RDC8 - Pairbreaking detectors

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Initial comments

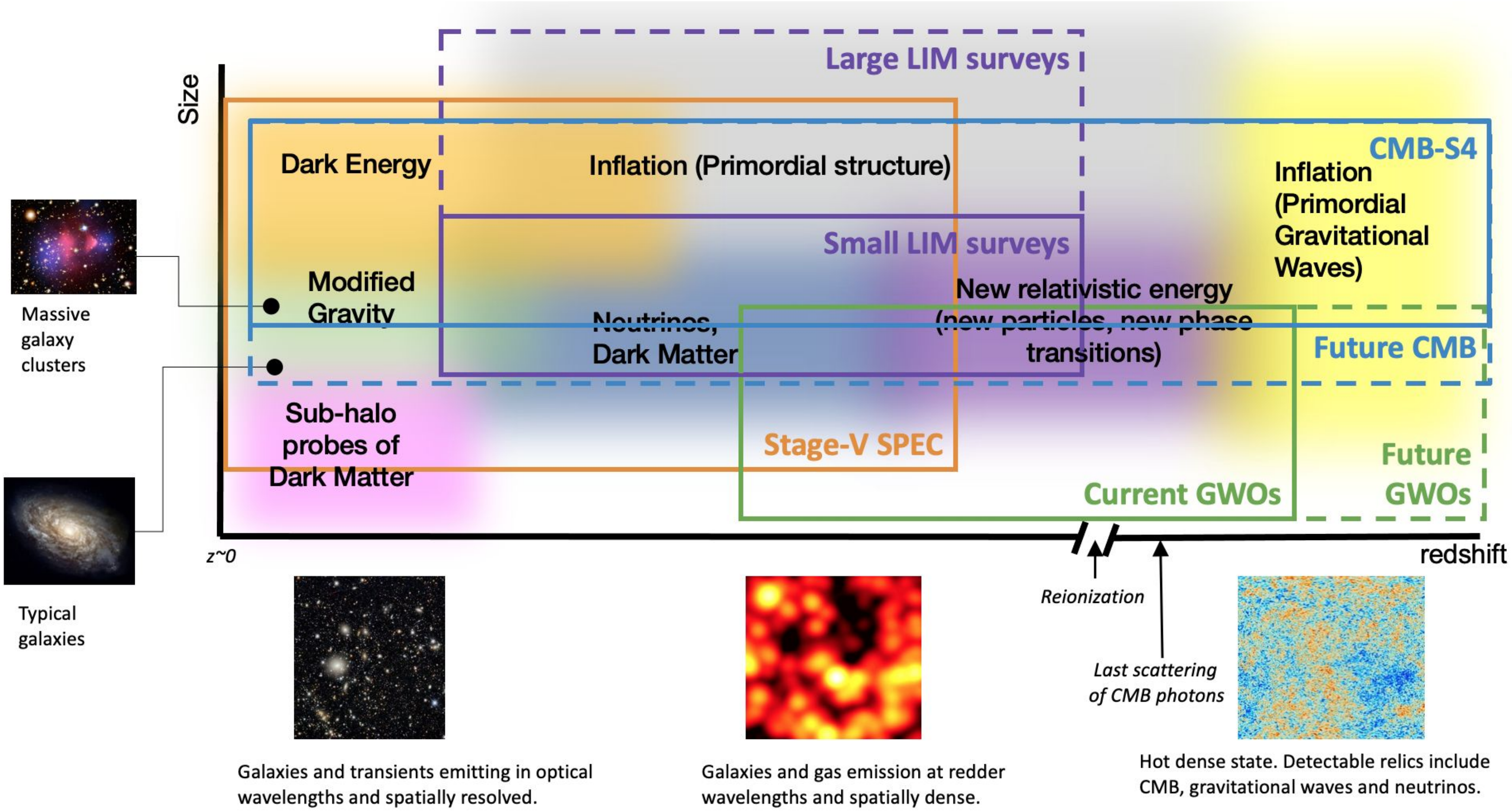
- Very broad topic!
  - Varied (and growing) technical approaches
  - Growing list of applications
- “Pair breaking”
  - Refers to detection schemes where signal power is dissipated at the key sensing element
  - Contrast to sensing schemes that coherently amplify, upconvert, mix, etc… prior to power dissipation

