CPAD Instrumentation Frontier at Caltech 8-10 October, 2016 New Technologies for Discovery II

Cryogenic Detectors: Overview of the Field

Kent Irwin
Stanford University

Why cryogenic detectors?

High sensitivity and low noise give you many advantages

… but at a cost in complexity

LOW THRESHOLD

- WIMP Detection

NUCLEAR RECOIL DISCRIMINATION

- WIMP Detection

SENSITIVITY TO LOW POWER LEVELS

- CMB

QUANTUM-LIMITED (OR SUB-SQL) SENSING

- Axion / Hidden-photon detection
- Quantum information

HIGH SPEED

- Communications, Timing
- Quantum Information

HIGH EFFICIENCY

- X-ray materials analysis
- Quantum Information

HIGH RESOLUTION

- X-ray spectroscopy

Overview Outline

- The components of a cryogenic detector
- State of the art of cryogenic detectors in HEP applications

Schematic Outline

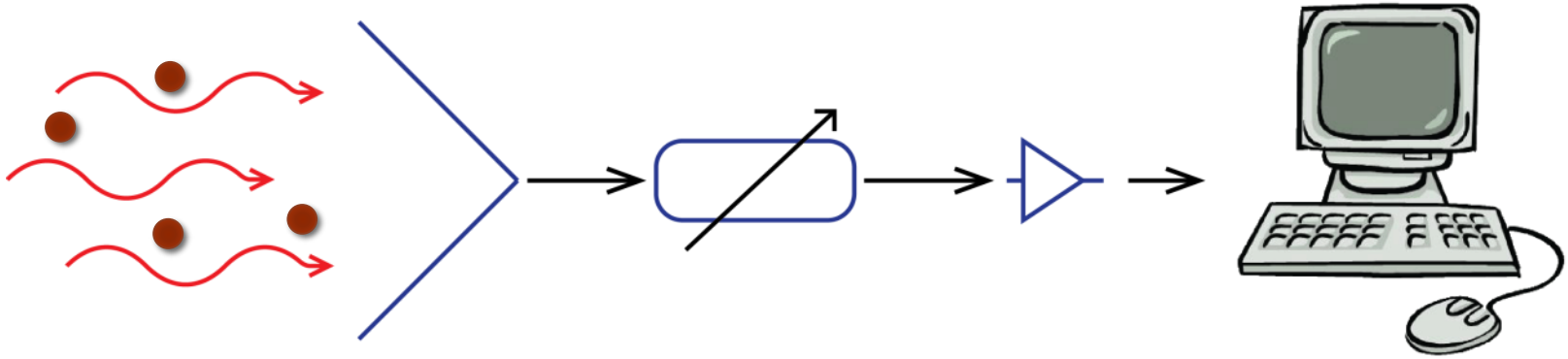
1.Signal

2.Coupling

3.Sensor

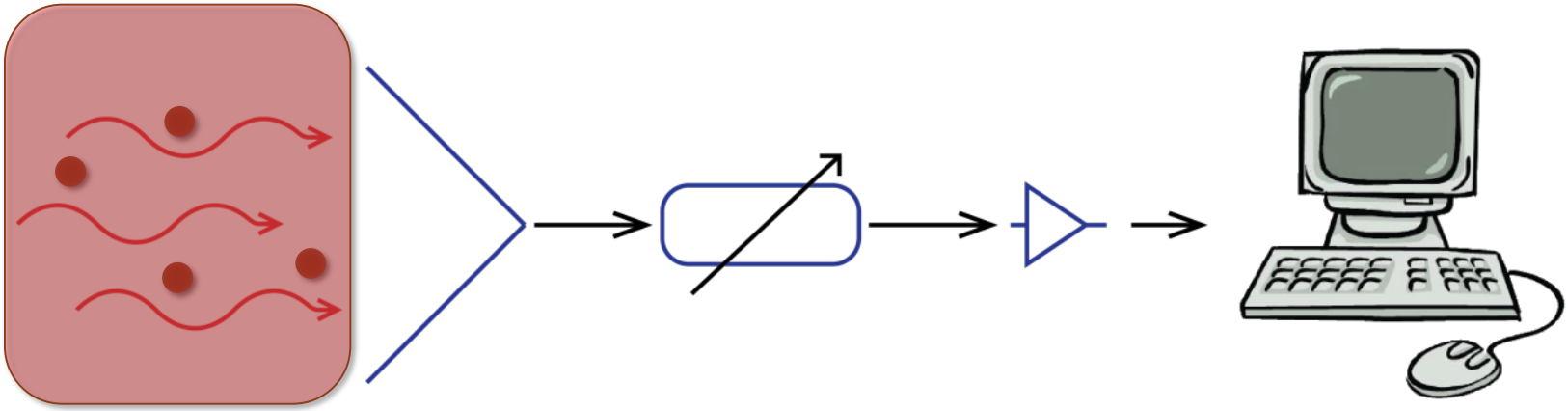
4. Coherent Preamp

5.Readout DAQ, Software



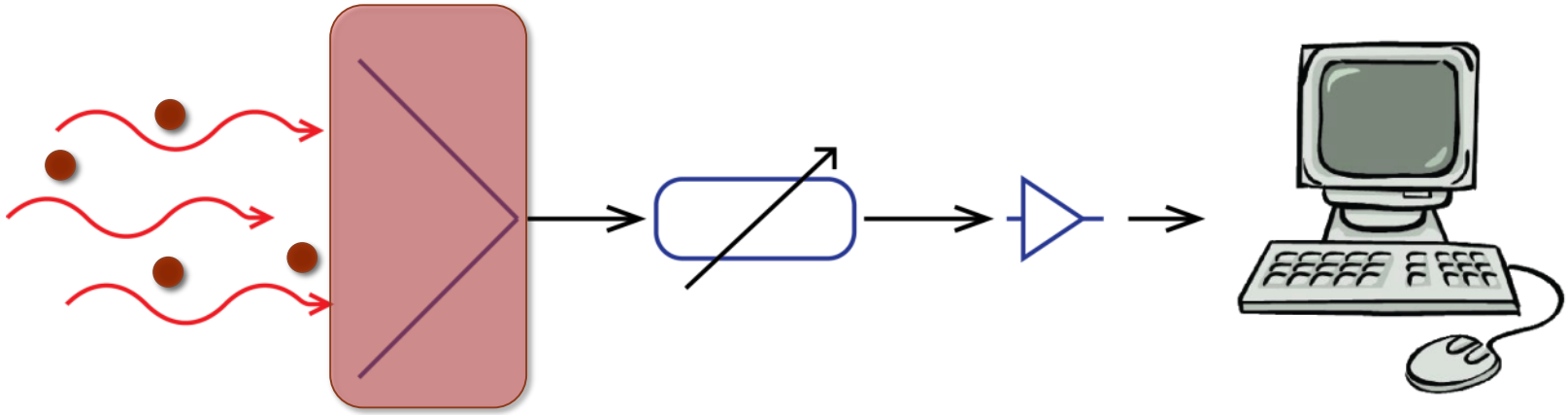
1. The signal: what are we looking for?

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



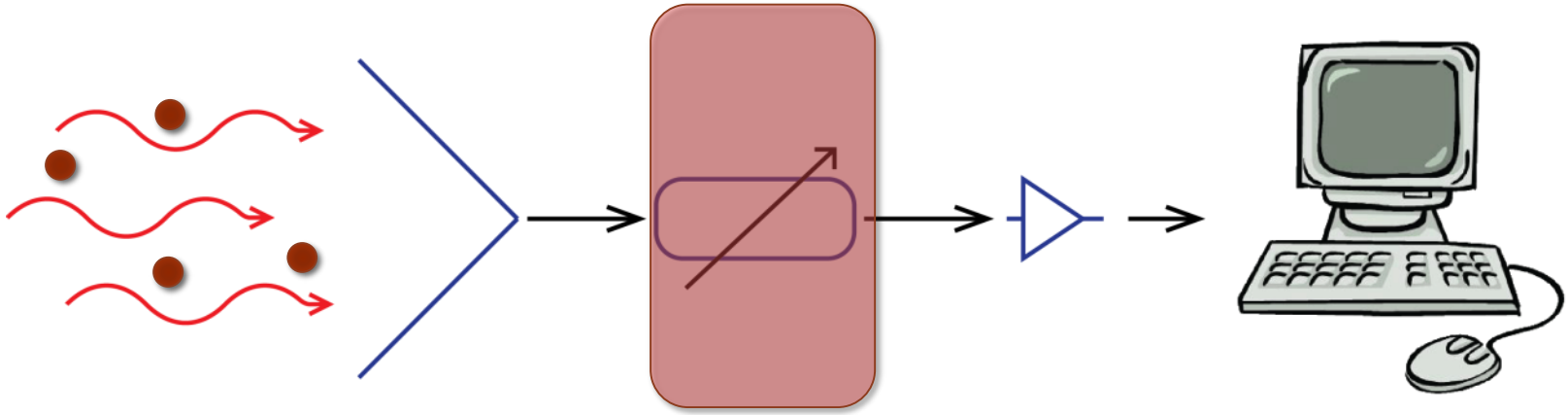
2. Coupling: absorbers, antennas, filters, etc.

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



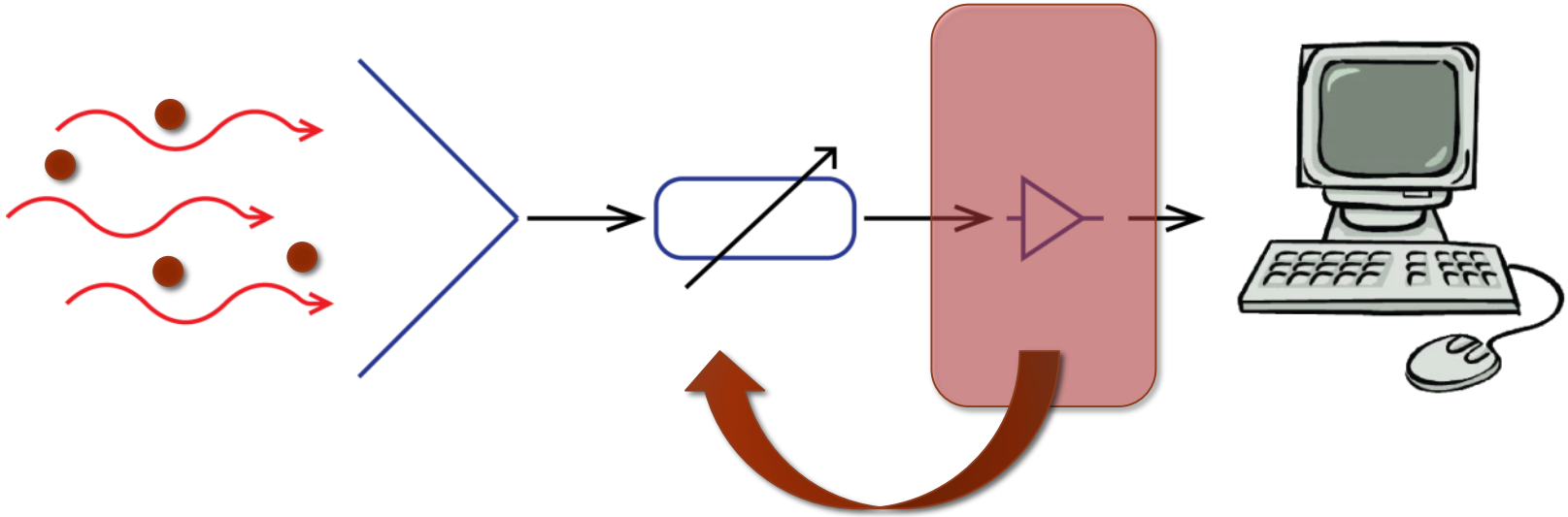
3. Sensors: TES, MKID, Resonator, ...

