FERMILAB-SLIDES-24-0118-SQMS

Evaluating radiation impact on transmon qubits in above and underground facilities

Tanay Roy, Francesco De Dominicis, Ambra Mariani, Mustafa Bal, Nicola Casali, Ivan Colantoni, Francesco Crisa, Angelo Cruciani, Fernando Ferroni, Dounia L Helis, Lorenzo Pagnanini, Valerio Pettinacci, Roman M Pilipenko, Stefano Pirro, Andrei Puiu, Alexander Romanenko, David v Zanten, Shaojiang Zhu, Anna Grassellino, Laura Cardani

SQMS division, Fermilab

arXiv 2405.18355

RISQ 2024 Workshop

30 May 2024

National Quantum Initiative Act (2018)

10 yr plan to accelerate the development of **quantum information science & technology applications.**

*DOE shall establish and operate **NQI Science Research Centers** to conduct basic research to accelerate scientific breakthroughs in quantum information science and technology.*

5 NQI DOE centers (2020)

SQMS **SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS** CENTER

C²QA Co-design Center for Quantum Advantage

Quantum Systems Accelerator

Q-NEXT

QUANTUM SCIENCE CENTER

SQMS Center highlights

34 partner institutions

> 535 collaborators

Fermilab
Northwestern University
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AMES NATIONAL LABORATORY
NASA Ames Research Center
NIST
COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT
COPPIN STATE UNIVERSITY
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USC University of Southern California
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

SQMS brings together hundreds of experts from more than 30 DOE national labs, academia, industry and other federal and international entities to bring transformational advances in QIS

The Quantum Garage

Tour tomorrow

Don't miss!!

8 extra large dilution refrigerators, numerous qubits and cavities, nanofab tools and materials science capabilities

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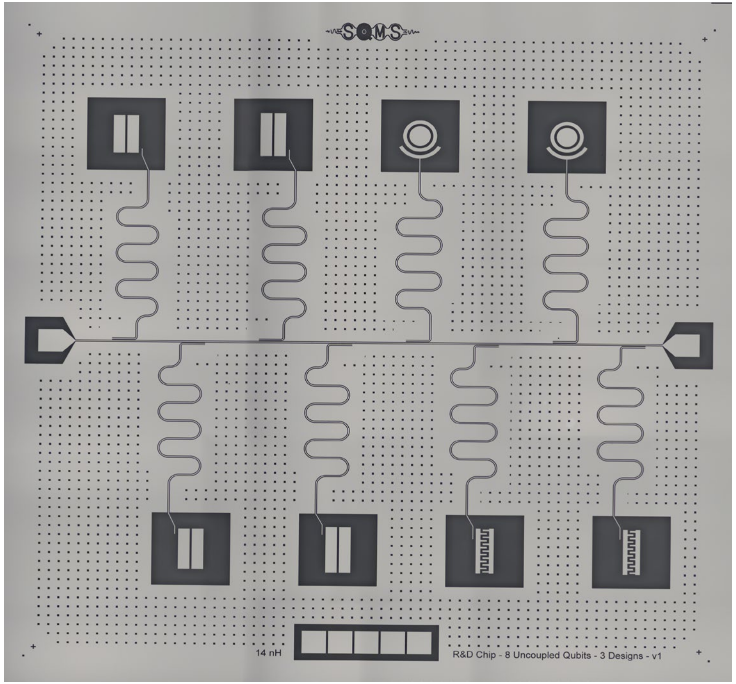
Superconducting devices



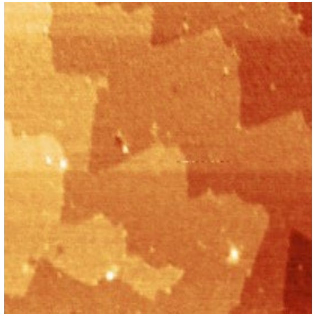
2D Transmons

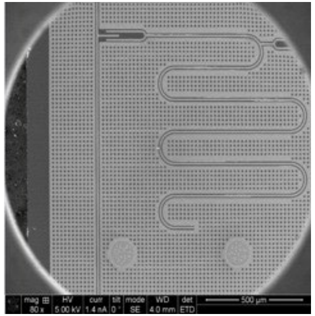
3D SRF cavities

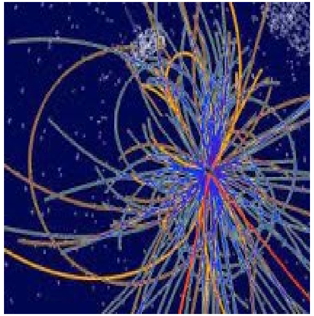
Bal et al. npj Quant. Info. 10, 43 (2024)
Roy et al. PoS LATTICE2023, 127

Science & Technology Innovation Chain

Materials → High-coherence devices → Systems integration → New platforms for quantum computing & sensing → Quantum advantage

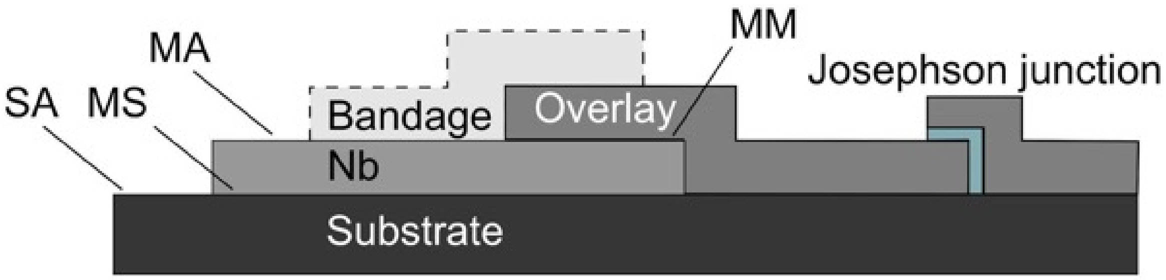




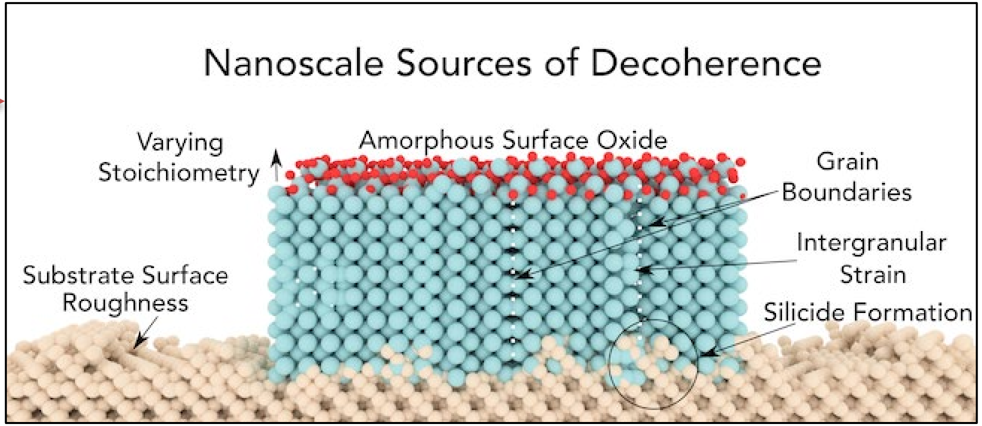


Developing a full understanding of sources of decoherence	Demonstrating devices with systematically higher coherence	Integrating devices into quantum processors	Deploying quantum computing and sensing facilities	Experiments with quantum computing and sensing advantage

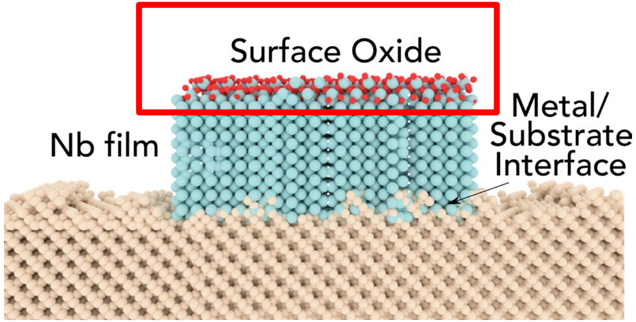
Decoherence channels in 2D



- Two-level systems (TLS)
- Bulk substrate losses
- Quasiparticles

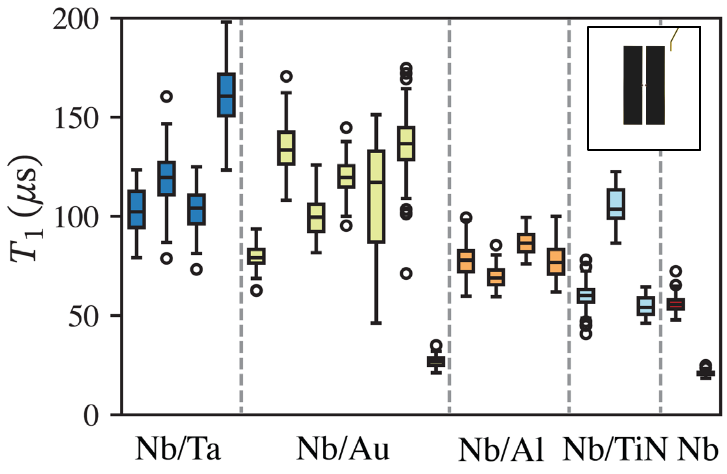


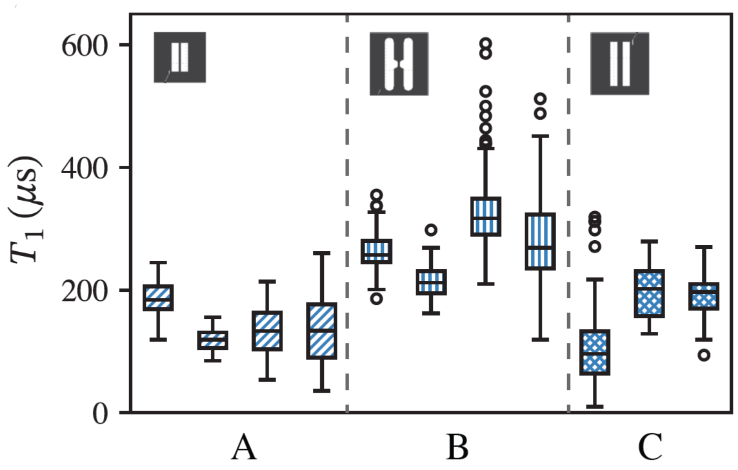
Surface encapsulation



Average T_1 = 320 μs

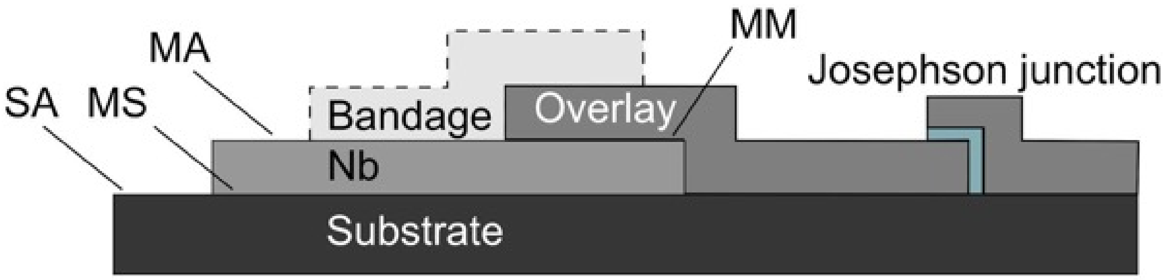
Best $\mathbf{T_1}$ **= 600** $\boldsymbol{\mu s}$





