Readout and Noise Sensing Schemes for Qubit Detectors

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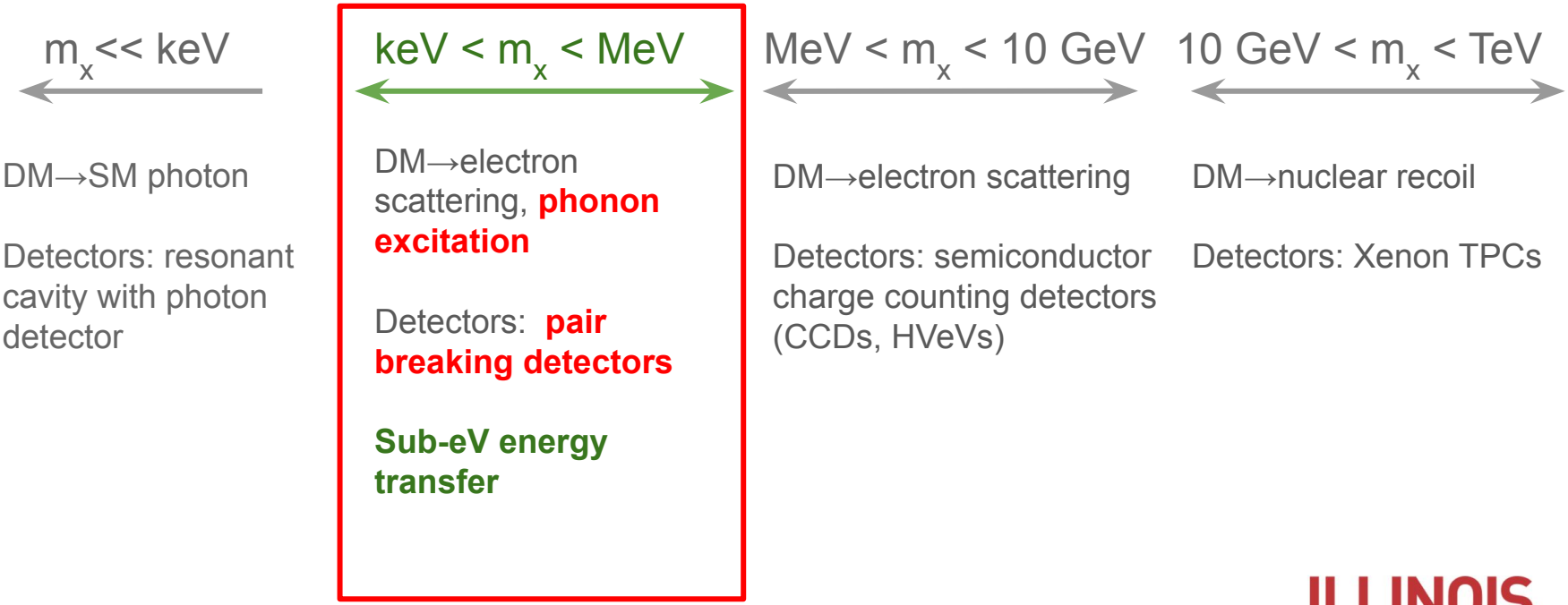
Fermilab ILLINOIS TECH

Dark Matter



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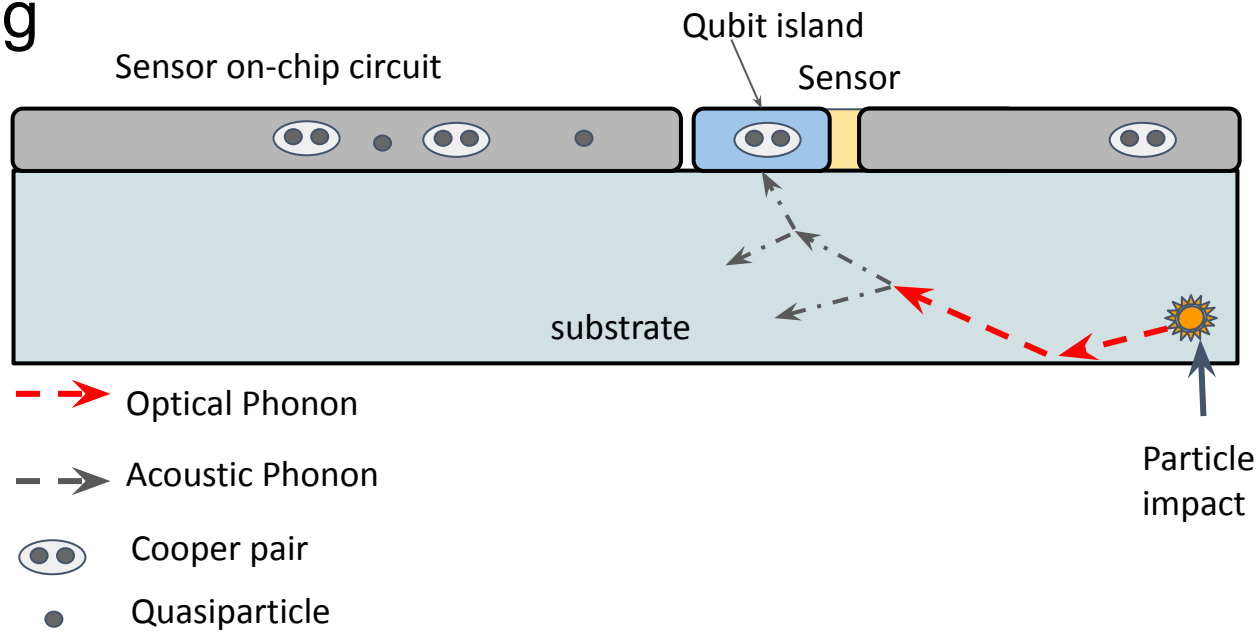
Pair Breaking Detectors: Particle Detection Via Phonon Sensing



- A particle deposits energy into the device substrate (sapphire) exciting phonons.
- Phonons zips through the chip scattering and downconverting to phonons.

