Learn more

Making, Probing and Tuning of Quantum Matter

Correlated Quantum Matter Group, Prof. Marc Janoschek

Contact us


Simon Flury


Jonas Philippe


Wolfgang Simeth


Gediminas Simutis


Dang Xuan Dang


Danielle Yahne

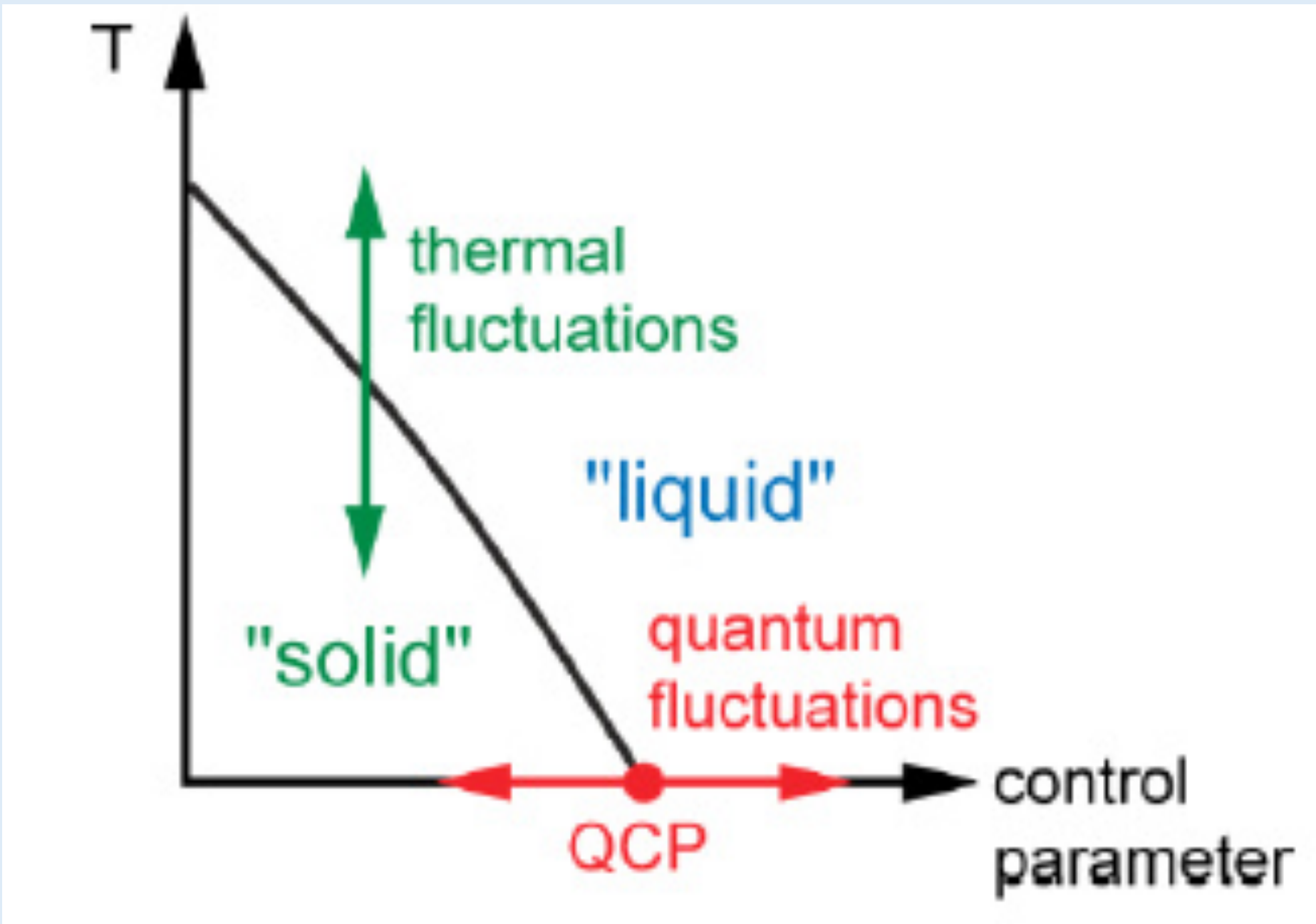

Marc Janoschek

Starting 2022

What is Quantum Matter !?

In principle, there is no clear definition of what quantum matter is. In a way this is deeply philosophical: All things are quantum at a level (i.e. this poster) because the underlying interactions are “quantum”. **We define ‘quantum matter’ as any state that exhibits macroscopic properties driven by dominant quantum interactions.**