Bal et al. npj Quant. Info. 10, 43 (2024)

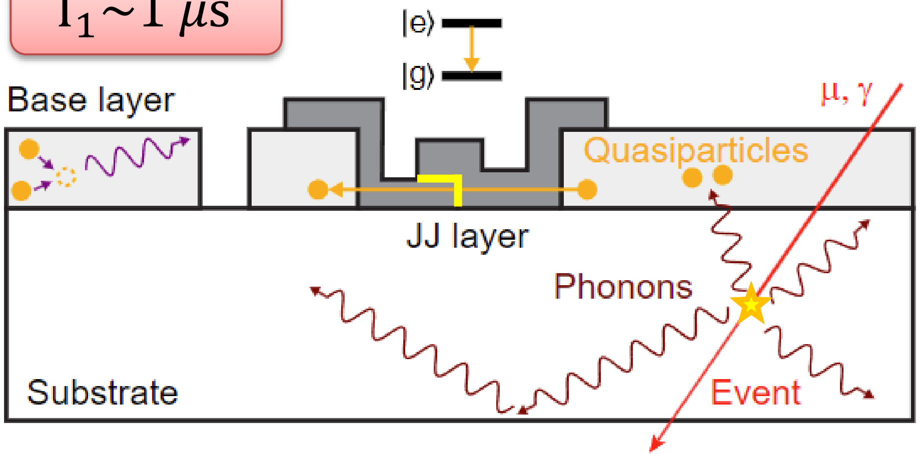
Decoherence channels in 2D



- Two-level systems (TLS)
- Bulk substrate losses
- Quasiparticles
  - ➢ Thermal
  - ➢ Infrared radiation
  - ➢ Ionizing radiation

Effect of radiation

$T_1 \sim 1\ \mu s$



Study time dynamics of a single qubit

Radiation resilient: Quantum processor

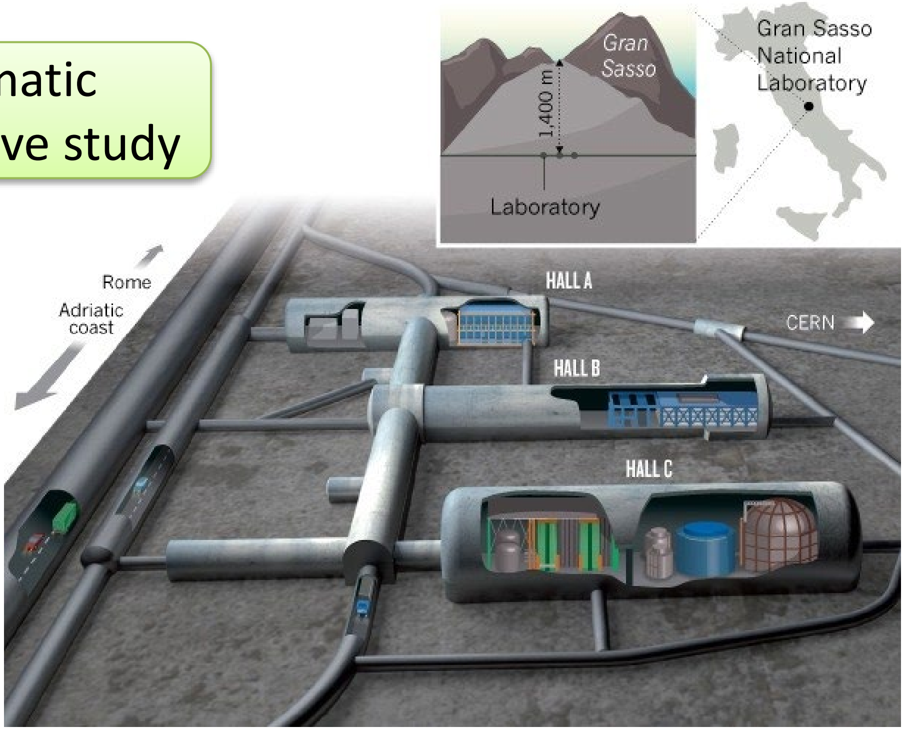
Radiation sensitive: Particle detector

Martinis, npj Quant. Info. 7:90 (2021)
Wilen *et al.*, Nature 594, 369 (2021)
Cardani *et al.*, Nat. Comm. 12, 2733 (2021)
McEwen *et al.*, Nat. Phys. 18, 107 (2022)
Thorbeck *et al.*, arXiv:2210.04780 (2022)
Cardani *et al.*, Eur. Phys. J. C 83:94 (2023)
Harrington *et al.*, arXiv:2402.03208 (2024)
Li *et al.*, arXiv:2402.04245 (2024)
McEwen *et al.*, arXiv:2402.15644 (2024)
and others…

Correlated error

Experimental locations

Systematic comparative study

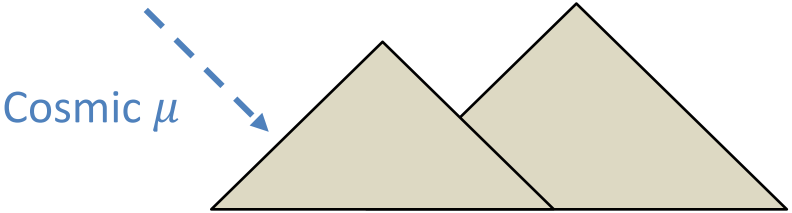


FNAL: above-ground

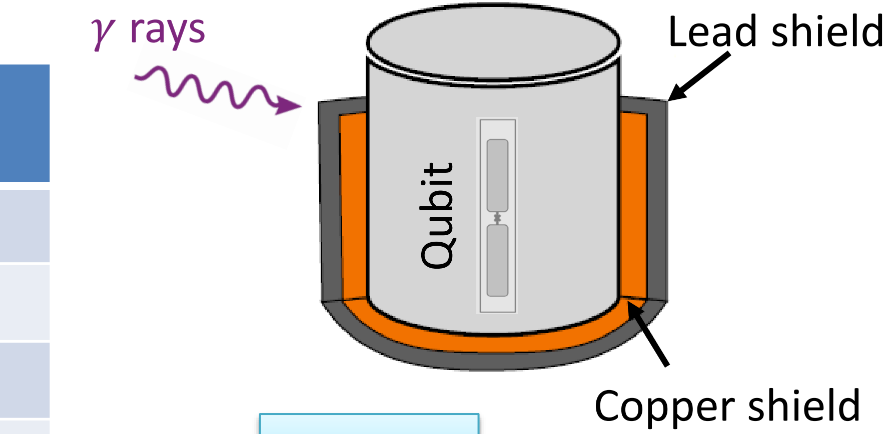
LNGS: deep underground

Simulated rates

- Far sources (can be shielded)
  - Muon particles
  - Environmental gamma rays
- Close sources (can't be shielded)
  - Radioactive contaminations



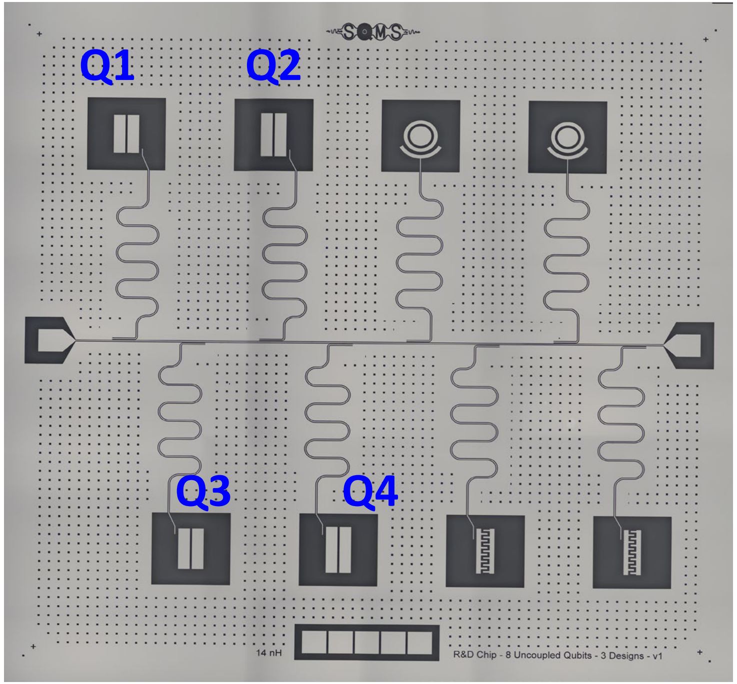
Source	FNAL ($ev/10^3 s$)	LNGS w. shields ($ev/10^3 s$)
Lab γ rays	46 ± 2	1.3 ± 0.1
Muons	8.0 ± 0.5	$< 10^{-5}$
Contaminations	2.7 ± 0.5	2.7 ± 0.5
Total	$\mathbf{57 \pm 3}$	$\mathbf{4.0 \pm 0.6}$



GEANT4

Cardani *et al.*, Eur. Phys. J. C 83:94 (2023)

