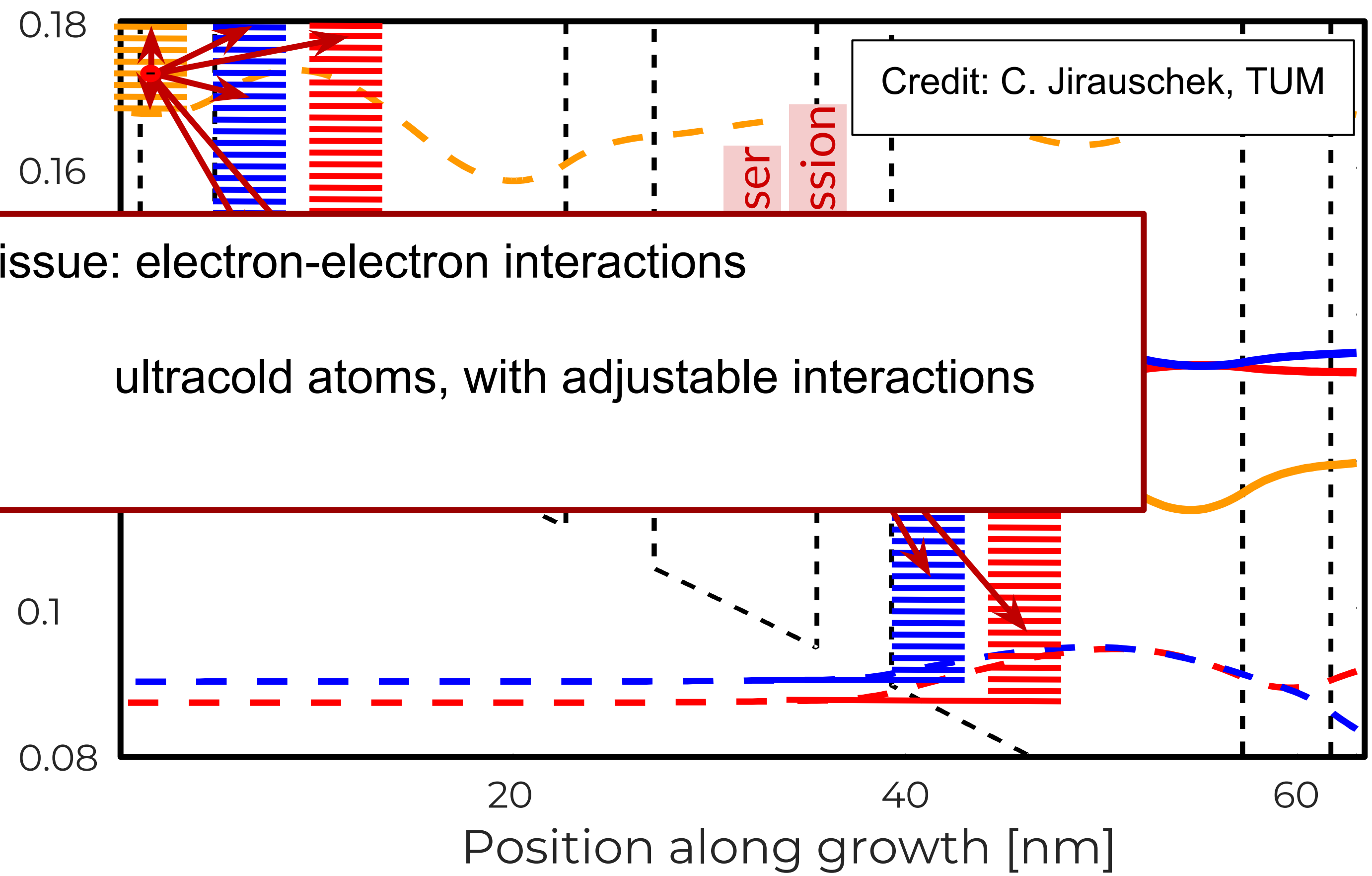


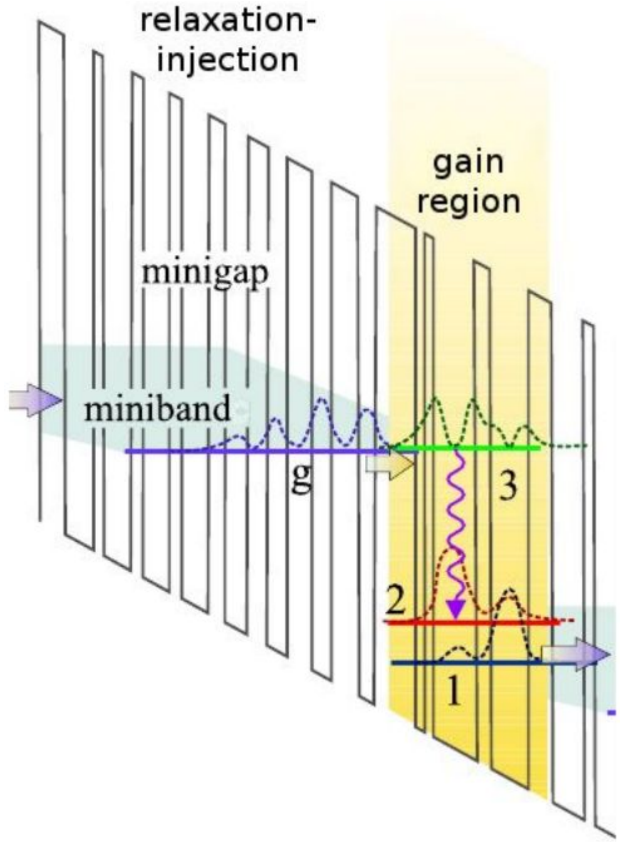
Challenging issue: electron-electron interactions

$\longrightarrow$ ultracold atoms, with adjustable interactions

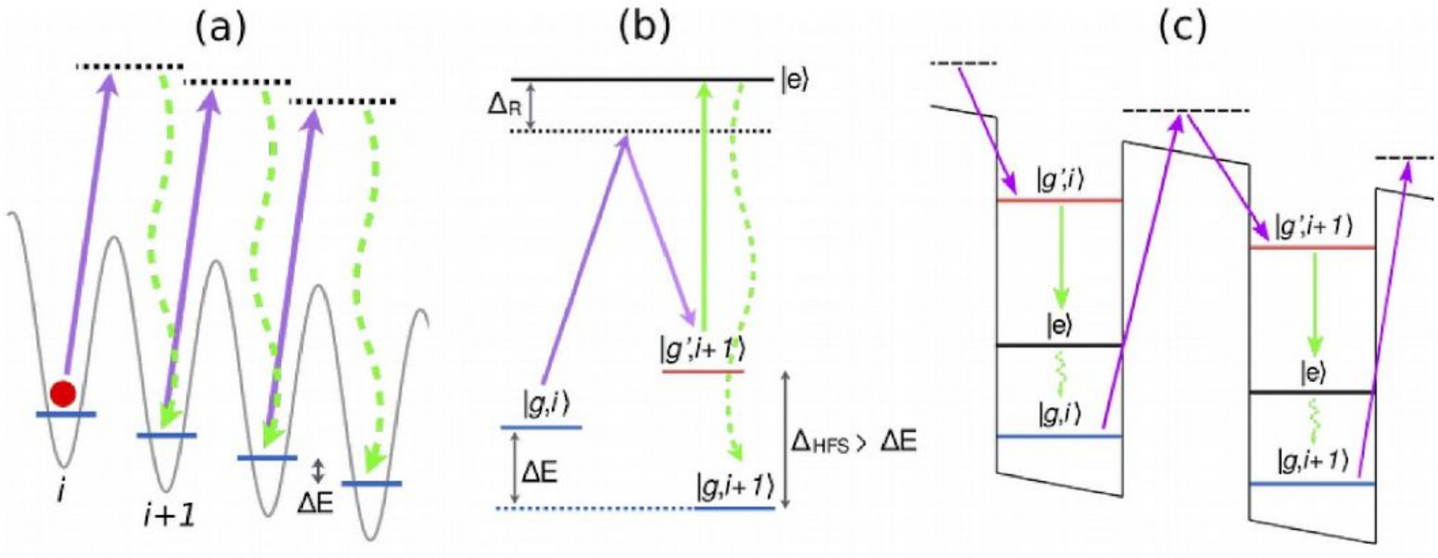
QCL carrier transport

Simulation of transport of fermionic carriers:

- design the potential energy landscape: unevenly spaced quantum wells (superlattice)
- coherent tunneling, g ⟶ 3
- coherent transition 3 ⟶ 2 (laser emission)
- incoherent dissipation, 2 ⟶ 1 (⟶ g)