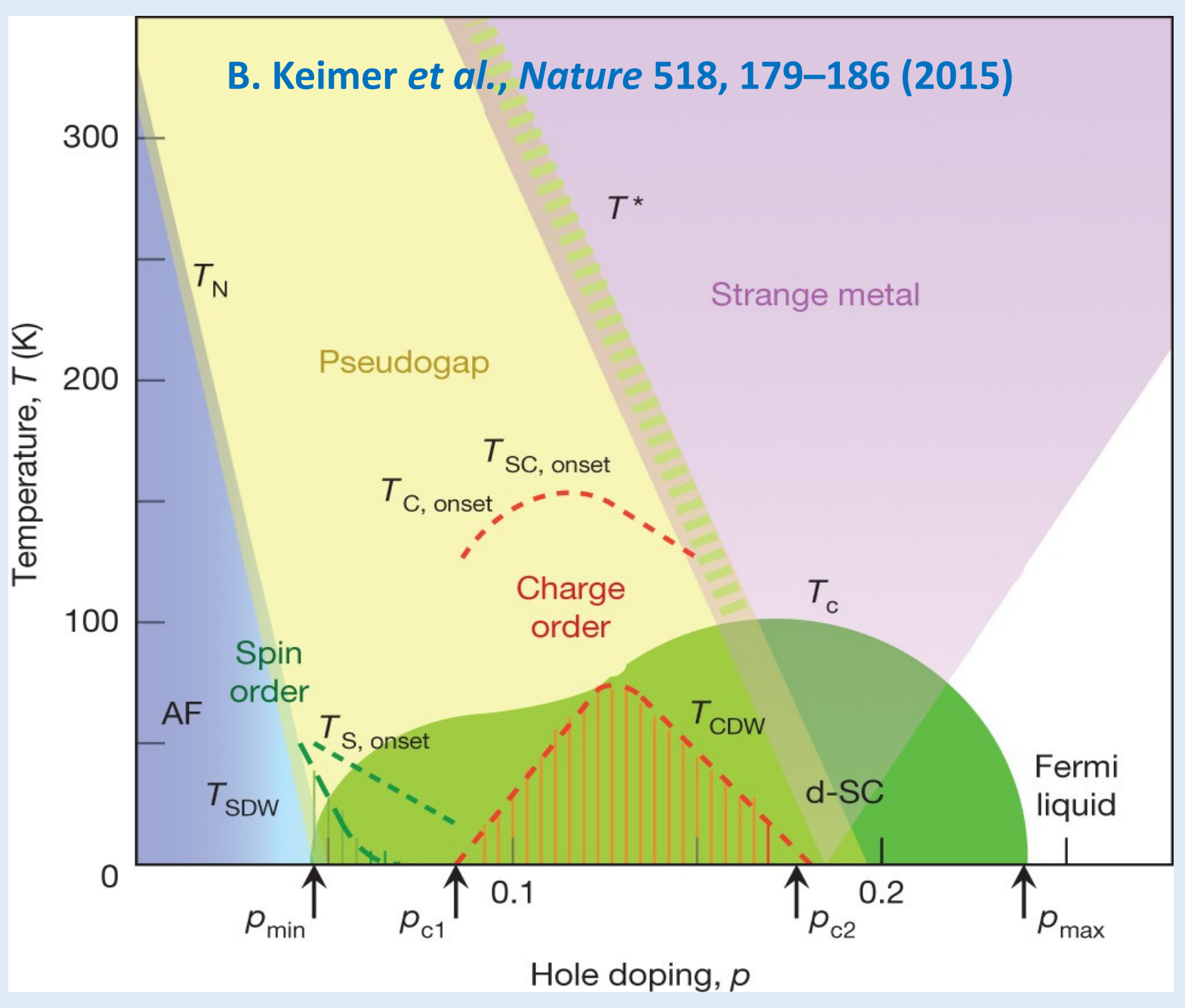
Quantum Fluctuations & Matter



Importance of quantum effects by comparing via their energy $\hbar\Gamma$:

Thermal fluctuations: $\hbar\Gamma < k_B T$.

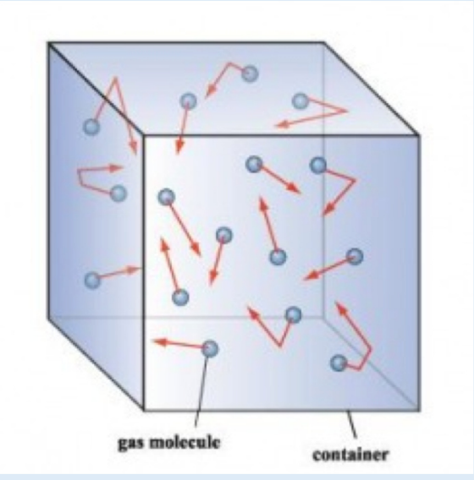
Quantum fluctuations: $\hbar\Gamma > k_B T$.



In correlated quantum materials strong quantum fluctuations frequently lead to rich phase diagrams with many competing phases. This is an example of high-temperature cuprate superconductors.

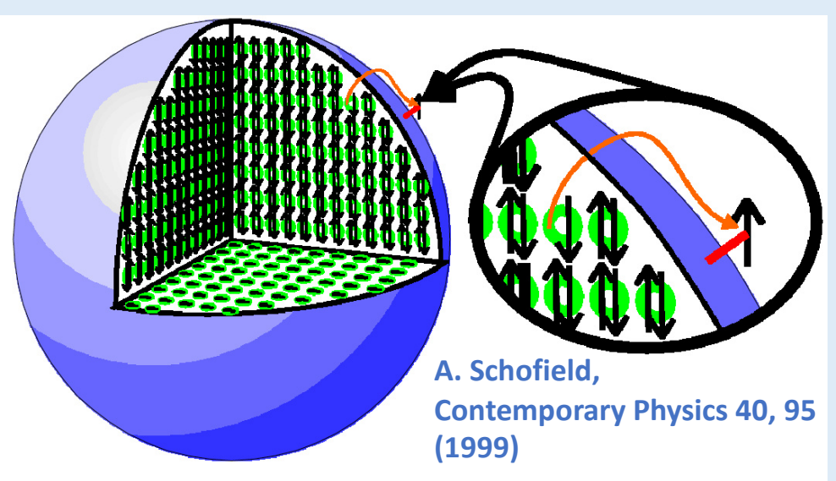
Levels of ’Quantumness’

Temperature



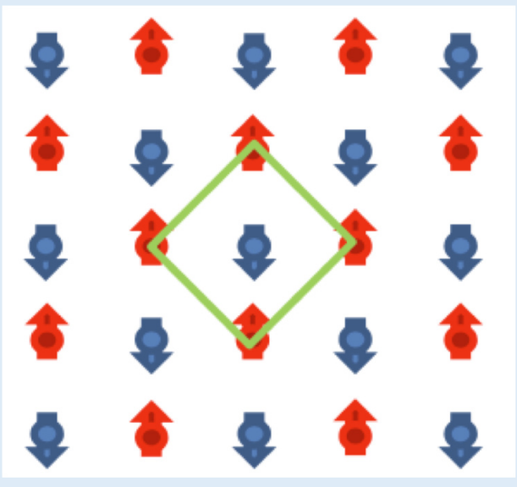
Ideal Gas

- Non-interacting particles
- Entirely described by classical statistics


A. Schofield, Contemporary Physics 40, 95 (1999)

Electron Gas (simple metal)

- Electrons follow Fermi-Dirac statistics!
- Electronic quasiparticle excitations, however, do behave like non-interacting particles!