Devices under study



- 4 transmons
- Similar frequency, geometry
- $T_1 \sim 100\ \mu s$

Parameter	Q1	Q2	Q3	Q4	Units
Material	Nb/Au	Nb/Ta	Nb/Ta	Nb/Ta	N/A
Qubit frequency	4717.4	4455.4	4451.3	4294.8	MHz
Readout frequency	7206.8	7055.0	6886.5	6714.5	MHz
Qubit π pulse length	0.150	0.091	0.124	0.160	μs
Qubit average T_1	84	141	131	214	μs
Readout pulse length	4.5	3.8	4.0	8.0	μs
Waiting period	5.0	10.0	5.0	5.0	μs
Cooldown period	50.0	70.0	70.0	10.0	μs
One iteration period	64.550	87.929	84.324	31.660	μs

arxiv: 2405.18355

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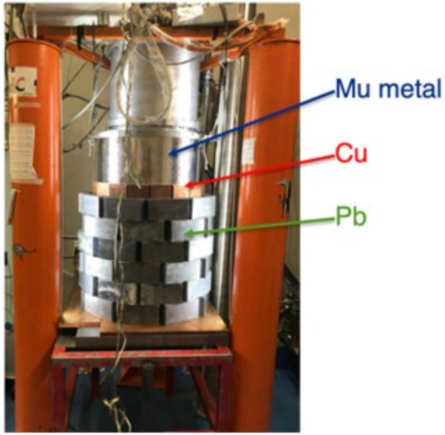
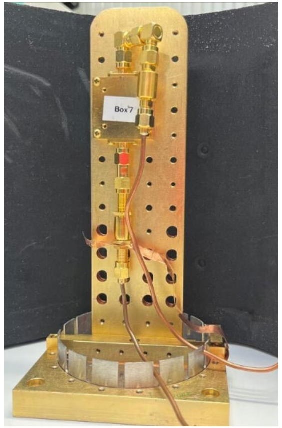
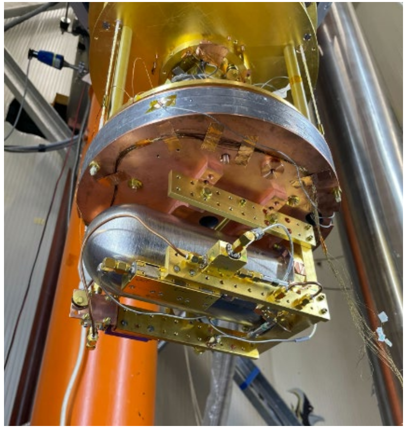
Comparison of standard T_1

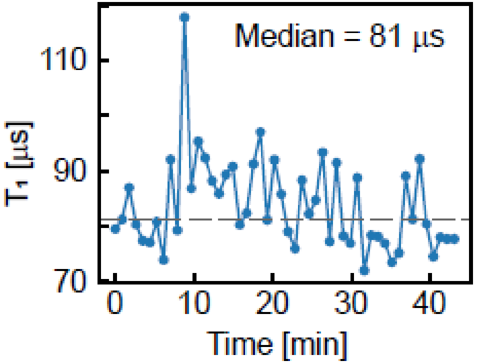
FNAL

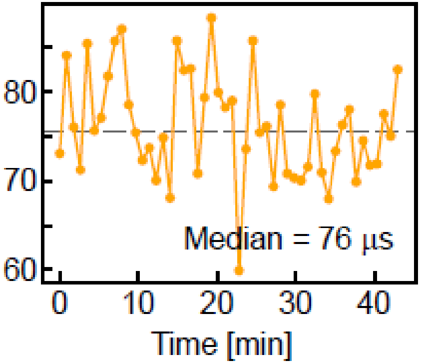
LNGS







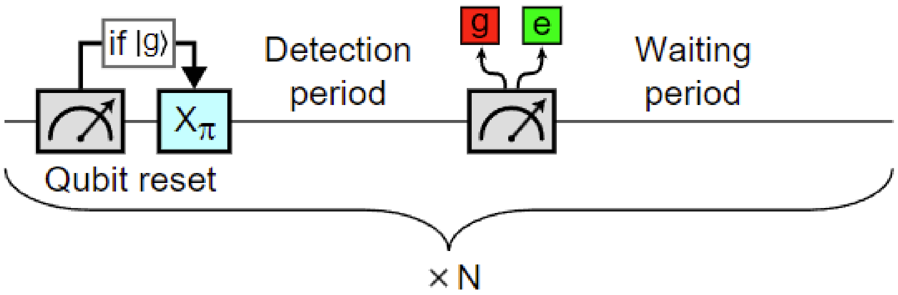




T_1 of same qubit shows similar avg. and fluctuations

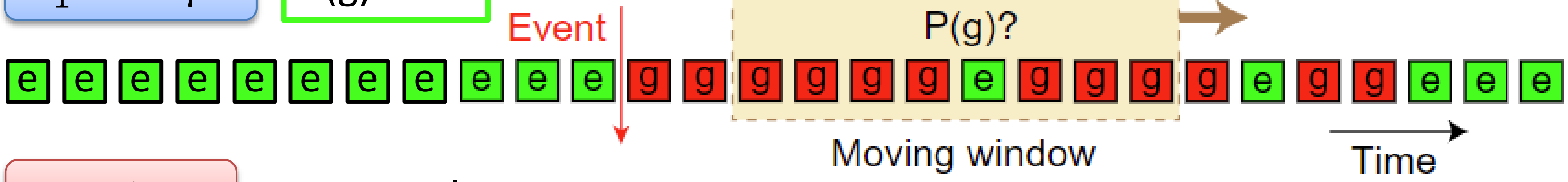
Detection protocol

- Prepare $|e\rangle$ through active reset
- Measure after 5 μs
- Wait and repeat



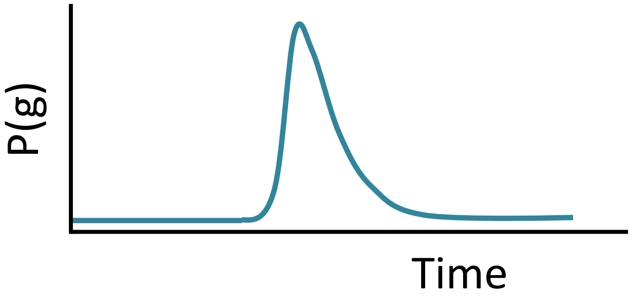
$T_1 \sim 100\ \mu s$

P(g) = 5%



$T_1 \sim 1\ \mu s$

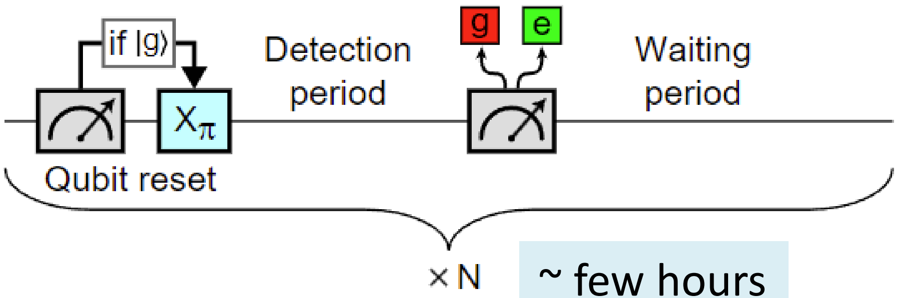
P(g) = 99%



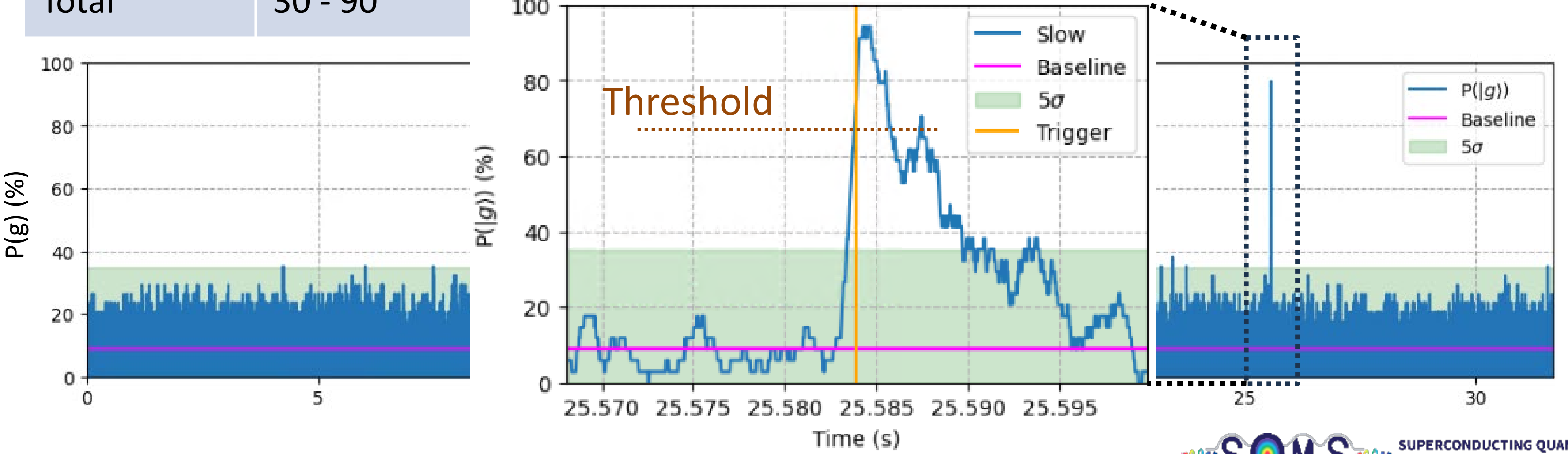
McEwen *et al.*, Nat. Phys. 18, 107 (2022)

Signal detection

Operation	Time (μs)
Readout	4 - 8
π pulse	0.09 – 0.160
Detection	5
Waiting	10 - 60
Total	30 - 90