Transport of fermions



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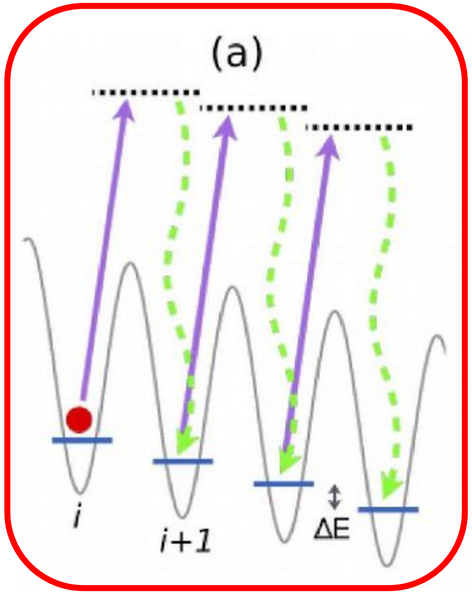
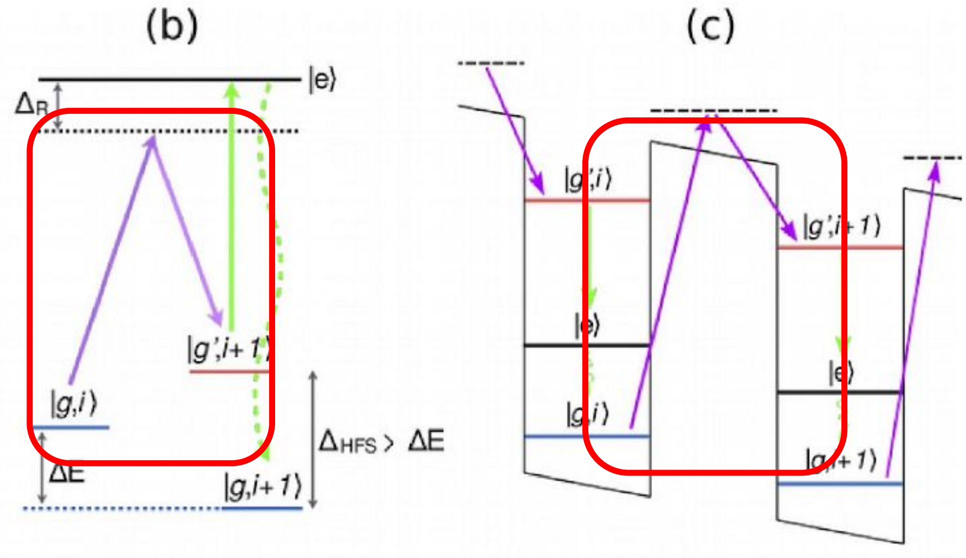


Potential energy landscape:

optical lattice tilted by linear potential
(gravity or magnetic field gradient)

