Quantum transport with Fermi gases: simulating electrons dynamics in QCL heterostructures
(WP2 - Quantum simulation with ultracold atoms)

Giacomo Roati

Qombs Mid-term Activity Report

13/5/2020

CNR-INO

QUANTUM FLAGSHIP

Qombs

OUR FRAMEWORK: ULTRACOLD (FERMI) GASES

Analog quantum simulators: quantum platforms whose Hamiltonians are as similar as possible to the simulated systems.

1) High scalability: implementation on large quantum systems (~10^5 particles…). Global control over many lattice sites or coupled quantum systems.

2) Powerful single-purpose “devices” for: phase transitions, thermodynamics, quench experiments, **quantum transport experiments**…

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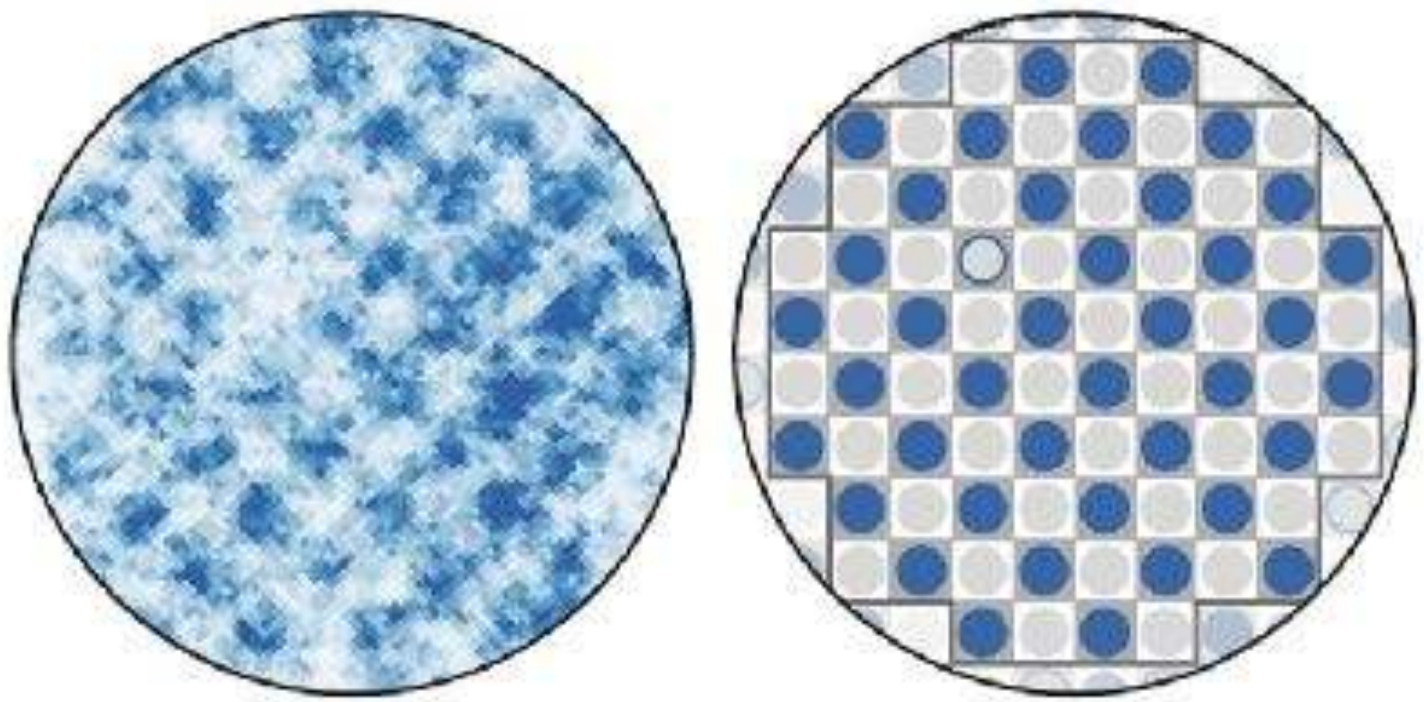
Ultracold atoms in optical potentials: ideal analog quantum simulators

- Bosons, fermions and mixtures
- Interaction control (Feshbach resonances)
- High-resolution detection (in-situ and momentum space)
- Programmable (holographic) arbitrary optical potentials

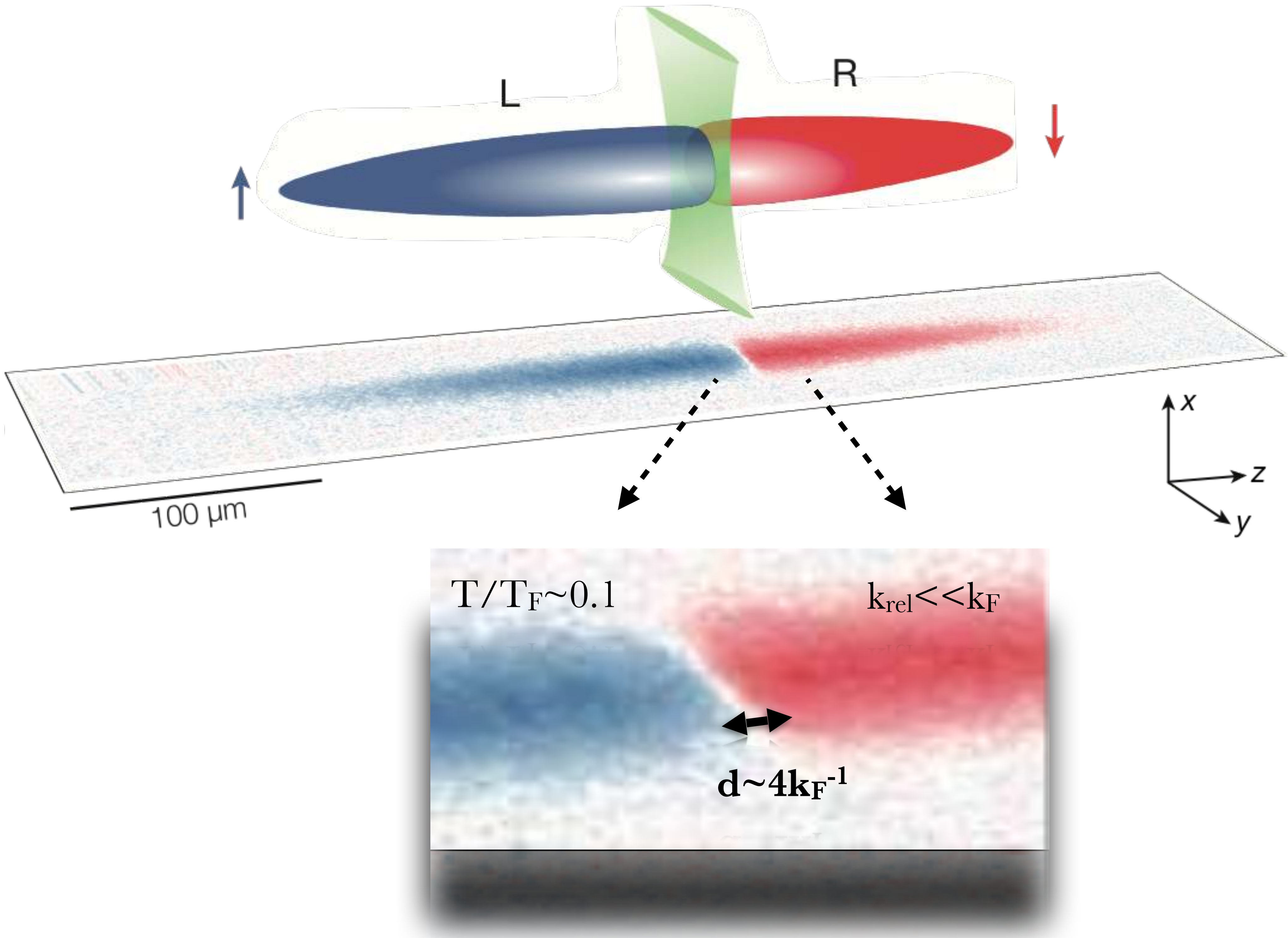
Ground state problems

- Hubbard model, probing high-Tc superconductivity



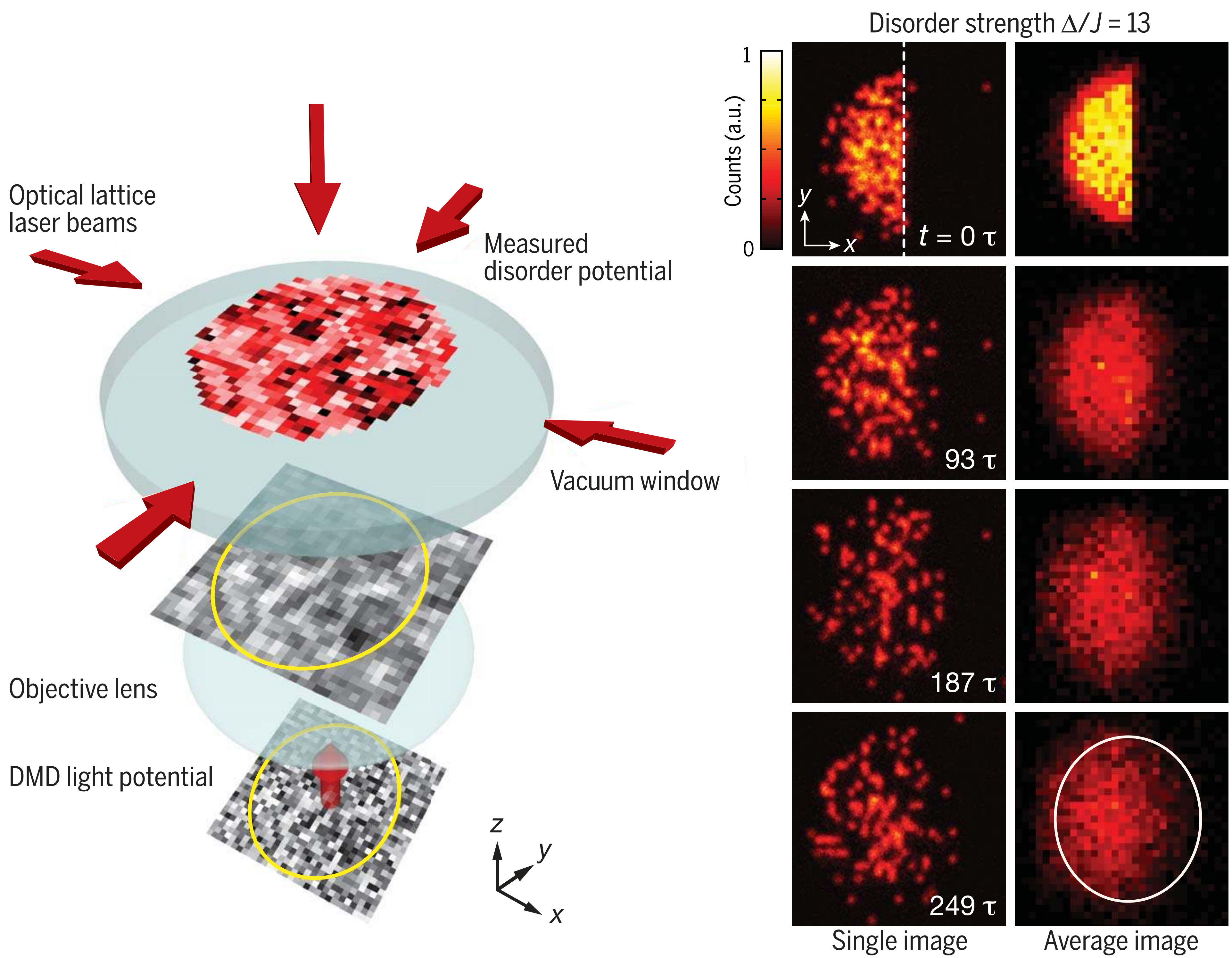
Mazurenko et al. Nature, 545 (2017)

Out-of-equilibrium dynamics (spin)



Valtolina, et al., Nature Physics 13 (2017)

Out-of-equilibrium dynamics (disorder)



Gross and Bloch, Science 357 (2017)

…we will simulate two central phenomena governing the comb emission:

The transport properties of electrons through the active medium

The four-wave mixing process creating squeezing and entanglement among the different modes.