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



4. Coherent amplifier

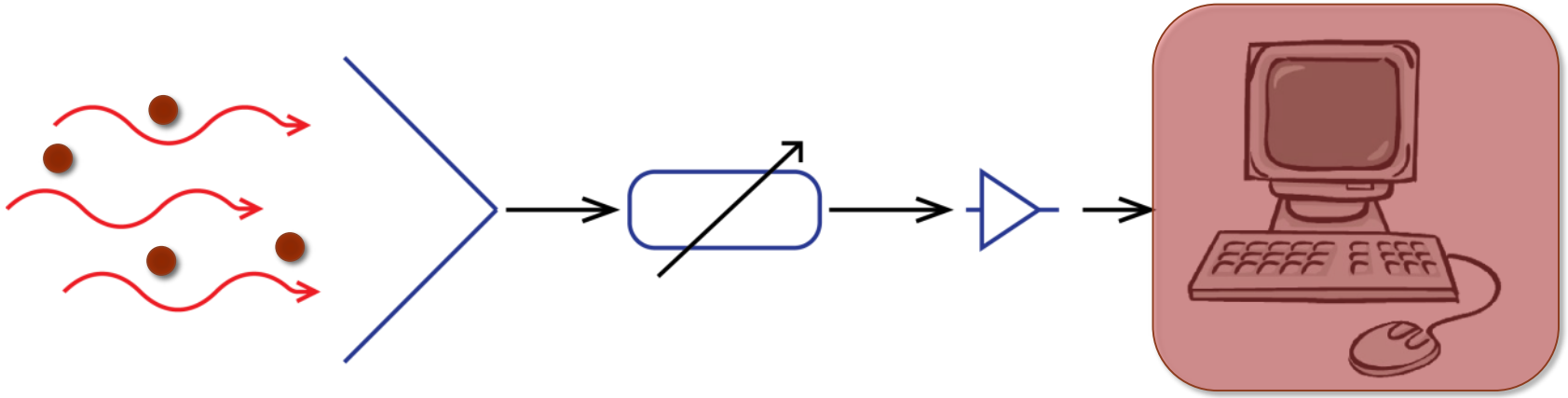
1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



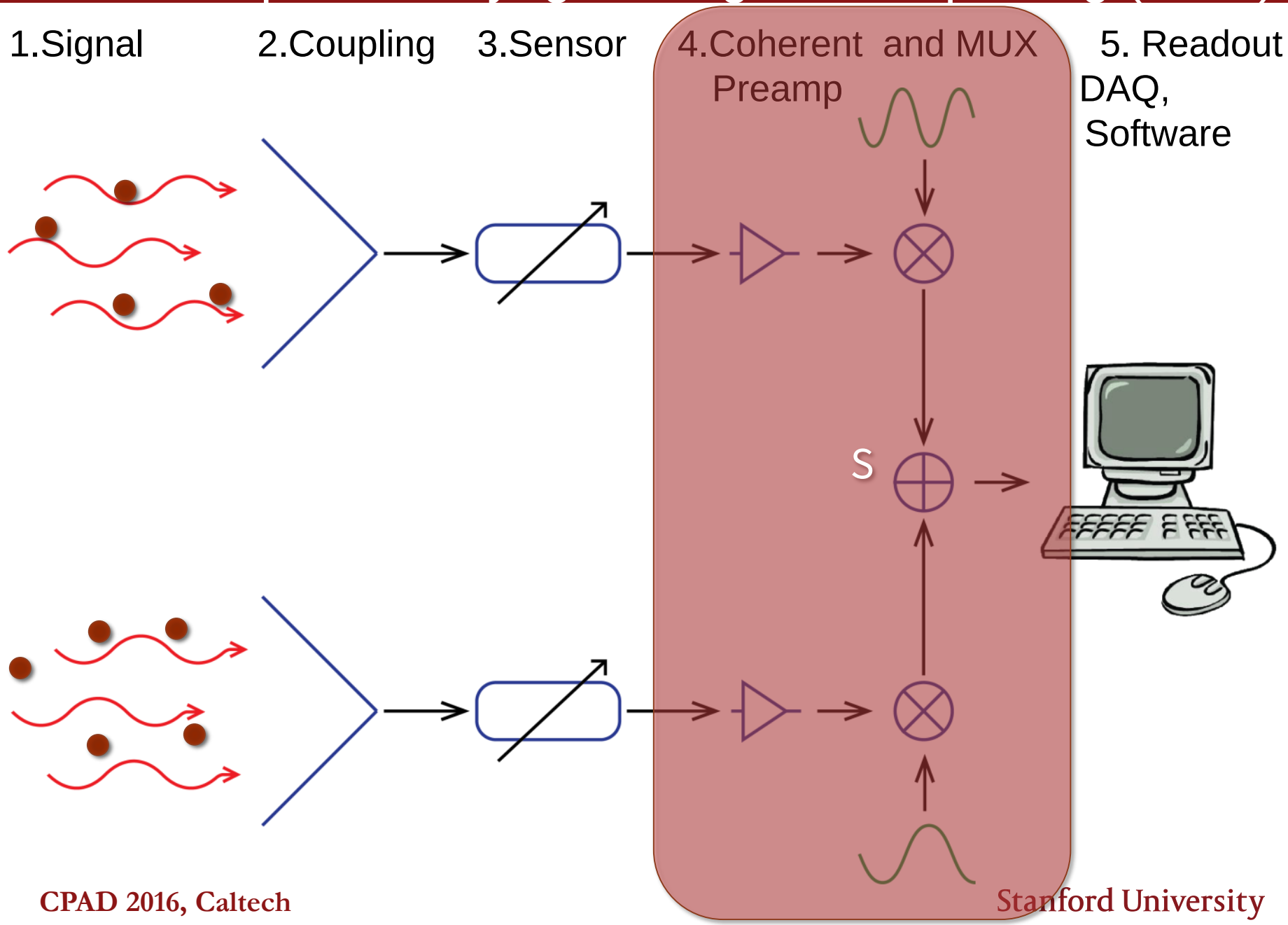
Optional non-classical operation:
(squeezing, entanglement…)

5. Room-temperature readout / DAQ

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



Optional: cryogenic signal multiplexing (MUX)



This session

11:30 **Cryogenic Detectors: Overview of the Field** *25'*
Speaker: Kent Irwin

11:55 **TES Development for CMB** *25'*
Speaker: Suzanne Staggs

12:20 **TES for Dark Matter Detection** *25'*
Speaker: Dr. Matt Pyle (UC Bekeley)

12:45 **Ir Based Low-Tc TES** *25'*
Speaker: Dr. Gensheng Wang (HEP, Argonne)

13:10 **Lunch** *1h30'* (Dabney Hall & Gardens)

14:40 **MKID Development for CMB** *25'*
Speaker: Erik Shirokoff (U. Chicago)

15:05 **Improving MKID sensitivity & resolution** *25'*
Speaker: Ben Mazin

15:30 **Broadband Microstrip-Coupled Titanium Nitride Kinetic Inductance Detectors: A Key Detector Technology for CMB-S4** *25'*
Speaker: Prof. Sunil Golwala (California Institute of Technology)

15:55 **Coffee Break** *30'* (Dabney Hall & Gardens)

16:25 **Multiplexing Readout for Large format TES & MKID arrays** *25'*
Speaker: Zeeshan Ahmed

16:50 **The DM Radio: A Superconducting Dark Matter Detector for Axions and Hidden Photons***25'*
Speaker: Dale Li

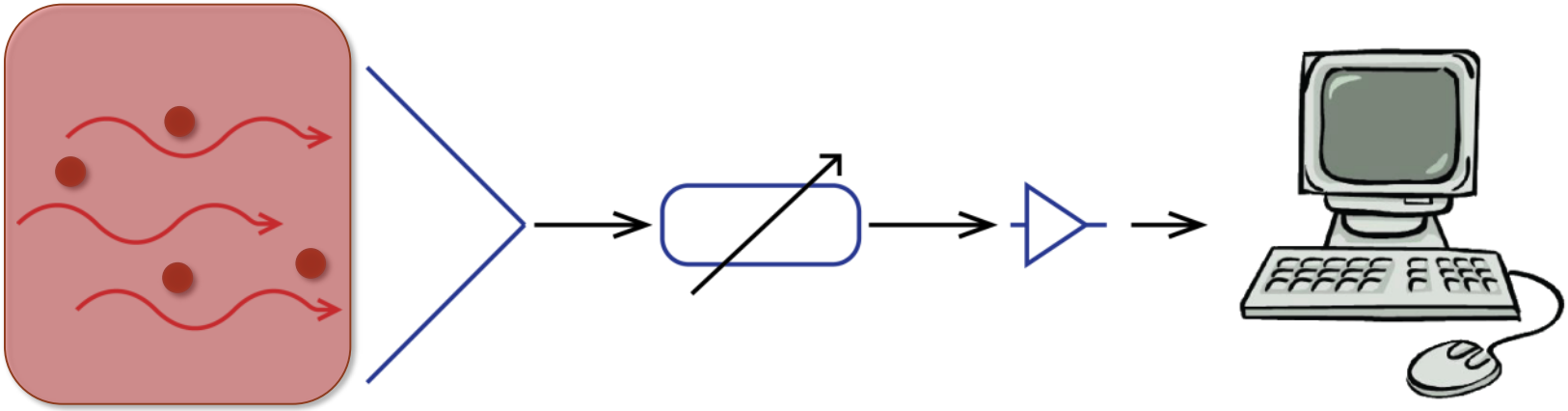
17:15 **Single Photon Microwave detectors for axion searches** *25'*
Speaker: Dr. maxime malnou (JILA University of Colorado Boulder)

17:40 **Cryogenic CCDs** *25'*
Speaker: juan estrada (fermilab)

18:05 **Localized Electrons in Dielectric Layers** *12'*
Speaker: Dr. Sergey Pereverzev (LLNL)

1. The signal: what are we looking for?

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



What can cryogenic detectors detect?