deep lattice ⟶ negligible tunnelling

Transport of fermions

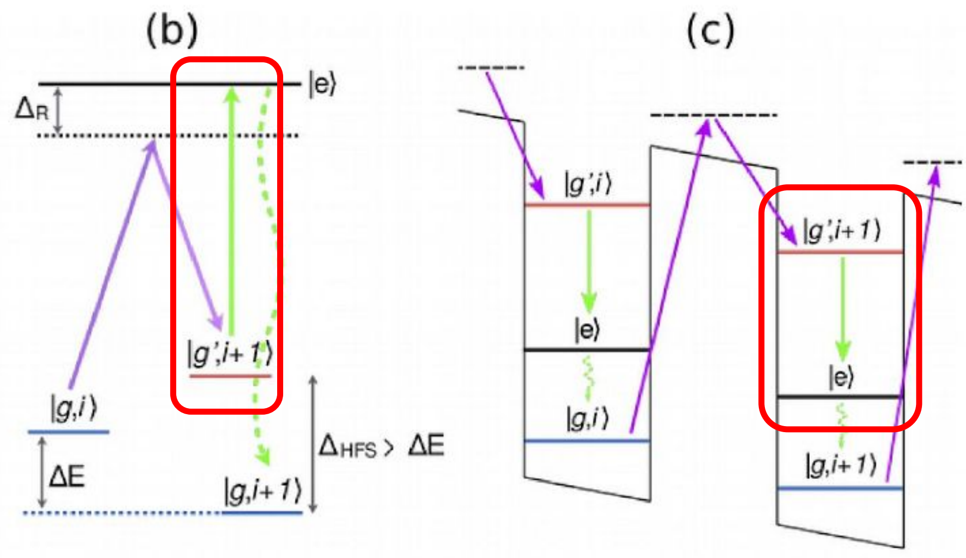


Tunnelling between neighbouring sites

induced

by Raman transitions

Transport of fermions

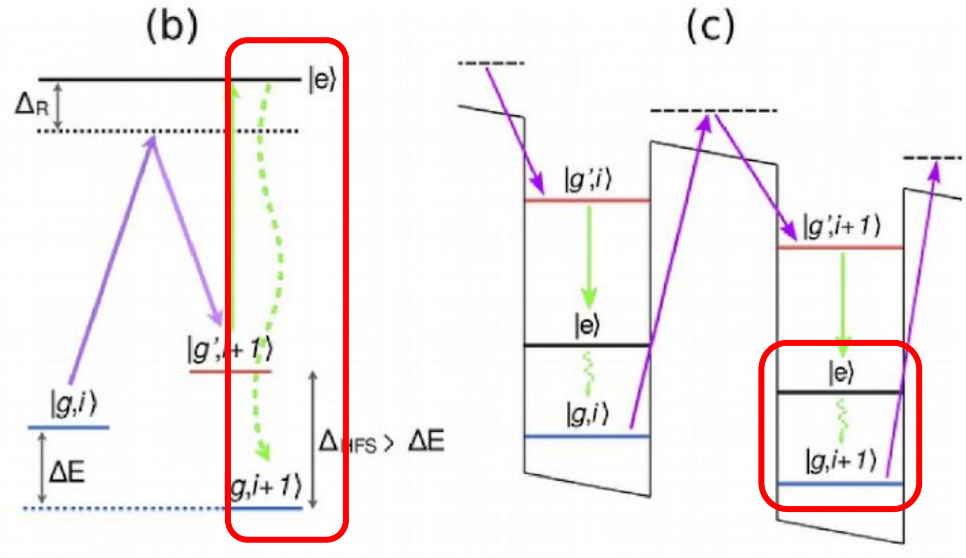


Laser emission

simulated/replaced

by (optical) excitation toward excited atomic state

Transport of fermions

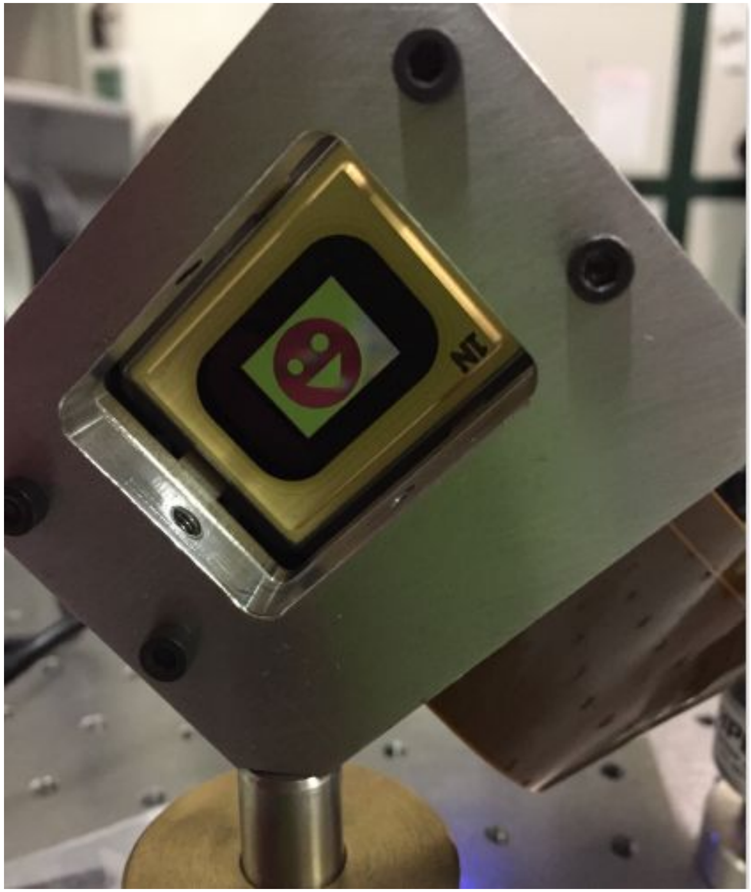