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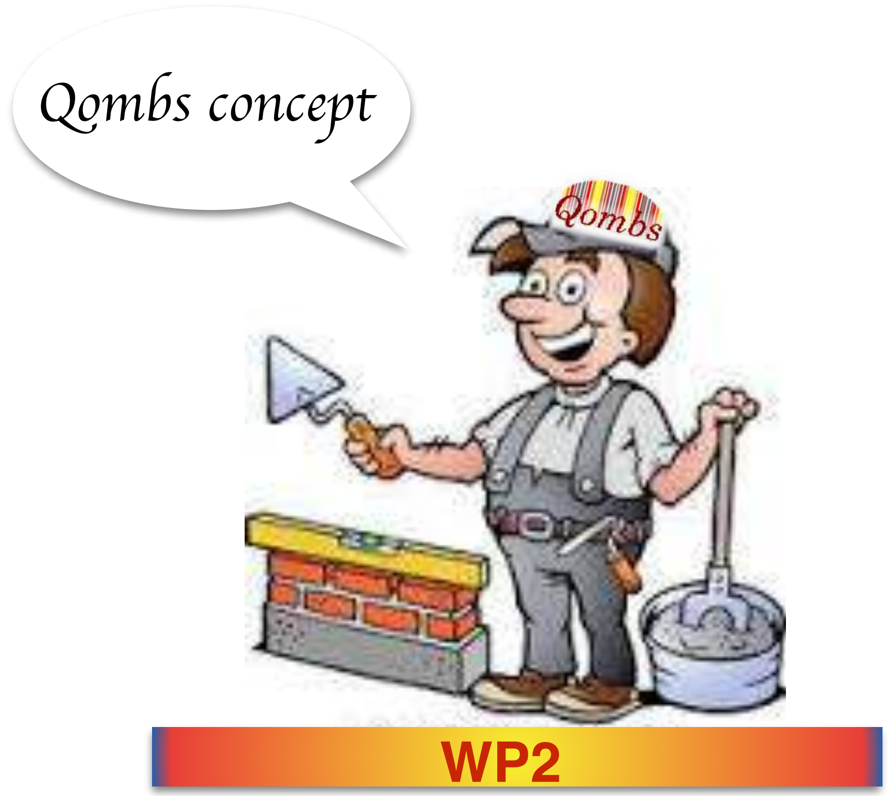
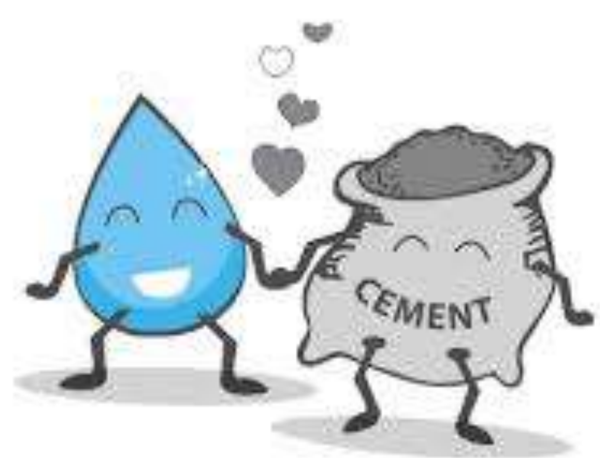
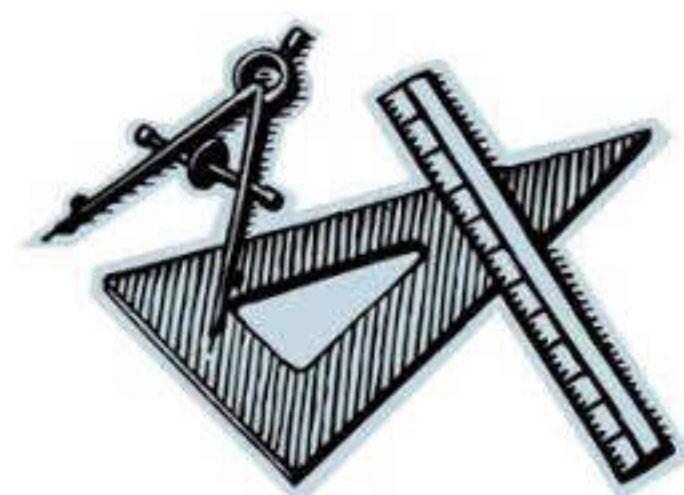


Ultracold (Fermi) gases

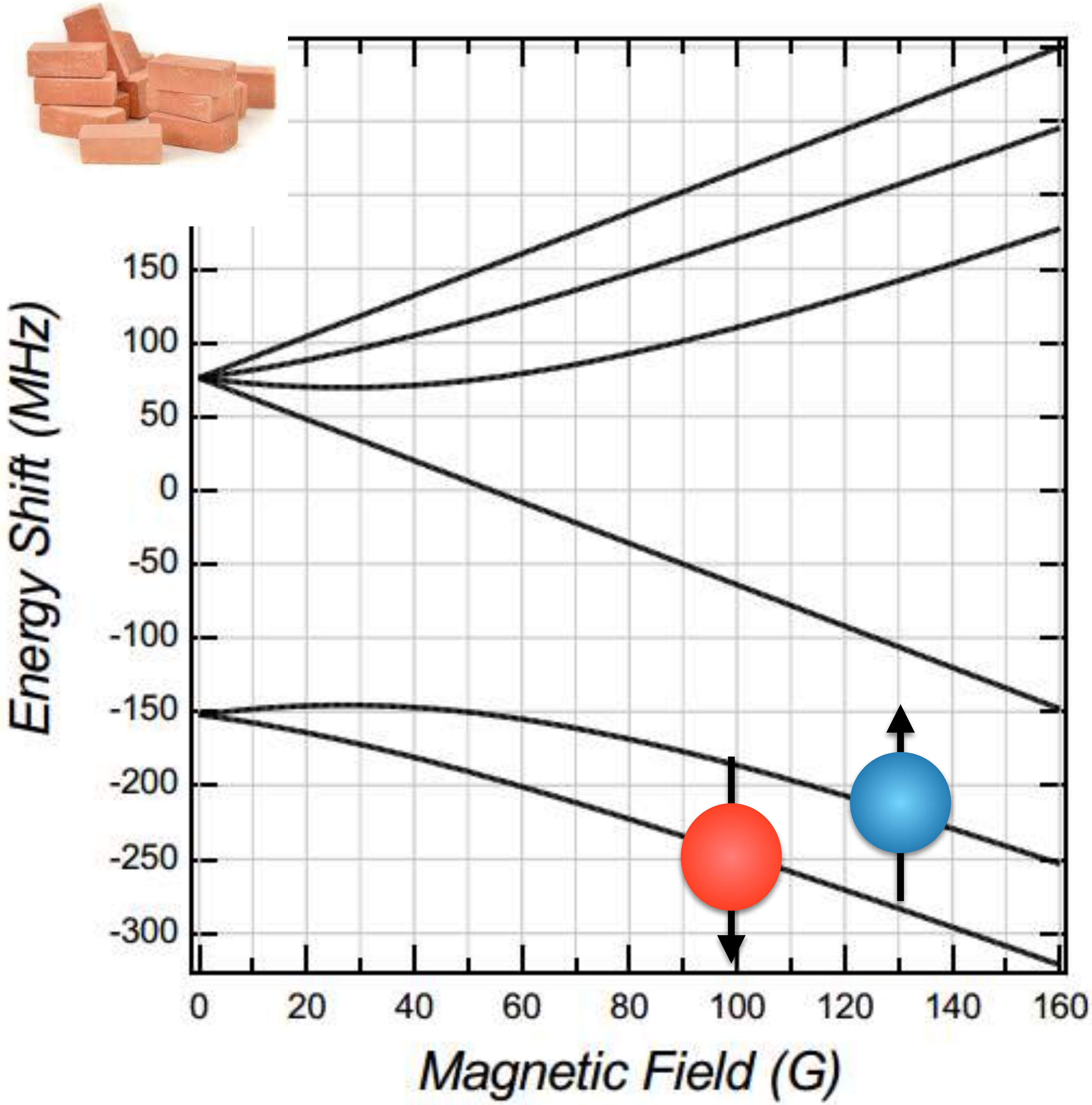


Tunable interactions



Engineering potentials

Our fermionic system: lithium-6



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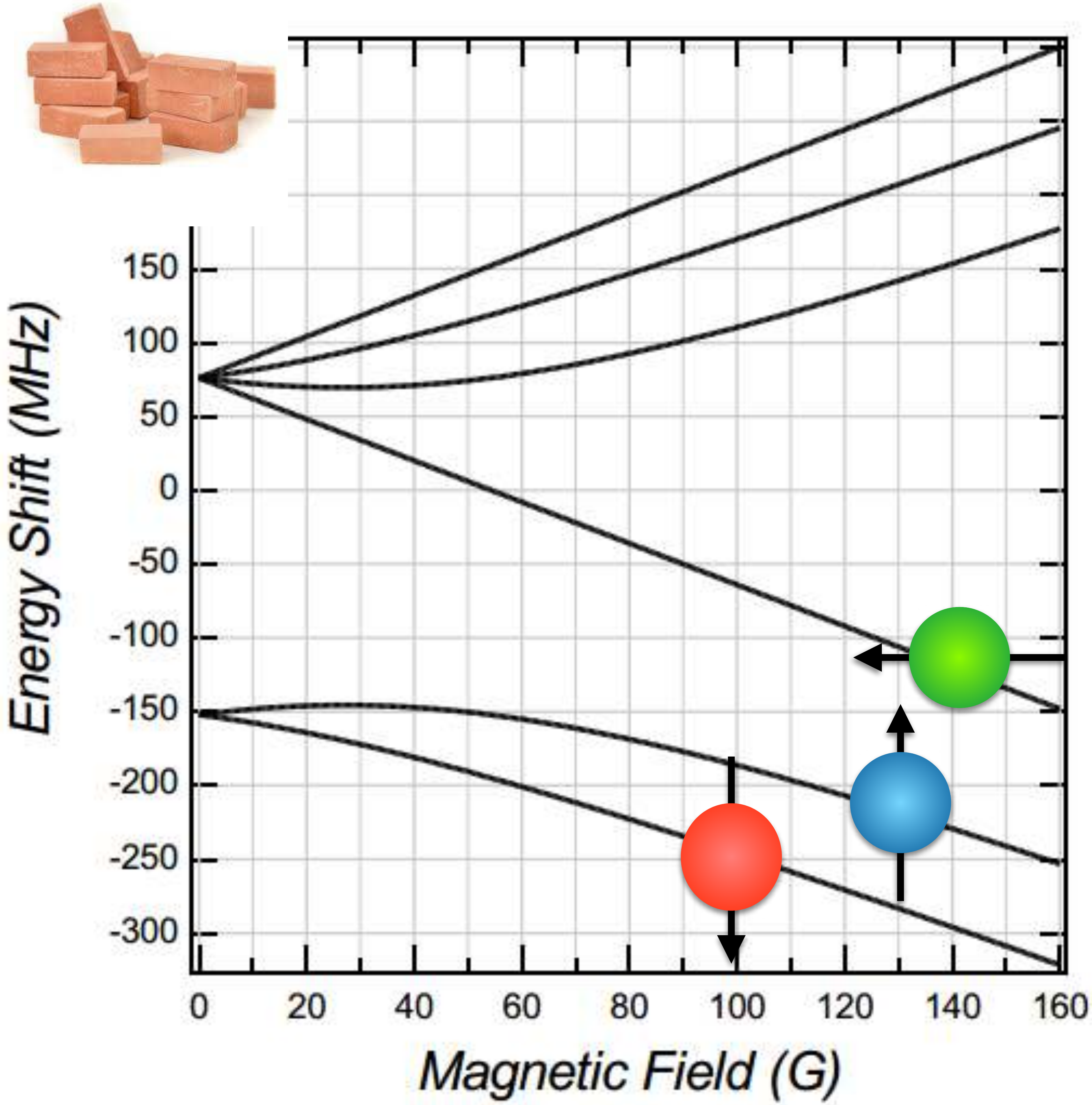
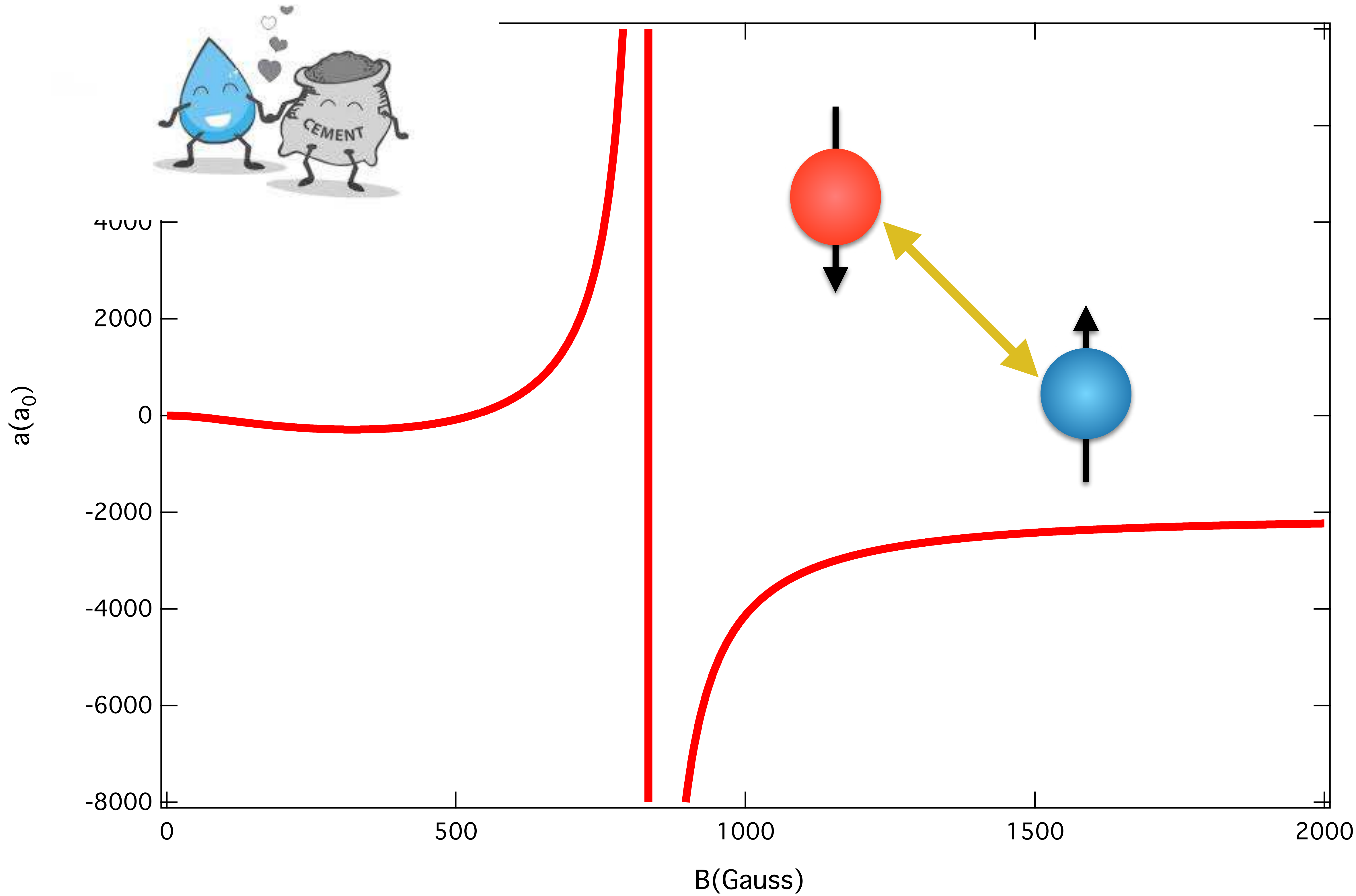