Example: "Long"-lived, free elementary particles

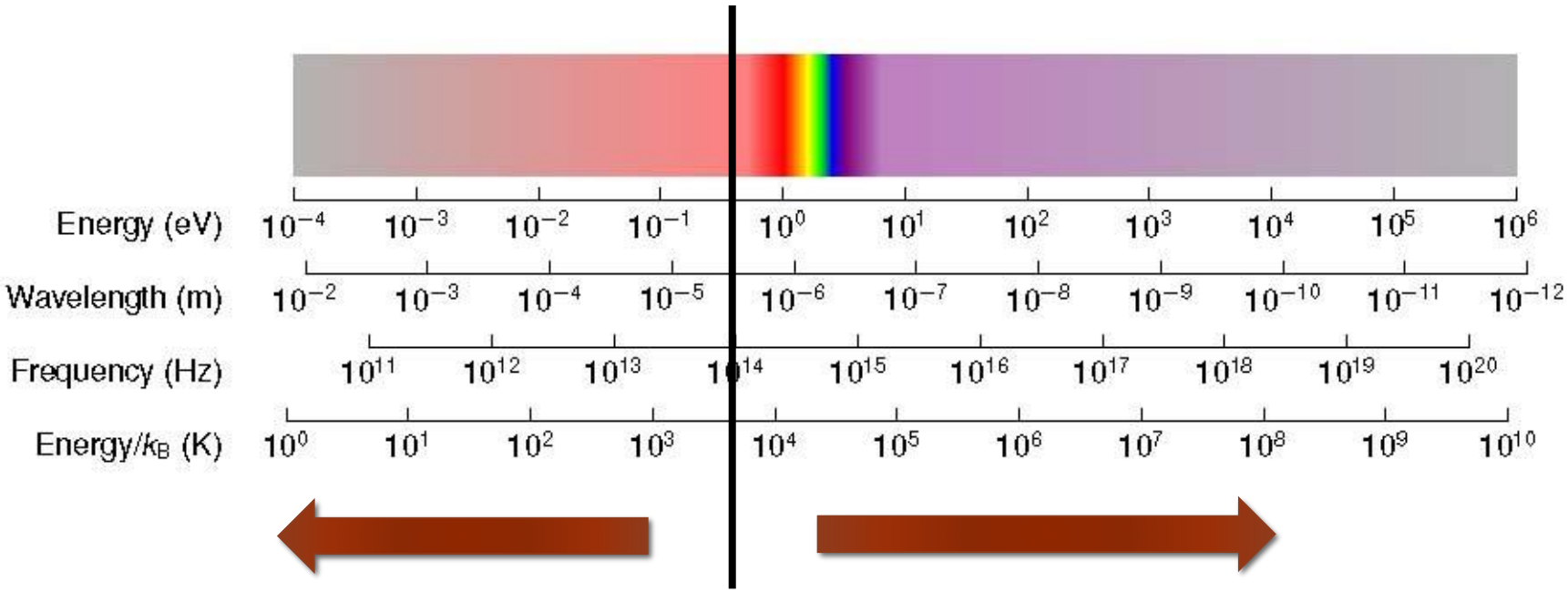
	Spin 0 bosons	**Spin ½ fermions**	**Spin 1 bosons**	**Spin 3/2 fermions**	**Spin 2 bosons**
Standard model + gravity		Electron	Photon / EM wave		Graviton / gravity wave
		Muon			
		Neutrinos electron, mu, tau			
Dark matter-candidates (incomplete)	Axion	Neutralino WIMPs	Hidden photon	Gravitino	
Dark energy			(expansion history via photons)		

What can cryogenic detectors detect?

Cryo-det used | Cryo-det could be used | ???

	Spin 0 bosons	Spin ½ fermions	Spin 1 bosons	Spin 3/2 fermions	Spin 2 bosons
Standard model + gravity		Electron	Photon / EM wave		Graviton / gravity wave
		Muon			
		Neutrinos electron, mu, tau			
Dark matter-candidates (incomplete)	Axion	Neutralino WIMPs	Hidden photon	Gravitino	
Dark energy			(expansion history via photons)		

Fields and particles: photons



<u>Electromagnetic field detection</u>

Photon noise:

$S_P = 2hf\,P(1+n)$

<u>Photon detection</u>

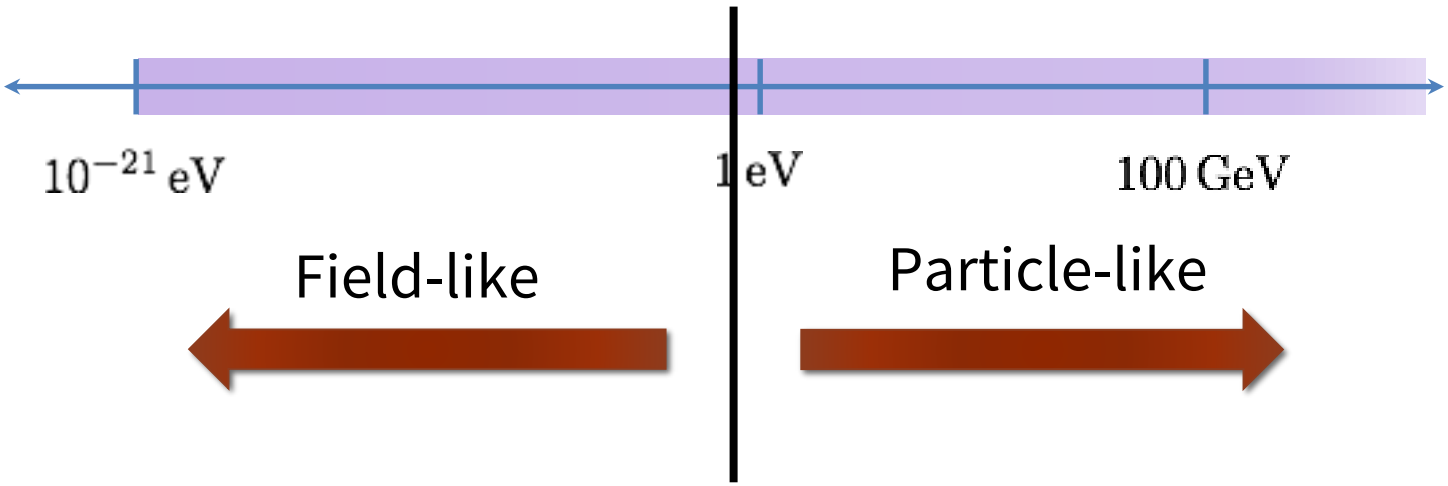
Energy resolution

$\Delta E_{rms}^2 = k_B T^2 C$ for thermal calorimeter

Can measure:

Power, polarization (spin), energy (frequency), phase

Fields and particles: dark matter



Light (field) DM

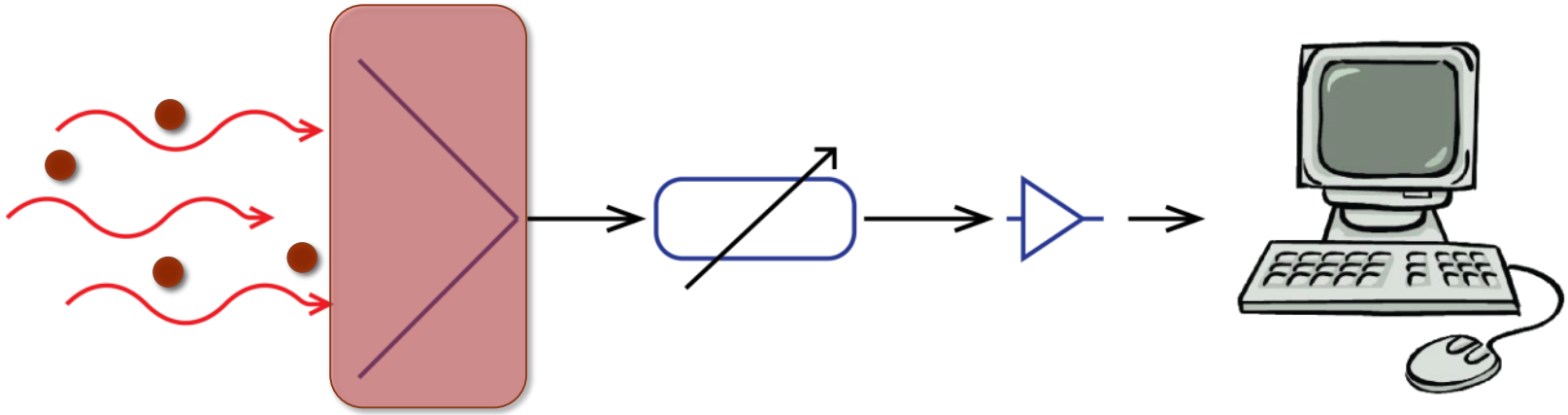
- Must be a boson
- Non-thermal generation
- Light Scalar (QCD axion, ALP)
- Vector (hidden photon)

Heavy (particle) DM

- Can be thermal generation
- e.g. WIMPs, ALPs, hidden photons

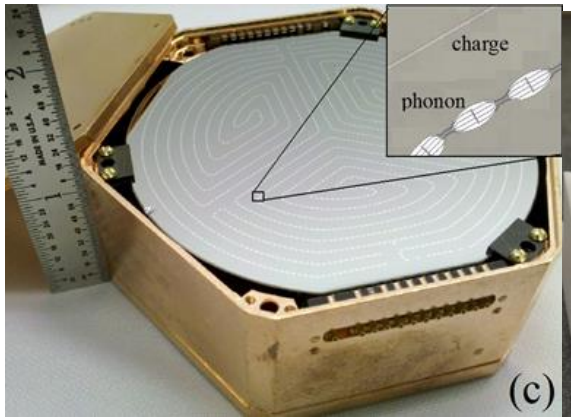
2. Coupling: absorbers, antennas, filters, etc.

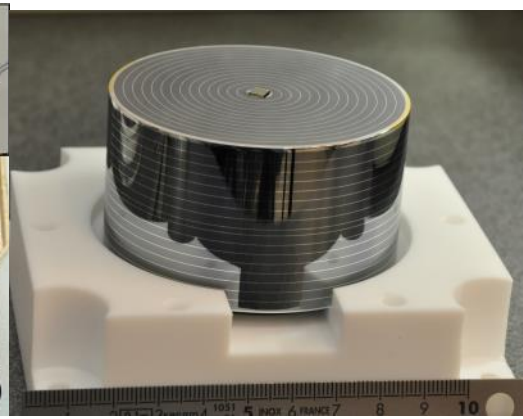
1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



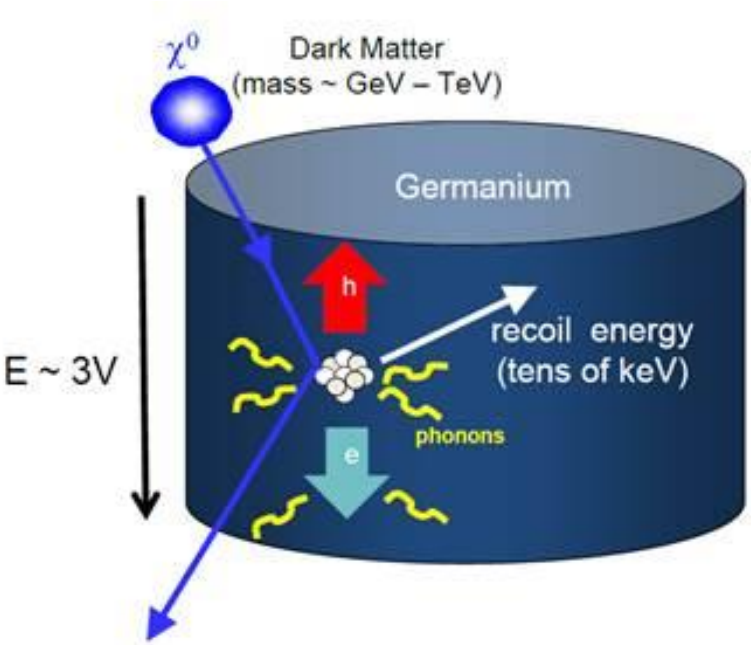
Cryogenic detector coupling to WIMPs

Nuclear recoil in semiconductor crystals: Large crystals for low coupling measurements

