Understanding quasiparticle dynamics in a superconducting qubit through phonon burst-induced correlated errors

Emanuela Celi
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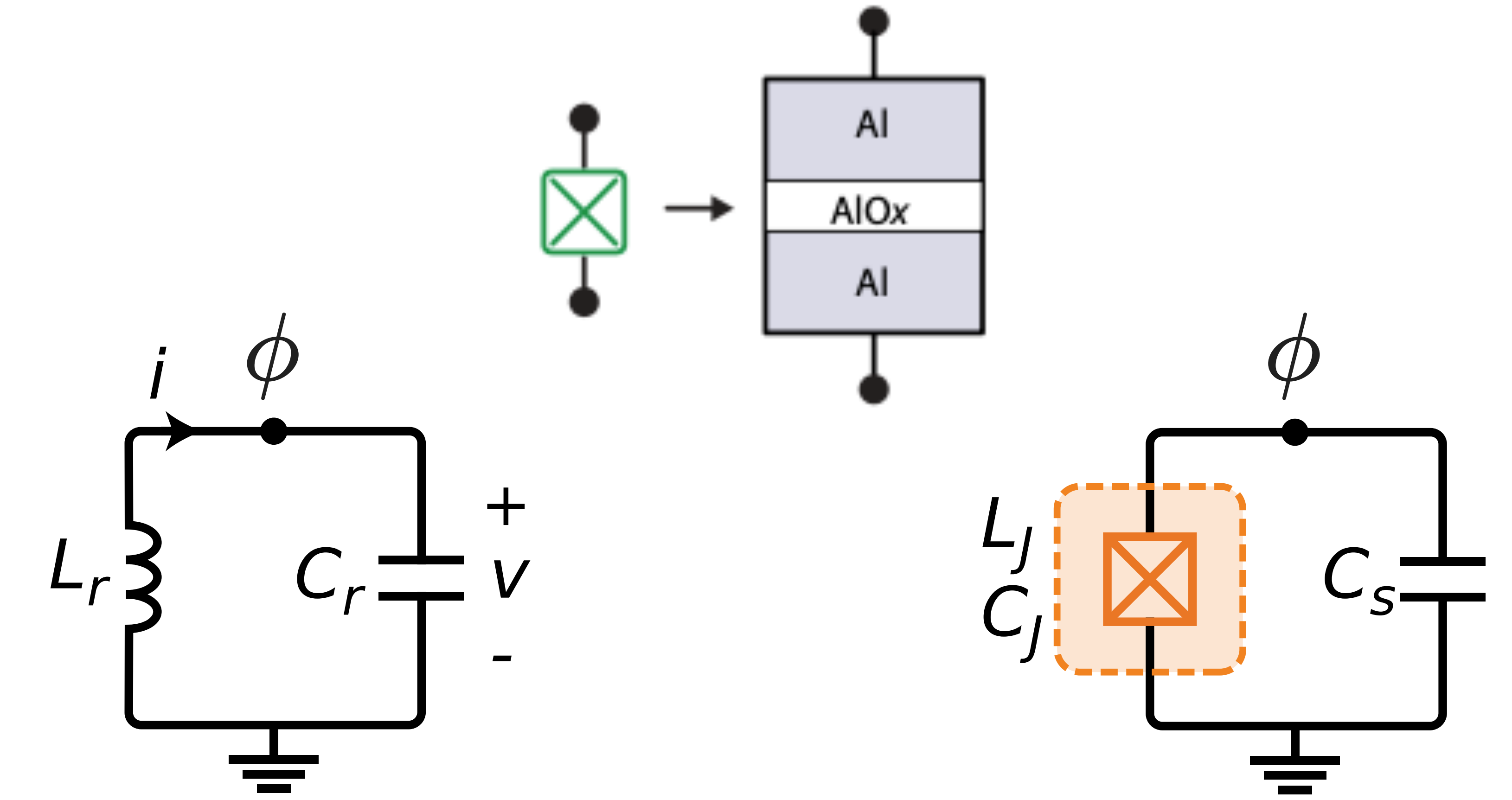
Superconducting qubit → anharmonic oscillator

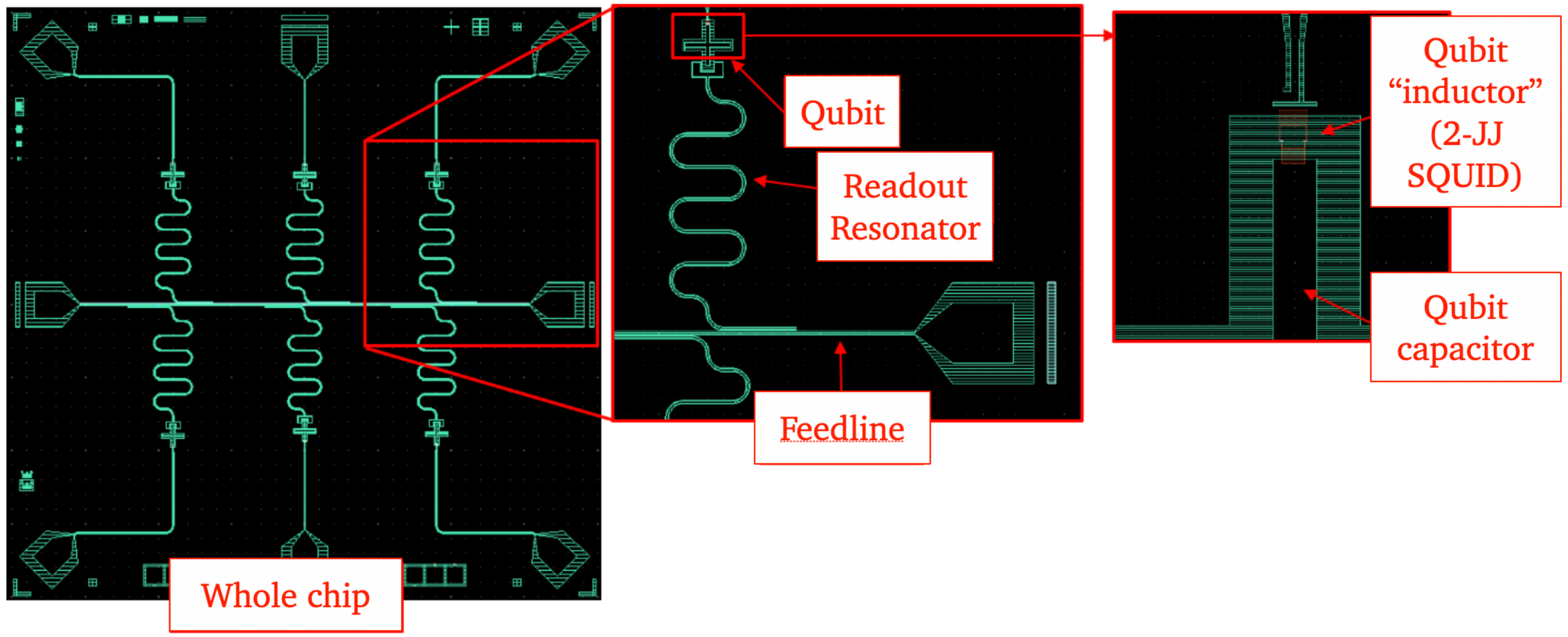
Substitute the inductor with a Josephson Junction

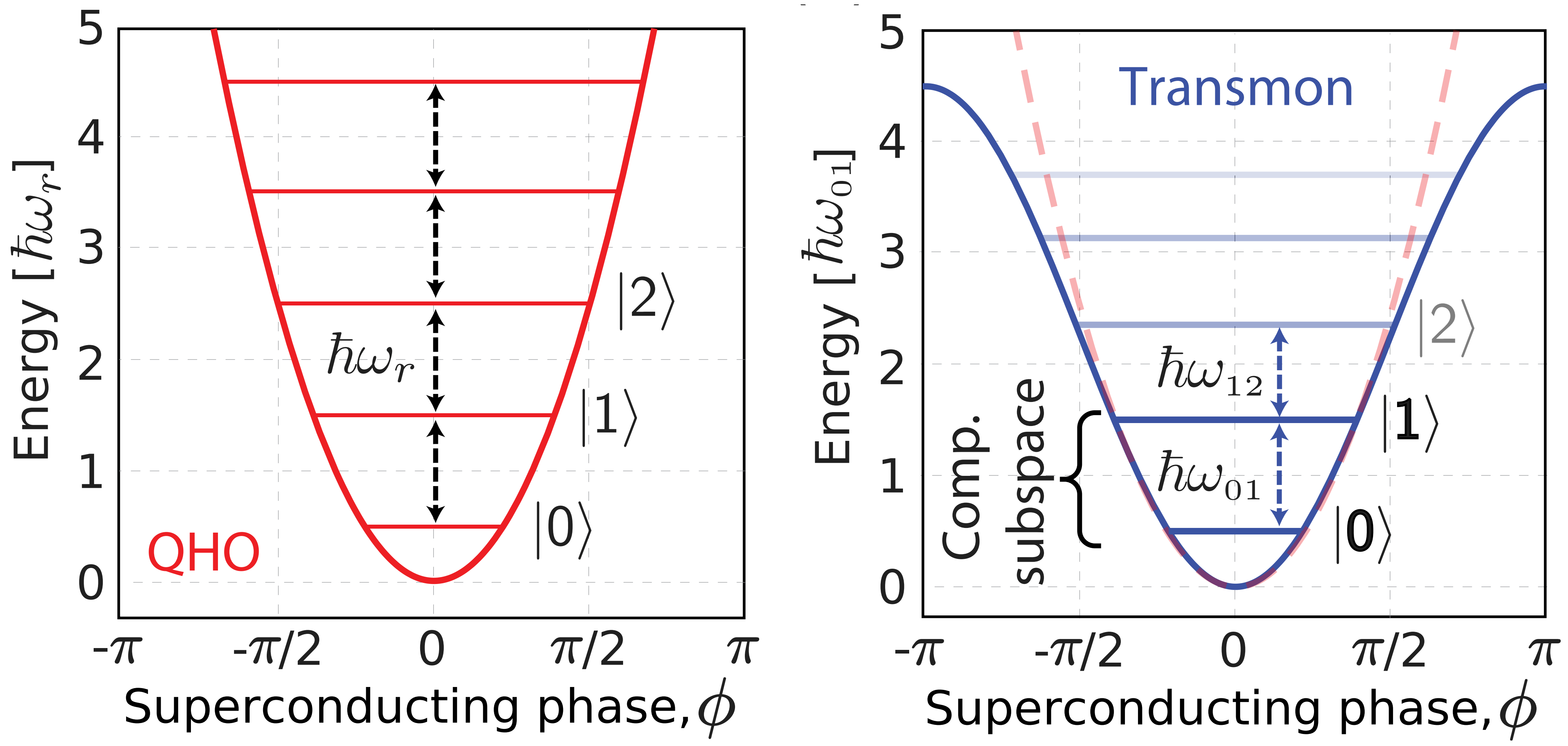
$$H = 4E_C n^2 - E_J \cos(\phi)$$

charge energy — Josephson energy

JJ acts as a non-linear inductor.

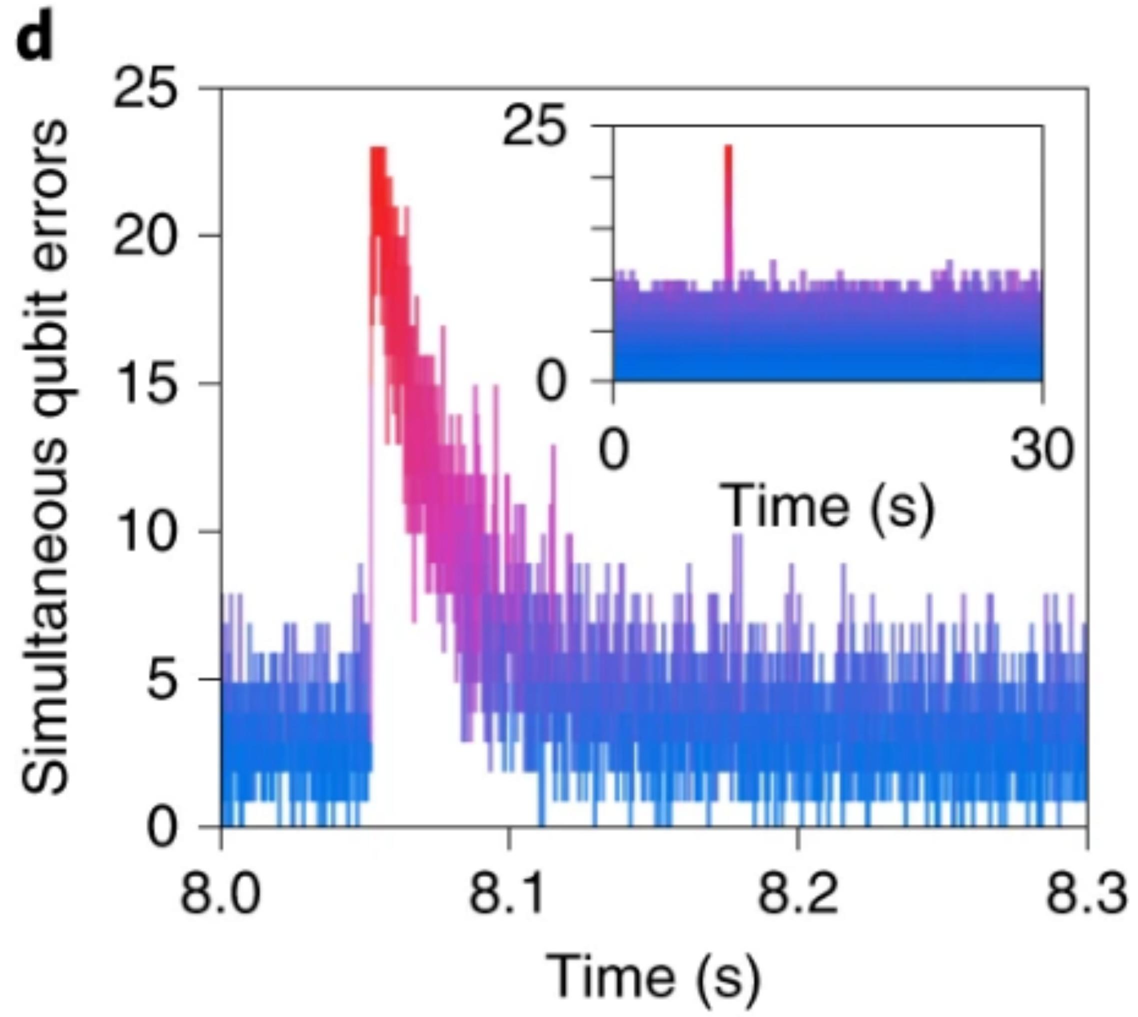






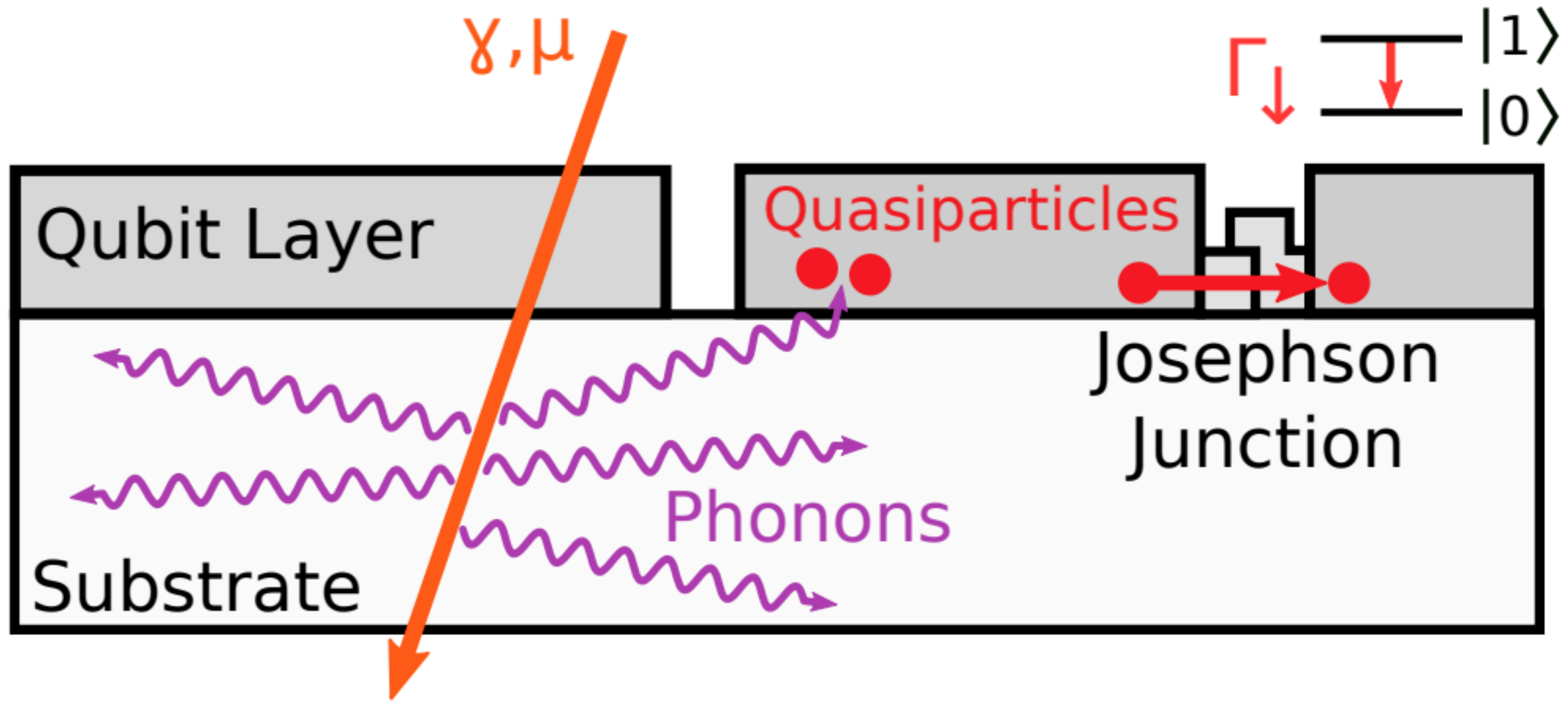
Quasiparticle poisoning

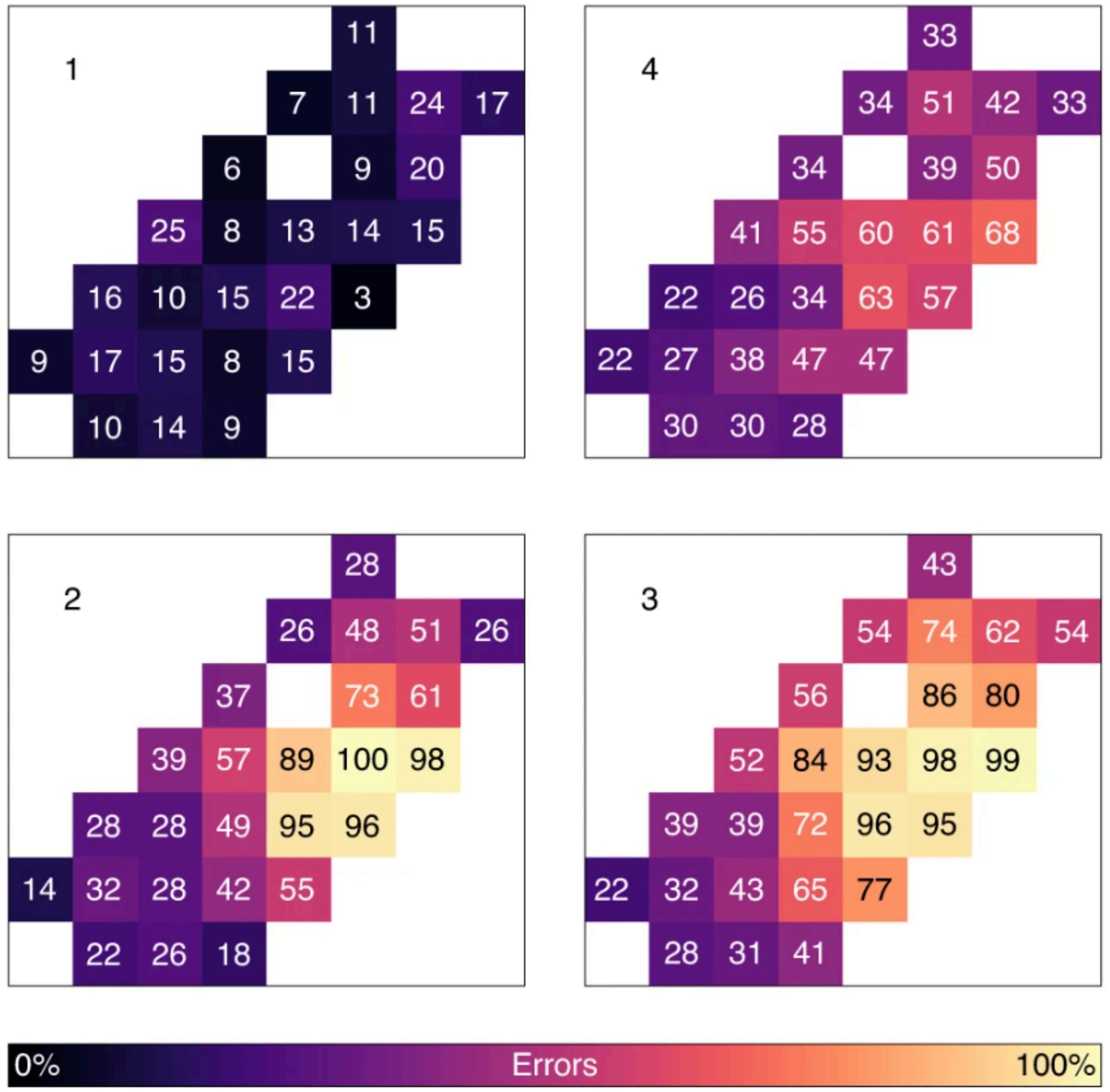
[Google Quantum AI (2022)](#)



- Relaxation → loss of qubit state in a T_1 time scale ($|1\rangle \rightarrow |0\rangle$)
- Athermal phonons produced in the substrate breaks the Cooper pair creating quasiparticles which tunnel through the JJ producing relaxation

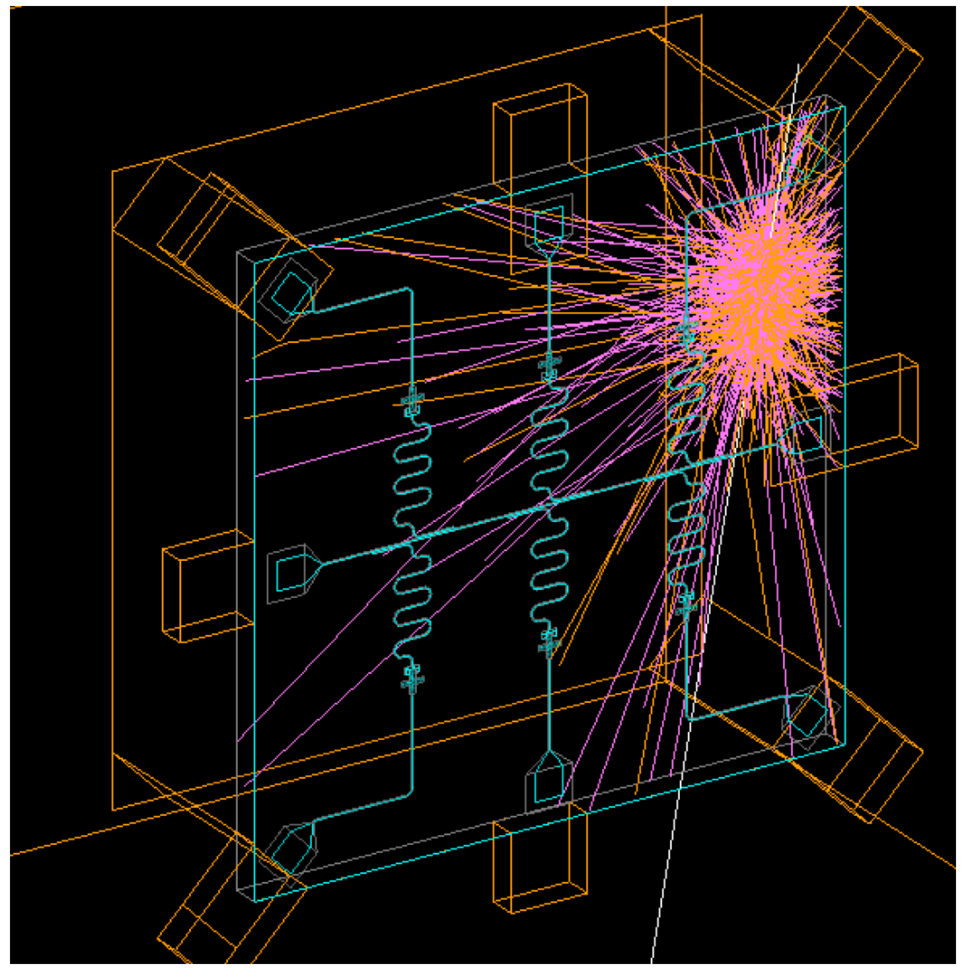
$\Delta = 180\ \mu\text{eV}$ for Aluminum





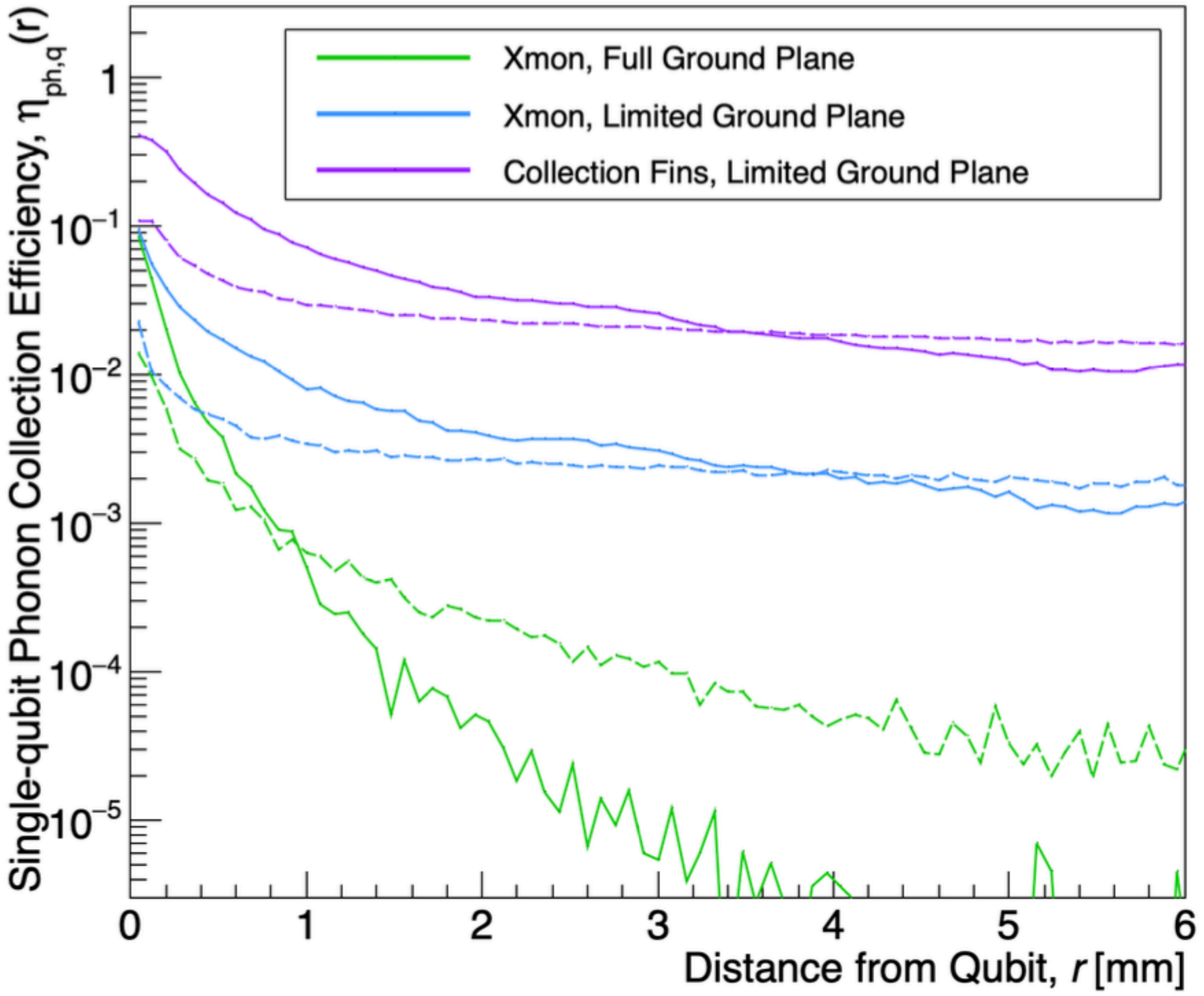
Can we use qubits as low temperature detectors for measuring particles depositing energy in the substrate?