Incoherent dissipation

simulated/replaced

by spontaneous emission decay

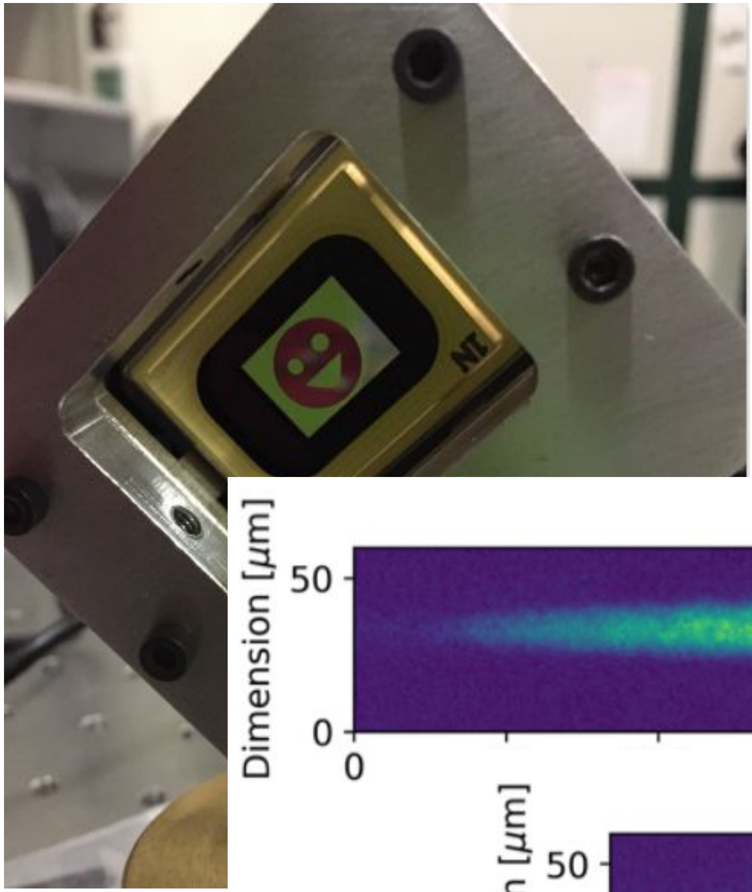
Potential energy landscape



Engineer the quantum well for ultracold ^{6}Li atoms

using Digital Micromirror Device (DMD)

Potential energy landscape



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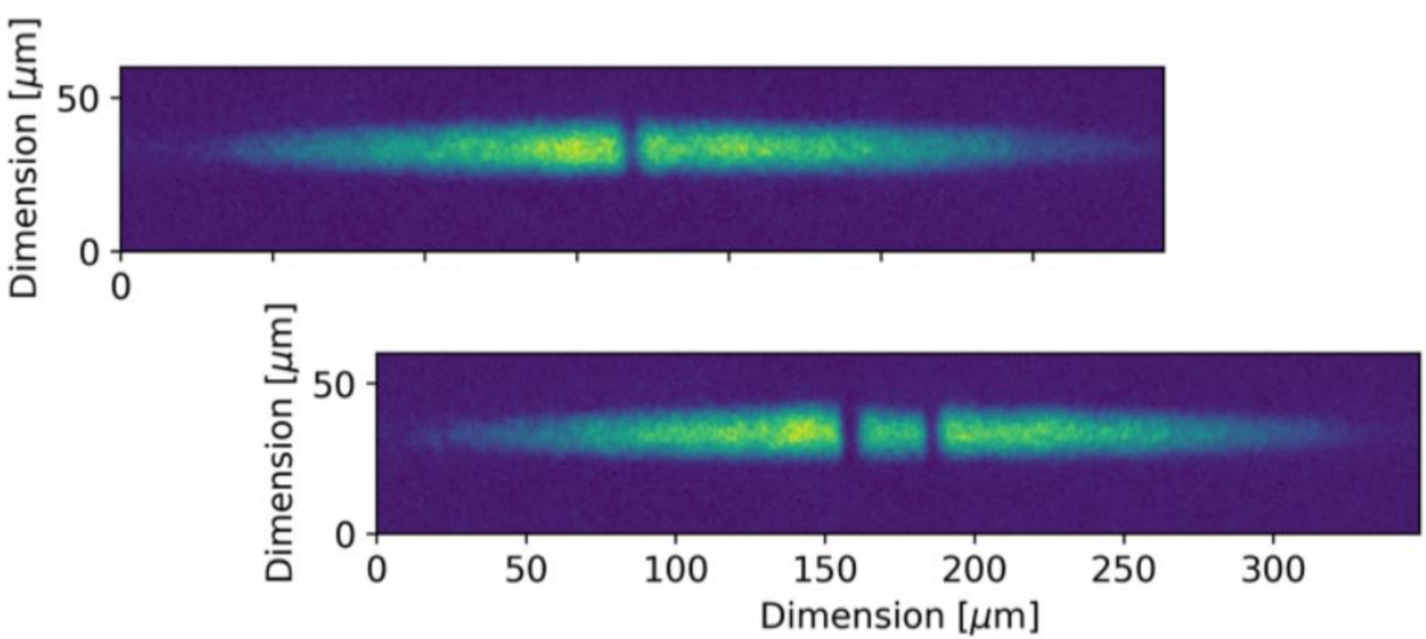
In situ image of ultracold fermionic Li atoms