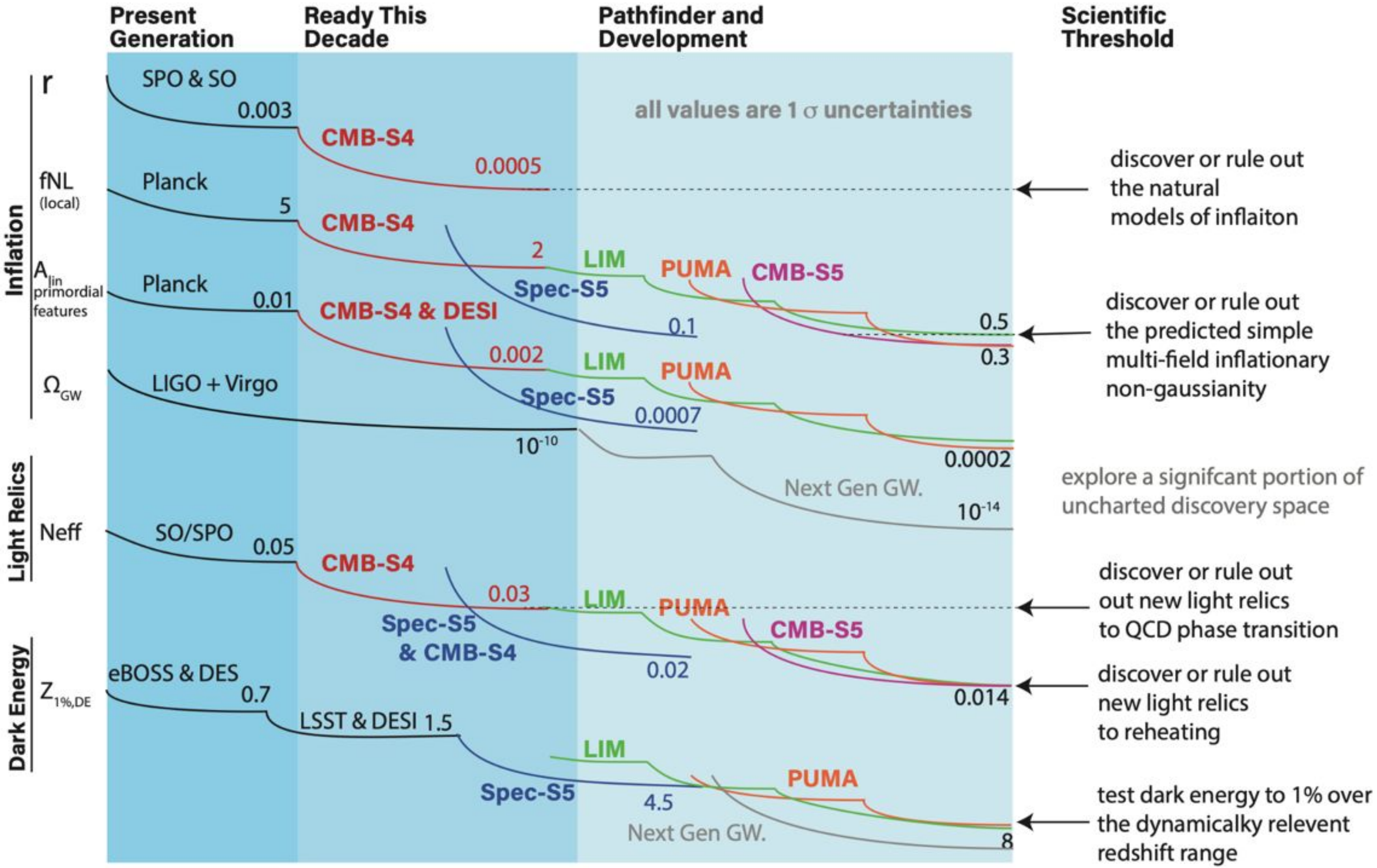
Outline

- Brief overview of HEP science drivers
- Breakdown by broad classes of technologies
  - TES
  - MKIDs
  - Junction-based devices (qubits, QCD, etc…)
  - S"N”SPDs

