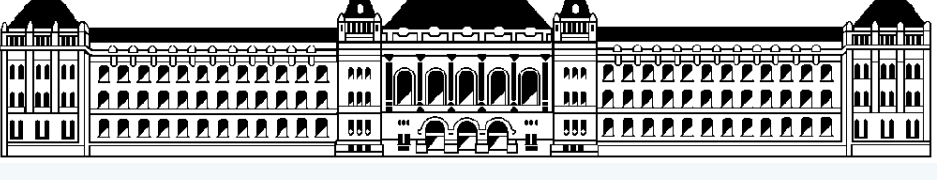


Synthetic Topological Andreev Qubit & Simulator (STAQuS)

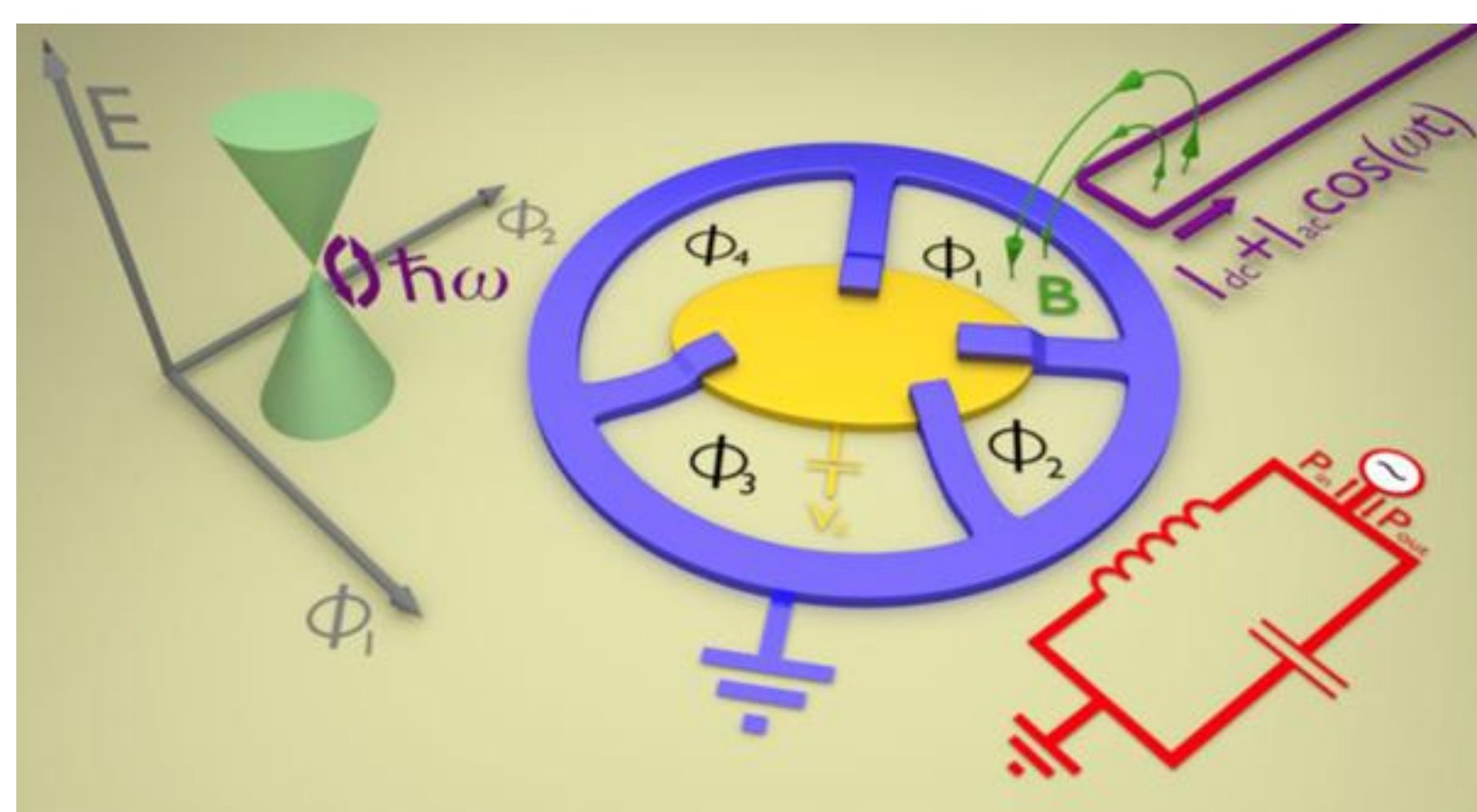
HU	Budapest University of Technology & Economics (BME)		Szabolcs Csonka
SK	Pohang University of Science and Technology (POSTECH)		Gil-Ho Lee
SK	Korea Advanced Institute of Science and Technology (KAIST)		Gil Young Cho
F	CEA Grenoble (CEA) / PHELIQS		Julia Meyer