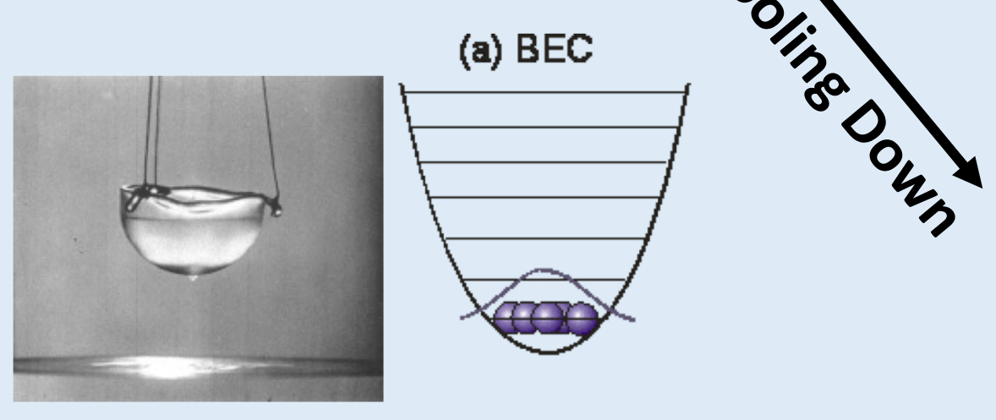


Magnet

- Classical physics cannot account for magnetism (Bohr-van Leeuwen theorem)!
- Magnetic order requires Pauli exclusion principle
- Magnetism is a macroscopic quantum state with broken rotational symmetry.

Learn more about Quantum Matter Physics

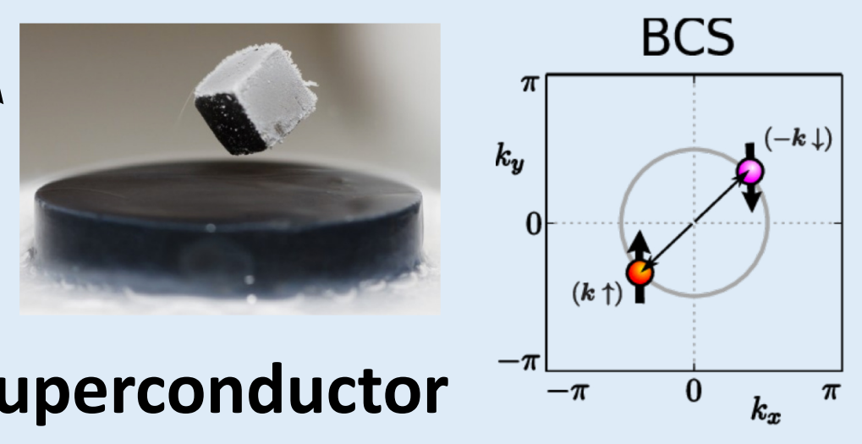
Cooling Down



Superfluid

- Bose-Einstein condensation of He atoms into ground state
- Macroscopic quantum state with zero viscosity.

Cooling Down



Superconductor

- Electronic quasiparticles form Cooper pair (spin-singlet) in k-space.
- A finite energy quantum is required to break the pair. Macroscopic quantum state exhibiting the Meissner effect.

‘Quantumness’

Why is Quantum Matter interesting?

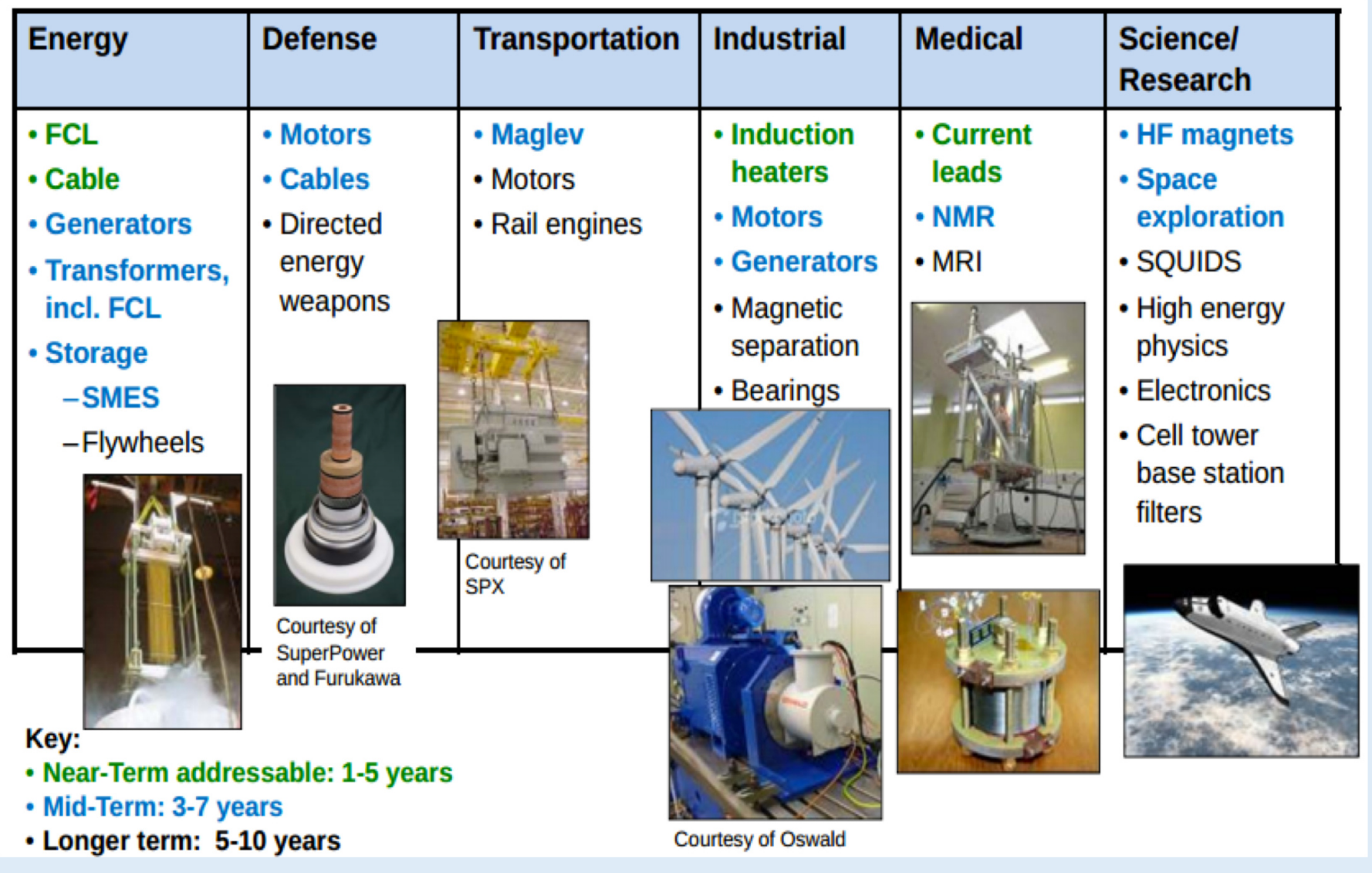
Quantum matter states are already used in current day applications but many recently discovered states are promising for future applications.