Science drivers

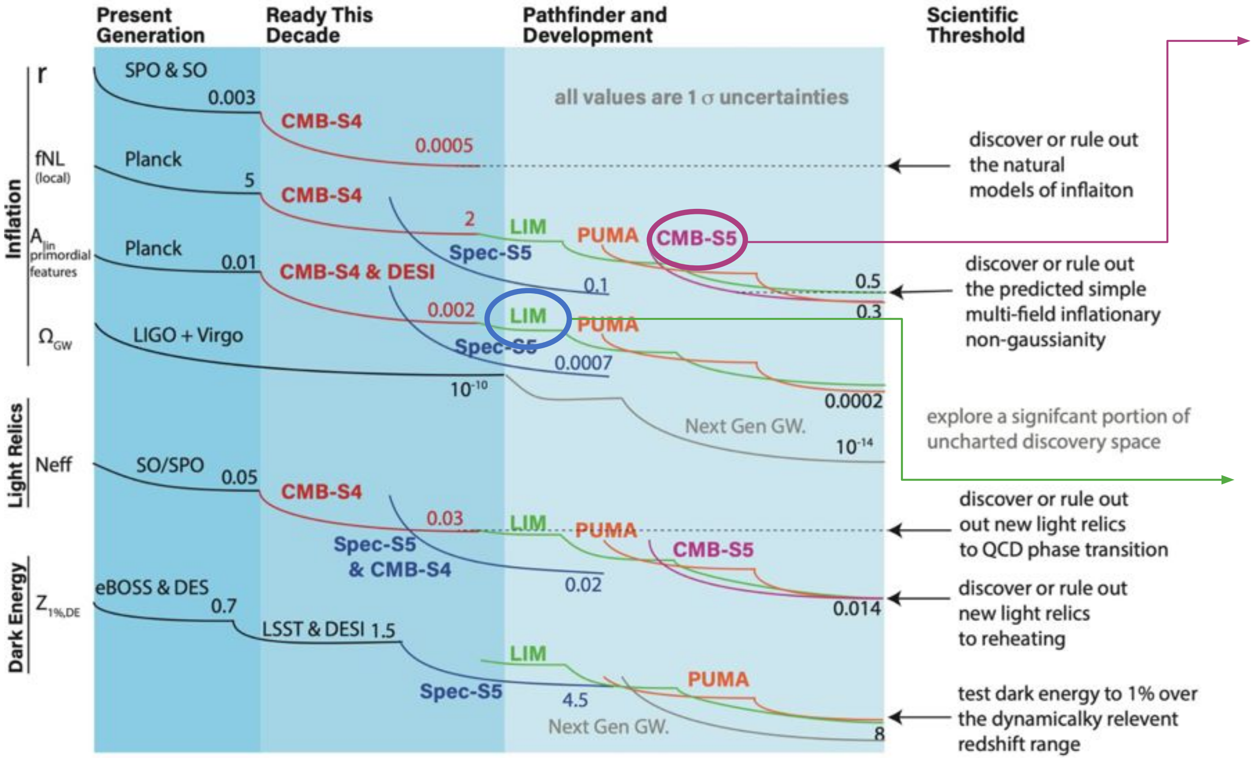
Cosmological Surveys





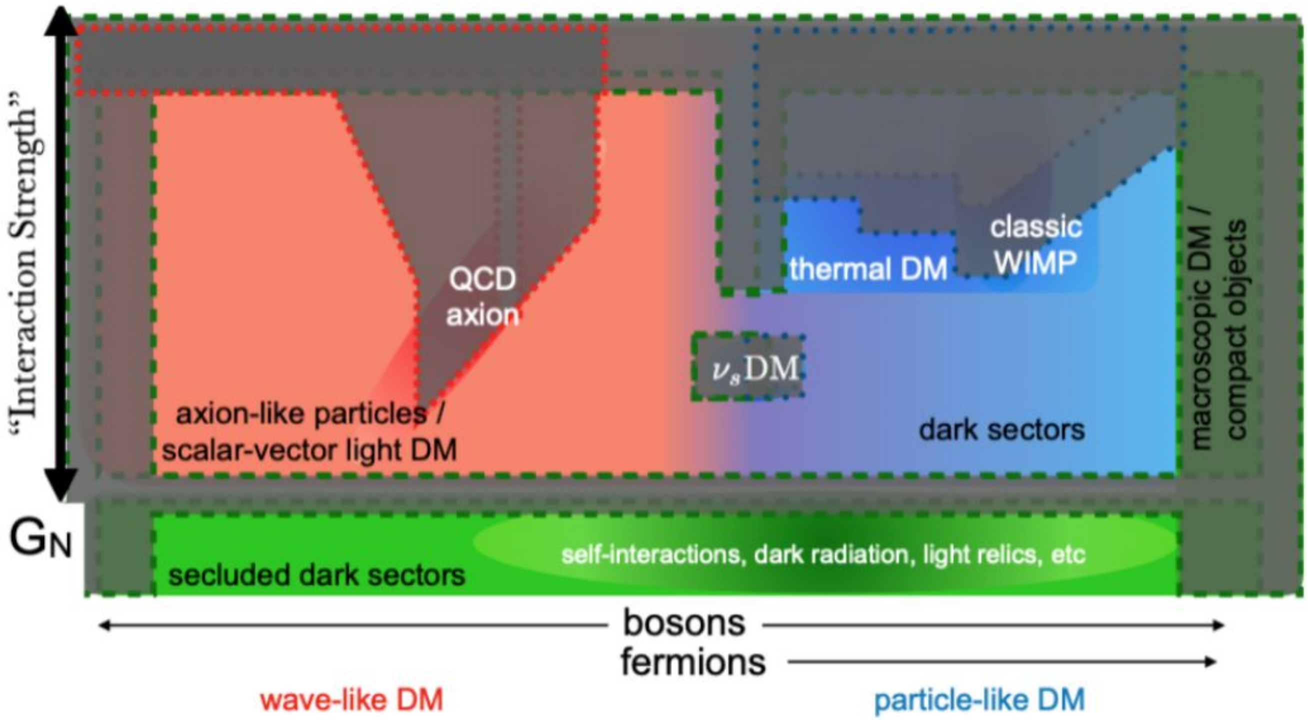
Present Generation
Ready This Decade
Pathfinder and Development
Scientific Threshold
Inflation
r
SPO & SO
0.003
CMB-S4
0.0005
all values are 1 σ uncertainties
discover or rule out the natural models of inflaiton
fNL (local)
Planck
5
CMB-S4
2
LIM
PUMA
CMB-S5
Spec-S5
0.1
0.5
0.3
A lin primordial features
Planck
0.01
CMB-S4 & DESI
0.002
LIM
PUMA
Spec-S5
0.0007
0.0002
discover or rule out the predicted simple multi-field inflationary non-gaussianity
Ω GW
LIGO + Virgo
10-10
Next Gen GW.
10-14
explore a signifcant portion of uncharted discovery space
Light Relics
Neff
SO/SPO
0.05
CMB-S4
0.03
LIM
PUMA
CMB-S5
Spec-S5 & CMB-S4
0.02
0.014
discover or rule out out new light relics to QCD phase transition
discover or rule out new light relics to reheating
Dark Energy
Z 1%,DE
eBOSS & DES
0.7
LSST & DESI 1.5
LIM
PUMA
Spec-S5
4.5
Next Gen GW.
8
test dark energy to 1% over the dynamicalky relevent redshift range

MM-WAVE COSMOLOGY



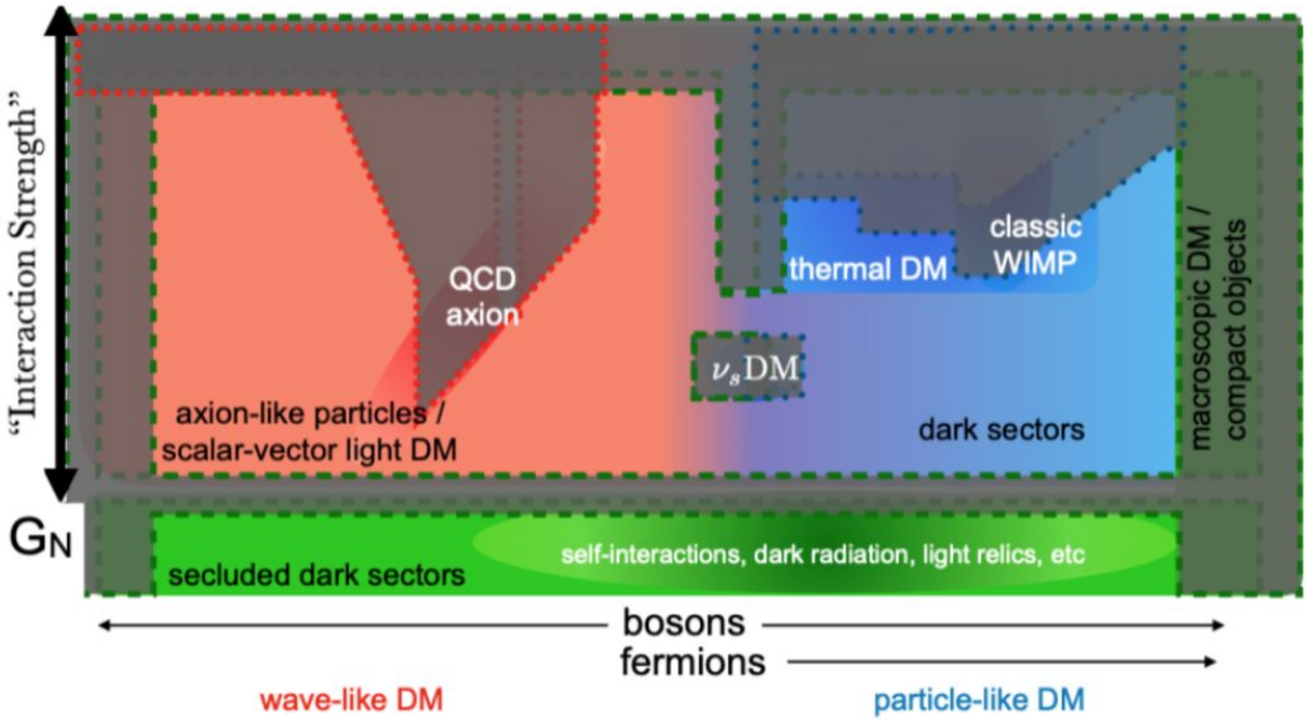
- CMB imaging at higher frequencies & resolution
  - New CMB scattering (kSZ, Rayleigh)
  - Requires 10x increase in densities typical for CMB experiment
- Mm-wave spectroscopy for Line Intensity Mapping
  - 3D survey of large volume universe
  - Requires >100x current densities for CMB experiment