Expected energy threshold



- Use G4CMP to simulate the phonon dynamics in specific geometries
- Actual qubit design not optimized for particle detection → low phonon collection efficiency
- Can estimate the phonon collection efficiency vs. the distance from the phonon production

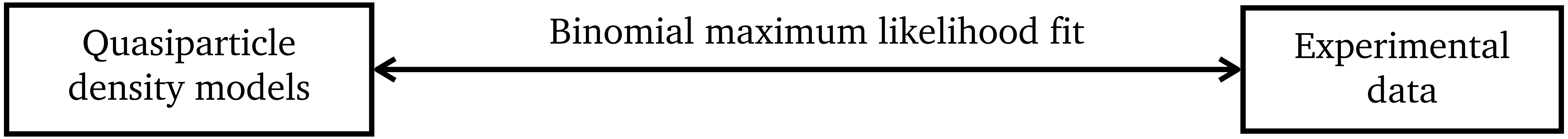
Design	Number of Qubits N_q	Qubit Design	Ground Plane	Si-SC phonon absorption prob. $p_{a,s}$	Si-Cu phonon absorption prob. $p_{a,c}$	Spatially-averaged phonon collection eff. $\eta_{ph,sp}$	Chip Threshold $E_{thr,chip}$
1	6	Xmon	Full	1.0	0.1	0.14%	737 eV
2	6	Xmon	Full	0.1	0.1	0.12%	860 eV
3	6	Xmon	Limited	1.0	0.1	2.07%	49 eV
4	6	Xmon	Limited	0.1	0.1	1.44%	71 eV
5	6	Xmon	Full	1.0	1.0	0.14%	737 eV
6	6	Xmon	Full	0.1	1.0	0.12%	860 eV
7	6	Xmon	Limited	1.0	1.0	1.76%	58 eV
8	6	Xmon	Limited	0.1	1.0	0.76%	135 eV
9	2	Xmon	Full	1.0	0.1	0.05%	1157 eV
10	10	Xmon	Full	1.0	0.1	0.24%	574 eV
11	2	Xmon	Limited	1.0	0.1	1.38%	41 eV
12	10	Xmon	Limited	1.0	0.1	2.39%	57 eV
13	6	Collection Fins	Limited	1.0	0.1	17.0%	O(0.1) eV
14	6	Collection Fins	Limited	0.1	0.1	12.6%	O(0.1) eV

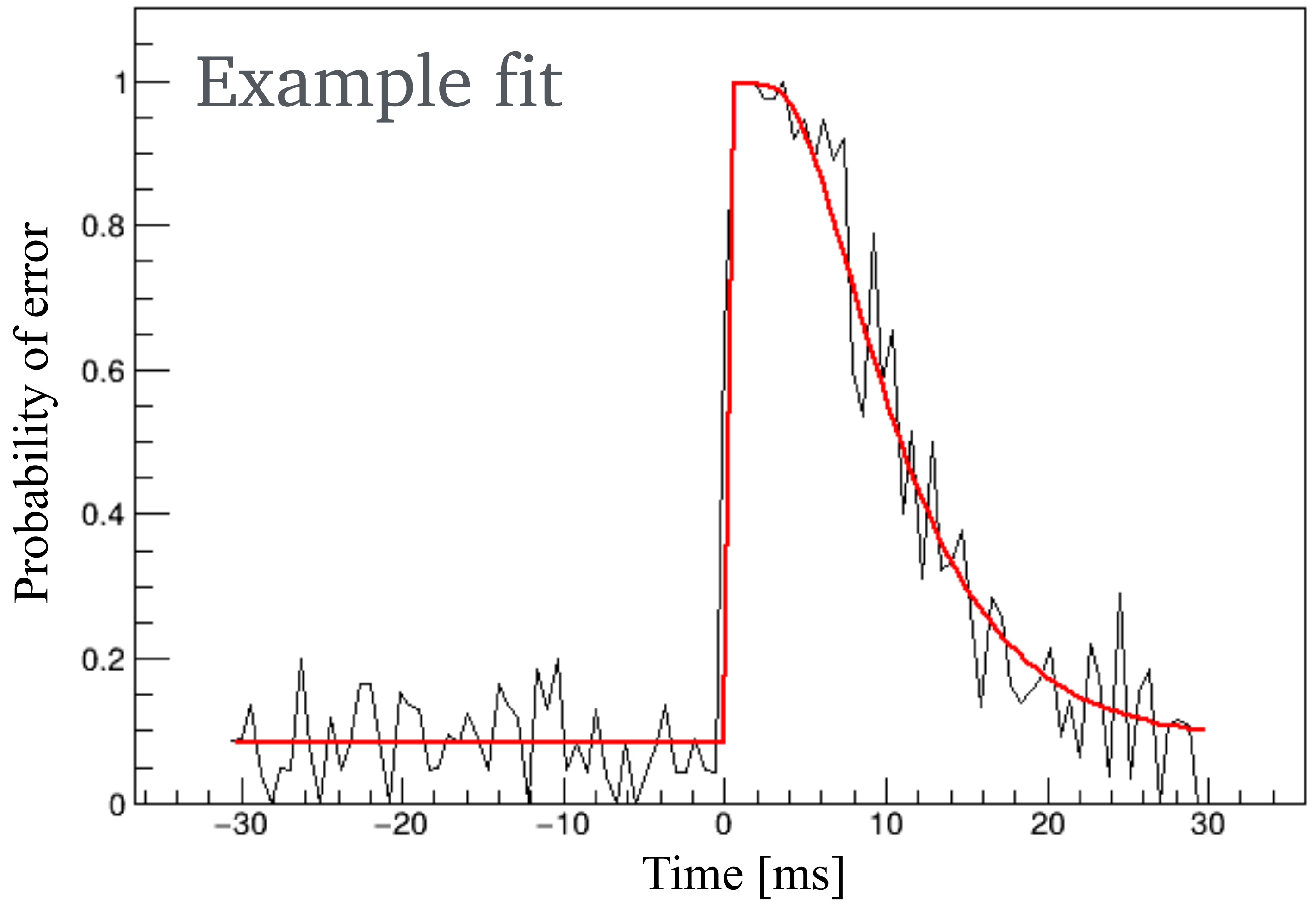


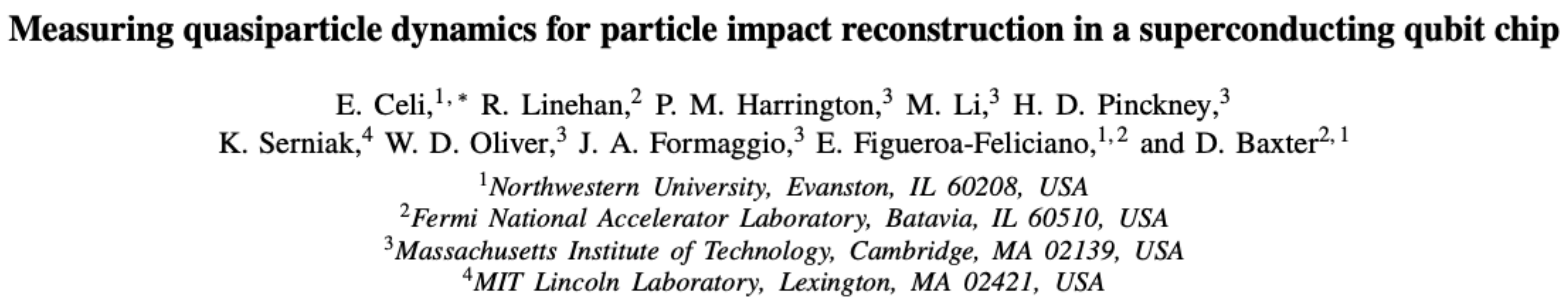
Linehan et al, (2024)

Analysis goals

1. Validate the Quasiparticle density model through a fit on the experimental data
2. Reconstruct energy deposited in individual qubits and in the substrate







Measuring quasiparticle dynamics for particle impact reconstruction in a superconducting qubit chip

E. Celi,[1,*] R. Linehan,[2] P. M. Harrington,[3] M. Li,[3] H. D. Pinckney,[3]
K. Serniak,[4] W. D. Oliver,[3] J. A. Formaggio,[3] E. Figueroa-Feliciano,[1,2] and D. Baxter[2,1]

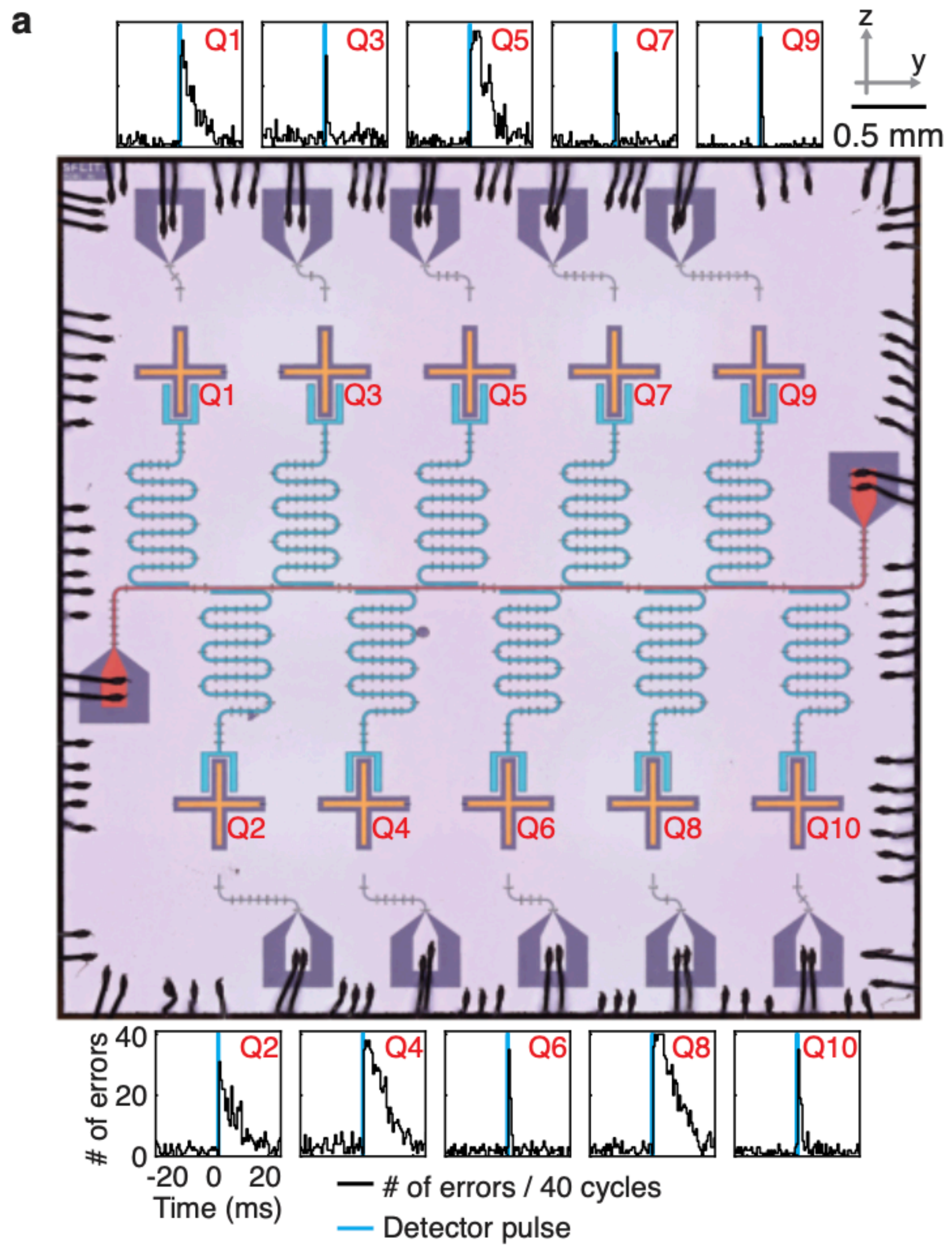
[1]*Northwestern University, Evanston, IL 60208, USA*
[2]*Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[3]*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[4]*MIT Lincoln Laboratory, Lexington, MA 02421, USA*

Massachusetts Institute of Technology
Fermilab
Northwestern University

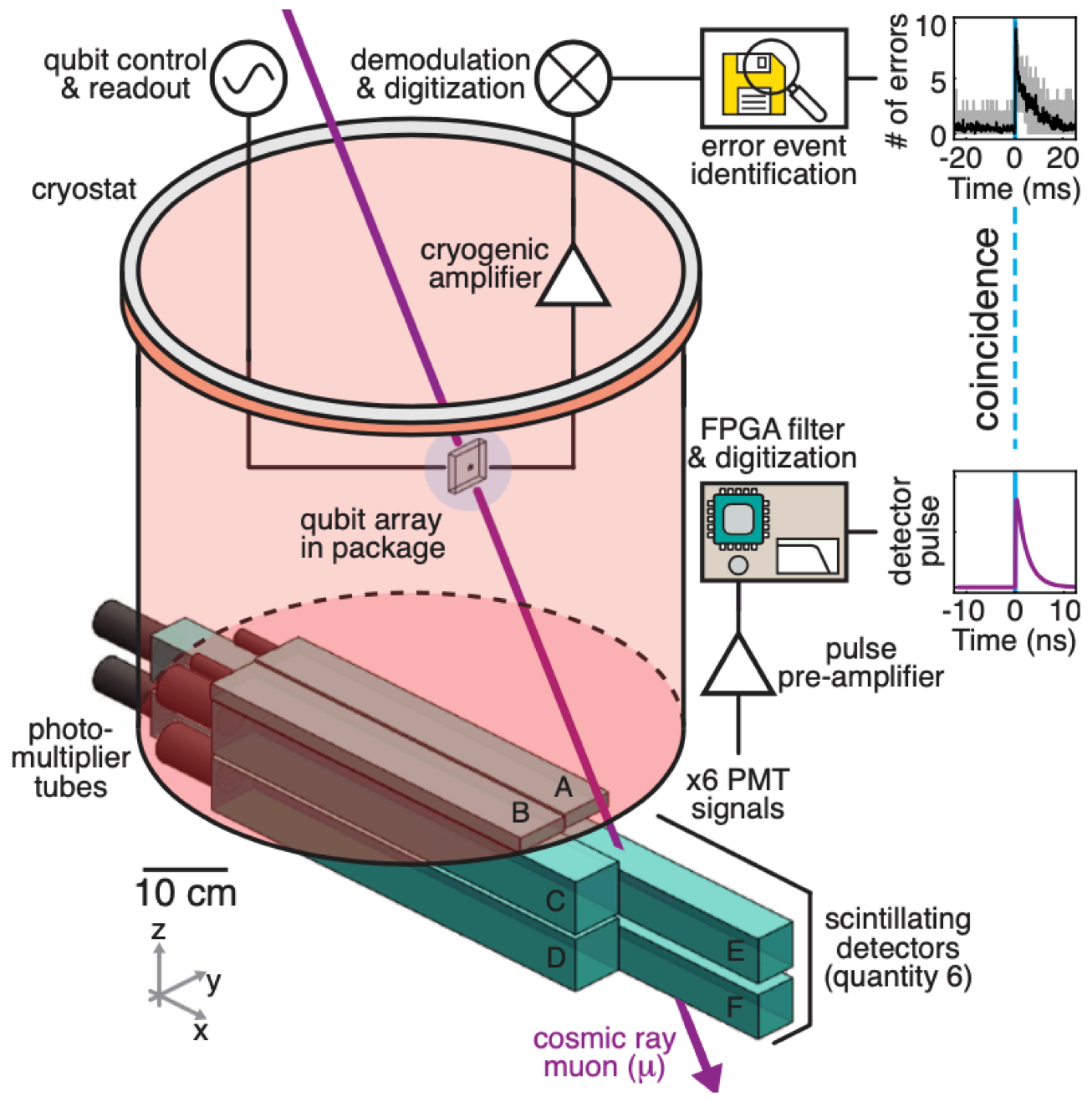
Celi et al. (2026)

Experimental data

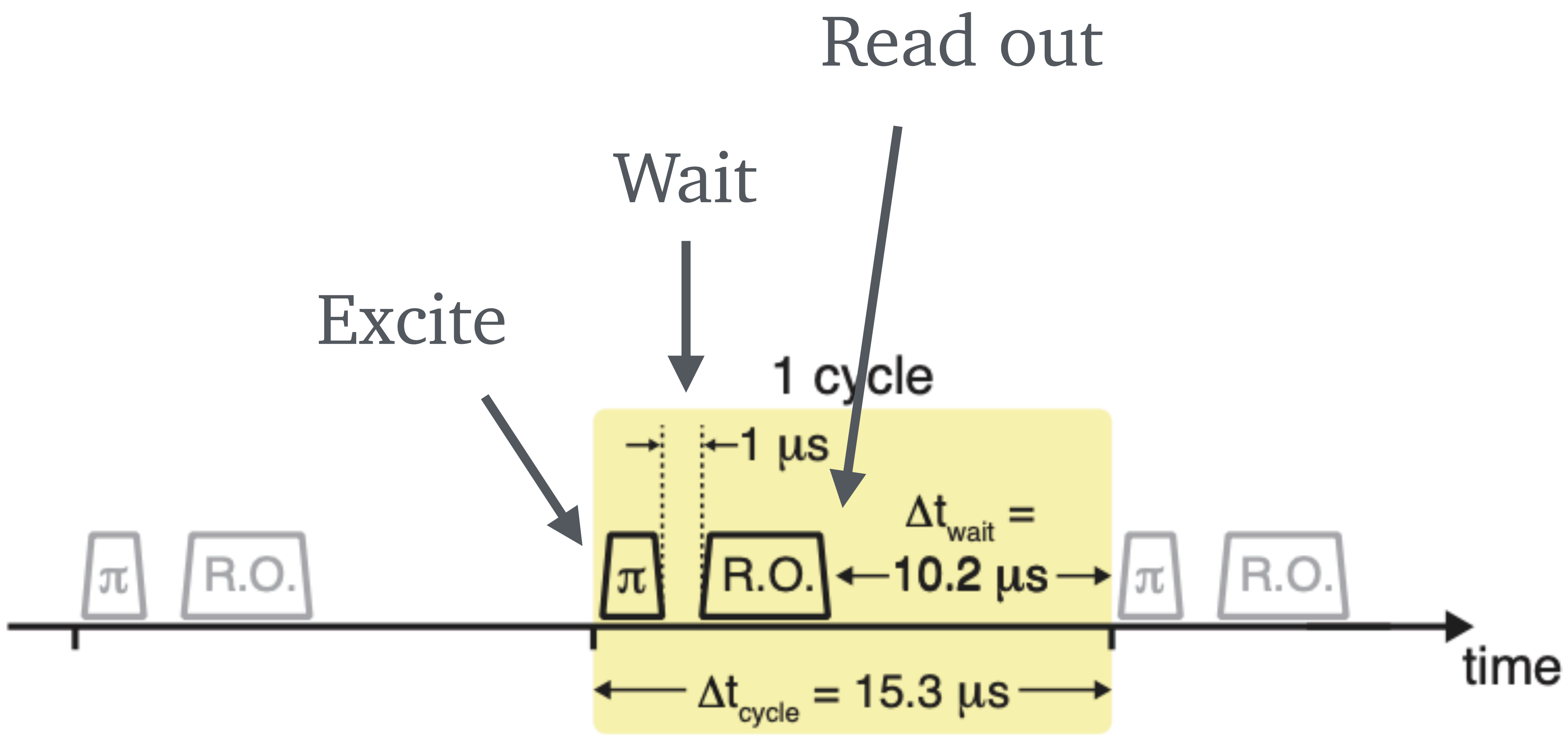
- Array of 10 fixed-frequency transmon qubits (Aluminum on Silicon)
- Coincidences between muon scintillating detectors and correlated errors
- ~266 hr background data (~10 mHz event rate)
- ~16 hr ^{137}Cs source data (~100 mHz event rate)
- Only 5 qubits available for the analysis → slow recovery

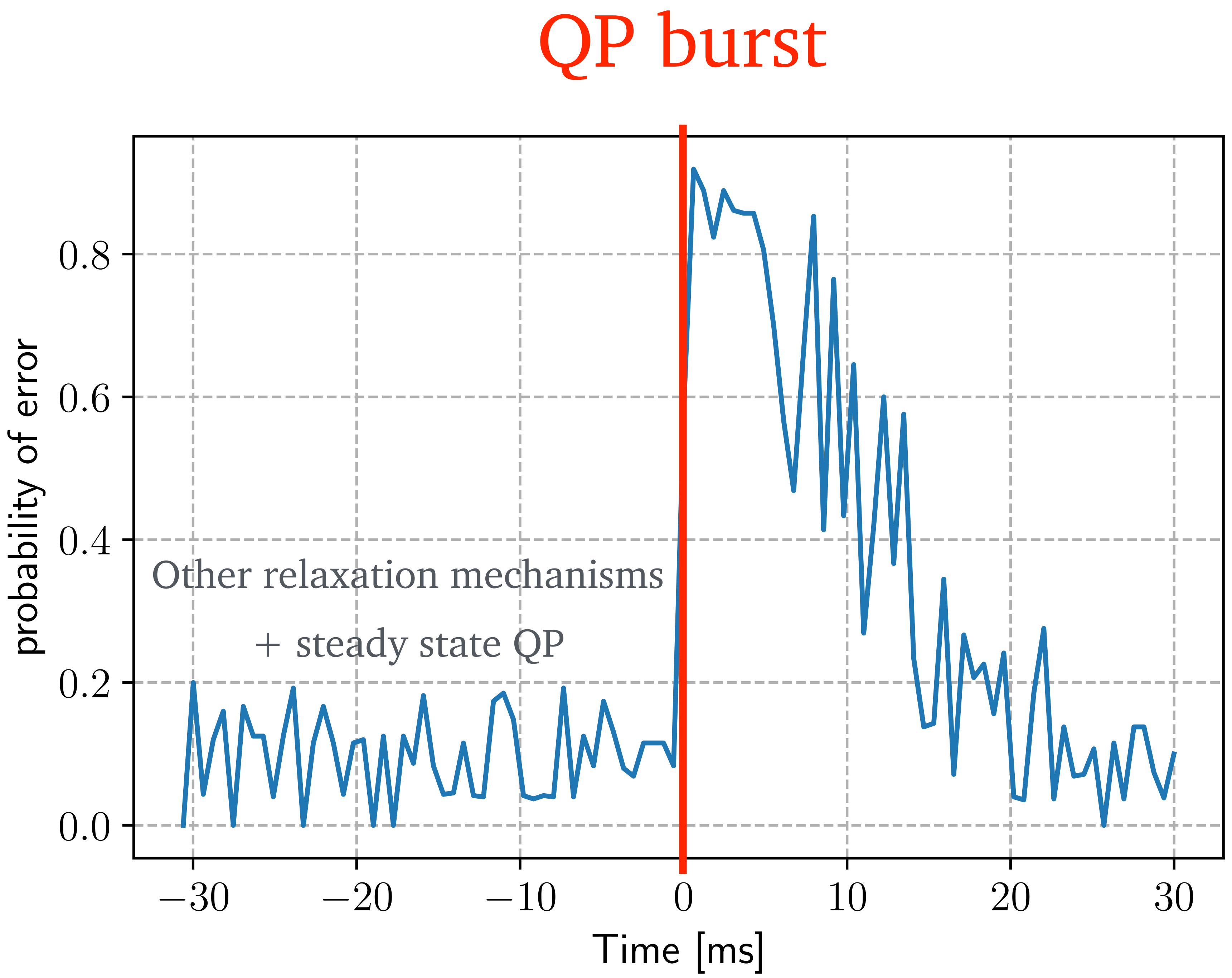


Harrington et al, (2024)



Pulse sequence





Prob of error = #of errors/#of measurements

Bin → set of 40 measurements

Quasiparticle density model

QP dynamics is dominated by **QP self-recombination**, **linear loss** and **QP generation** mechanisms. The probability of relaxation in a time Δt is:

$$p_r = 1 - e^{-\Gamma(t)\Delta t}$$

$$= 1 - \exp\left[\frac{-\alpha E_{\text{dep}}}{E_{\text{dep}}\left[\tau_{ss} r\left(e^{t/\tau_{ss}} - 1\right)\right] + \beta e^{t/\tau_{ss}}} - \gamma\right]$$

Where:

$\alpha = \Delta t \sqrt{\frac{2\omega_q \Delta}{\pi^2 \hbar}}$

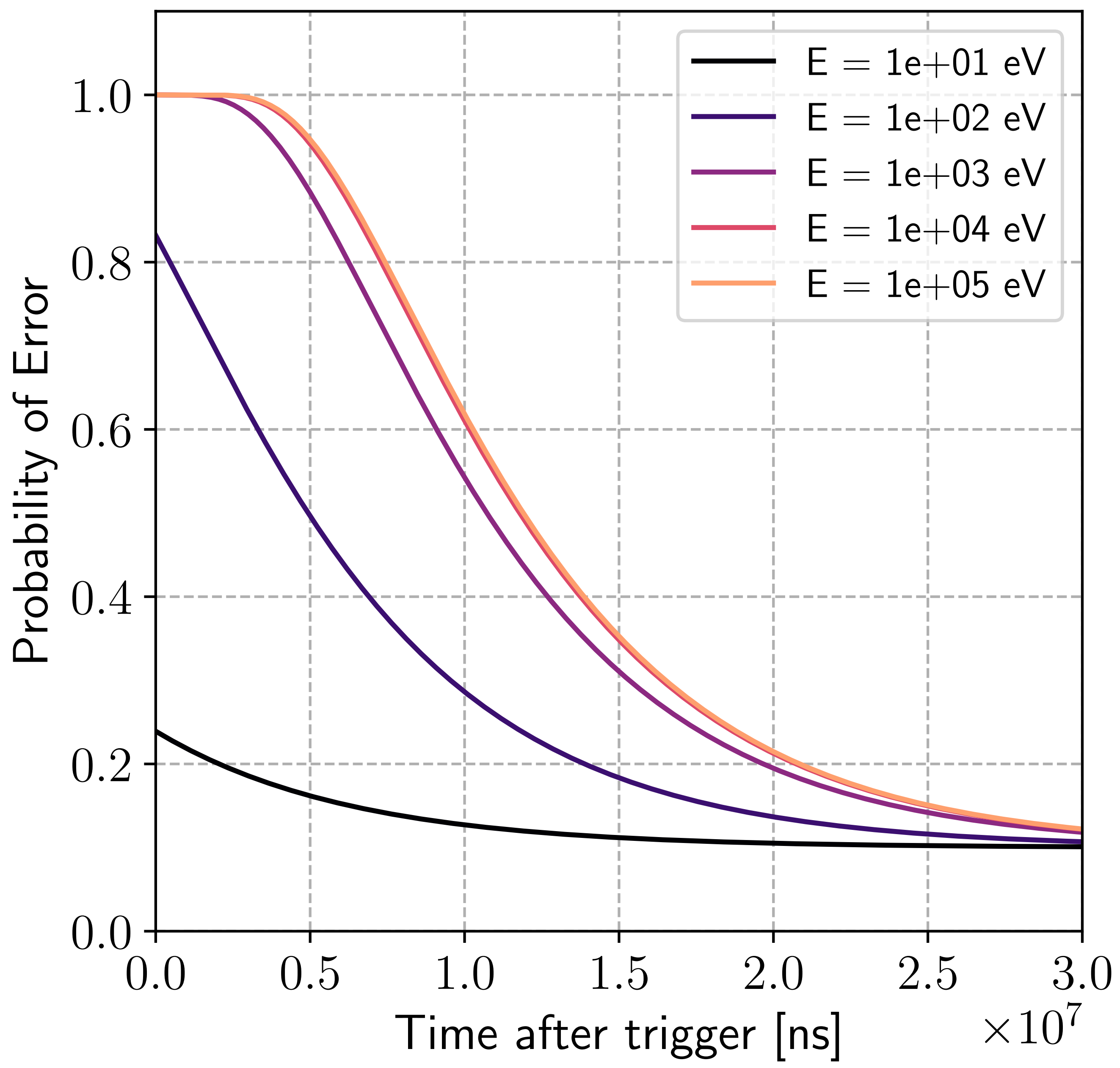
$\beta = \frac{n_{CP} V \Delta}{\epsilon}$

