EXCELLENCE IN DETECTOR AND INSTRUMENTATION TECHNOLOGIES (EDIT)

Argonne NATIONAL LABORATORY

SUPERCONDUCTING DETECTORS

CLARENCE CHANG
Argonne National Lab

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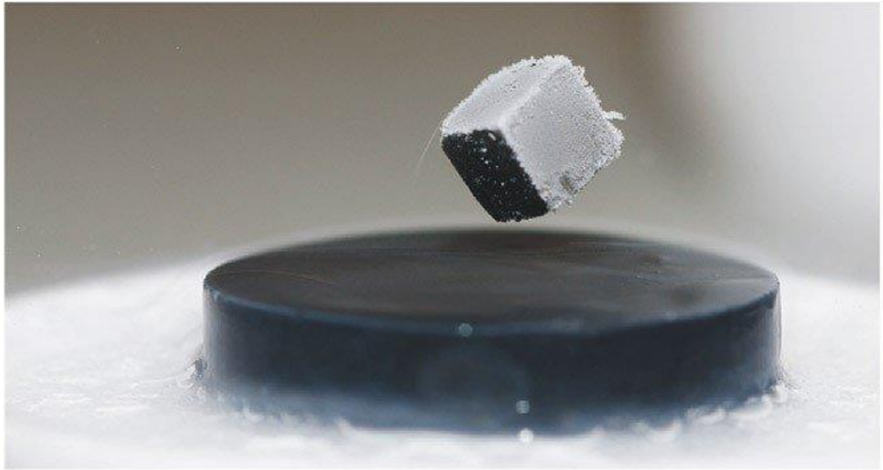
SUPERCONDUCTIVITY

Common perceptions



SUPERCONDUCTING SENSORS

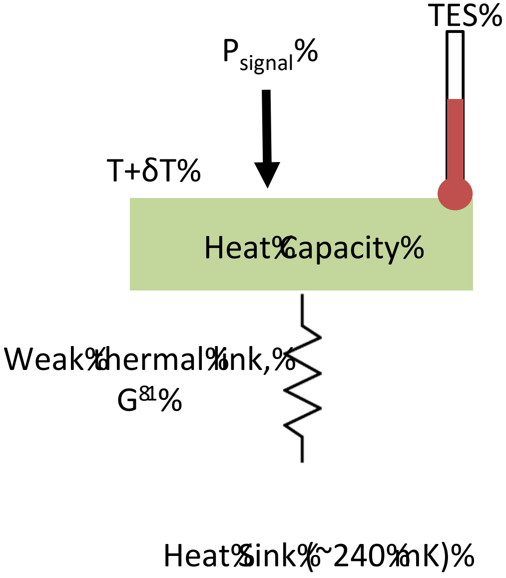
- There are applications that require/benefit from low temperatures
  - Sensing applications where signal thresholds are <1eV (gap of Si)
  - Amplification of low freq EM signals
  - Calorimetric/bolometric applications where noise from thermal fluctuations need to be minimized
- Superconductivity corresponds to phase transition that takes place at these temperatures and energy scales
  - Rich set of phenomena
  - Can develop/build many kinds of devices
  - Integrate to realize complex detectors

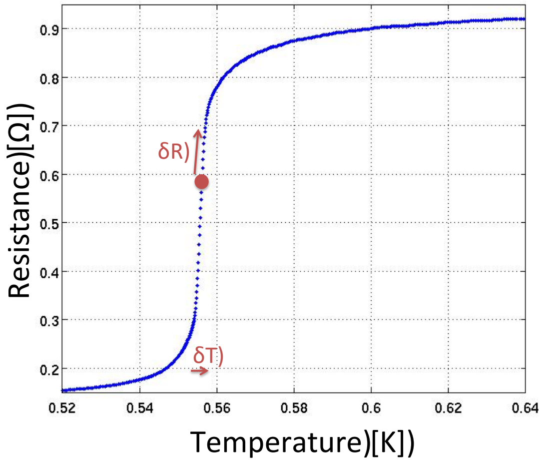
TOPICS/OUTLINE

- TES
  — Principles
  — Applications
- MKID
  — Principles
  — Applications
- SQUIDs/Josephson Junctions
  — Principles
  — Applicatoins
- SNSPD
  — Principles
- Fabrication
- Cooling

SUPERCONDUCTORS HAVE A RESISTIVE TRANSITION

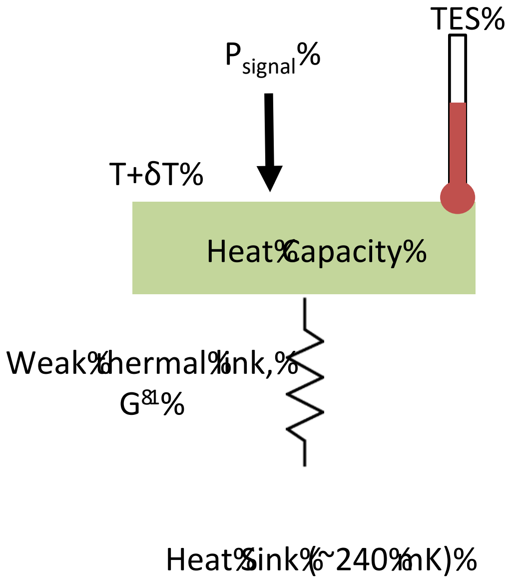
MODERN TES

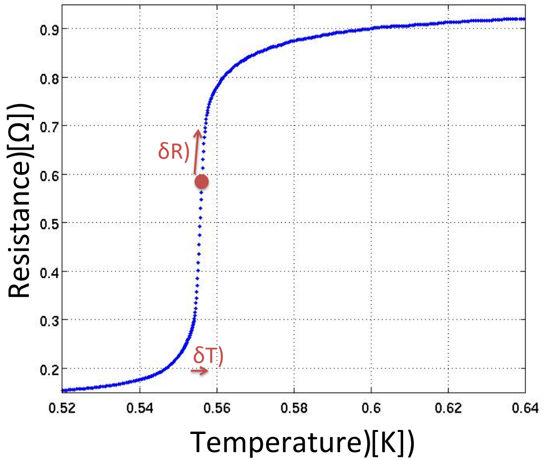




$$P_{Joule} = \frac{V_0^2}{R(T)}$$

MODERN TES

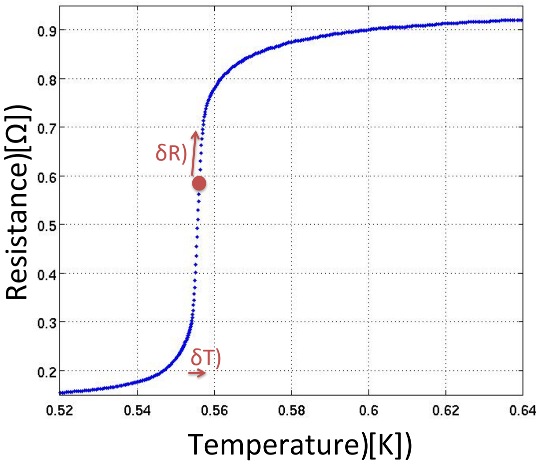




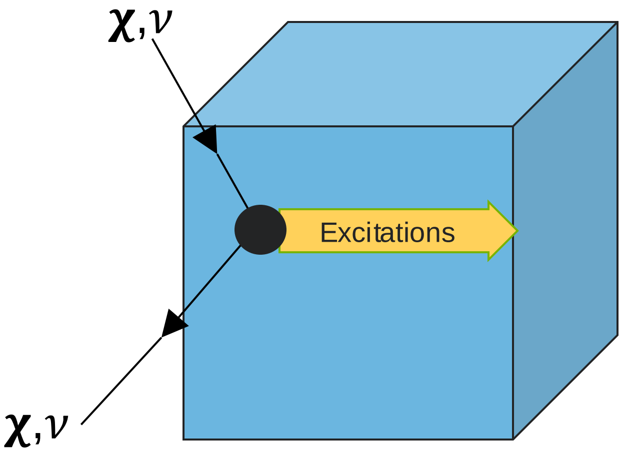
$$\delta P_{Joule} = \frac{d}{dT}\left(\frac{V_0^2}{R(T)}\right) = -\left(\frac{V_0}{R}\right)^2 \frac{dR}{dT}\delta T$$

OPERATING PRINCIPLES

- Device stabilizes at T_c. Temperature is nearly constant.
- Linearity:
  - $\Delta P_{absorbed} \approx \Delta P_{bias} = V_{bias} \times \Delta I_{TES}$
- Increased bandwidth
- Voltage bias using shunt resistor
  - Measure current using high sensitivity SQUID
- Fundamental noise comes from thermal fluctuations (~kT), which can be made small by choosing suitable T_c.



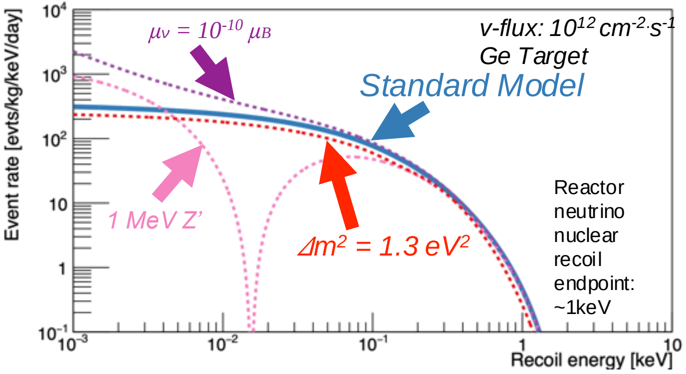
PARTICLE INTERACTIONS IN MASSIVE TARGETS

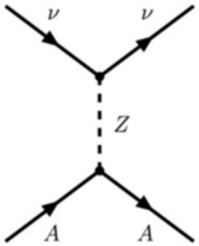


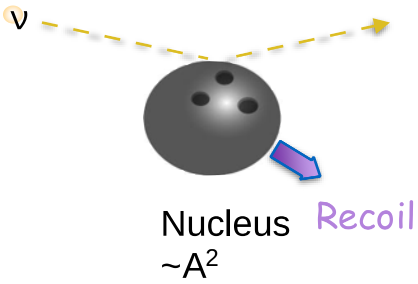
- Recoil energy from particles (dark matter, neutrinos) interacting w/ target
  - **ns**: Initial recoil
  - ***μs***: athermal excitations
    - Collective excitations: Phonons, rotons, magnons
    - Ionization, scintillation
    - Photon emission
  - **ms**: thermalization
- Recoil spectrum for low mass DM and CEvNS rising exponentially at lower energy
  - Pushes for lower thresholds

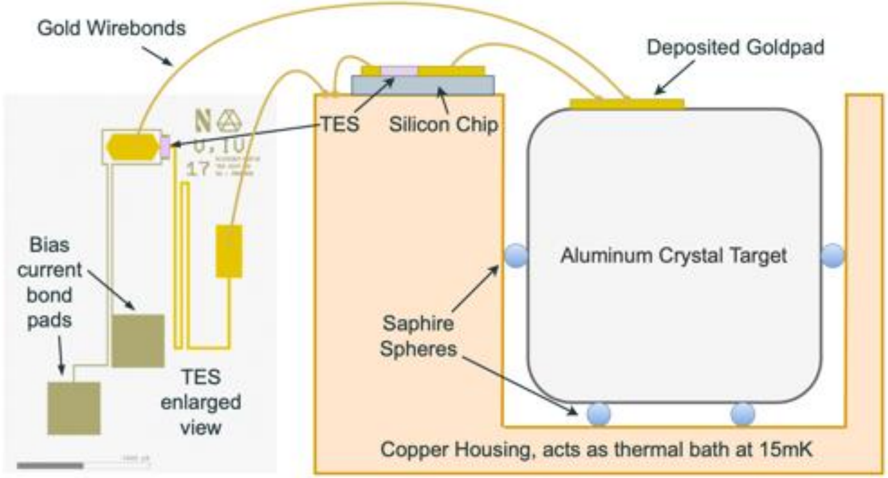
LARGE MASS BOLOMETERS FOR CEVNS

Ricochet (Q-Array)



