C04

Quantum Simulation of the Origin of the Universe Using Superconducting Circuits

Bring the early universe into the superconducting circuits.

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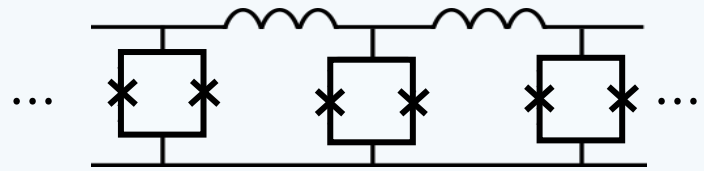
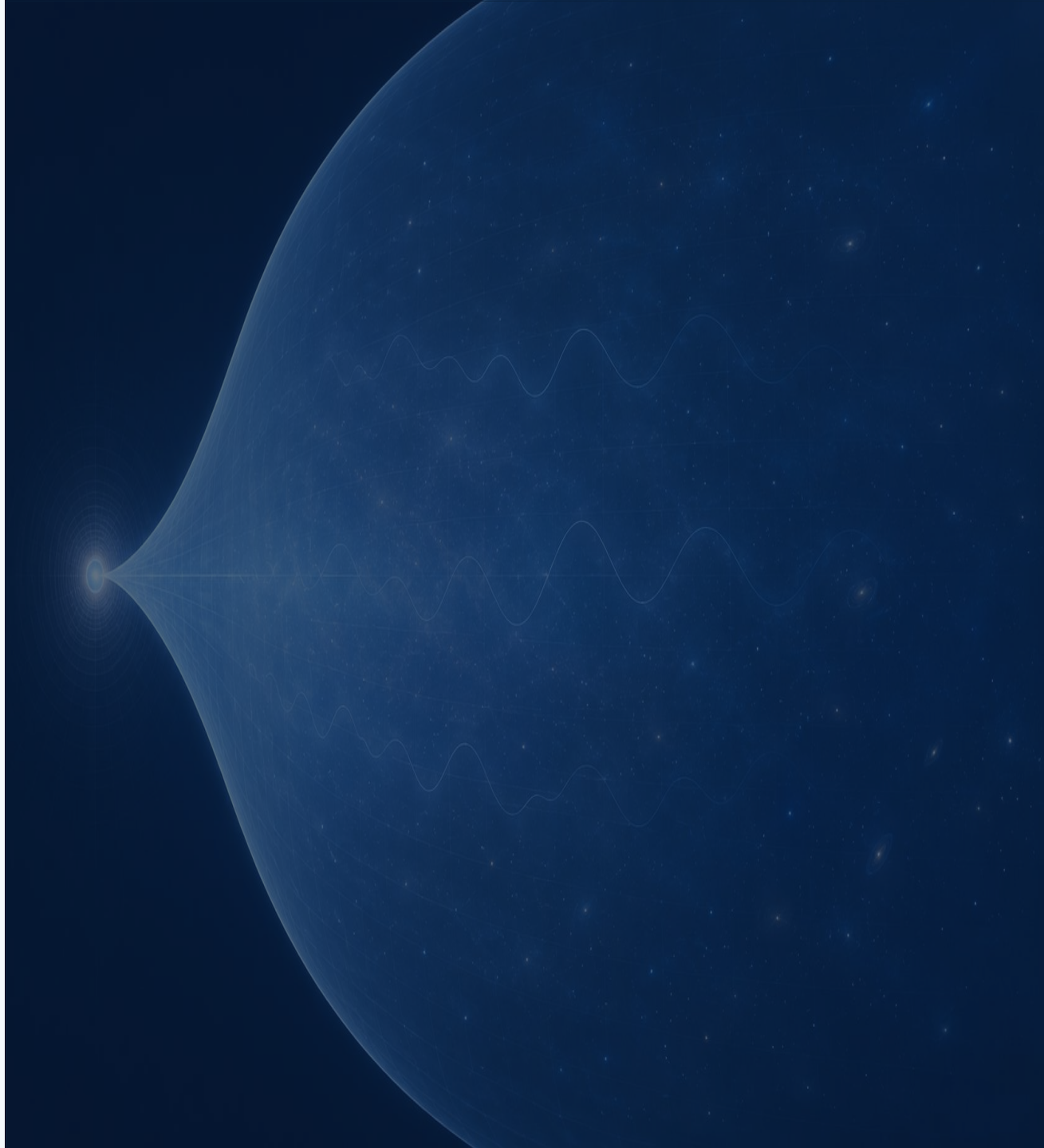
Hiroshima University