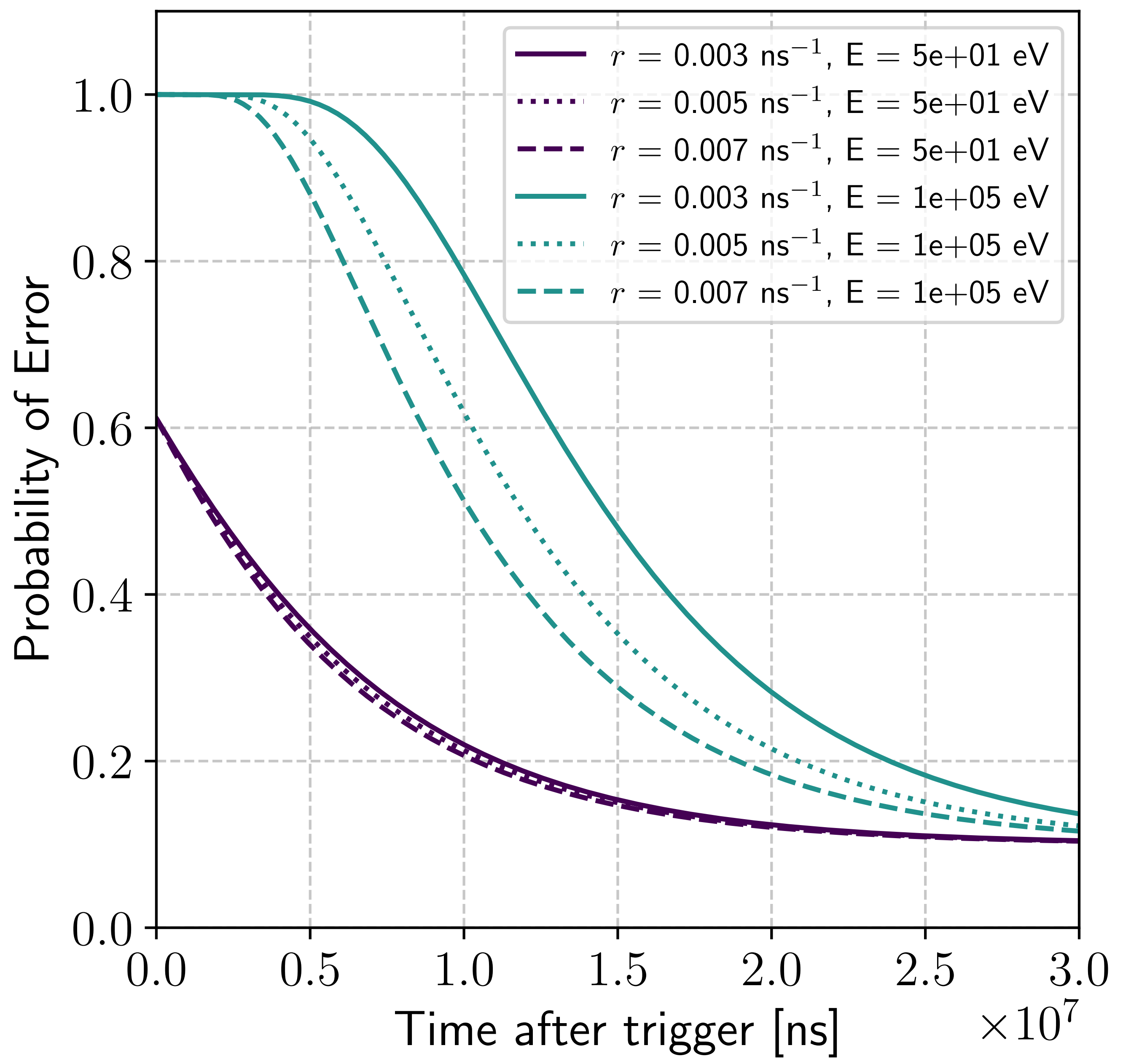
$\gamma =$ baseline

$r =$ recombination constant rate

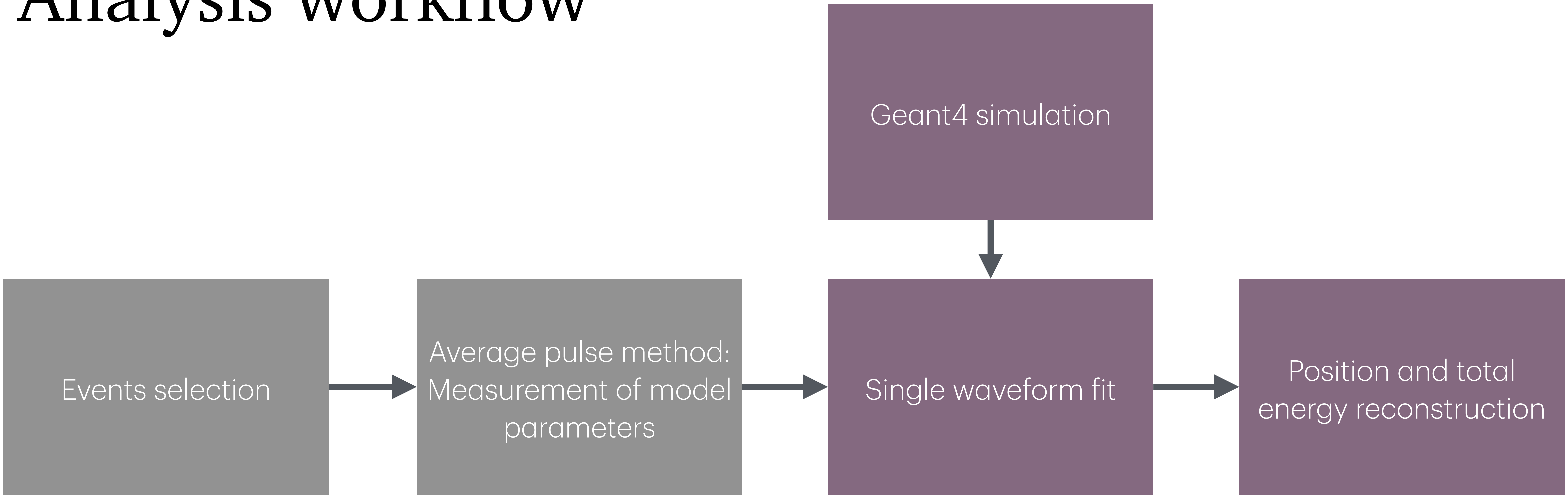
$\tau_{ss} =$ linear loss decay time

$E_{dep} =$ Energy deposited in the qubit





Analysis workflow



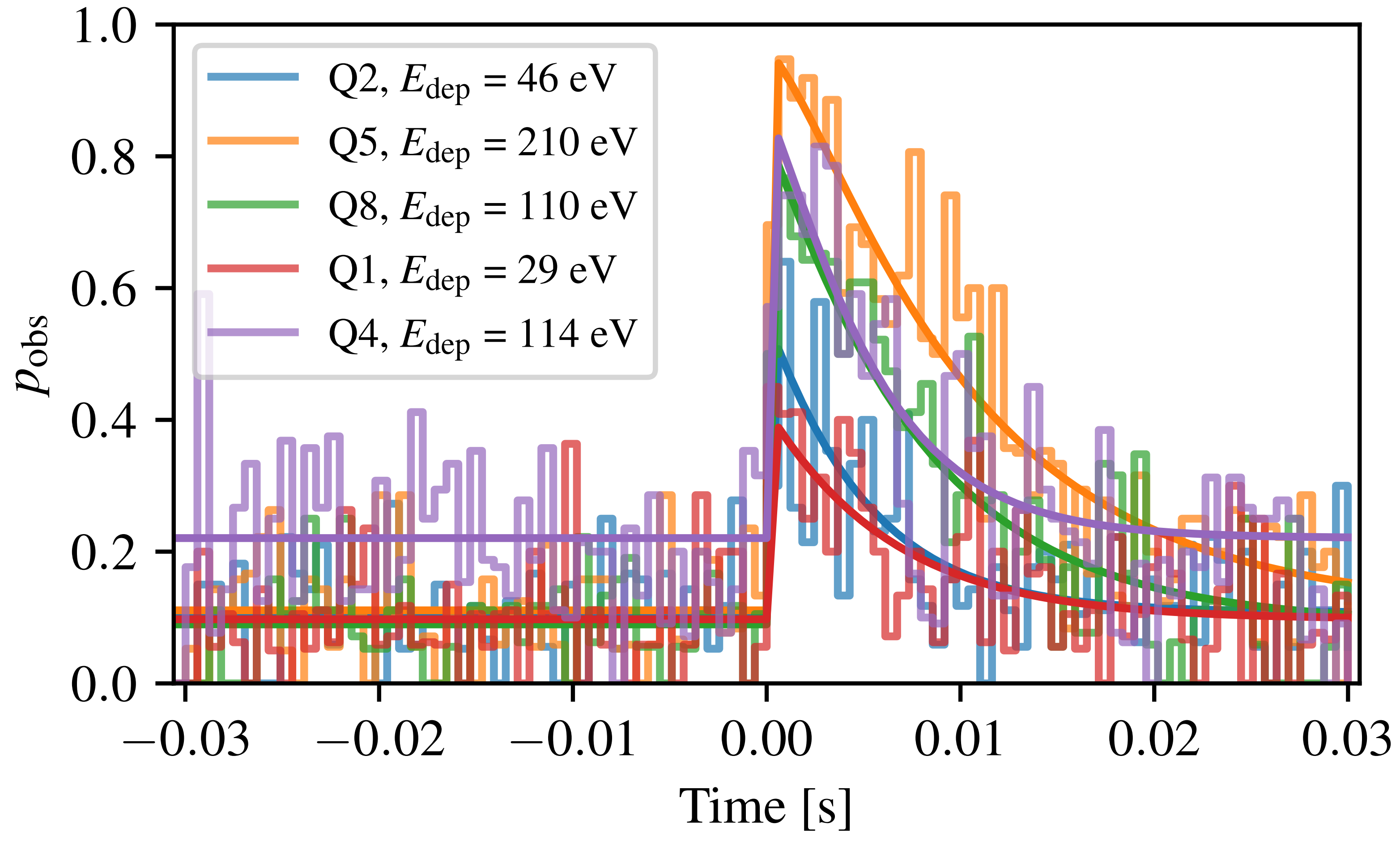
Waveform fit

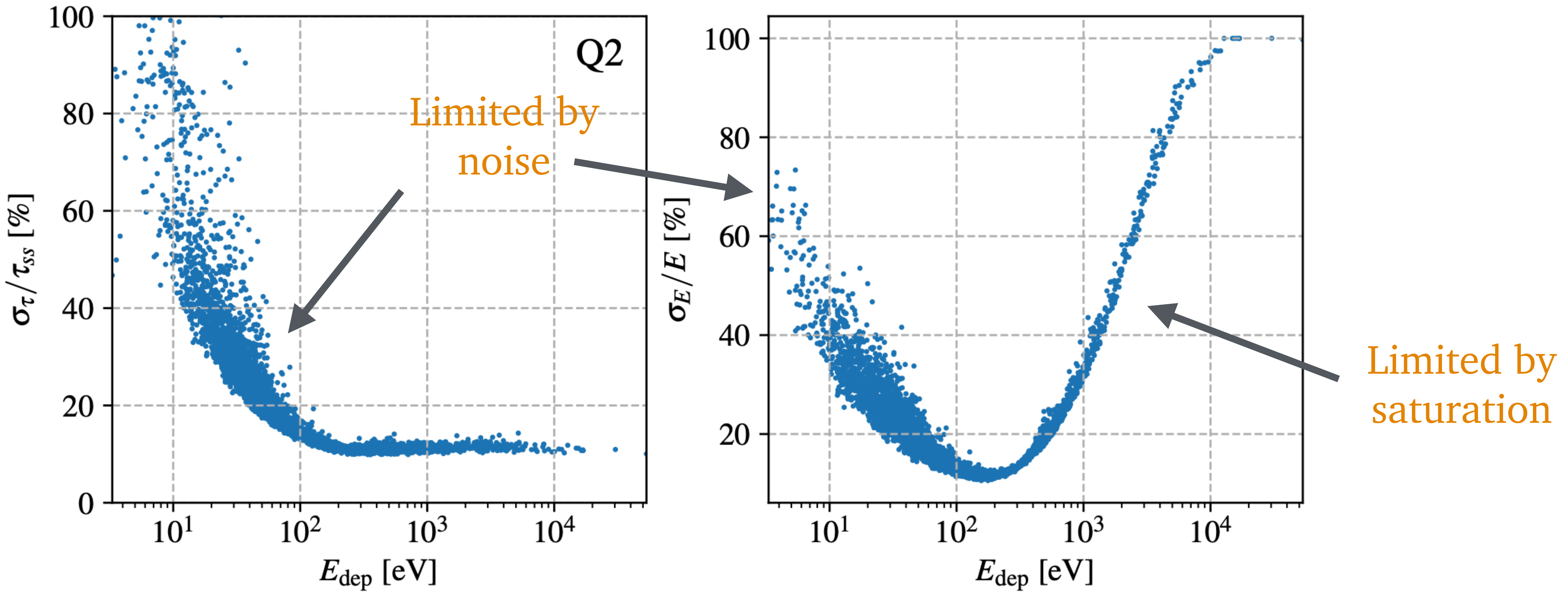
Fit every waveform with QP density model for each qubit:

→ $\boldsymbol{r}$ estimated independently with the average pulse method

→ fit uncertainty depends strongly on E_{dep}

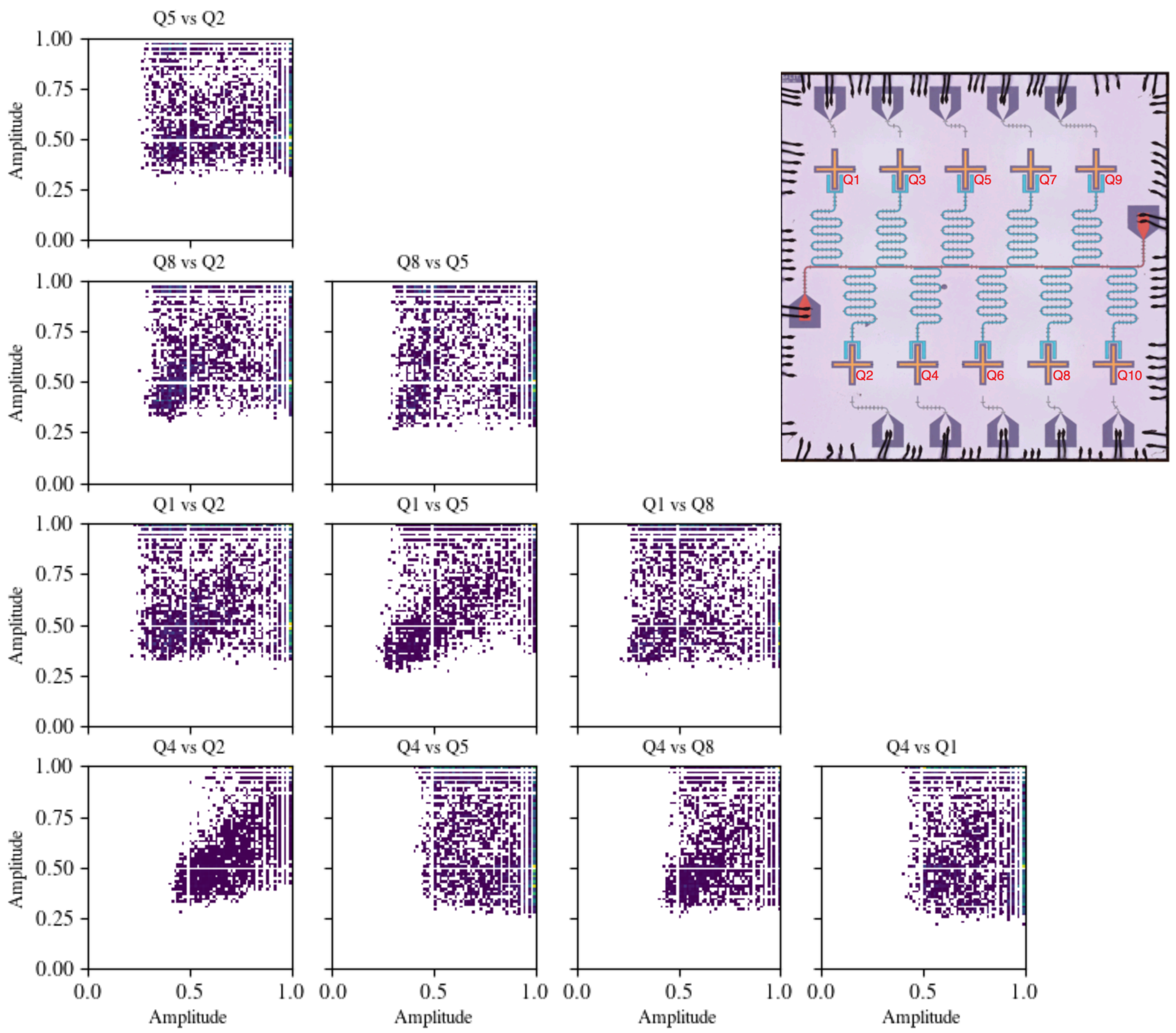
$$p_r = 1 - e^{-\Gamma(t)\Delta t}$$
$$= 1 - \exp\left[\frac{-\alpha E_{\mathrm{dep}}}{E_{\mathrm{dep}}[\tau_{ss} r(e^{t/\tau_{ss}} - 1)] + \beta e^{t/\tau_{ss}}} - \gamma\right].$$

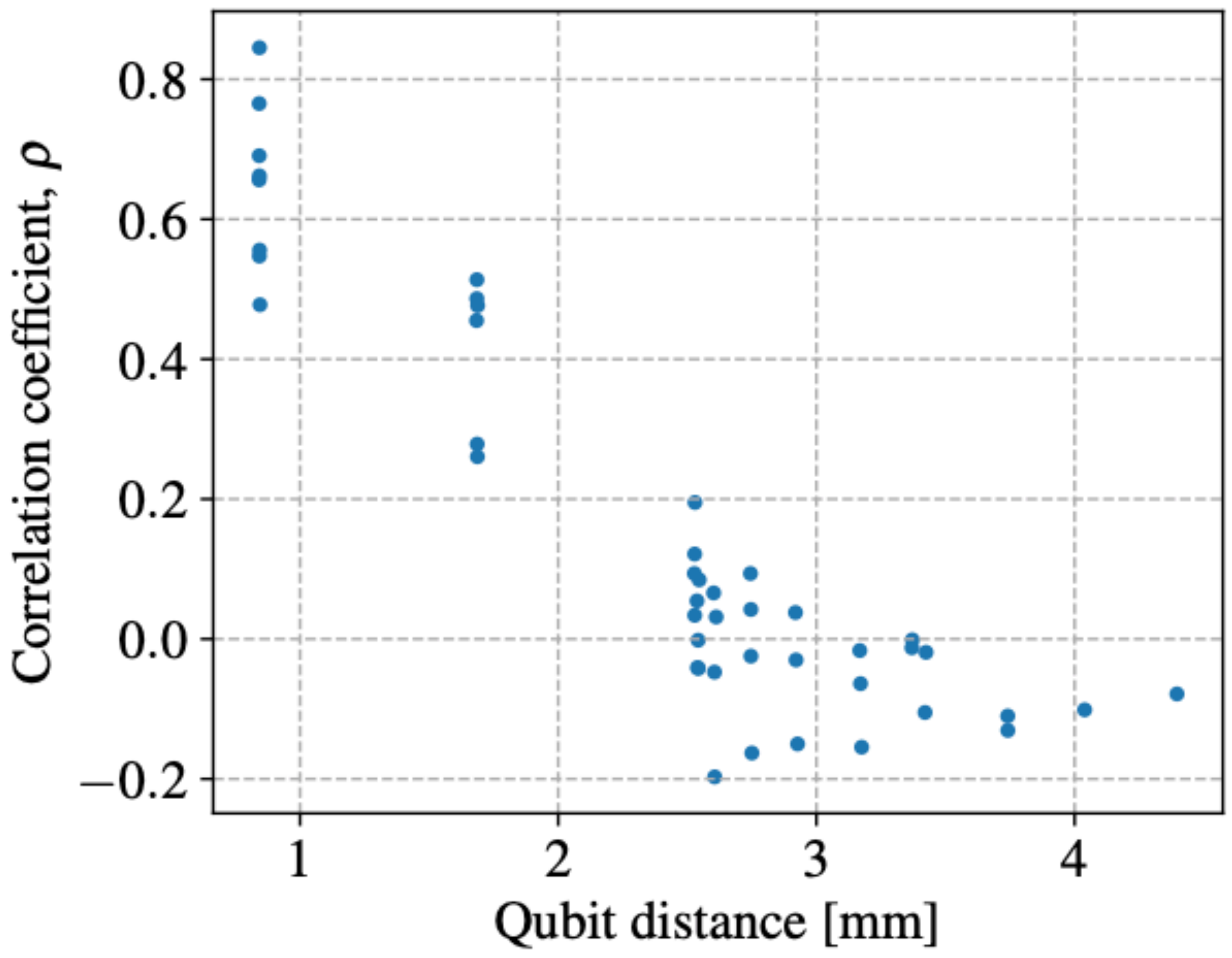




Amplitude correlation

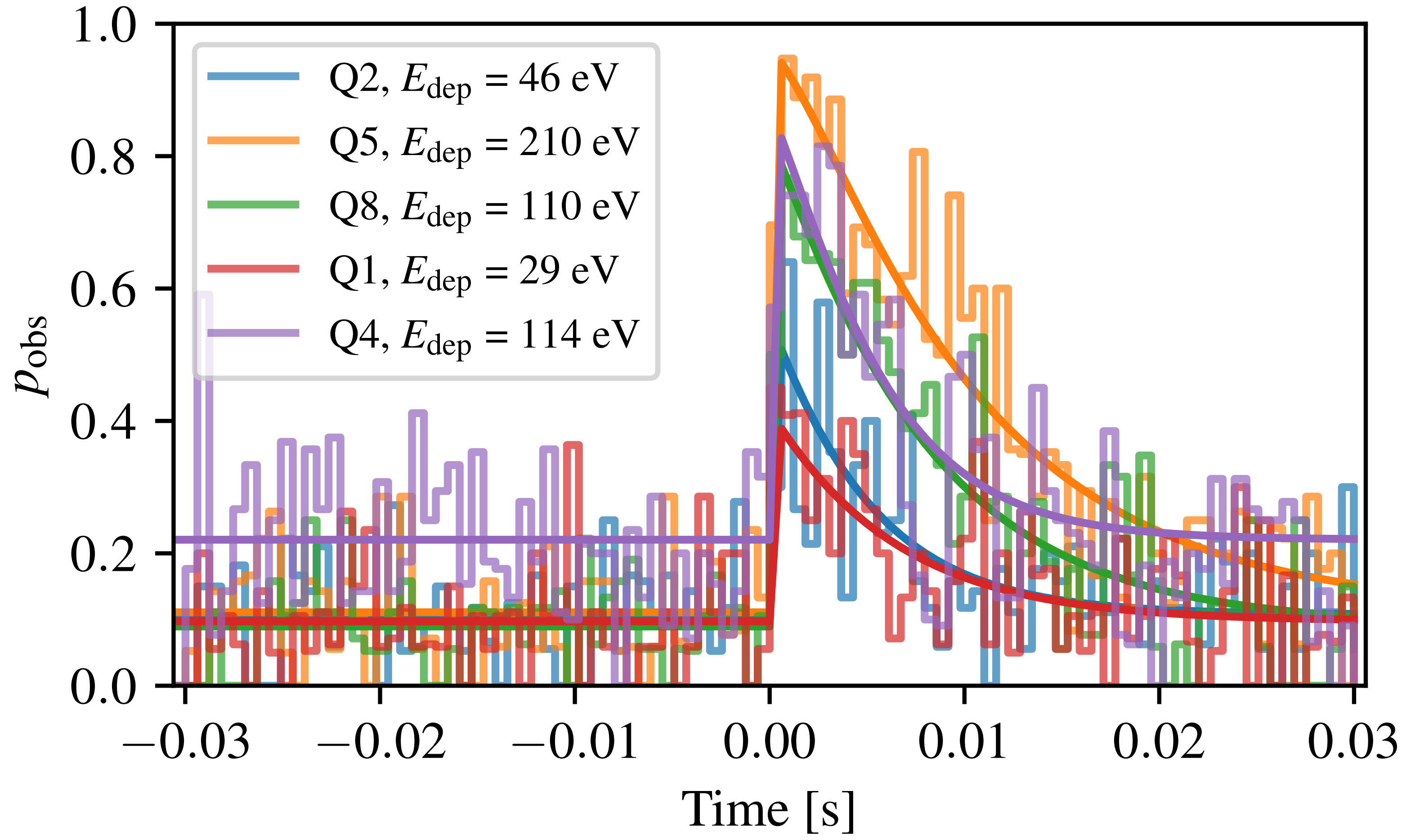
CP breaking process is activated by athermal phonons which keep the information about event position
→ energy deposited is correlated among qubits

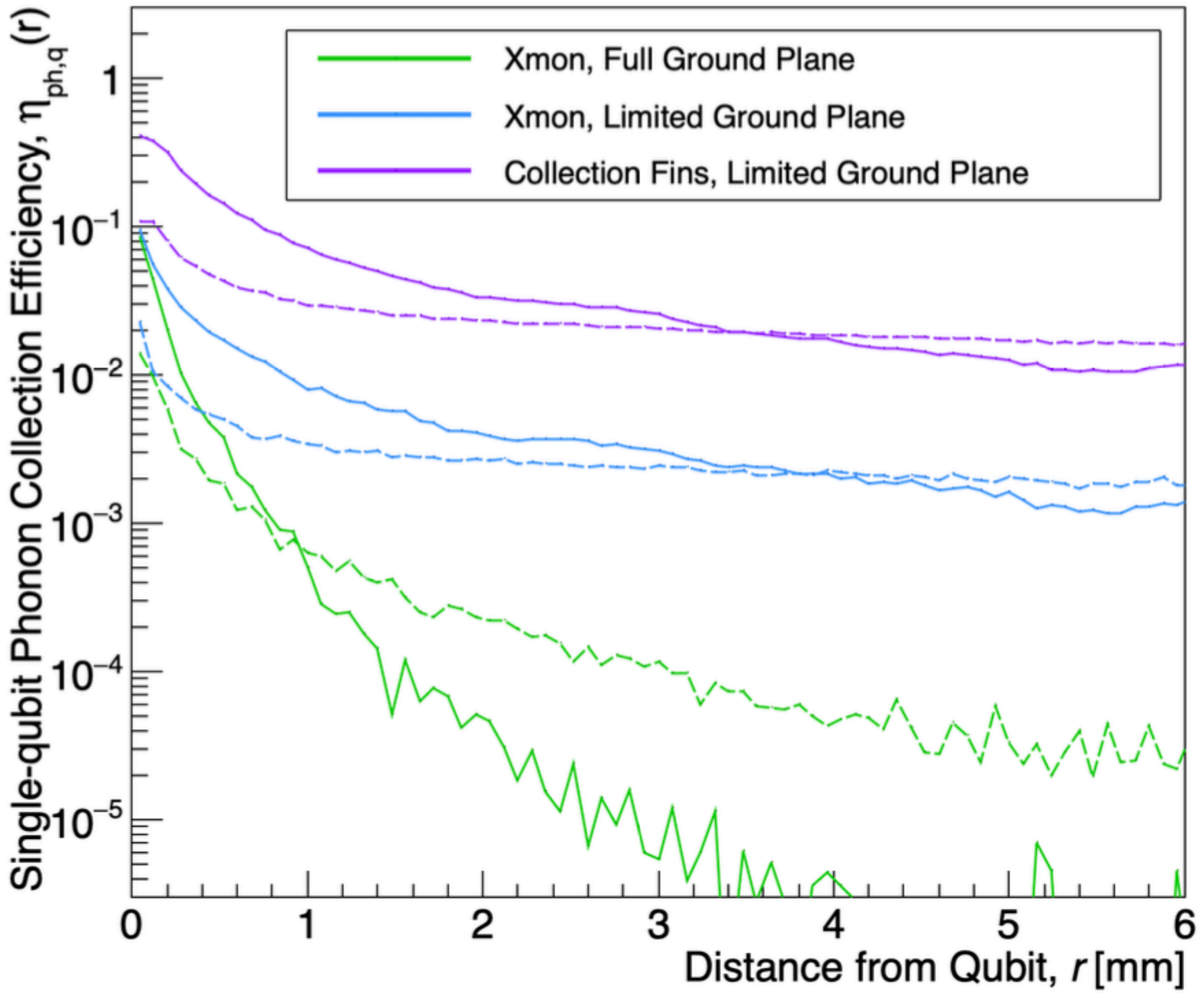




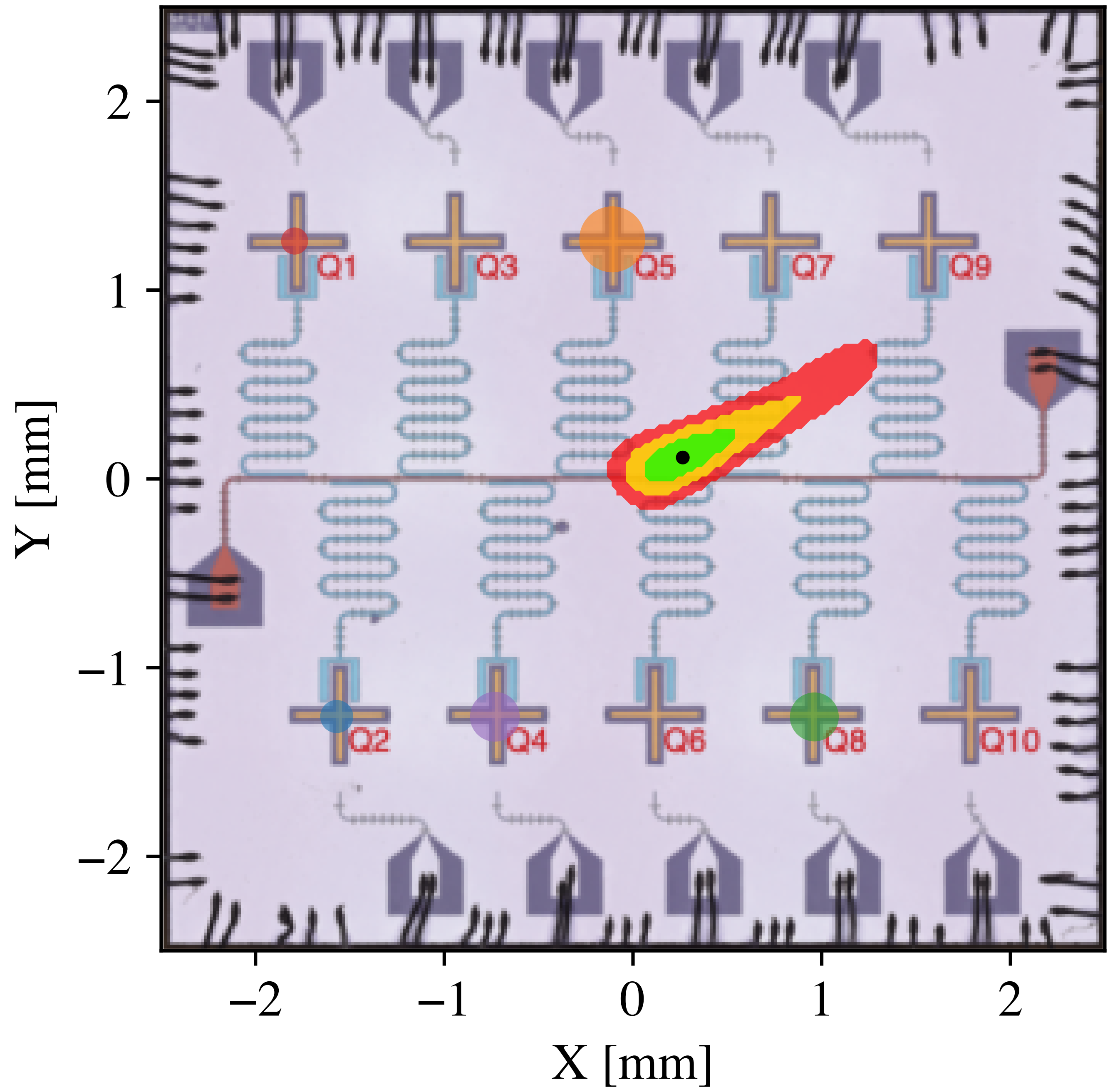
Position reconstruction

Single-qubit energy deposited + Phonon collection efficiency = **Total energy** and position reconstruction





Linehan et al, (2024)



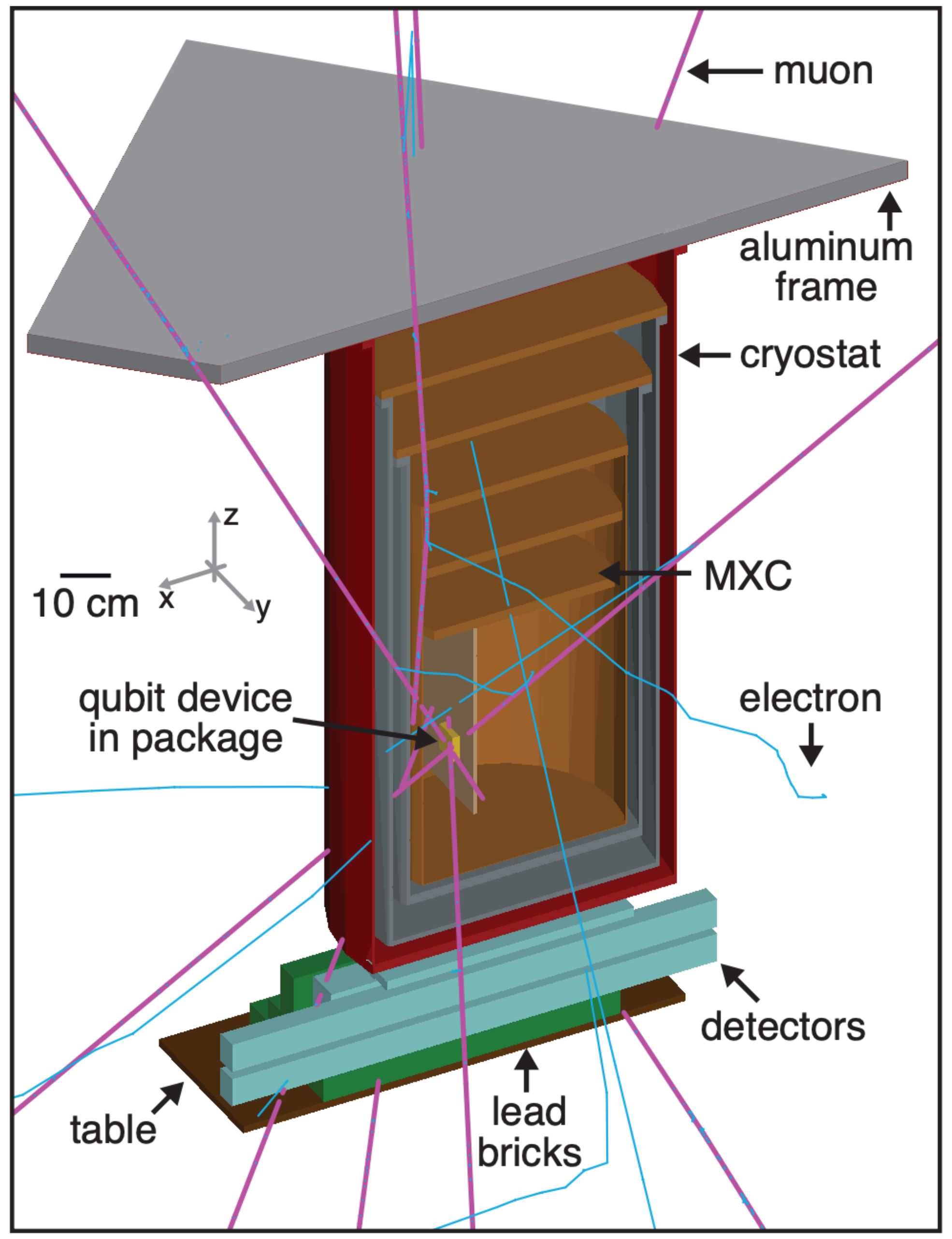
Geant4 validation

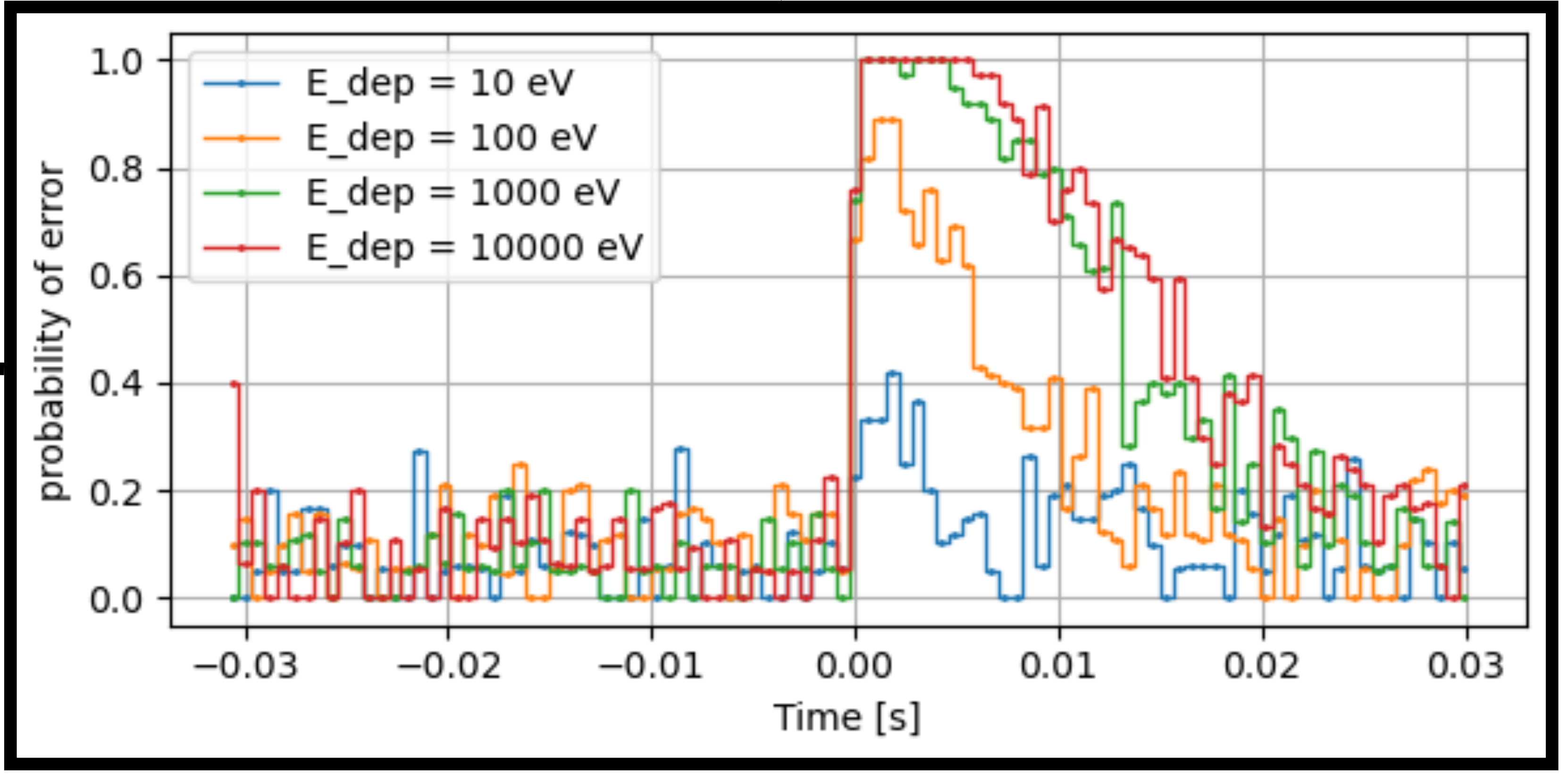
Simulate the ^{137}Cs source in cryostat geometry → Extract total energy released in the chip → Replicate the energy deposited from solid state simulations