~ few hours



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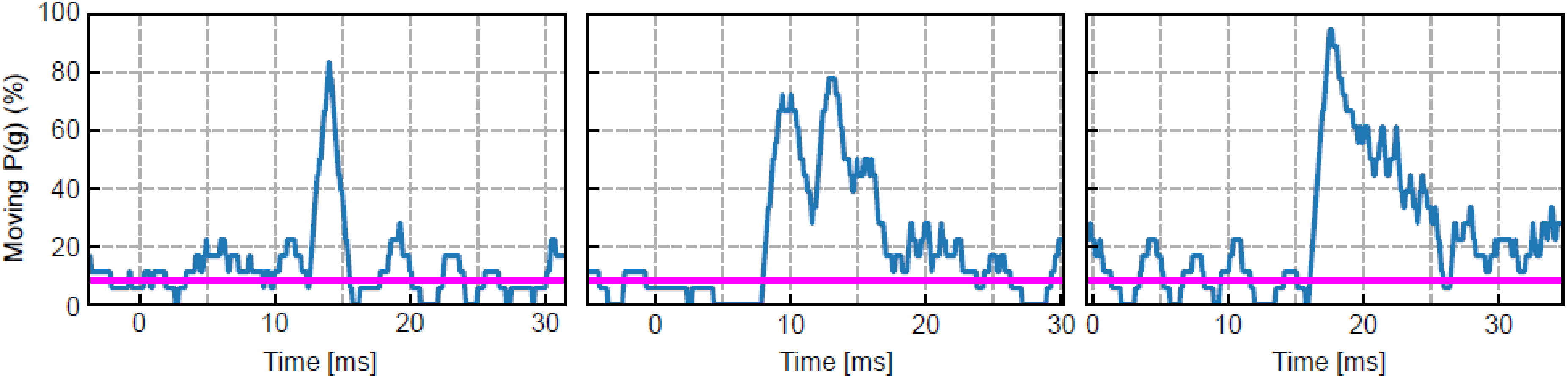
Different pulse shapes



Fast falling edge

Medium falling edge

Slow falling edge

Milli-second timescale

Similar time-profile observed at both locations

Above-ground measurements

$T_1 > 130\ \mu s$

Qubit #	Measured ev/10^3 s
Q2	10.2 ± 0.5
Q3	10.0 ± 0.2
Q4	6.4 ± 0.1

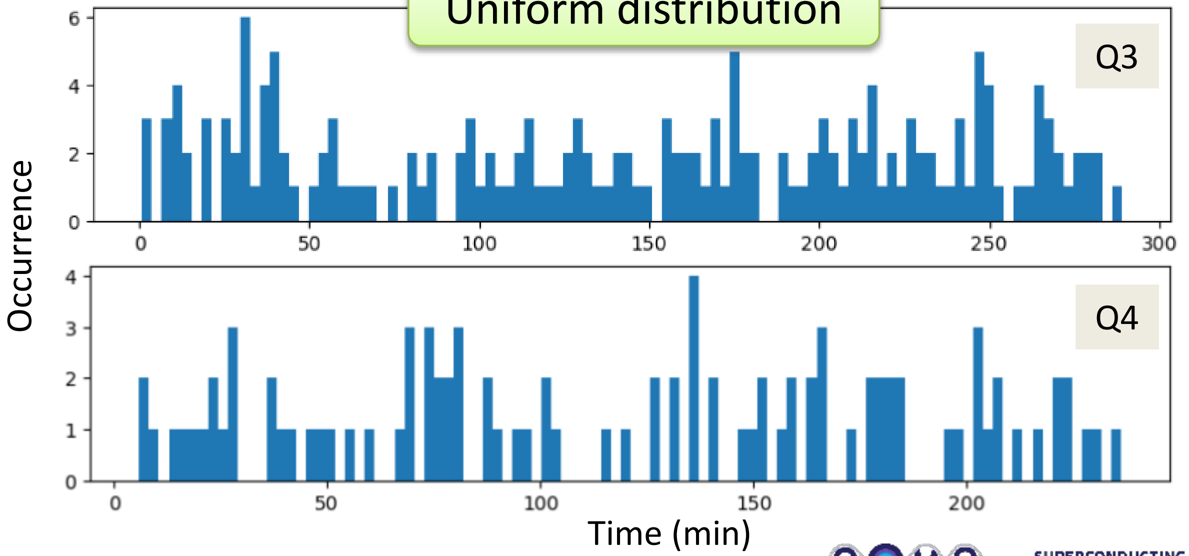
Predicted
$\sim$57 ev/10^3 s

10-20% efficiency

Cosmic μ

Environmental γ rays

Uniform distribution



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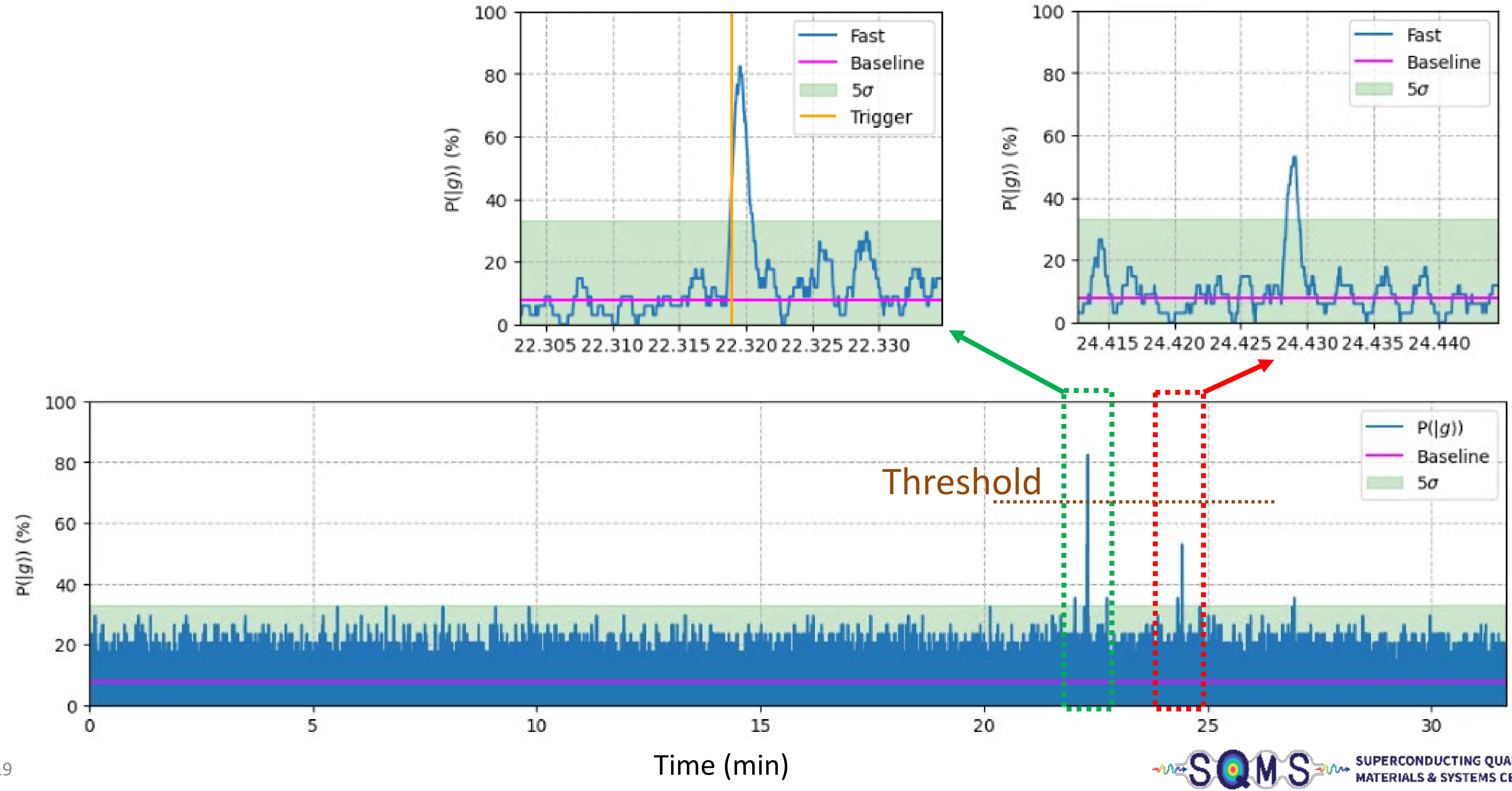
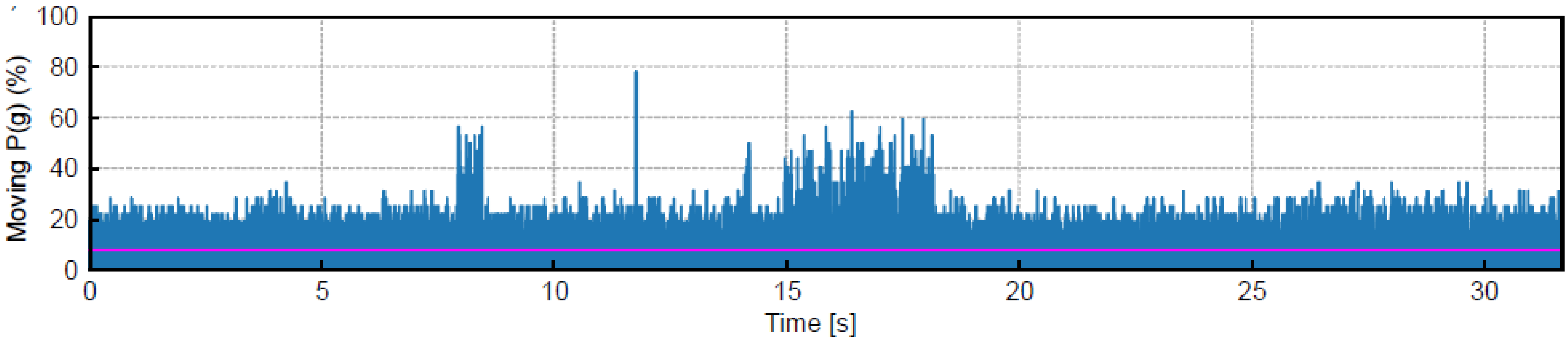
Missed events