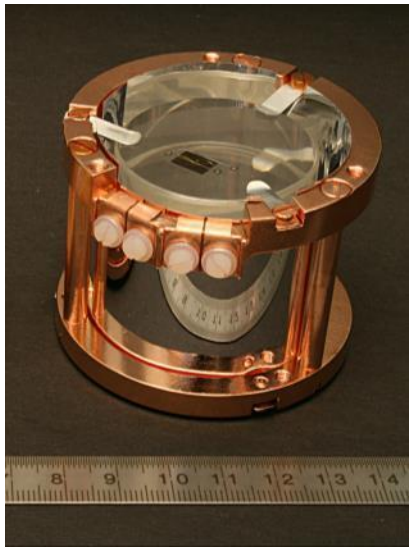




CDMS **EDELWEISS-II**

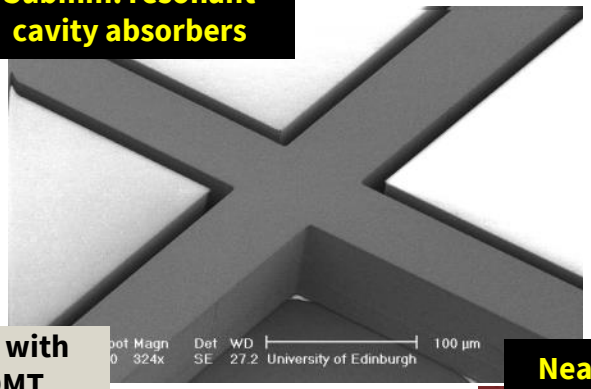


And CaWO4 scintillators: CRESST



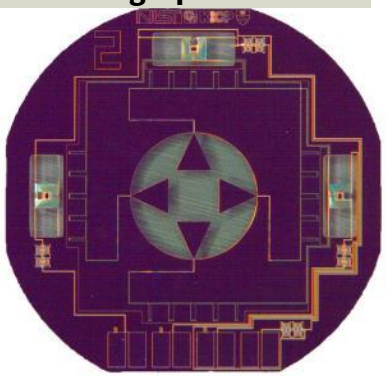
Coupling to photons: from CMB to γ-ray

Submm: resonant cavity absorbers

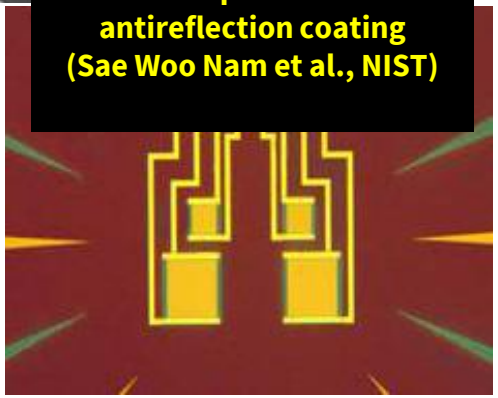


Soft x-ray: Bi thin fims

CMB: feedhorns with lithographic OMT



Near IR & optical: TES with antireflection coating (Sae Woo Nam et al., NIST)



Gamma-ray: thick superconducting foil

Energy (eV)	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}
Wavelength (m)	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}
Frequency (Hz)	10^{11}	10^{12}	10^{13}	10^{14}	10^{15}	10^{16}	10^{17}	10^{18}	10^{19}	10^{20}	
Energy/k_B (K)	10^{0}	10^{1}	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	10^{7}	10^{8}	10^{9}	10^{10}

3. Sensors: TES, MKID, Resonator ...

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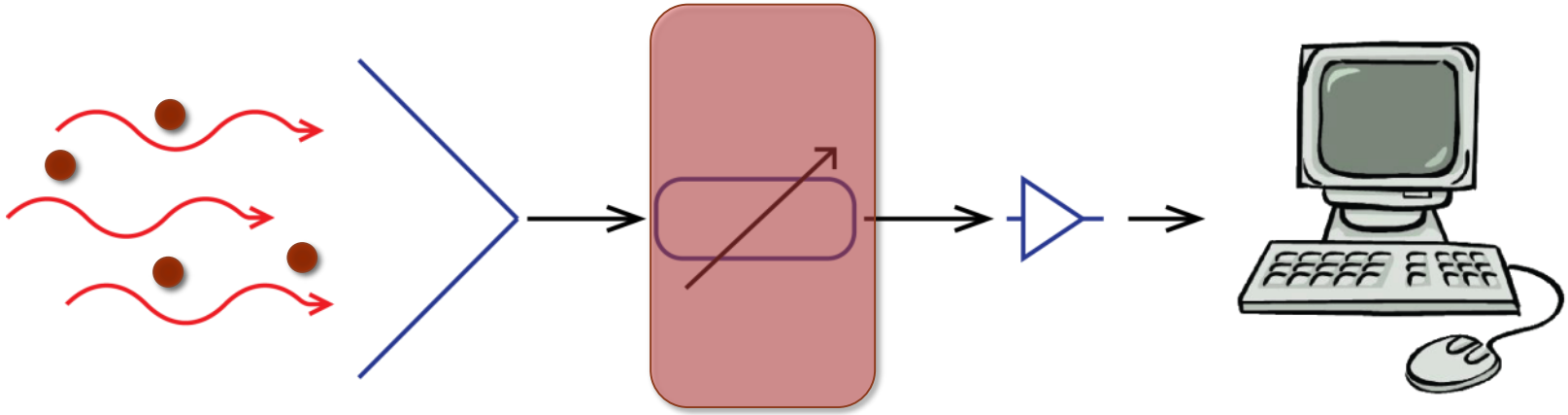


3 relevant sensor types for HEP

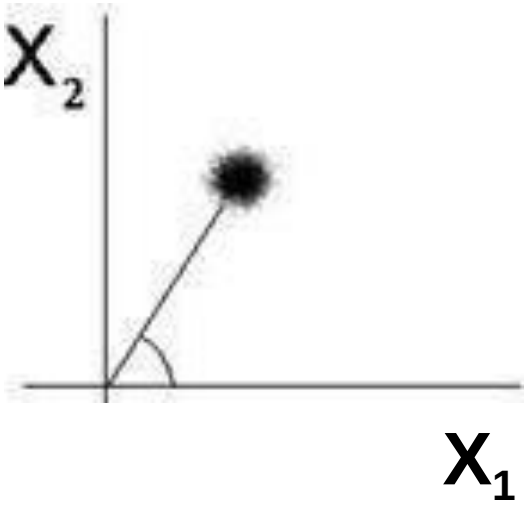
- Coherent amplifier
- Calorimeter (measures energy, e.g. WIMP)
- Bolometer (measures power, e.g. CMB)

Coherent amplifier limited by quantum noise

Consider an electromagnetic field:

$$E(x, t) = X_1(x,t)\cos(\omega t) + X_2(x,t)\sin(\omega t)$$

Heisenberg uncertainty places a fundamental limit on how well you can know both amplitude **and** phase, or both $\mathbf{X_1}$ and $\mathbf{X_2}$

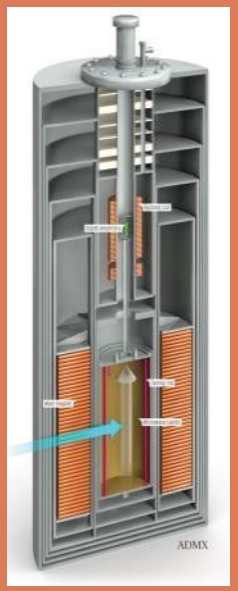


- Phasor diagram shows how well you can measure / amplify cosine and sine simultaneously – result is a ball of 'noise' of magnitude ½ photon (+ ½ photon from amplification). This is the Standard Quantum Limit (SQL)
- Incoherent detectors measure only amplitude – with no quantum noise.
- Squeezing / entanglement: measure only one quadrature – with no quantum noise

Coherent amplifiers for light-field dark matter

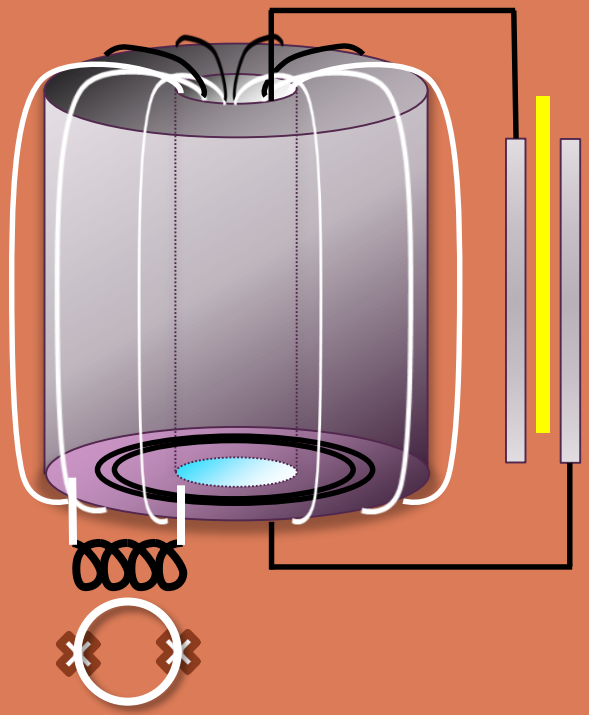
ADMX

- Axion dark matter search
- Cavity resonator
- Microstrip SQUIDs and parametric amplifiers



DM Radio

- Axions and hidden photons
- Lumped-element resonator
- dc SQUIDs, ac SQUIDs, and parametric amplifiers

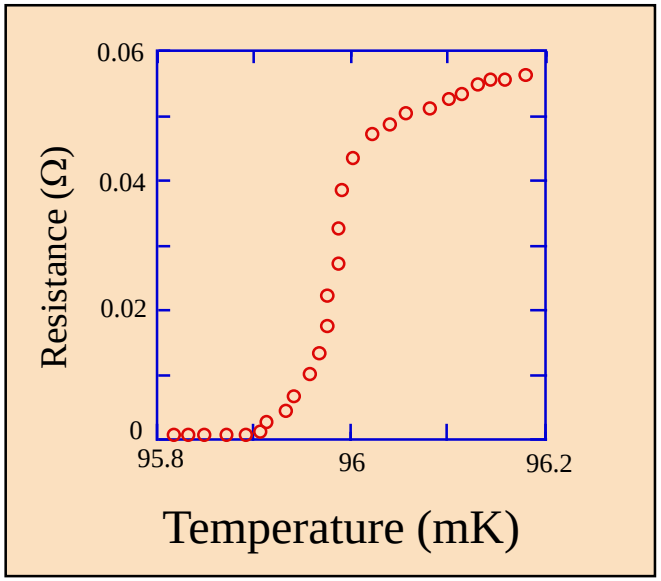


Superconducting transition-edge sensor (TES)

In 1938, Donald Hatch Andrews invented a thermal sensor based on this transition: the superconducting transition-edge sensor (TES).

He used it to build:

1. The world's first particle calorimeter (alpha)
2. The world's first infrared imager (real time!)

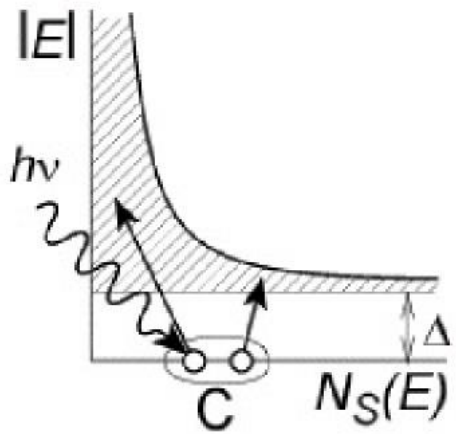


D.H. Andrews

A real-time infrared image taken with a TES in 1945

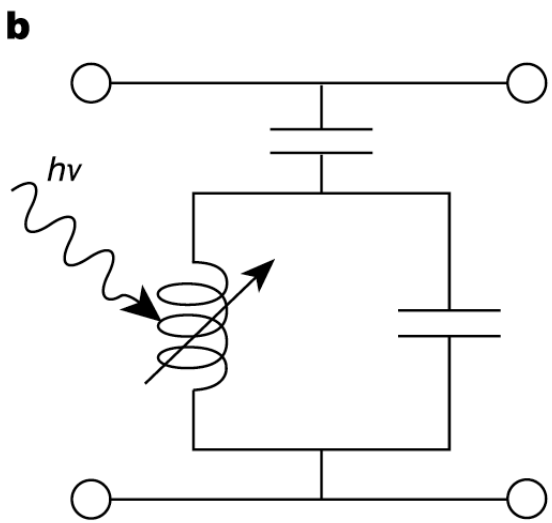
Modern TES: K.D. Irwin, APL 66, 1998 (1995).