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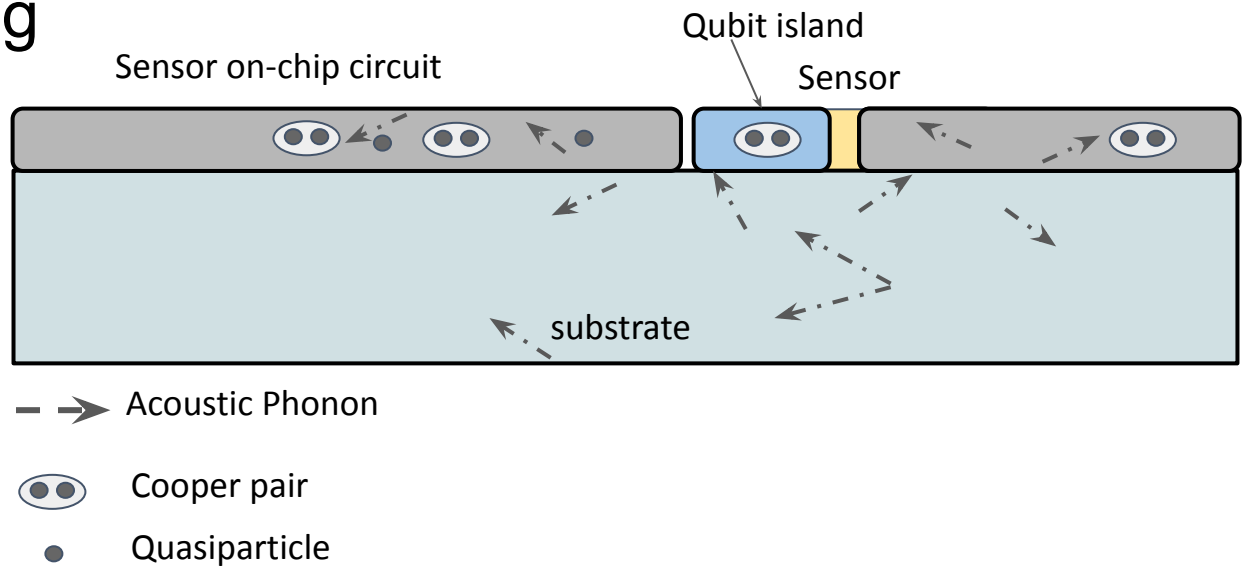
Pair Breaking Detectors: Particle Detection Via Phonon Sensing



- A fraction of the phonons are enter the superconductor film and break Cooper pairs.

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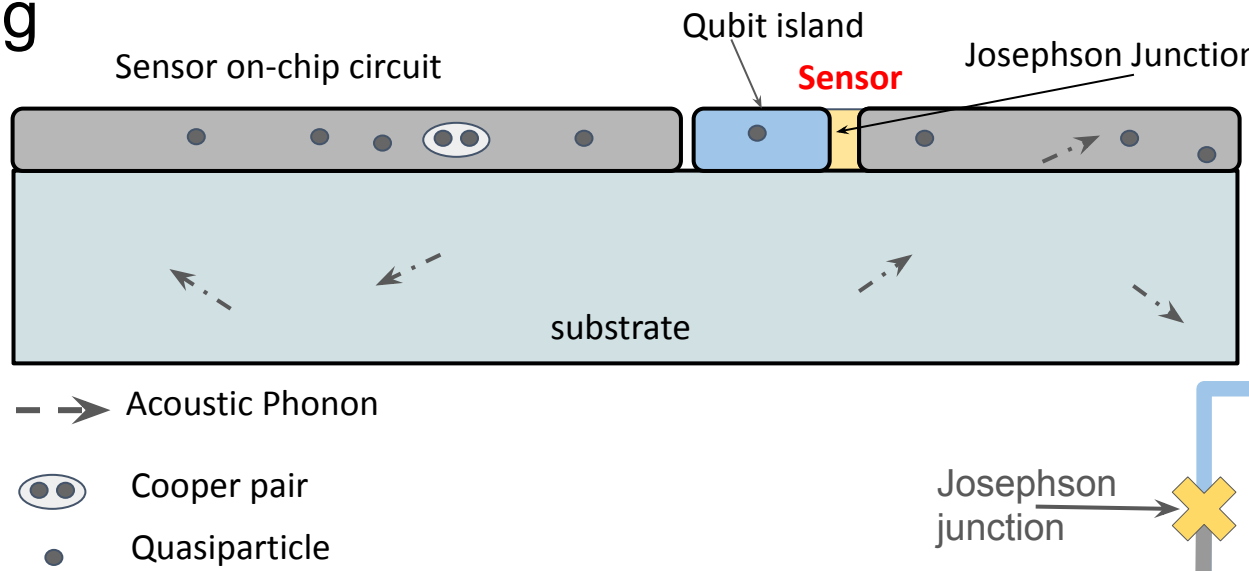
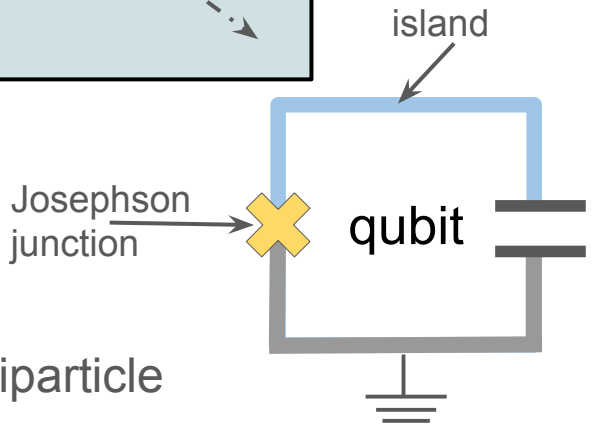
Pair Breaking Detectors: Particle Detection Via Phonon Sensing