E_{tot}^{G4in}

E_{dep}^{G4in}

Mock data





Process simulated pulses using same experimental cuts

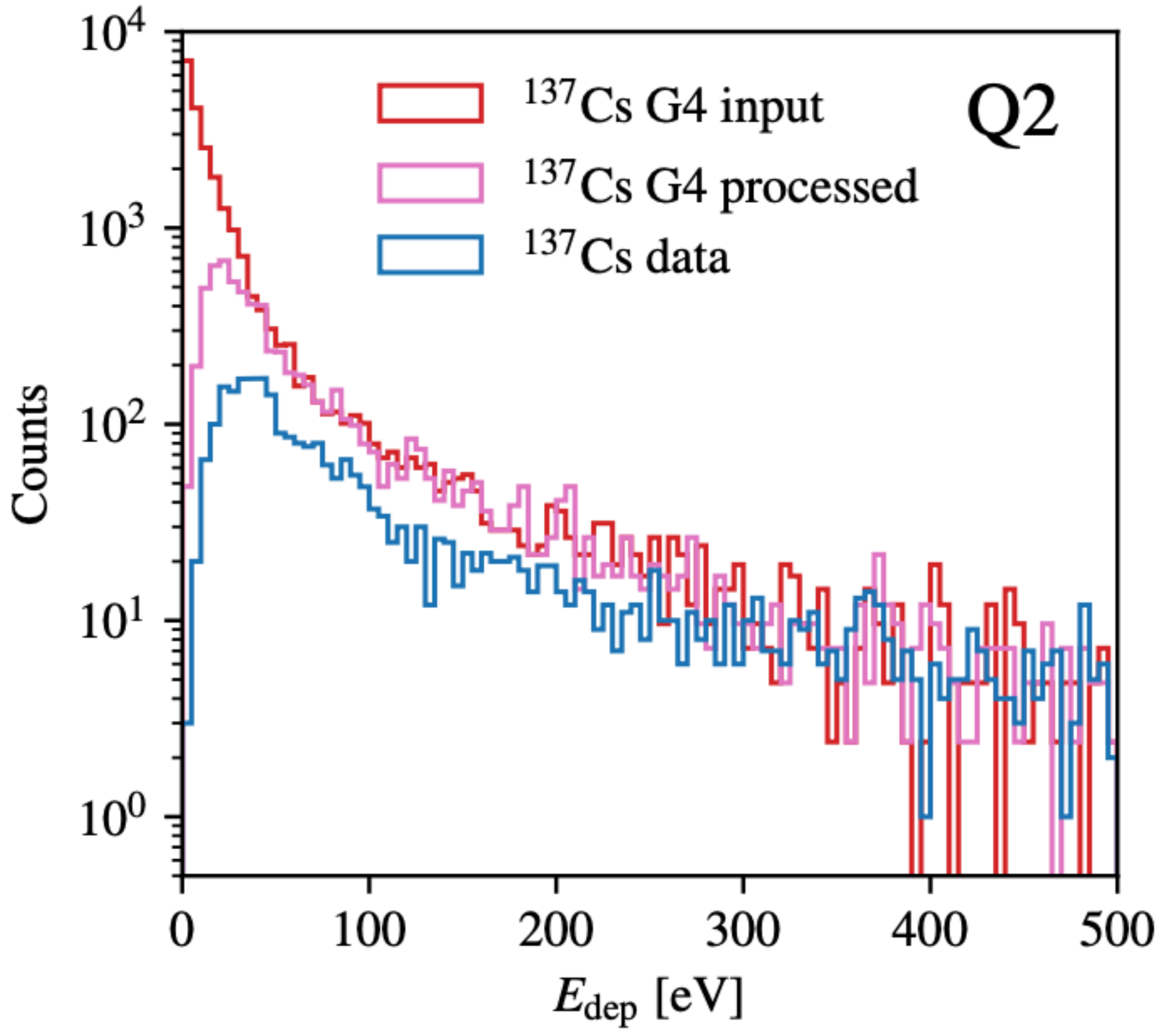
E_{tot}^{G4rec}, E_{dep}^{G4rec}

Compare results!

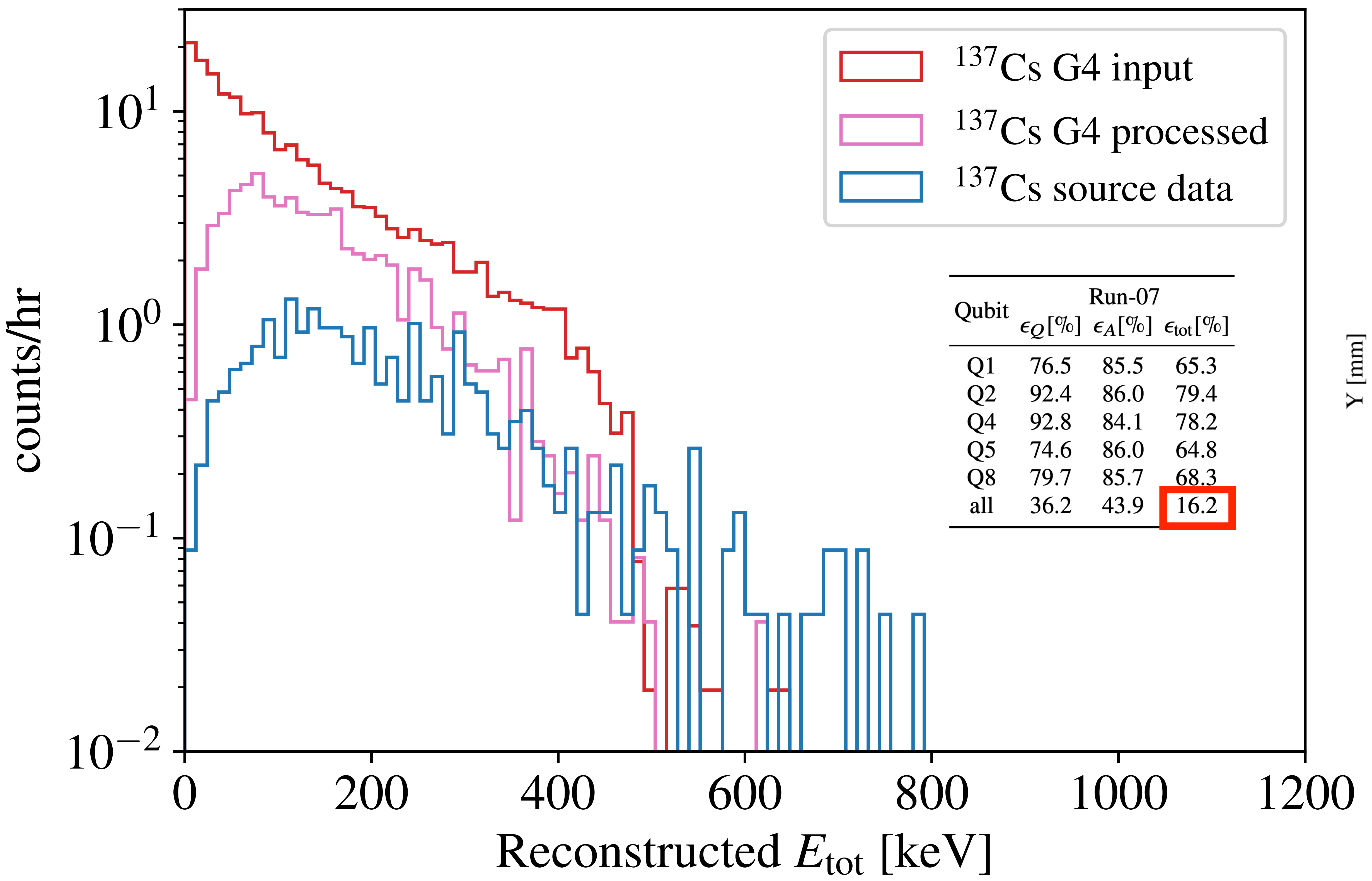
Energy spectrum → ^{137}Cs data + simulation

Applying same analysis cuts are for processed Geant4 waveforms and real data, the agreement among the two spectra is pretty good. Slope difference to be attributed to simulation uncertainties on the probability of phonon absorption and the substrate interfaces

Single qubit energy deposition

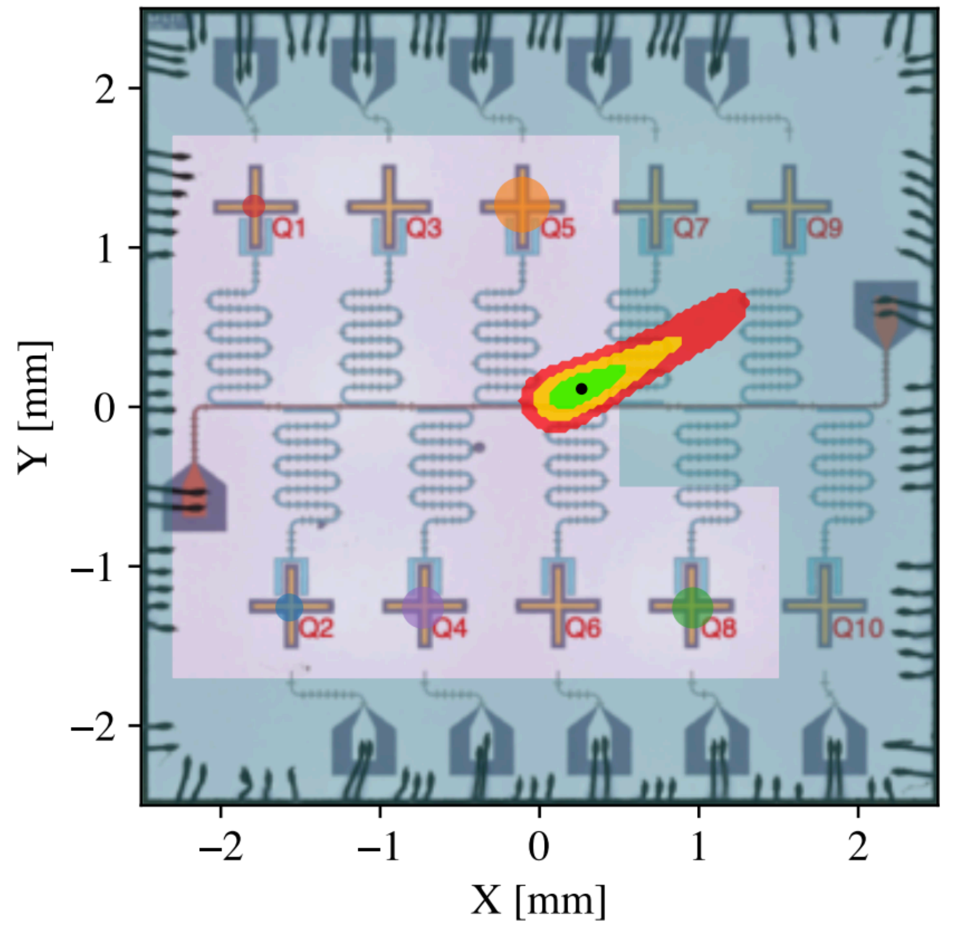


Total substrate energy



Qubit	Run-07 ϵ_Q[%]	ϵ_A[%]	ϵ_{tot}[%]
Q1	76.5	85.5	65.3
Q2	92.4	86.0	79.4
Q4	92.8	84.1	78.2
Q5	74.6	86.0	64.8
Q8	79.7	85.7	68.3
all	36.2	43.9	16.2

Additional fiducial cut to avoid phonon reflections



Conclusion and acknowledgments

- This work demonstrates that the pulse shape of correlated decoherence events is extremely useful in understanding qubits' response as sensors
- Superconducting qubit arrays can be used as potential tools to sense position and total energy for particle detection

See D. Baxter talk for more on superconducting qubits!

Acknowledgments:

- **NU/FNAL**: Emanuela Celi, Dan Baxter, Tali Figueroa-Feliciano, Ryan Linehan
- **MIT/LL**: Will Oliver, Kyle Serniak, Joe Formaggio, Patrick Harrington, Doug Pinckney, Mingyu Li
- My involvement in this work has been done through Northwestern's participation in the Quantum Science Center.

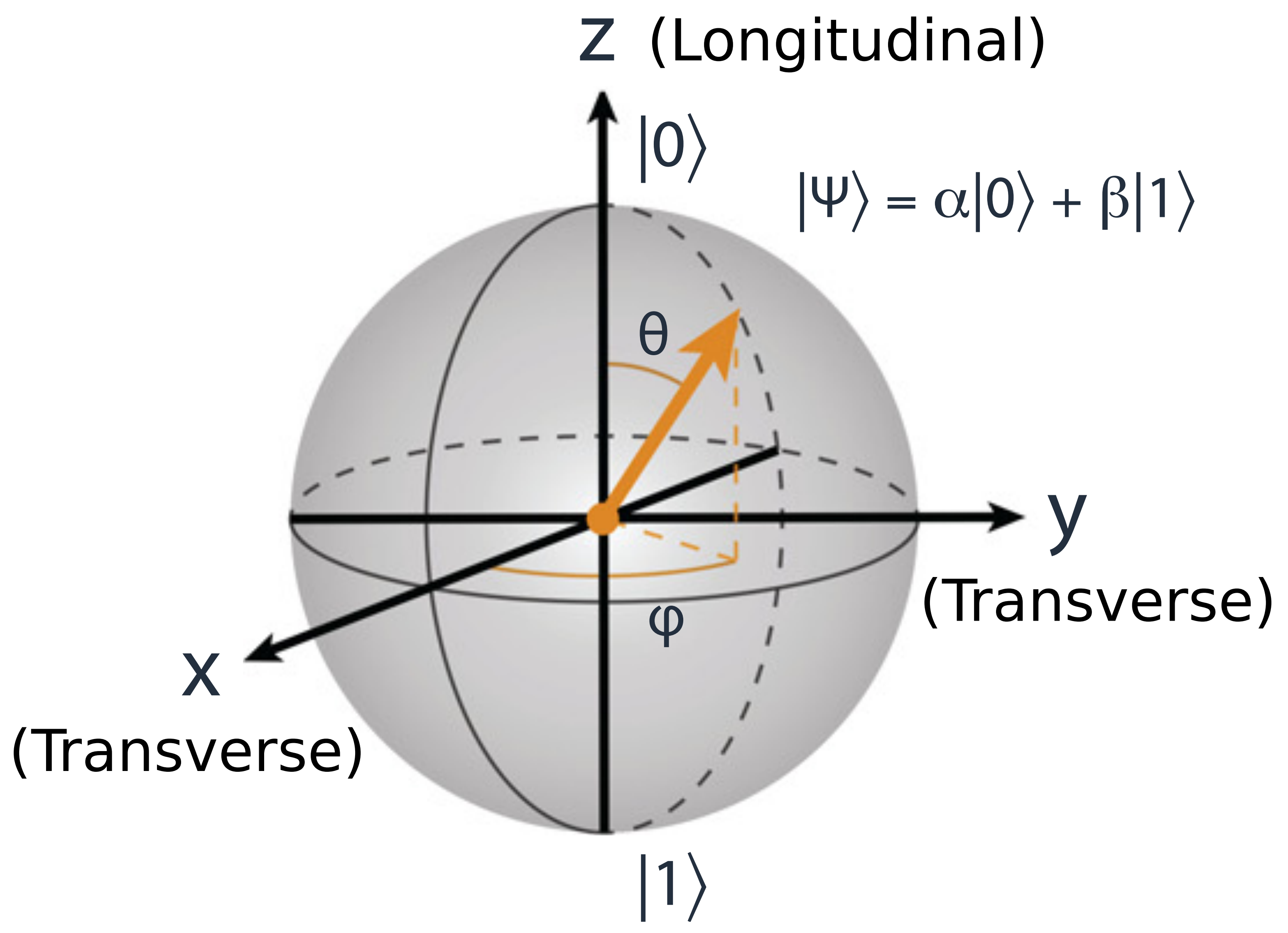
Thanks for the attention

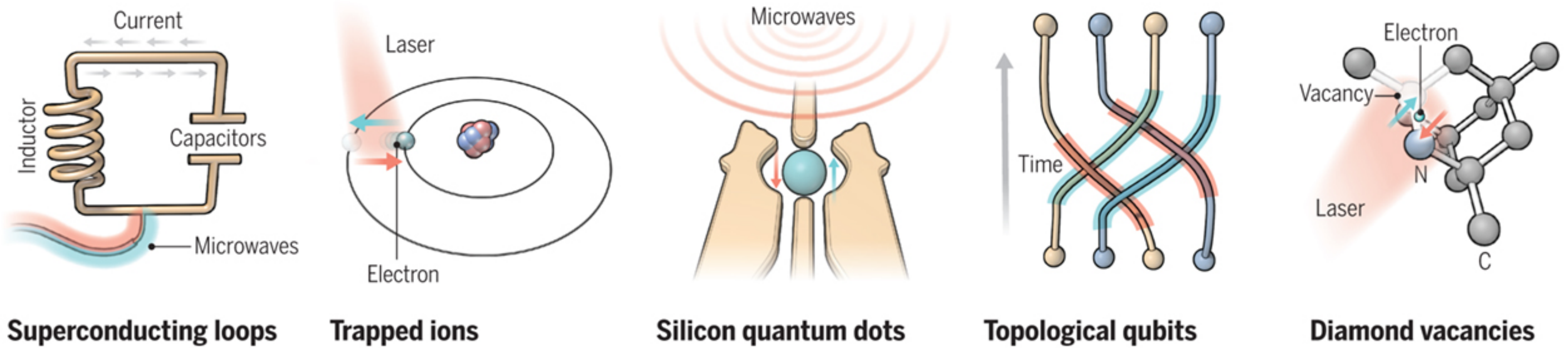
Backup

What is a qubit?

- Qubit: any two level quantum system
- Multiple qubits can form entangled states
- Quantum logic gates are represented as controlled rotations of the state vector in the Block sphere