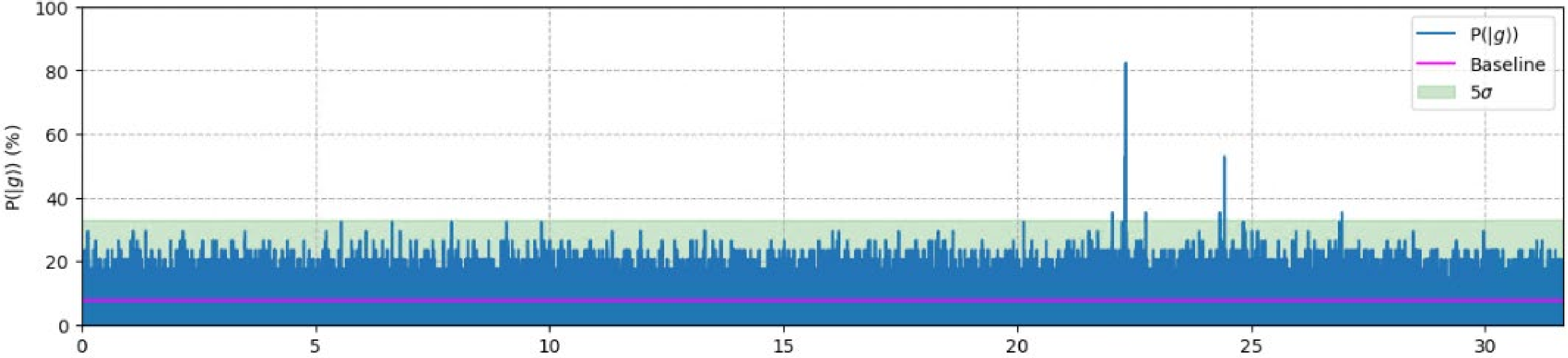


Baseline fluctuations

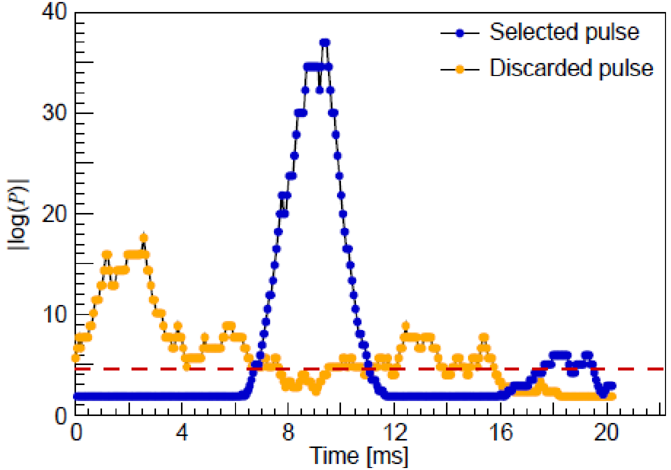


- Lasts for sub-second to about a minute
- Visible on all qubits
- Not associated with preceding pulses

New analysis strategy



- Compute T_1' using P_{avg} and wait period
- Compute binomial probability P of obtaining a sequence
- Trigger if $P < 1\% \Rightarrow |\log P| > 4.6$



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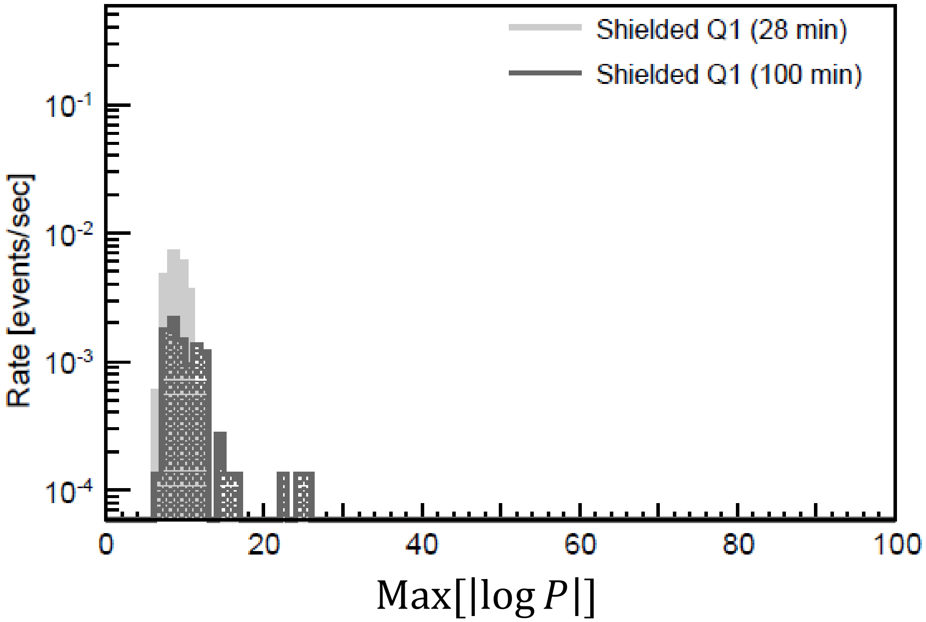
Underground data



Qubit	Rate (ev/10^3s)	Observed /simulated
Q1 (1)	23 ± 4	6
Q1 (2)	10 ± 1	2.5

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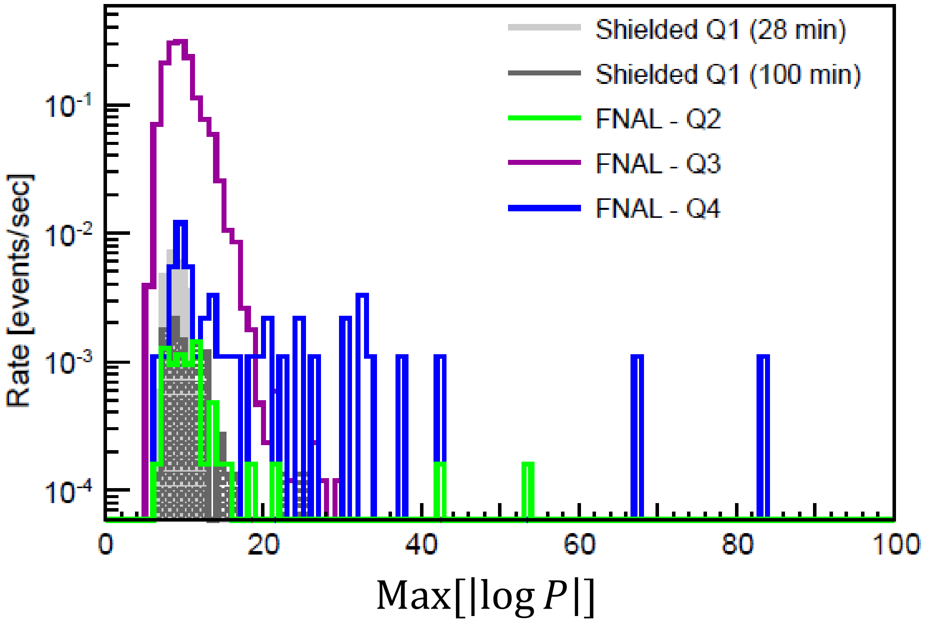
Comparison with above-ground data



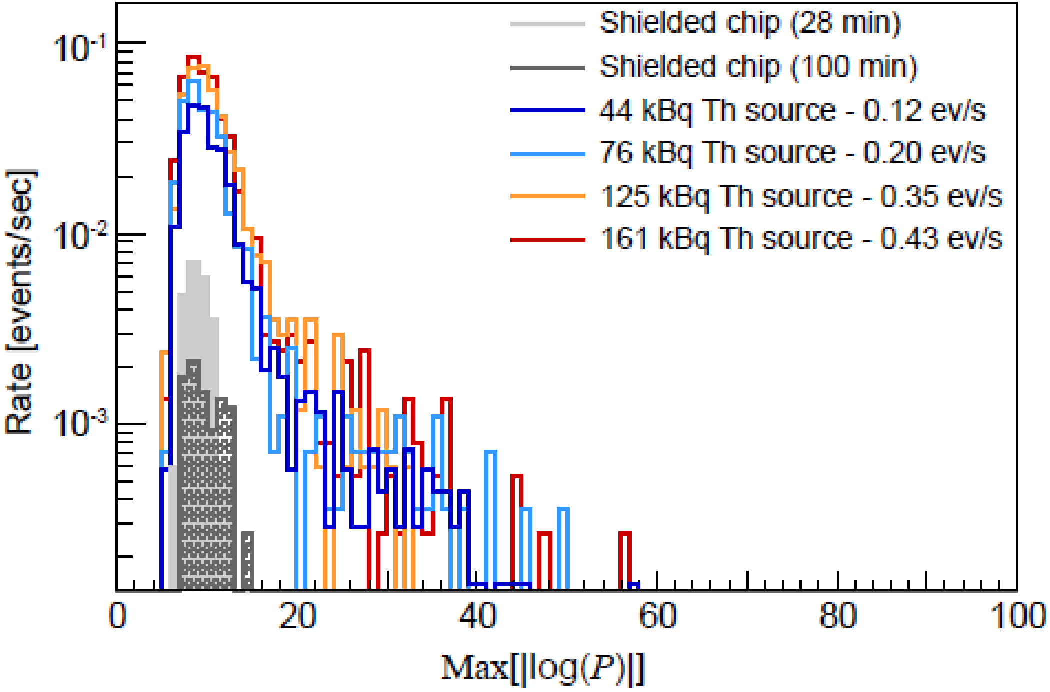
Qubit	Rate (ev/10^3s)	Observed /simulated
Q1 (1)	23 ± 4	5.75
Q1 (2)	10 ± 1	2.50
Q2	5 ± 1	0.09
Q3	1100 ± 10	19.30
Q4	45 ± 2	0.79