Magnetism


Early Chinese compass (400 BC) from lodestone is an early application of magnetism–an inherent quantum state.


The current revolution in electromobility is based on high-performing permanent magnets in generators and motors.

Superconductivity



Energy	Defense	Transportation	Industrial	Medical	Science/ Research
• FCL • Cable • Generators • Transformers, incl. FCL • Storage –SMES –Flywheels	• Motors • Cables • Directed energy weapons	• Maglev • Motors • Rail engines	• Induction heaters • Motors • Generators • Magnetic separation • Bearings	• Current leads • NMR • MRI	• HF magnets • Space exploration • SQUIDS • High energy physics • Electronics • Cell tower base station filters

Courtesy of SuperPower and Furukawa

Courtesy of SPX

Courtesy of Oswald

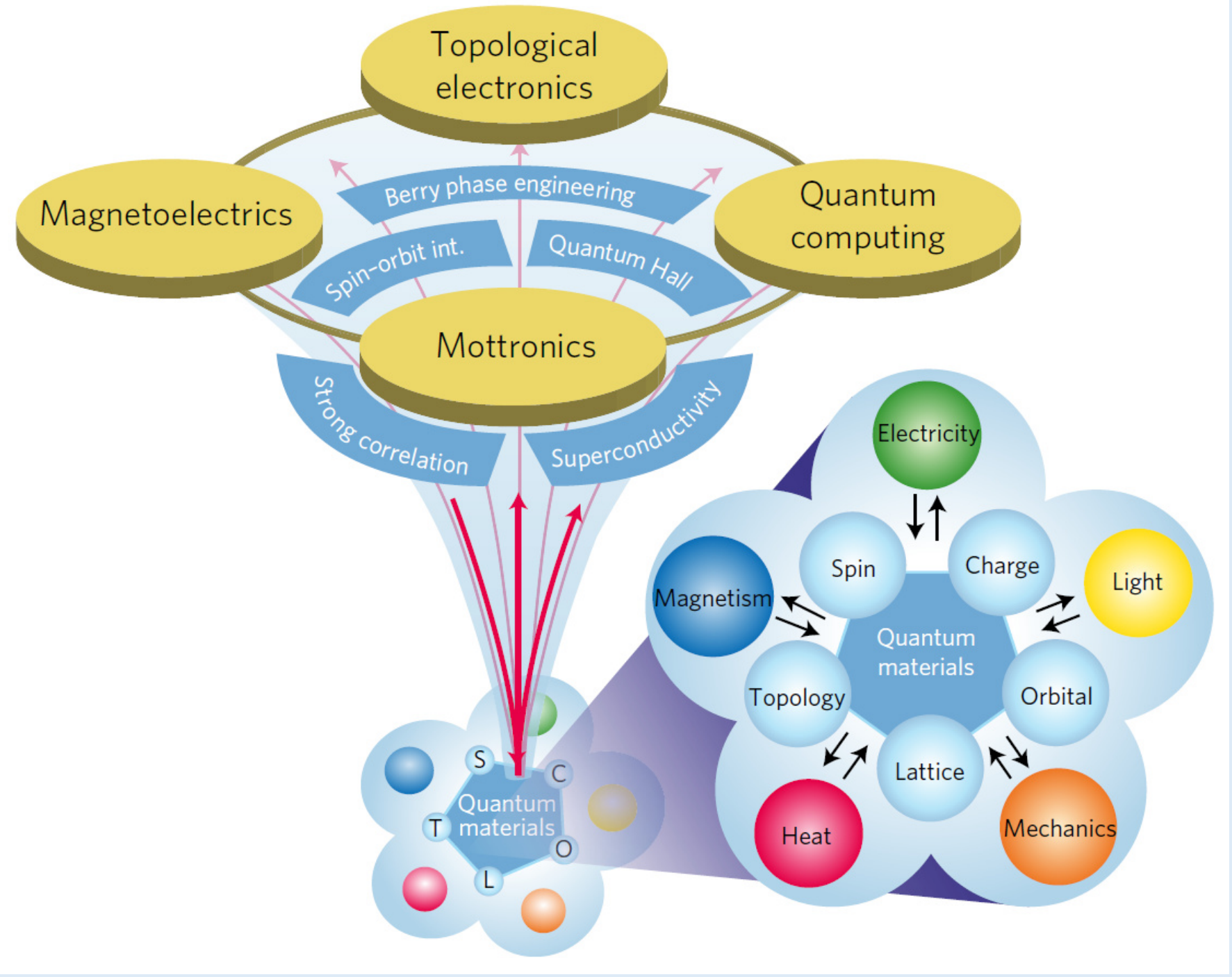
Key:
- Near-Term addressable: 1-5 years
- Mid-Term: 3-7 years
- Longer term: 5-10 years

Source: International Superconductivity Industry Summit

There are already many existing applications of high-temperature superconductors.


An emerging application is quantum computing based on superconducting qubits.