- Sensor readout extracts the quasiparticle density
- Qubit: The density is probed by measuring the quasiparticle tunneling rate. (**decay and parity switching rate**)

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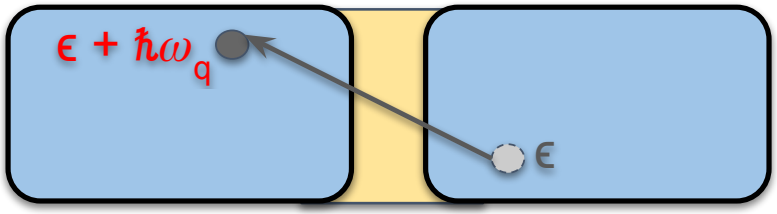
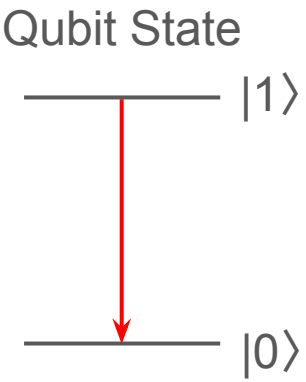
Qubit Relaxation





Qubit Parity

Even ↔ Odd

$$\Gamma_{10} = C_{10} x_{QP}$$

- Energy is transferred from the qubit to the tunneling quasiparticle, relaxing it.

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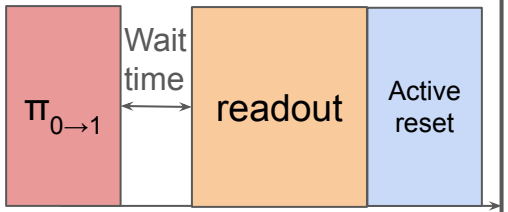
Energy Sensing With A Superconducting Qubit: Decay

Relaxation Scheme



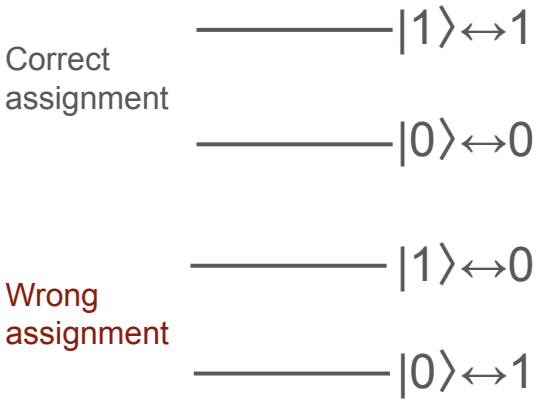
Signal = Readout value is 0

$P(signal) \approx P_{decay}*(1-\mathbf{P_{err}}) +$

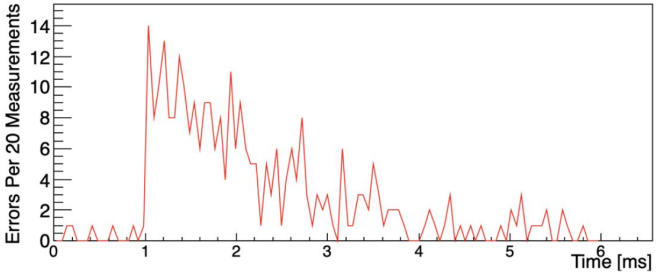
$(1-P_{decay})*\mathbf{P_{err}}$

$P_{decay} = P_{QP\text{-}decay} + \mathbf{P_{NQP\text{-}decay}}$

Qubit state readout



Simulated Waveform: Relaxation



Waveform generated from number of 0s per 20 measurements

Noise Sources: **Non-QP decay, Readout errors**

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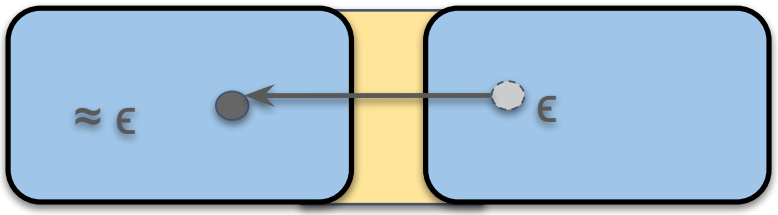
Parity Switching



Qubit State — Qubit Parity

$|1\rangle$

Even ↔ Odd

$|0\rangle$

$$\Gamma_{00} = C_{00}\mathbf{x}_{QP}$$

- The qubit's logical state is preserved

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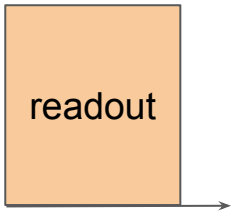
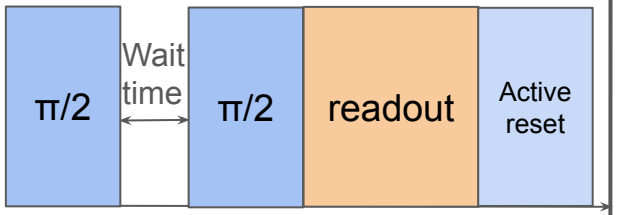
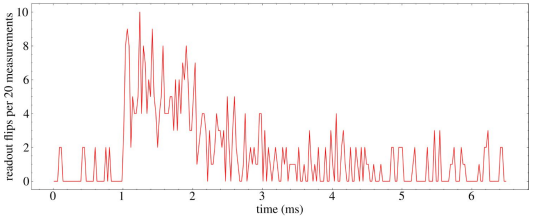
Energy Sensing With A Superconducting Qubit: Parity