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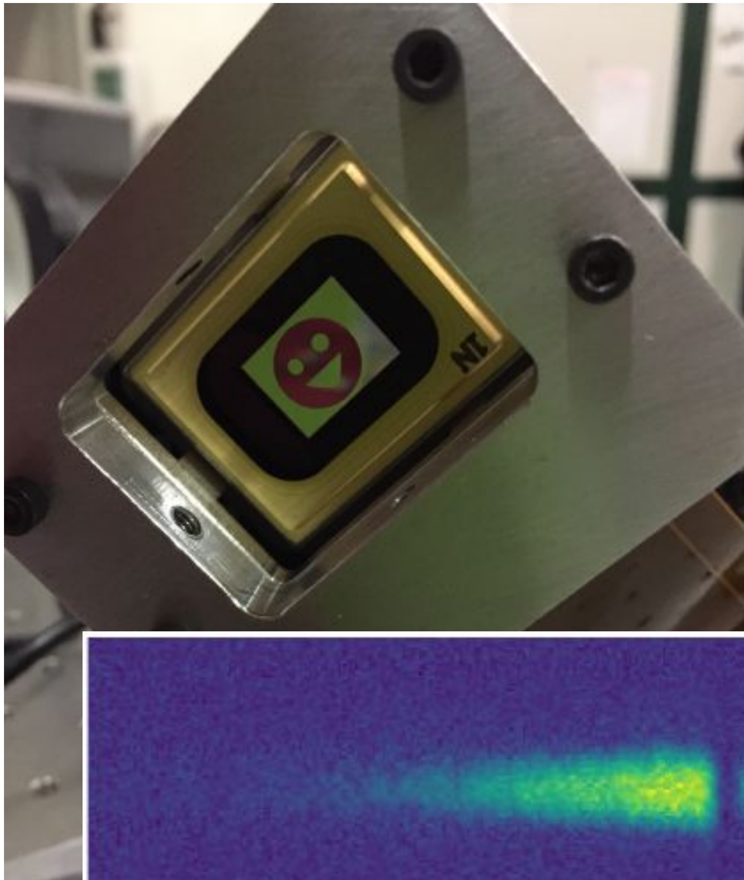

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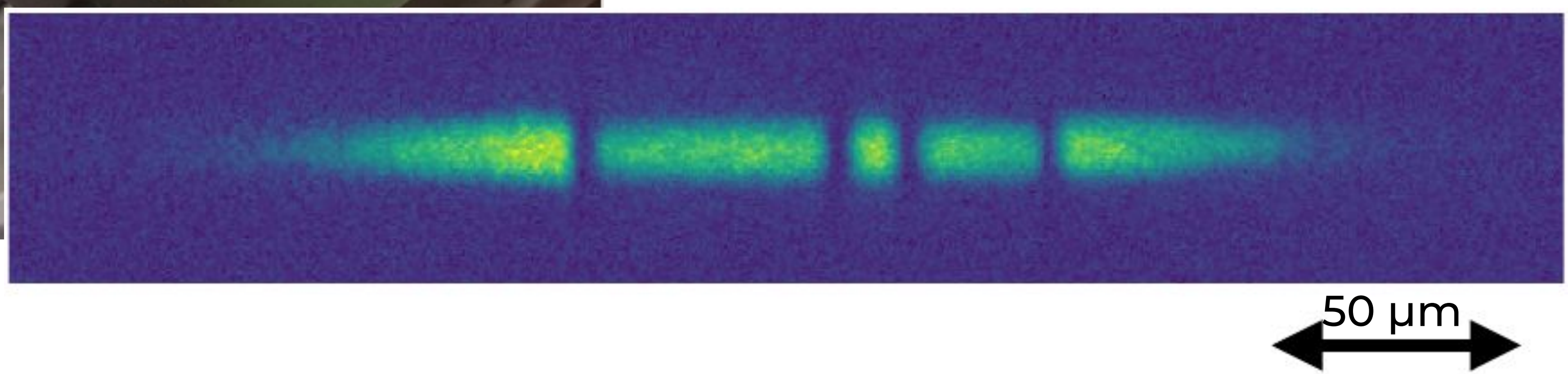