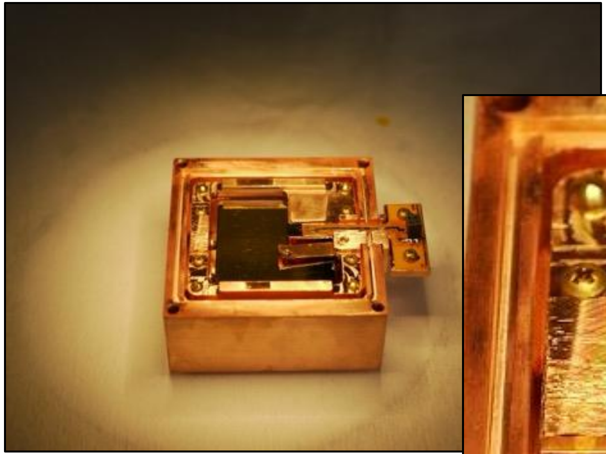


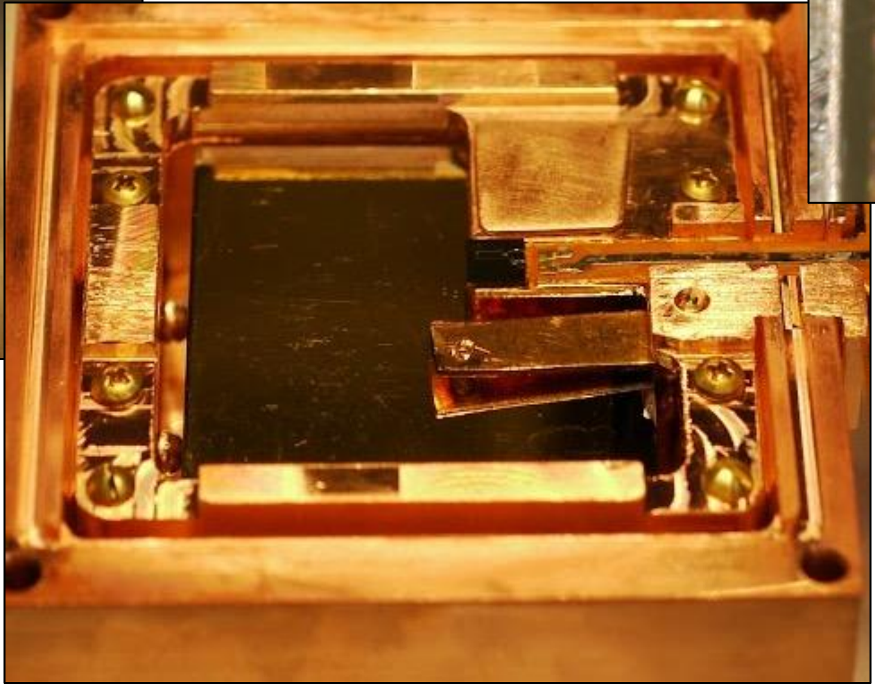


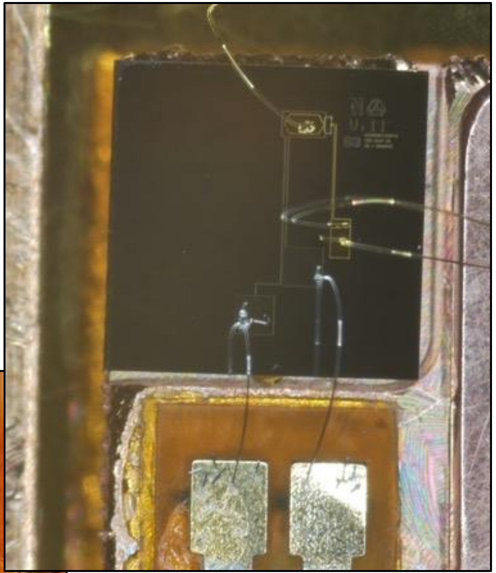


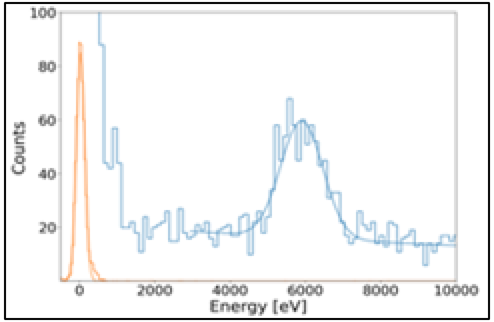
RICOCHET (Q-ARRAY)

Large mass bolometer

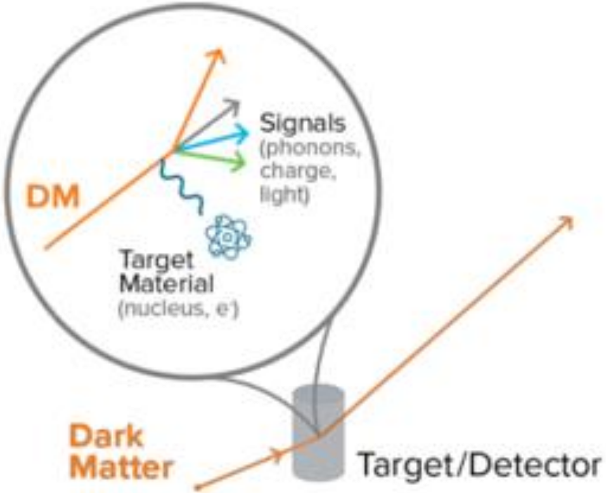


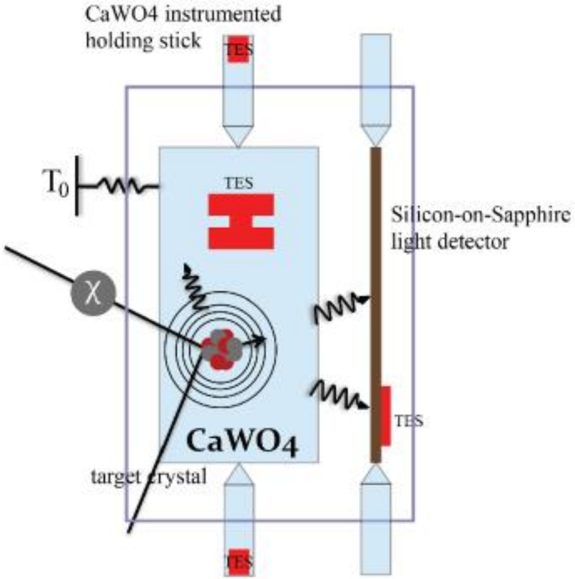


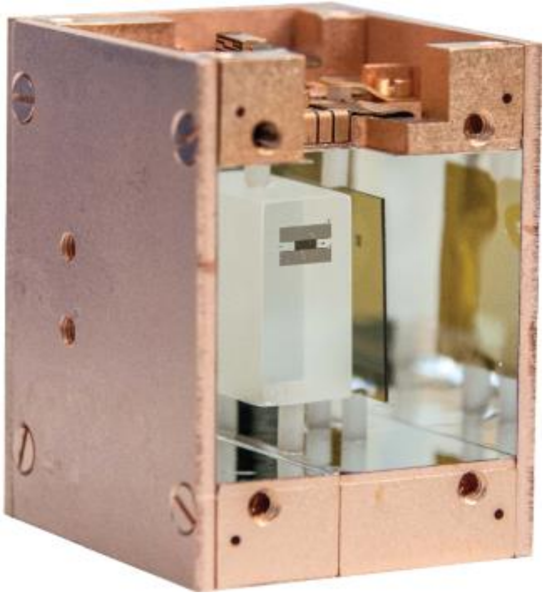


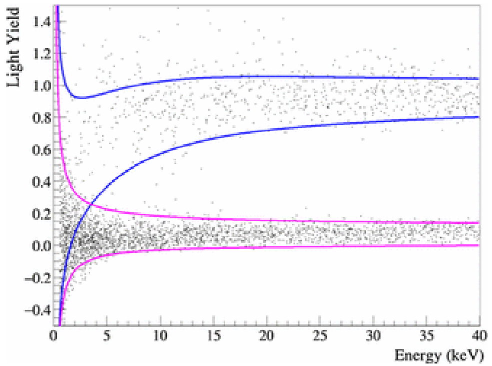


DARK MATTER
CRESST





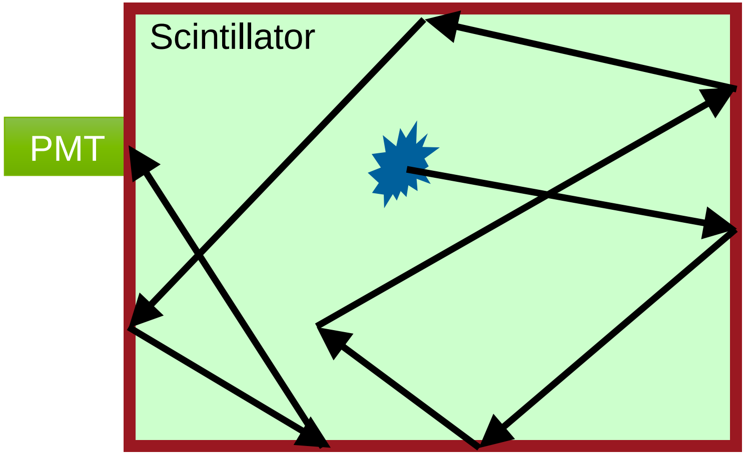




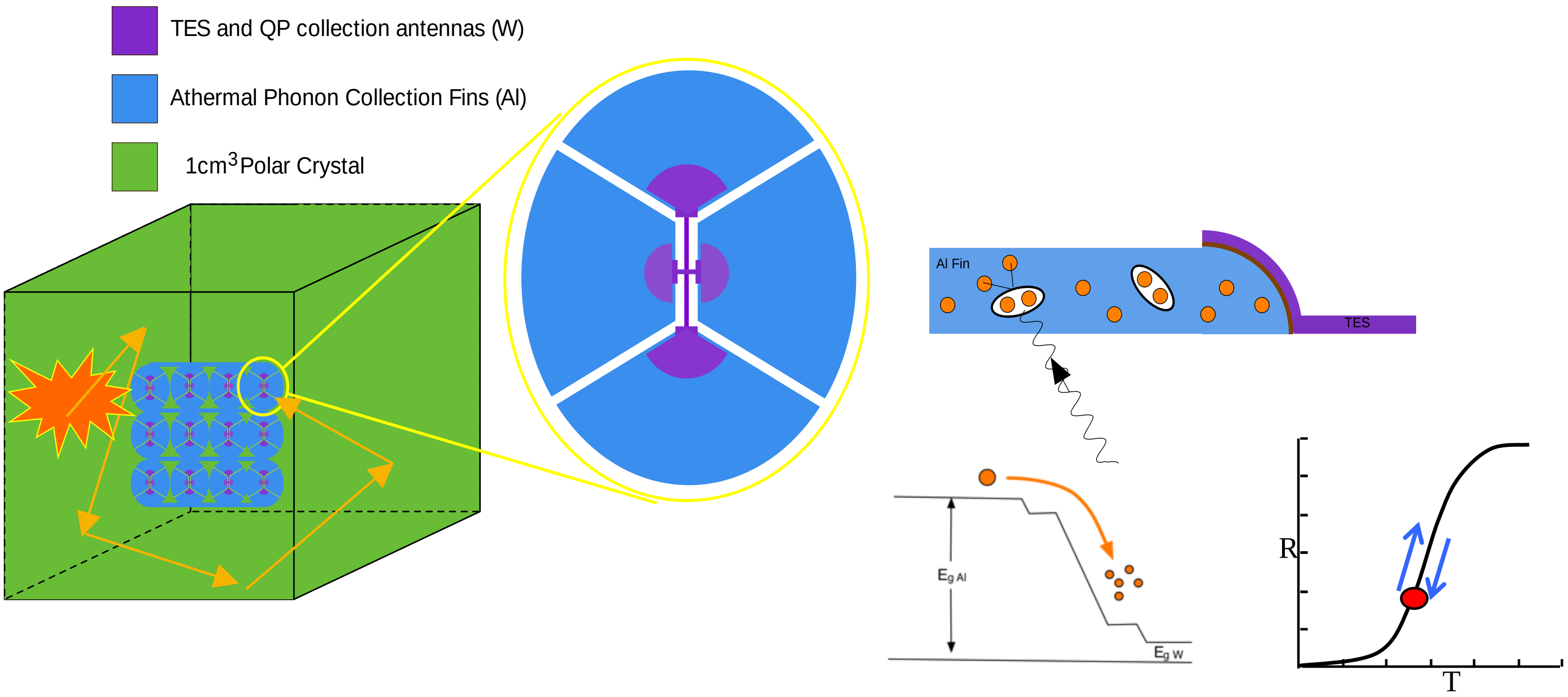
ATHERMAL SIGNALS

E.g. from PMTs…

- Will these detectors have the same energy sensitivity?
- Yes, if:
  - Lifetime of the athermal excitation (photon) is really long
  - Excitation absorption dominated by sensor