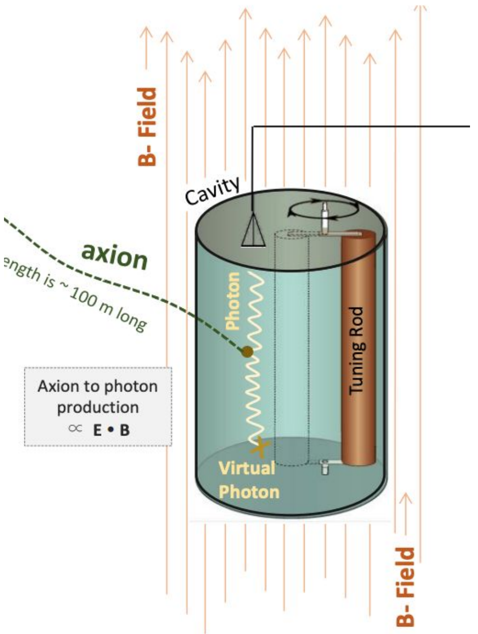
Dark Matter

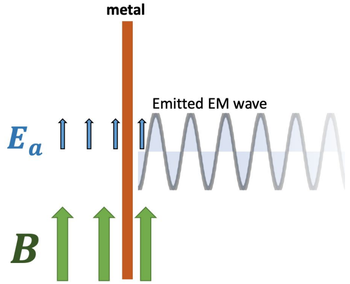


"Interaction Strength"
QCD
axion
thermal DM
classic
WIMP
ν_sDM
axion-like particles /
scalar-vector light DM
dark sectors
macroscopic DM /
compact objects
G_N
self-interactions, dark radiation, light relics, etc
secluded dark sectors
bosons
fermions
wave-like DM
particle-like DM