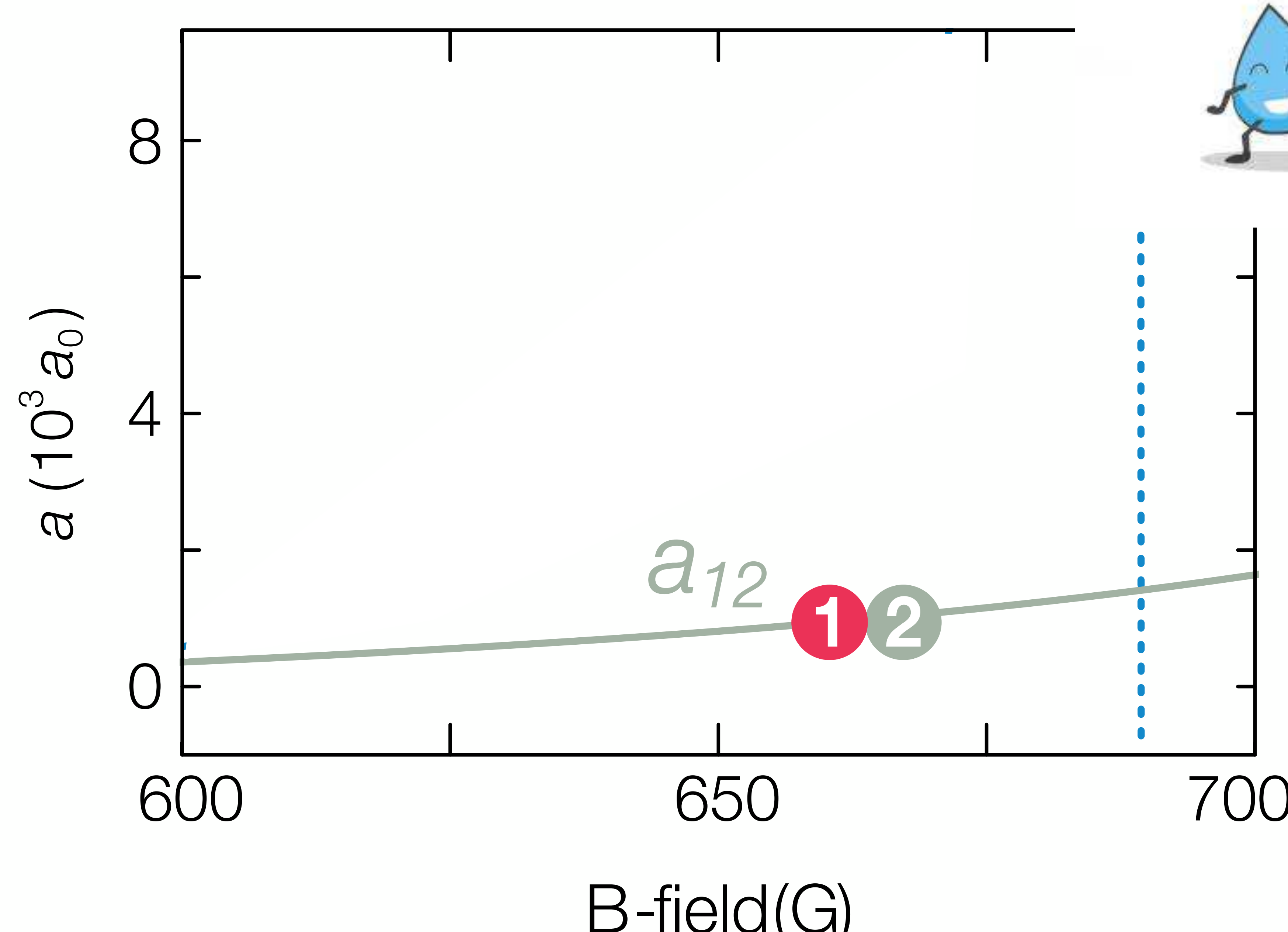
Magnetically tunable atomic interactions

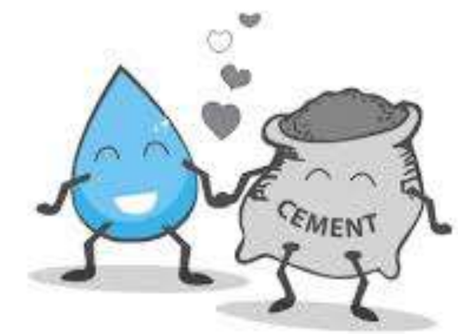
Feshbach resonance: an unique tool!



Magnetically tunable atomic interactions

Typically they are globally tuned on the whole system.





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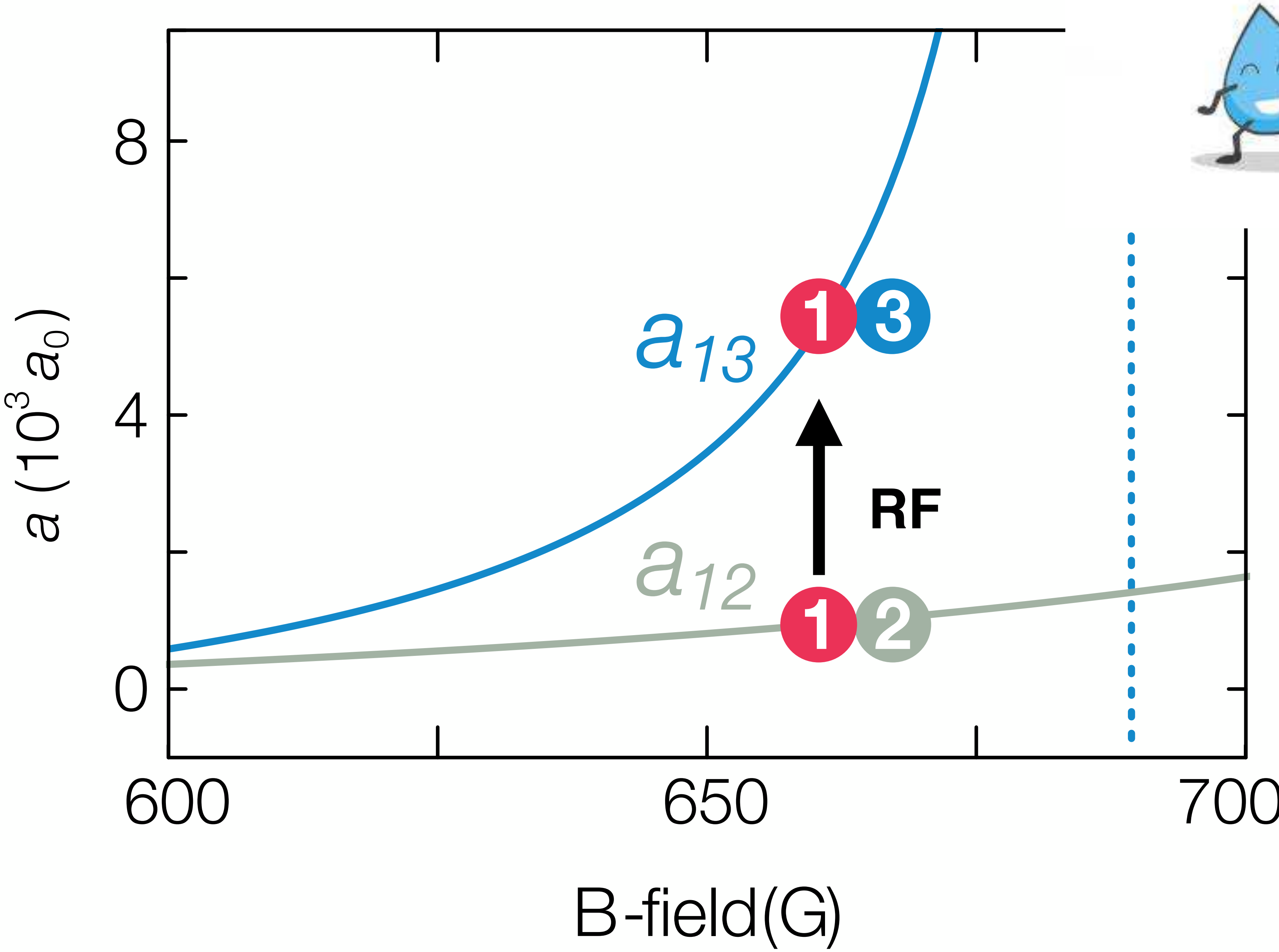
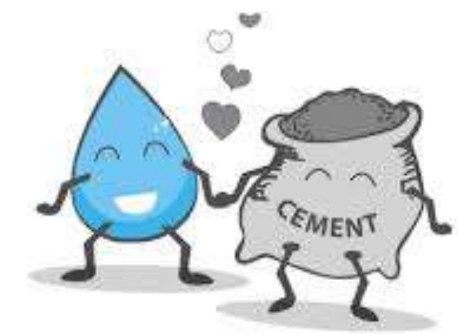
Making them "local" by driving RF transitions between internal states

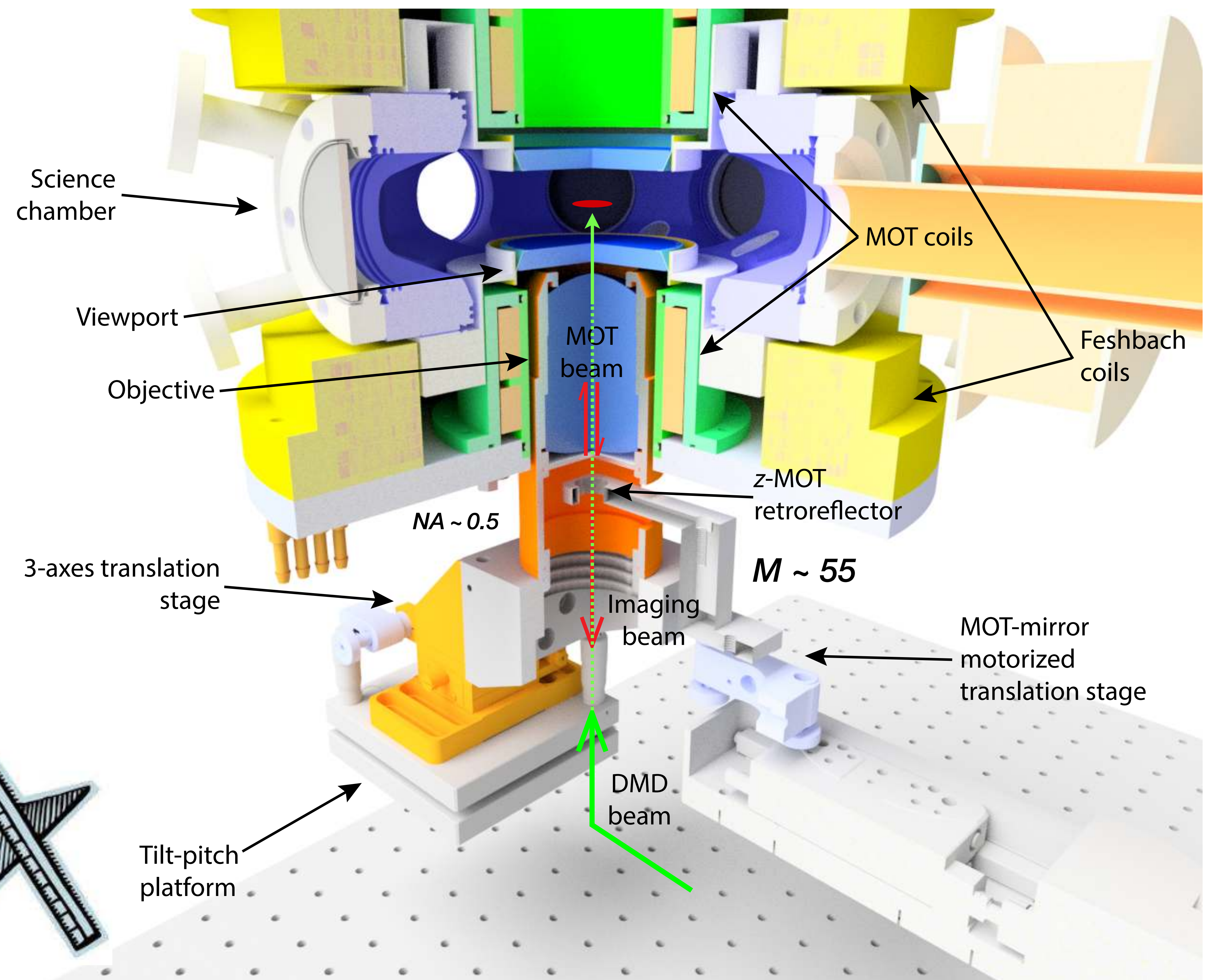
(_creating localized interacting impurities_)