Abstract

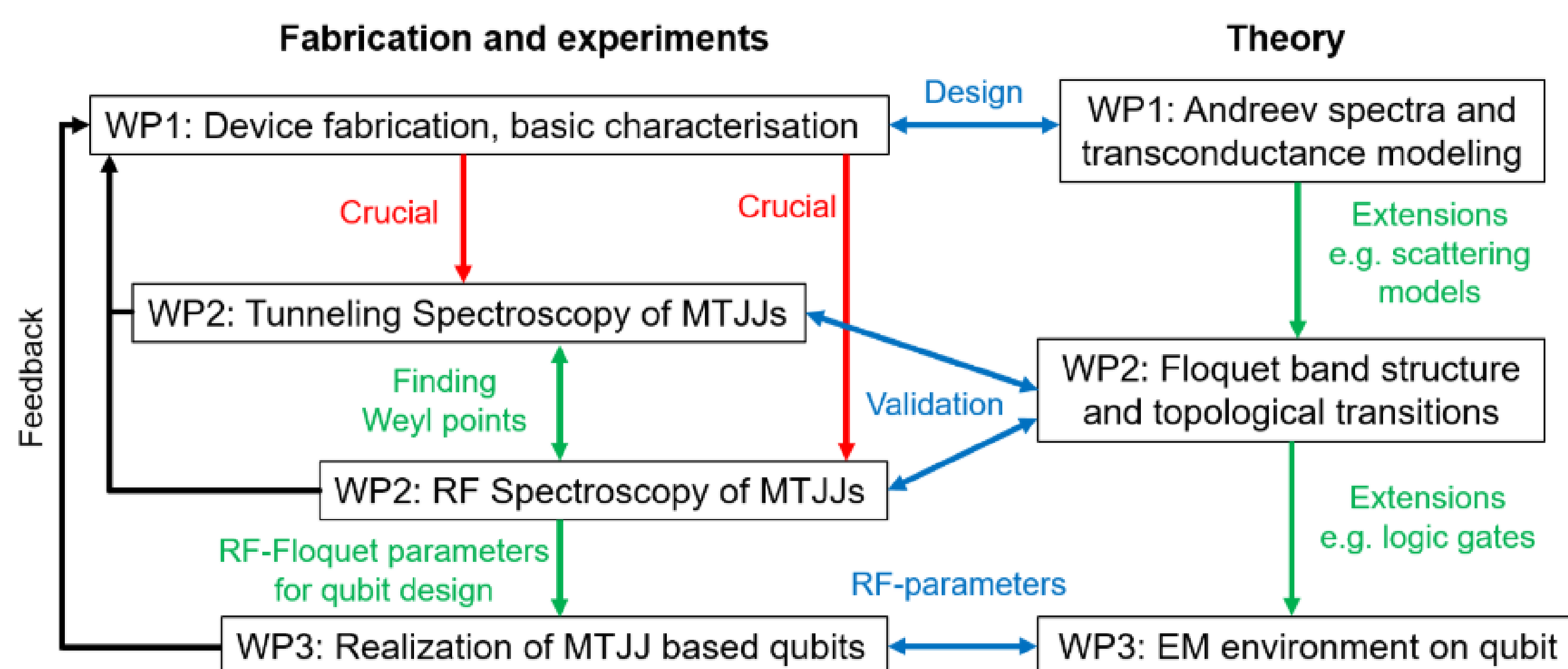
The field of quantum technology is driven by two major directions: Quantum Computation (QC), which targets universal gate-based systems, and Quantum Simulation (QS), which models complex many-body problems beyond classical hardware. As topological phases become crucial for fault-tolerant QC, developing robust quantum simulators and protected qubits is increasingly important. Our project tackles this by establishing Multi-Terminal Josephson Junctions (MTJJs) as a unified platform for both. The project leverages the multi-dimensionality of Andreev Bound States (ABS) in $(n+1)$ -terminal JJs, where superconducting phase differences serve as synthetic quasi-momenta. This enables electrically tunable synthetic Brillouin zones capable of simulating complex band structures, including Weyl semimetals. We combine high-mobility semiconductor–superconductor hybrids with highly transparent, gate-tunable graphene junctions, enabling precise control and Floquet engineering. Using DC and RF techniques, band structures, transport, and quantum geometry can be measured with high resolution. Over three years, the consortium will focus on four-terminal JJs (4TJJs) and Floquet-driven three-terminal JJs (3TJJs) to pursue two scientific goals: (i) realizing Weyl-type and Floquet-topological phases, and (ii) demonstrating a protected ‘0– π qubit’, recently proposed to emerge from a partially looped 3TJJ in the tunneling limit. This project directly addresses the QuantERA topic “Quantum Phenomena and Resources (QPR)” by advancing higher-dimensional ABS topology and protected qubits. The technology is currently at TRL 2-3, and by reaching TRL 4 we expect to demonstrate Weyl-type topology in 4TJJs, realize Floquet-engineered MTJJ bands, and implement the first MTJJ-based protected qubit prototype.