Parity Measurement Scheme

Direct Parity Measurement	Ramsey Parity Measurement
 arXiv:2405.17192	
Signal = Readout flip $\|0\rangle \leftrightarrow \|1\rangle$ between consecutive shots	Signal = Readout flip $\|0\rangle \leftrightarrow \|1\rangle$between consecutive shots
$P(\text{signal}) \approx (P_{switch})*(P_{noth} + \mathbf{P_{err}} + P_{switch})$ $+ 2P_{noth}*\mathbf{P_{err}}$	$P(\text{signal}) \approx (P_{switch} + P_{QP\text{-}decay} + 2\mathbf{P}_{NQP\text{-}decay} +2\mathbf{P_{err}})$

Simulated Waveform: Ramsey



Waveform generated from number of flips per 20 measurements

Noise Sources: **Non-QP decay, Readout errors**

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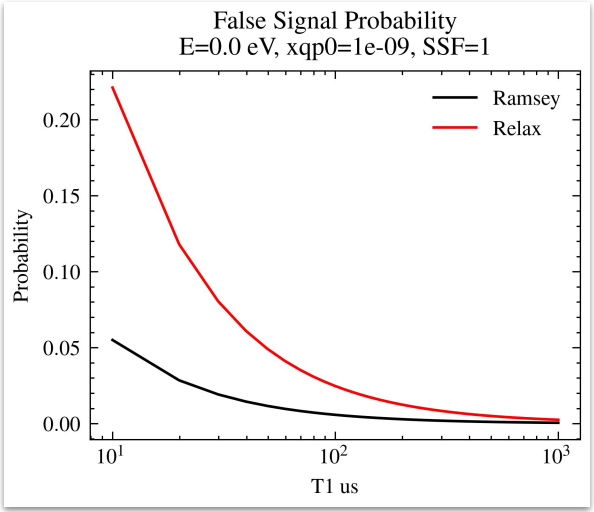
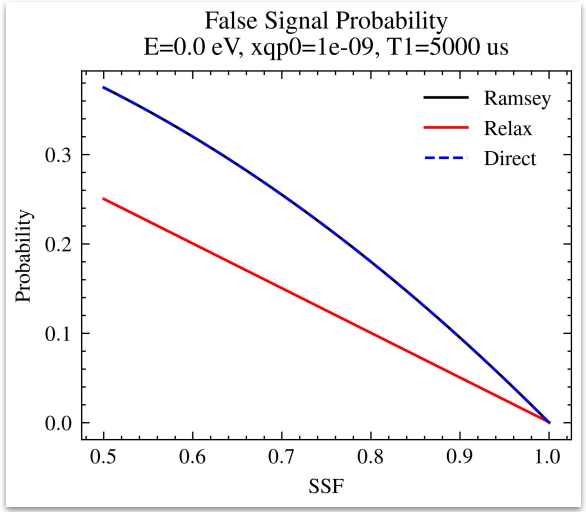
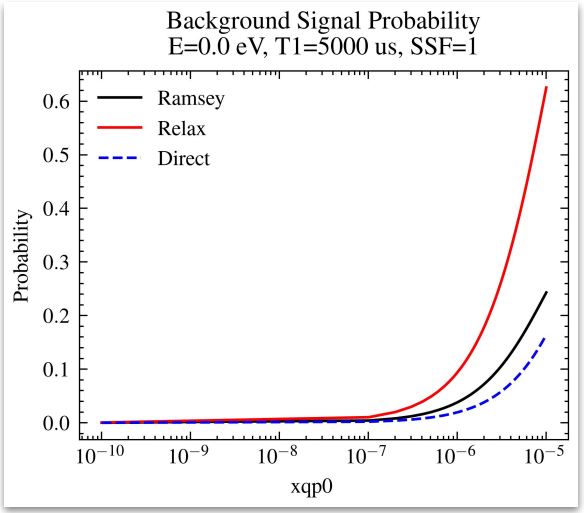
False Signal Contributions And The Baseline Signal







The contribution of **non-QP qubit decays** to **false signals.**

The contribution of **readout errors** to **false signals**

The **baseline signal** contribution from the **background parity switching** rate.

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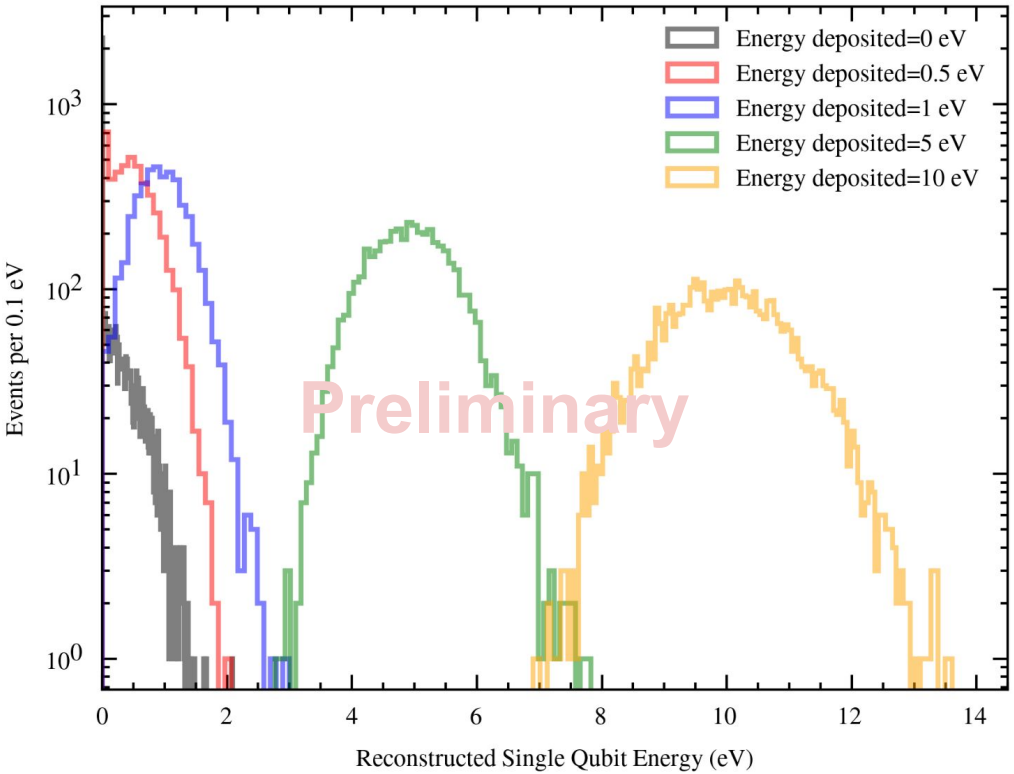
Results From Simulation Of The Ramsey Method