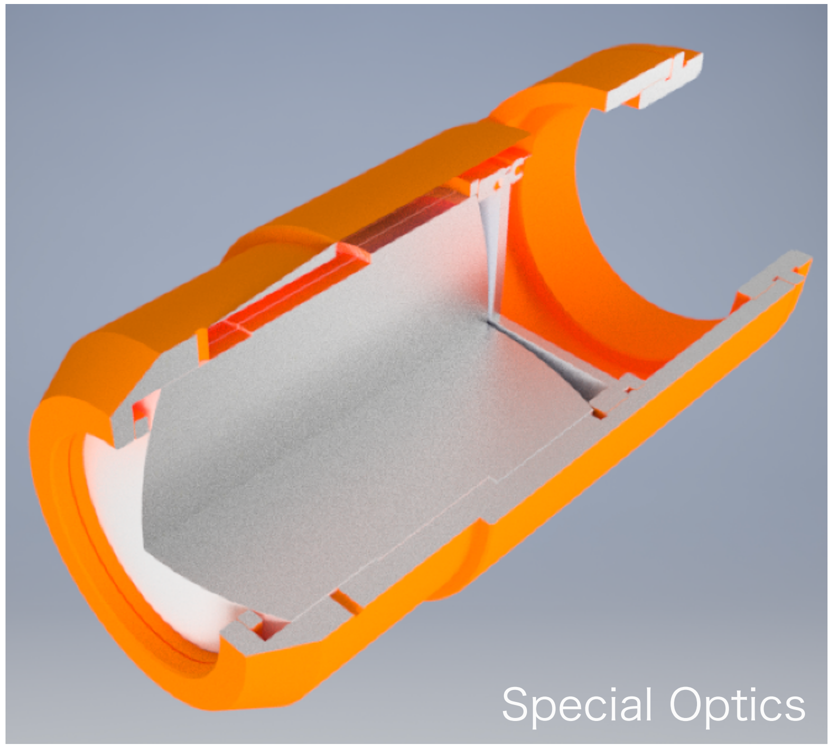


OUR SET-UP FOR HIGH-RESOLUTION DETECTION

Milestone: Test of arbitrary optical potentials made with DMD (mesoscopic lattice and disorder)



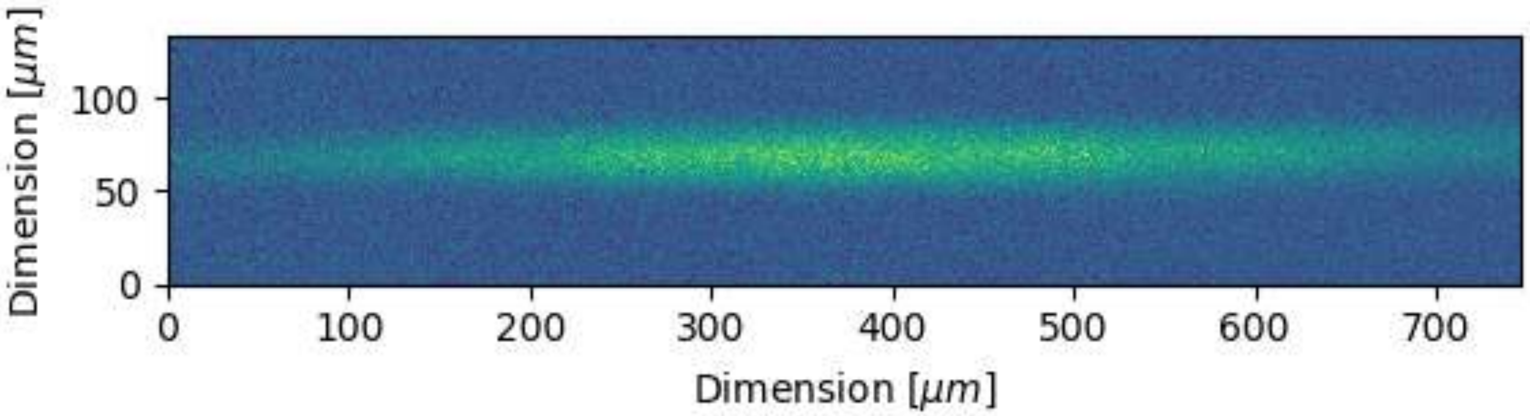
High-resolution achromatic objective



Manifactured by Special Optics:
NA: 0.45
Effective Focal Length: 47mm
Field Of View: 0.3mm
Working Distance: 13.1mm vacuum + 6mm silica + 6mm air = 25.1mm
AR coating: 532nm, 671nm and 1064nm
Housing Material: Ultem

Wavelength	Expected resolution	Measured resolution
670 nm	924 nm	(921 ± 16) nm
532 nm	740 nm	(773 ± 16) nm

Fermi gas of lithium atoms imaged by the objective

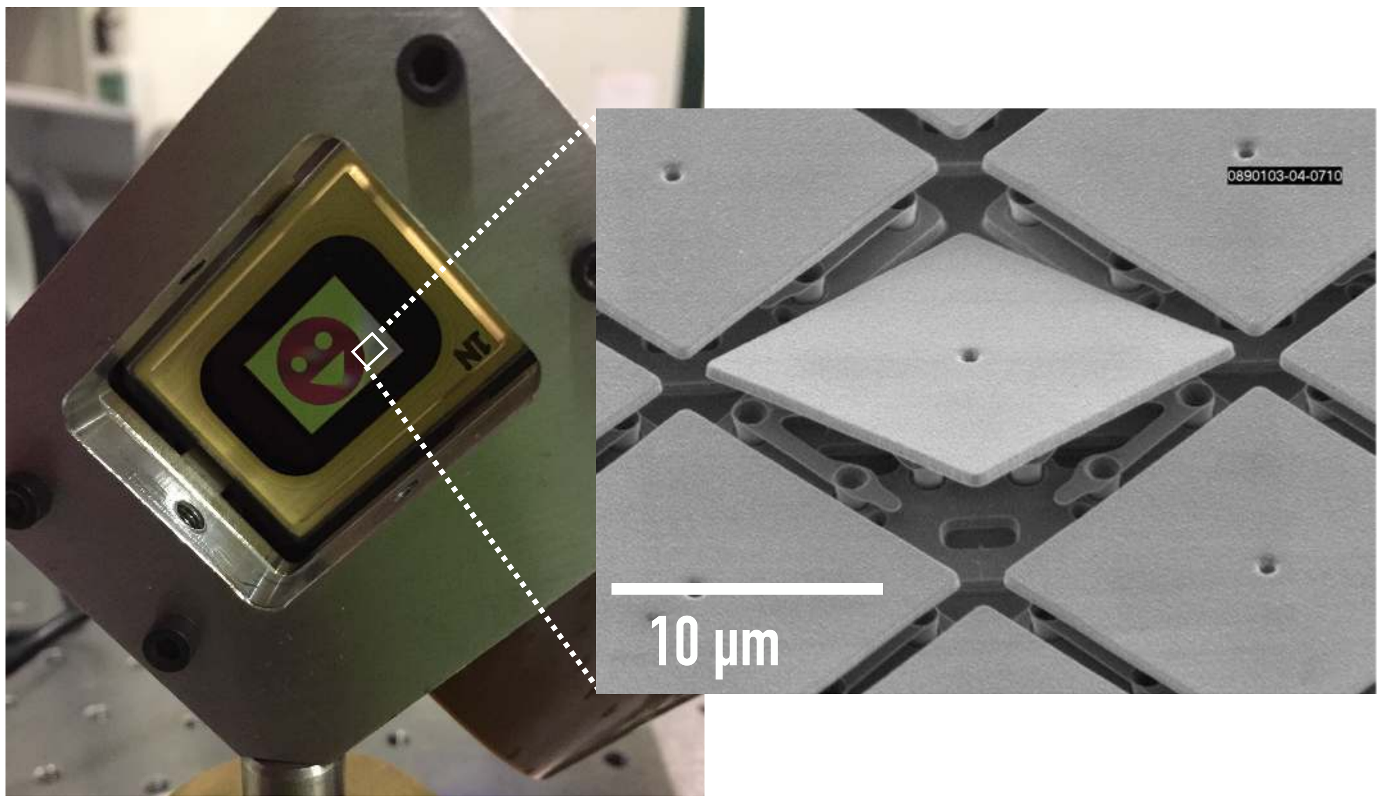


OUR SET-UP FOR ARBITRARY OPTICAL POTENTIALS

Milestone: Test of arbitrary optical potentials made with DMD (mesoscopic lattice and disorder)

D2.4 :Transport of Fermi gas

Digital Micromirror Device (DMD)



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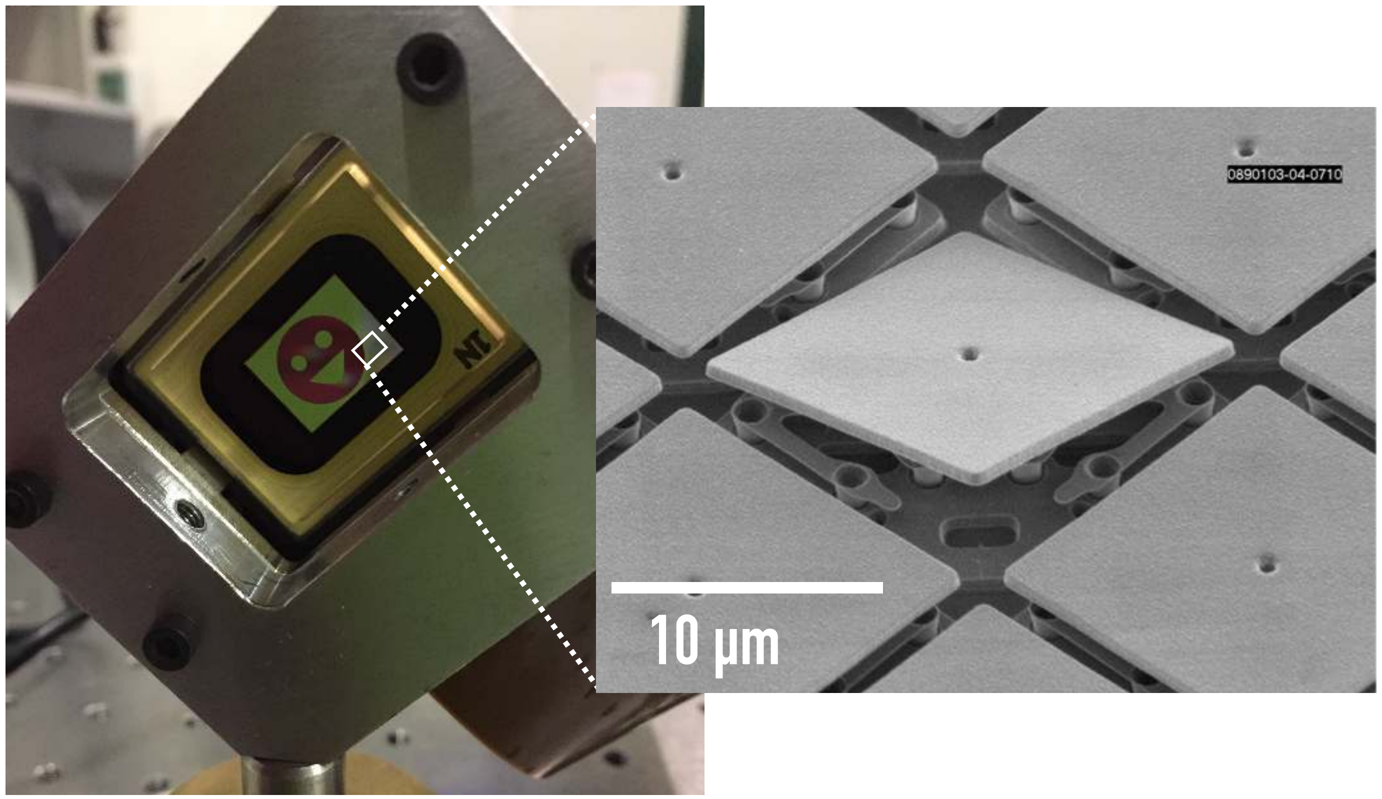