Targeted breakthroughs

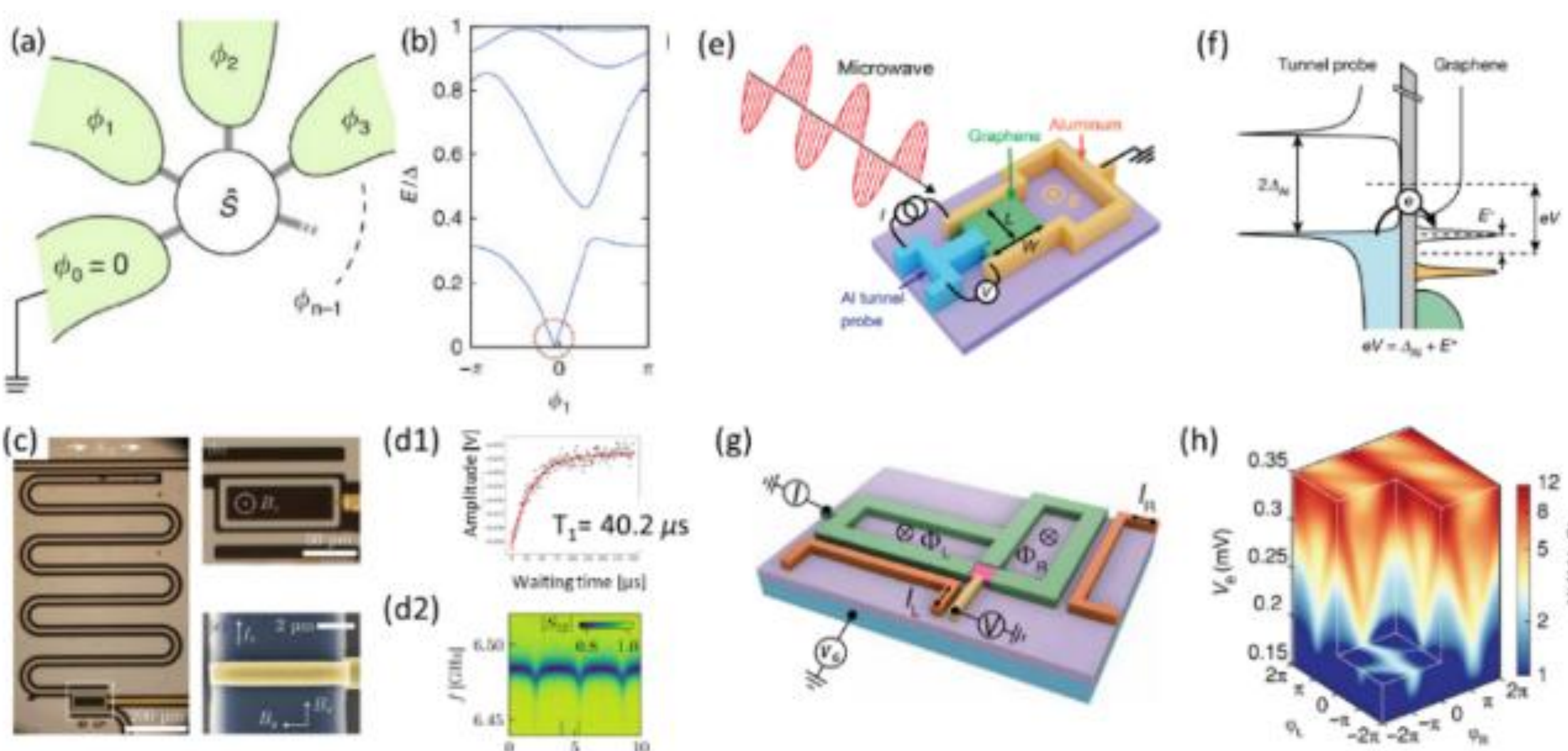


- 1) Synthetic Weyl / Floquet bands
 - $\{\phi_i\}$ function as synthetic quasi-momenta
 - Allows for the simulation of Weyl-bands(left)
 - Emulation of higher-dimensional steady Floquet states
- 2) MTJJ-based 0– π –type qubit
 - MTJJ as a pathway towards transmon-fluxonium hybrid qubits
 - Simultaneous insensitivity to charge and flux noises

Work Plan



Relevant work performed within the consortium



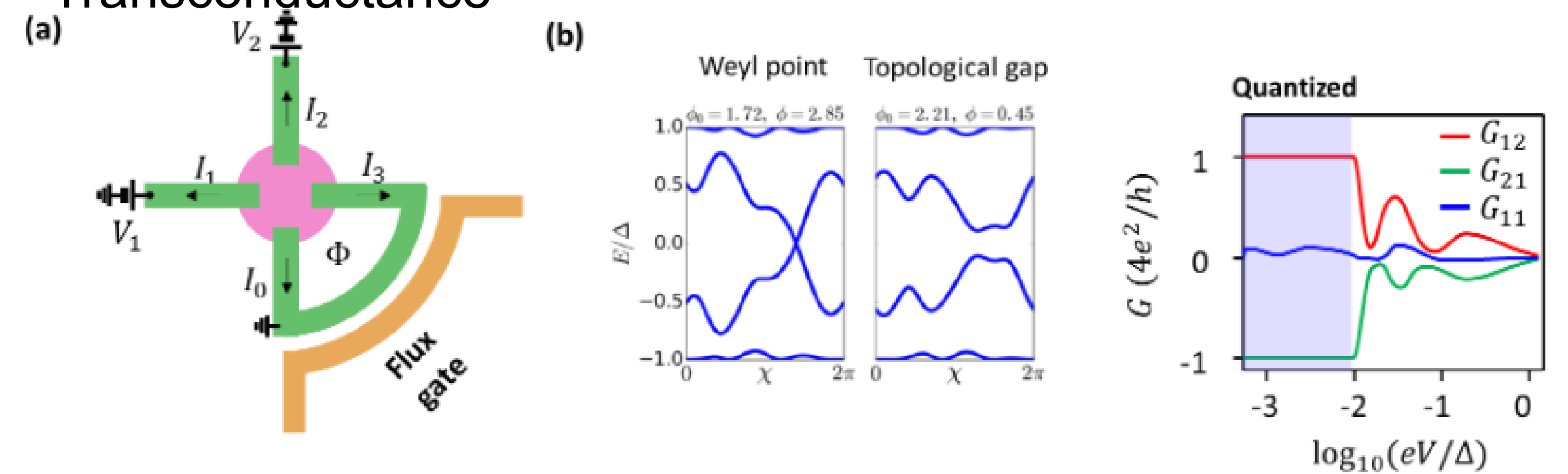
(a, b) Pioneering theoretical study by **CEA** group, showing the spectrum of Andreev bound states tuned by multiple superconducting phase differences, where a Weyl point (red circle) emerges. (c, d) Microwave spectroscopy, and T_1 measurement of a transmon (d2), demonstrated in **BME** group. Device images (c) of the microwave resonator coupled to an InAs 2DEG and the measured spectrum (d2). (e–f) Experimental investigation of Floquet Andreev bands via tunnelling spectroscopy by **POSTECH/KAIST** group. (g–h) A 3-terminal Josephson junction (3TJJ) of the same groups, where the phase differences are individually controlled by flux gates to tomographically project the Andreev bound states formed in the 3TJJ.