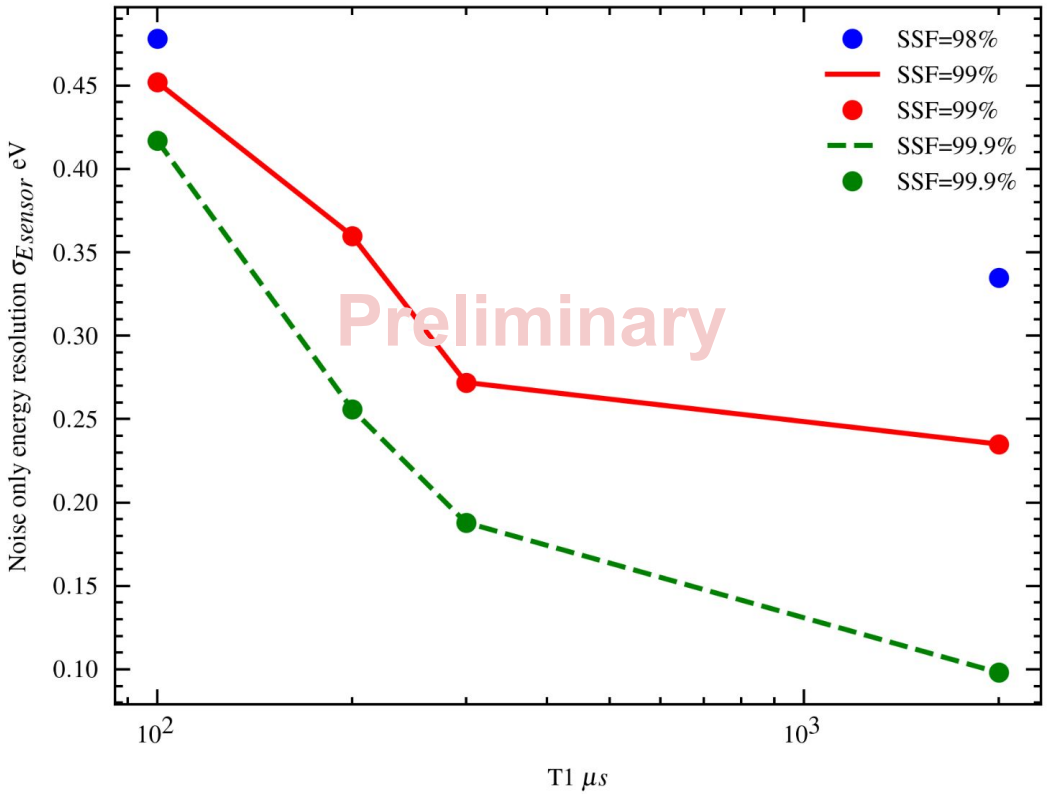


Reconstructed energy from **simulated** Ramsey method where energy is deposited into a **single aluminum qubit island**.

The simulated qubit has:

- **xqp0 = 10^{-9}**
- **phonon to QP efficiency η_{qp}=0.6**
- **T1= 100 us** and
- **Readout fidelity = 98%**,
- resulting in a **sensor resolution $\sigma_{E,sensor}$ = 0.47 eV**

Estimate Of Energy Resolution Of The Ramsey Method



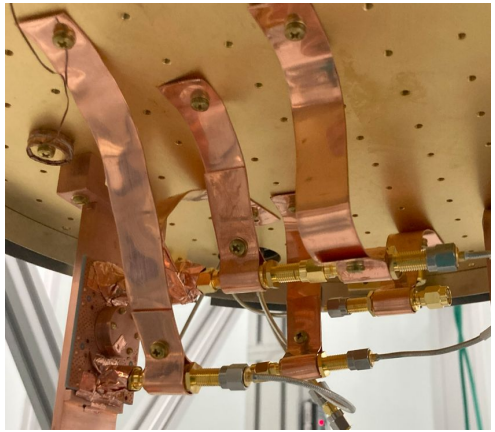
Preliminary energy resolutions estimation from noise only Ramsey **simulations**.