ATHERMAL PHONON SENSOR TECHNOLOGY



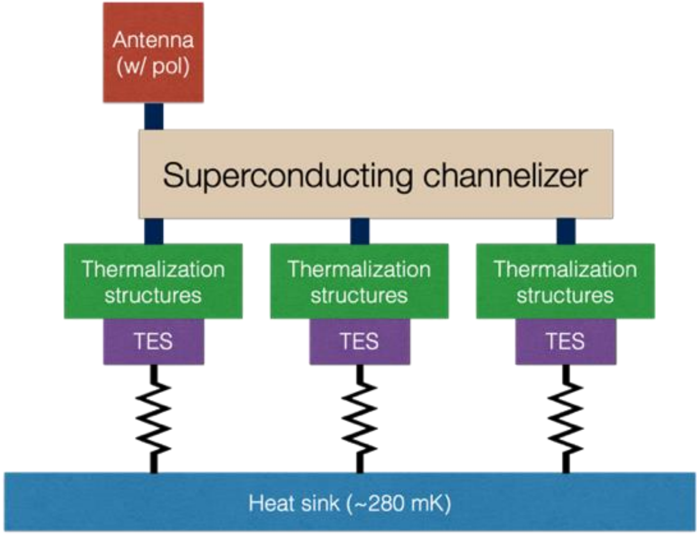
DARK MATTER

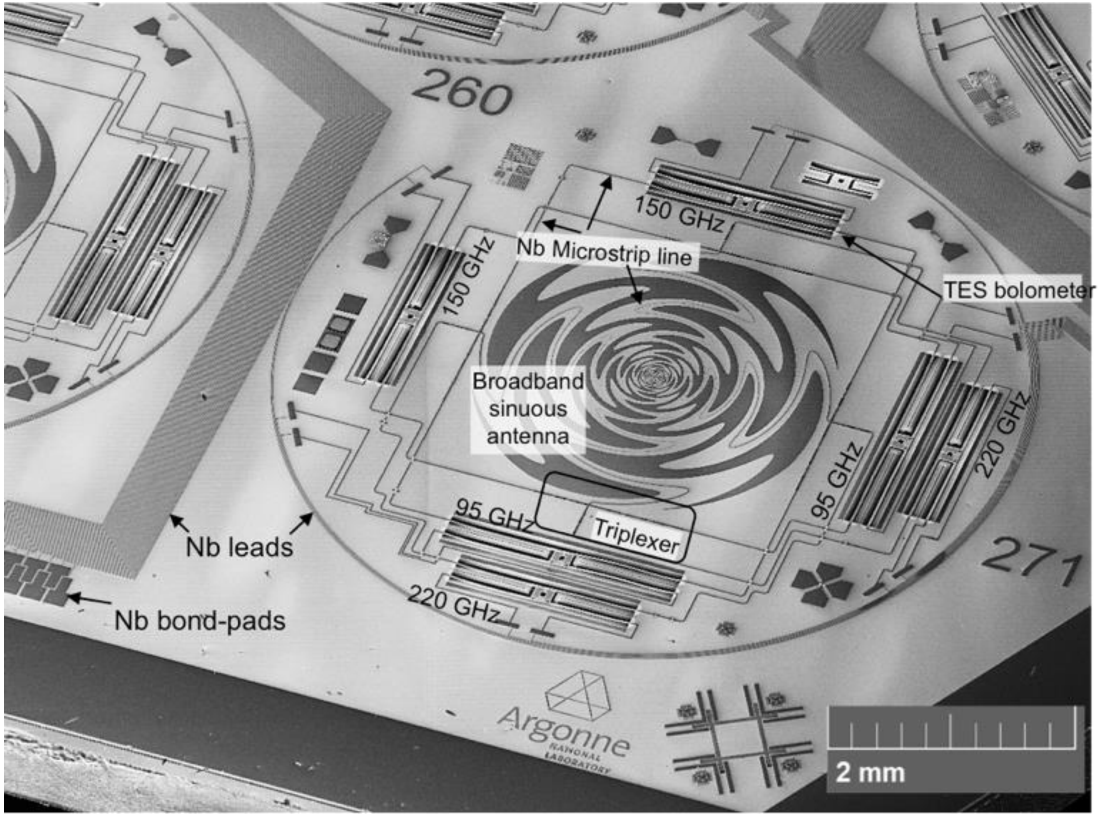
SuperCDMS

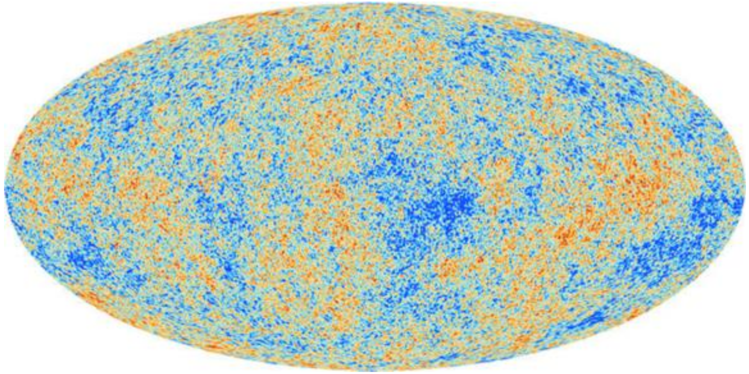
- Athermal phonon sensing
  - — Ideally, sensor noise determined by (small) thermal TES
  - — Target volume determined by crystal size
  - — Timing of athermal signal provides add'l information for discriminating events

PHOTON DETECTORS FOR CMB

Antennas and filters





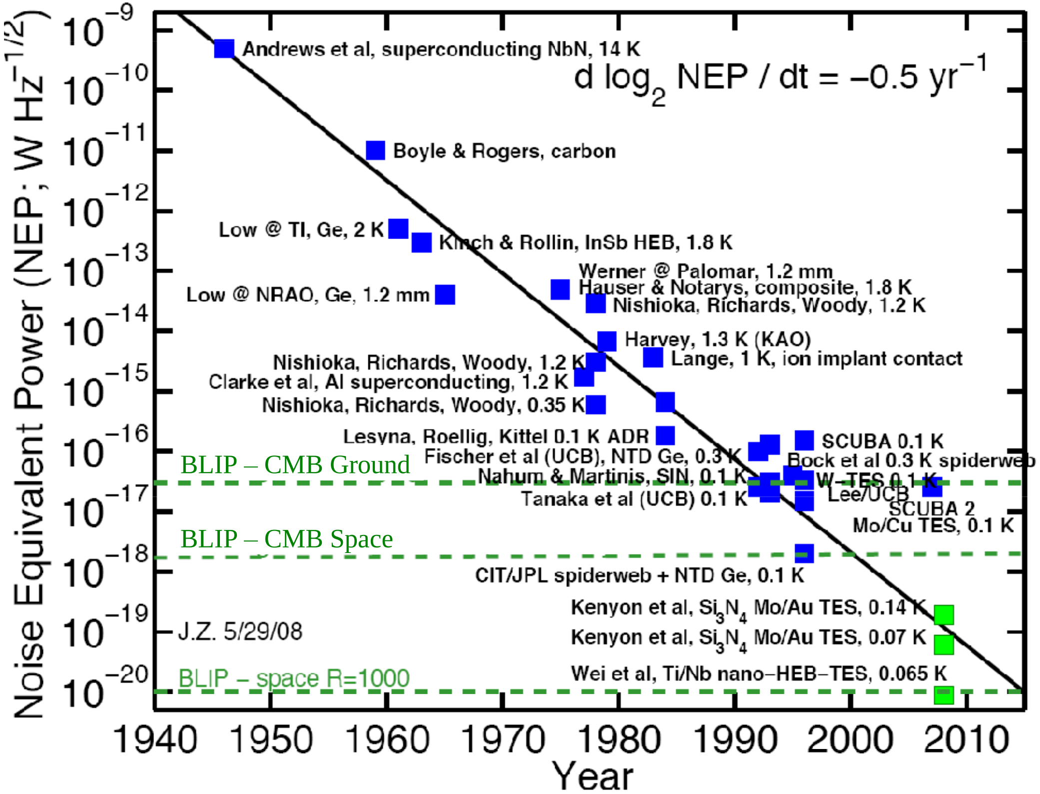


- Photons follow Bose-Einstein statistics
- Mean occupation number (average number of photons)

$$< n >= \frac{1}{e^{h\nu/kT} - 1}$$

- Variance

$$< n^2 >= n(n+1)$$

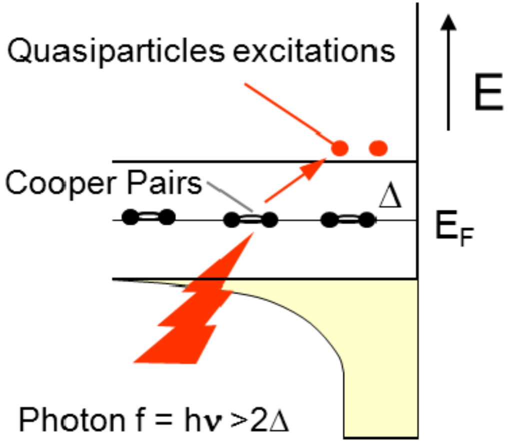


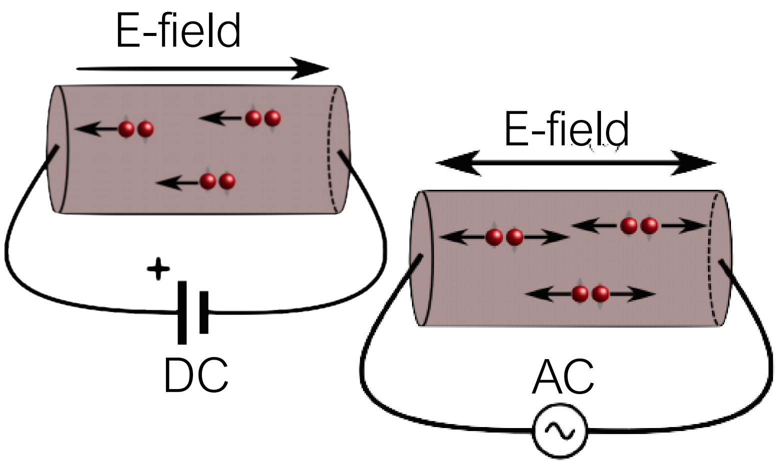
Need a lot of detectors.

COOPER PAIRS

KINETIC INDUCTANCE

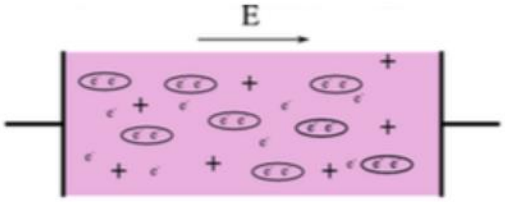
- Pairing of electrons into Cooper pairs
  - Energy gap between ground state and next excited state
- Quasiparticles are Cooper pair “excitations”
  - Fermions vs bosons
  - “Broken” Cooper pairs
- Cooper pairs have mass and momentum
  - Do not scatter. Charge flow (current) has no dissipation (real(Z) = 0)
  - Inertial response to changes in E-field. Charge flow lags field (imag(Z) ≠ 0)

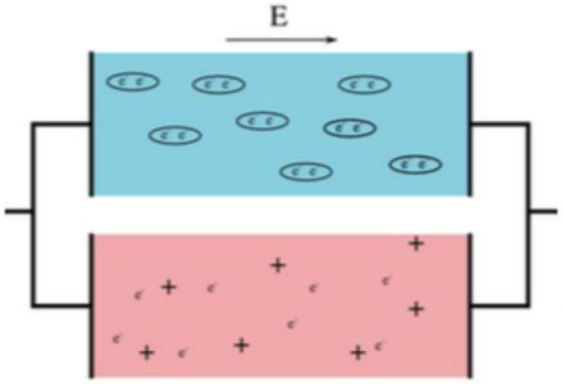




SURFACE IMPEDANCE

- Imagine superconductor as a fluid with two particles (Cooper pairs and quasiparticles)
- Complex conductivity depends on contributions from both
  - Cooper pairs:
    - No dissipation. Kinetic inductance.
  - Quasiparticles:
    - Dissipate
    - Small kinetic inductance
- Total complex conductivity depends on the population of pairs vs qps
  - Breaking pairs lead to a change in the complex impedance

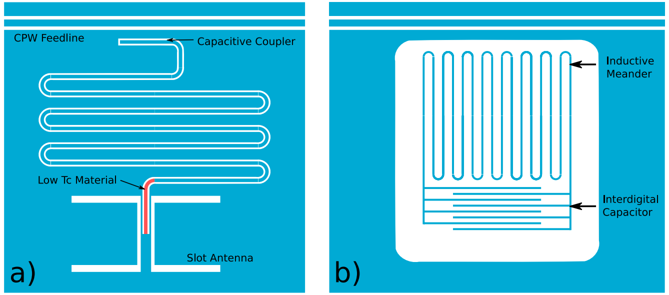




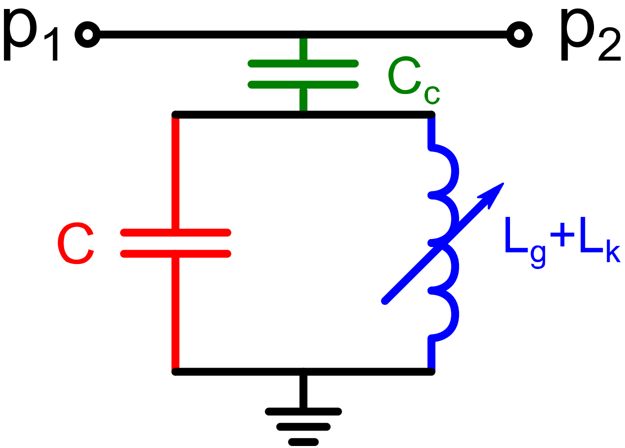
KINETIC INDUCTANCE DETECTORS

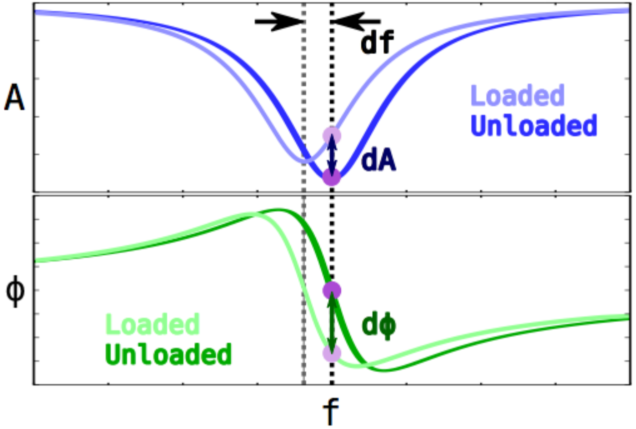
Measure Lk, Rs shift using LC resonator

- Two methods: distributed, lumped element
- Resonator complex transfer function → phase + amplitude, frequency + Q