Bloch sphere



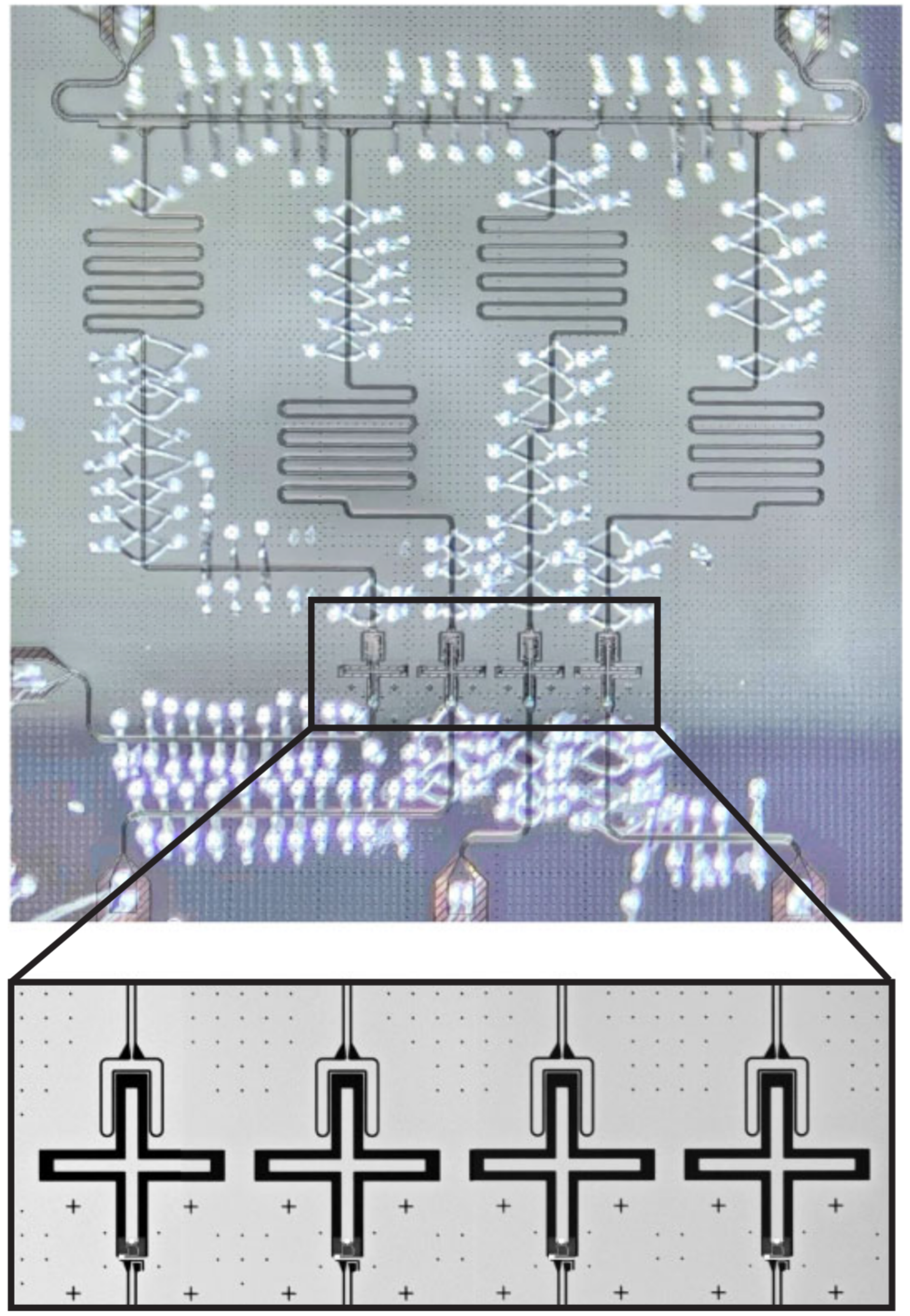


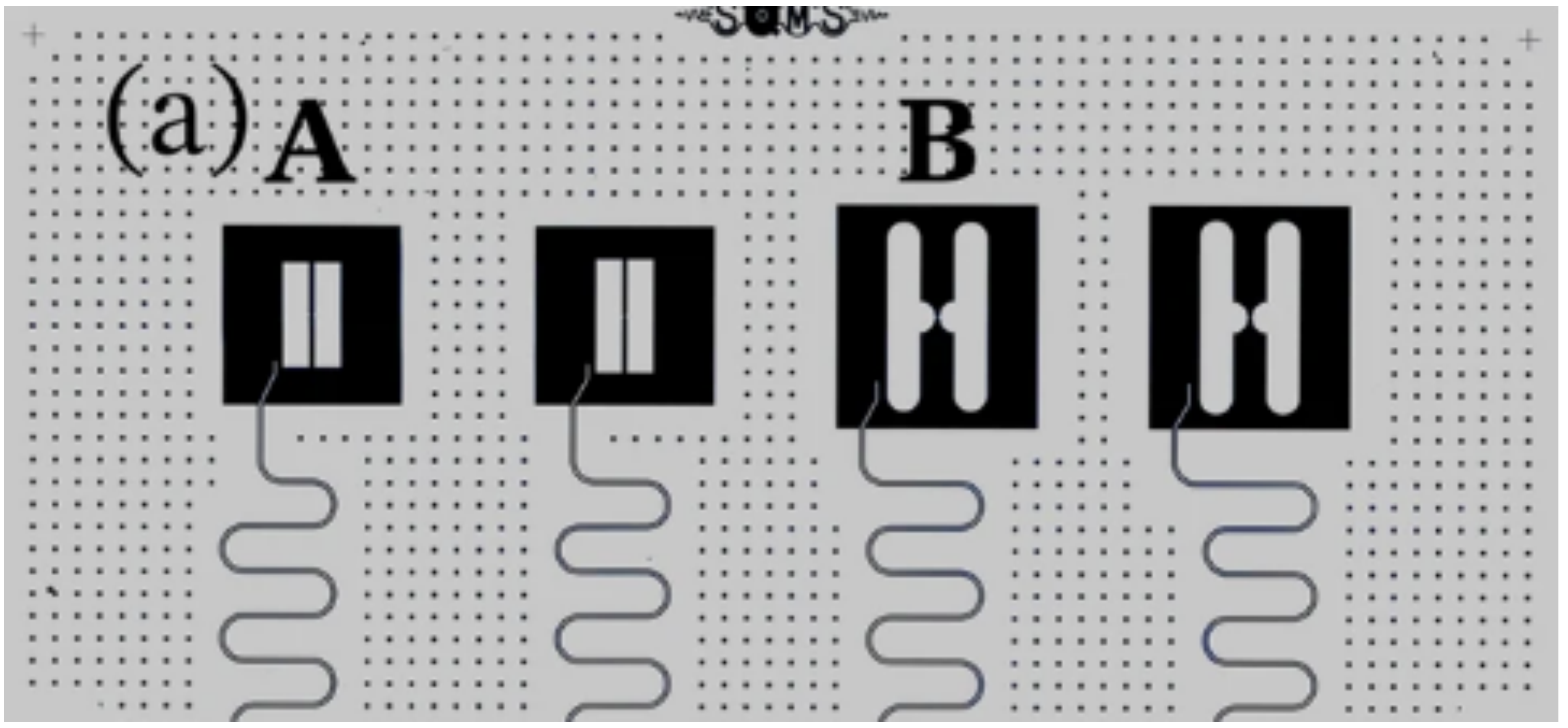
+ others

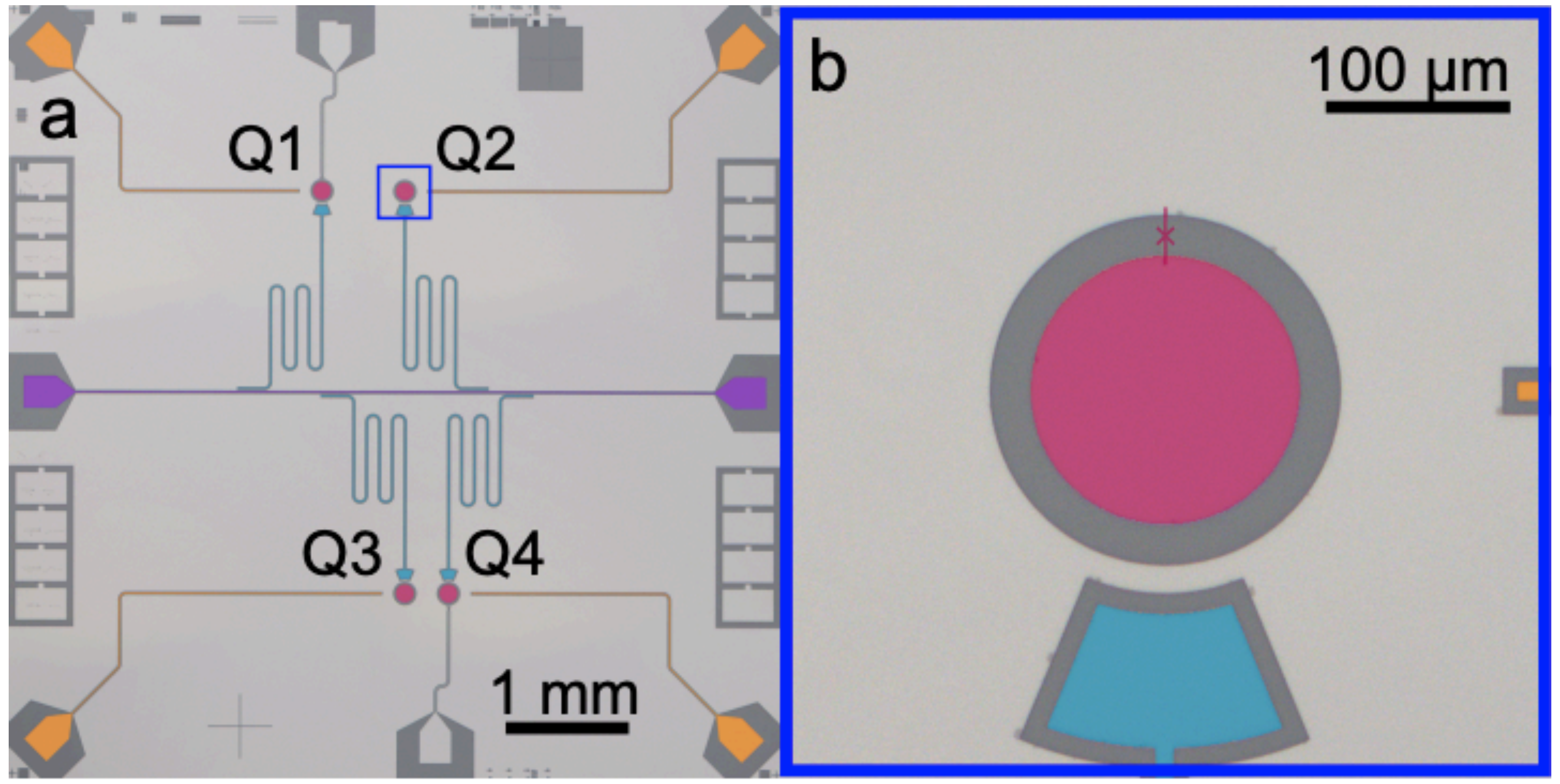
An example

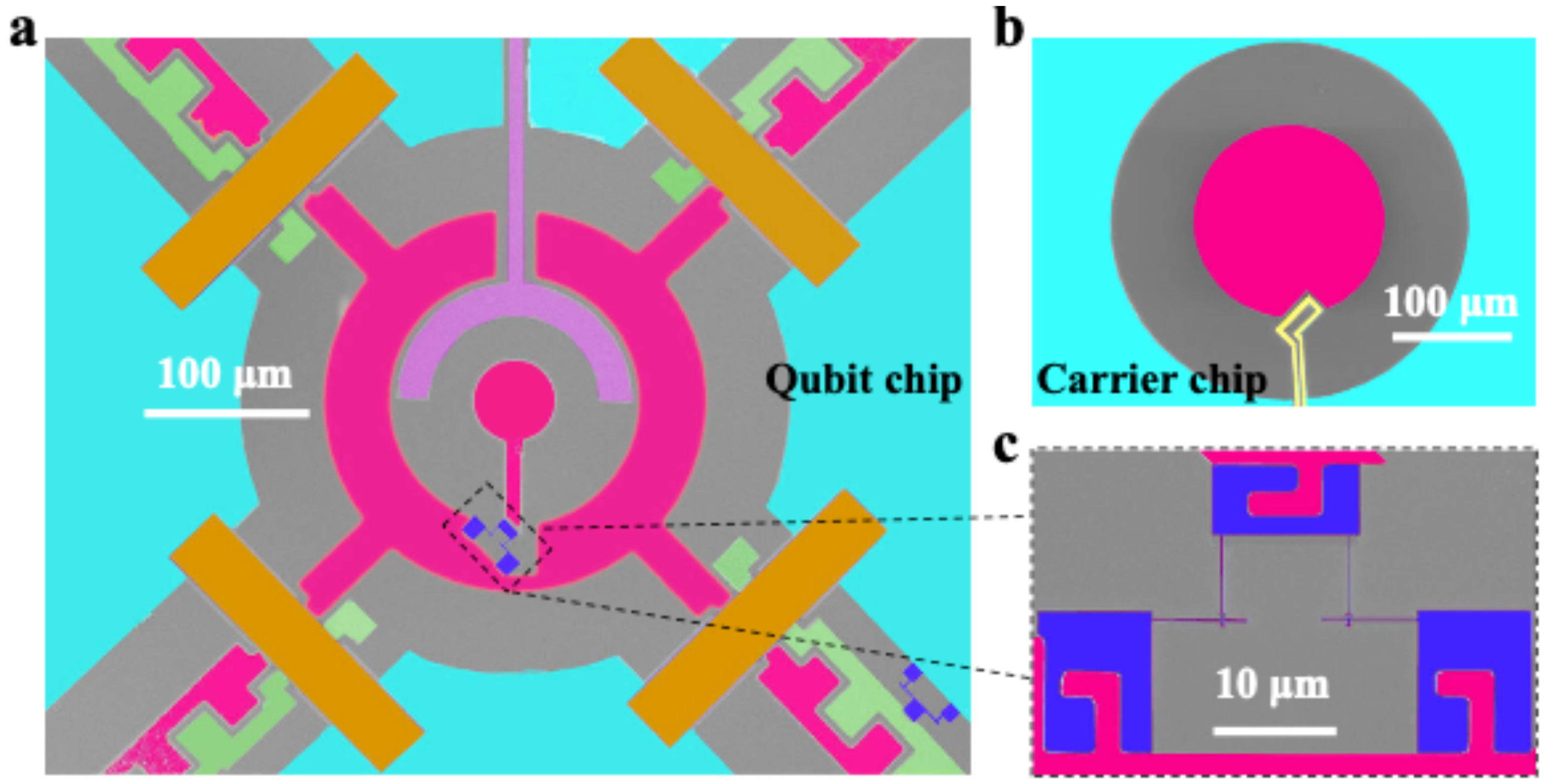

Qubit
Readout Resonator
Feedline
Whole chip
Qubit "inductor" (2-JJ SQUID)
Qubit capacitor

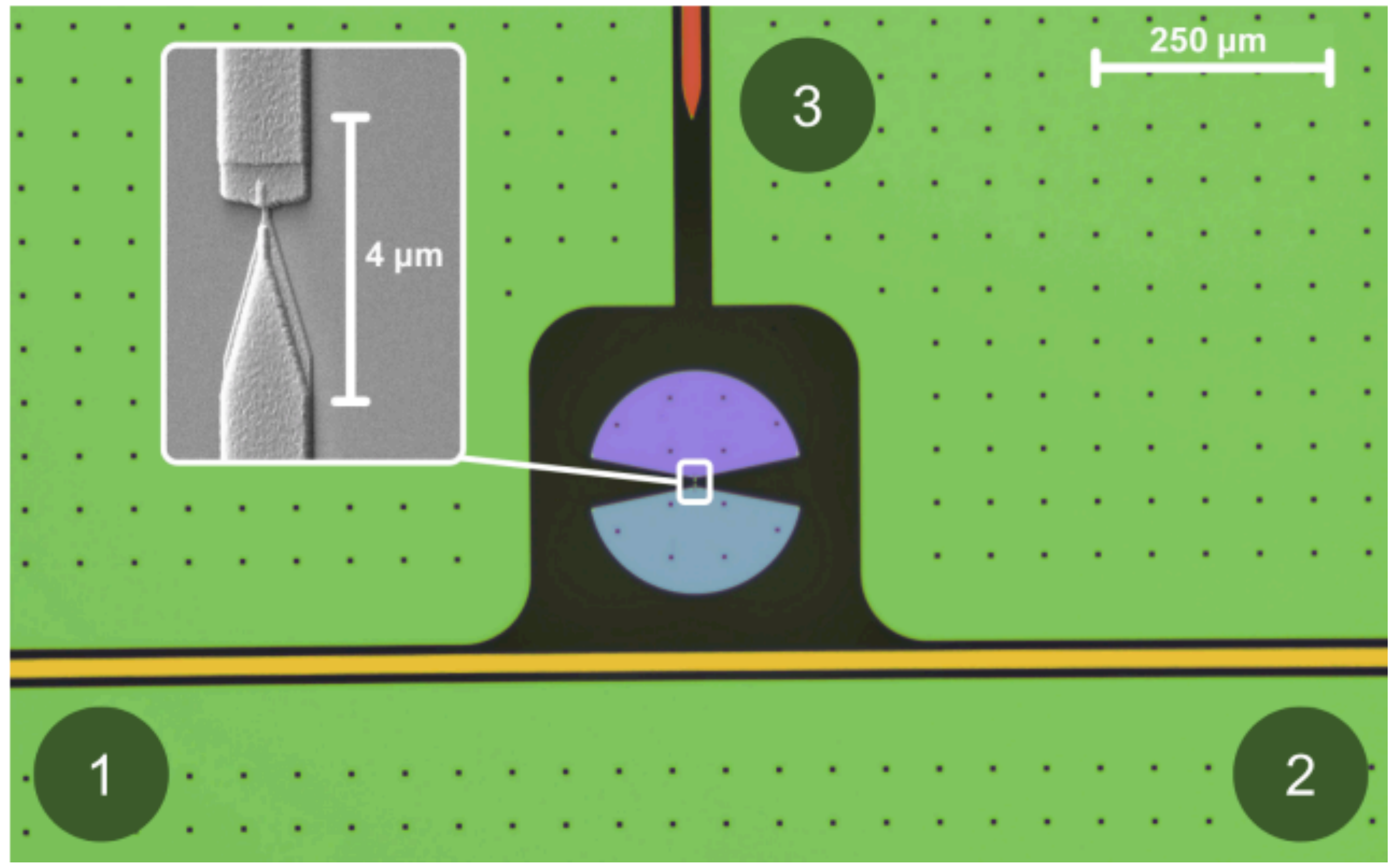
Some geometries



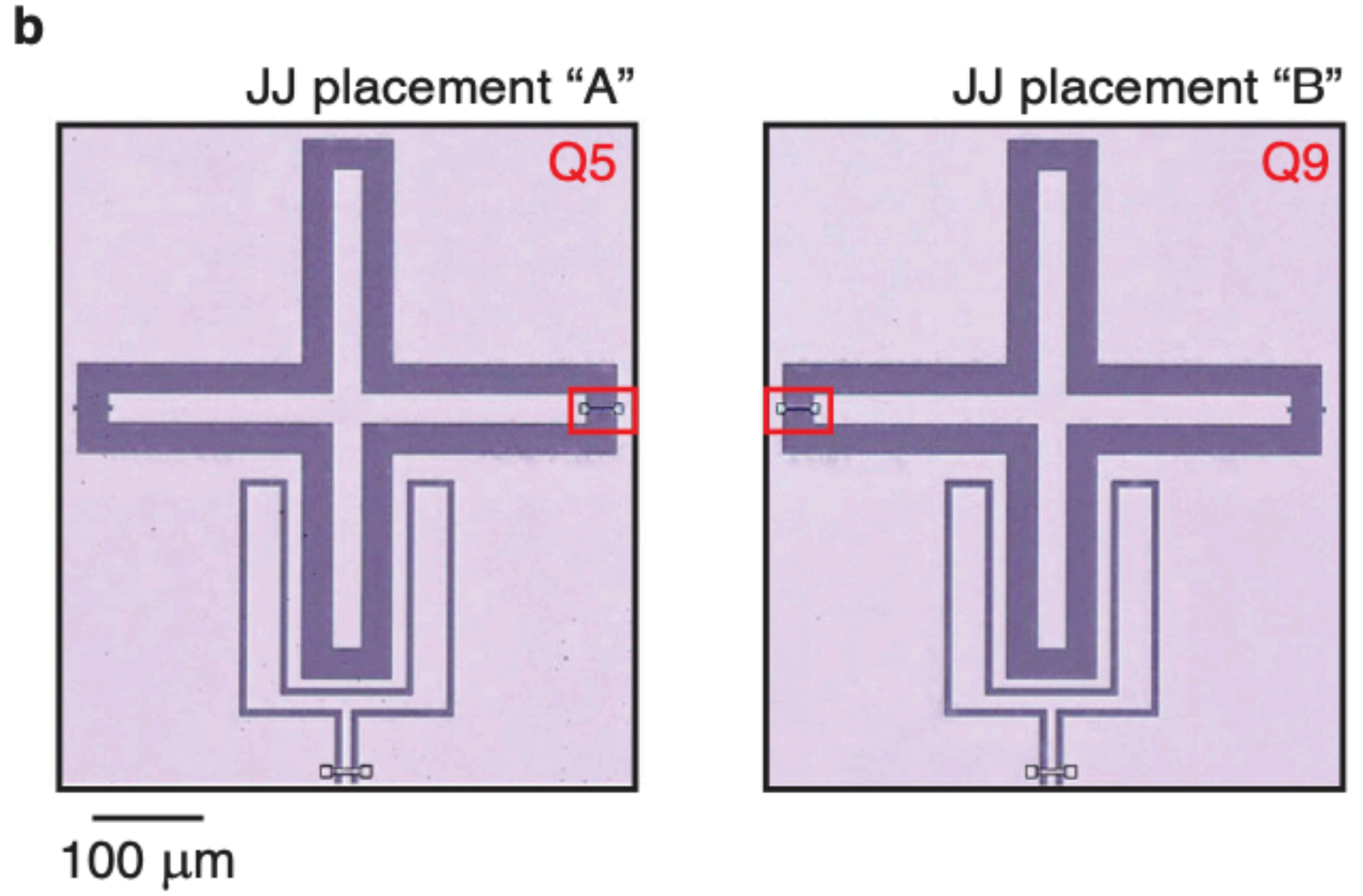


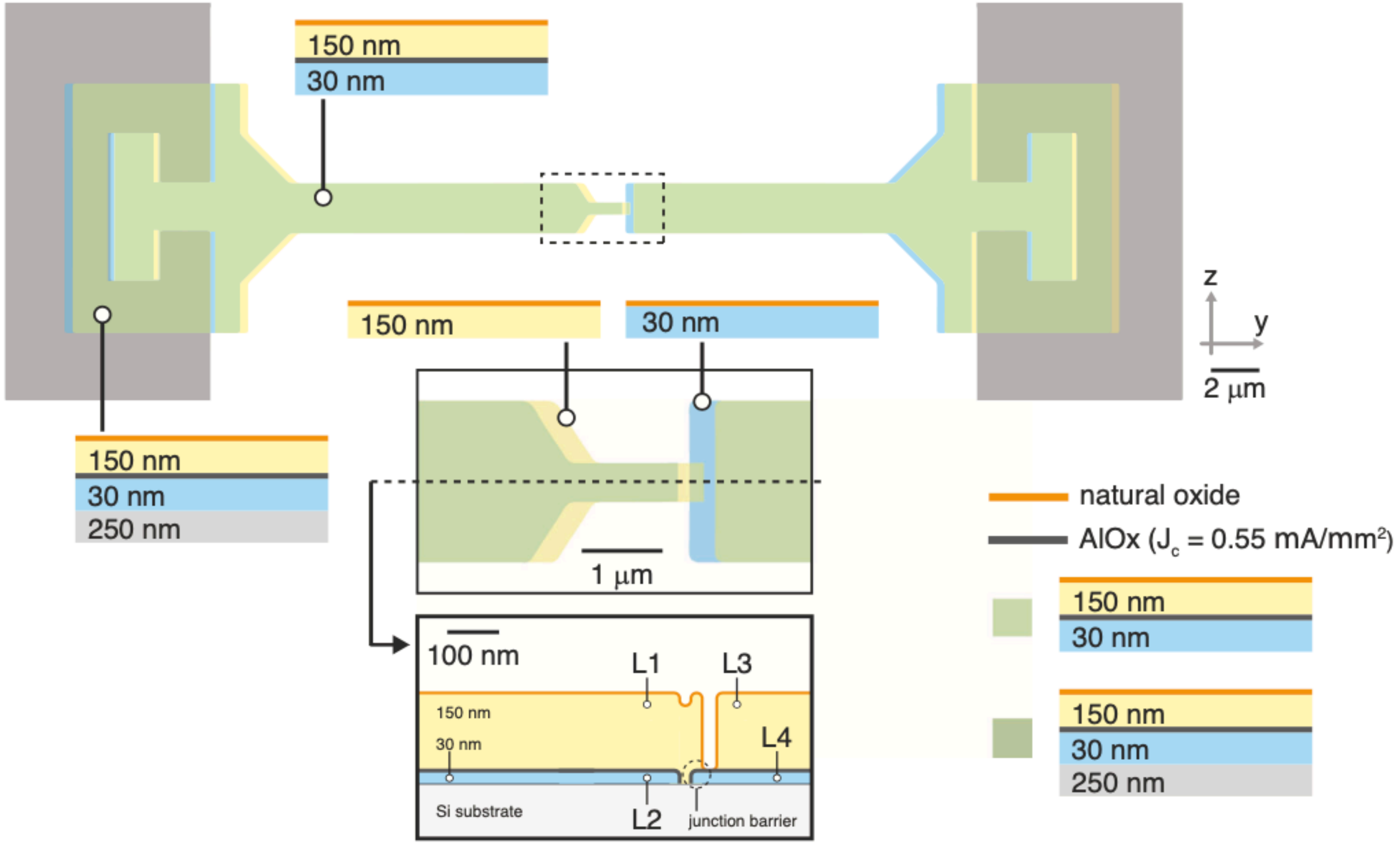






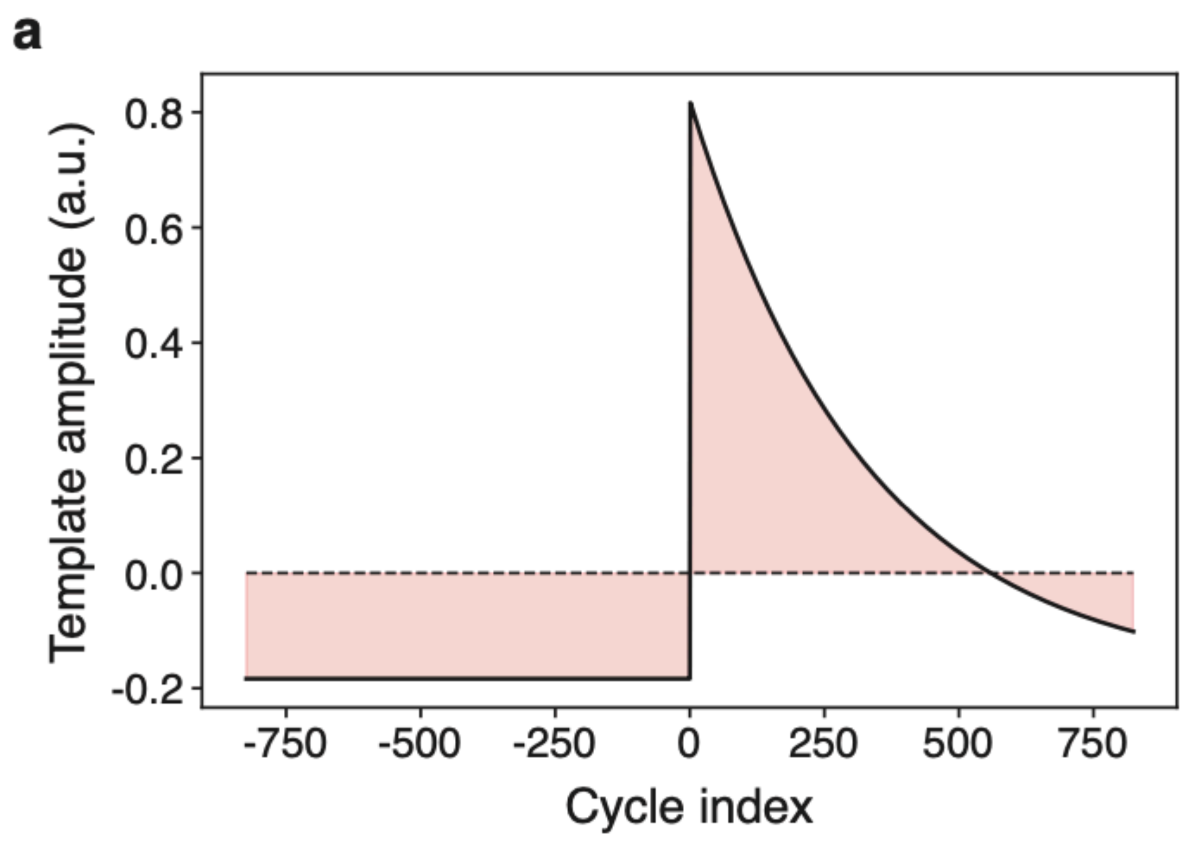
Fabrication

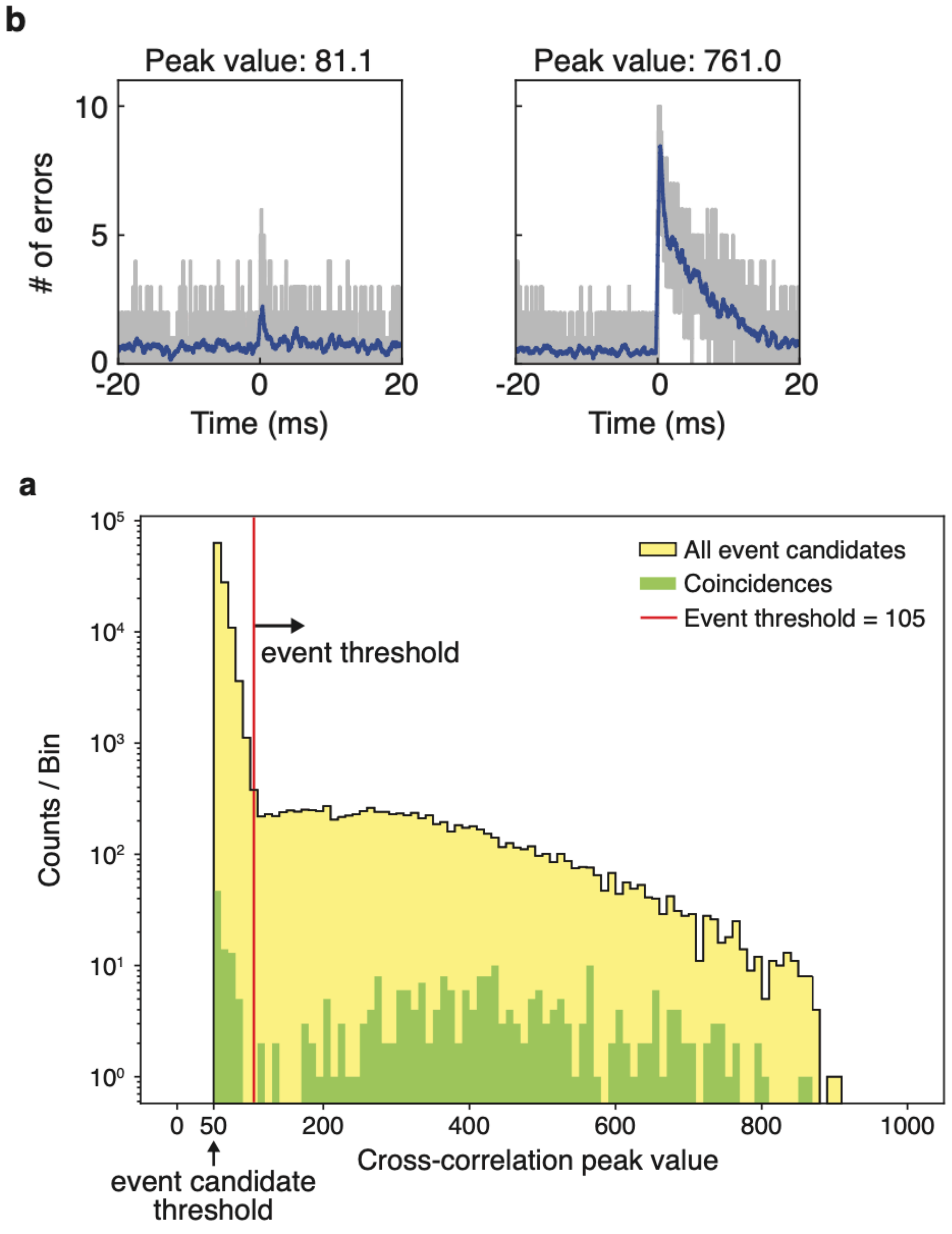


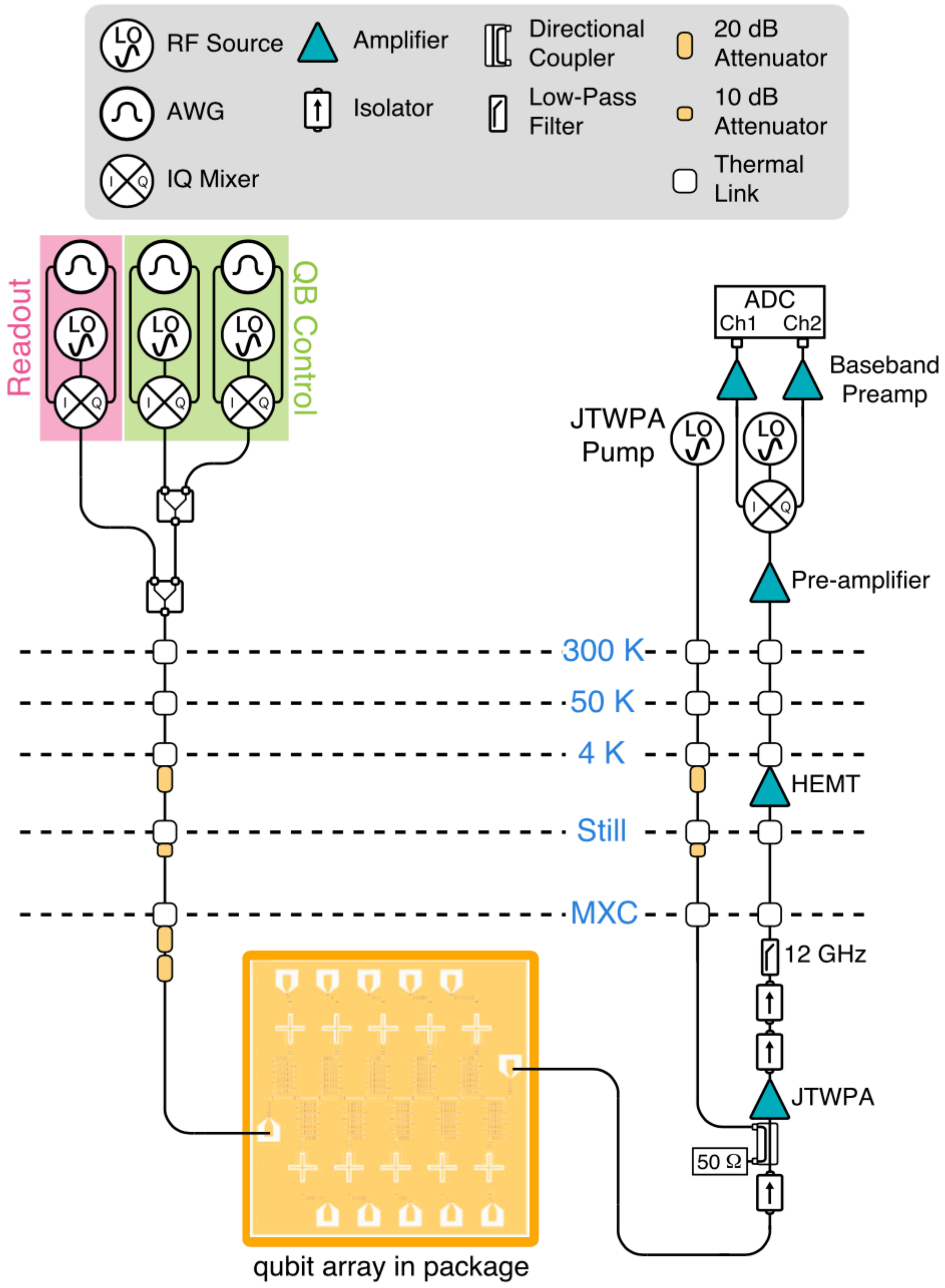


[Harrington et al, (2024)]

Measurement and trigger







[Harrington et al, (2024)]

Model parameters

Probability of relaxation in a time Δt:

$$p_r = 1 - e^{-\Gamma(t)\Delta t}$$

$$= 1 - \exp\left[\frac{-\alpha E_{\mathrm{dep}}}{E_{\mathrm{dep}}\left[\tau_{ss} r\left(e^{t/\tau_{ss}} - 1\right)\right] + \beta e^{t/\tau_{ss}}} - \gamma\right]$$

Qubit name	ω_q [GHz]
Q1	4.534
Q2	4.370
Q4	4.697
Q5	4.453
Q8	4.501

Parameter	Value
n_{cp}	$4 \times 10^{24}\ \mathrm{m}^{-3}$
Δ	$180\ \mu\mathrm{eV}$
V	$6975\ \mu\mathrm{m}^3$
ϵ	0.6

Where:

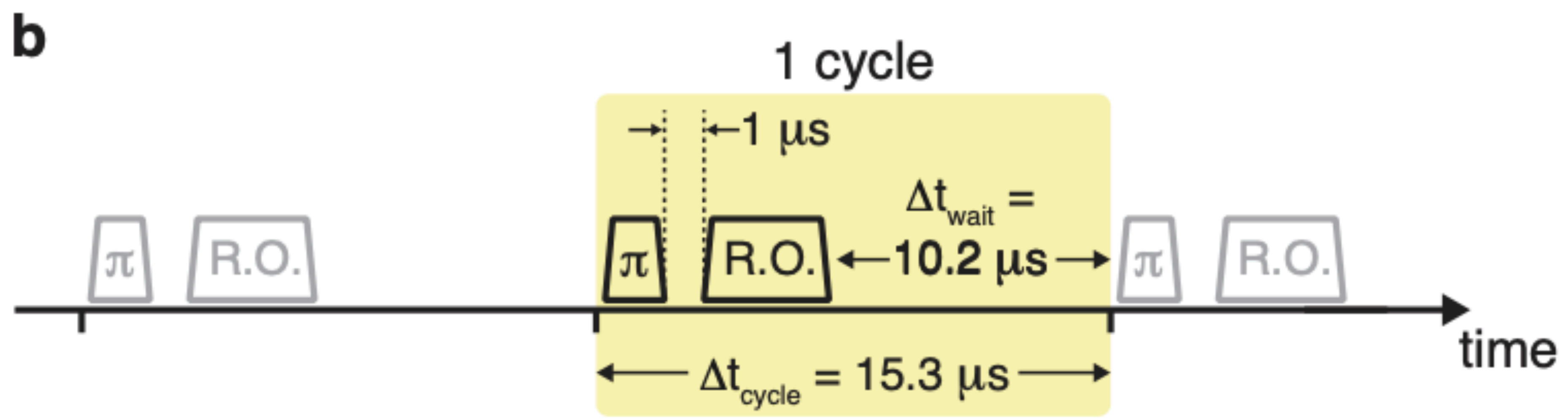
$$\alpha = \delta t \sqrt{\frac{2\omega_q \Delta}{\pi^2 \hbar}}$$

$$\beta = \frac{n_{CP} V \Delta}{\epsilon}$$

γ = baseline

Parameter	Description
Material	SC material
δt	QDR time step
r	Recombination rate
s_0	Linear loss rate
g	QP generation rate
n_{CP}	Superfluid (CP) density
Δ	SC gap energy
V	Island volume
ϵ	Phonon-to-QP efficiency
F	QP-creation Fano factor
$\omega_q/2\pi$	Qubit frequency
N	Measurement binning