Novel Quantum Matter States



Y. Tokura, Masashi Kawasaki & Naoto Nagaosa Nature Physics 13, 1056–1068 (2017)

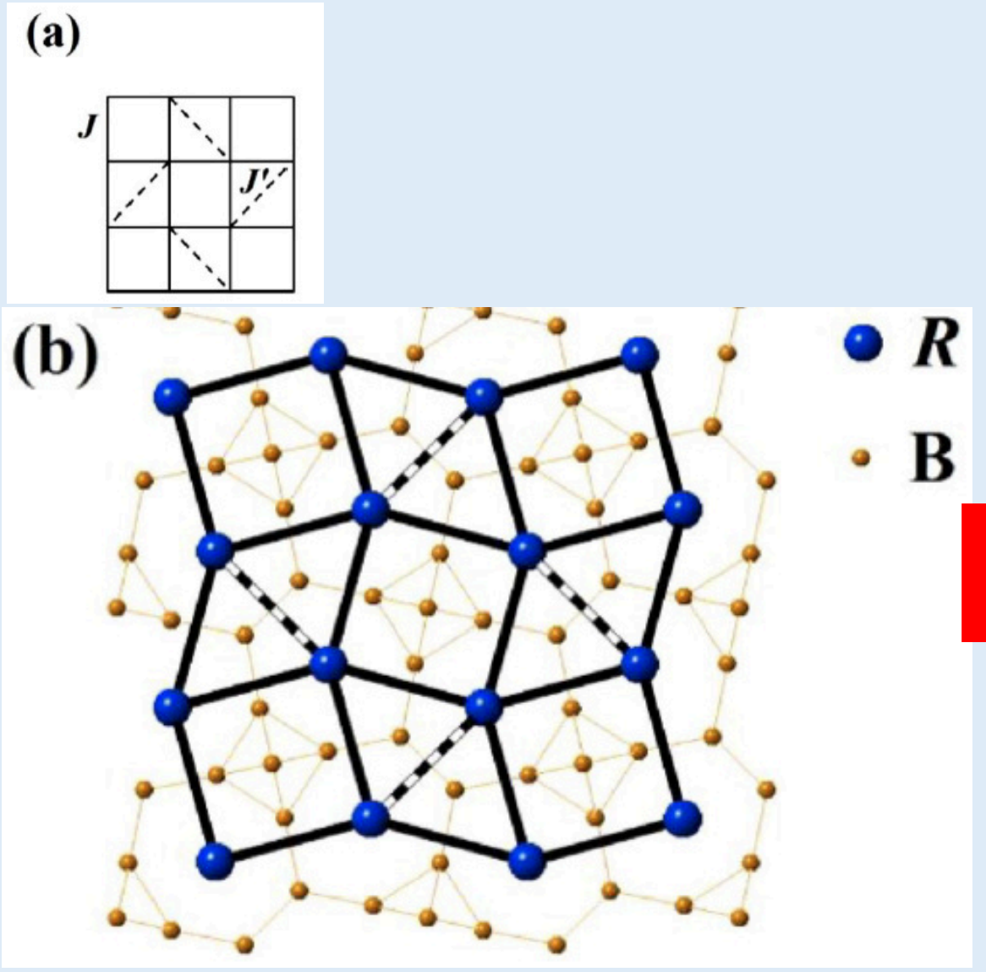
Novel quantum matter states emerging from multiple coupled degrees of freedom have large potential for future applications.

What we do ...

Our group works on revealing the atomic-scale underpinnings of quantum materials. Our research is based on a synergistic loop of **making, probing & tuning quantum materials**. We carry out experiments both in conventional laboratories as well as at large-scale research facilities at the Paul Scherrer Institute (PSI).

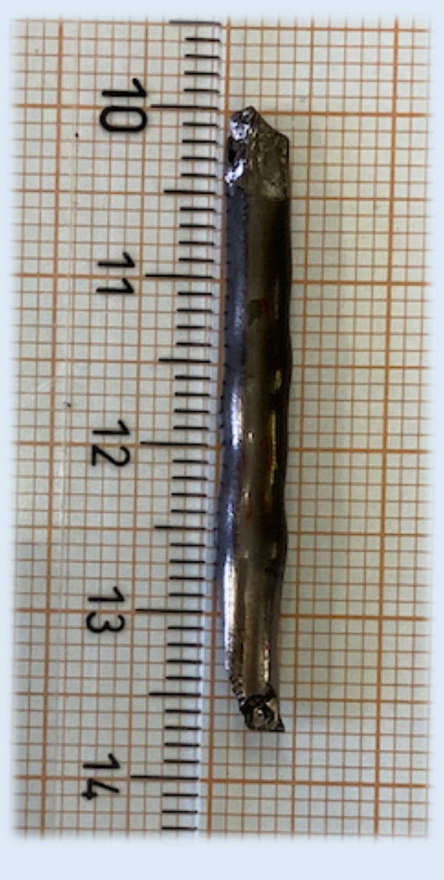
MAKING

By using solid state chemistry we grow materials with underlying lattices and symmetries that support the formation of quantum matter states.



For example, materials of the familiy RB_4 (R = rare earth) grow on a frustrated Shastry-Sutherland lattice that promotes quantum fluctuations.