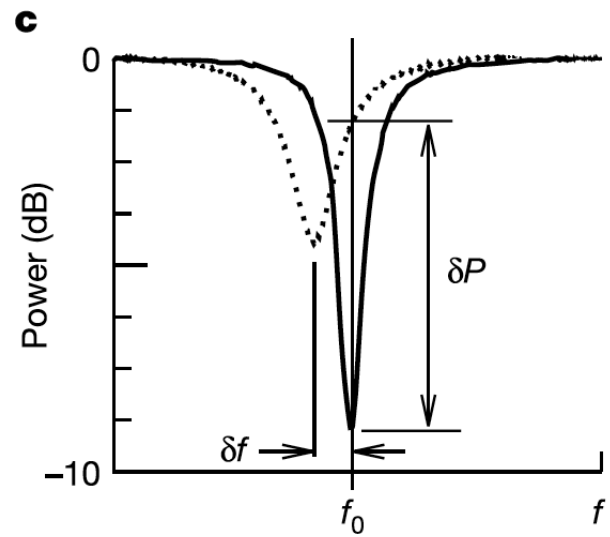
Microwave kinetic inductance detector (MKID)



Energy Gap
Silicon – 1.10000 eV
Aluminum – 0.00018 eV

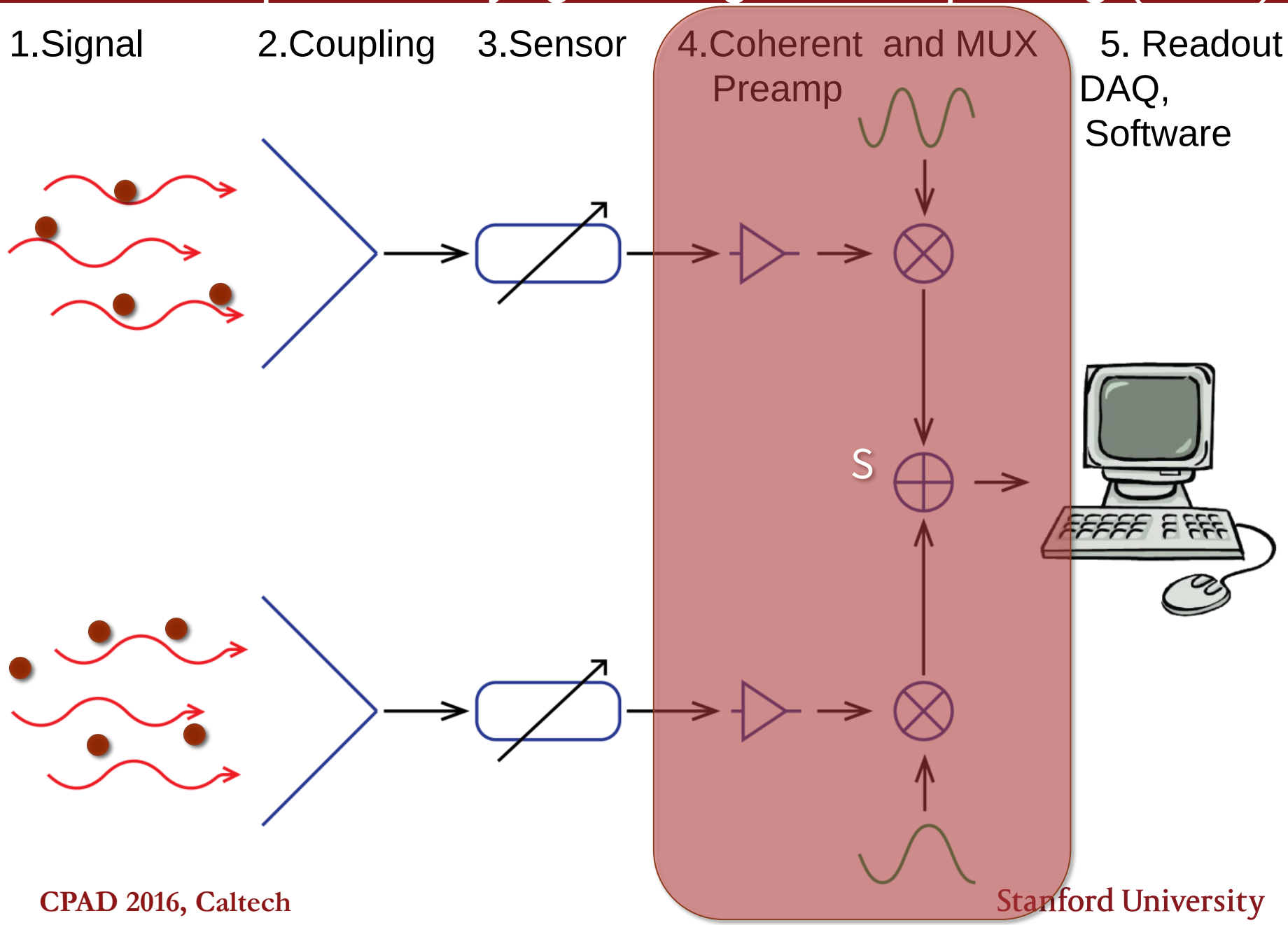
Much smaller generation-recombination noise



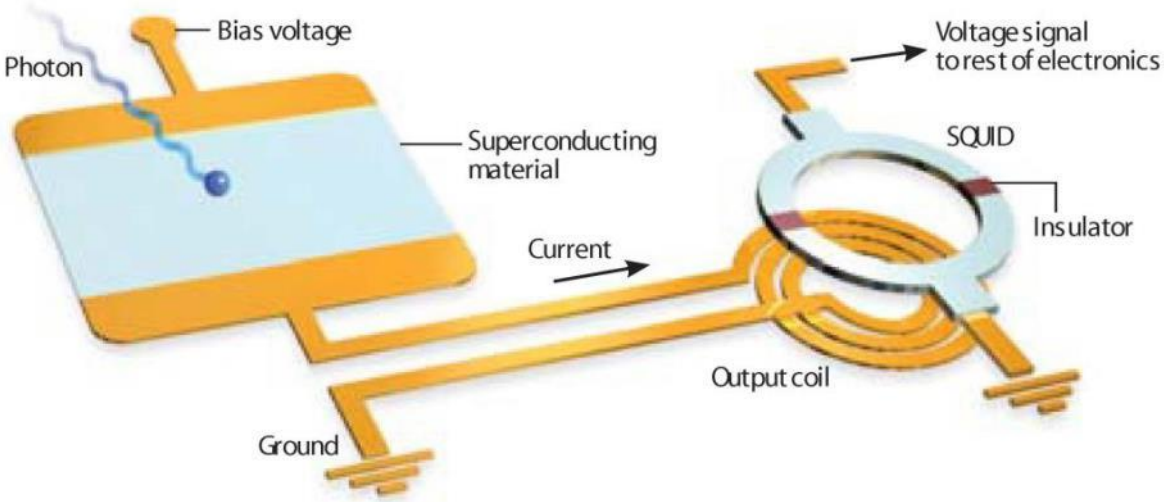


P. Day, Nature, vol. 425, pp. 817-821, 2003

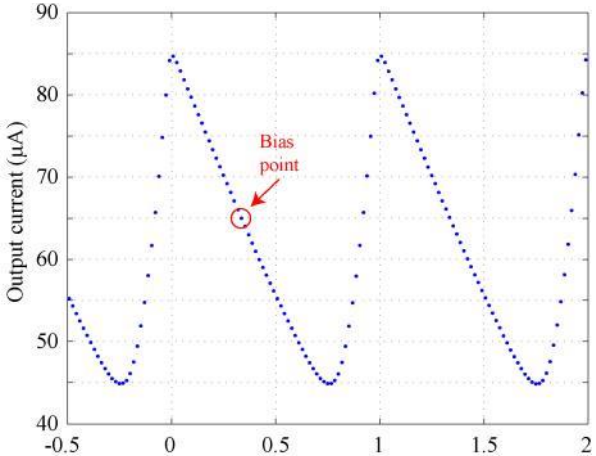
Optional: cryogenic signal multiplexing (MUX)