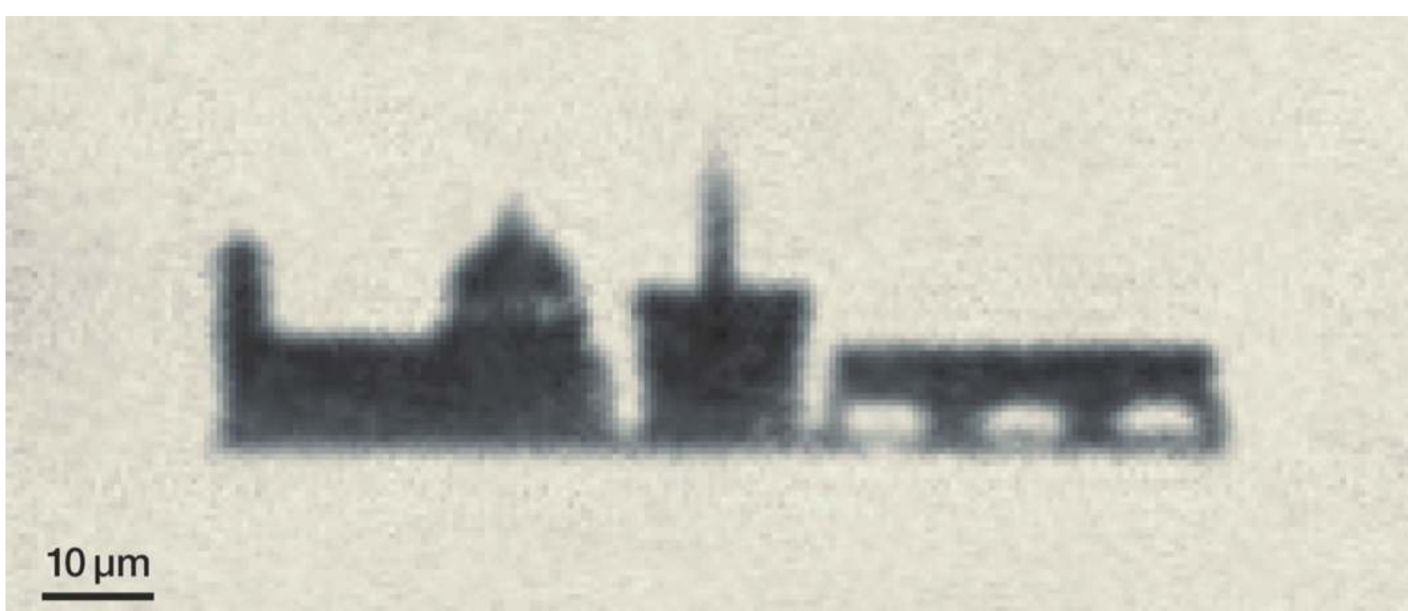

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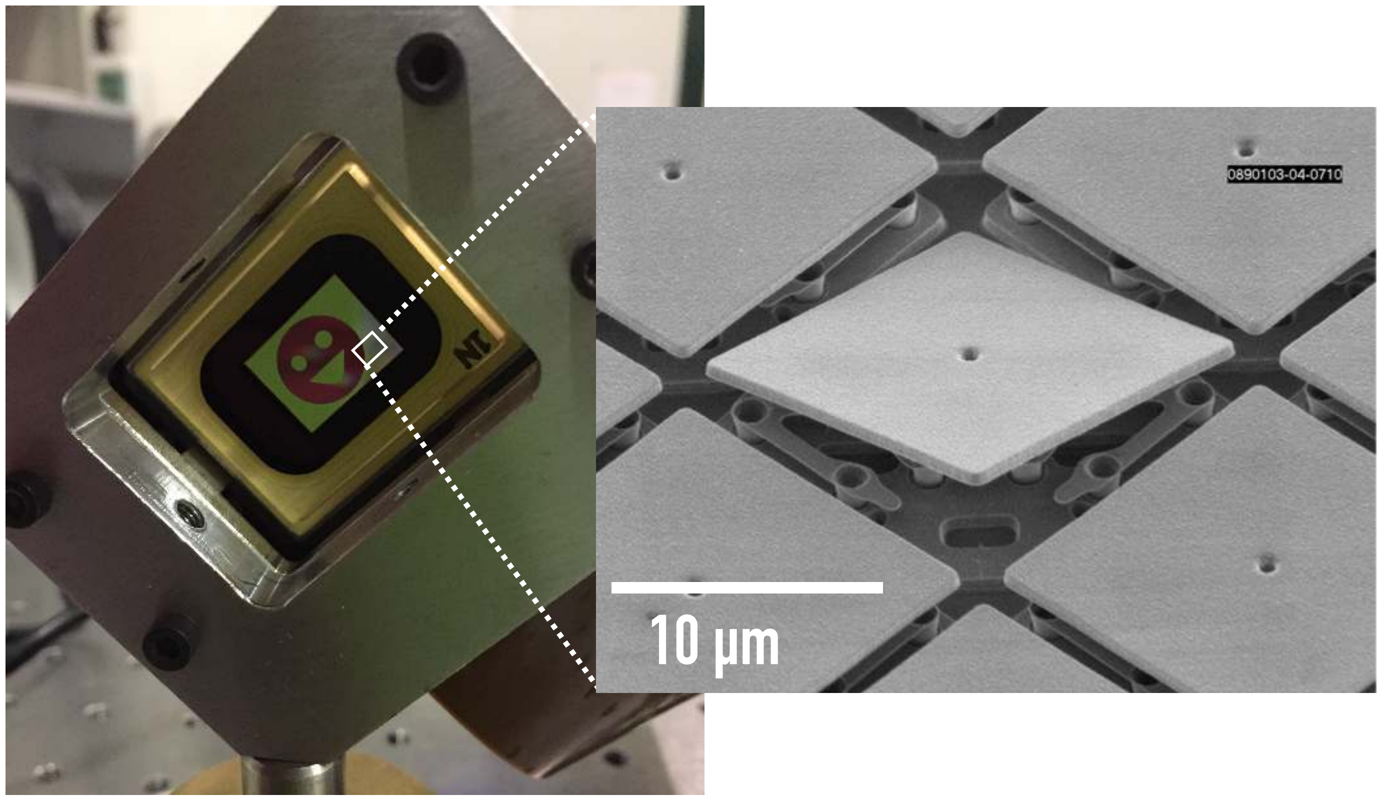
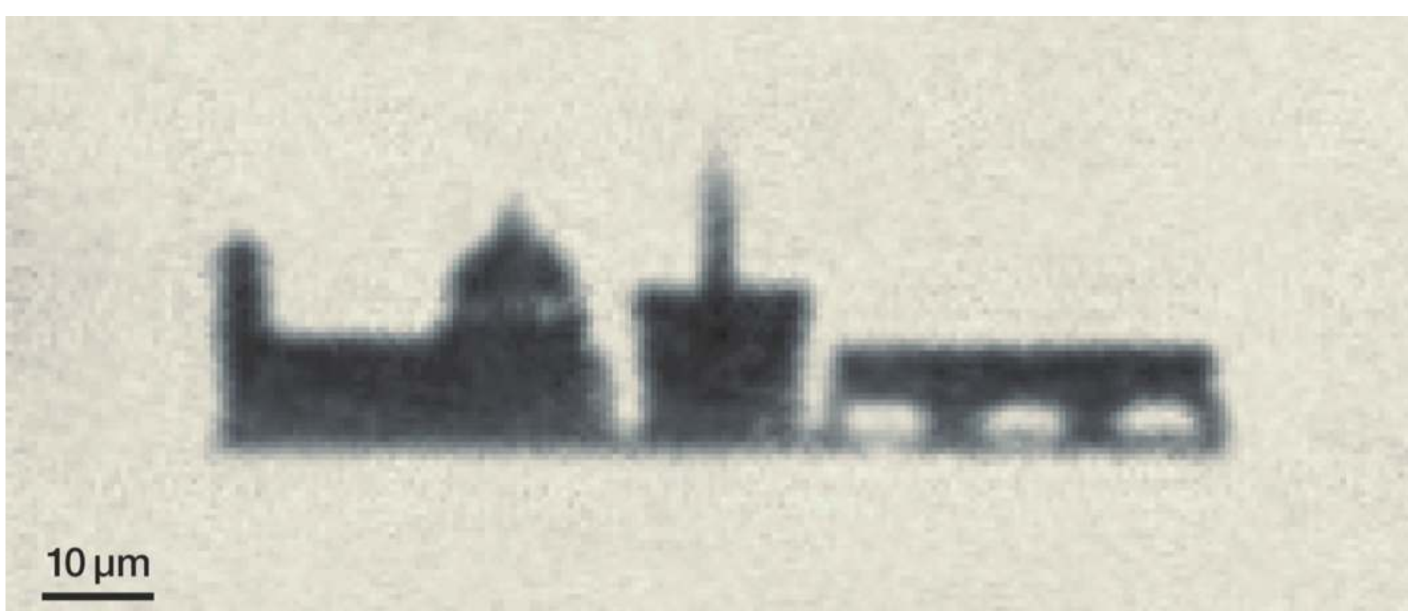
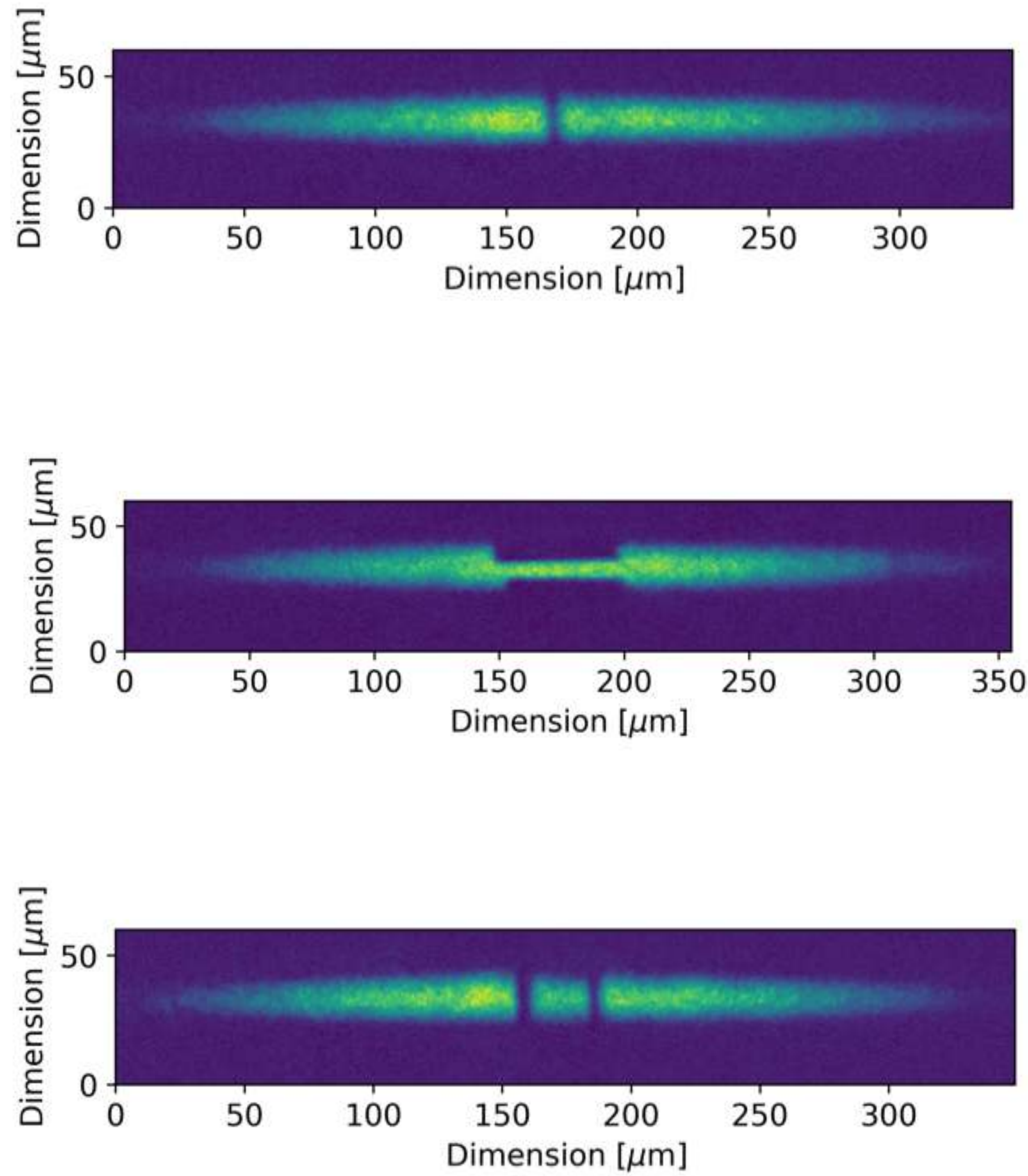




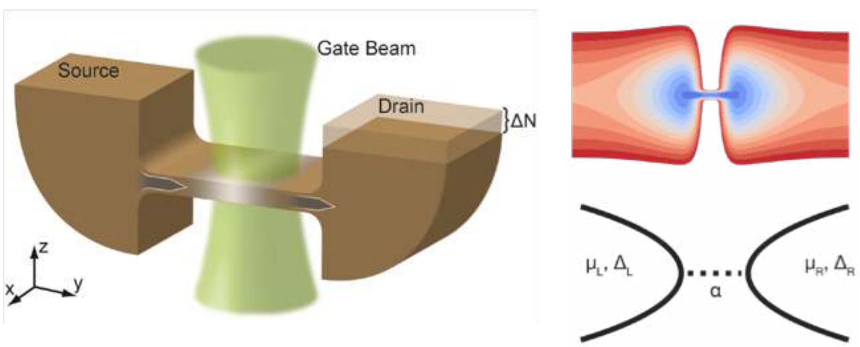
Mesoscopic transport



Our set-up: a machine for quantum transport

D2.4 :Transport of Fermi gas

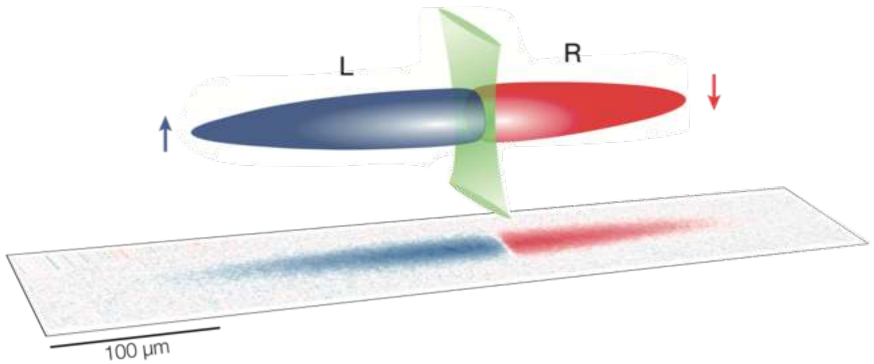
Transport through narrow ballistic channels



ETH

Brantut et al., Science 337 (2012)
Stadler et al., Nature 491 (2012)
Krinner et al., PRL 110 (2013)
Krinner et al., Nature 517 (2015)
Husmann et al., Science 350 (2015)

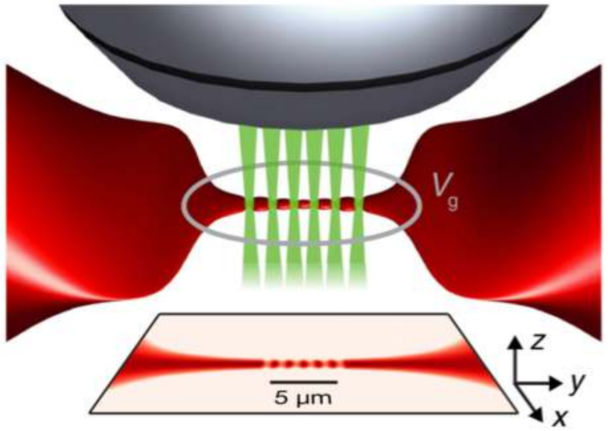
Spin and heat transport



MIT, Toronto, ETH, **INO-CNR**, MPQ

Sommer et al., Nature 472 (2011)
Brantut et al., Science 342 (2013)
Bardon et al., Science 344 (2014)
Valtolina et al., Nat. Phys. 13 (2017)
Nichols et al., Science 363 (2019)
Lebrat et al., arXiv:1902.05516 (2019)