Distributed Lumped element



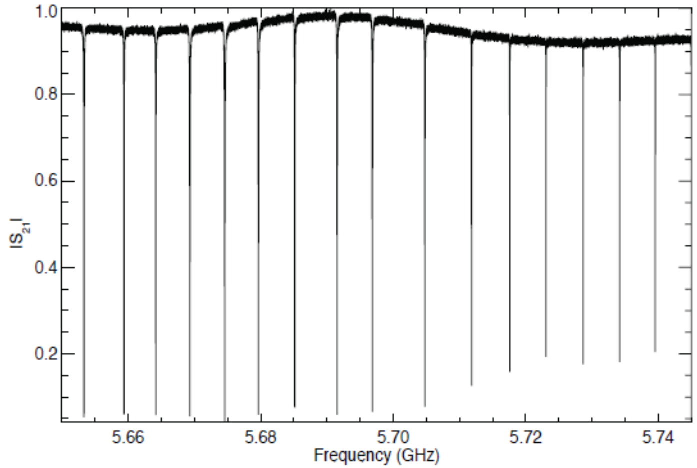


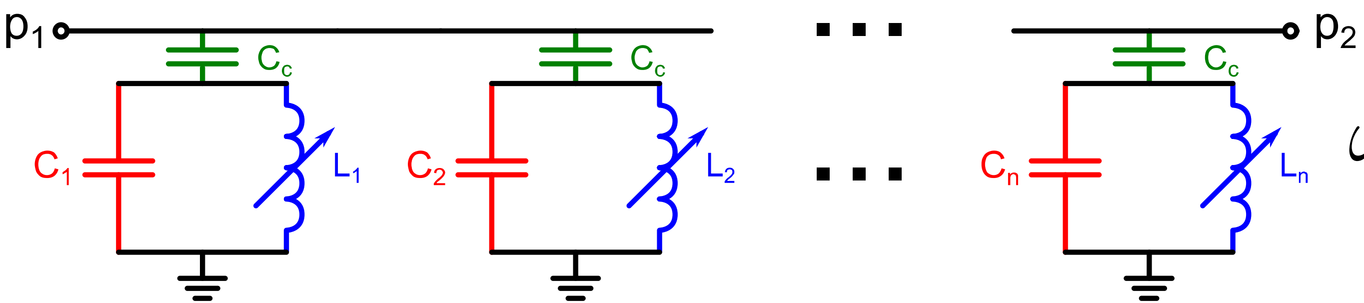
$$w_0 = \frac{1}{\sqrt{LC}}$$

$$Q_i = \frac{w_0 L}{R}$$

NATURALLY MULTIPLEXED

- LC resonator has specific F0
- Multiple resonators on a single line (just design w/ different f0s)
  - Readout w/ RF electronics
- Should be able to achieve few 10^3 / octave



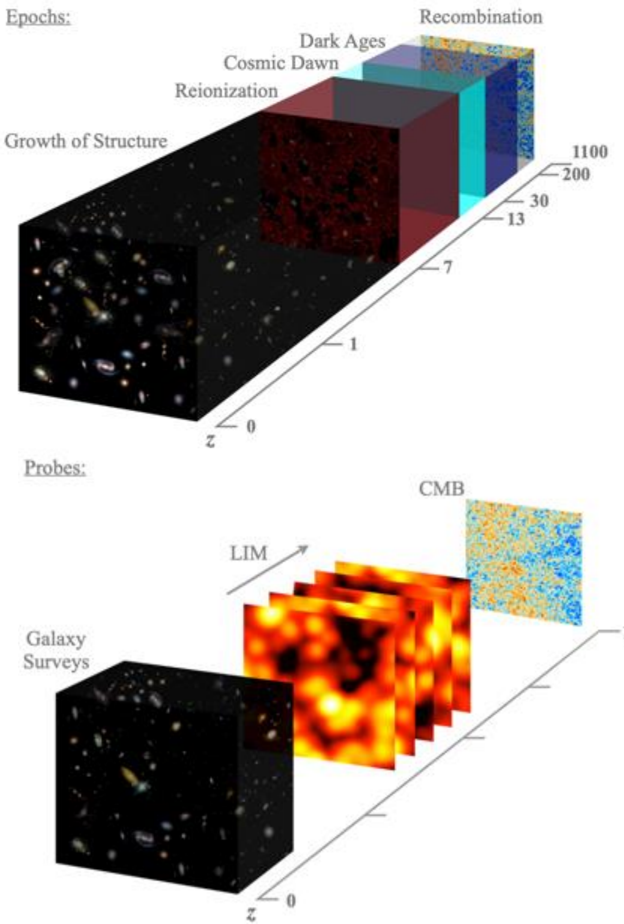


$$\omega_n = \frac{1}{\sqrt{L_n C_n}}$$

LINE INTENSITY MAPPING

Like CMB, only spectroscopic

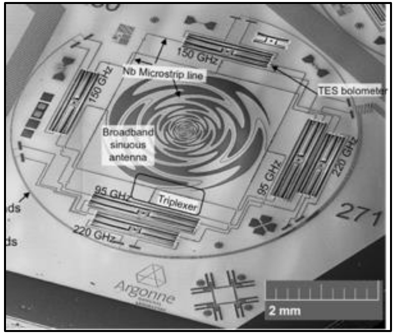
- Measure aggregate emission from lots of galaxies
  - Don’t resolve individual galaxies
  - Only measure overall distribution
- Emission dominated by a few lines
  - Detected wavelength is redshifted
- 3D distribution of galaxies
  - Low angular resolution (2D map)
  - Low spectral resolution (redshift)

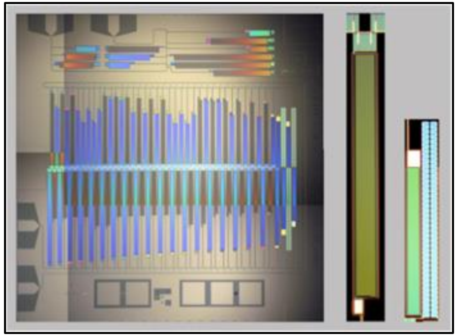


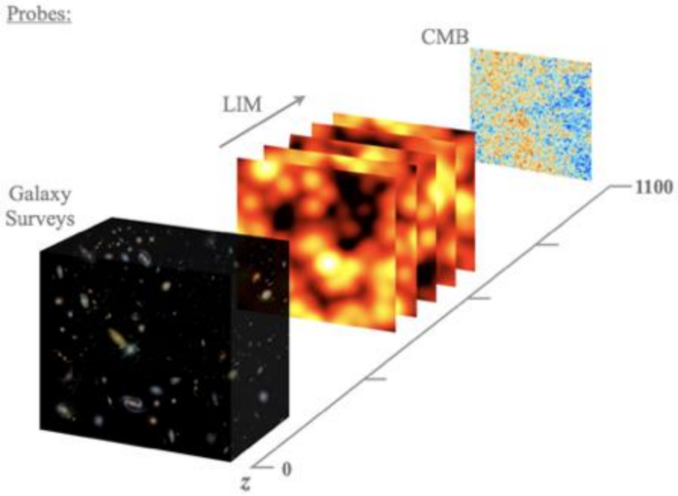
TECHNICAL CHALLENGE

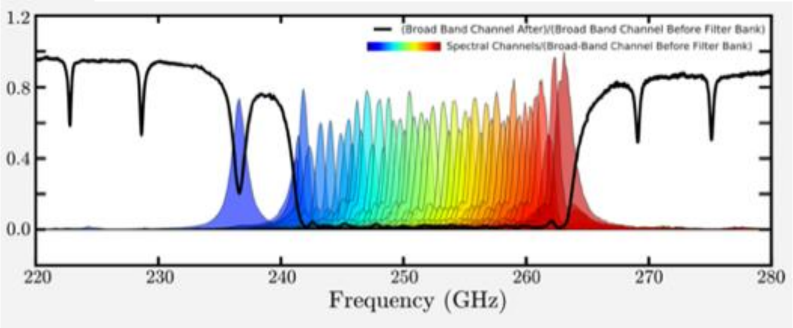
Requires increasing channel density

- “Spectroscopy” requires >100X over current densities typical for CMB experiment