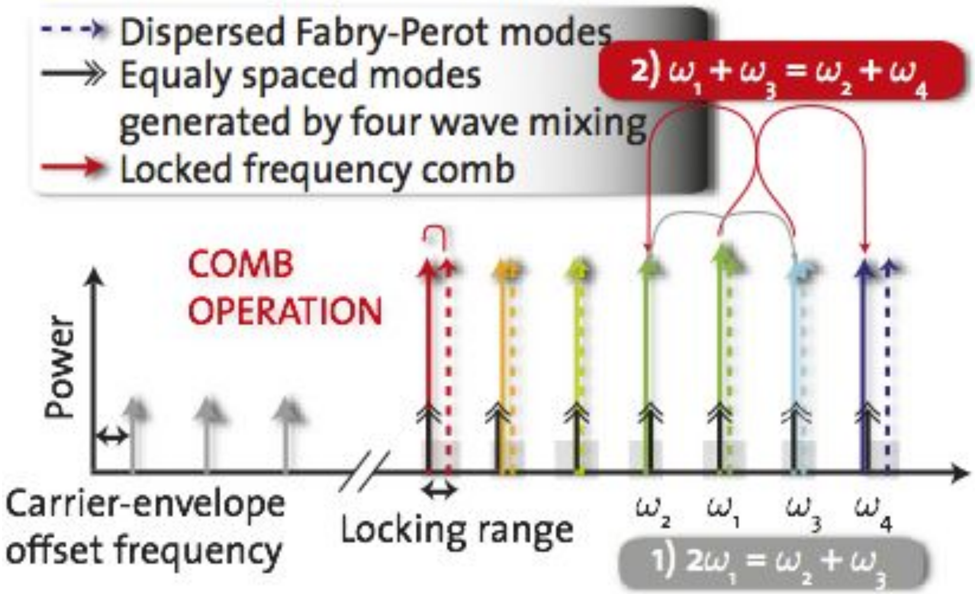
QCL frequency combs

Frequency Comb due to intracavity Four-Wave Mixing (FWM)

Non-linear $\chi^{(3)}$ medium, $P_{NL} = \chi^{(3)} E^3$

Low dispersion $\rightarrow$ phase-matching

A. Hugi et al., "Mid-infrared frequency comb based on a quantum cascade laser," Nature 492, 229-233, 2012



QOMBS: search for non-classical correlations between "teeth" of the comb

QCL frequency combs

Frequency Comb due to
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QOMBS: search for non-classical correlations between “teeth” of the comb

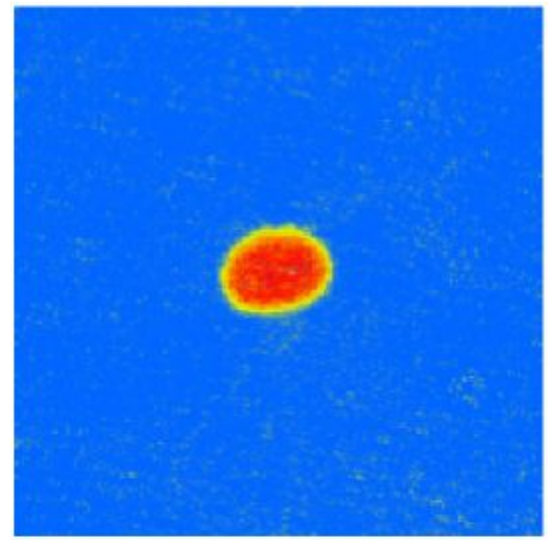
Attenuation in atmosphere of mid-IR ≪ visible / near-IR light

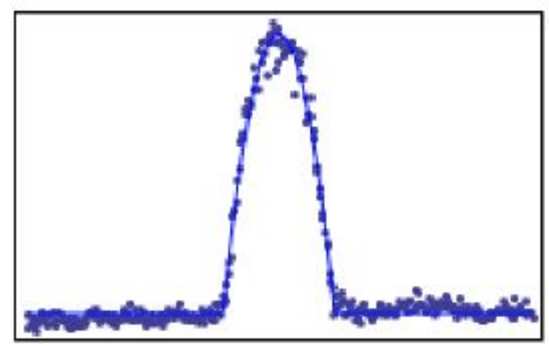
Application: point-to-point free-space quantum communication

An atomic comb

Bose-Einstein condensate of Rb atoms
coherent matter wave

analogous to cavity mode of em field





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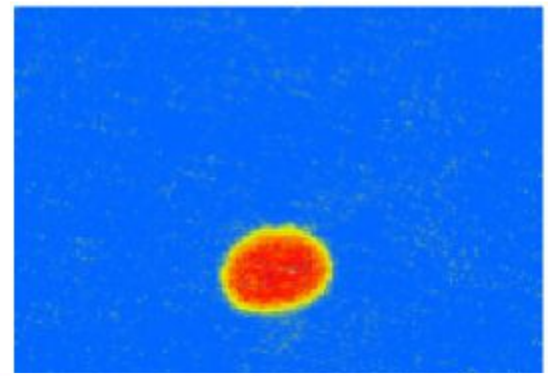
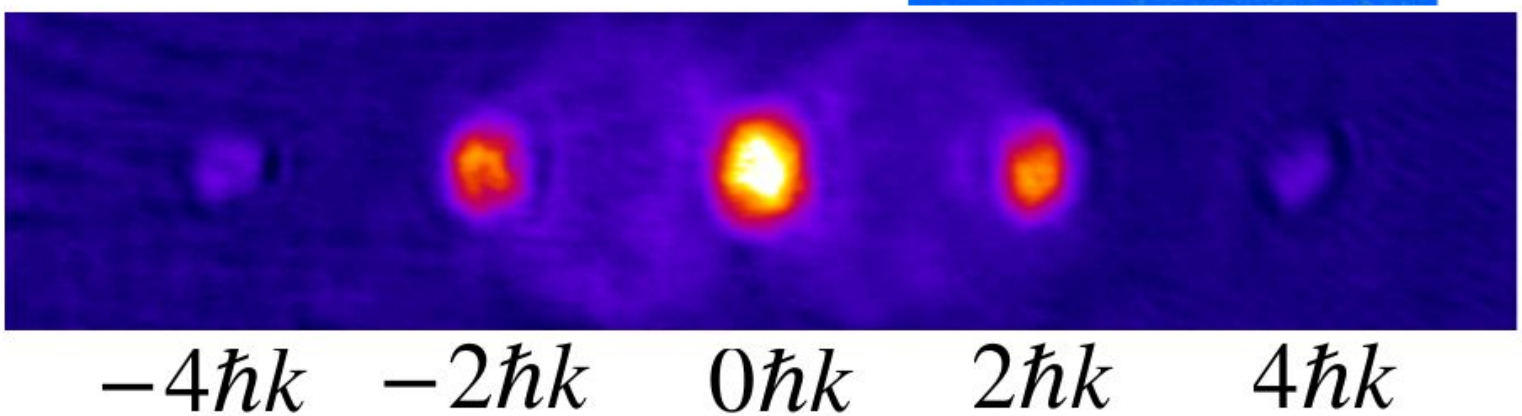