The simulated qubit has:

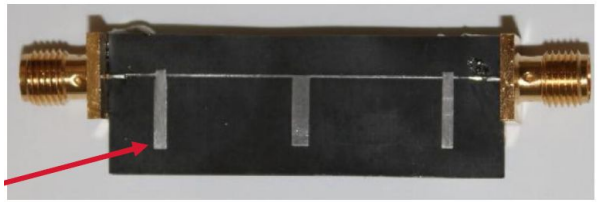
- **xqp0 = 10^{-9}**

Steps To Improve Sensitivity

- Increase **IR filtering/shielding** to reduce baseline χ_{QP}.
- **Integrate parametric amplifiers**.
- Investigate **charge fluctuation**



Parametric amplifier



Improved IR filtering

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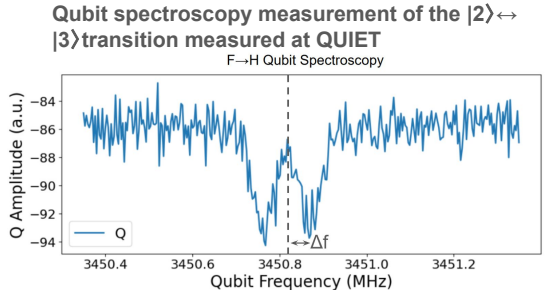
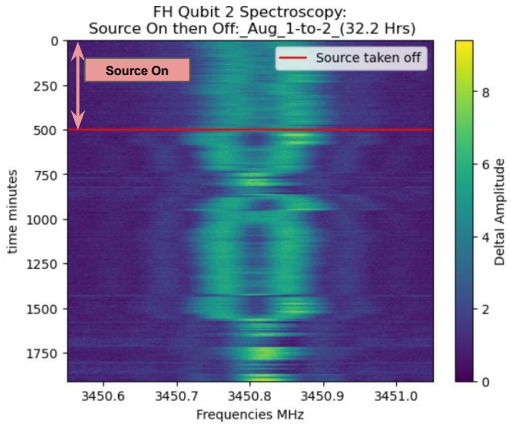
Offset Charge Fluctuation Of a Ta-on-Sapphire Transmon

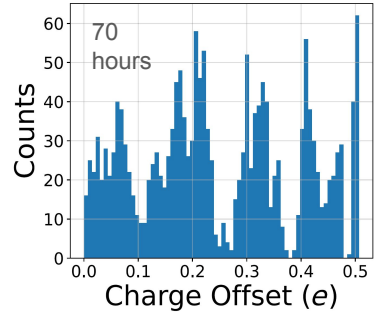
DOI: 10.1103/PRXQuantum.3.030307

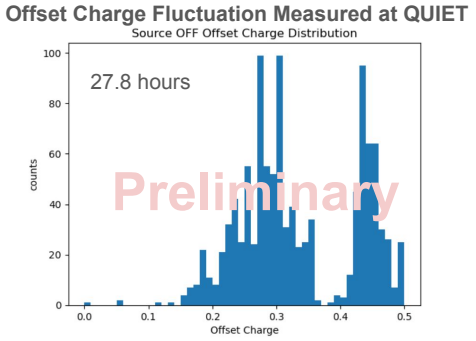
- Investigating the **charge fluctuation** of our qubits to develop ways of mitigating dephasing errors
- Monitored the **offset charge** via the $|2\rangle \leftrightarrow |3\rangle$ transition frequency
- With further investigation we will identify the quasi-stable offset charge states and quantify the rate of charge fluctuation.

$$f = f_c + \Delta f \cdot \cos(2\pi n_g)$$









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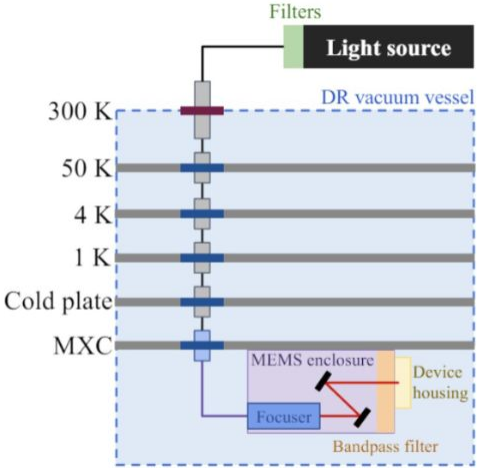
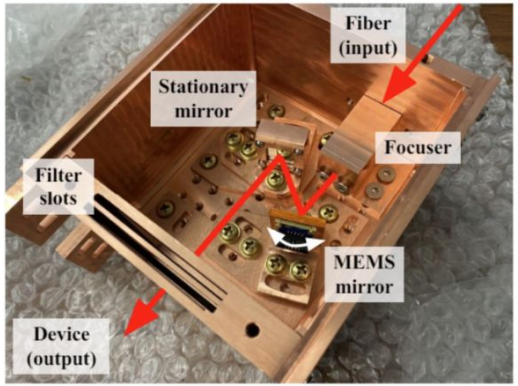
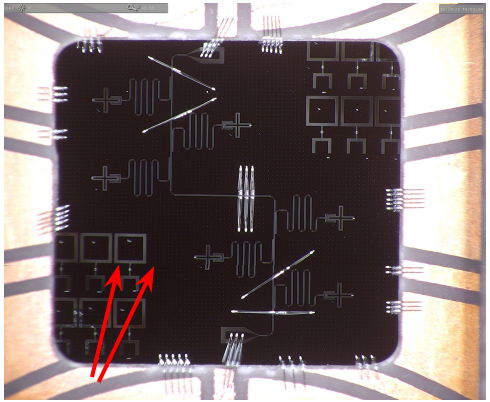
Next Steps: Measurement



Optical Path



Cryogenic setup for with steerable mirror


Witness junctions for phonon generation

Fabricated By Sara Sussman (Fermilab)

- Monitor the quasiparticle tunneling rate after energy deposition in the substrate/superconducting film via:
  - **Cryogenic steerable photon source**
  - **Phonon generating junctions**

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Summary

- The qubit can be used to detect particle impacts by probing the quasiparticle density via monitoring the
  - Qubit relaxation rate
  - Qubit parity switching rate
- Improving the IR population near the qubit to reduce the background
- Characterizing the detectors with a photon source and phonon injector junctions.