Goal of the C04

> Making the elusive quantum phenomena in the early universe visible with superconducting quantum circuits

Key features of the C04

A largely open direction

Simulating 3+1-dimensional inflationary mode dynamics in laboratory systems

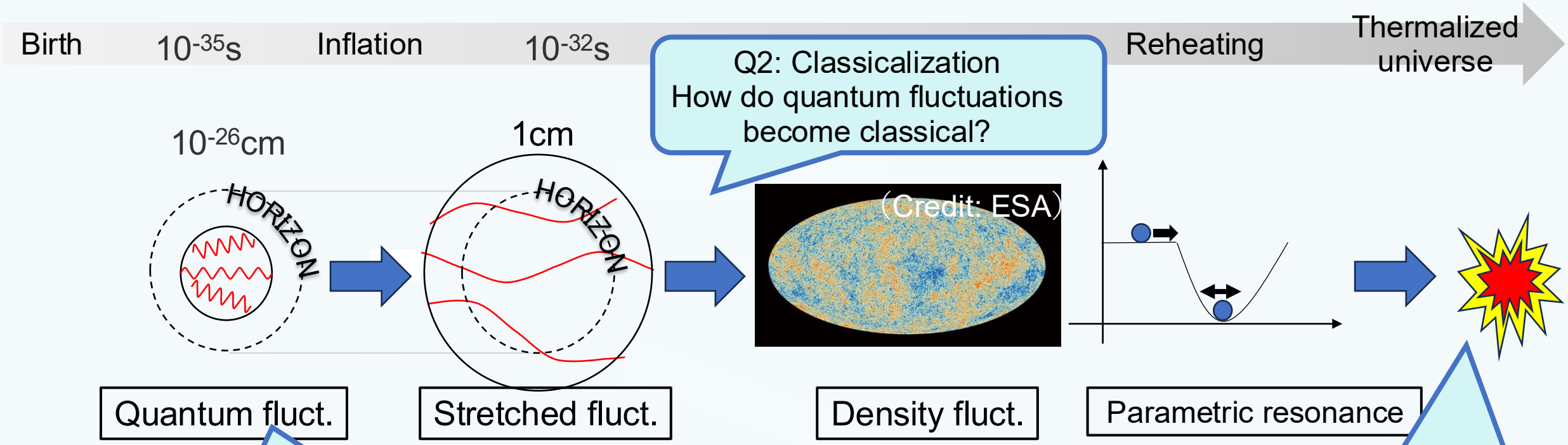
Superconducting quantum technology

Fast temporal control / Microwave quantum measurements

Future directions

Nonlinearity: non-Gaussianity / Classicalization / Thermalization

Questions Explored in This Project



Q2: Classicalization
How do quantum fluctuations become classical?

Q0: Quantum origin
Did structure originate from quantum fluctuations?

Q1: Non-Gaussianity
How do quantum processes appear as non-Gaussian correlations?

Q3: Quantum thermalization
How low-occupation modes and quantum correlations behave?

What analogue systems make possible

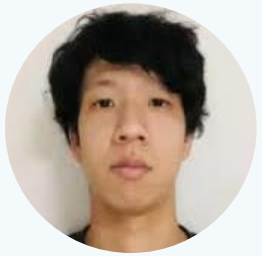
Repeatable tests

Model comparisons

Toward complex processes

Research Strategy and Team Structure

An integrated approach from modeling to circuit design and experiments

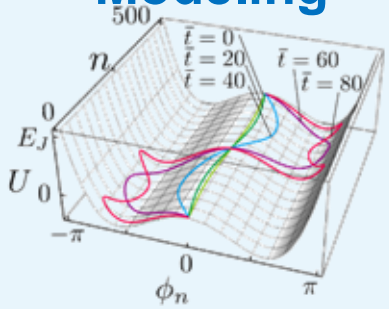


Kyushu Univ.
A. Matsumura
Quantum gravity & cosmology
Analyze quantum dynamics in the early universe

Hiroshima Univ.
H. Katayama
Analogue gravity theory
Bridge cosmology and superconducting circuits