References

- [1] F. J. Matute-Cañadas, L. Tosi, and A. Levy Yeyati, *Quantum Circuits with Multiterminal Josephson-Andreev Junctions*, *PRX Quantum* 5, 020340 (2024)
- [2] J. S. Meyer and M. Houzet, *Conductance quantization in topological Josephson trijunctions*, *Phys. Rev. B* 103, 174504 (2021)
- [3] S. Park, W. Lee, S. Jang, Y.-B. Choi, J. Park, W. Jung, K. Watanabe, T. Taniguchi, G. Y. Cho, and G.-H. Lee, *Steady Floquet-Andreev states in graphene Josephson junctions*, *Nature* 603, 421–426 (2022)
- [4] R.-P. Riwar, M. Houzet, J. S. Meyer, and Yu. V. Nazarov, *Multi-terminal Josephson junctions as topological matter*, *Nat. Commun.* 7, 11167 (2016)
- [5] P. Brooks, A. Kitaev, and J. Preskill, *Protected gates for superconducting qubits*, *Phys. Rev. A* 87, 052306 (2013)
- [6] B. van Heck, S. Mi, and A. R. Akhmerov, *Single fermion manipulation via superconducting phase differences in multiterminal Josephson junctions*, *Phys. Rev. B* 90, 155450 (2014)