This work will enable us to develop an understanding of energy dissipation in qubits and move closer to building a prototype dark matter detector.

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Acknowledgments

- **IIT**: Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Jialin Yu
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Supplementary

Dark Matter Candidates, Their Detection Channels And Best Target materials

TABLE II. Summary of our results. The material properties relevant for the optimization of the target are the atomic mass number A, proton number Z, electronic band gap E_g, speed of sound c_s, optical phonon energy ω_O, average phonon energy ω_{ph}, and the Born effective charges and the high-frequency dielectric constant that enter the quality factor Q. Achieving lower detector energy thresholds ω_{min} is also crucial in several cases.

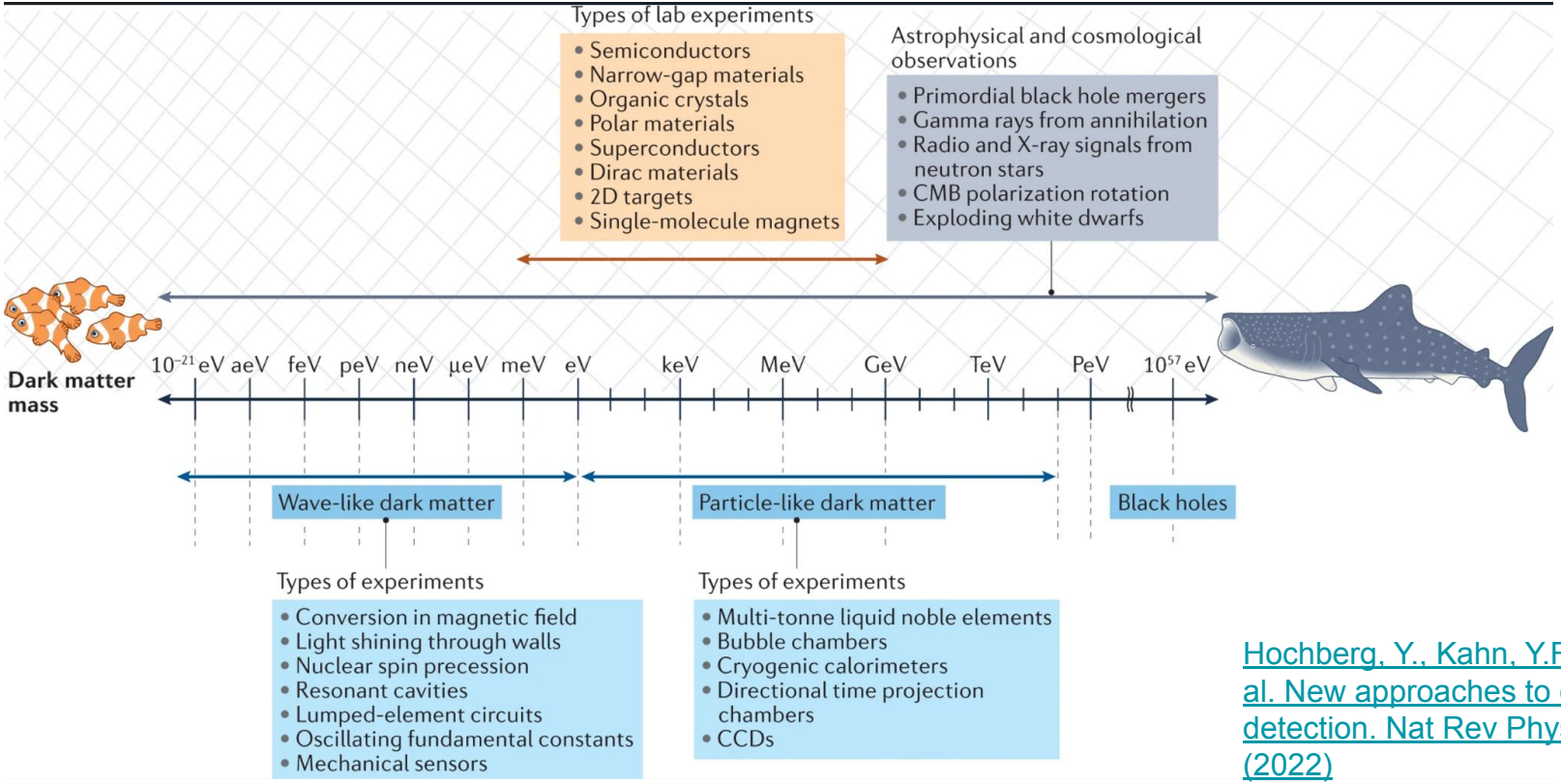
Light dark photon mediator (Sec. III, Fig. 1)

	Quantity to maximize to reach …		
Detection channel	… lower m_χ	… lower $\bar{\sigma}_e$	Best materials
(Optical) phonons	ω_O^{-1} [Eq. (24)]	Quality factor Q defined in Eq. (27)	SiO_2, Al_2O_3, $CaWO_4$
Electron transitions	E_g^{-1} [Eq. (28)]	Depends on details of electron wave functions	InSb, Si
Nuclear recoils	$(A\omega_{\mathrm{min}})^{-1}$ [Eq. (29)]	$(Z/A)^2\omega_{\mathrm{min}}^{-1}$ [Eq. (31)]	Diamond, LiF

Hadrophilic scalar mediator (Sec. IV, Figs. 2, 3)