Different total rates

Other sources of noise produce radiation-like signatures

Underground measurements with Th sources

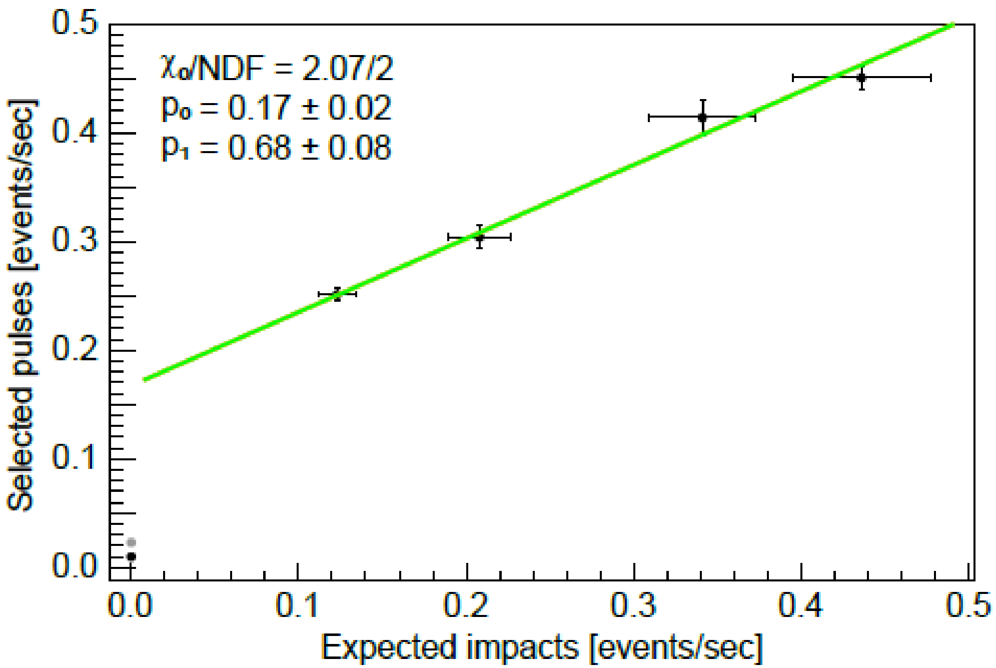
Thorium



Transmons are sensitive to strong γ source

Underground measurements with Th sources

Thorium



Linear behavior

Potential for a detector

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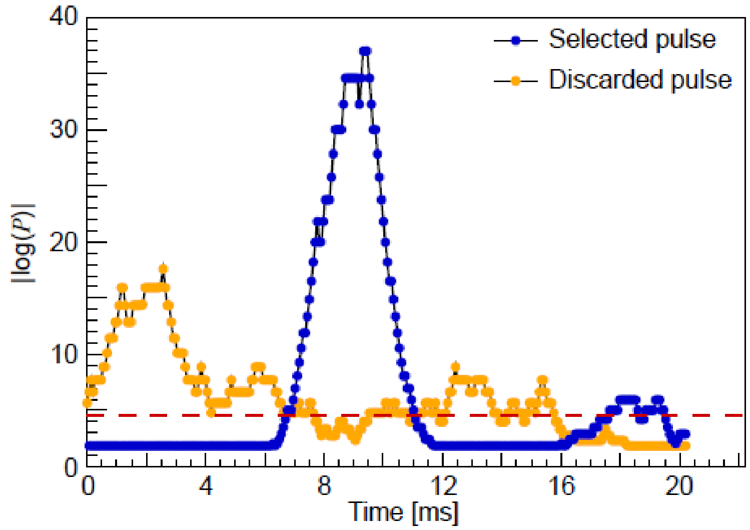
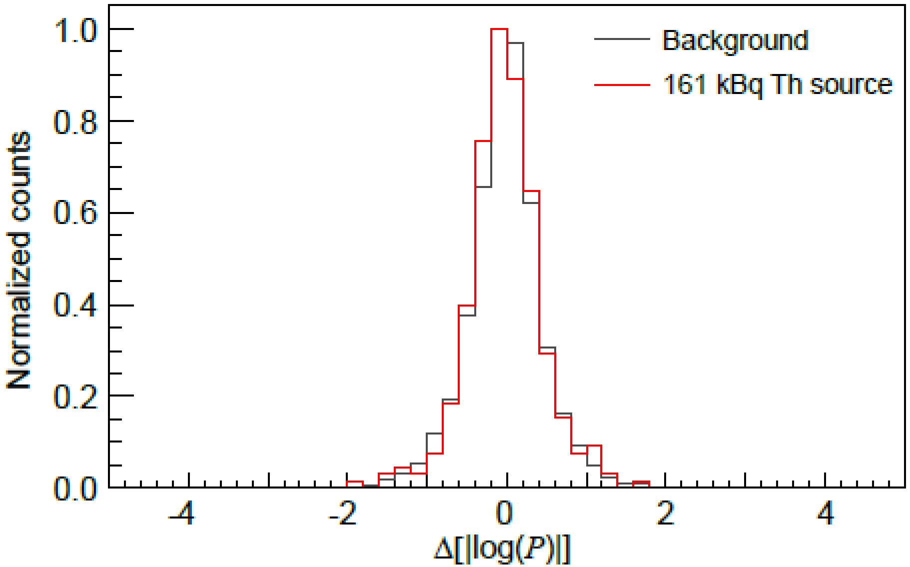
Study of TLS activation



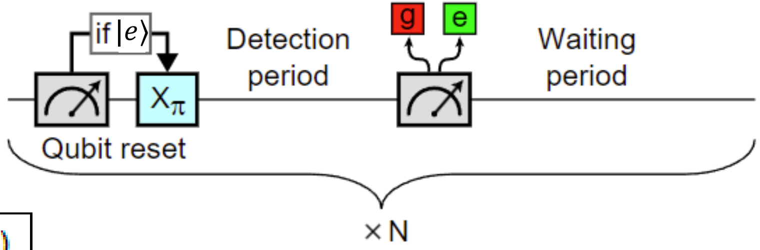


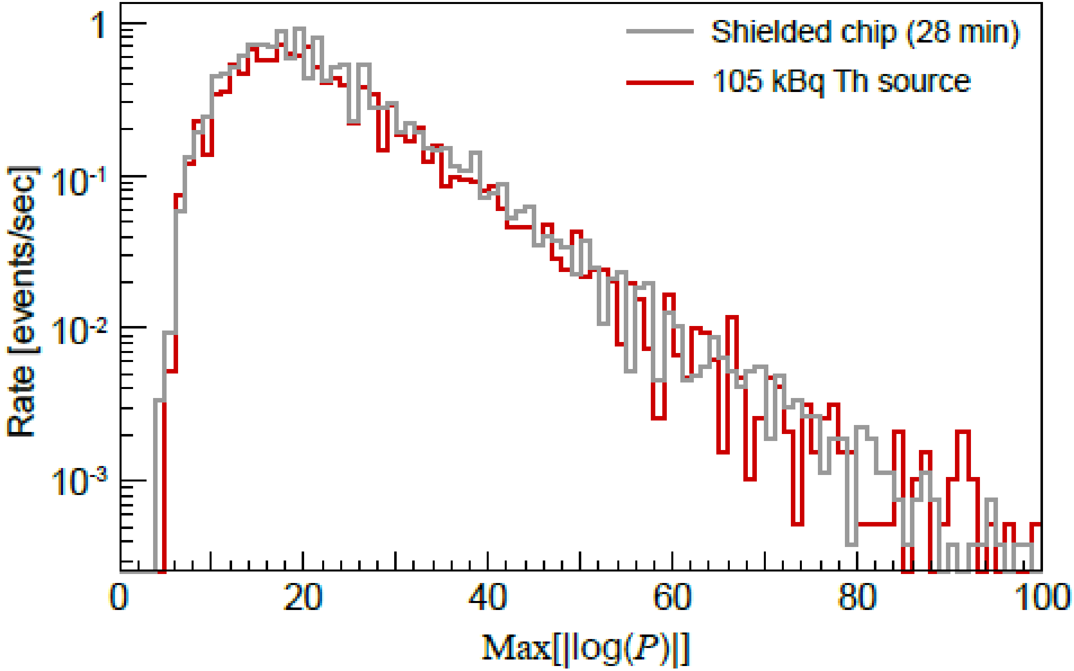
Check log P before & after

No significant difference

$|g\rangle \rightarrow |e\rangle$ transition

- Reset to $|g\rangle$
- Measure after a waiting period





No significant difference

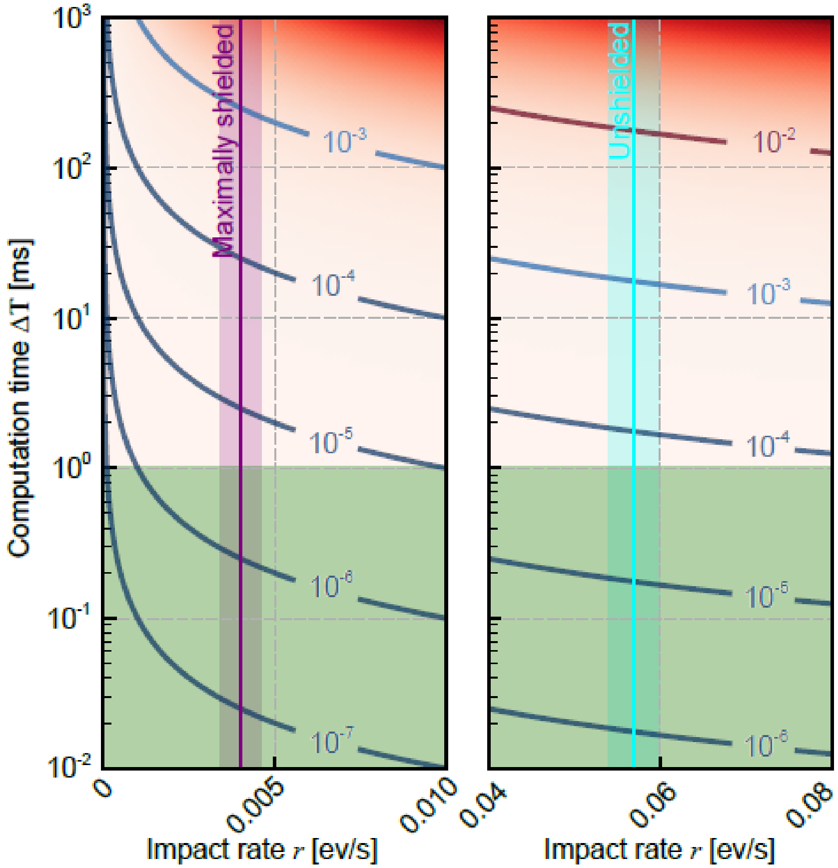
Radiation impact on computation

r = Rate of impact
ΔT = Time window

$$P_{impact} = 1 - e^{-r.\Delta T}$$

$P_{impact} < 0.1\%$ if
$\Delta T < 17$ ms (unshielded)
$\Delta T < 250$ ms (shielded)