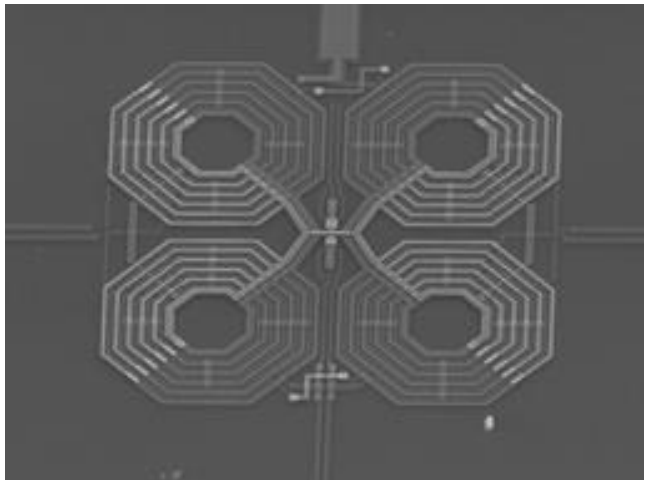
SQUID readout



SQUID response



Input flux

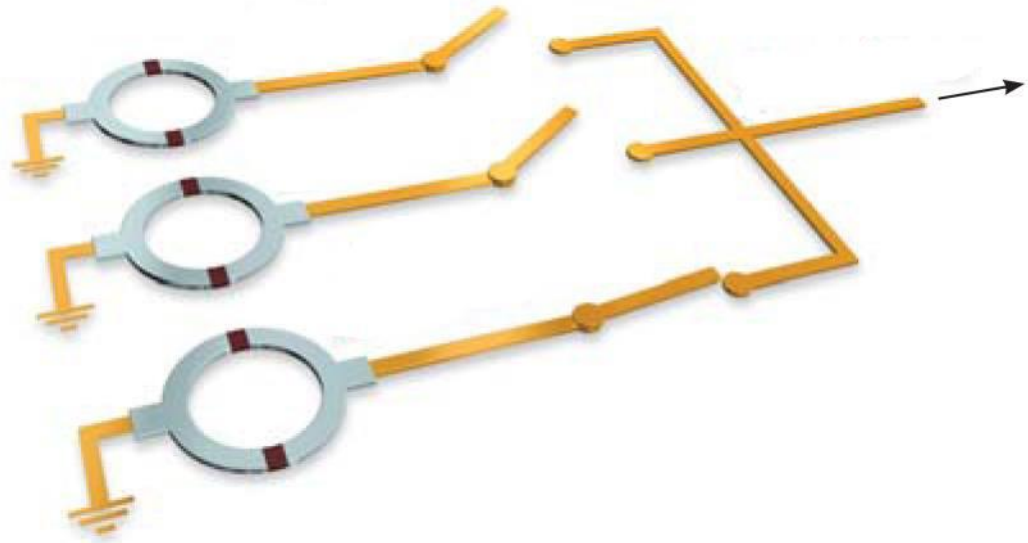


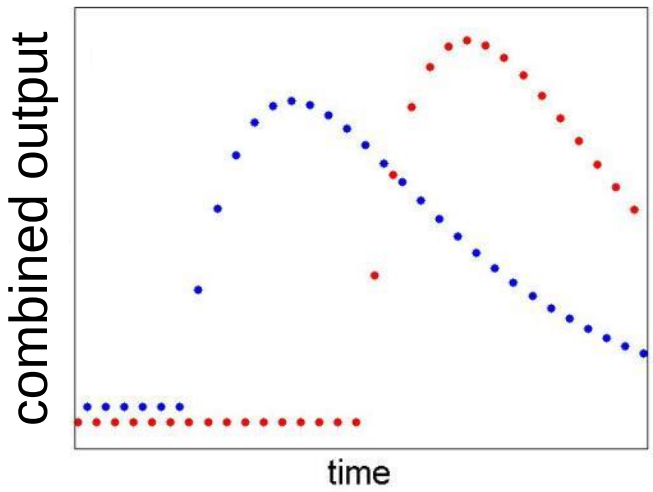
Single SQUID

Need sensitive electronics with flux feedback

SQUID multiplexing

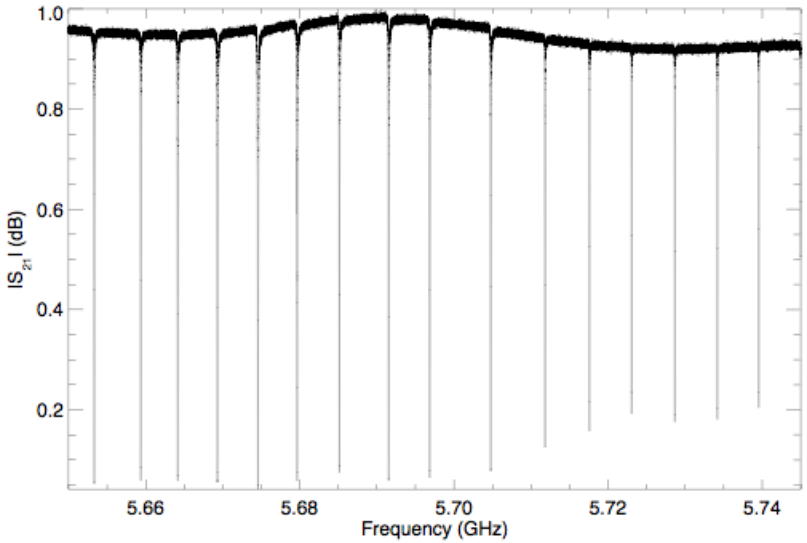
For large LTD arrays, multiplexing becomes necessary to minimize complexity and heat load from wires





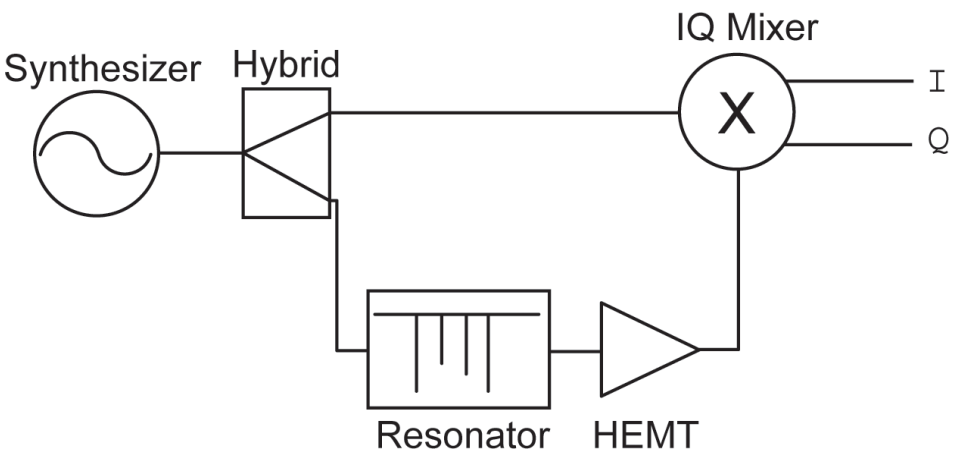
Example: multiplexing allows multiple TES detectors to be sampled with one output line

Microwave readout: both MKID & TES



IQ readout of amplitude and phase using homodyne mixing

Standard microwave technique with both analog and digital implementations



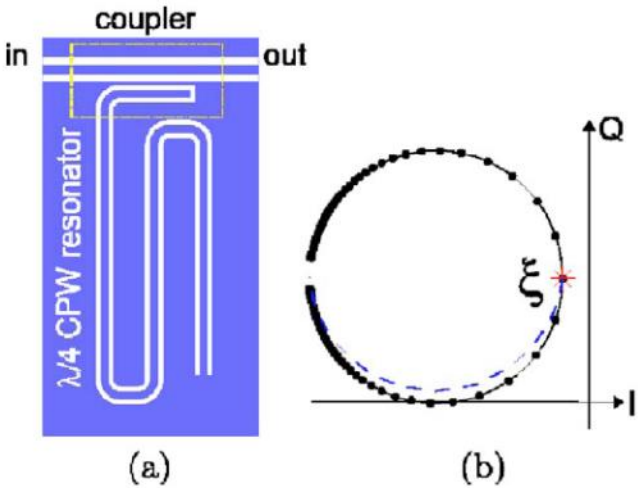
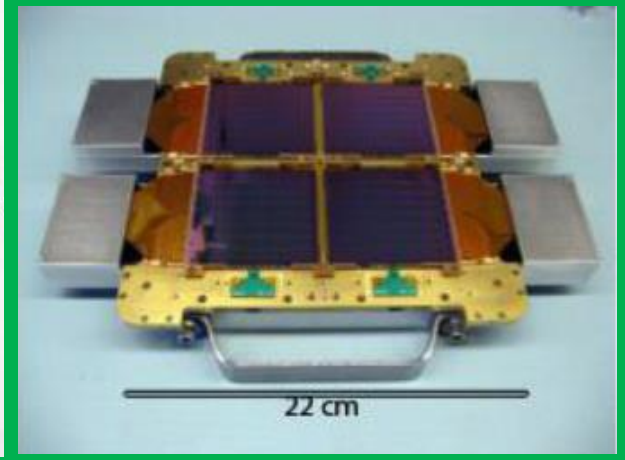