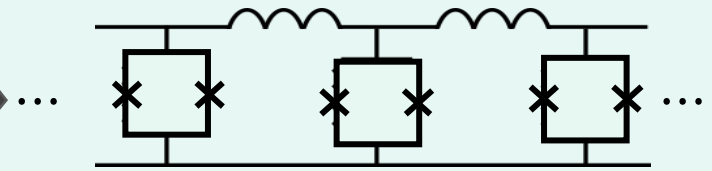
Yokohama Natl. Univ.
Y. Yamanashi
Superconducting-circuit experiments
Device design and low-temperature measurement

Modeling



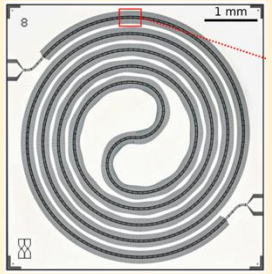
What to measure
Extract target quantum dynamics

Circuit design



How to build
Translate model into superconducting circuits

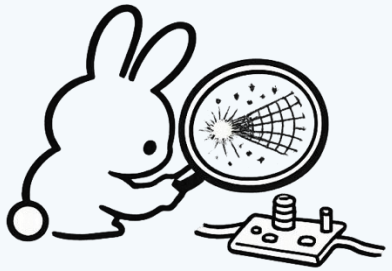
Experimental demonstration



How to measure
Specify feasible parameters and measurement methods

Related Previous Studies

Analogue = same dynamics, different physical system



Hawking radiation

Quantum correlations from effective horizons

- Analogue black holes [Unruh, PRL 46, 1351 (1981)]
  fluids, optics, BECs, circuits, etc.
- BEC experiments [Steinhauer, Nat. Phys. 12, 959 (2016)]
  correlations / entanglement

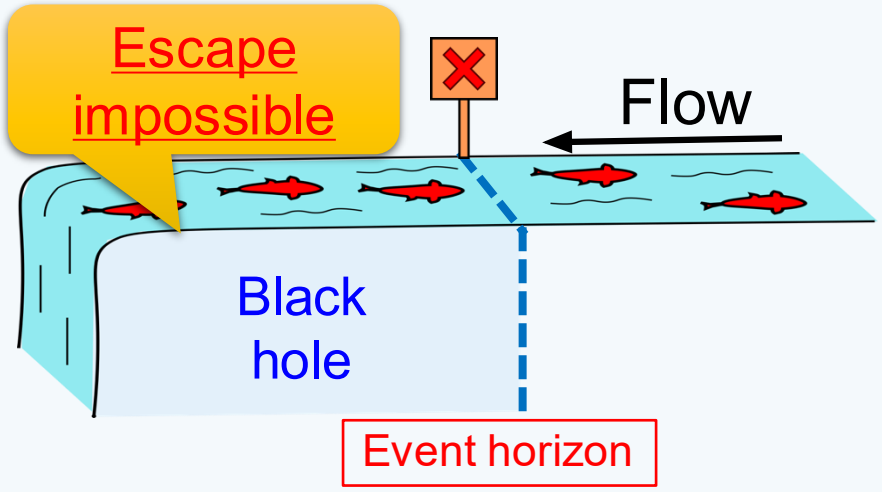
Cosmological particle creation

Quantum correlations from evolving backgrounds

- Analogue expanding universes
  BECs, ion traps, fluids of light, circuits etc.
- BEC experiments [Viermann et al., Nature 611, 260–264 (2022)]
  particle production / correlations

$a(t) \propto t^{\gamma}$ (1 e–fold)

Effective horizons from engineered flows



C04 targets **inflationary FLRW modes** with access to **quantum correlations**.

Controllability
programmable de Sitter dynamics

Quantum measurement
access to entanglement

Engineered nonlinearity
non-Gaussianity

fast parameter tuning

microwave quantum measurement

Josephson nonlinearity

Modeling

Target Dynamics: Inflationary Field Modes

Inflaton scalar field

$$\varphi(\boldsymbol{x},t) = \underbrace{\varphi_0(t)}_{\text{background}} + \underbrace{\delta\varphi(\boldsymbol{x},t)}_{\text{fluctuations}}$$

Friedmann–Robertson–Walker metric

$$\mathrm{d}s^2 = a^2(\eta)(-\mathrm{d}\eta^2 + \mathrm{d}\boldsymbol{x}^2)$$

Conformal time: η

Lagrangian density

$$\chi(\boldsymbol{x},\eta) = a(\eta)\delta\varphi(\boldsymbol{x},\eta)$$

$$\mathcal{L} = \left[\frac{1}{2}\partial_\eta\chi^2 - \frac{1}{2}\nabla\chi^2 + \frac{1}{\eta^2}\left(2 - \frac{m^2}{H^2}\right)\frac{\chi^2}{2}\right]$$