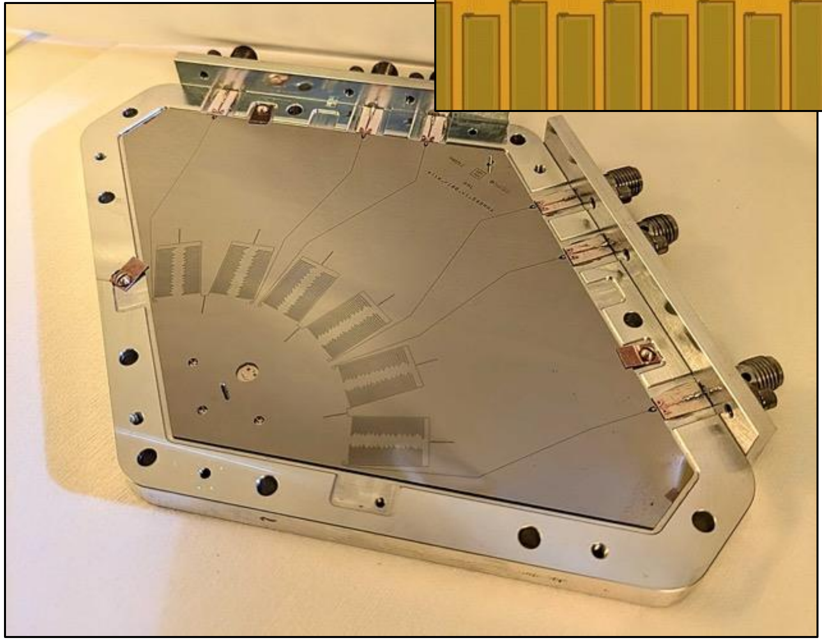


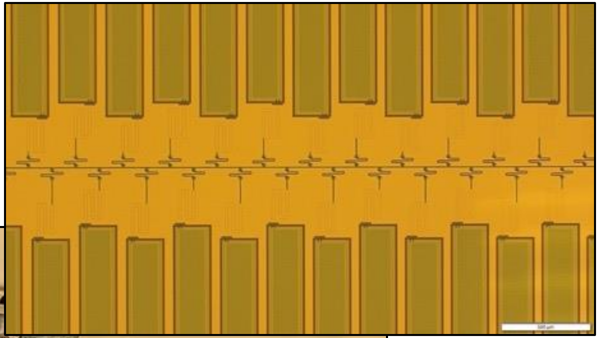


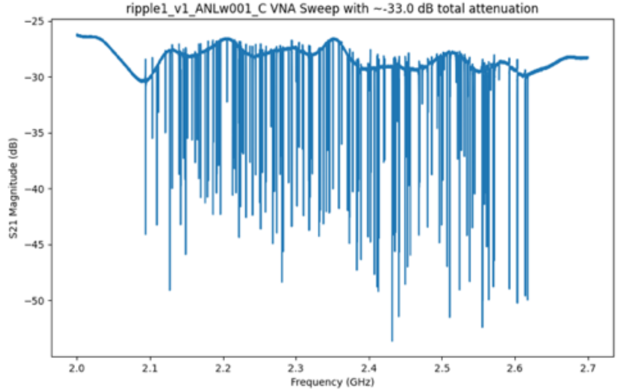


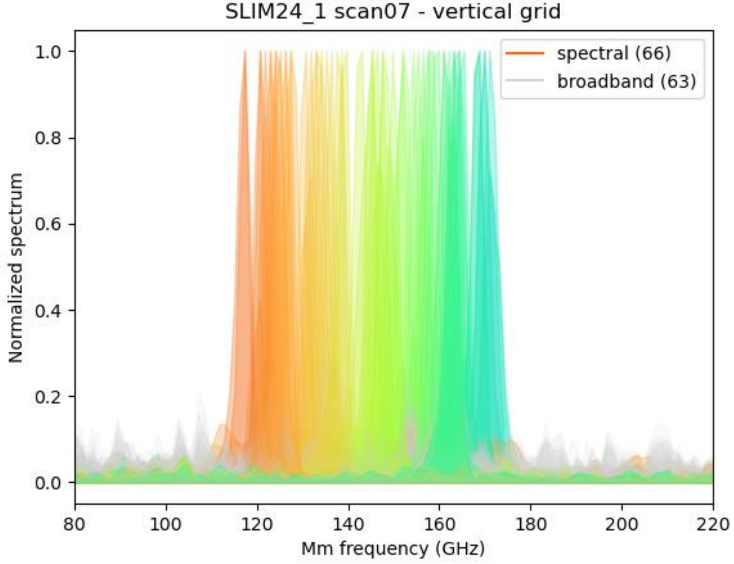


SPECTROMETER ARRAYS





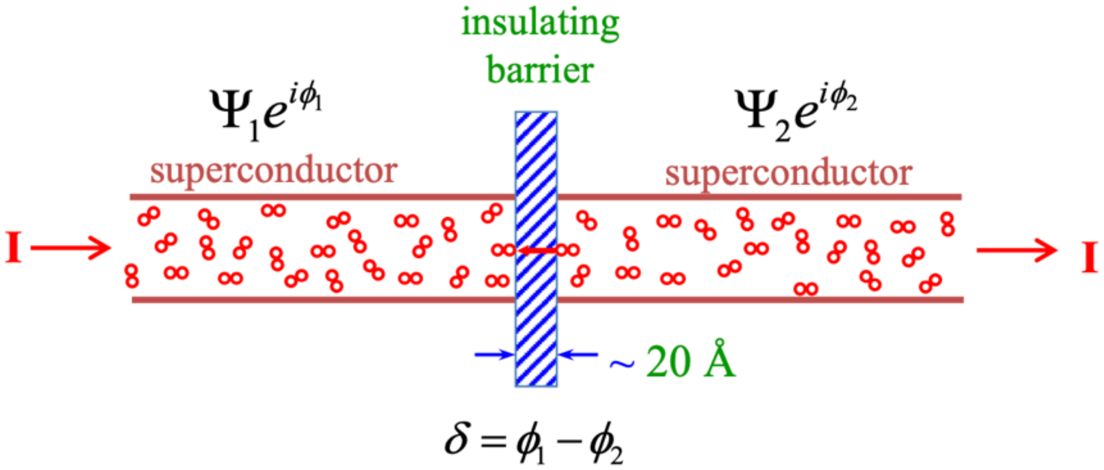




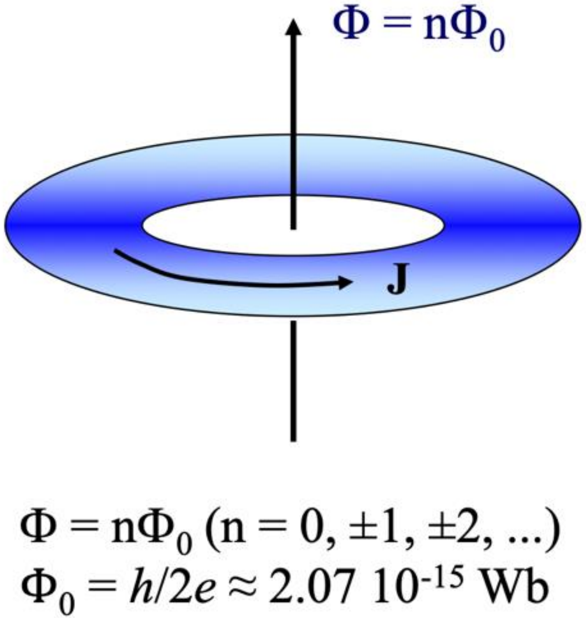
MACROSCOPIC COHERENT QUANTUM STATE

COHERENT QUANTUM STATE

“Macroscopic,” can access phenomena with “reasonable” size devices

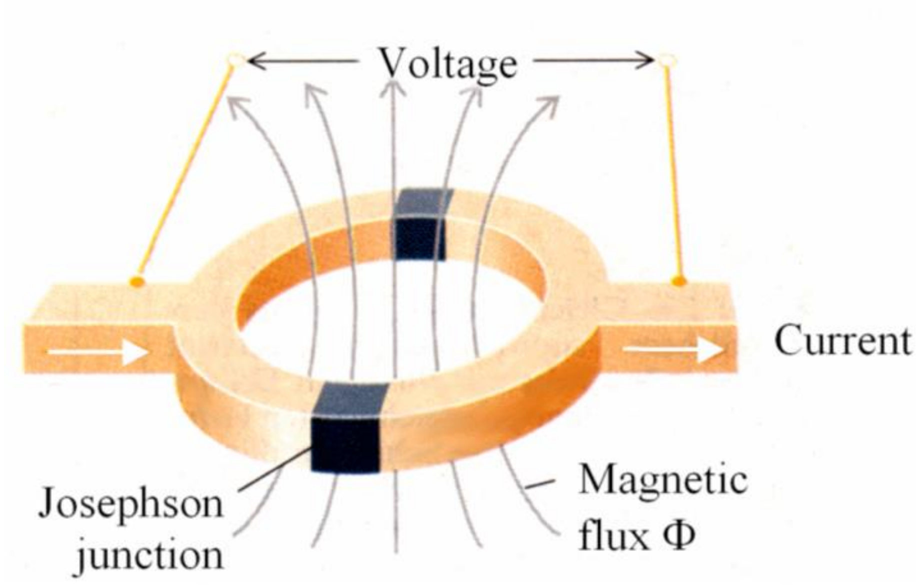


Tunneling

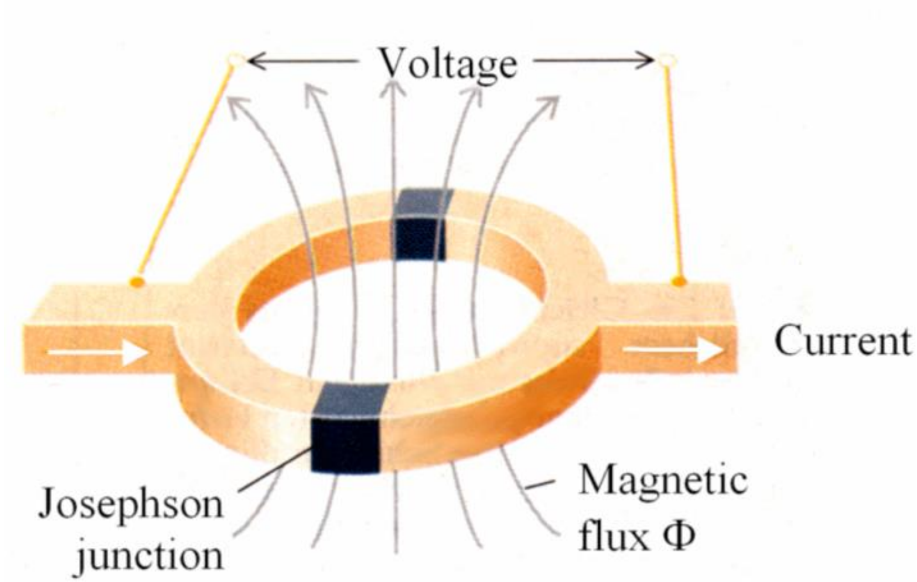


Flux quantization

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE

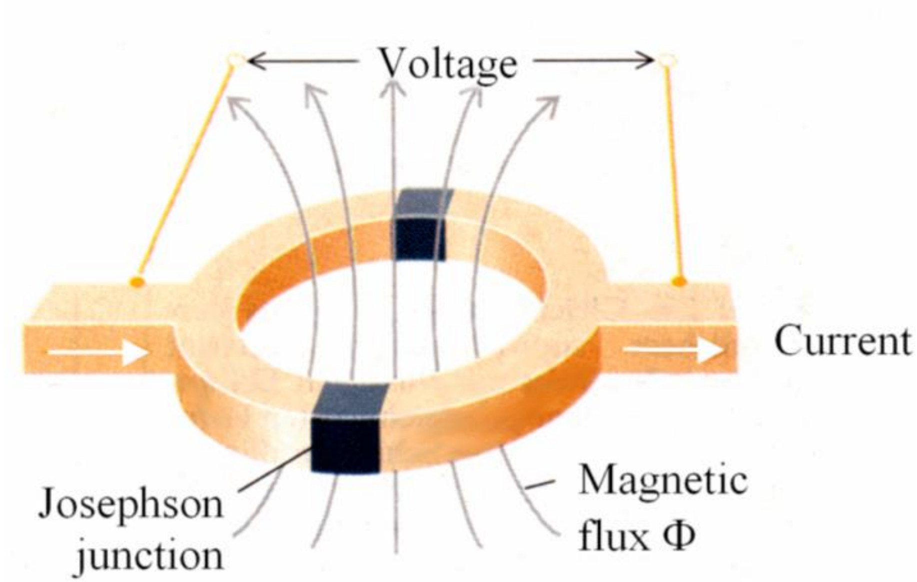


SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE



$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

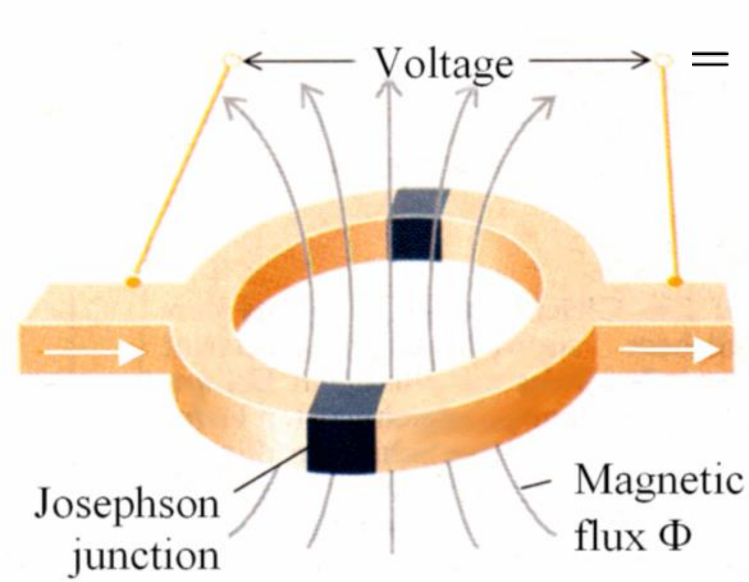
SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE



$$\text{Current} = I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE



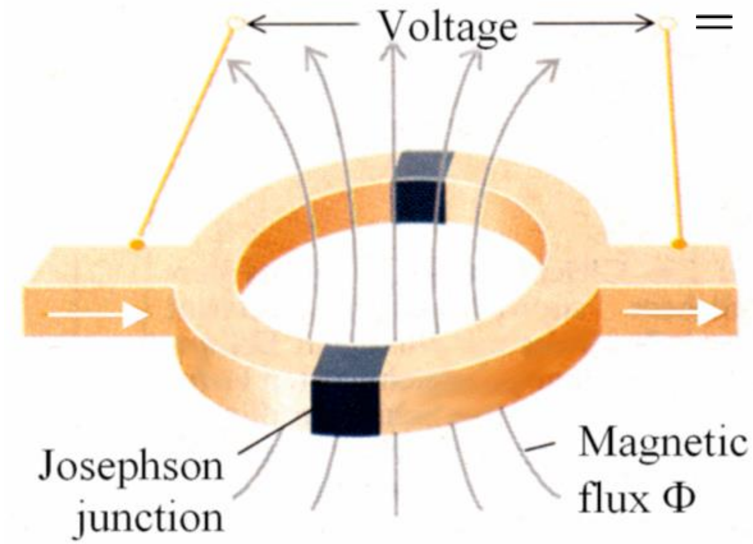
$$= \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

$$\text{Current} = I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE

For Current > I_c,
there will be a voltage

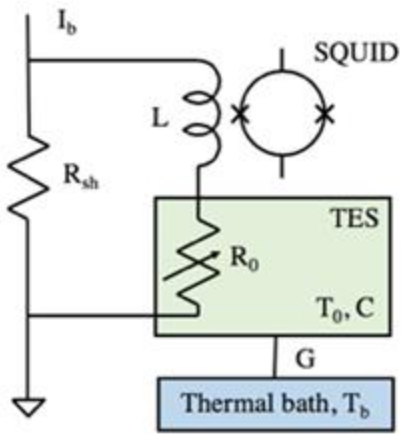


$$\text{Voltage} = \frac{\Phi_0}{2\pi}\frac{d\phi}{dt}$$

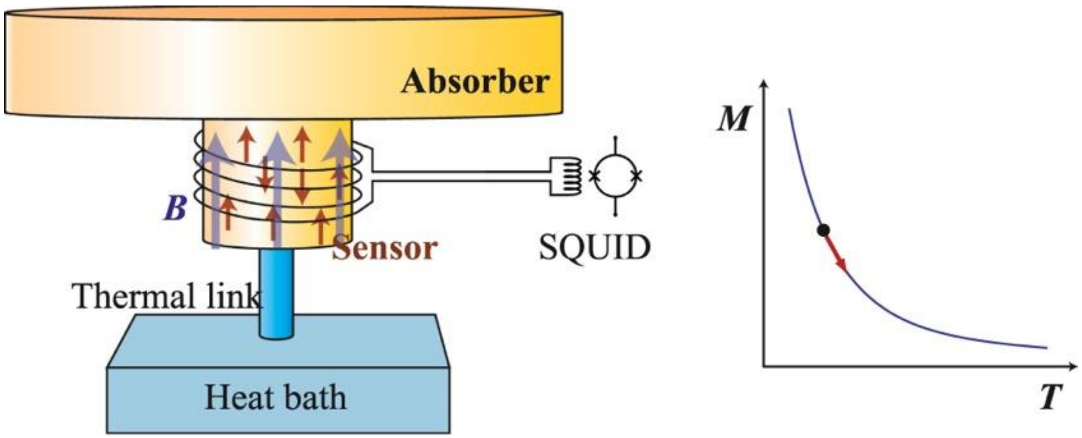
$$\text{Current} = I_c \sin\phi + \frac{\Phi_0}{2\pi R}\frac{d\phi}{dt} + C\left(\frac{\Phi_0}{2\pi}\right)^2 \frac{d^2\phi}{dt^2}$$