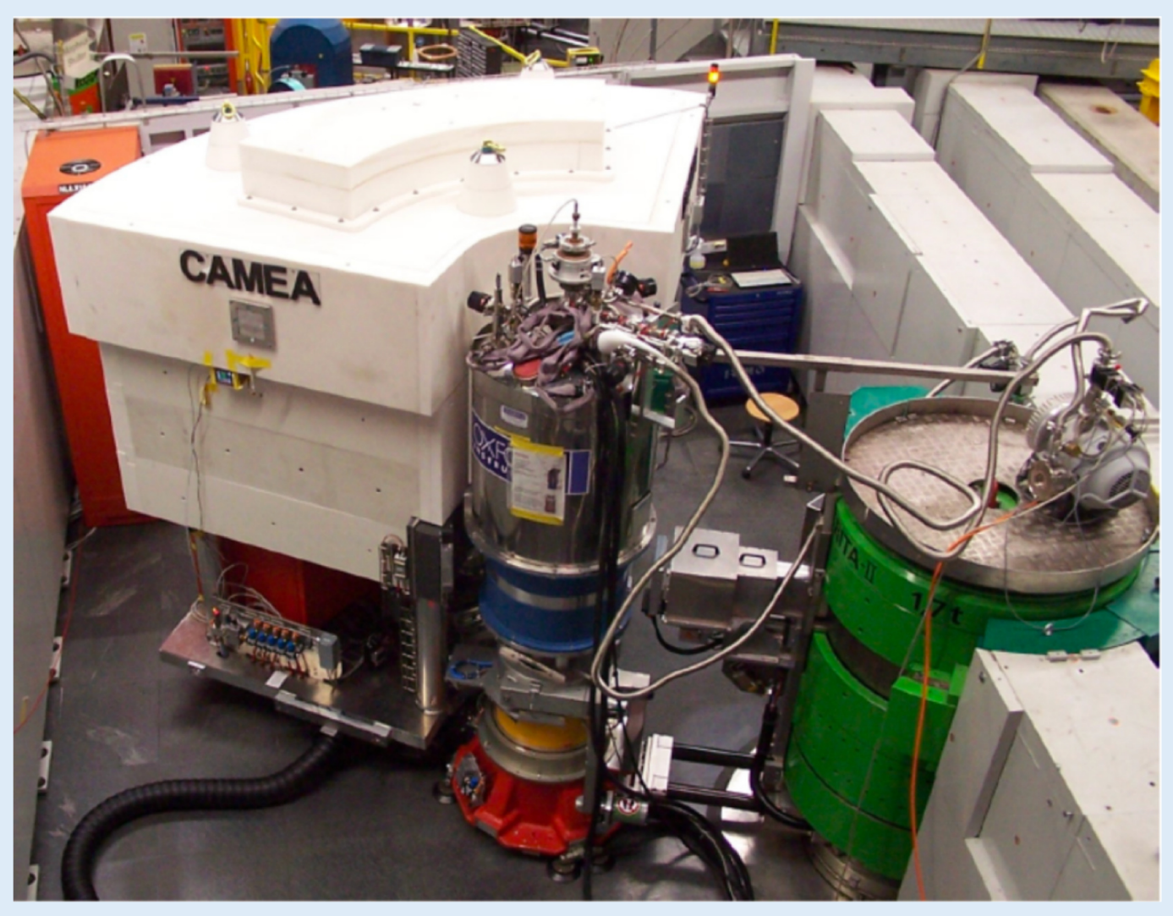

High pressure float zone furnace for growth of single-crystals.



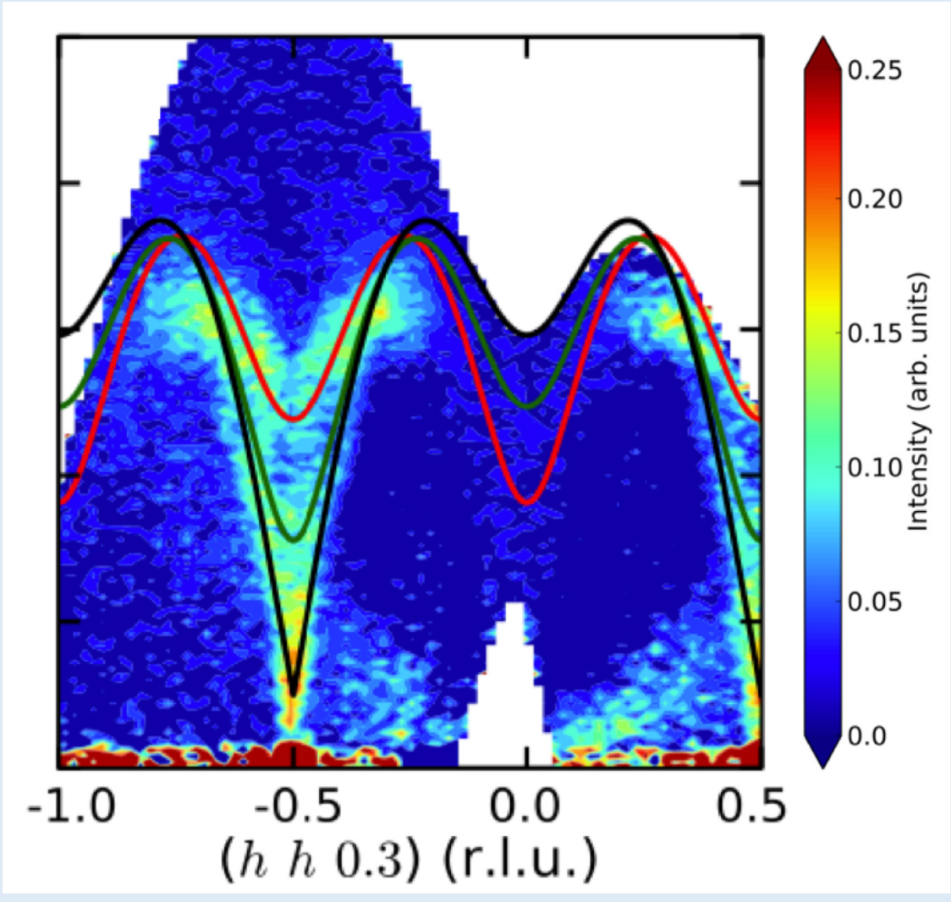
Large single crystals for neutron spectroscopy

PROBING

By using neutron diffraction and spectroscopy, we determine the underlying magnetic order and atomic scale interactions.



Learn more about neutron scattering at PSI



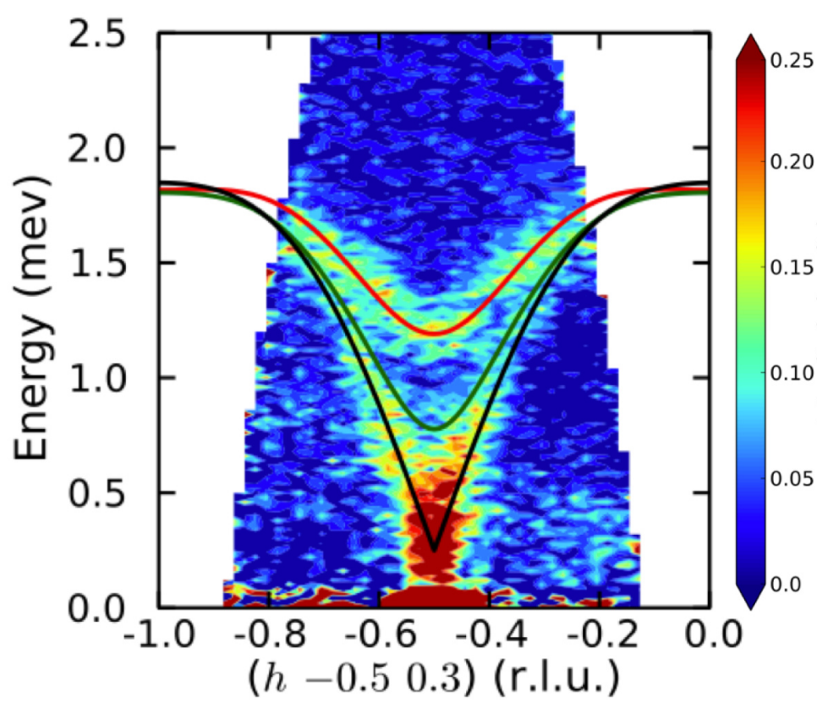
Example: Measured spin wave spectrum of $CeRhIn_5$ using time-of-flight spectroscopy.