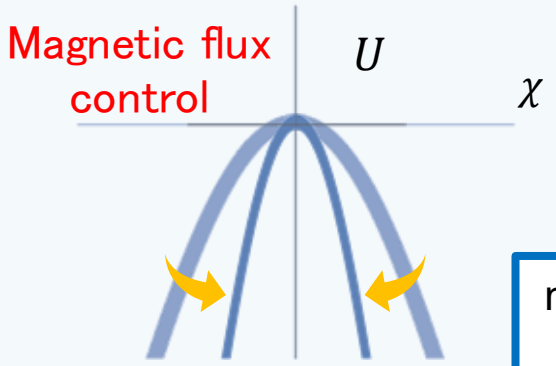
Equation of motion

$$\partial_\eta{}^2\chi - \nabla^2\chi - \frac{1}{\eta^2}\left(2 - \frac{m^2}{H^2}\right)\chi = 0$$

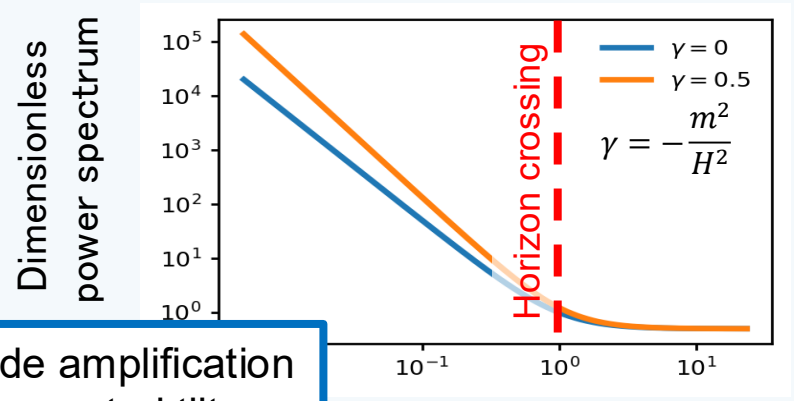
Circuit Design

Circuit translation : SQUID Array

Time-dependent potential

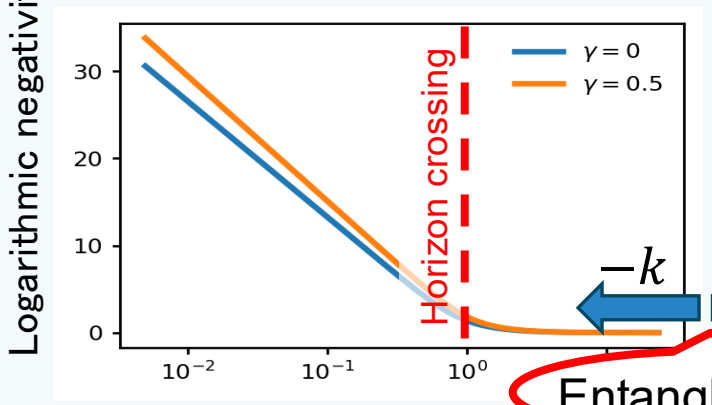


Cosmological observable imprint



mode amplification
spectral tilt

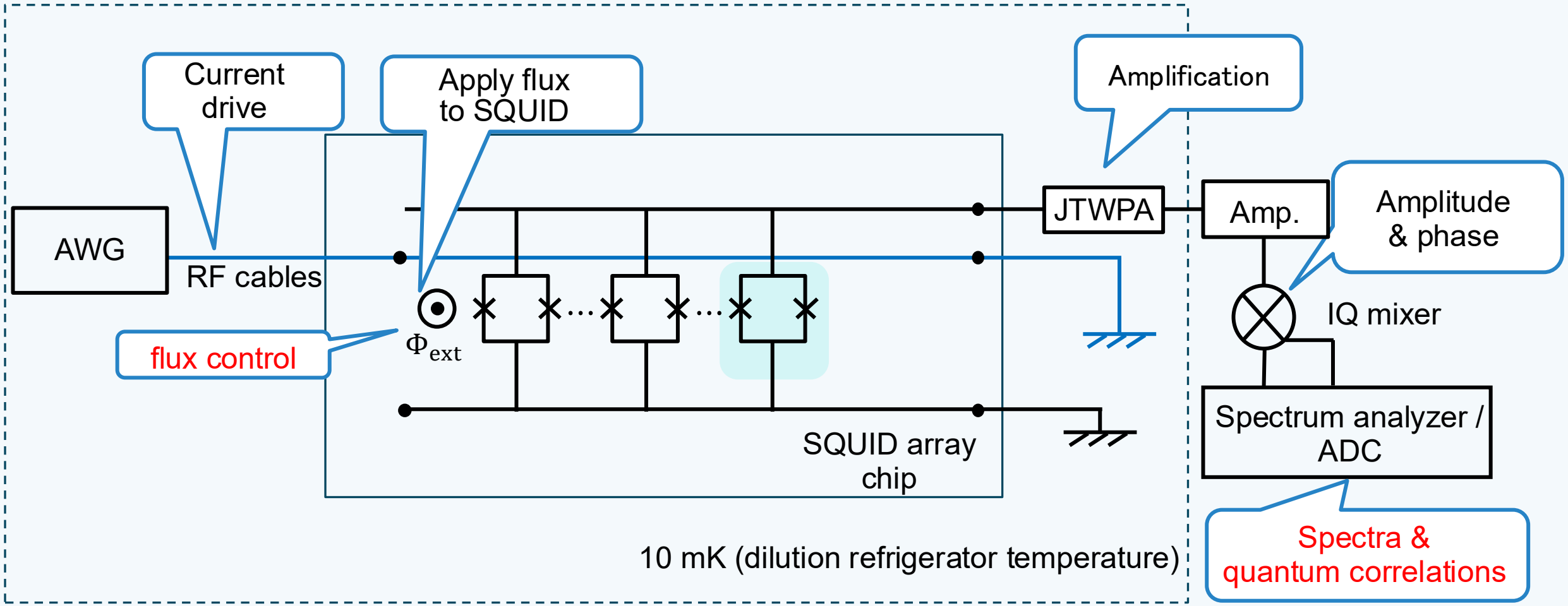
Underlying quantum nature



Entangled Pair

Experimental Demonstration

Measurement Scheme: Microwave Readout

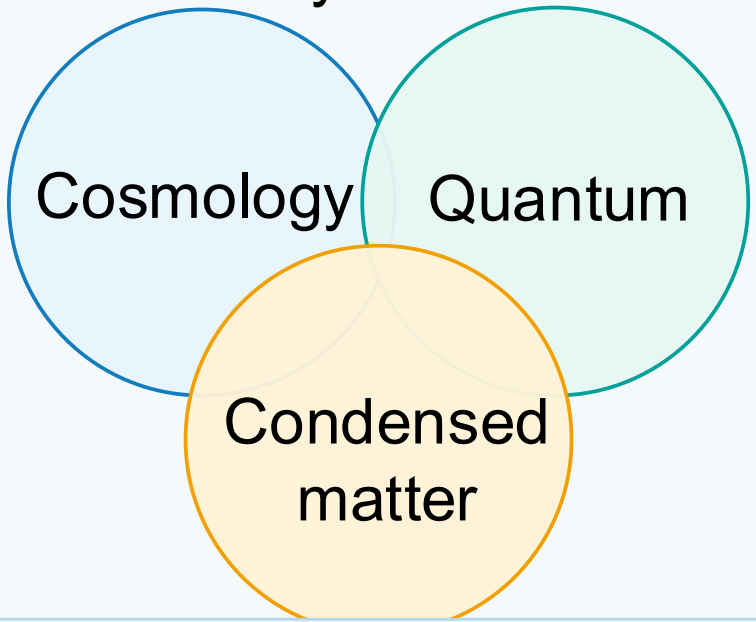


Role in the Research Area and Internal Collaboration

Make quantum processes of the early universe **measurable** in the laboratory.

Offer a new perspective

Reframe early-universe quantum processes experimentally



Feedback to the Research Area

Interpretive guidelines / observational proposals
Clues to mechanisms

Develop a new approach combining quantum cosmology and low-temperature condensed-matter physics

Internal collaboration

A01/A02

Theoretical models, key observables

B01/B02

Link analogue dynamics to cosmological observables

C03

Superconducting circuit implementation and microwave readout

Postdoctoral Researcher Recruitment

We are looking for a postdoc to join C04.

Affiliation: Hiroshima University
Location: Higashi-Hiroshima, Hiroshima

Research background:
Quantum field theory / cosmology / gravity
Quantum information / quantum optics
Superconducting circuits / condensed matter
or related fields

For application details,
please scan the QR code.

If you know someone who may be interested, please let us know.