Figure credit: Ben Mazin, UCSB

CMB polarimeters in the field

ACTpol

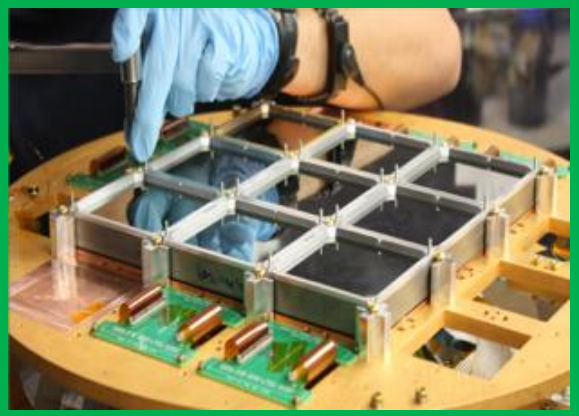
SPIDER



Keck Array

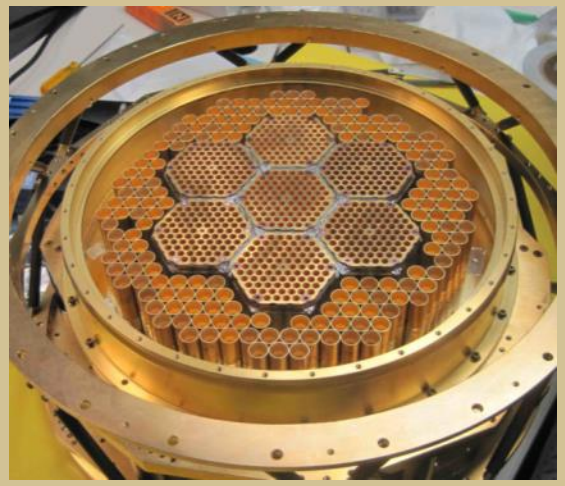
TDM

BICEP-3



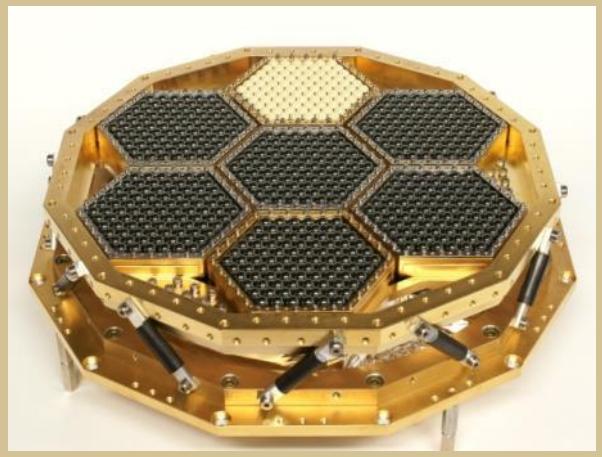
+ SPIDER, BICEP-3

SPTpol



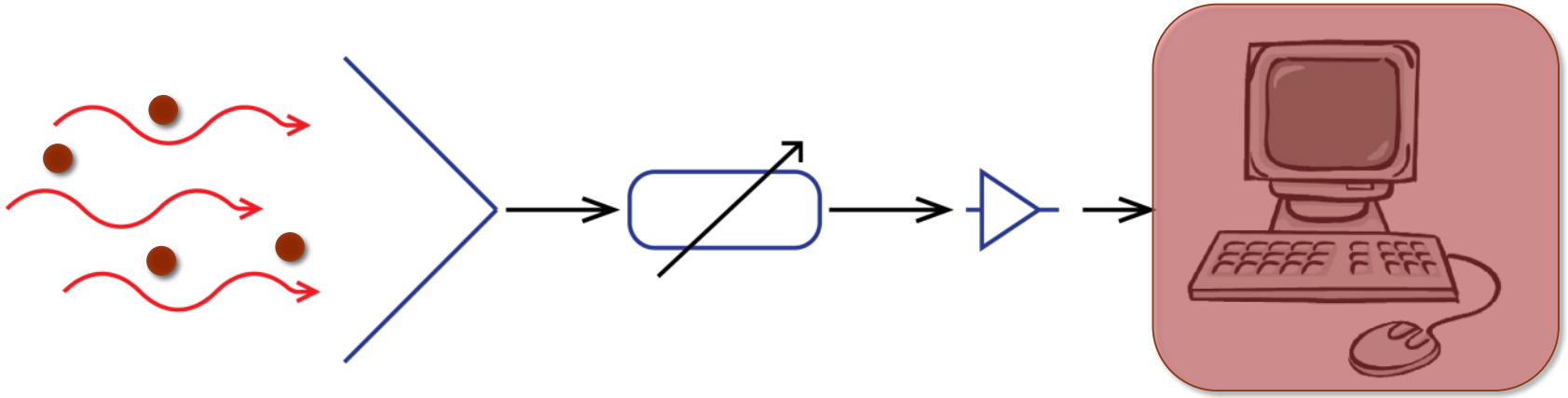
FDM

POLARBEAR



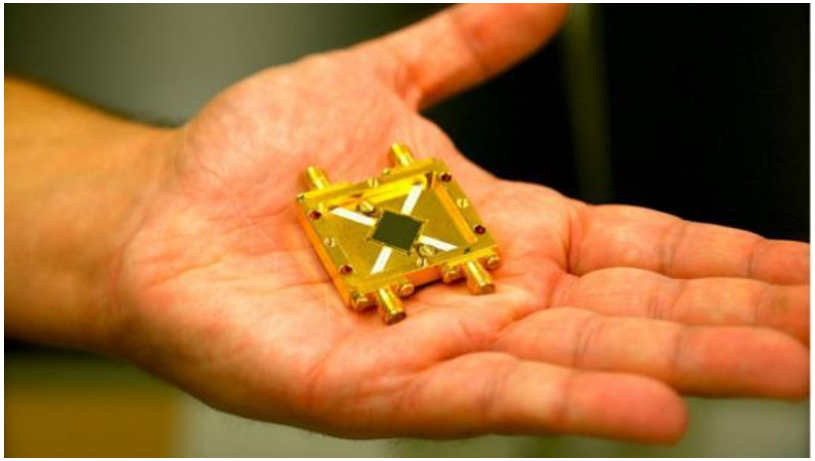
3. Room-temperature readout / DAQ

1.Signal 2.Coupling 3.Sensor 4. Coherent Preamp 5.Readout DAQ, Software



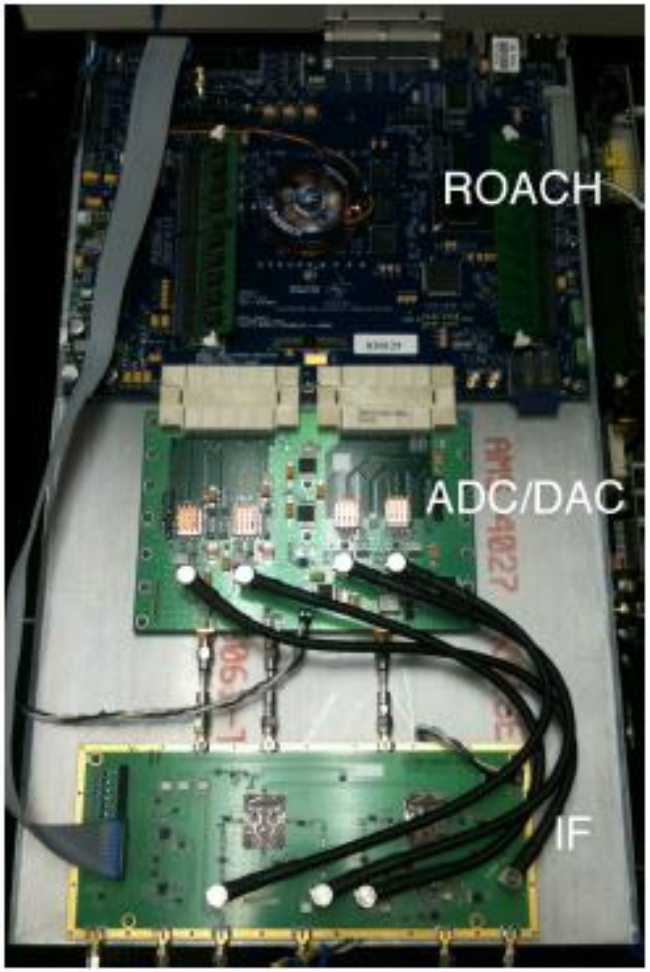
Roach electronics for MKIDs and microwave SQUIDs

2048-pixel ARCONS MKID optical camera



ROACH in MKIDs: McHugh, rev. Sci. Instrum. **83**, 044702 (2012)

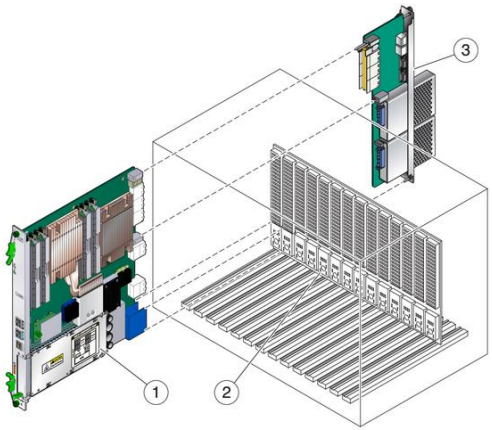
ROACH electronics for ARCONS



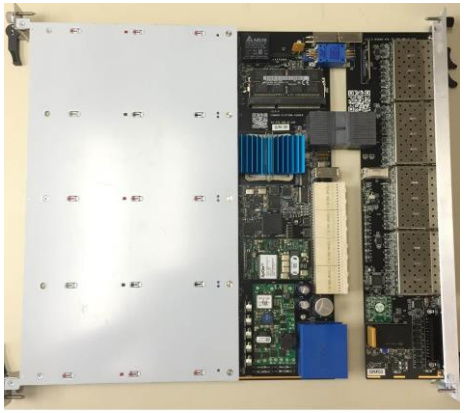
SLAC LCLS-based MKID and TES readout electronics

High performance room-temperature electronics

- Warm (300 K) electronics are needed to synthesize input microwave tones to drive the microwave SQUIDs and to channelize and demodulate the output microwave tones
- Frequency of tones is adjusted to track pixel resonance
- Base on existing ATCA based ADC/DAC/FPGA project for LCLS-II
- Xilinx XCK060 FPGA
- A carrier card provides
  - 4GHz bandwidth of signal generation and measurement, can track up to 4000 resonances.
  - Two AMC daughter cards are mounted on each carrier. Each AMC has two dual channel TI ADC32RF45 3Gs/s digitizers with internal DDC, and 2 dual channel 4Gs/s DACs with DDS, along with band selection multiplexers, and local oscillators.
- Electronics / RF design nearing completion, full hardware prototype in late 2016.



ATCA shelf and cards



Carrier card

J. Frisch, S. Smith, D. Van Winkle, R. Herbst, SLAC

State of the art: cryogenic calorimeters for HEP

Sub-K Calorimeter	Location	Detection mode	Absorber Total mass	Sensor type	# Sensor # Crystal
WIMP					
CRESST II (2003–)	Gran Sasso Italy	Noneq. phon. and scint.	$CaWO_4$ 5.4 kg	TES	18
EDELWEISS III (2015–)	LSM Modane France	Eq. thermal and ion.	Ge 22 kg	NTD Ge +HEMT	36
SuperCDMS (2012–)	Soudan, USA SNOLAB, Canada	Noneq. phon. and ion.	Ge 9 kg	TES +JFET	120 15
Beta decay					
ECHo (2012–)	Heidelberg Germany	Eq. thermal	Au:^{163}Ho 0.2μg	MMC	16
$0\nu\beta\beta$ **decay**					
CUORE (2015 –)	Gran Sasso Italy	Eq. thermal	TeO_2 741 kg	NTD Ge	988
AMoRe Pilot (2015 –)	Yang Yang S. Korea	Noneq. phon. and scint.	$CaMoO_4$ 1.5 kg	MMC	5
LUCIFER (2010–)	Gran Sasso Italy	Eq. thermal and scint.	ZnSe 431 g	NTD Ge	1

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-particle-detectors-non-accel.pdf

State of the art: cryogenic bolometers for HEP

Sub-K CMB Experiment	Location	Aperture	Sensor type	# Sensors (planned)	Frequency (planned)	Bands (planned)
Ground-based						
Atacama Cosmology Telescope (2007–)	Chile	6 m	TES	1,800 (5,334)	90–150 GHz (28–220 GHz)	2 (5)
BICEP/Keck (2006–)	South Pole	26/68 cm	TES	3,200	95–220 GHz	3
CLASS (2015–)	Chile	60 cm	TES	36 (5,108)	40 GHz (40–220 GHz)	1 (4)
POLARBEAR / Simons (2012–)	Chile	3.5 m	TES	1,274 (22,764)	150 GHz (90–220 GHz)	1 (3)
South Pole Telescope (2007–)	South Pole	10 m	TES	1,536 (16,260)	95–150 GHz (95–220 GHz)	2 (3)
Balloon						
EBEX (2013–)	McMurdo	1.5 m	TES	~1,000	150–410 GHz	3
PIPER (2016–)	New Mexico	2 m	TES	5,120	200–600 GHz	4
SPIDER (2014–)	McMurdo	30 cm	TES	1,959	90–280 GHz	3
Satellite						
Planck HFI (2003–)	L2	1.5 m	NTD	52	100-857 GHz	9

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-particle-detectors-non-accel.pdf