P. Das, M. Janoschek et al. Phys. Rev. Lett. 113, 246403 (2014)

SYNERGISTIC LOOP

MODELING

Finally, we compare our neutron scattering data to already existing models. In addition, in collaboration with our theory colleagues, we may also create new ones. This allows us to determine the underlying effective low-energy Hamiltonian that stabilizes the observed emergent phases.



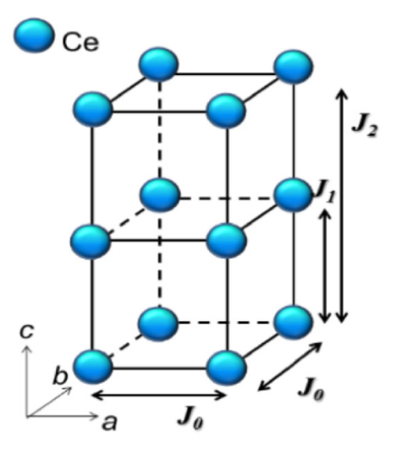
Measured spin wave spectrum of $CeRhIn_5$ compared to the calculated one (solid lines).

P. Das, M. Janoschek et al. Phys. Rev. Lett. 113, 246403 (2014)

$$\mathcal{H} = \sum_{i<j} J_{ij}\left[\left(S_{x,i}S_{x,j} + S_{y,i}S_{y,j}\right) + \delta S_{z,i}S_{z,j}\right]$$

$$J(\boldsymbol{q}) = 2J_0\left[\cos(2\pi q_x) + \cos(2\pi q_y)\right] + 2J_1\cos(2\pi q_z) + 2J_2\cos(4\pi q_z)$$

Derived model Hamiltonian to calculate the spin wave spectrum and compare it to the measured one.



● — $\omega(q)$
● — $\omega(q+k)$
○ — $\omega(q-k)$

$$\xrightarrow[\text{with measurements}]{\text{By comparison}} \left.\begin{matrix} J_0 \\ J_1 \\ J_2 \end{matrix}\right\} \text{Exchange interaction parameters}$$