$$= \int A \cdot dl = \int \nabla\phi \cdot dl = 2\pi n = n\Phi_0$$

FLUX-VOLTAGE TRANSDUCER



TES ammeter

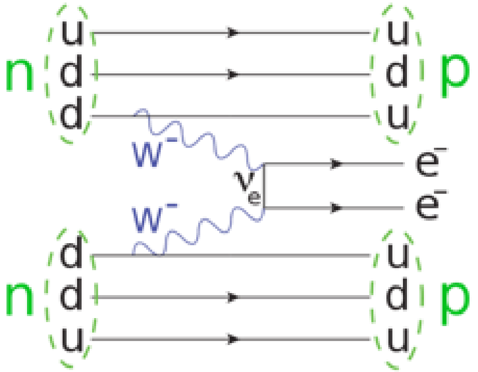


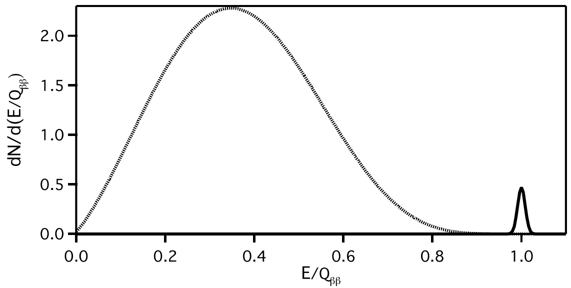
Readout Metallic Magnetic Calorimeter

AMORE

Neutrinoless Double Beta Decay search

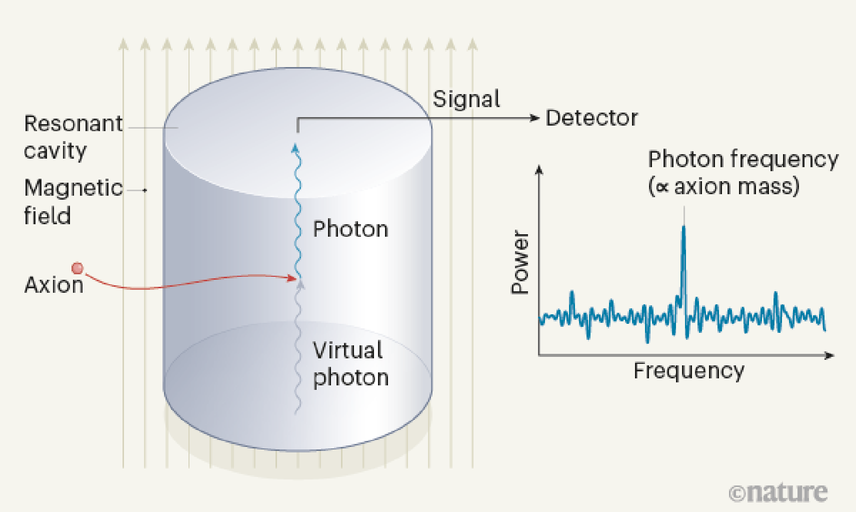
(a) (b)

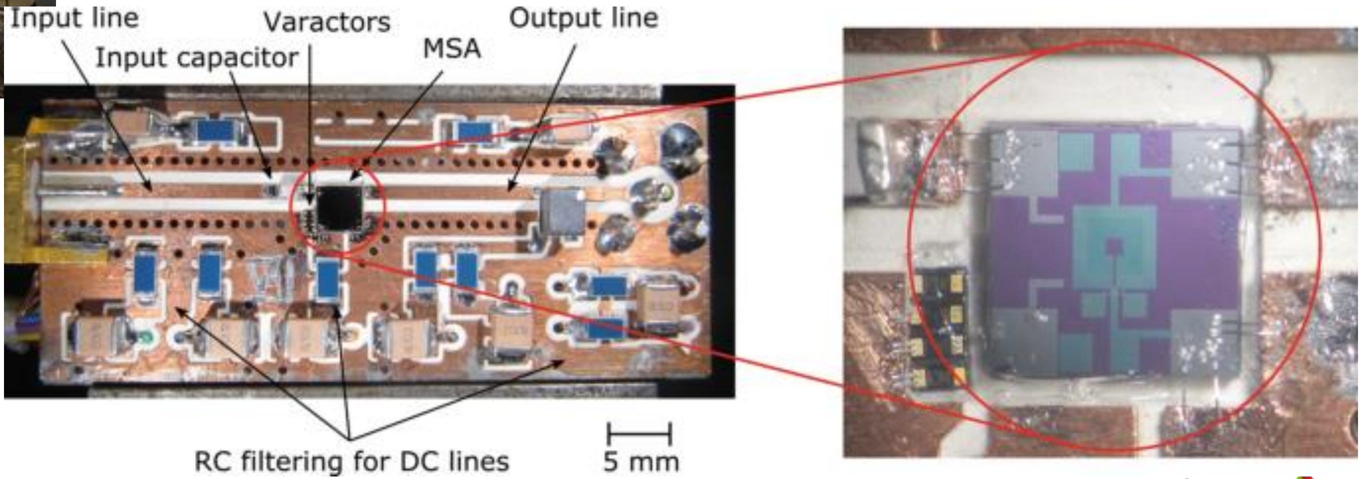




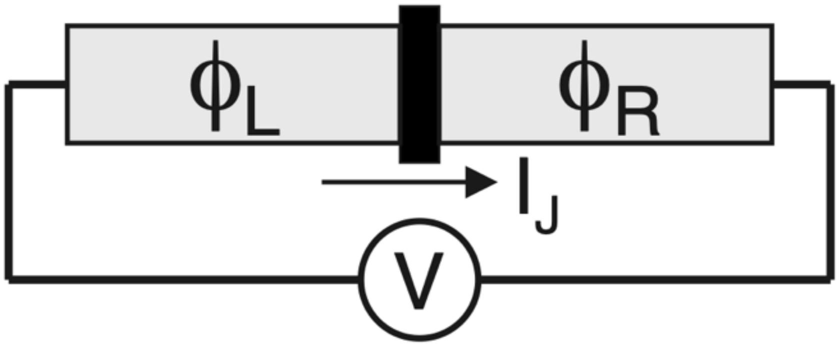
SQUID AMPLIFIER

ADMX





RF SQUID



$$I_J = I_0 \sin\delta$$

$$V = \frac{\Phi_0}{2\pi}\frac{d\delta}{dt},$$

$$\frac{dI_J}{dt} = I_0 \cos\delta\, \frac{2\pi}{\Phi_0} V.$$

$$L_J = \frac{\Phi_0}{2\pi I_0 \cos\delta}.$$

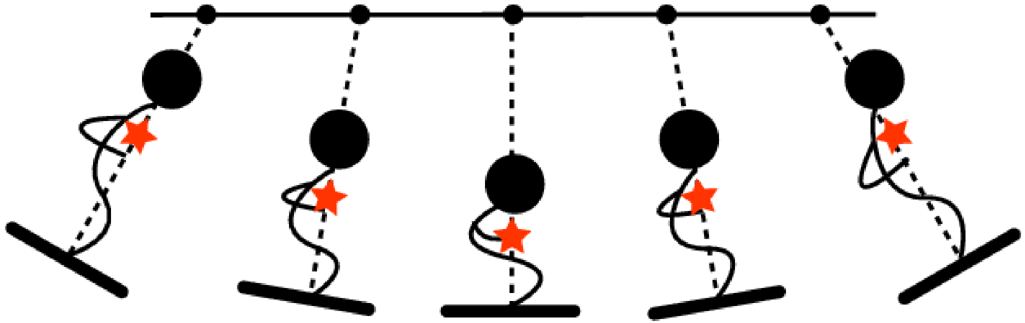
PARAMETRIC AMPLIFICATION

- Harmonic oscillator whose physical properties (**parameters**) vary with time

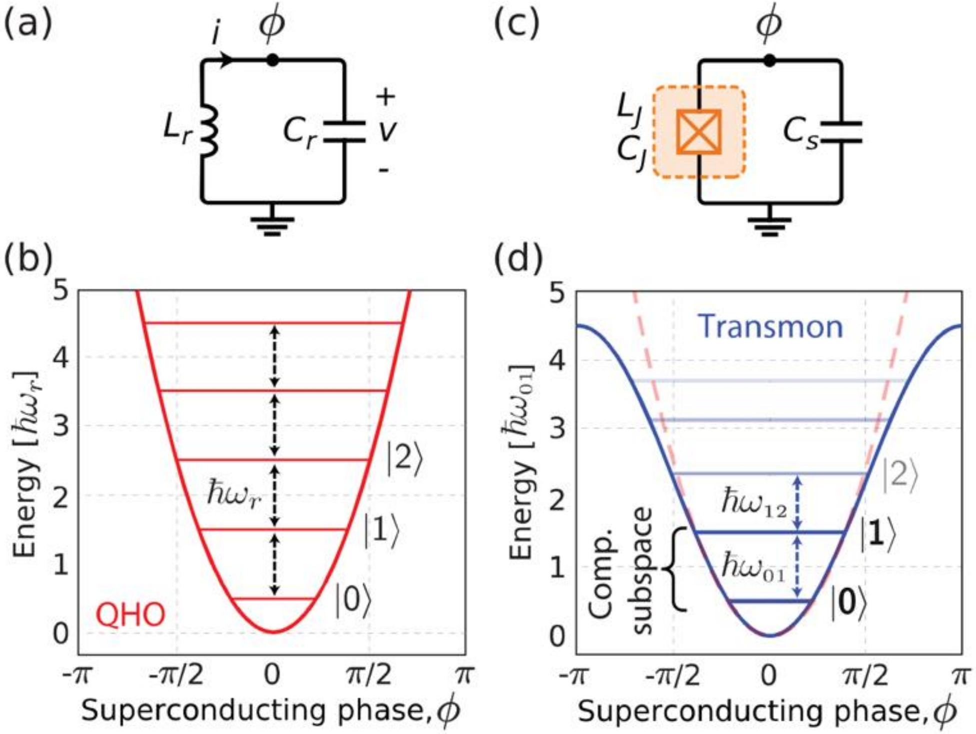
$$\frac{d^2x}{dt^2} + \beta(t)\frac{dx}{dt} + \omega^2(t)x = 0$$

  — Nonlinear inductance provides this parametric property for an electric circuit

- Can pump the oscillator by varying β, ω such that the oscillator phase locks to the pump and absorbs energy