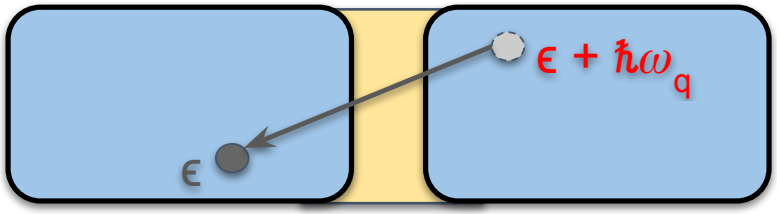
	Quantity to maximize to reach …		
Detection channel	… lower m_χ	… lower $\bar{\sigma}_n$	Best materials
(Acoustic) phonons	$c_s/\omega_{\mathrm{min}}$ [Eq. (36)]	Light mediator: $\omega_{\mathrm{min}}^{-1}$ [Eq. (35)] Heavy mediator: c_s^{-1} or $\omega_{\mathrm{ph}}^{-1}$ or $A\omega_{\mathrm{ph}}$ depending on m_χ [Eqs. (37), (38), (39)]	Diamond, SiO_2 All complementary
Nuclear recoils	$(A\omega_{\mathrm{min}})^{-1}$ [Eq. (29)]	Light mediator: $\omega_{\mathrm{min}}^{-1}$ [Eq. (40)] Heavy mediator: A [Eq. (43)]	Diamond, LiF CsI, Pb compounds

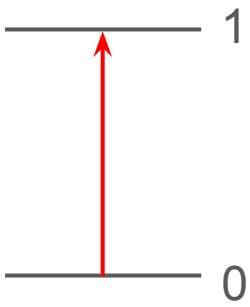
Dark Matter Mass Range And Corresponding Detectors



Hochberg, Y., Kahn, Y.F., Leane, R.K. et al. New approaches to dark matter detection. Nat Rev Phys 4, 637–641 (2022)

Qubit Heating





Even ↔ Odd

- Energy is transferred to the qubit from the tunneling quasiparticle, exciting it.
- $\Gamma_{01} = C_{01}\chi_{QP}$

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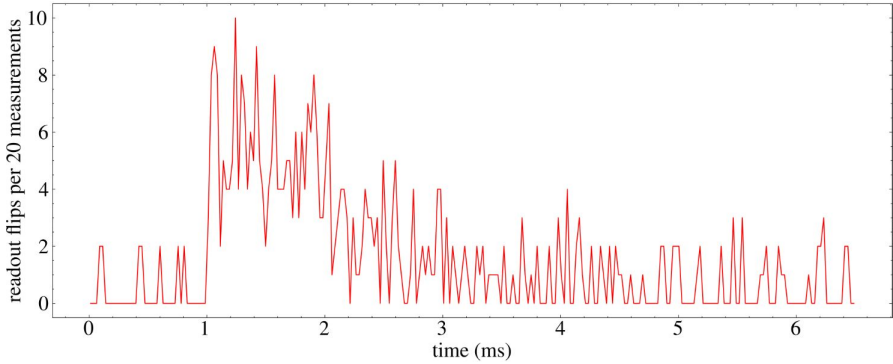
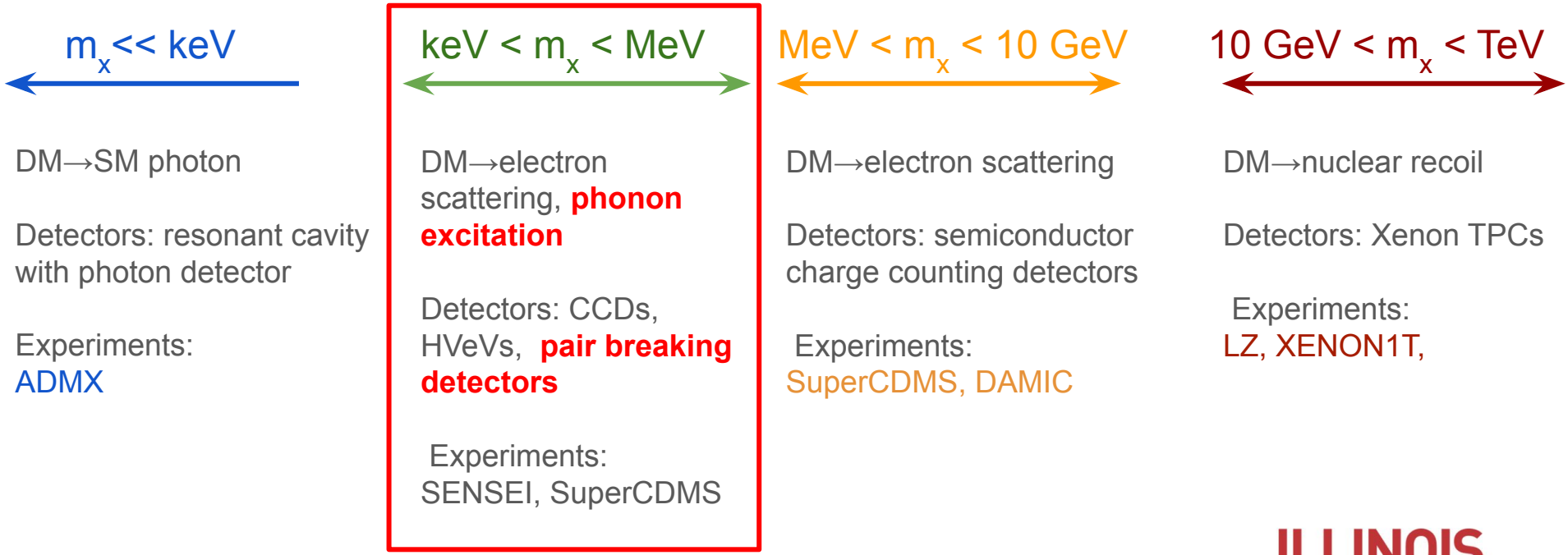

readout flips per 20 measurements
0
2
4
6
8
10
0
1
2
3
4
5
6
time (ms)

Dark Matter



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