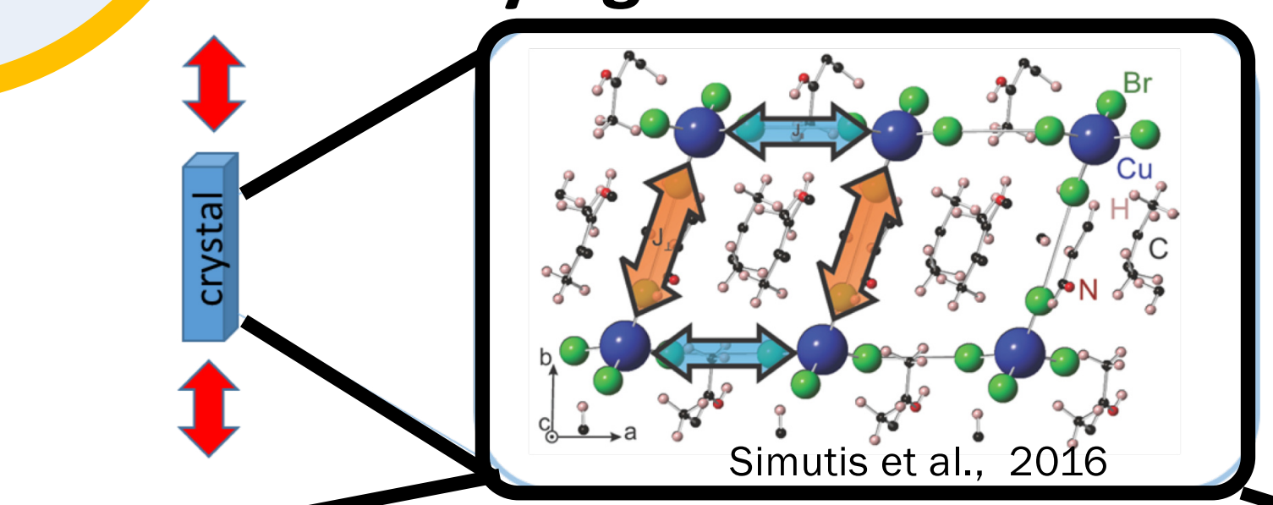
Spin

Quantum Monte Carlo Methods

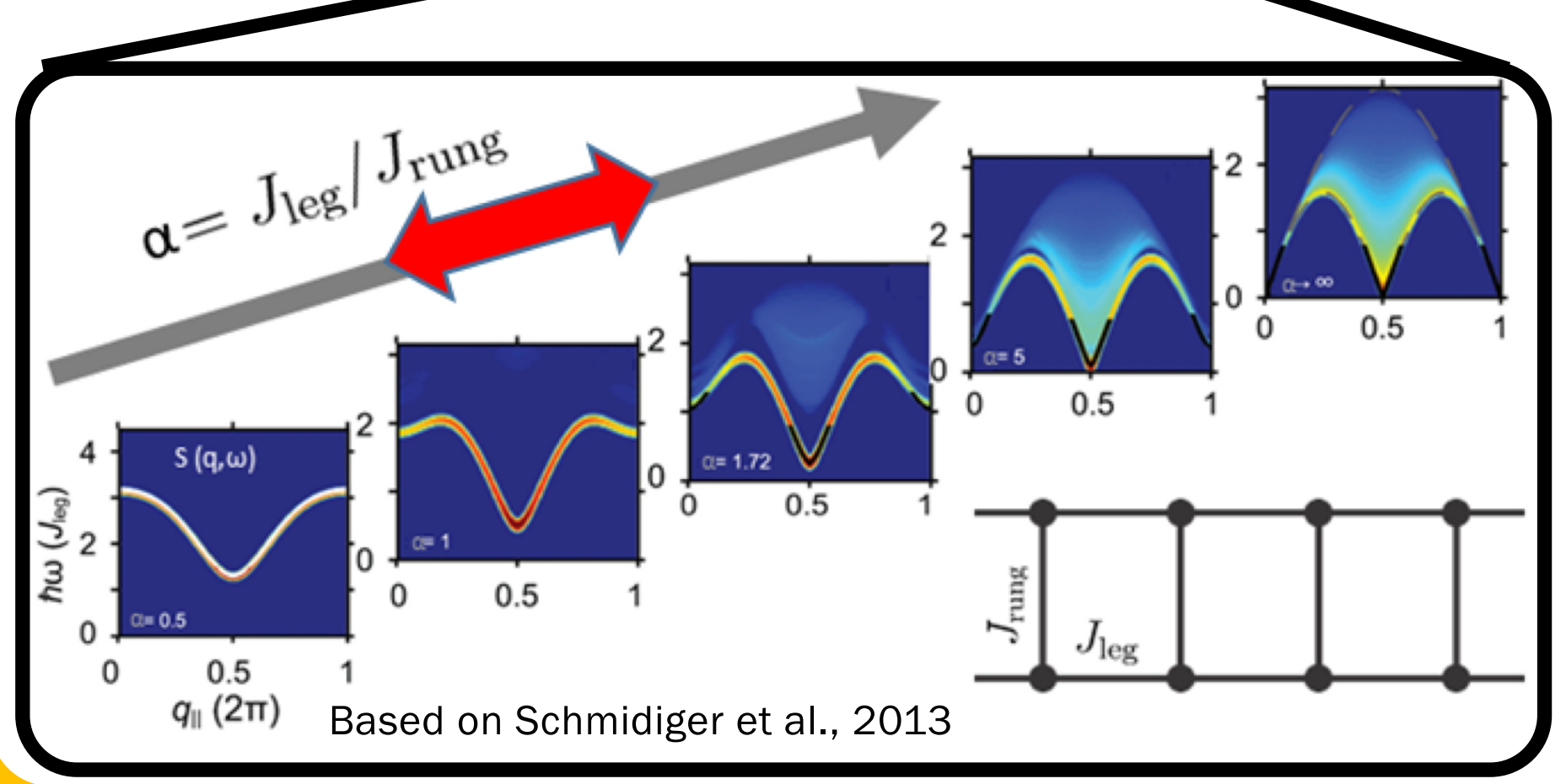

Theory collaborator Shizeng Lin

TUNING

By using external control parameters, such as strain, we ’tune’ the underlying interactions to control the behavior of quantum matter.

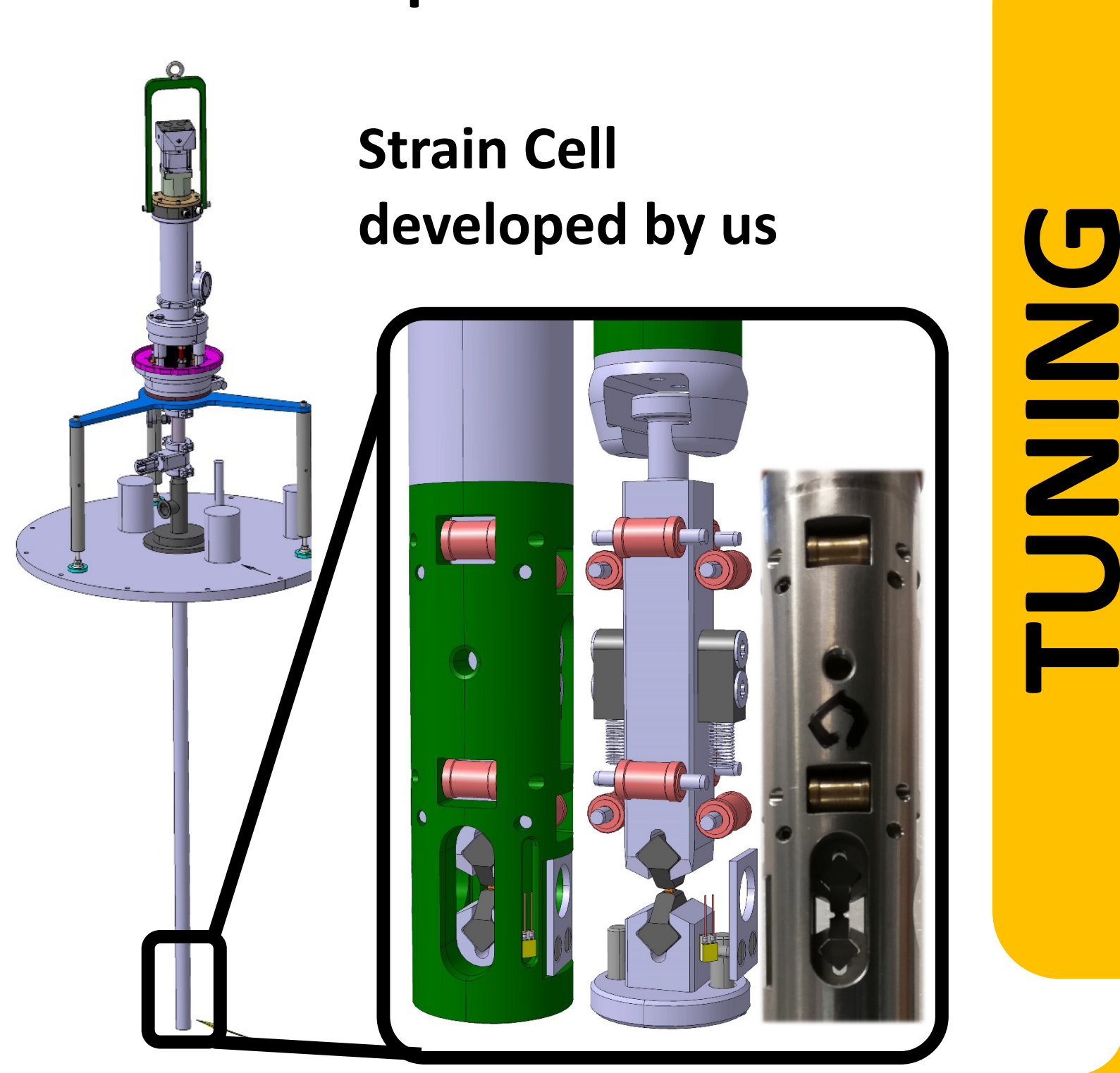


Simutis et al., 2016



Based on Schmidiger et al., 2013

Strain Cell developed by us



University of Zurich^{UZH}

PAUL SCHERRER INSTITUT

PSI