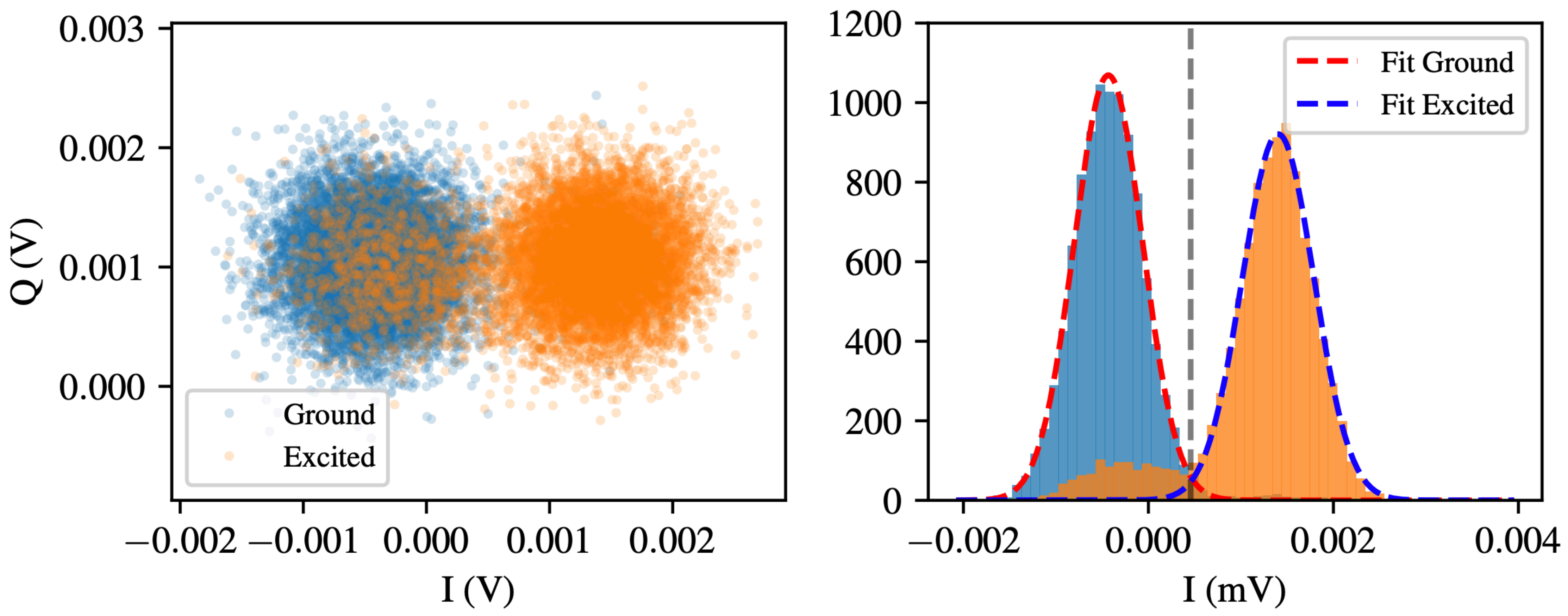
δt = time step = $1\mu s$ + 1/2 R.O. = $3\mu s$



Readout fidelities

- Single shot fidelity calibration every ∼45 min
- Calculate separation fidelity from IQ plots
- Adjust probability of relaxation accounting for readout fidelities:

$$p_{\text{obs}} = p_r \cdot p_g + \left(1 - p_r\right) \cdot p_{ge}$$
$$= p_r \cdot \mathcal{F} + p_{ge}$$



Qubit name	$\frac{\omega_q}{2\pi}$ [GHz]	Run-07		Run-13	
		$\mathcal{F}$ [%]	p_{ge} [%]	$\mathcal{F}$ [%]	p_{ge} [%]
Q1	4.534	99.96	0.02	99.75	0.13
Q2	4.370	99.65	0.20	98.51	0.79
Q4	4.697	99.70	0.13	99.25	0.35
Q5	4.453	99.92	0.04	99.58	0.22
Q8	4.501	99.16	0.47	98.04	1.02

Fit procedure

For each waveform sample, the probability of finding s errors is given by a binomial distribution: $p(s) = \binom{N}{s} p_{obs}^{s} \left(1 - p_{obs}\right)^{(N-s)}$

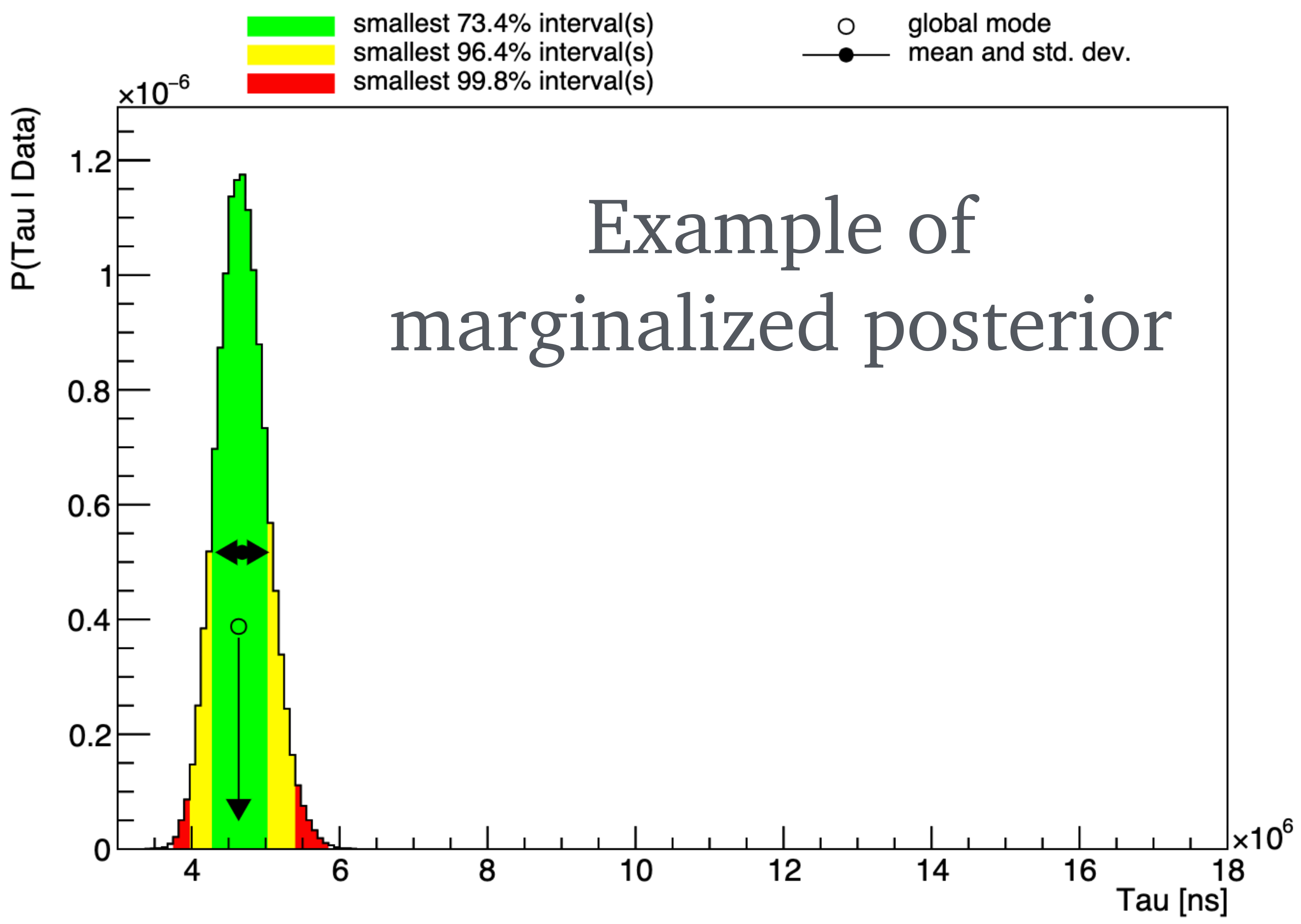
The joint probability of acquiring a set of measured waveform samples $\{s_i\}$ at times $\{t_i\}$:

$$\mathscr{L}\left(\{s_i\} \mid S(t)\right) = \prod_i \binom{N}{s_i} p_{obs}^{s_i}(t_i) \left(1 - p_{obs}(t_i)\right)^{(N-s_i)}$$

- **Binomial Maximum Likelihood fit** for each acquired waveform
- Bayesian approach → integrate the joint posterior pdf:

$$p\left(S(t;\hat{\theta}) \mid \{s_i\}\right) = \mathscr{L}\left(\{s_i\} \mid S(t;\hat{\theta})\right) \pi(\hat{\theta})$$

- **BAT**: software using Markov Chain Monte Carlo algorithms to integrate the posterior pdf

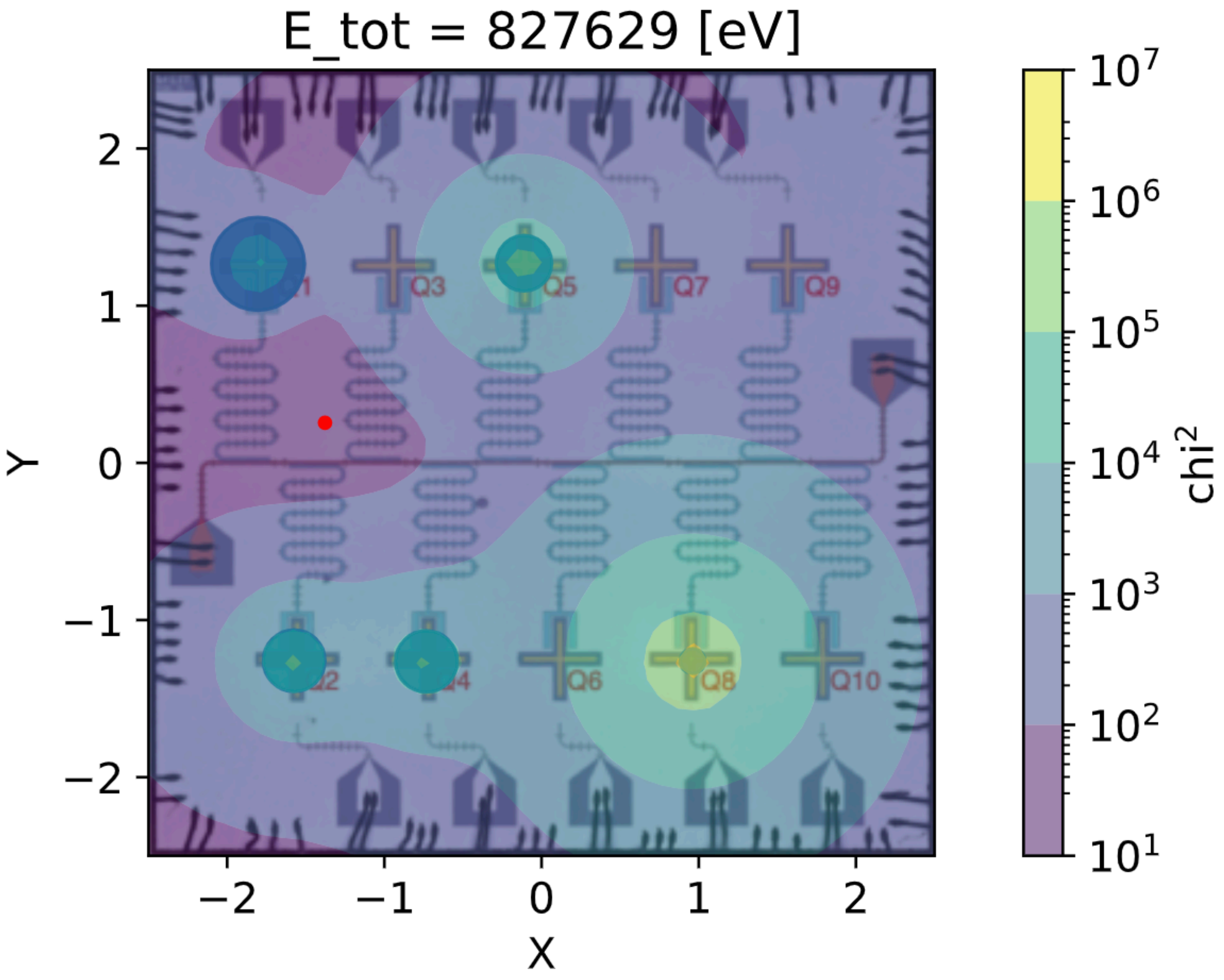


Position reconstruction

1. Take as input the energy extracted with the energy fit and its uncertainty
2. Get the phonon dispersion function from G4CMP simulation
3. Apply position reconstruction algorithm:

$$\chi^2(x, y, E_{tot}) = \sum_{i=1}^{N} \left(\frac{S_i^{\mathrm{obs}} - S_i^{\mathrm{model}}(x, y, E_{tot})}{\sigma_i} \right)^2$$

Point-like energy deposition on XY



Quasiparticle density model

Knowing the superfluid (CP) density n_{CP} for a given material, it is then possible to model the normalized quasiparticle density $x_{qp} = n_{qp}/n_{CP}$ with:

$$\frac{dx_{qp}}{dt} = -rx_{qp}^2 - s_0 x_{qp} + g$$

r = recombination constant (expected to be as large as its theoretically motivated value 0.05)

s_0 = linear loss due to QP trapping

g = QP generation

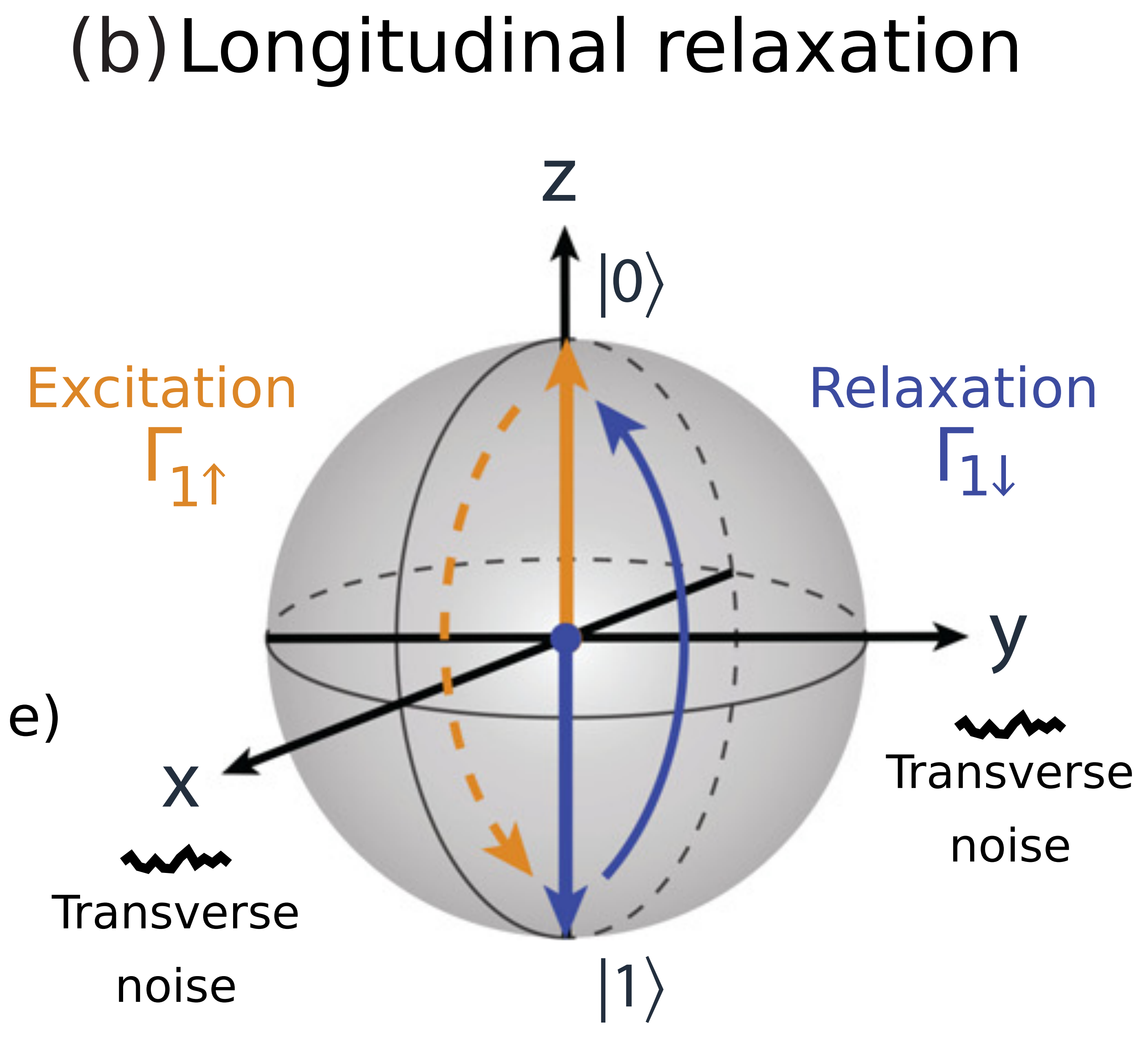
$$\begin{aligned} x_{qp} &= x_i \frac{1-r'}{e^{t/\tau_{ss}} - r'} + x_0 \\ &= \left[\frac{E_{\text{dep}}\epsilon}{n_{CP} V \Delta}\right] \frac{1-r'}{e^{t/\tau_{ss}} - r'} + x_0. \end{aligned} \quad (8)$$

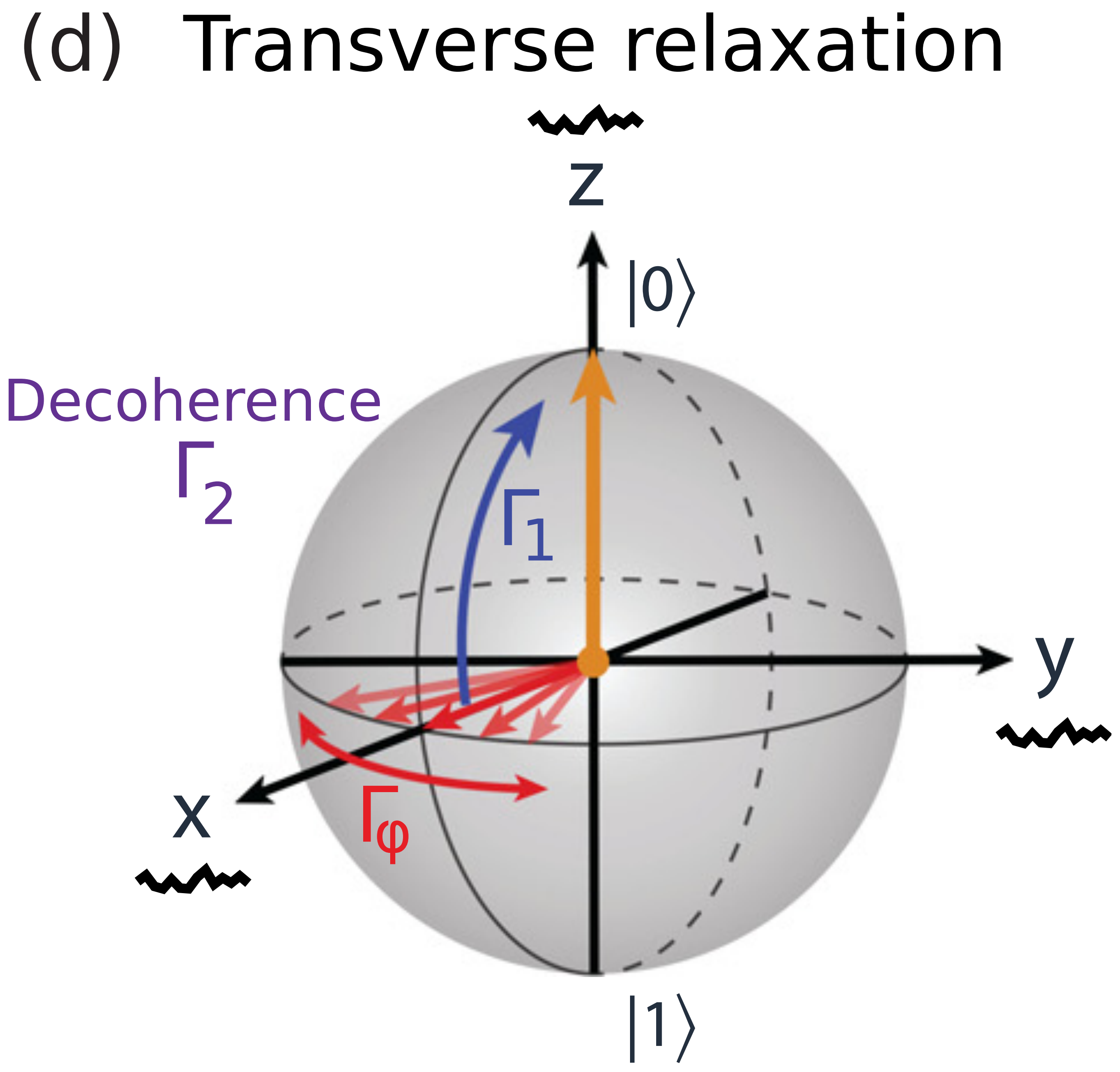
Here, τ_{ss}, r', and x_0 are functions of r, s_0, g, and x_i.[3] Notably, τ_{ss} is the "steady-state" decay time for the QP relaxation, found when x_{qp} becomes small enough that self-recombination becomes subdominant.

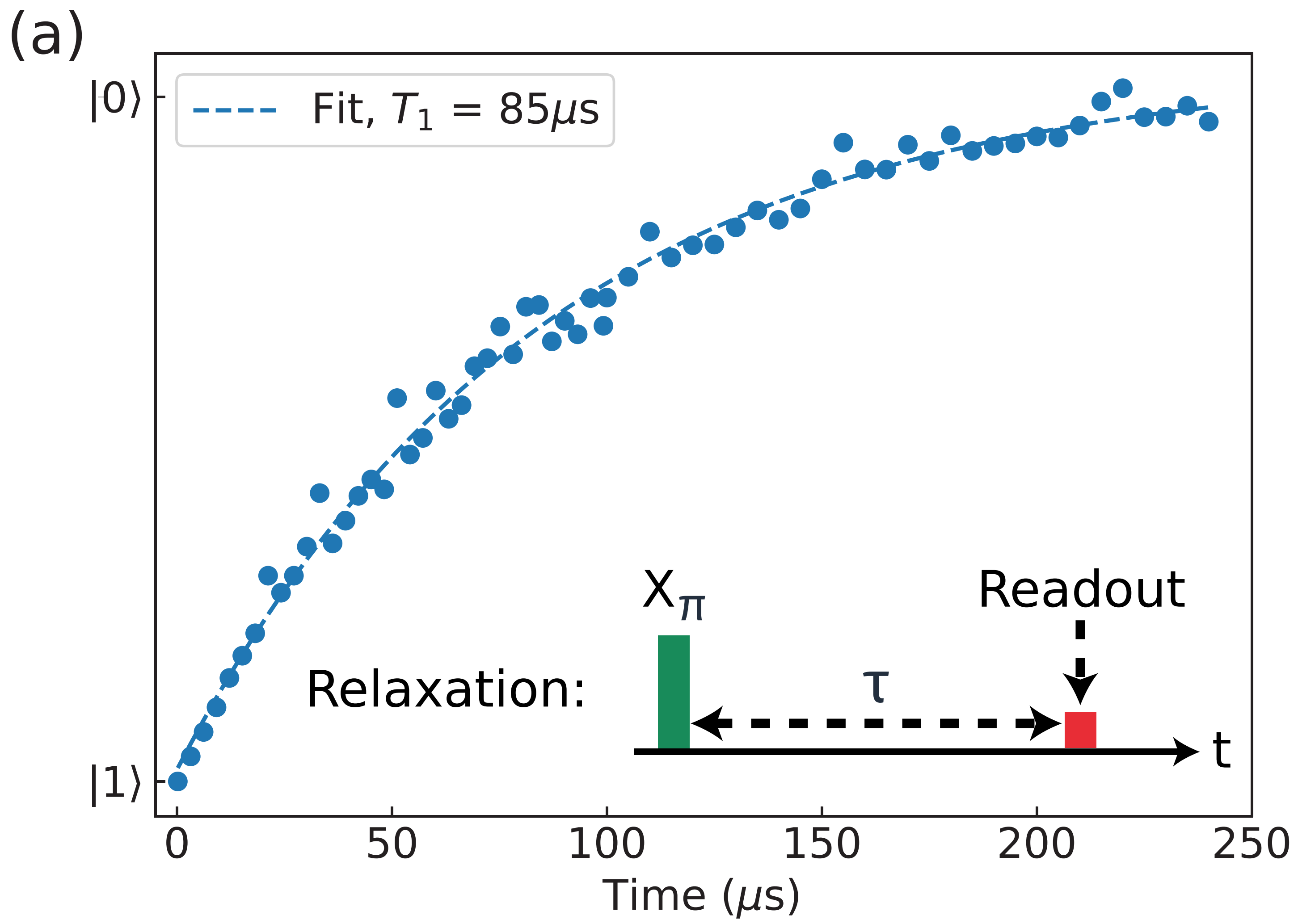
$$\Gamma(t) = \sqrt{\frac{2\omega_q \Delta}{\pi^2 \hbar}} \left(\left[\frac{E_{\text{dep}}\epsilon}{n_{CP} V \Delta}\right] \frac{1-r'}{e^{t/\tau_{ss}} - r'} + x_0 \right) + \Gamma_{\text{other}}.$$

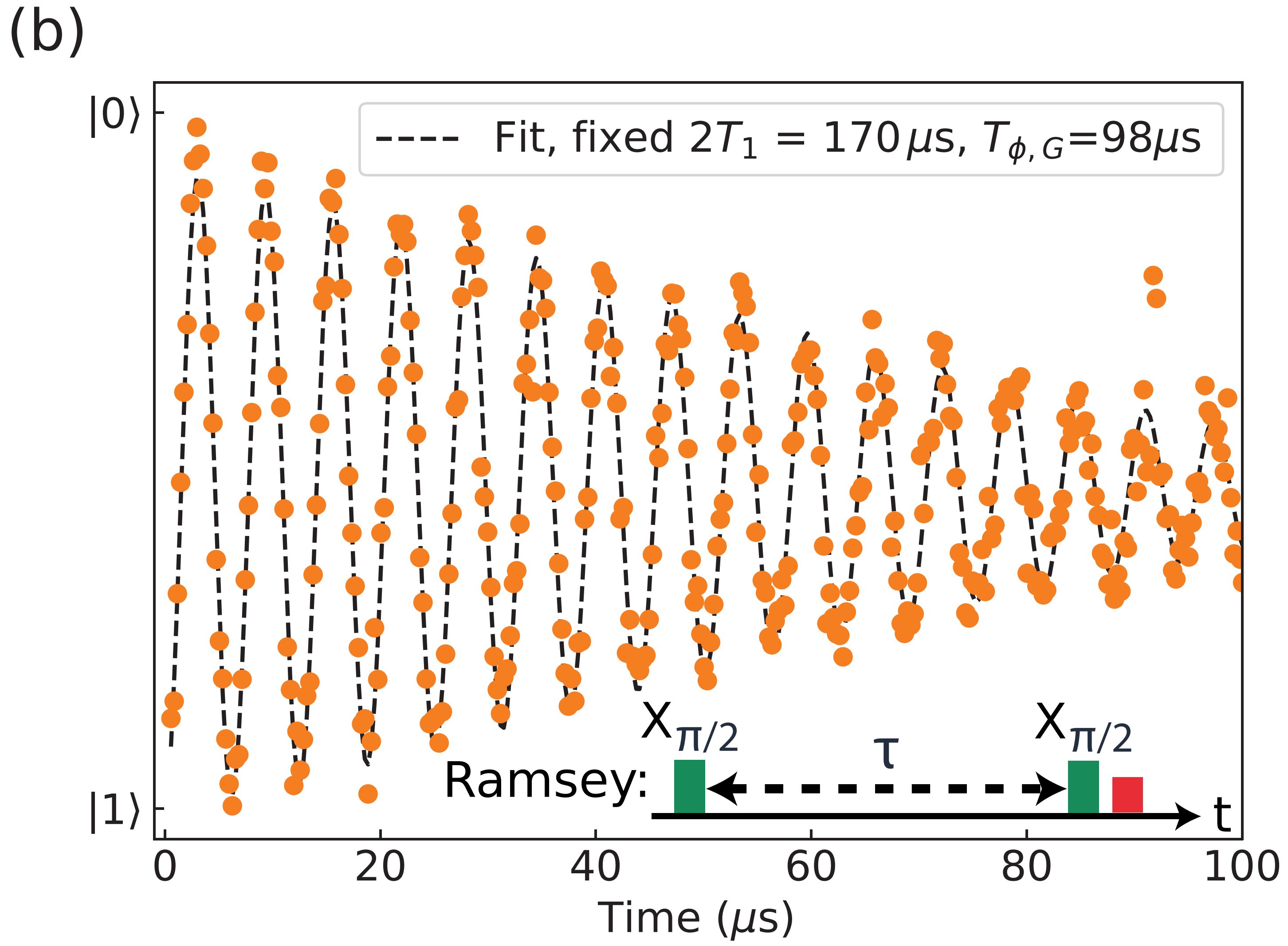
$$r' = \tau_{ss} x_i r / \left[\tau_{ss} x_i r + 1\right]$$