Tunneling through structures

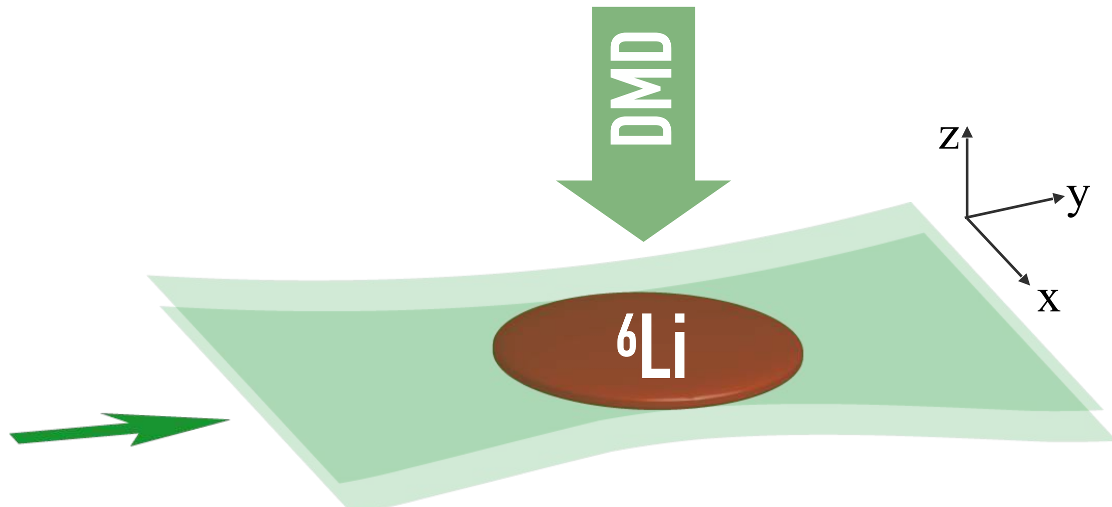


ETH, **INO-CNR**, Princeton, Toronto

Valtolina et al., Science 350 (2015)
Burchianti et al., PRL 120 (2018)
Lebrat et al., PRX 8 (2018)
Brown et al., Science 363 (2019)
Anderson et al., PRL 122 (2019)

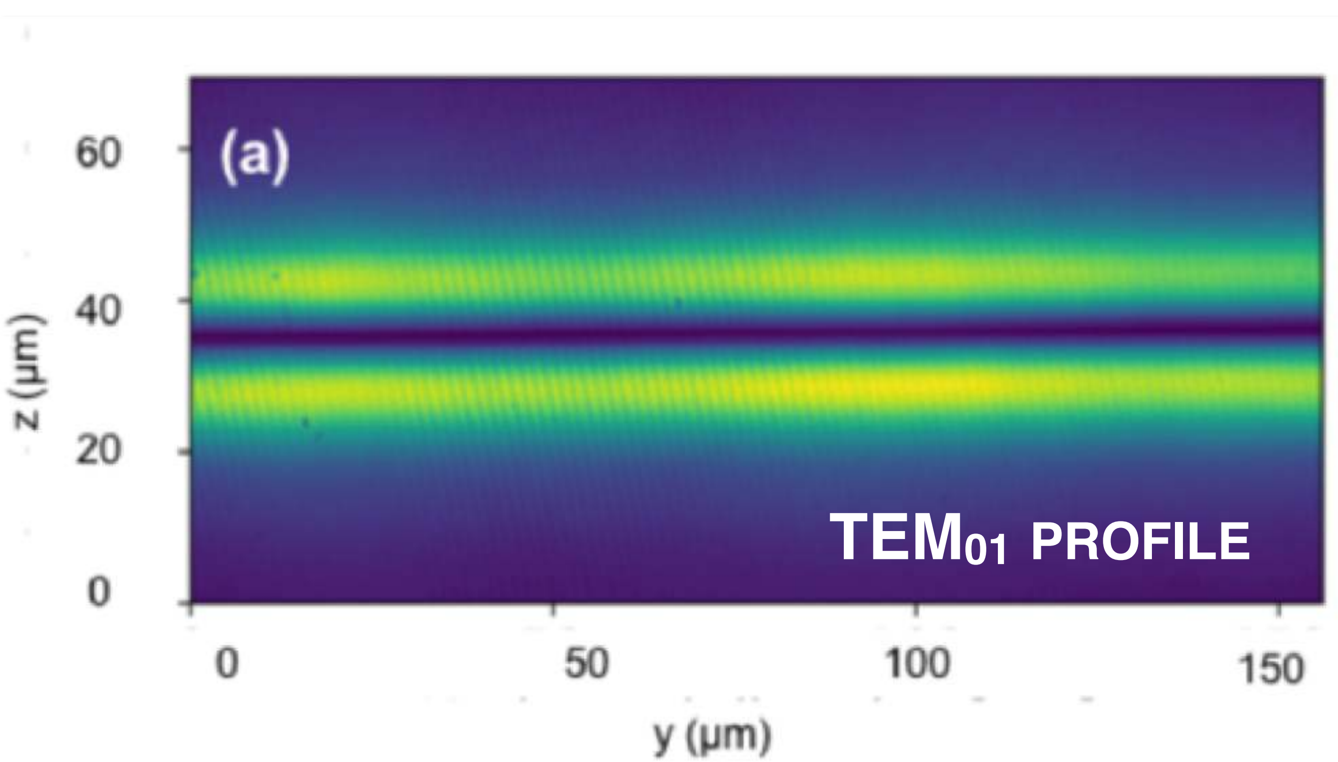
OUR SET-UP FOR SINGLE 2D POTENTIAL

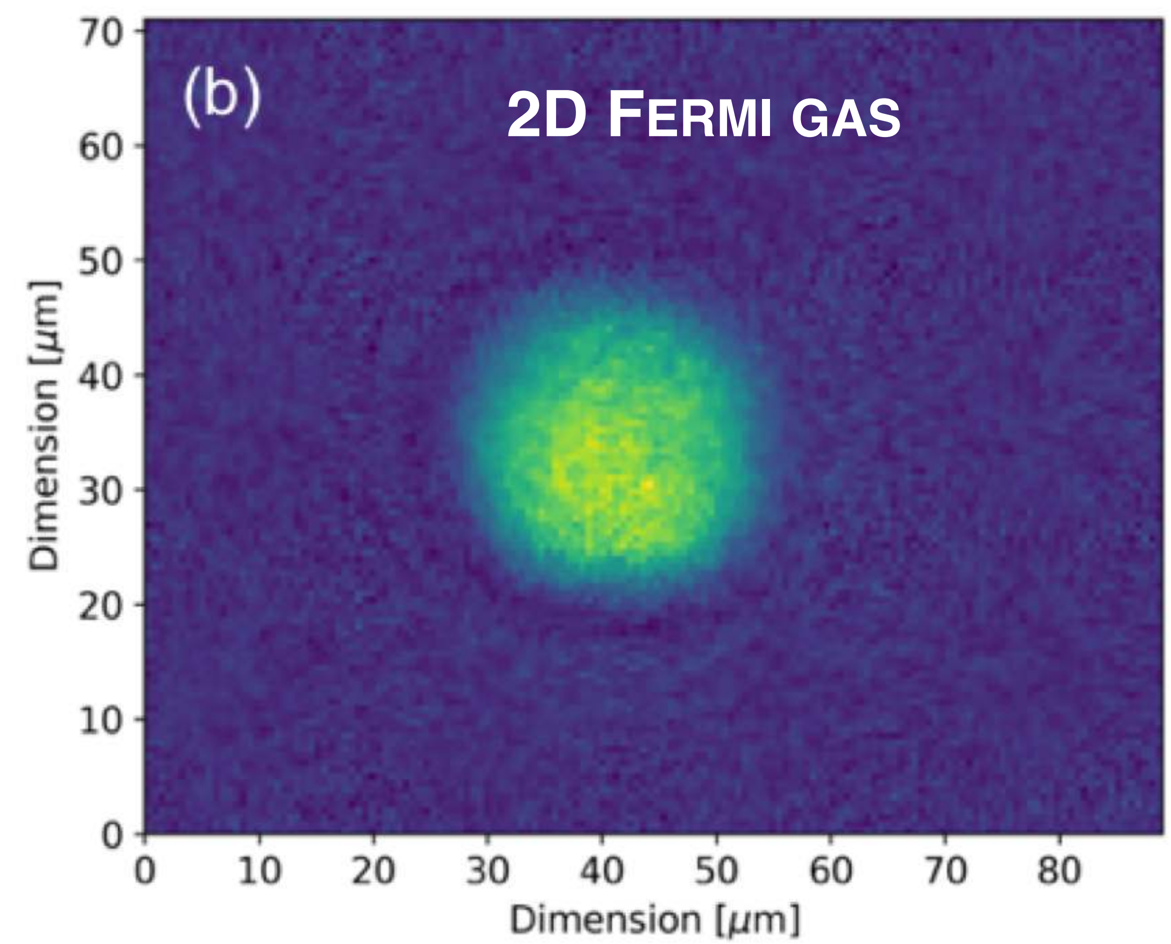
D2.4 :Transport of Fermi gas
T2.3 : Dissipative transport in the presence of interactions and disorder



Simulating a single plane of a QLC: fully controllable "in-plane" electrons dynamics.

TEM_{01} beam



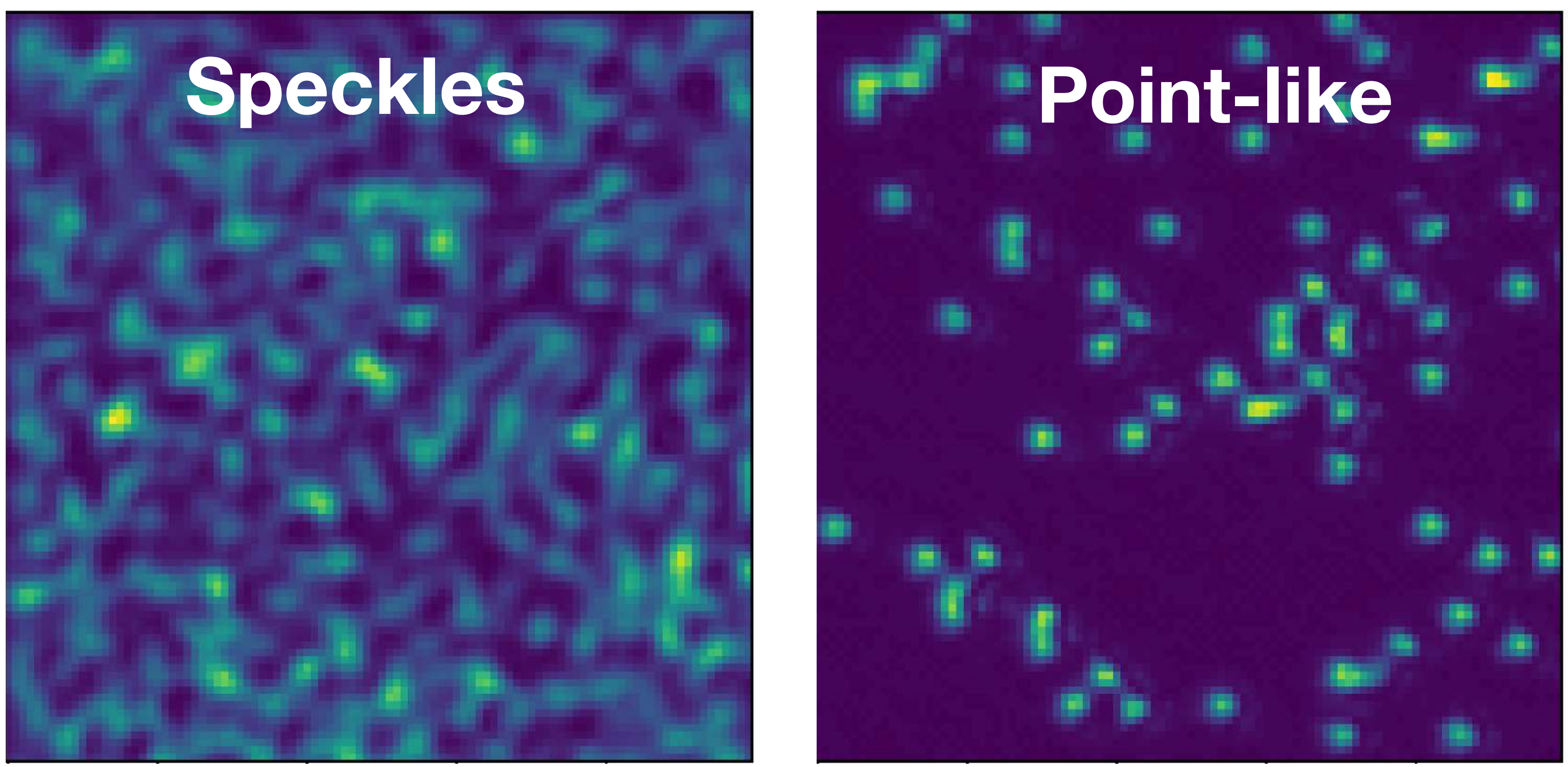


OUR SET-UP FOR DISORDER POTENTIALS

T2.3 : Dissipative transport in the presence of interactions and disorder

Mimicking the intra-plane disorder of QCL heterostructures with DMD tailored disorder patterns (at 532 nm). **Average disorder size up to 1um**, comparable with the mean interparticle spacing.