Dark Matter

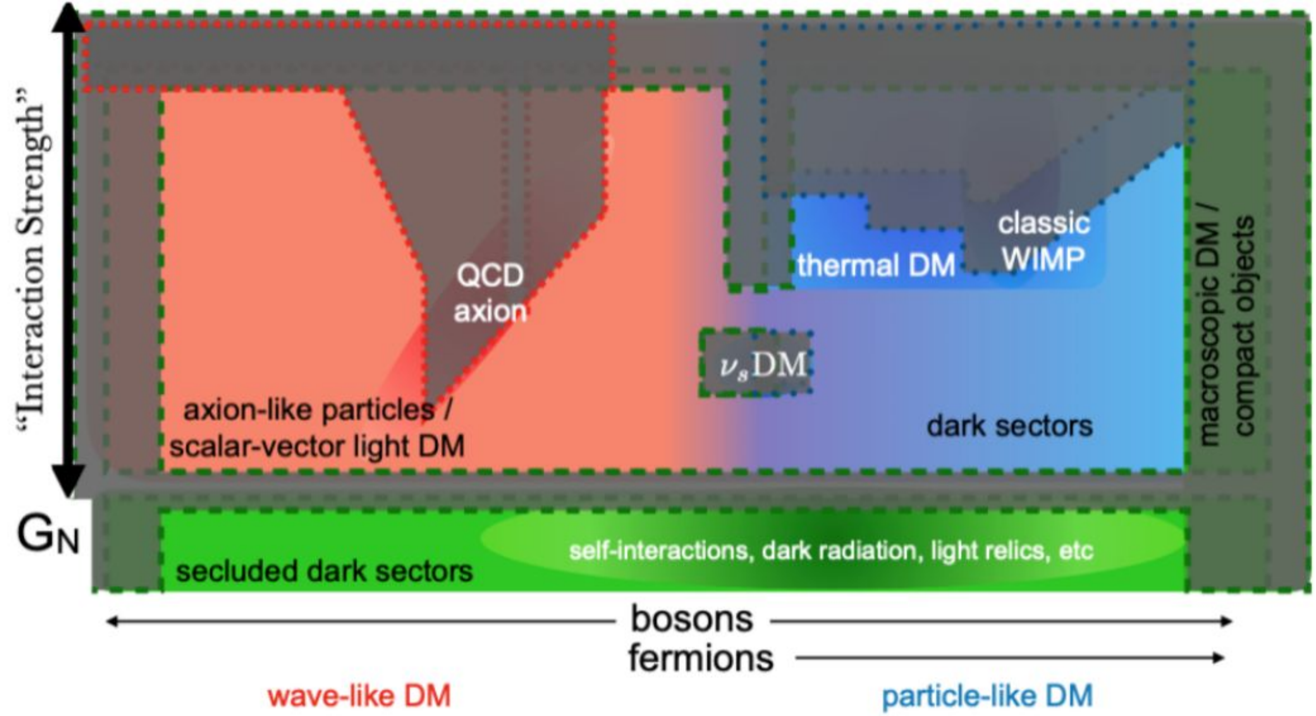


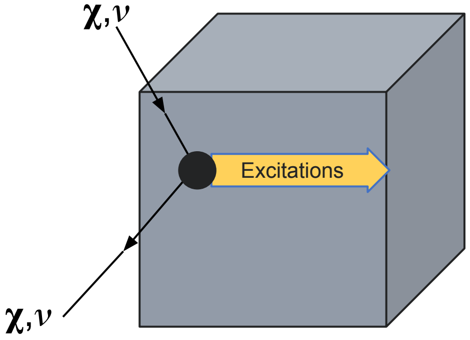




Convert to a "non-dark" excitation (e.g. photon) w/ frequency corresponding to DM mass. Detect these excitations.

Dark Matter





Scatter off target material. Recoil spectrum rises toward lower energies. Measure events and this recoil spectrum.

- **Optimizing low-threshold neutrino detectors:** The work here aims to expand the ever-growing CEvNS program and to fully exploit the physics reach of CEvNS in the next decade. It includes not just lowering energy thresholds but improving background rejection techniques, understanding detector responses at the eV-scale, and moving toward larger detector masses. Enabling technologies have many synergies with direct neutrino mass measurements and recoil-imaging directional dark matter detectors.

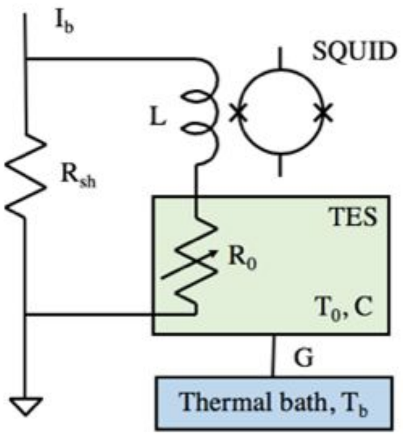
Critical HEP science

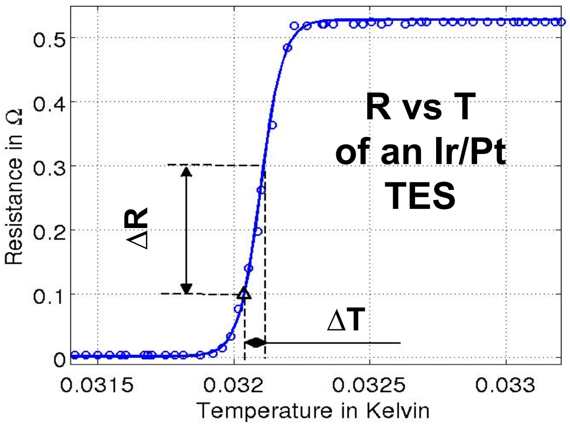
- Largest science drivers currently from Cosmic Frontier
  - Detectors for future large cosmological surveys (longer wavelengths)
  - Dark Matter
    - Low mass wave and particle candidates
- Signals from these science experiments are below the cut-off of Si/semiconductor gaps
- Broader HEP applications already being explored
  - Low energy neutrinos via CEvNS
  - Initial investigations of response to high energy particles

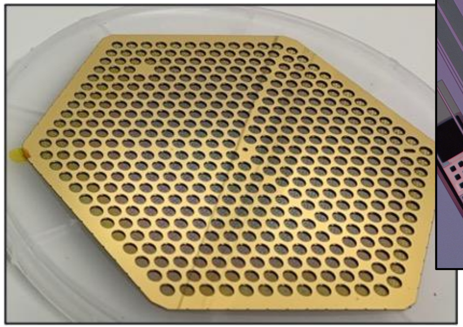
Technology overview

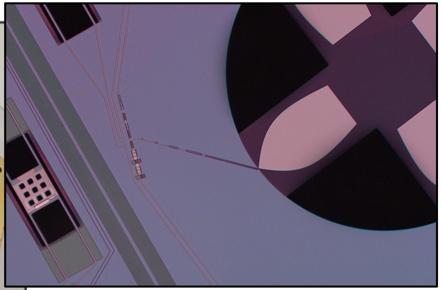
Transition Edge Sensors (TES)

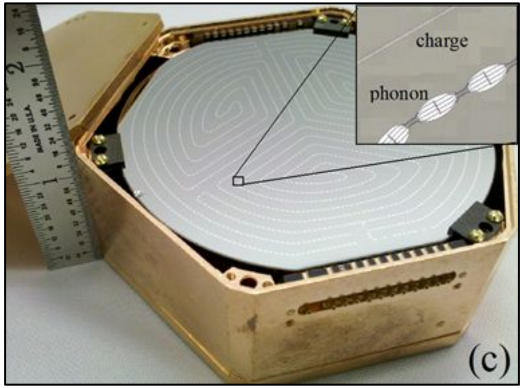
- Sense temperature with weak thermal link
- Voltage-bias establishes negative feedback
  - linearizes response, increase bandwidth
  - suppresses readout noise
- Signal current measured by low-impedance low-noise SQUID amplifiers
  - SQUID-based multiplexing enables operation of large arrays
- Sensitivity dominated by thermal fluctuation noise
  - Well understood theory of noise and operation
  - At low temperatures scales as T^n, n~3-5