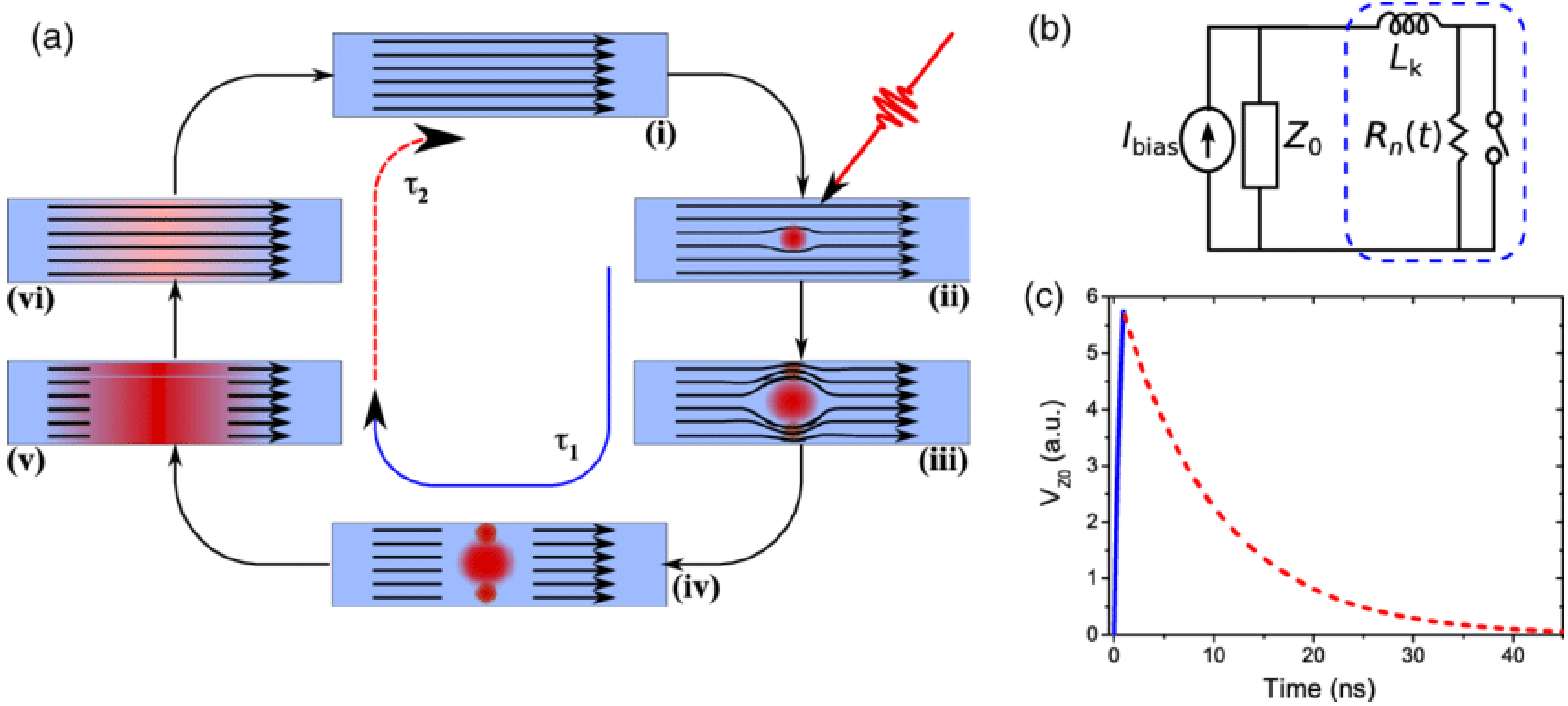


QUBITS


(a)
i
ϕ
L_r
C_r
+
V
-
(c)
ϕ
L_J
C_J
C_S
(b)
Energy [ħω_r]
ħω_r
|2⟩
|1⟩
|0⟩
QHO
5
4
3
2
1
0
-π
-π/2
0
π/2
π
Superconducting phase, ϕ
(d)
Transmon
Energy [ħω_01]
ħω_12
ħω_01
|2⟩
|1⟩
|0⟩
Comp. subspace
5
4
3
2
1
0
-π
-π/2
0
π/2
π
Superconducting phase, ϕ

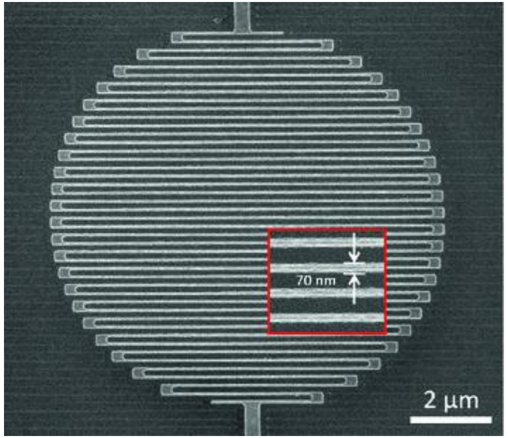
NEW TECHNOLOGIES

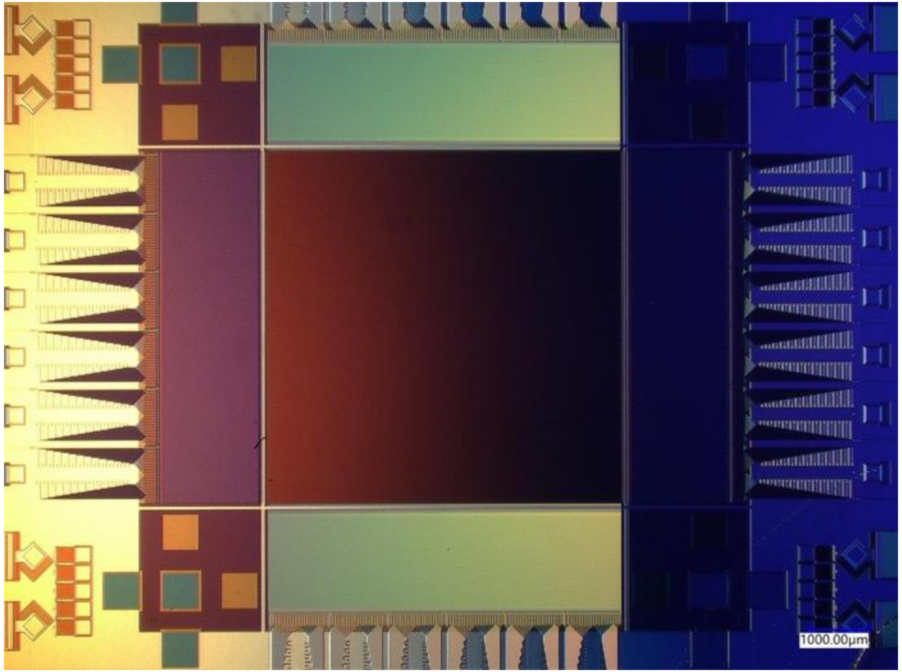
SUPERCONDUCTING “NANO”-WIRE SINGLE PHOTON DETECTOR



SUPERCONDUCTING “NANO”-WIRE SINGLE PHOTON DETECTOR

- Very high detection efficiency
- Negligible dark counts
- Fast timing
- Developing arrays

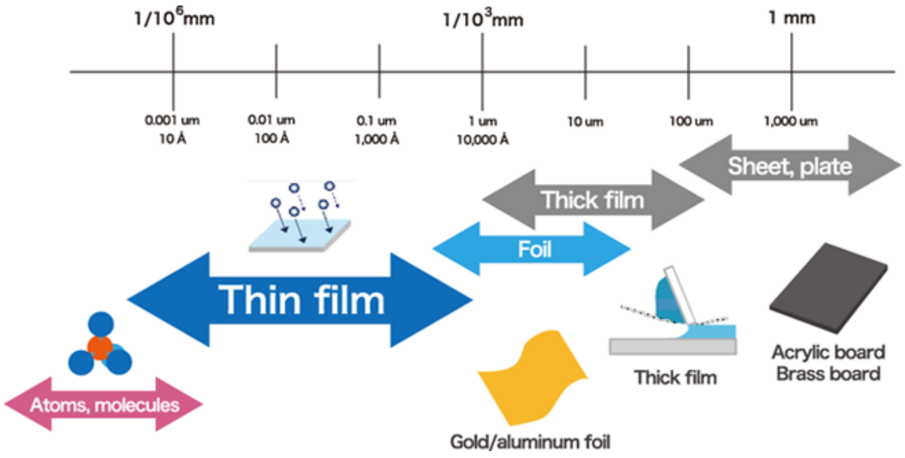




MICRO/NANO-FABRICATION THIN-FILM PROCESSING

THIN FILM PROCESSING

- Layers are nearly 2D sheets
  - Lateral feature sizes are ~2 um – 200 ums wide and long
  - Thickness is 10s-100s nm thick
- Materials only approximated by basic condensed matter principles
  - Many materials have multiple crystalline structures
  - Thin films are not crystalline, but are granular
  - Material composition is not infinitely pure



FABRICATION PROCESSES

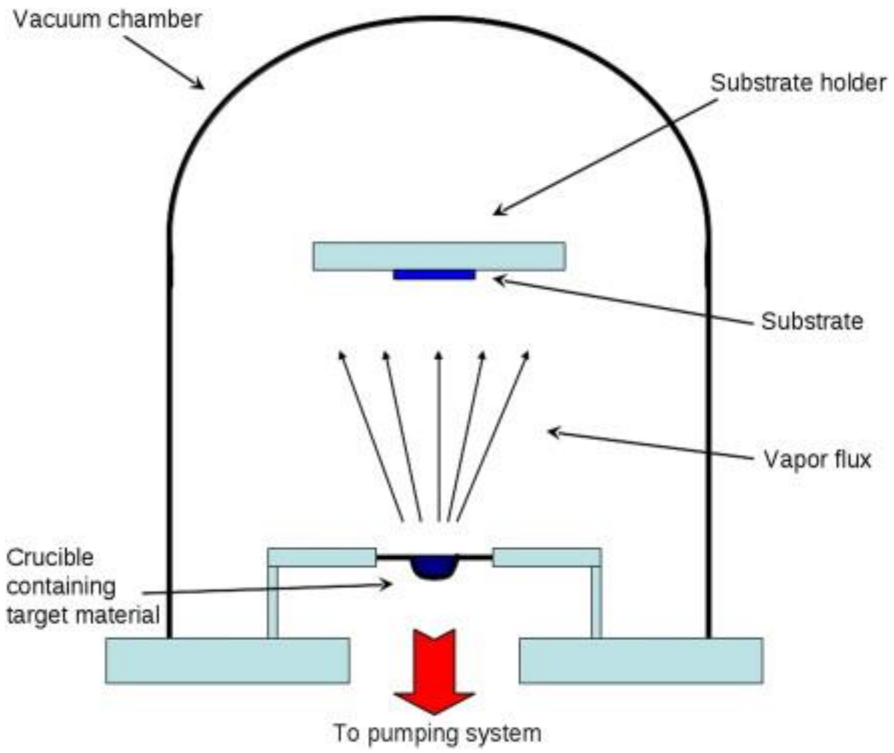
- Adding material: deposition
- Removing material: etching/lift-off
- Patterning material: lithography

FABRICATION PROCESSES

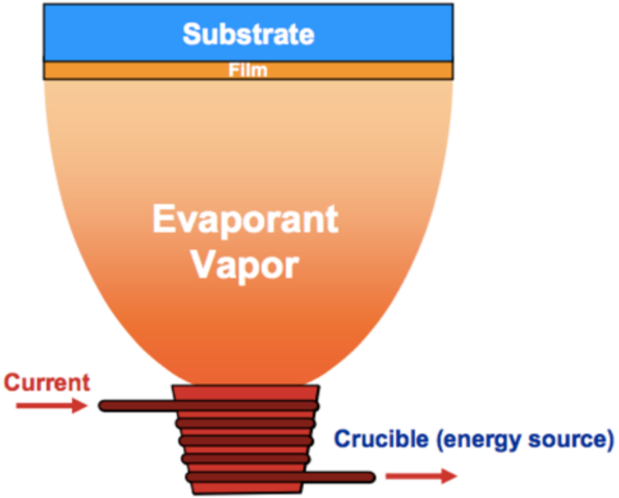
- Adding material: deposition
- Removing material: etching/lift-off
- Patterning material: lithography

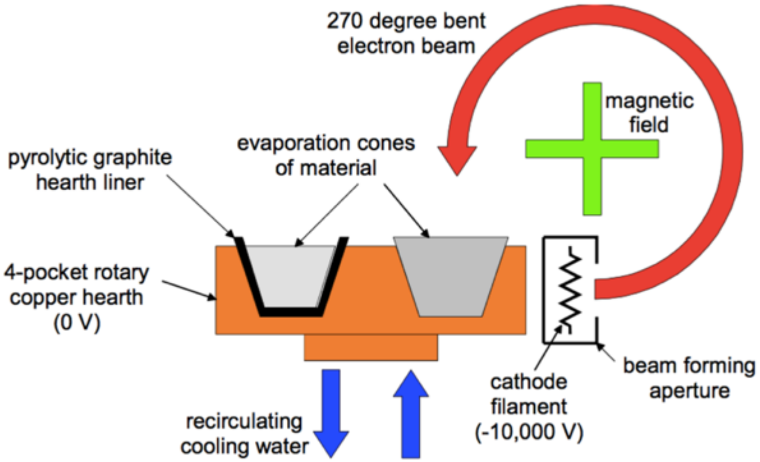
PHYSICAL VAPOR DEPOSITION (PVD) - EVAPORATION

- Heat target material to high temperature.
- Material in the (hot) vapor moves to target and condenses to form thin film.
- Not all materials readily evaporated. Need to get things sufficiently hot.
- Material transport is directional, challenging for uniform deposition over a large surface (needs large target, or large transport distance)
- Condensed material is “sticky,” leading to non-conformal films (good for lift-off, bad for step coverage)



PHYSICAL VAPOR DEPOSITION (PVD) - EVAPORATION



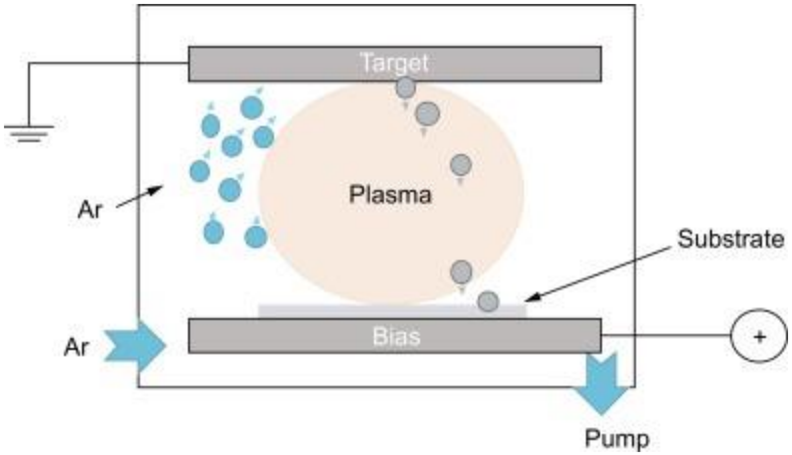


resistance heating: limited to ~1800C. Can also heat crucible leading to contamination

e-beam: heat W filament, capture electrons with B-field and direct beam into target. Can achieve temperatures ~3000C.