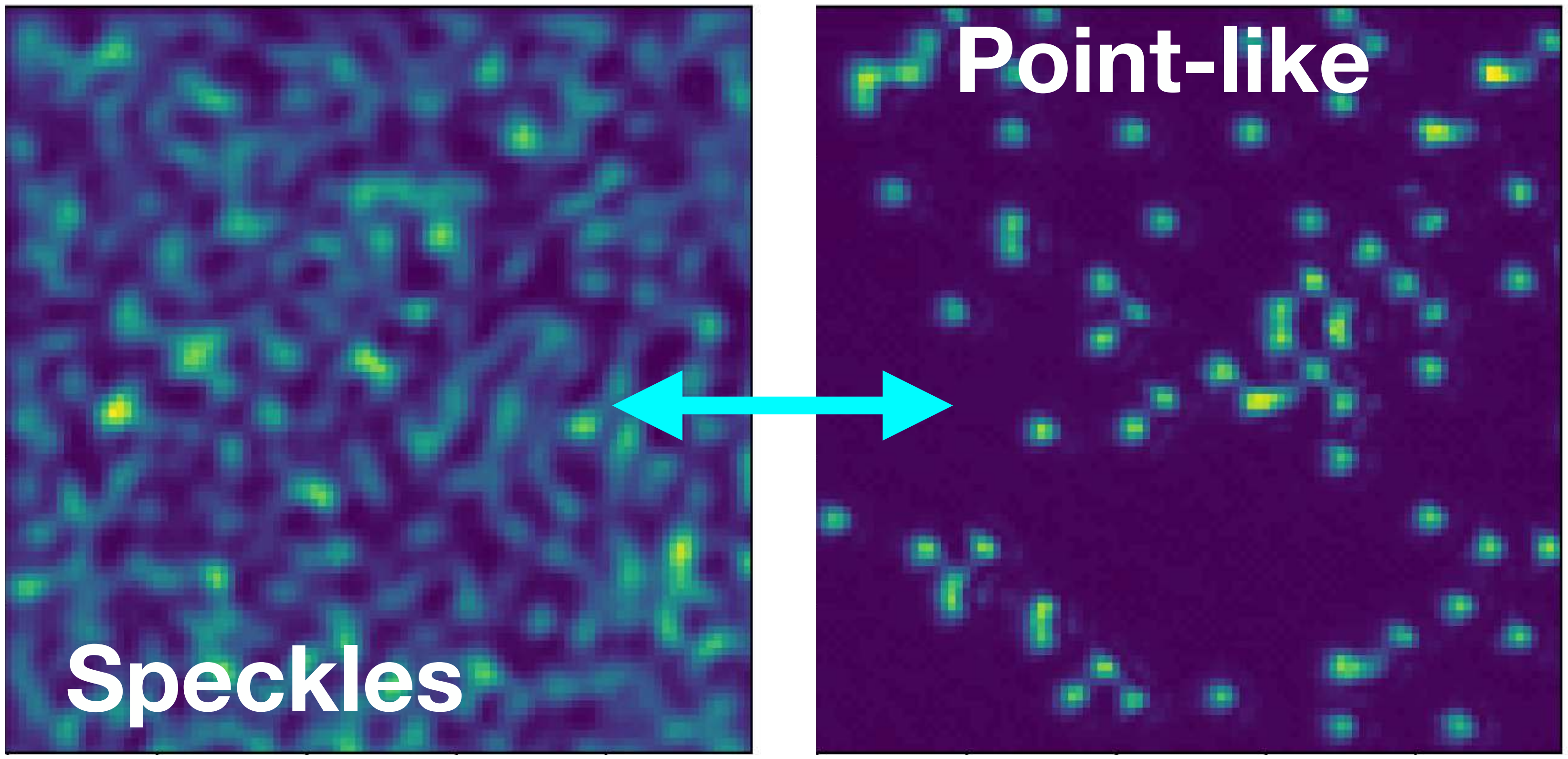
High-resolution controlled disorder



OUR SET-UP FOR DISORDER POTENTIALS

T2.3 : Dissipative transport in the presence of interactions and disorder

Point-like (Bernoulli disorder)= impurities in materials. Low percolation threshold in 2D, ideal for observing the quantum effects of disorder

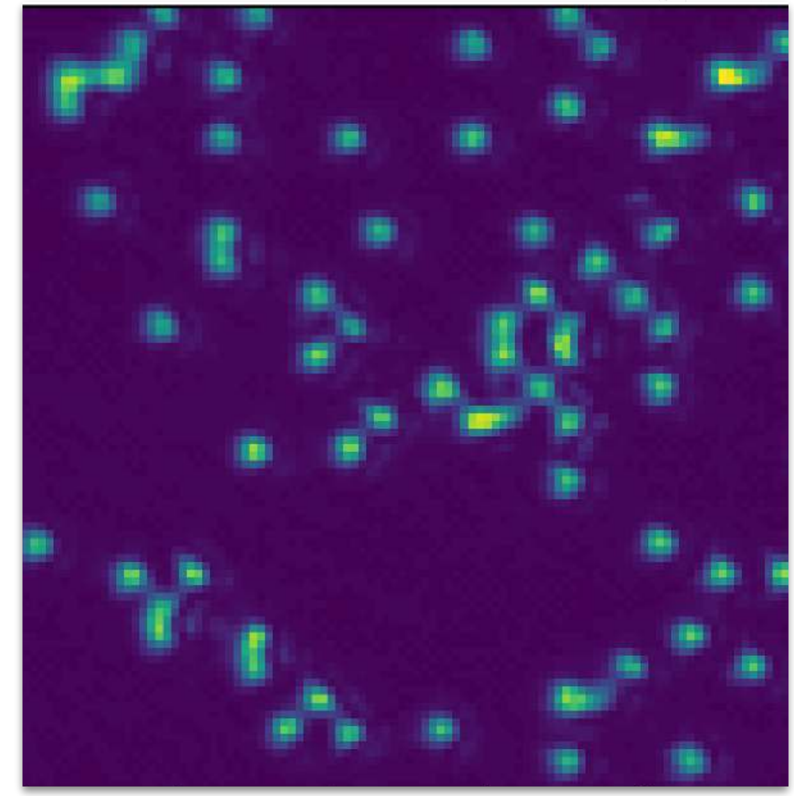


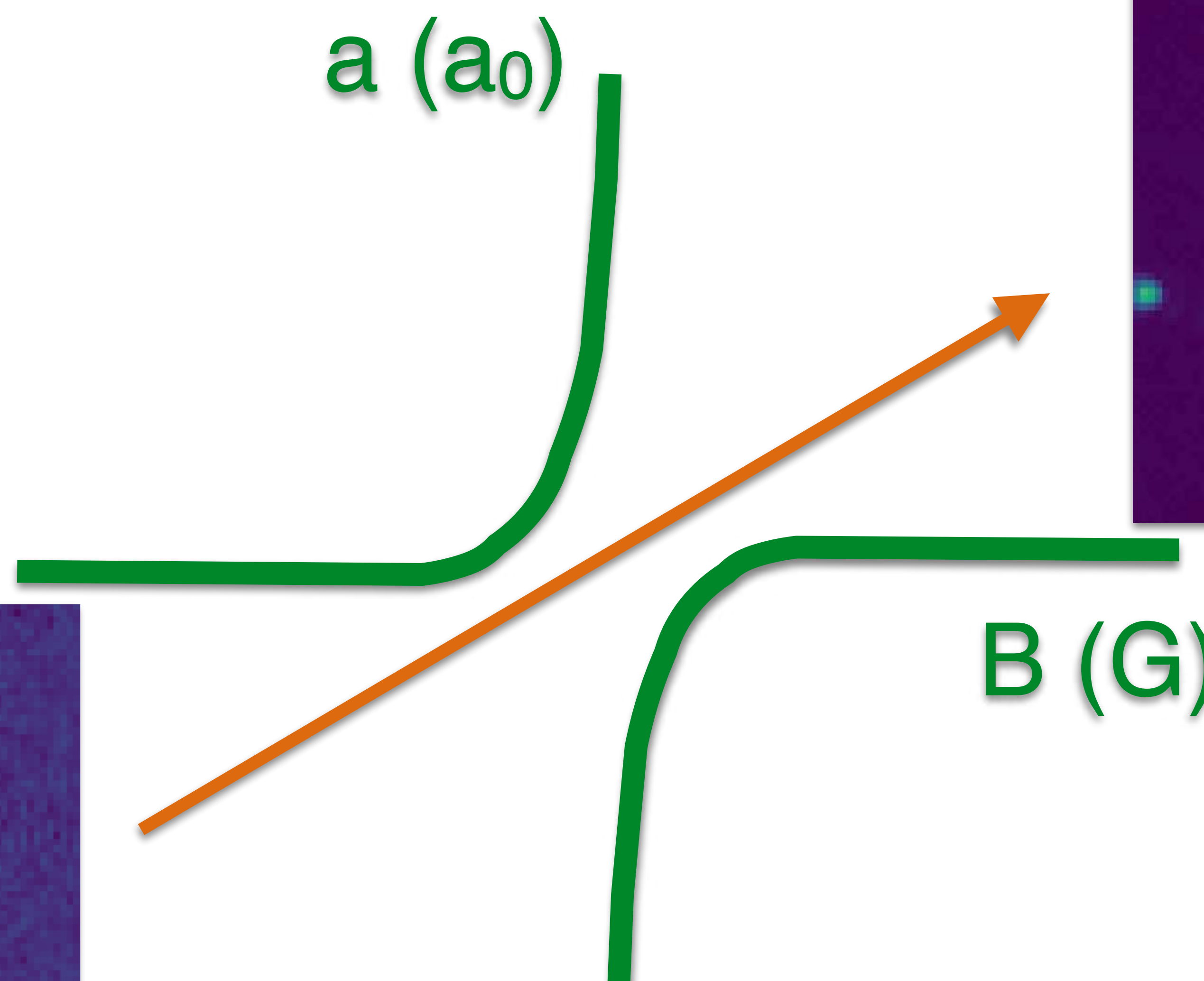
Completely tunable:

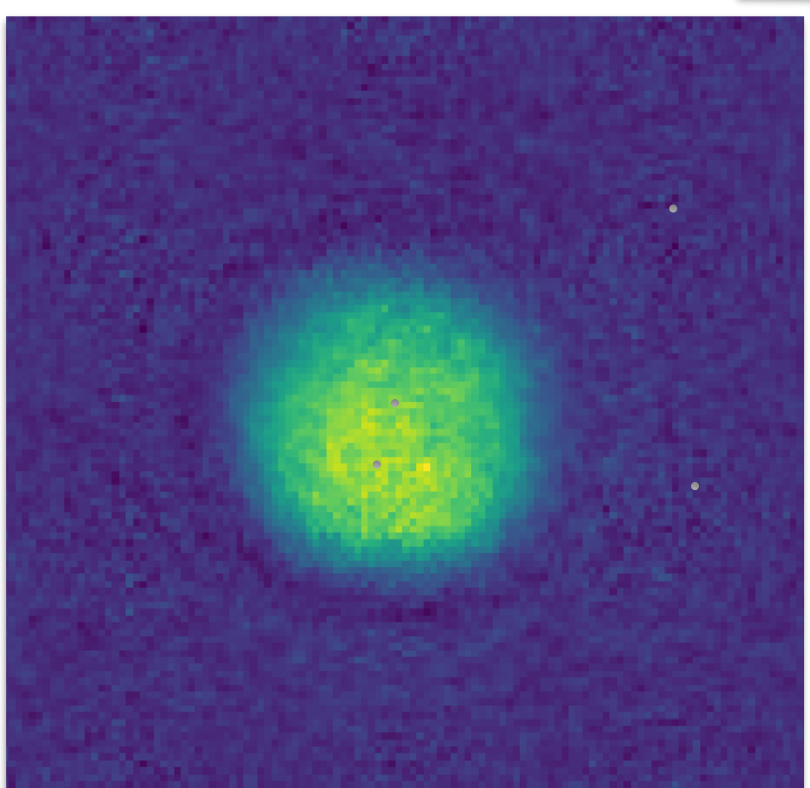
i. Disorder density (DMD)
ii. Disorder amplitude (laser intensity)
iii. Mean disorder size (DMD+resolution)
iv. Disorder correlations (DMD +resolution)
v. Disorder dynamics (DMD)

Intensity-change rate 1 us
DMD switch rate 10 us (few Fermi times)

Electron-electron and **electron-impurities** scattering play a crucial role defining the conducting properties of materials and **on the performance of QCLs.**





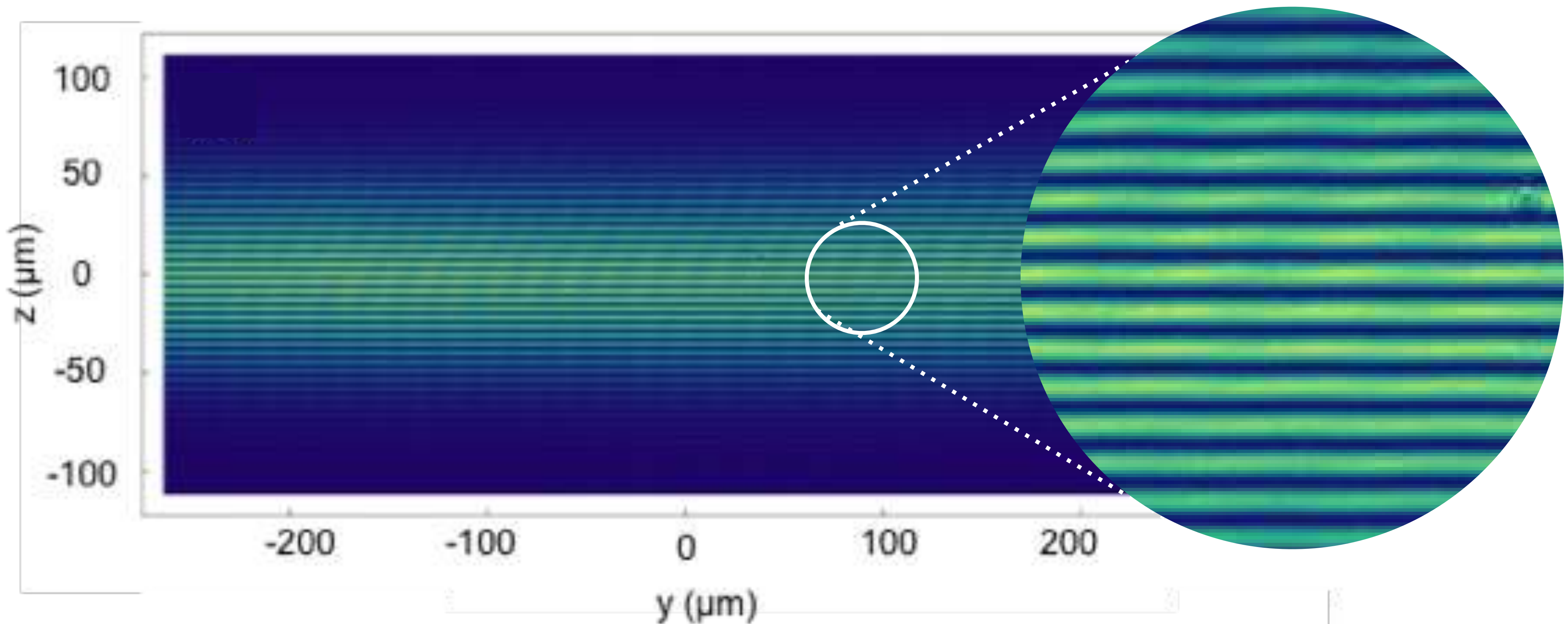


These phenomena represent a challenge for the most advanced numerical approaches: **atomic quantum simulation.**