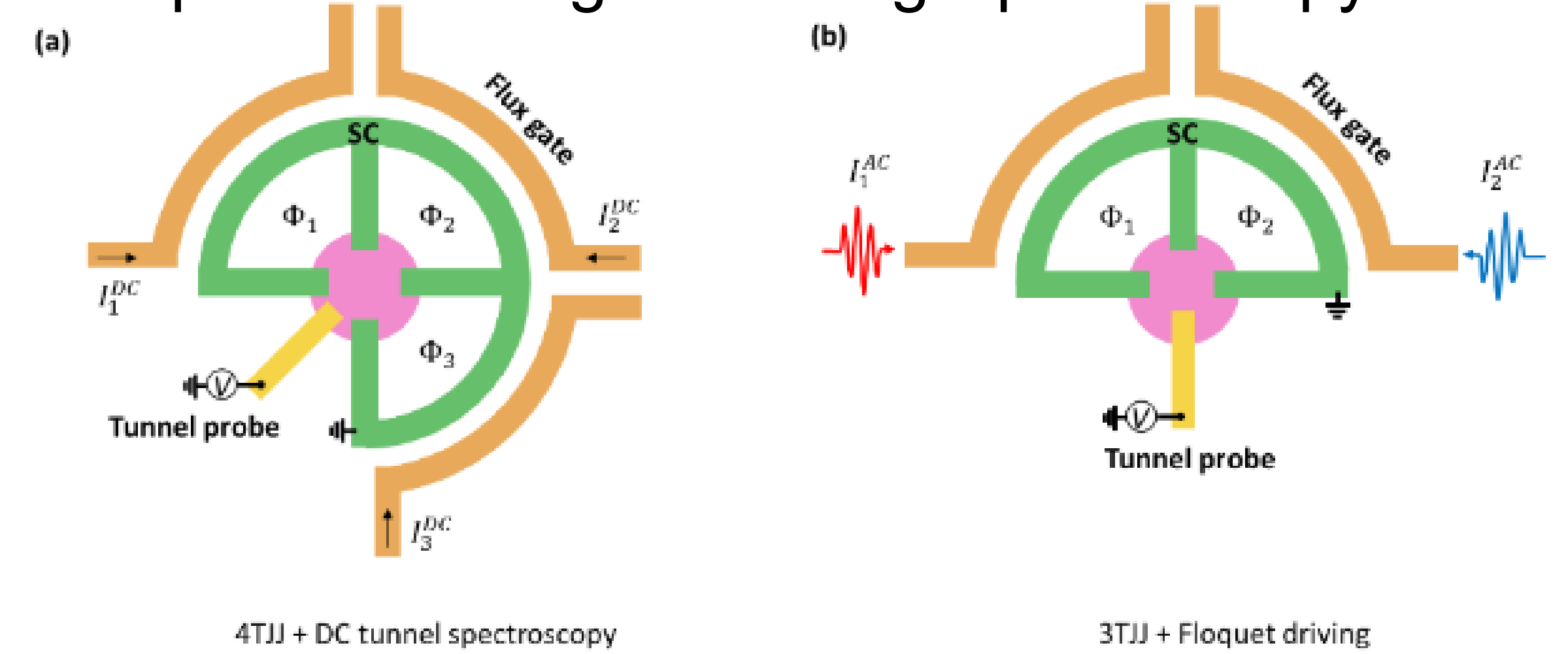
Work Packages

WP1 Fabrication and characterization: Quantized Transconductance



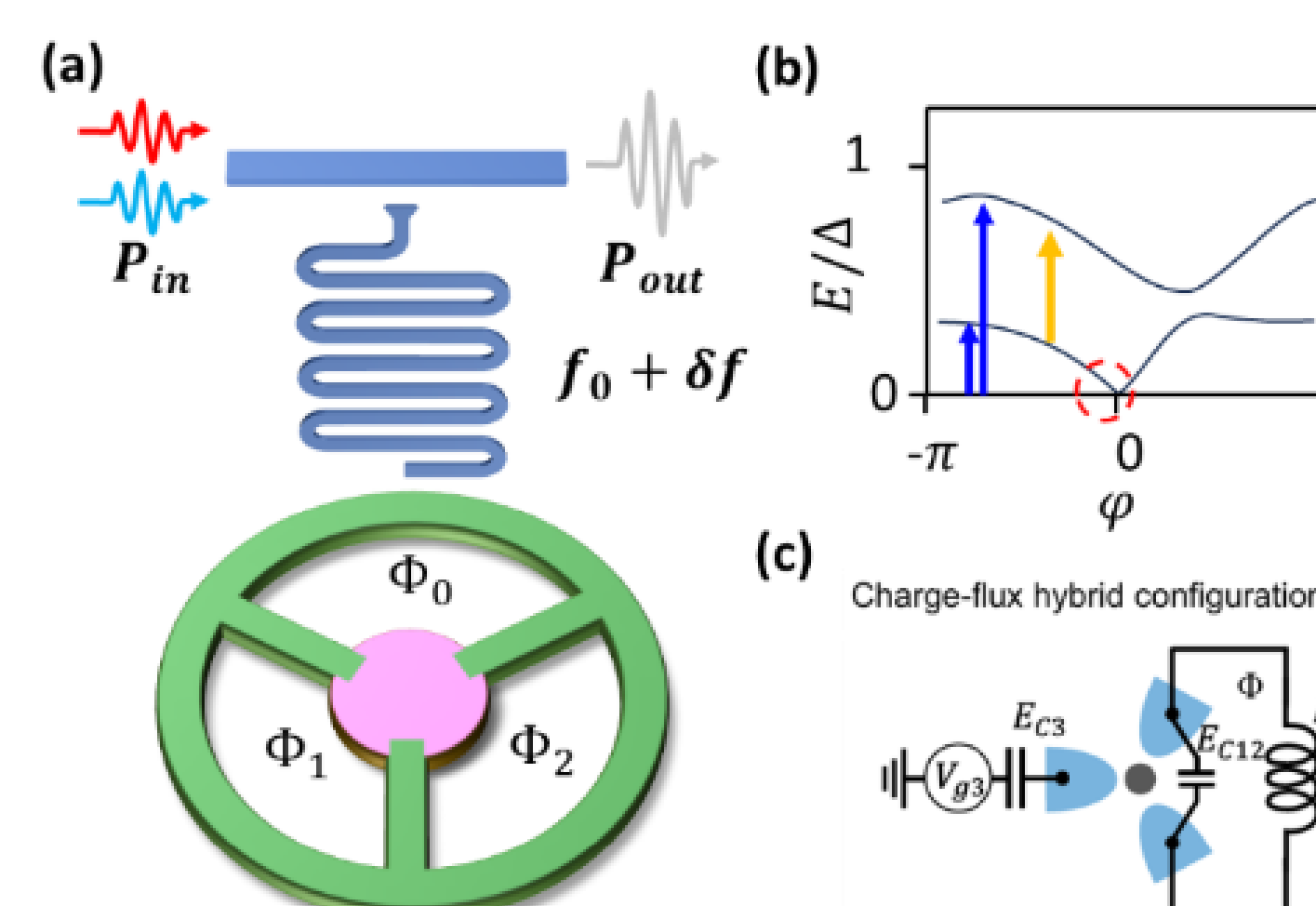
(a) Schematic of a four-terminal Josephson junction (4TJJ). (b) Left: Cuts through the Andreev bound-state spectrum reveal a Weyl point at $\phi_0 = 1.72$ (gapless) and a nontrivial topology at $\phi_0 = 2.21$ (gapped) [2]. Right: Time-averaged conductance

WP2-a Superconducting Tunneling Spectroscopy



(a) Schematics of a four-terminal Josephson junction (4TJJ) integrated with three superconducting loops. A superconducting tunnel probe is used to map the Weyl-semimetal-like Andreev band structure in the 4TJJ. (b) Schematics of a three-terminal Josephson junction (3TJJ) integrated with two superconducting loops. Fluxes, Φ_n , I_n^{DC} , and simultaneous AC drives, I_n^{AC} , with unequal amplitudes and finite phase offset, realize a **Floquet-induced topological band**.

WP2-b Resonator-based RF spectroscopy



(a) Microwave spectroscopy scheme for a multiterminal Josephson junction. A resonator is inductively coupled to the junction. Readout uses two-tone microwave spectroscopy. The states are controlled by three superconducting phase differences (Φ_n), each induced by magnetic fluxes and tuned via dc flux lines. (b) Illustration of Andreev level transitions of a multi-terminal junction. The red circle indicates the Weyl point. (c) Illustrative figure of Protected qubit based on MTJJ from [1].

WP3 Protected qubit based on MTJJ

1. Theoretically determine the optimal circuit parameters to reach this transmon-fluxonium regime (**CEA** with **KAIST**)
2. Realize such a hybrid charge/flux qubit and explore its performance (**BME** with **POSTECH**).