Noise and decoherence



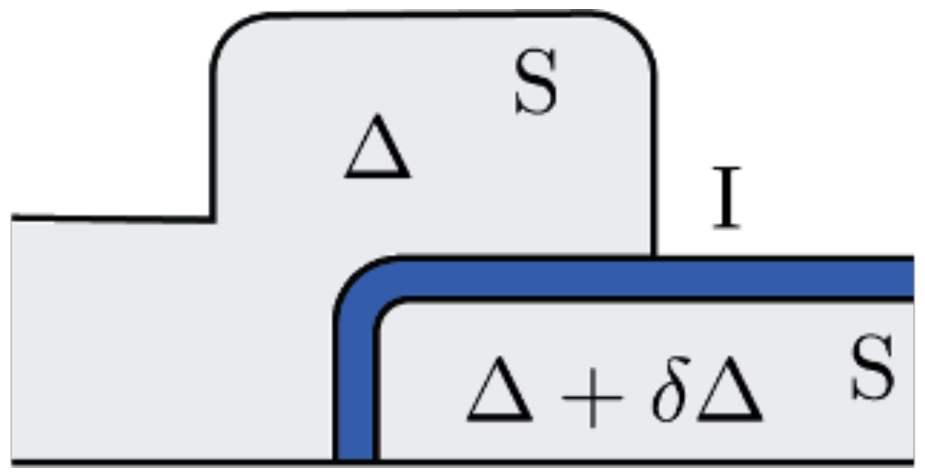






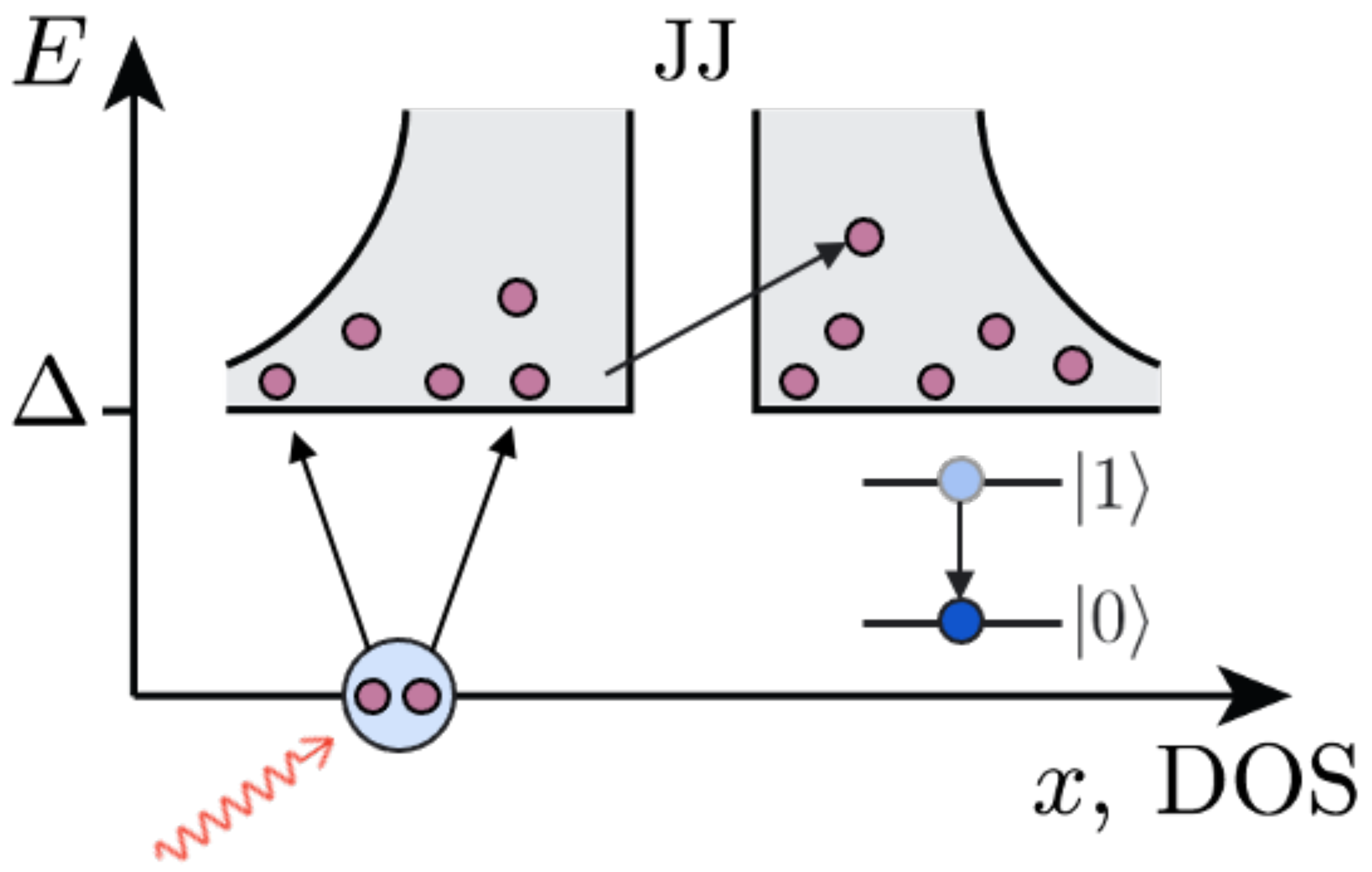
Gap engineering

Design a potential barrier on the JJ to prevent CP from tunneling

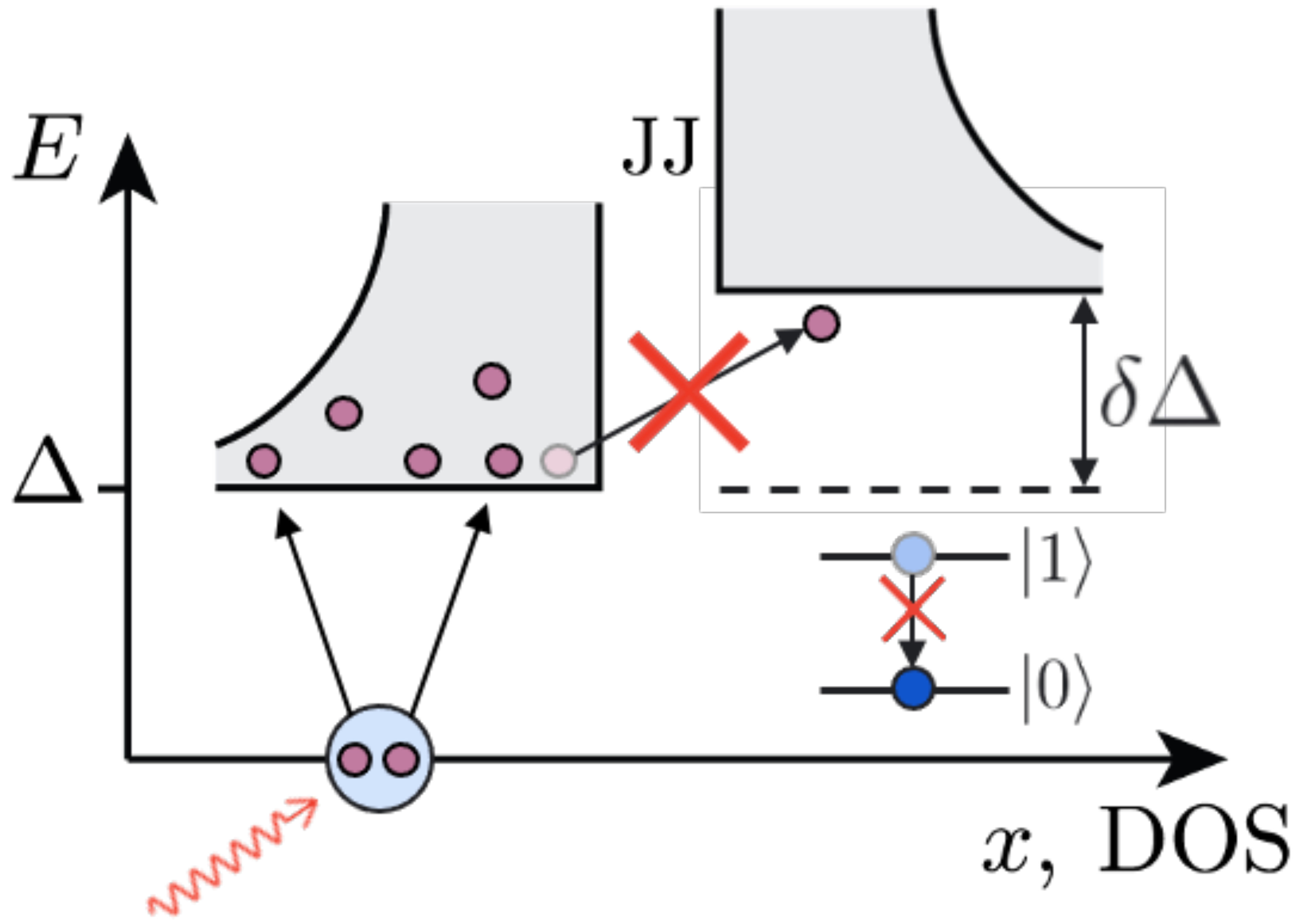


Δ = 180 μeV for Aluminum

Before



After



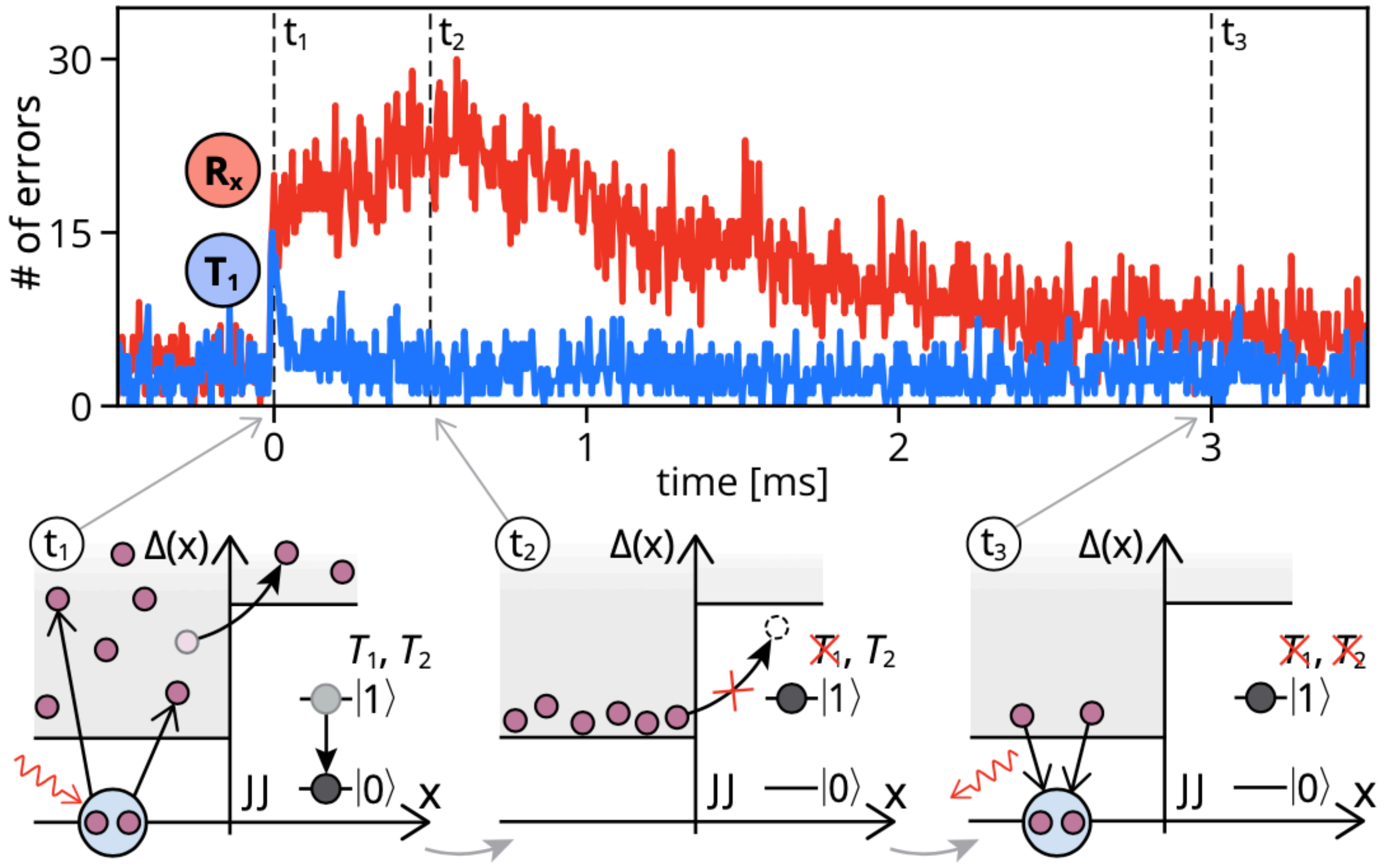
Google Quantum AI (2024)

But… not enough

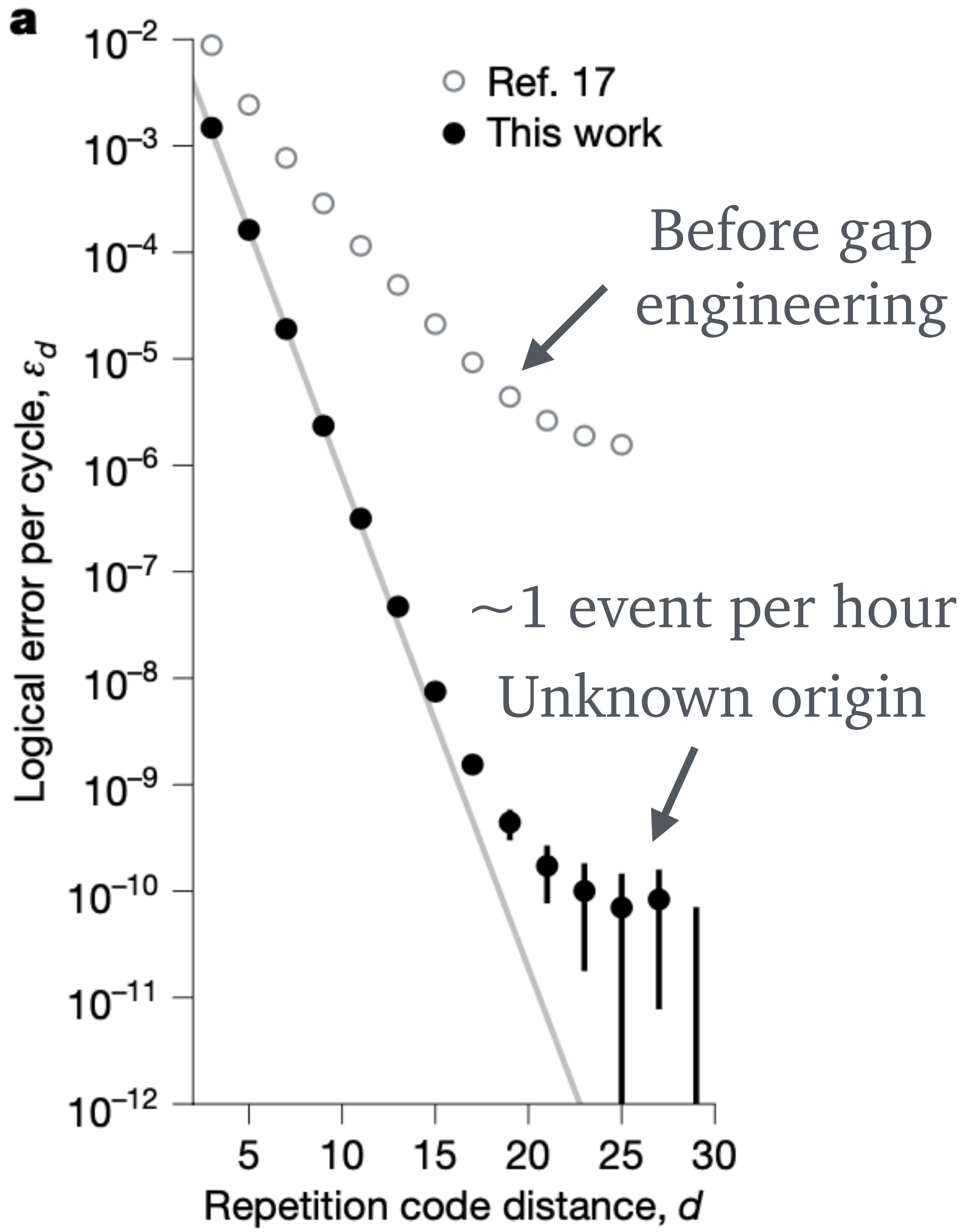
- Gap engineering helps reducing the logical qubit error rate, but it is not enough
- Charge accumulation in the capacitor leads to a frequency shift → dephasing error rate increase

Possible mitigation strategies:

- Phonon trapping Copper back-metallization
- Intermediate layers between substrate and SC film



Kurilovich et al - Google (2025)



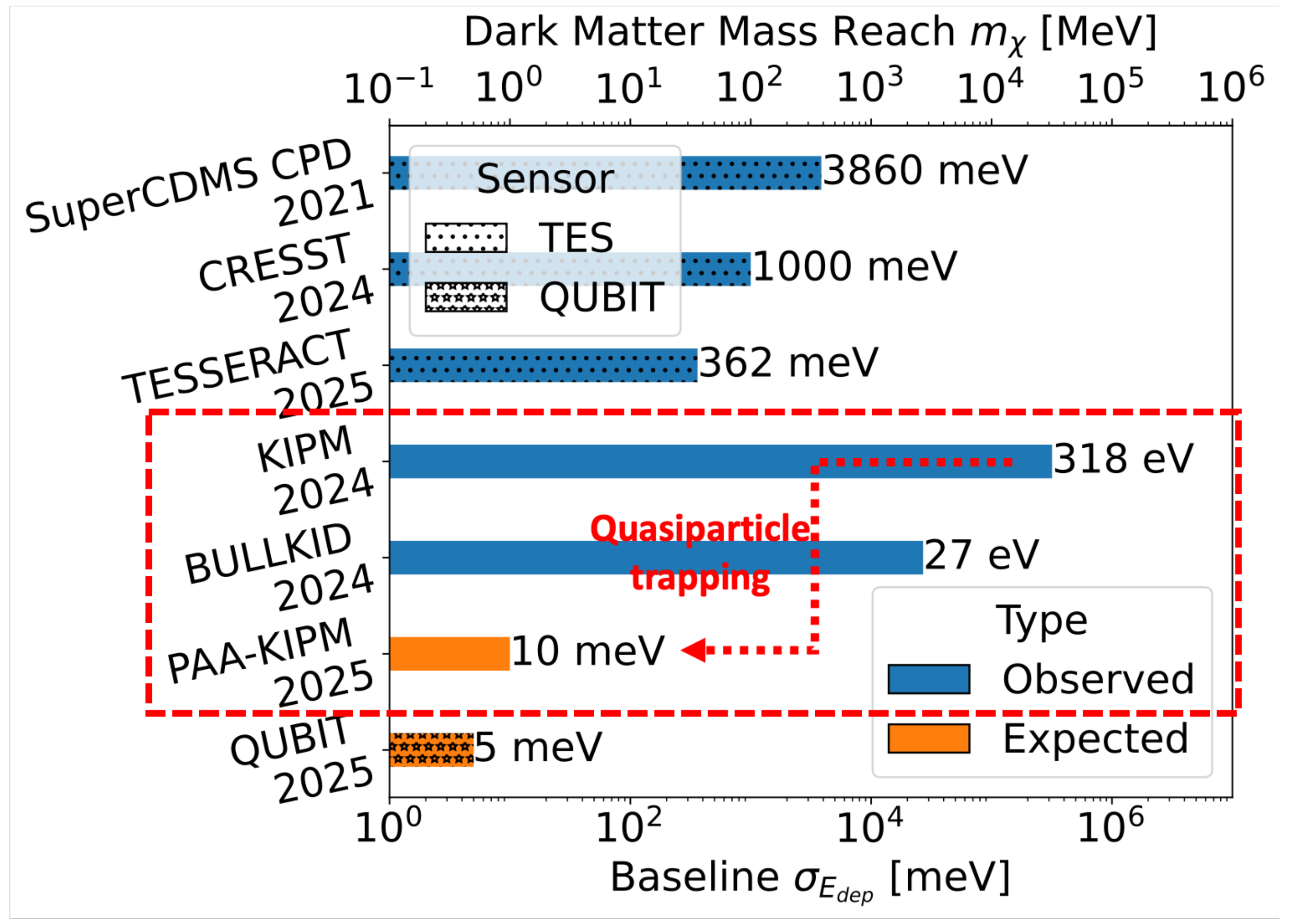
Superconducting detectors in DM searches

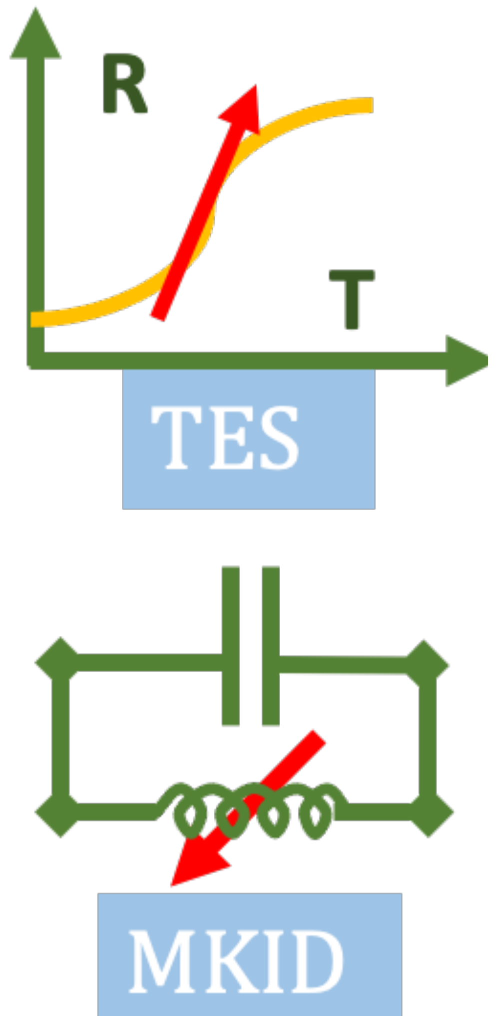
Something we know very well

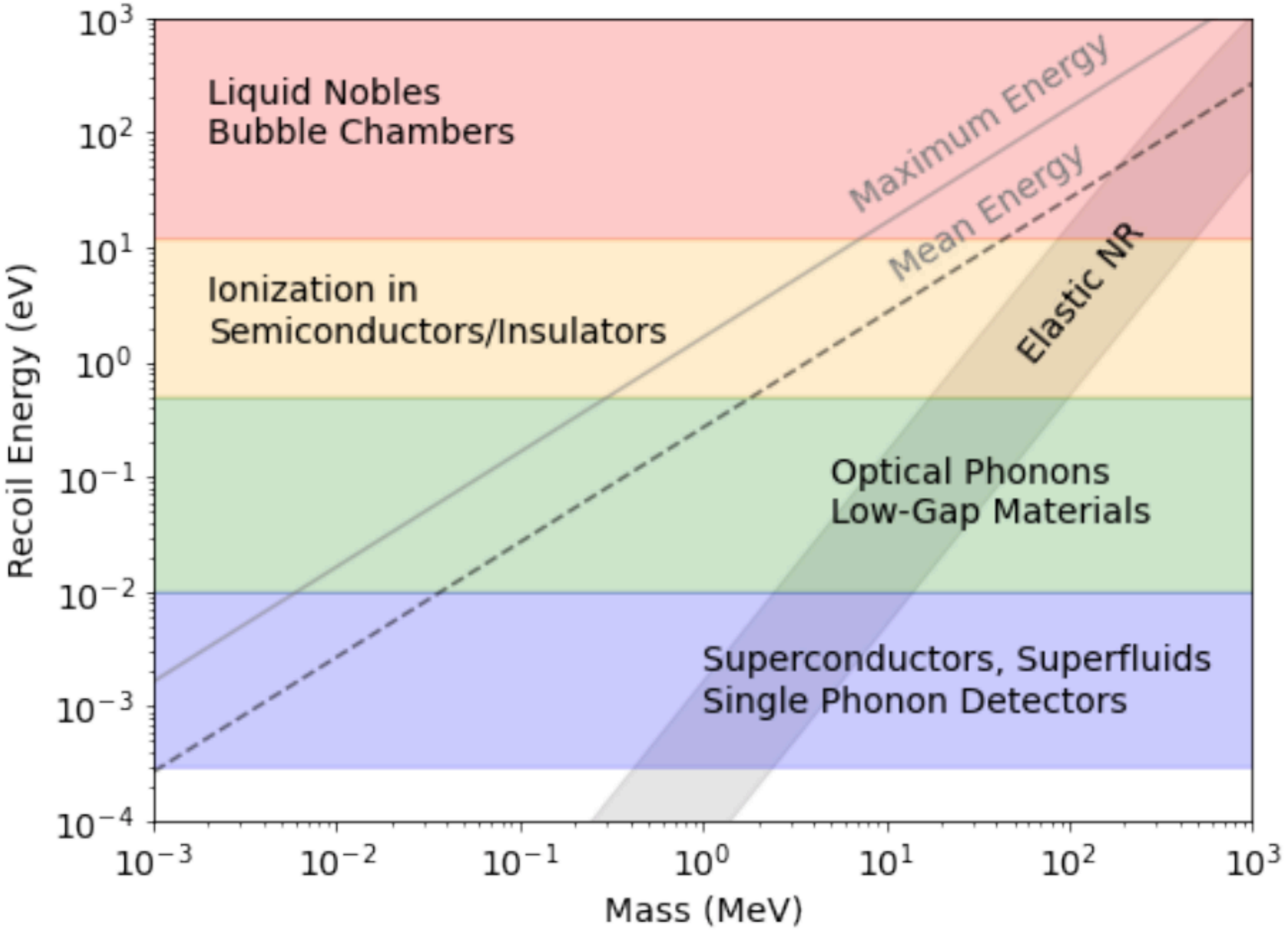
→ Transition Edge Sensors (TES)

→ Kinetic Inductance Detectors (KID)

CP breaking detection



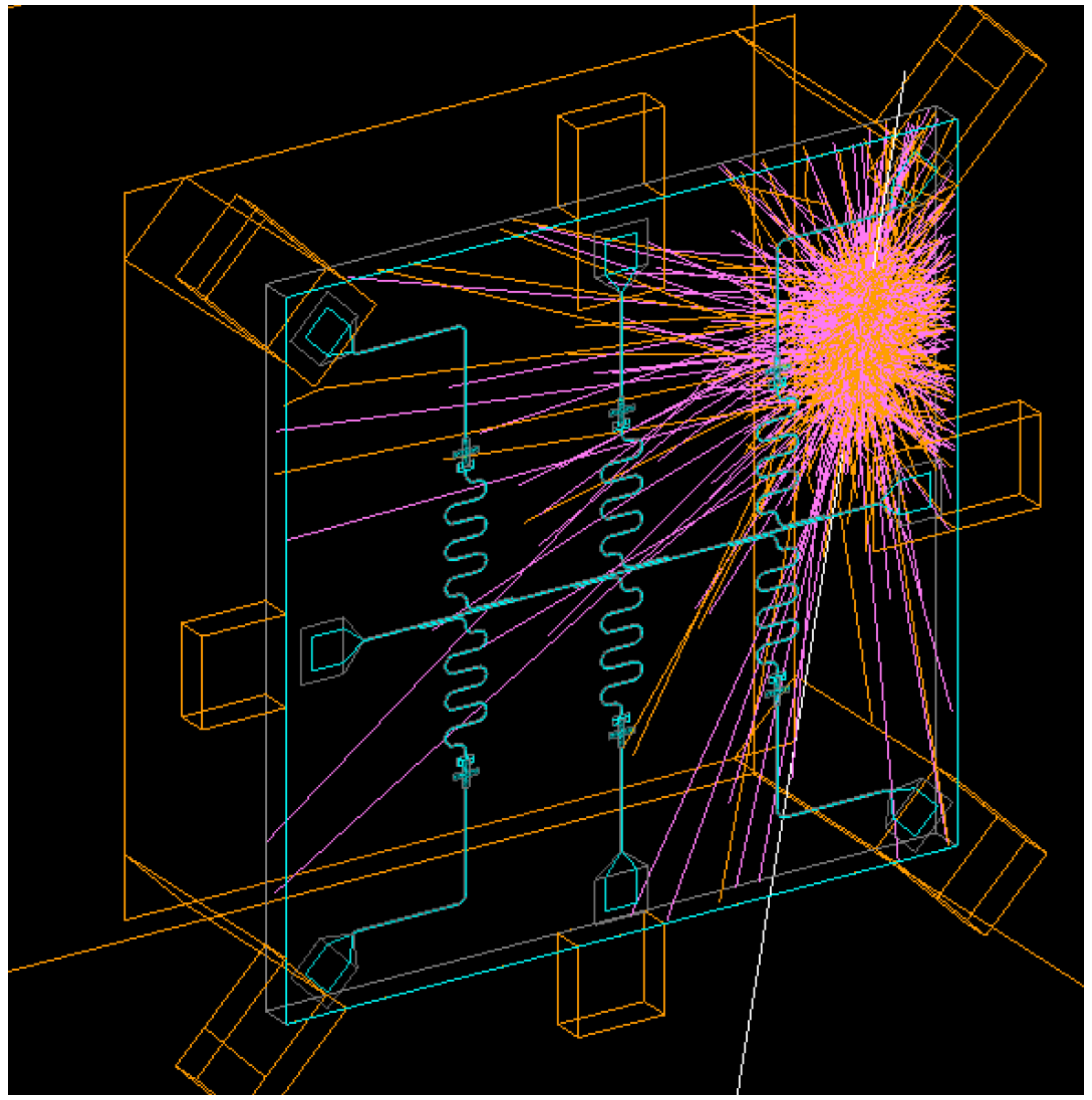




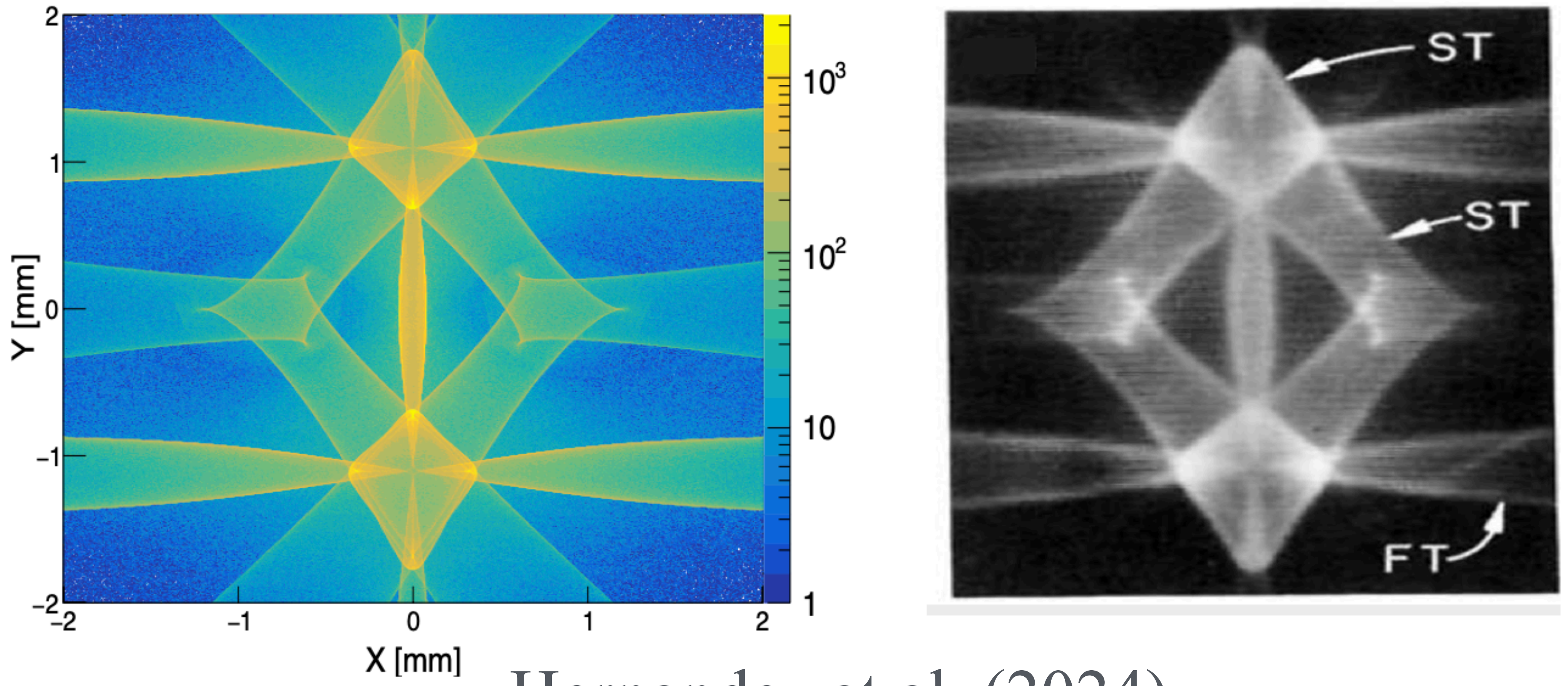
Snowmass2021

Solid state simulations

- G4CMP is a Geant4 library that allows simulating phonon dynamic on specific geometries
  Two main processes:
  → anharmonic down-conversion, $\Gamma_{\text{anh}} = A\nu^5$
  → isotopic scattering, $\Gamma_{\text{scatter}} = A\nu^4$
- Several materials now implemented
- Main uncertainty:
  → **probability of phonon absorption at the interface** with superconducting film ($p_{a,s}$) and copper frames ($p_{a,c}$)