OUR SET-UP FOR MULTI-WELLS POTENTIALS

D2.1: Realization of Fermi gas in one-dimensional optical lattice

Large-spacing lattice: d ~ 5μm



Each plane **can be** considered as a 2D atomic plane (QLC heterostructures)

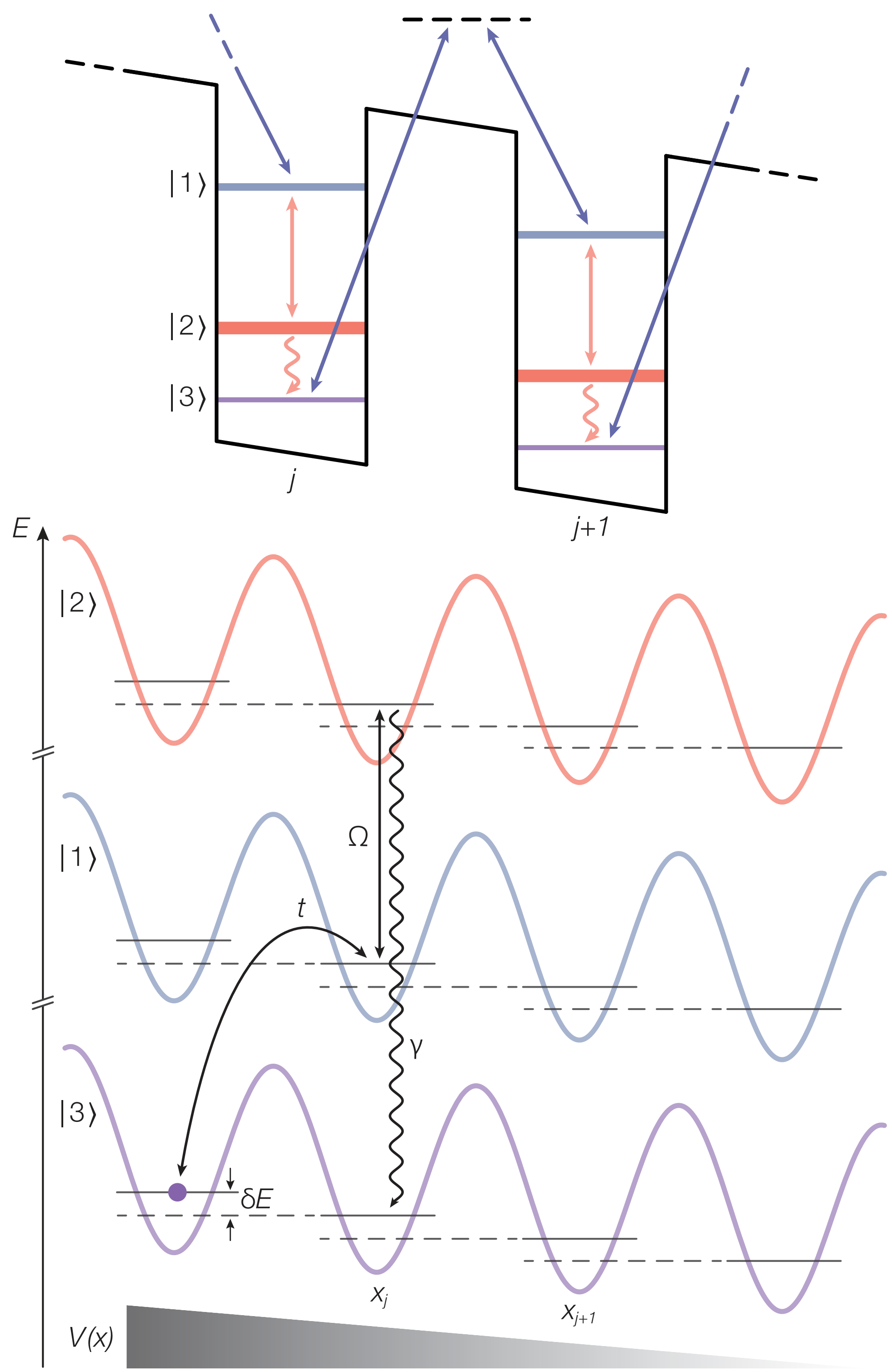
Each plane **can be** individually addressed and manipulated via imaging and holographic techniques (with high resolution)

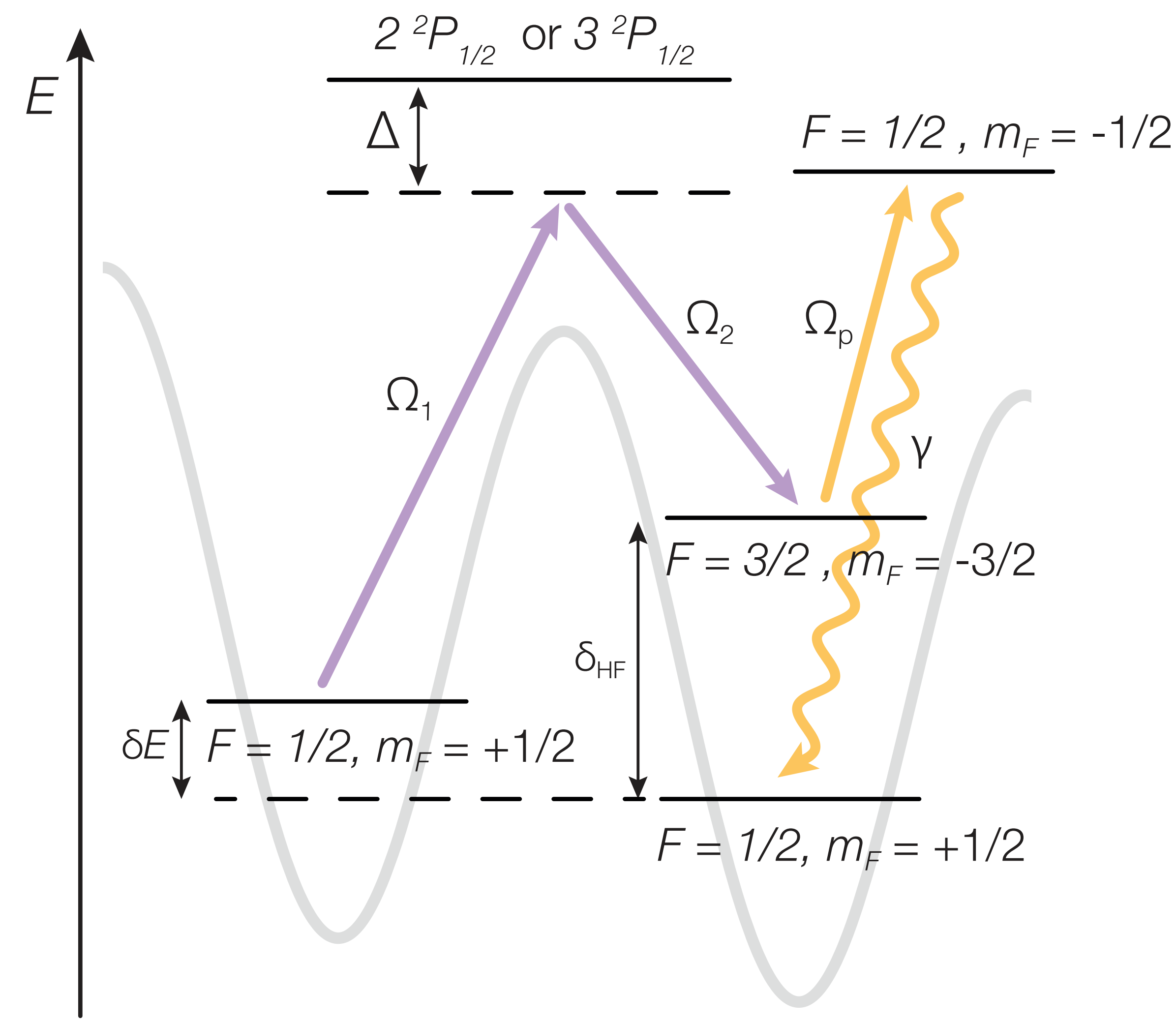
Driving transport between different planes: inducing inter-plane coupling

TRANSPORT IN MULTI-WELLS POTENTIALS

D2.2 Realization of Raman-assisted tunneling

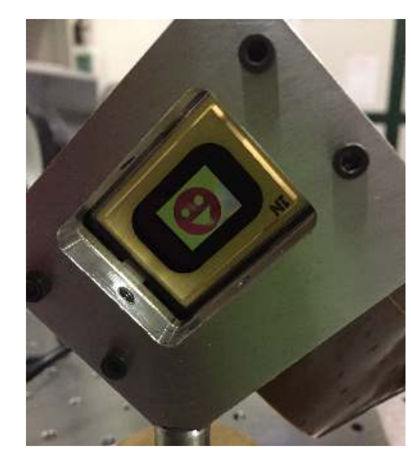
D2.4 :Transport of Fermi gas





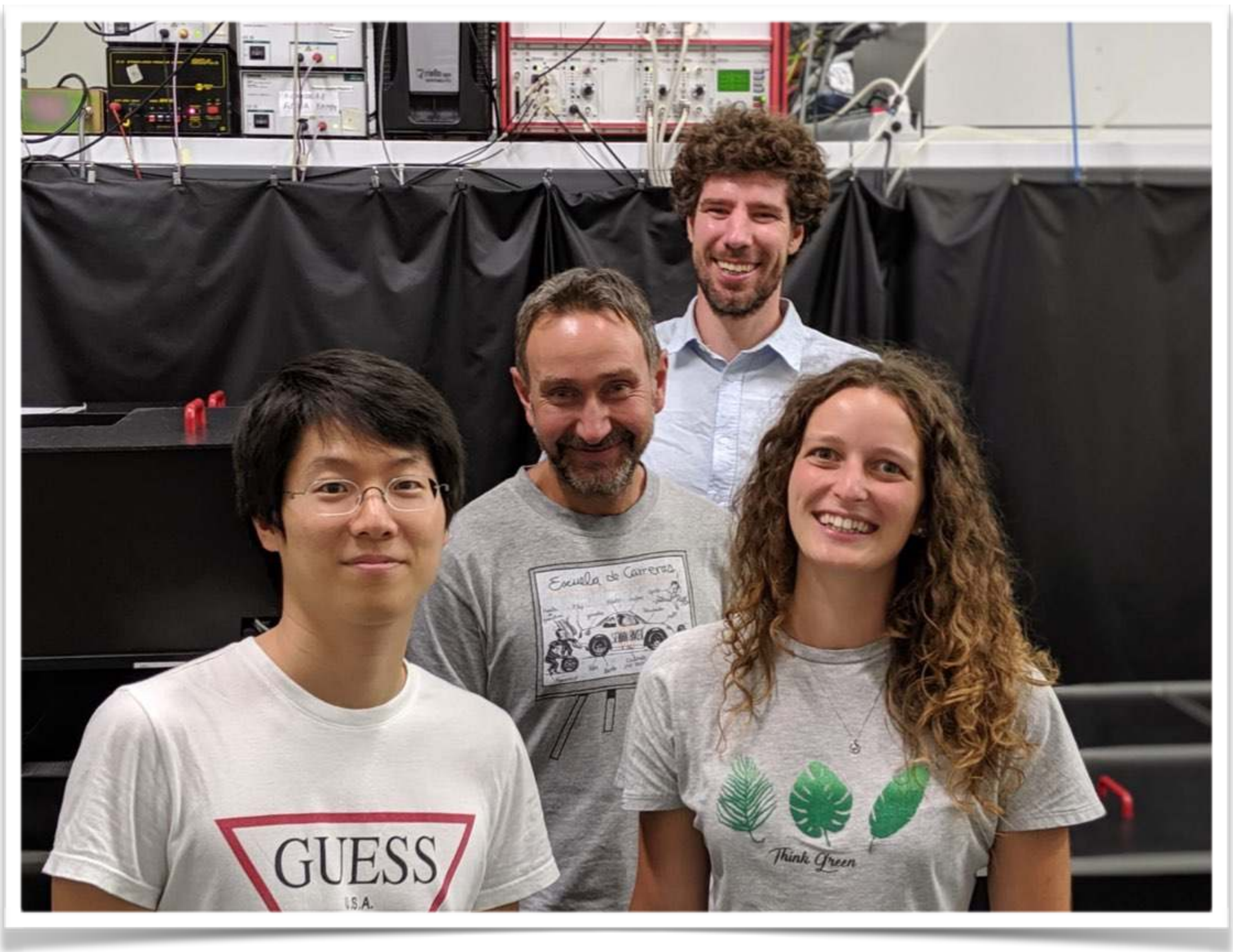
Raman-concept scheme

(D_1 & D_2 lines + DMD)



Our Plan: next steps

i. Raman scheme final design and implementation (via DMD)
ii. Dynamics in 2D single plane + disorder and interactions (weak repulsive)
iii. Loading Fermi gases in one-dimensional lattice
iv. Transport in multi-layer geometry



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