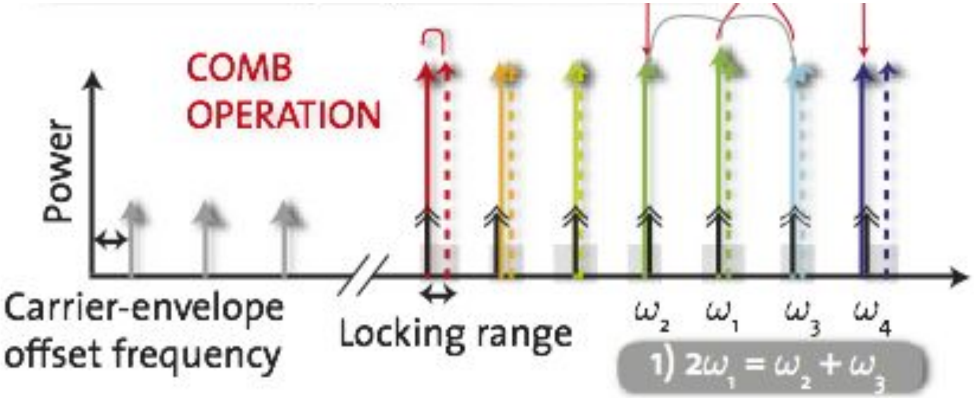


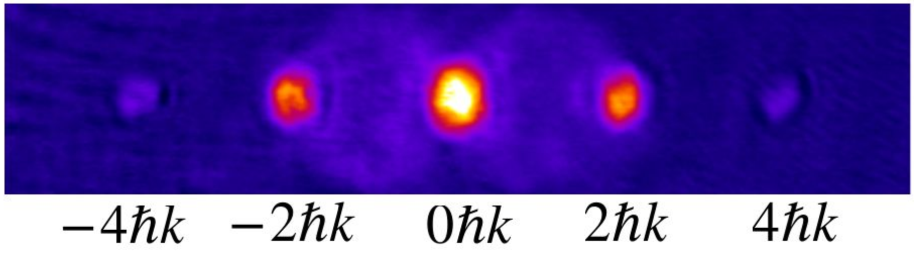
Periodic potential (optical lattice) pulsed in time $\longrightarrow$

matter wave mode split into multiple momentum components

evenly spaced, $p = n\,(2\hbar k)$

An atomic momentum comb





Frequency comb $\omega_j = j\,\omega_0 + \delta$

$\chi^{(3)}$ non-linearity

$$i\,\partial_t E(x) = \chi^{(3)} E^*(x)\,E(x)\,E(x)$$

Comb of momentum $p_n = n\,p_0$

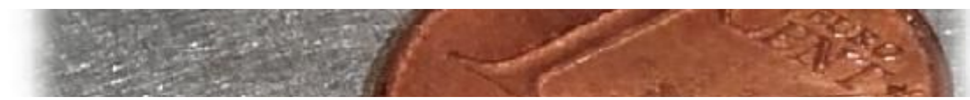
Contact interactions

$$i\,\partial_t \psi(x) = g\,\psi^\dagger(x)\,\psi(x)\,\psi(x)$$

Conclusions

QOMBS aims to lead to a new generation of QCLs and QCL-combs

QOMBS is application-driven, employing existing cold atoms platforms adapted to simulate specific features: transport and correlations



QOMBS develops QCL-combs and QCL-combs-related/based devices: detectors, spectrometers, current drivers…

-Thank you-