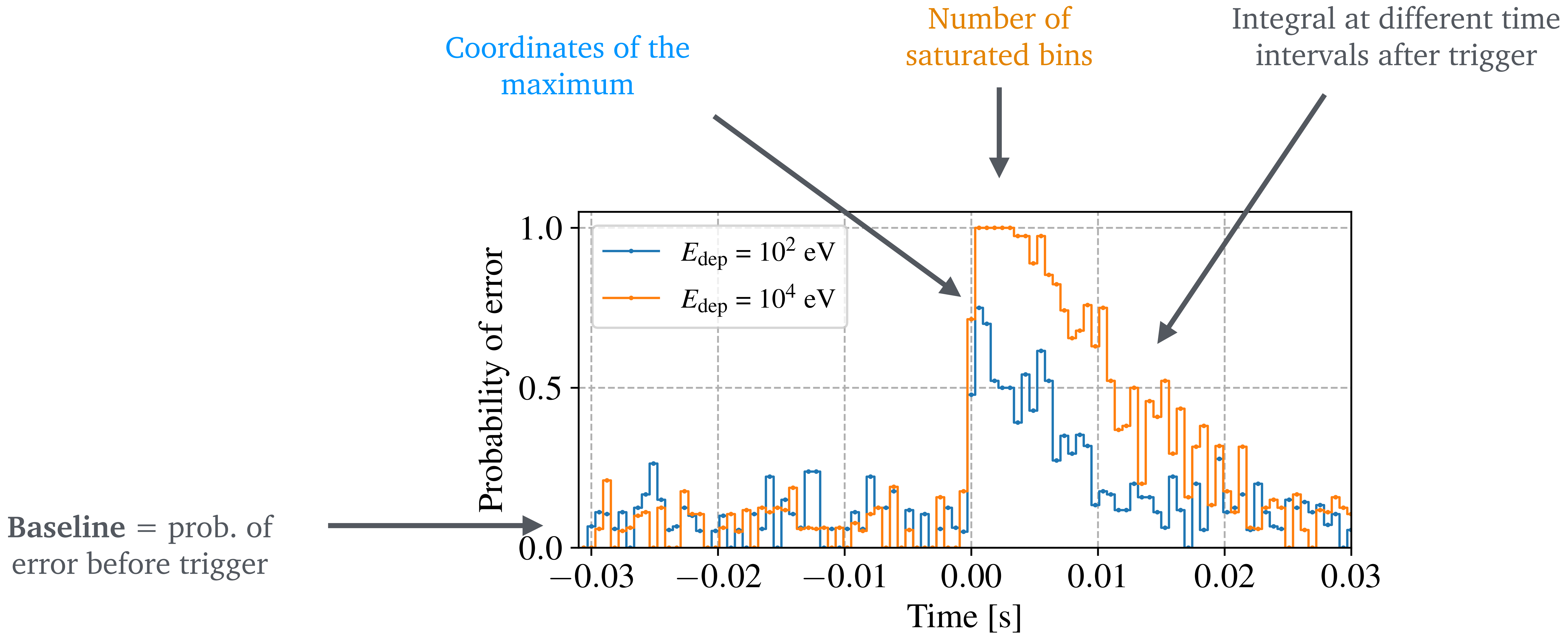


Example GaAs



Hernandez at al. (2024)

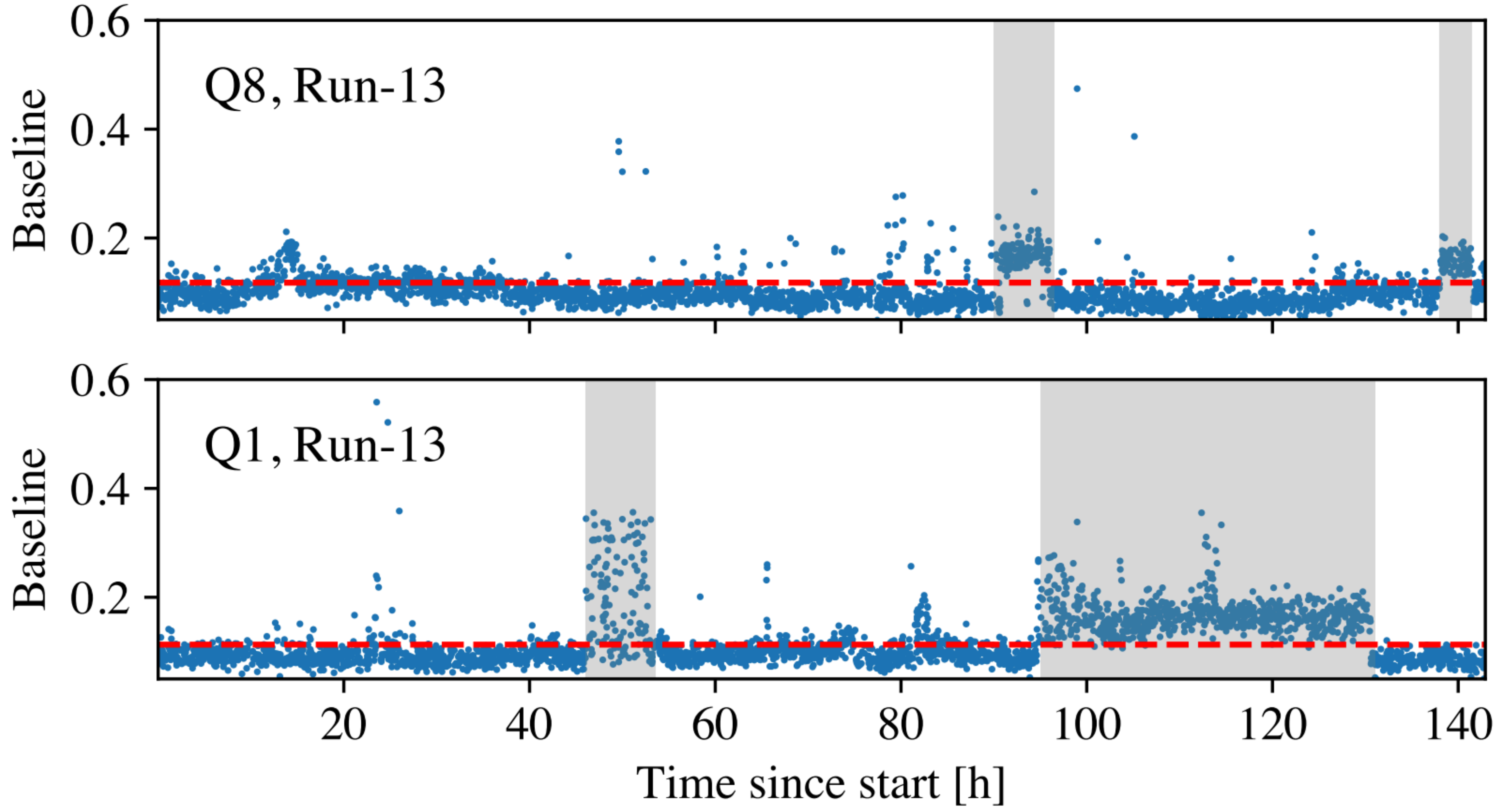
Base variables

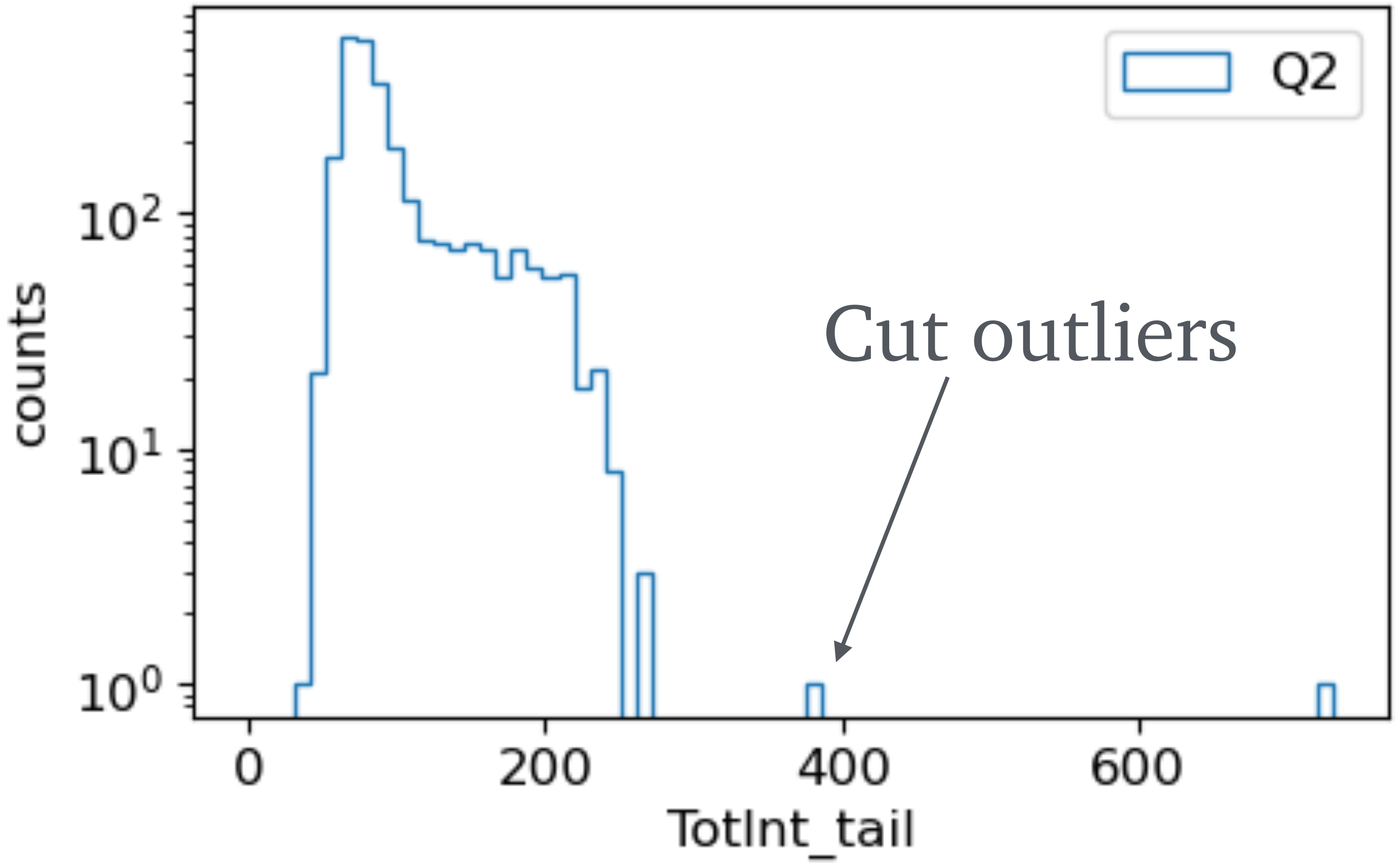


Events selection

- Baseline instabilities over time
  → typical Two Level Systems (TLS) behavior
- Quality cuts applied

	^{137}Cs run			Bkg run		
Qubit	Run-07			Run-13		
	ϵ_Q[%]	ϵ_A[%]	ϵ_{tot}[%]	ϵ_Q[%]	ϵ_A[%]	ϵ_{tot}[%]
Q1	76.5	85.5	65.3	63.5	84.9	54.2
Q2	92.4	86.0	79.4	93.3	86.4	81.0
Q4	92.8	84.1	78.2	93.0	84.3	78.1
Q5	74.6	86.0	64.8	91.6	85.0	77.8
Q8	79.7	85.7	68.3	85.9	86.0	73.8
all	36.2	43.9	16.2	41.7	44.6	18.6



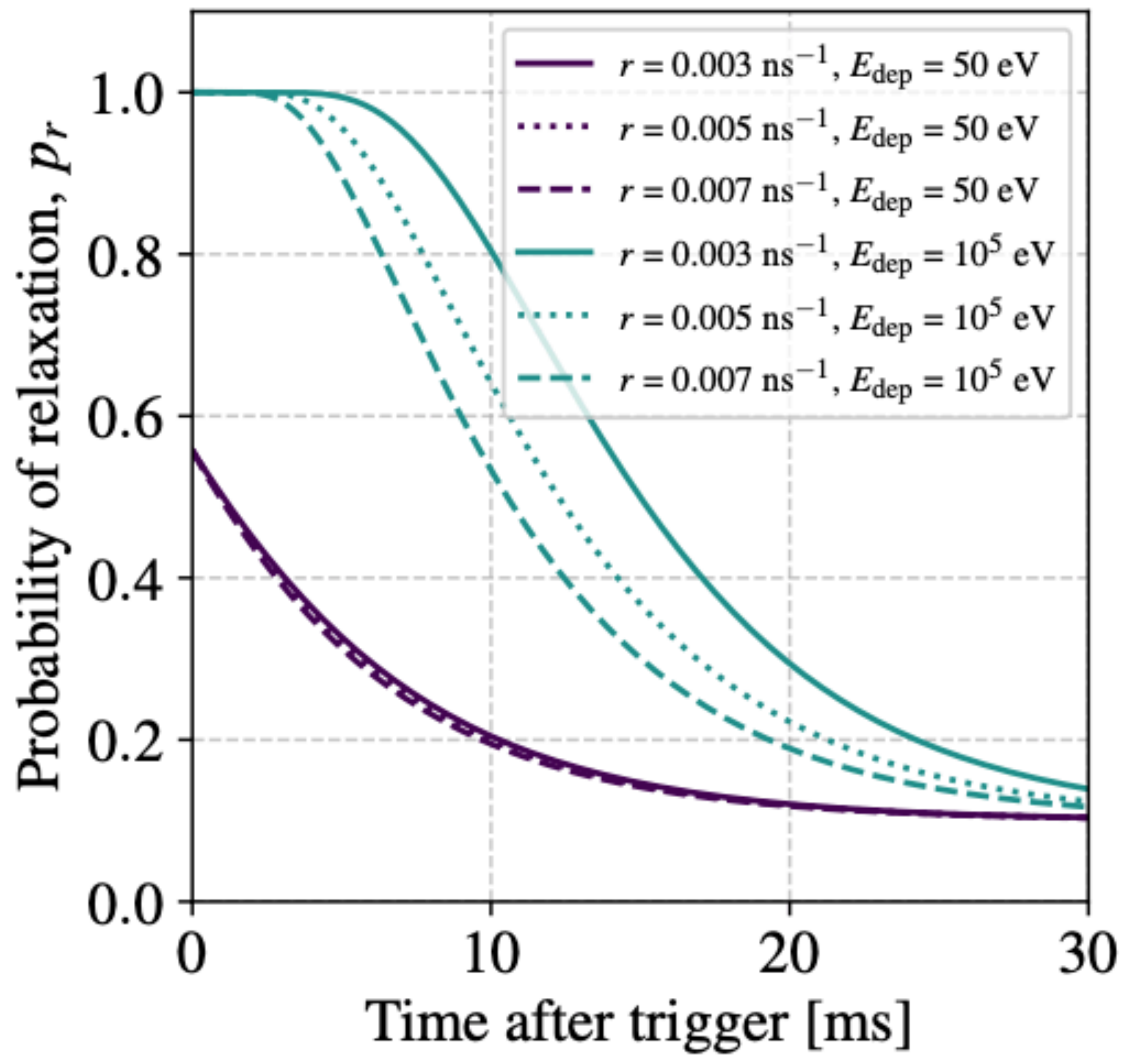


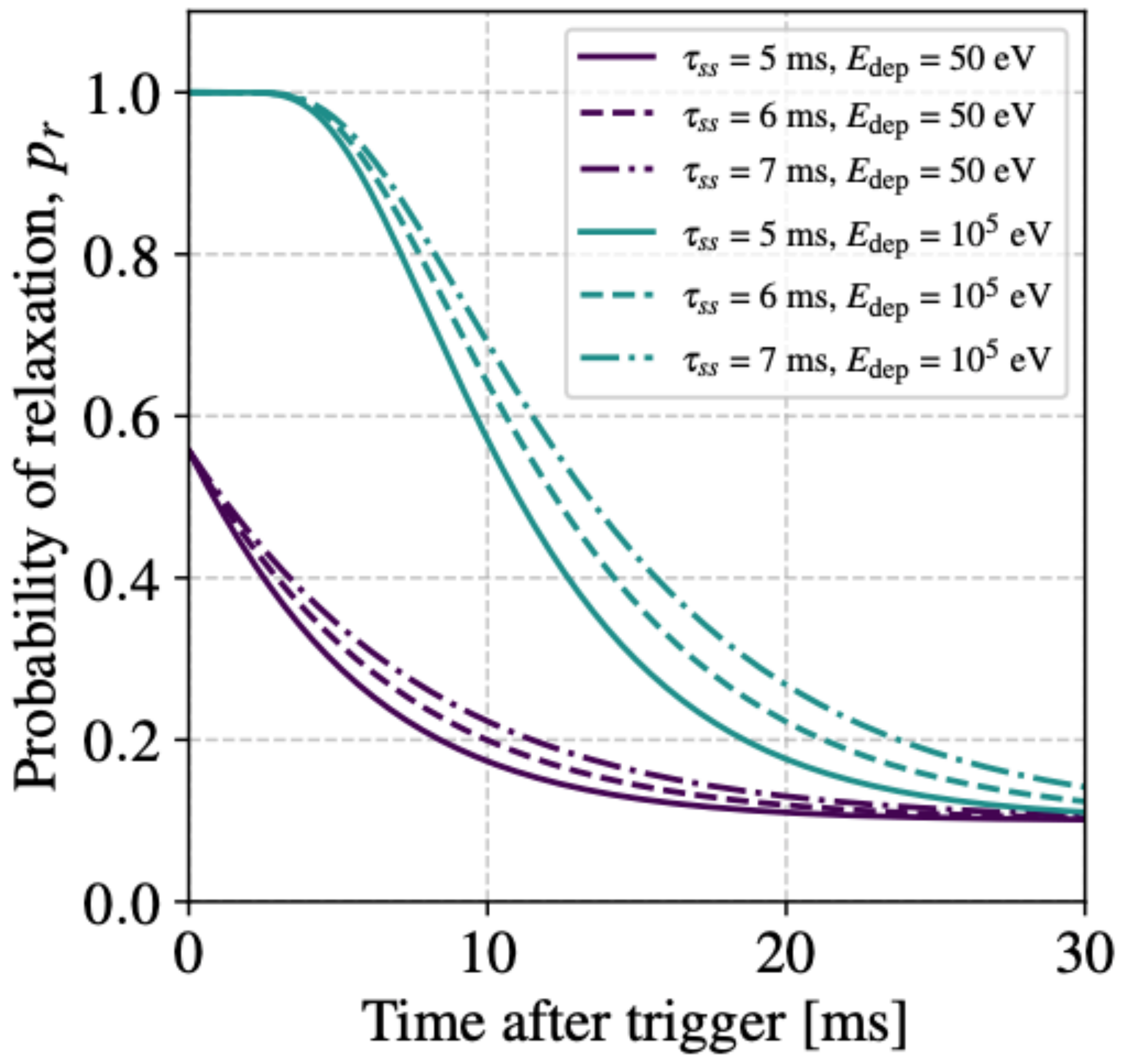
Average pulse

$$p_r = 1 - e^{-\Gamma(t)\Delta t}$$
$$= 1 - \exp\left[\frac{-\alpha E_{\rm dep}}{E_{\rm dep}[\tau_{ss} r(e^{t/\tau_{ss}} - 1)] + \beta e^{t/\tau_{ss}}} - \gamma\right].$$

Saturated events selection → number of saturated bins

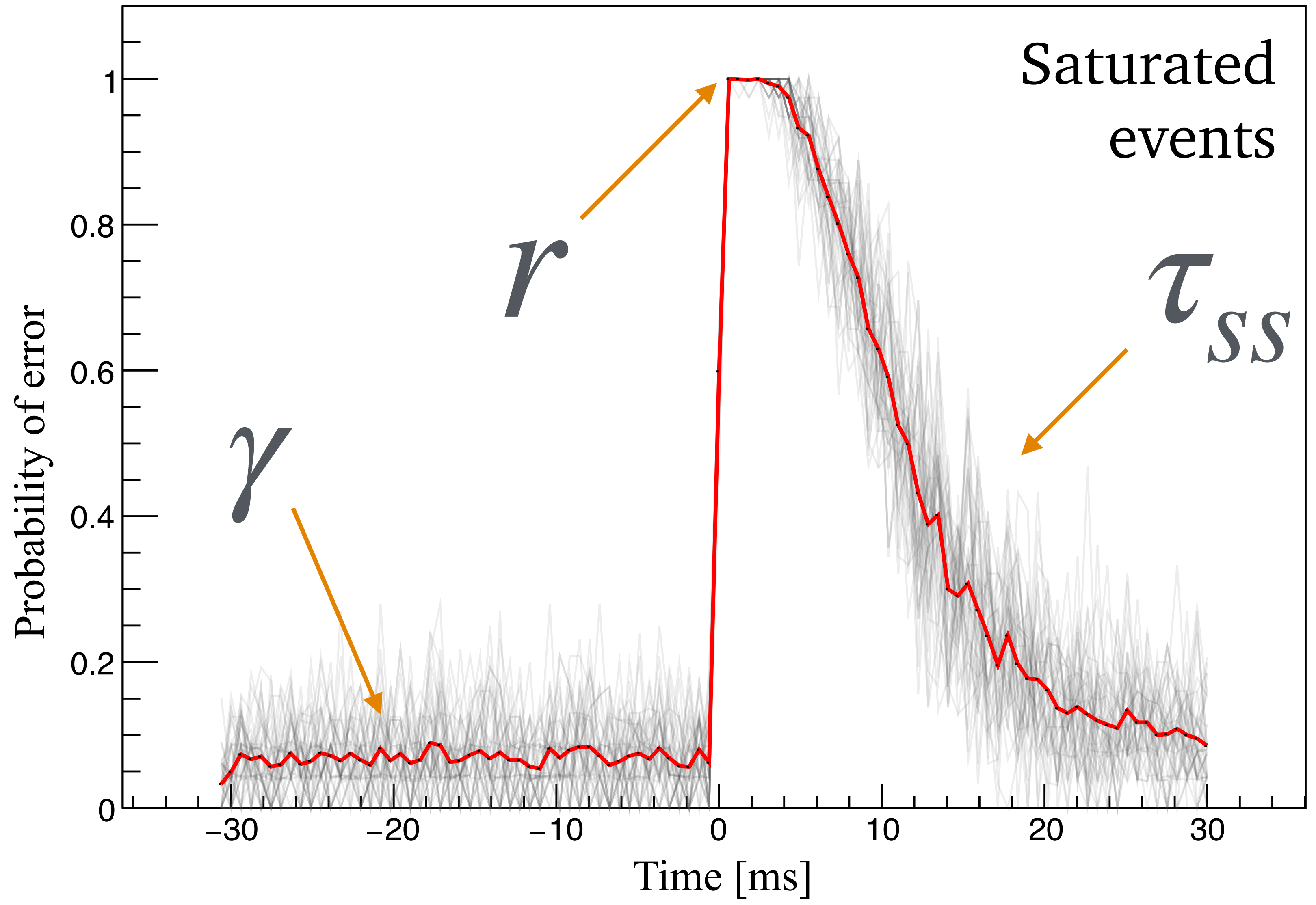
Low energy selection → Baseline RMS

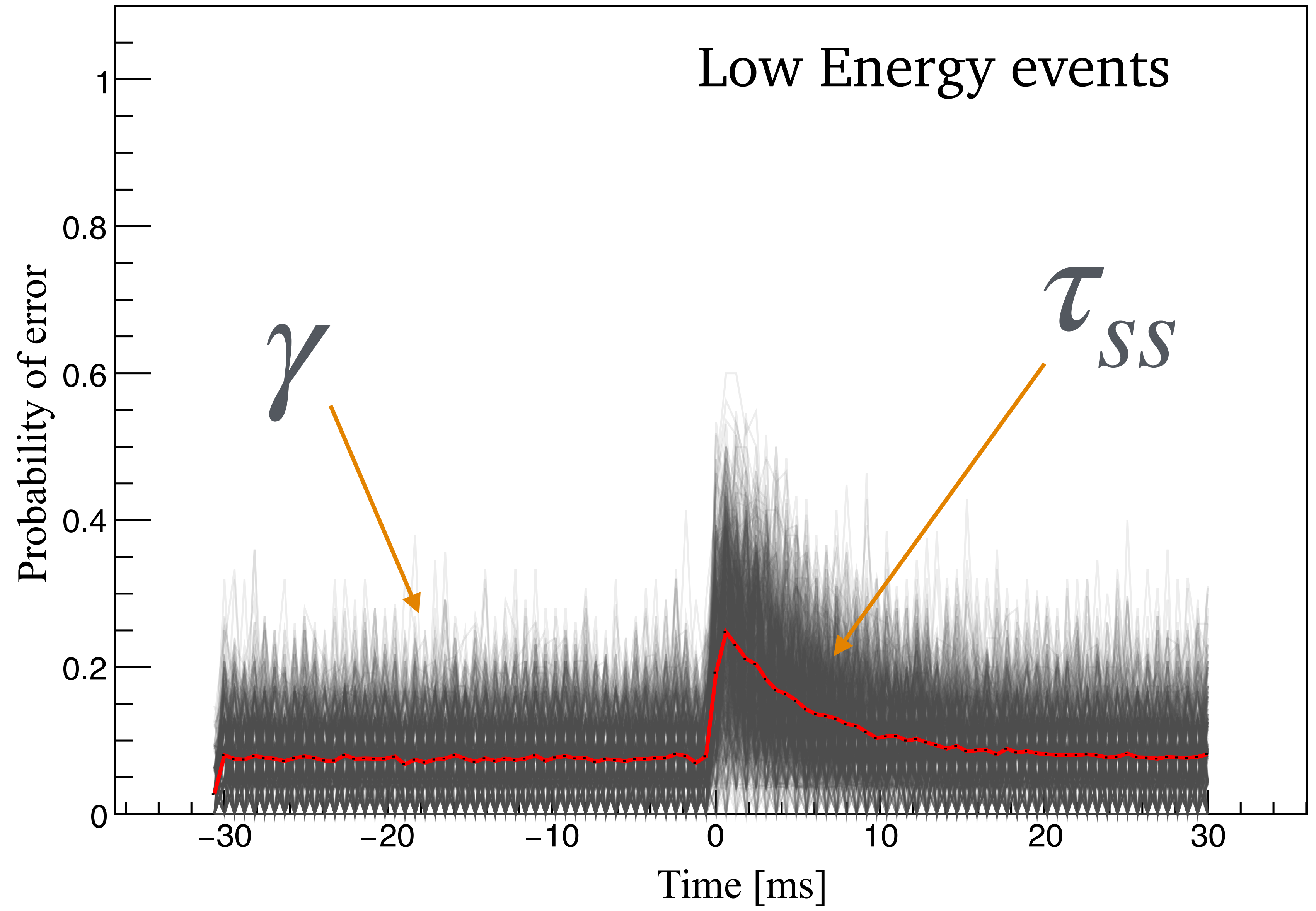




Red: Average pulse

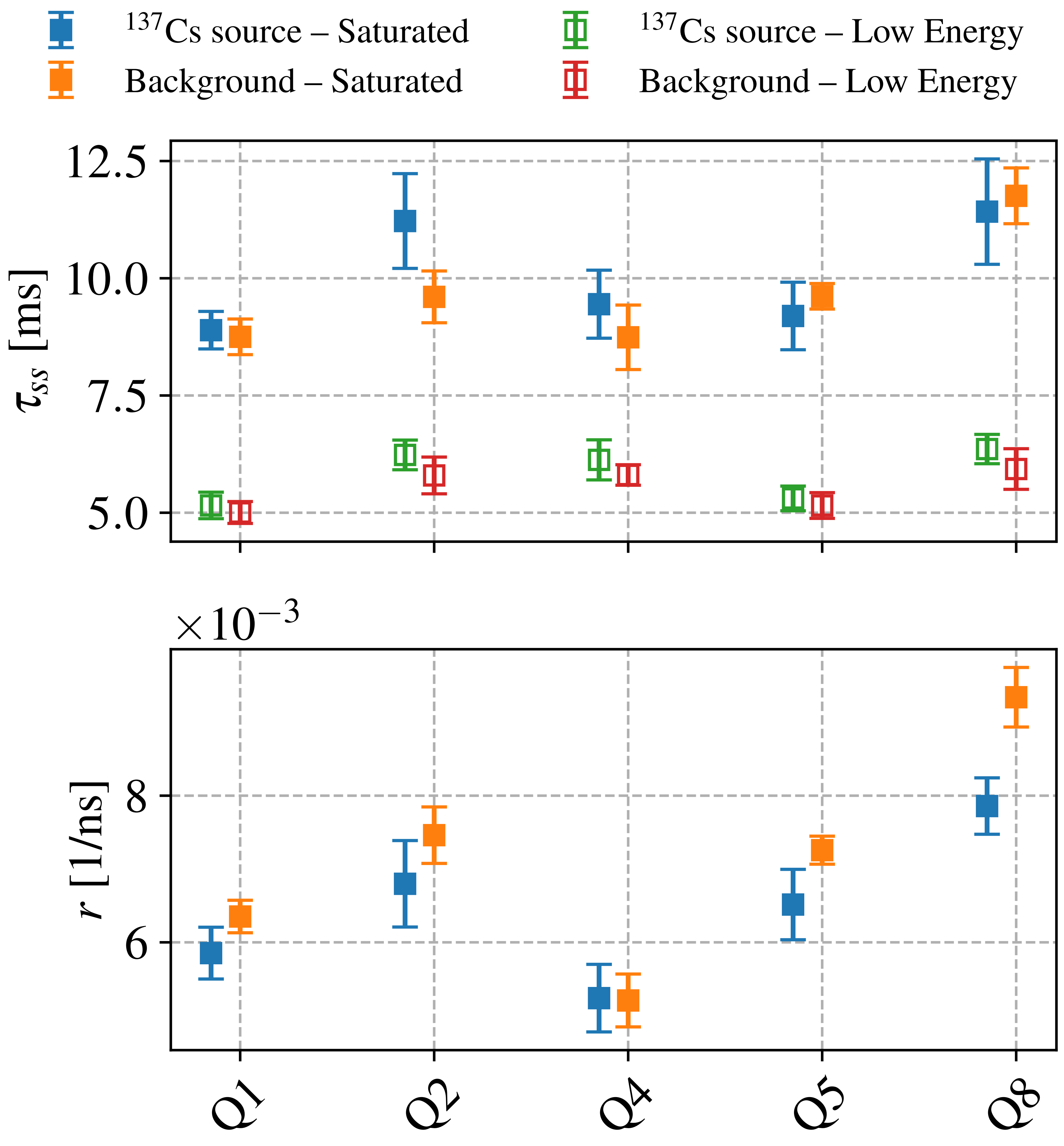
Grey: pulses averaged





Recombination constant results

- Good agreement among different datasets
- Previous measurements of ***r*** in the range 0.0059—0.125 ns^{-1}
- In line with previous results, we measured a factor 10 suppression respect to the theoretical expected value ***r* = 0.05** $\mathbf{ns^{-1}}$ in aluminum
- The analysis on saturated and low energy pulses shows an unexpected dependence of τ_{ss} on the energy deposited



→ other measurements artificially produced QP via phonon injectors or 3D cavities, we used only radioactivity!

Fit test with mock data

- Replicate pulse sequence following measurement scheme and QP density model with a set of input parameters
- Bias spotted on energy reconstruction for E_{dep}>500 eV