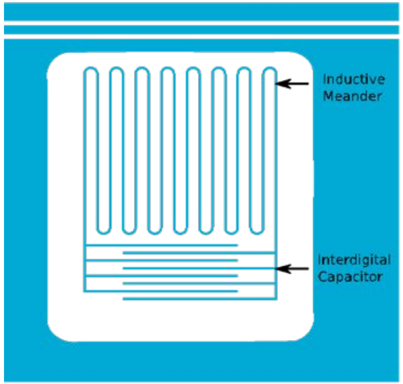


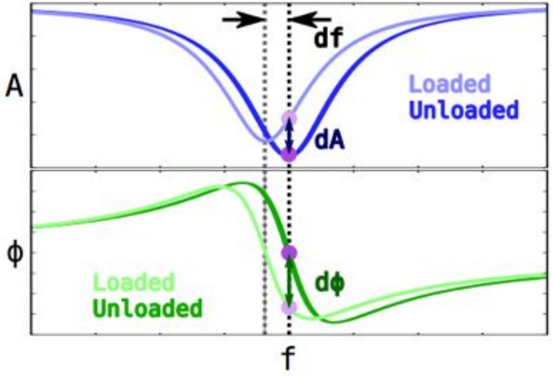


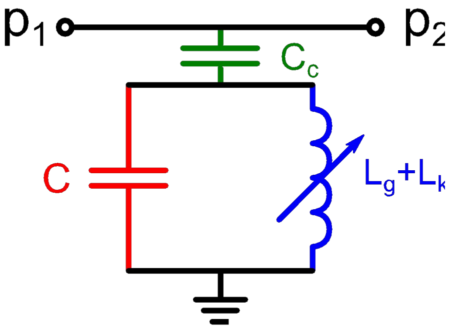


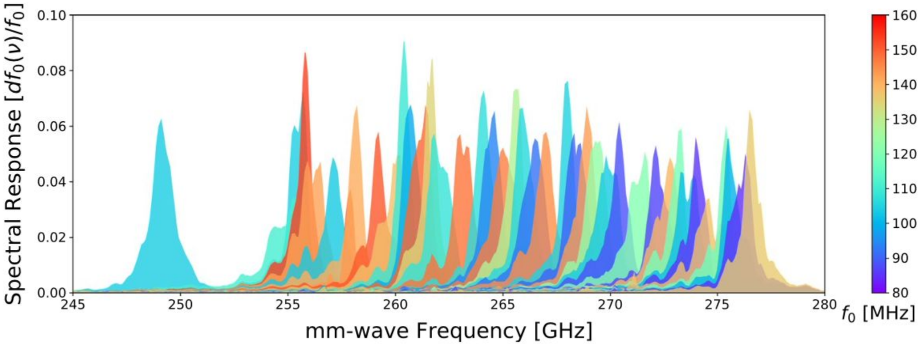
Microwave Kinetic Inductance Detectors (MKIDs)

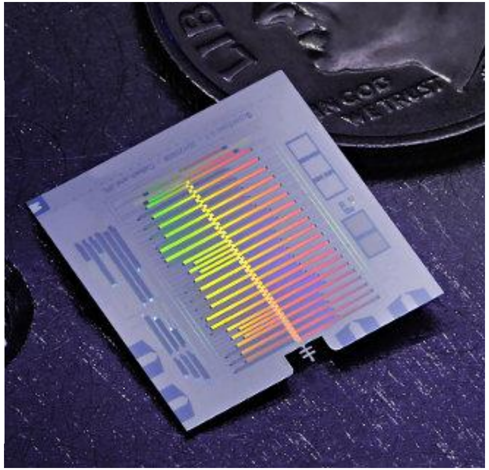
- Superconducting thin films
  - Kinetic inductance from Cooper pairs
  - Dissipation from quasiparticles
- Cooper pair vs quasiparticle distribution depends on coupled energy
- Measurable shift in resonant properties
- Intrinsically multiplexed.



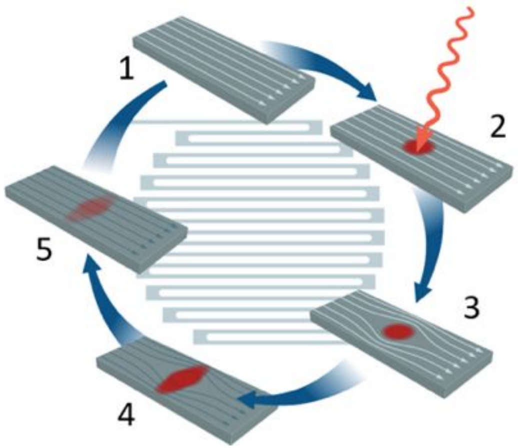


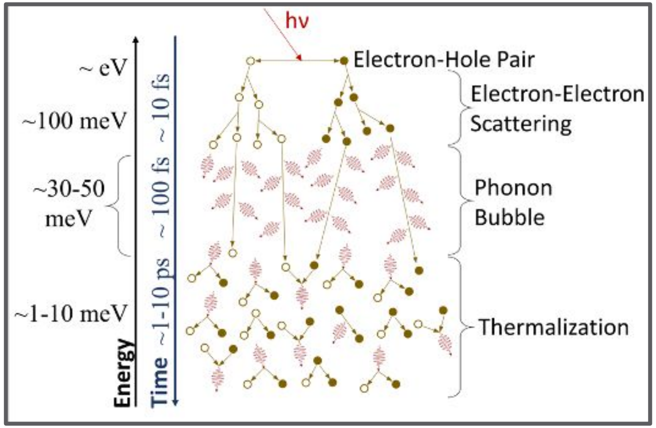




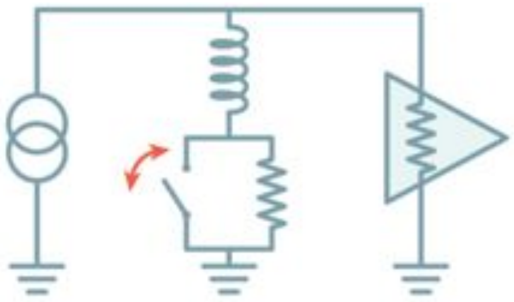


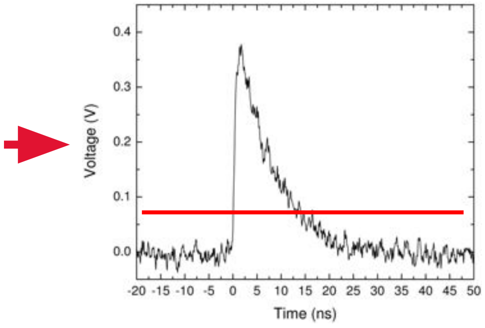
Superconducting Nanowire Single Photon Detectors