State of the art: cryogenic coherent amplifiers for HEP

QCD Axions and ALPs

- ADMX, ADMX-HF, other ADMX extensions

  Microstrip SQUIDs, para-amps

- CASPEr

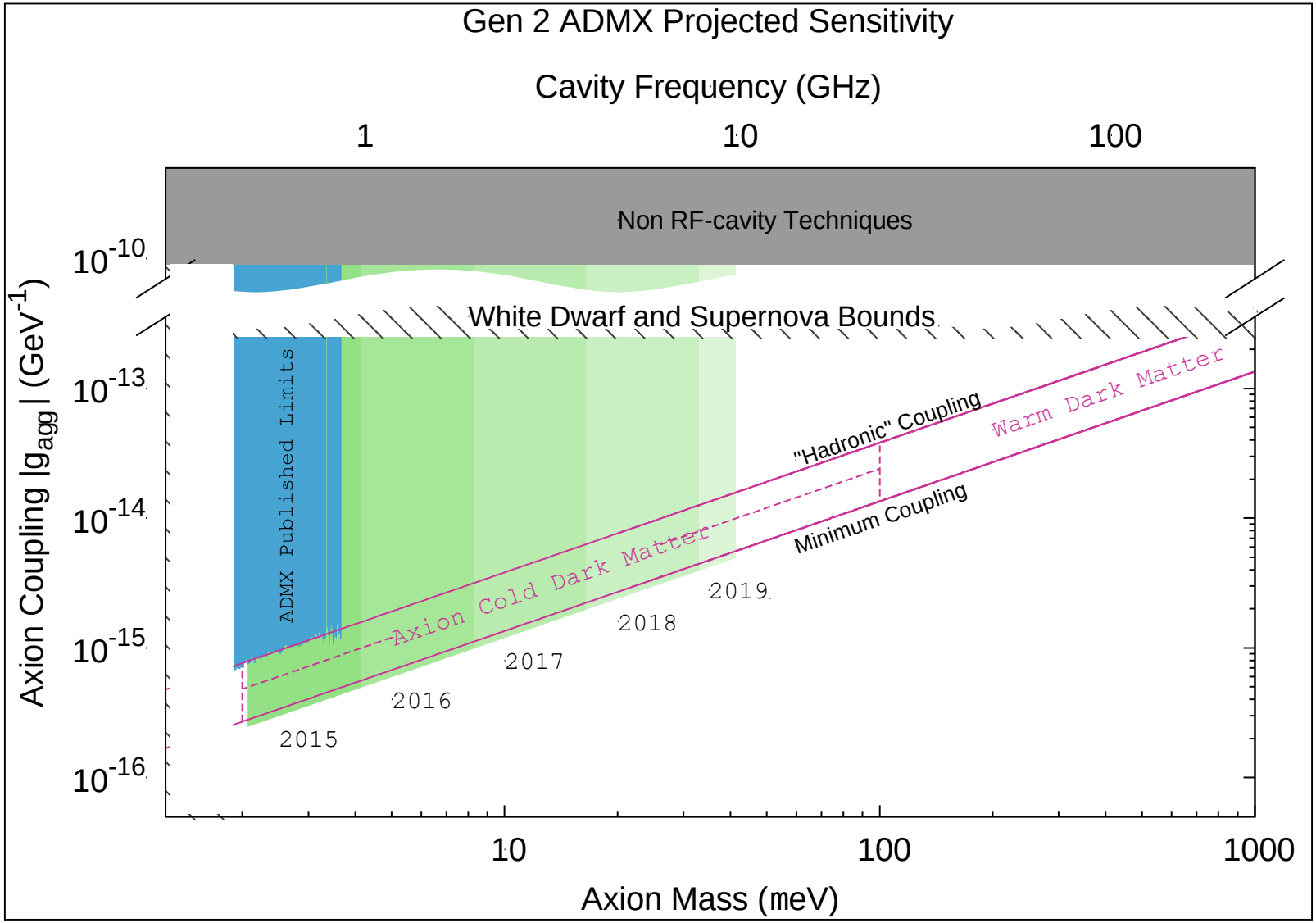
  SQUIDs

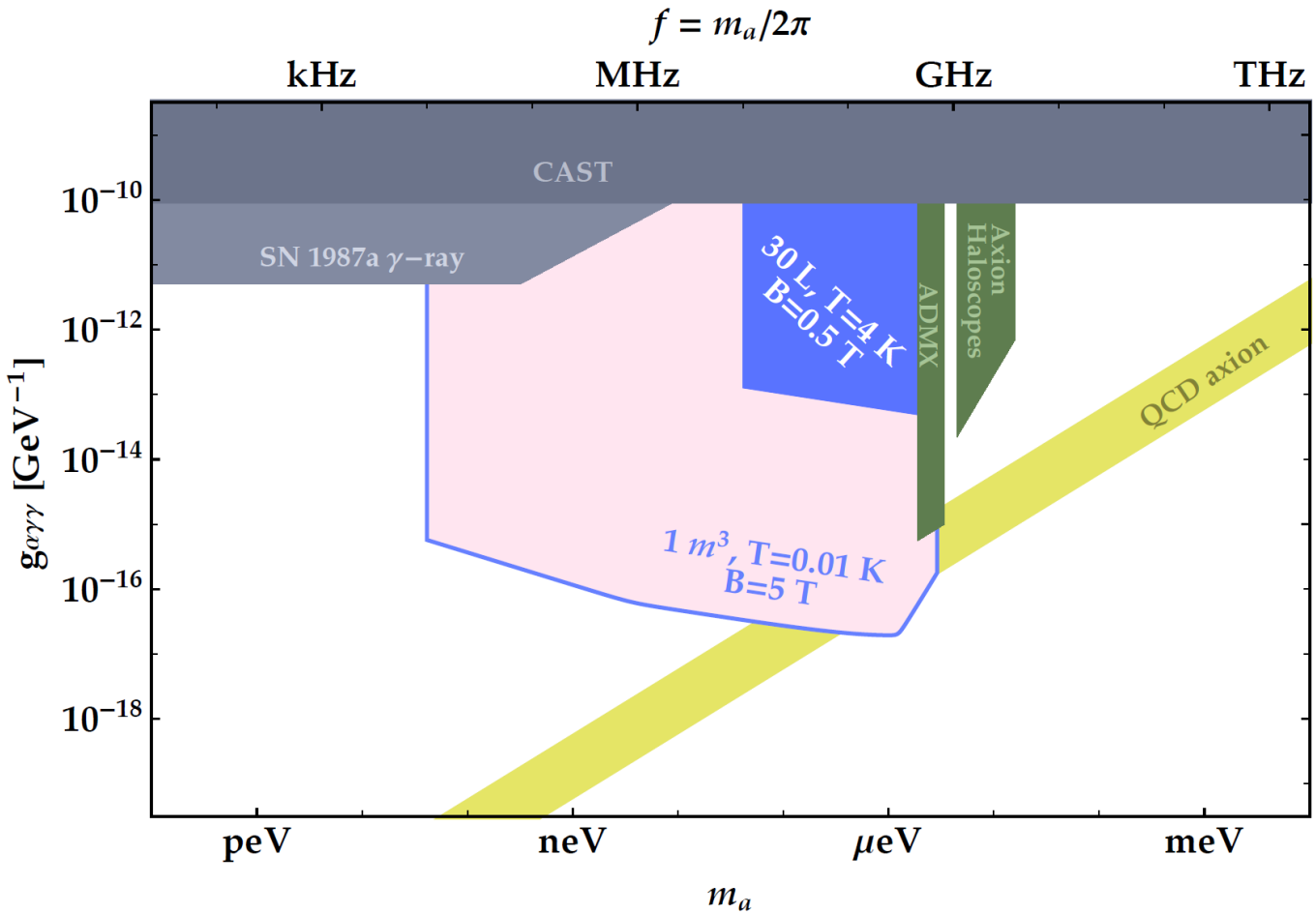
- DM Radio

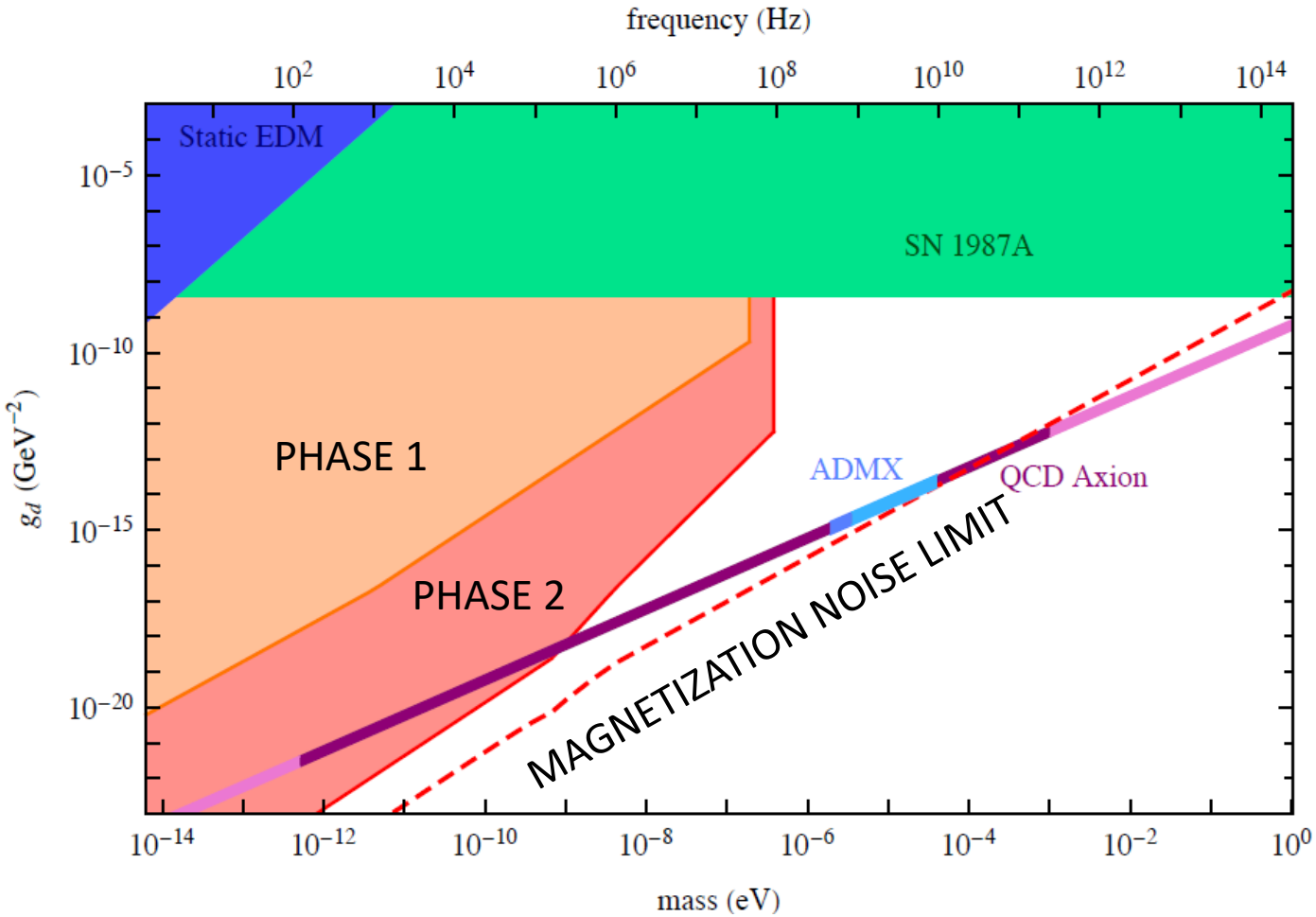
  SQUIDs, ac SQUIDs, para-amps

Hidden photons

- ADMX
- DM Radio


Gen 2 ADMX Projected Sensitivity
Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
ADMX Published Limits
"Hadronic" Coupling
Minimum Coupling
Axion Cold Dark Matter
Warm Dark Matter
2015
2016
2017
2018
2019
Axion Coupling |g_agg| (GeV^-1)
10^-10
10^-13
10^-14
10^-15
10^-16
10
100
1000
Axion Mass (meV)


$f = m_a/2\pi$
kHz
MHz
GHz
THz
CAST
SN 1987a γ−ray
30 L, T=4 K
B=0.5 T
ADMX
Axion
Haloscopes
QCD axion
1 m^3, T=0.01 K
B=5 T
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$g_{\alpha\gamma\gamma}$ [GeV^{-1}]
peV
neV
μeV
meV
m_a


frequency (Hz)
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Static EDM
SN 1987A
PHASE 1
PHASE 2
ADMX
QCD Axion
MAGNETIZATION NOISE LIMIT
g_d (GeV^{-2})
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
mass (eV)

This session

11:30 **Cryogenic Detectors: Overview of the Field** *25'*
Speaker: Kent Irwin

11:55 **TES Development for CMB** *25'*
Speaker: Suzanne Staggs

12:20 **TES for Dark Matter Detection** *25'*
Speaker: Dr. Matt Pyle (UC Bekeley)

12:45 **Ir Based Low-Tc TES** *25'*
Speaker: Dr. Gensheng Wang (HEP, Argonne)

13:10 **Lunch** *1h30'* (Dabney Hall & Gardens)

14:40 **MKID Development for CMB** *25'*
Speaker: Erik Shirokoff (U. Chicago)

15:05 **Improving MKID sensitivity & resolution** *25'*
Speaker: Ben Mazin

15:30 **Broadband Microstrip-Coupled Titanium Nitride Kinetic Inductance Detectors: A Key Detector Technology for CMB-S4** *25'*
Speaker: Prof. Sunil Golwala (California Institute of Technology)

15:55 **Coffee Break** *30'* (Dabney Hall & Gardens)

16:25 **Multiplexing Readout for Large format TES & MKID arrays** *25'*
Speaker: Zeeshan Ahmed

16:50 **The DM Radio: A Superconducting Dark Matter Detector for Axions and Hidden Photons***25'*
Speaker: Dale Li

17:15 **Single Photon Microwave detectors for axion searches** *25'*
Speaker: Dr. maxime malnou (JILA University of Colorado Boulder)

17:40 **Cryogenic CCDs** *25'*
Speaker: juan estrada (fermilab)

18:05 **Localized Electrons in Dielectric Layers** *12'*
Speaker: Dr. Sergey Pereverzev (LLNL)