$P_{impact} < 10^{-4}$ for modern transmons



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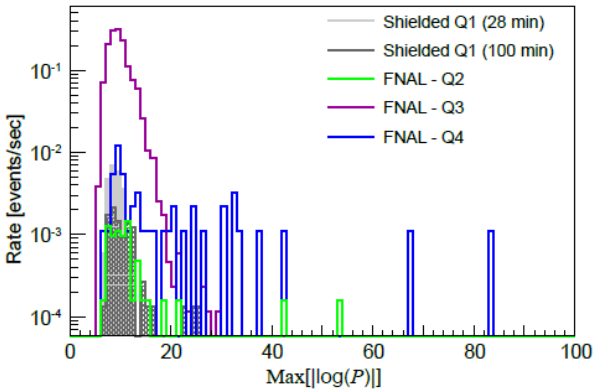
Summary

arXiv: 2405.18355

- **Above and underground comparative study using single qubits**
- **QP burst events last for several milli-seconds**
- **Radiation unlikely to play a major role in T_1 drops at short timescales**
- **Radiation should not limit single-qubit errors of contemporary devices**

Next steps

- Understanding the source of QP bursts
- Test on different materials and geometry
- Coincidence measurements on same and different chips
- Investigate sporadic instabilities
- Make qubits resilient against sudden T_1 drops



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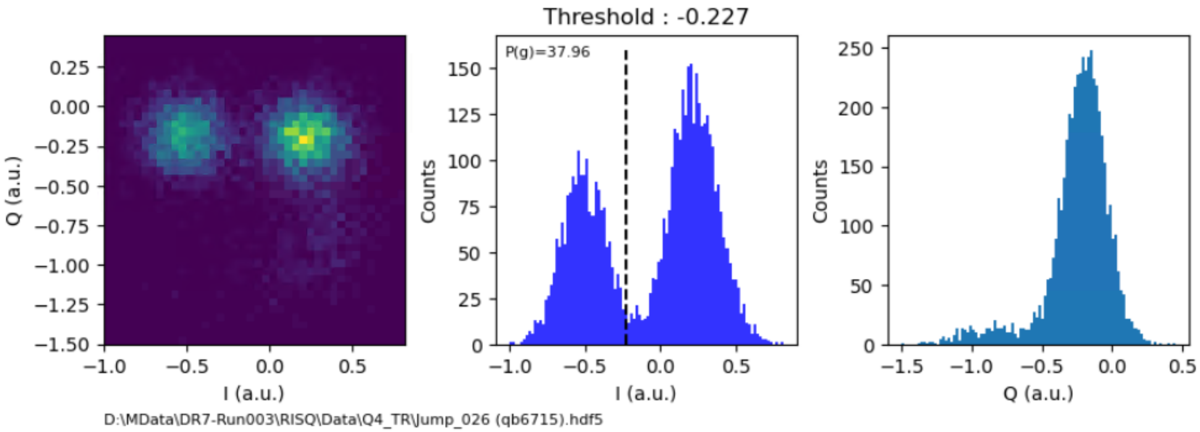
THANK YOU

This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359, and by the Italian Ministry of Foreign Affairs and International Cooperation, grant number US23GR09.

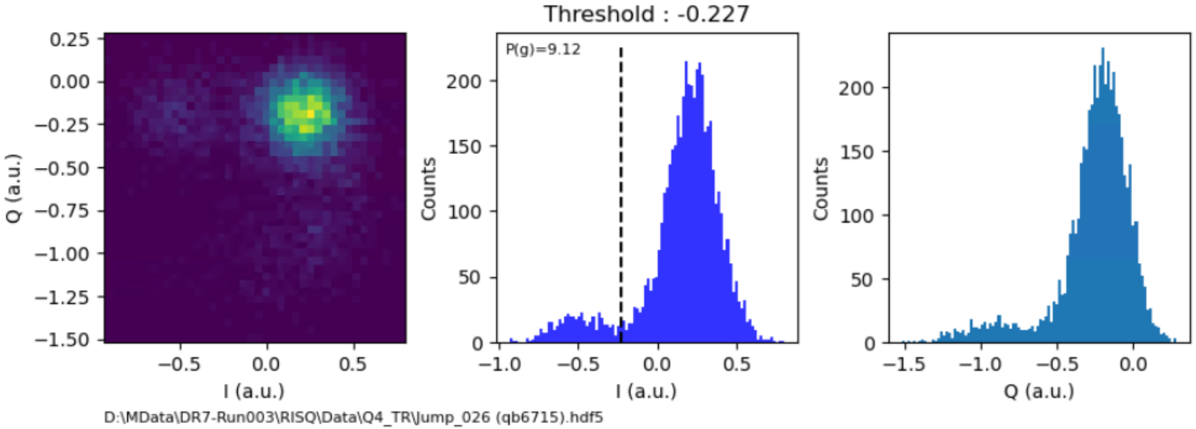
Extra slides

IQ blobs

Before reset



After reset



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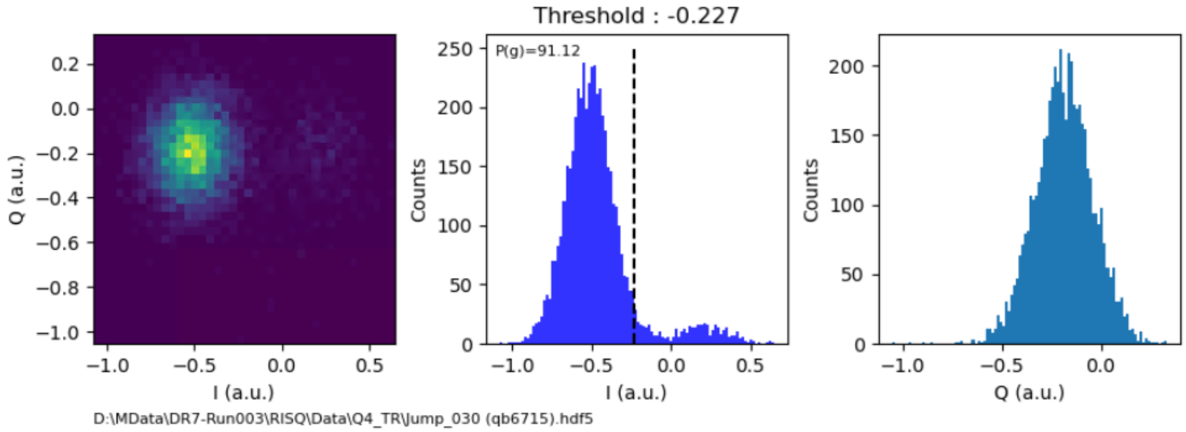
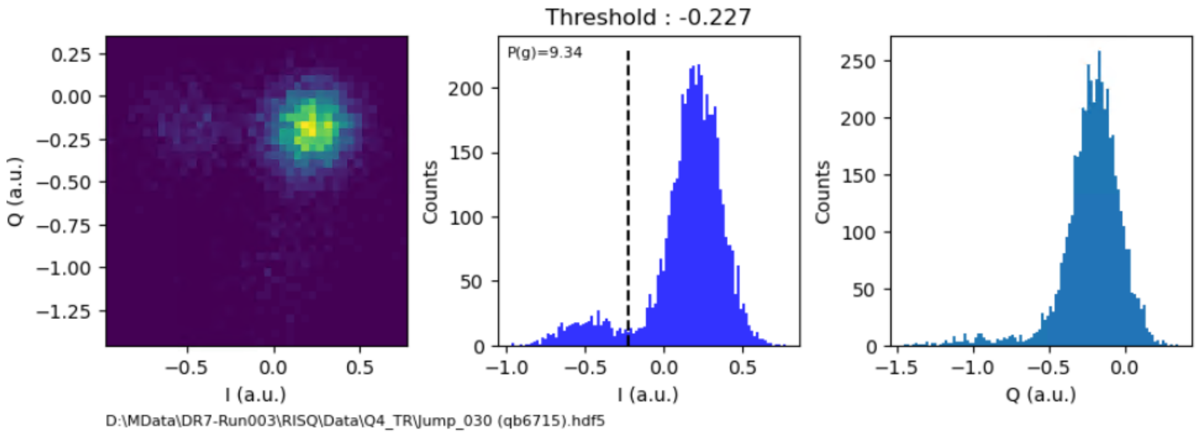
IQ blobs

Before reset



After reset



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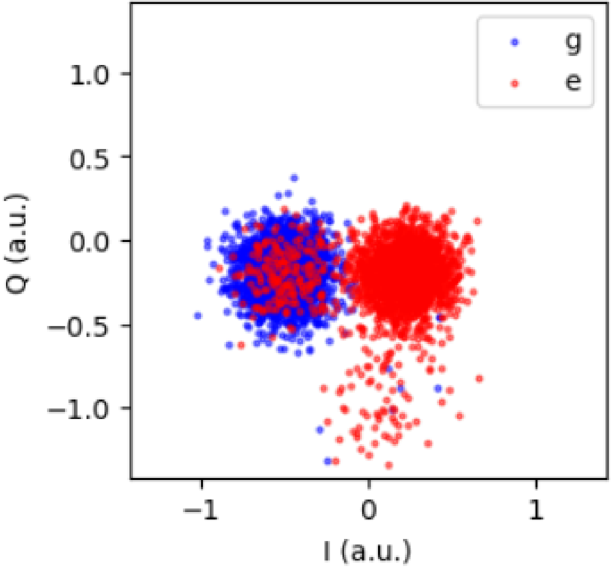
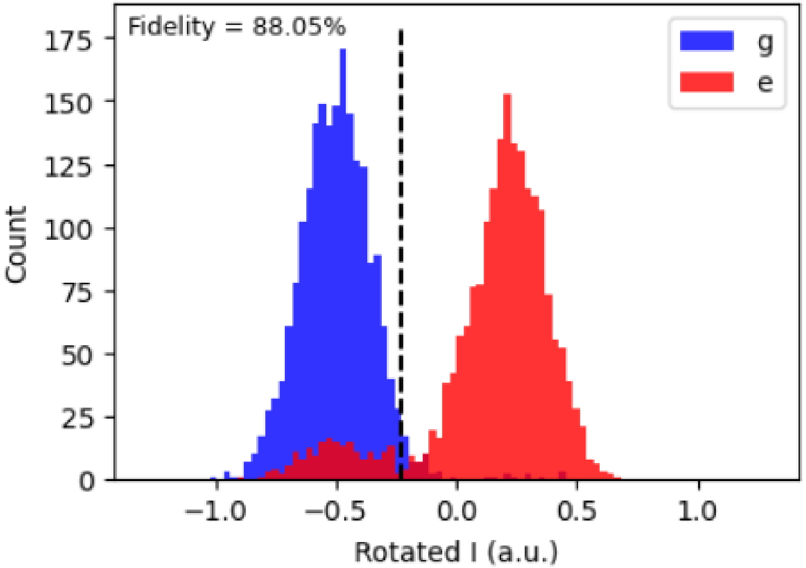
Readout fidelity