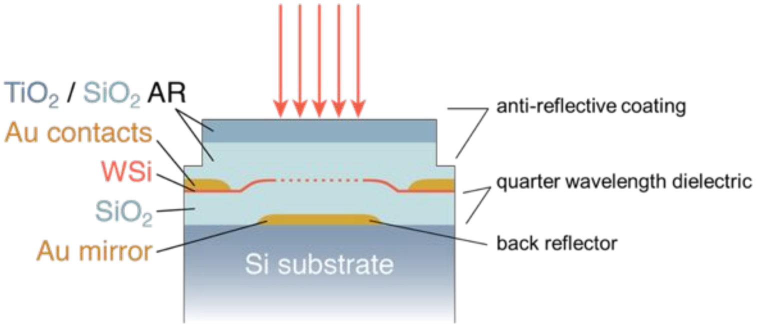




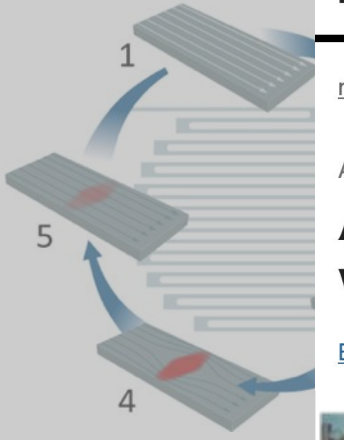
- Time-resolved single photon counting from UV to mid-IR
- Truly digital detection mechanism – reduced drift and zero read noise
- World-leading detector performance
- Operating temperature 1-4 K in most cases

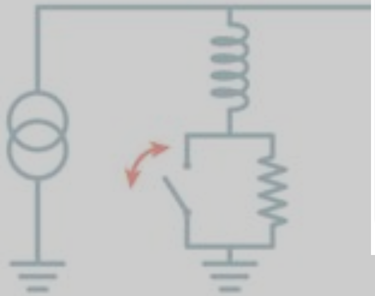






Superconducting Nanowire Single Photon Detectors





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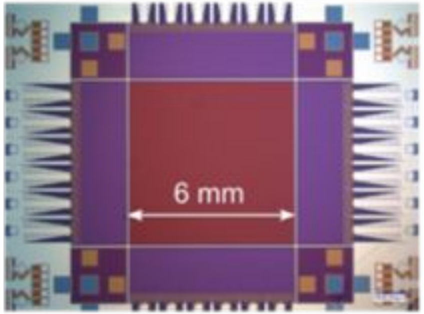
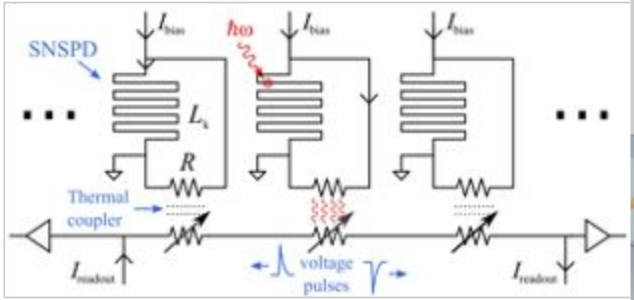
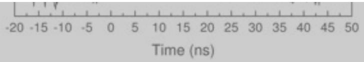
Article | Published: 25 October 2023

A superconducting nanowire single-photon camera with 400,000 pixels

B. G. Oripov, D. S. Rampini, J. Allmaras, M. D. Shaw, S. W. Nam, B. Korzh & A. N. McCaughan







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on counting from UV to
IR

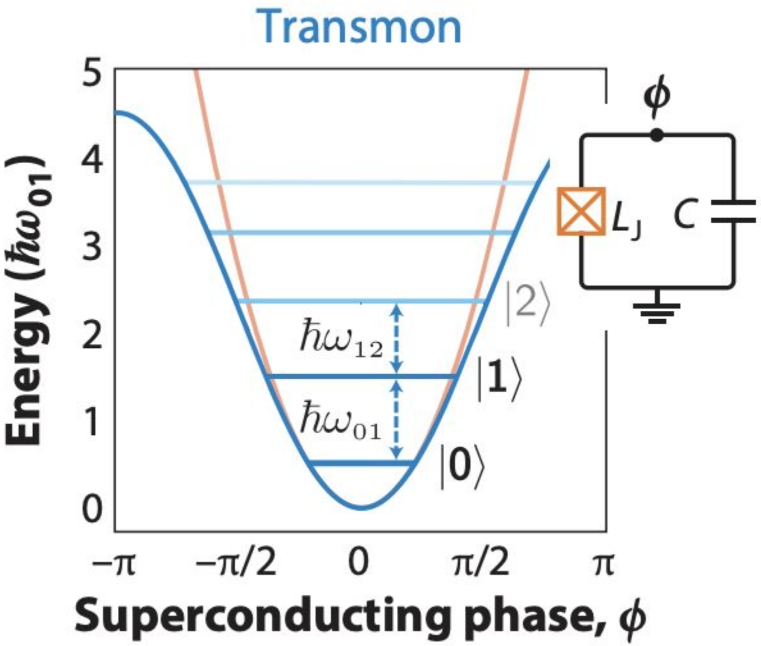
/ digital detection
hanism – reduced drift
zero read noise