D:\MData\DR7-Run003\RISQ\Data\Q4_TR\Hist_049 (qb6715).hdf5




```
Fidelity Matrix:
-----------------
| 97.1 | 9.7 |
----------------
| 2.9 | 90.3 |
-----------------
```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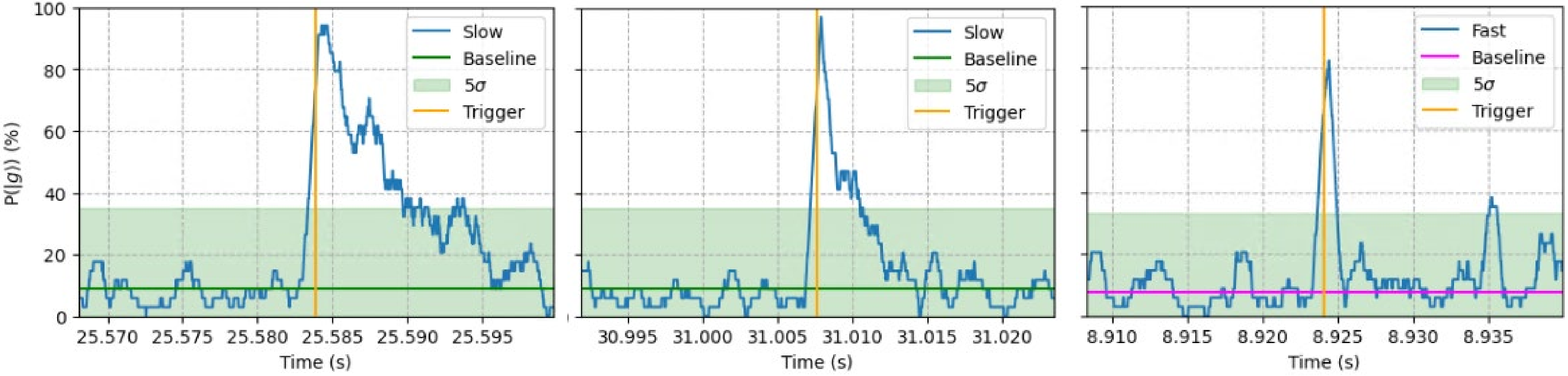
Different pulse shapes



Slow falling edge

Medium falling edge

Fast falling edge

Milli-second timescale

Similar time-profile observed at both locations

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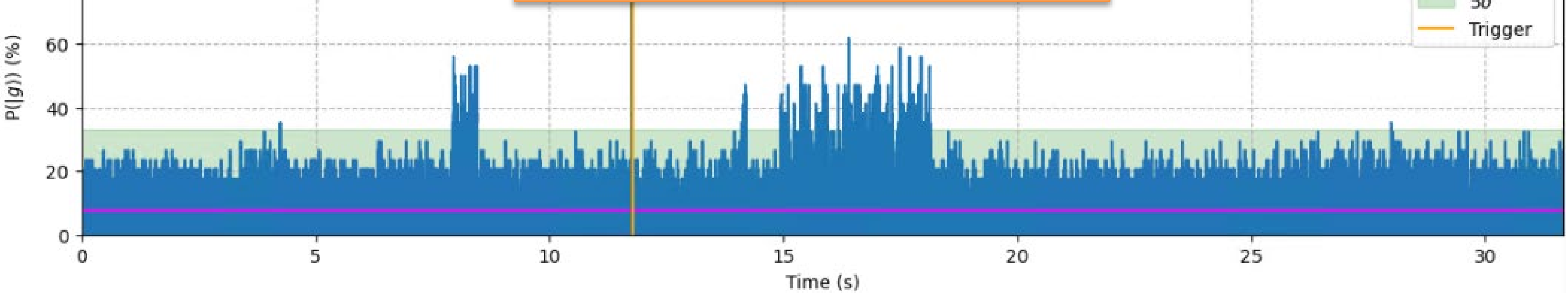
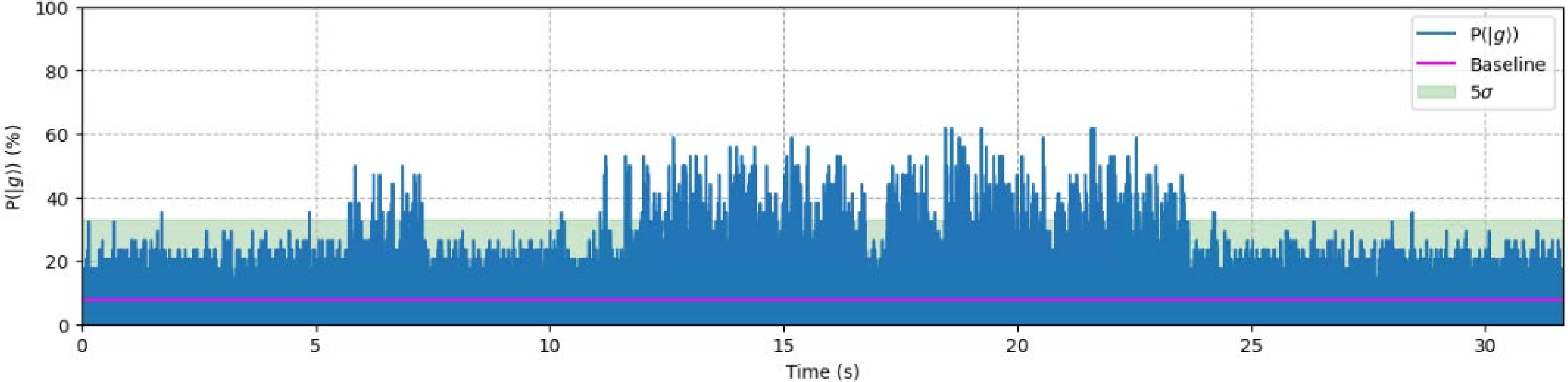
Sporadic fluctuations

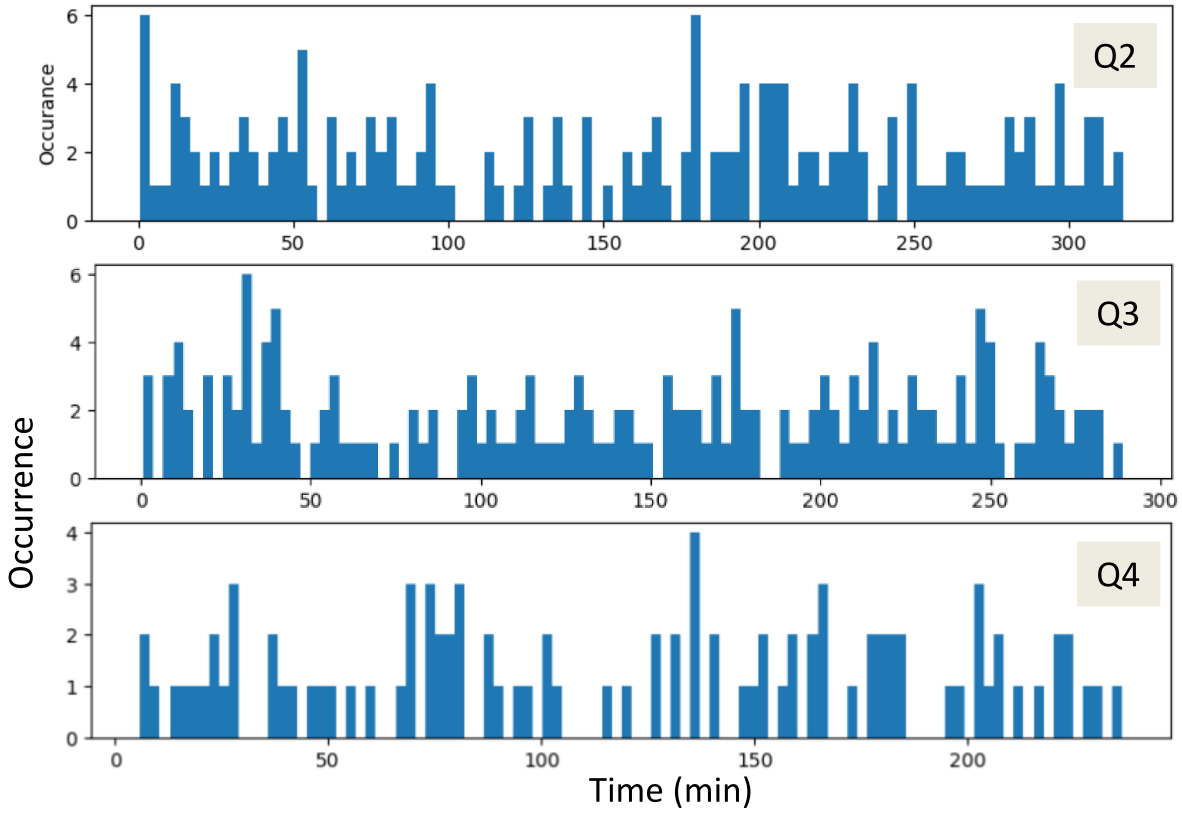
Visible in ~10% of the traces



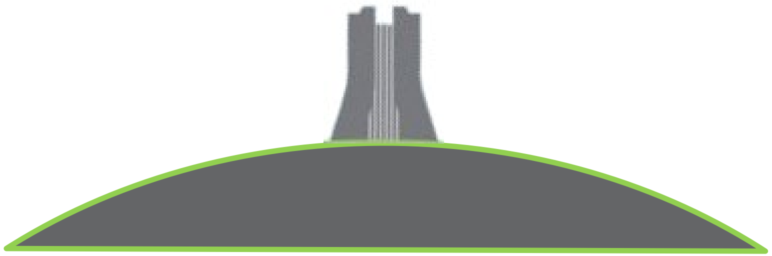


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Time distribution



Extras



```
FindMaximum[-Exp[-t / 1] + Exp[-t / 150], {t, 4}]
{0.960485, {t → 5.04426}}

FindMaximum[-Exp[-t / 0.6] + Exp[-t / 150], {t, 4}]
{0.974157, {t → 3.32618}}

FindMaximum[-Exp[-t / 1.6] + Exp[-t / 150], {t, 4}]
{0.942066, {t → 7.34334}}
```

PCB: K(40), Th(232), and U(238)

JJ thickness 40/90 nm

Readout Fidelity