d-leading detector
ormance

rating temperature 1-4
most cases

Superconducting Qubits as Microwave Photon Detectors

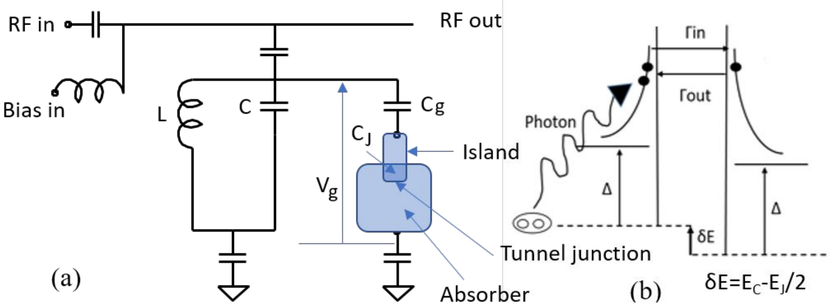
- Superconducting qubits are "artificial atoms" which obey the same Jaynes-Cummings Hamiltonian as natural atoms
- The presence of a single microwave photon can switch the qubit state, which can be probed later using a dispersive readout
- Work is currently ongoing to couple superconducting qubits to high-Q microwave cavities

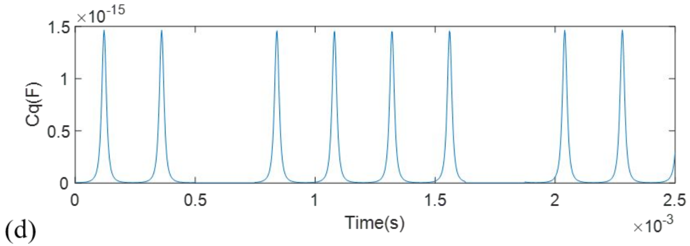


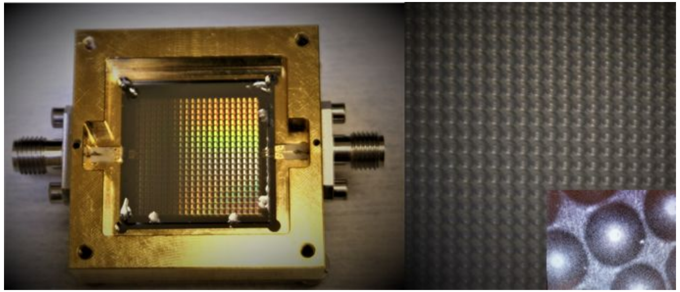
Kjaergaard et al (2021)

FNAL

Superconducting Qubits as Quasiparticle Detectors

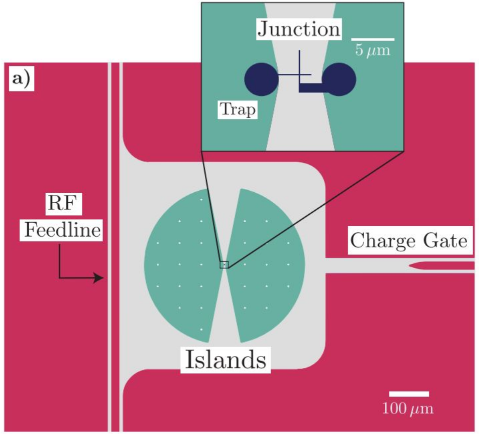


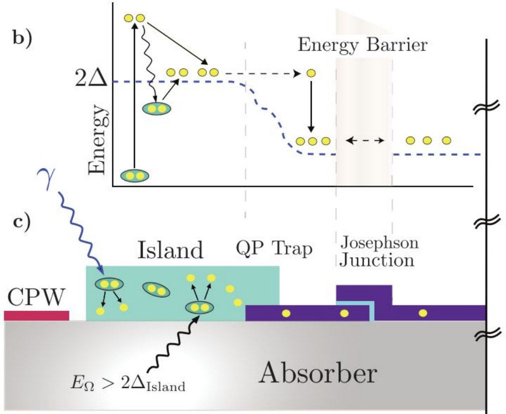




Echternach et al, *Nature Astronomy* (2018)

- The single cooper-pair box (charge qubit) is not often used for quantum computing because of its extreme sensitivity to non-equilibrium quasiparticles
- This bug becomes a feature when using the SCB as a quasiparticle detector
- This "quantum capacitance detector" is single-photon sensitive down to 1.5 THz (200 μm, 6.2 meV)
- Large arrays have been demonstrated (21x21) with efficient optical coupling via mesh absorbers and microlens arrays
- Transmon versions are also under investigation at SLAC





Fink et al, arXiv (2023)

Pair-breaking Detector Applications in HEP

SNSPD

- Low-noise Time-resolved single photon counting from 0.1 – 29 μm
- Photon detection for wave-like dark matter
- Readout of GaAs and LHe scintillator targets for particle-like dark matter
- NP and collider applications

MKID

- Far-infrared optical detectors, multiplexed to large arrays
- Phonon detection, multiplexed to large channel count for dark matter
- Cosmic surveys via sub-mm imaging and mm-wave LIM
- Energy-resolving/number-counting optical detection

TES

- Millimeter-wave measurements of cosmic microwave background
- Low-threshold phonon/bolometric detection for dark matter and neutrinos (CEvNS, NLDBD)
- Energy-resolving/number-counting optical detection

Qubit-based Technologies

- Single-photon detection for axion detection at microwave frequencies
- Terahertz single photon counting for axion detection (Quantum Capacitance Detector)

Different pair-breaking detectors have complementary strengths and weaknesses

Provocative Questions

- Are there technologies we are not representing in this taxonomy?
- Can the four detector types on the previous slide form four RDC work packages?
- What are the strengths/weaknesses of different collaboration models?
  - Project/experiment driven: typically includes integrated systems, but a narrow range of technologies
  - Broader technology collaborations(?): share ideas across various technologies, address common issues, does this adequately address gaps/integration? Sufficiently develop a path to full experiment?
- What facilities for materials and processing are critical for exploring and realizing new detector technologies?