PVD - SPUTTERING

- Apply voltage across noble gas (typically Ar)
- Electrons accelerated by E-field
- At large enough voltages, scattering off Ar atoms can ionize strip outer electron. Secondary electron accelerated, process repeats
- Ar ions accelerated into target by E-field. At large voltages, KE of Ar ion can knock target atoms out of target.
- Free target atoms transported to substrate to form film

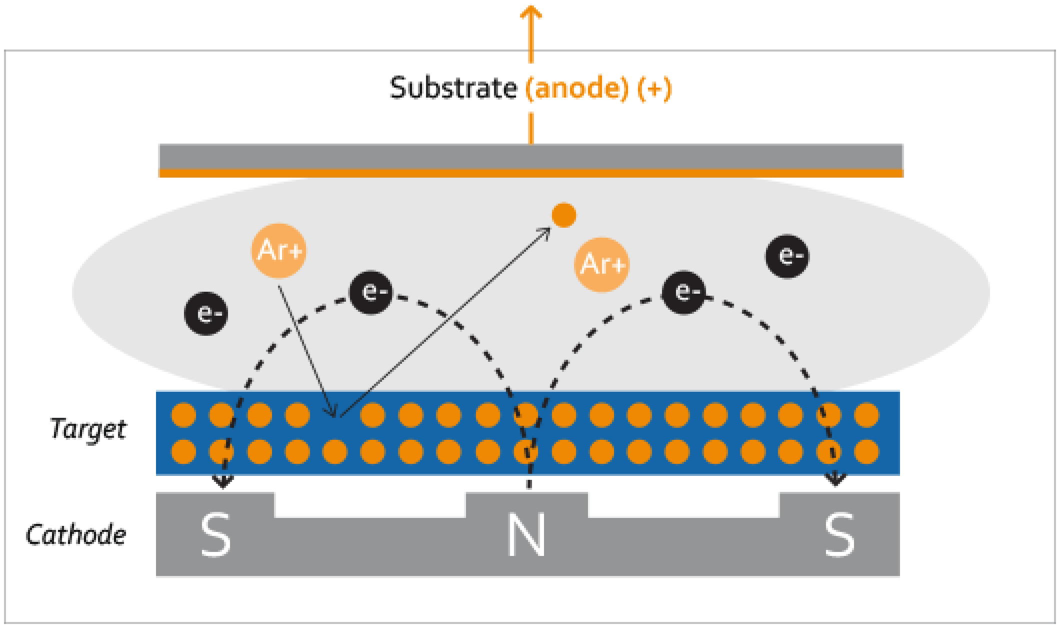


PVD - SPUTTERING

- Most materials can be sputtered.
- Atoms have high mobility leading to more conformal films (good for step coverage, bad for lift-off)
- large targets -> more uniform
- Plasma ionization is inefficient (<0.01%). Presence of a lot of Ar gas limits sputtering deposition rate as target atoms scatter off the gas.

PVD – MAGNETRON SPUTTERING

- Magnetron sputtering uses magnetic fields to confine electrons near target. Increases ionization efficiency. Can sputter with low gas concentrations and higher rates.



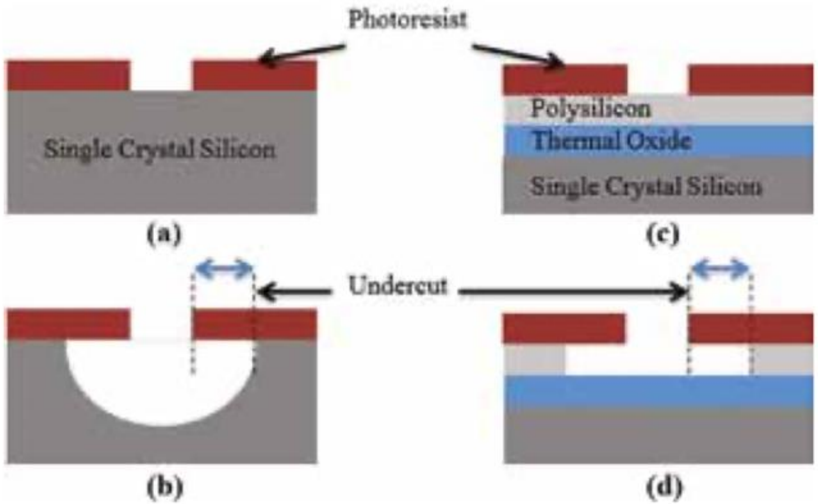
P

FABRICATION PROCESSES

- Adding material: deposition
- Removing material: etching/lift-off
- Patterning material: lithography

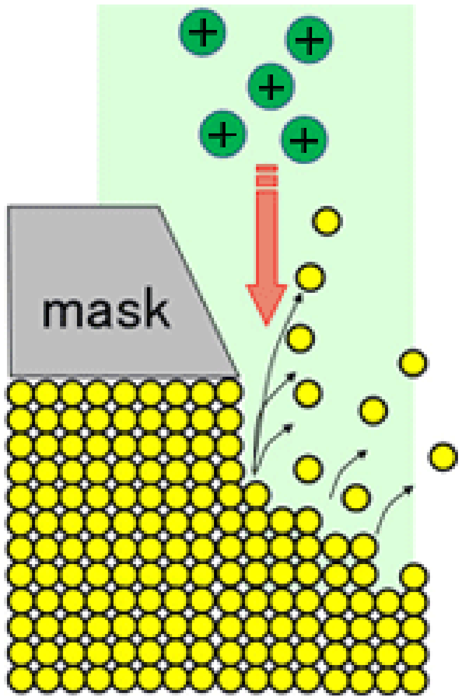
ETCHING - CHEMICAL

- etchant reacts with materials to form byproducts that are readily removed
- immerse wafer in etchant (liquid, gaseous)
- isotropic: process driven by diffusion, etchant removes material in all directions.
- selective: not all materials undergo same chemistry with etchant. Rate of etching varies by material. Some materials may never be etched.



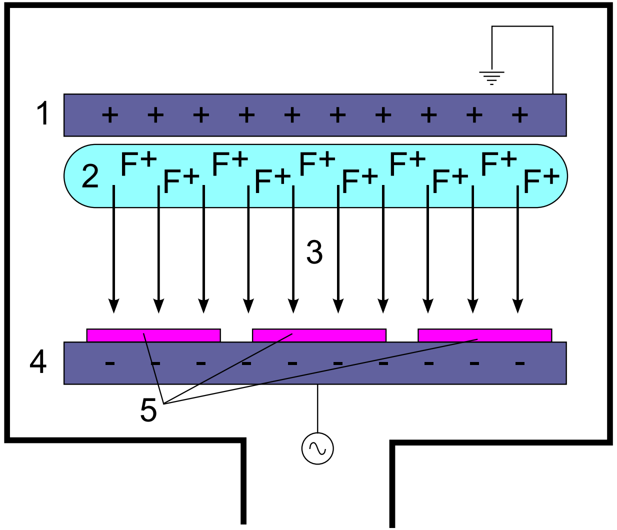
ETCHING - MECHANICAL

- bombard wafer with high KE ions.
- Ions collide with wafer material, sufficiently high KE will knock material off the wafer. (sputtering!)
- an-isotropic: process driven by field, ion transport is directional
- non-selective: very little dependence on substrate material. Good for removing inert material.
- Good at transferring mask pattern (very little undercut), but slow.



ETCHING – REACTIVE ION ETCH (RIE)

- Combination chemical / mechanical etch
  - inject a reactive gas (etchant)
  - apply voltage to produce a plasma, ionizing atoms in the gas. Gas ions are chemically active (radicals)
  - bombard wafer with radicals.
  - sputtering and chemical reactions take place
- Inductively Coupled Plasma (ICP) enables separate tuning of plasma concentration and kinetic energy.
- Better control of lateral etching than wet etching
- Etch chemistry can impact sidewall slope, etch selectivity, and cleanliness of etch

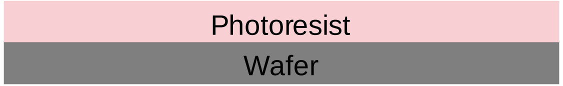


FABRICATION PROCESSES

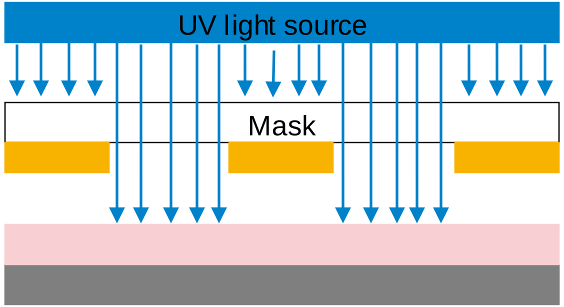
- Adding material: deposition
- Removing material: etching/lift-off
- Patterning material: lithography

PHOTOLITHOGRAPHY – PROCESS FLOW

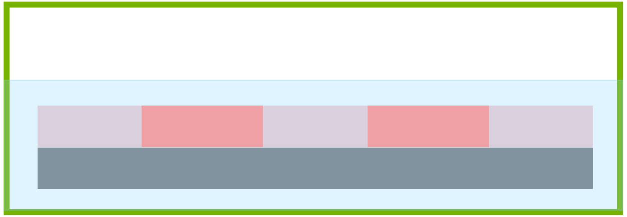
Transfer device designs onto wafer via photo sensitive polymers



Step 1: Coat wafer with photoresist – light sensitive material



Step 2: Expose resist with UV light*. Light causes polymers in resist to break apart



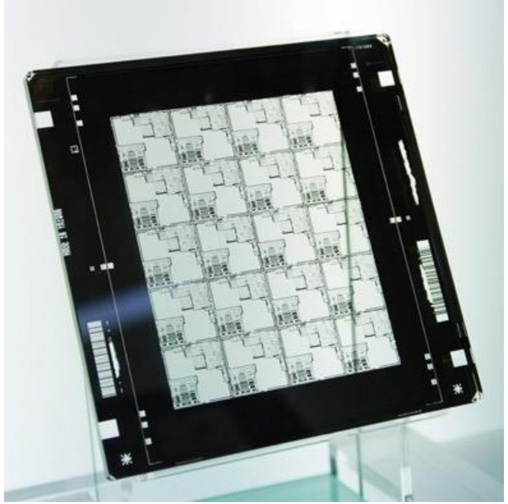
Step 3: Develop photoresist

Step 4: Dry wafer with finished pattern

* Smallest resolution set by wavelength of light source and numerical aperture of imaging system

PHOTOLITHOGRAPHY – MASK DESIGNS

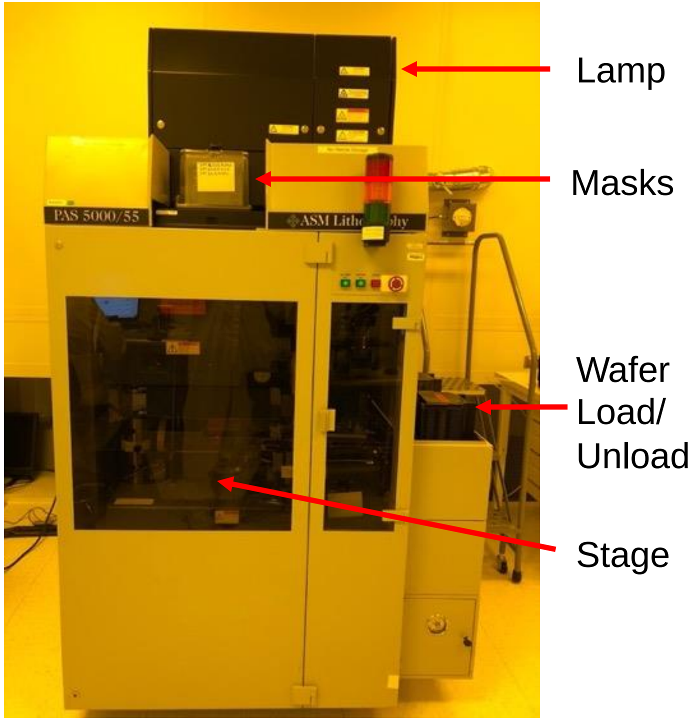
- Mask designs are created in CAD software
- Most common file type is '.gds' file
- Key functionality is 'cell' – like a unit cell in a crystal
- Basic cells are referenced in higher level cells to create complex designs
- CAD files are used to create a photomask or reticule (i.e. stencil)
- Photomask is made once (often by e-beam writer), used repeatedly



1: By Peellden - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=15946829

PHOTOLITHOGRAPHY – STEPPER

- Exposes a small portion of the wafer, then ‘steps’ and repeats
- High throughput photolithography
  - — Process tens to hundreds of wafers per hour
- Automatically aligns mask to layers on the wafer (to within ~100 nm)
- Need a mask for each pattern
- Limited field of view



PHOTOLITHOGRAPHY – MLA

- Uses a laser diode to expose the resist
- Raster the laser over the wafer line by line
- No mask needed – just gds file
  - Great for rapid R&D
- Field of view extends to the entire wafer
- Low throughput
  - 3 min process on stepper can take over an hour

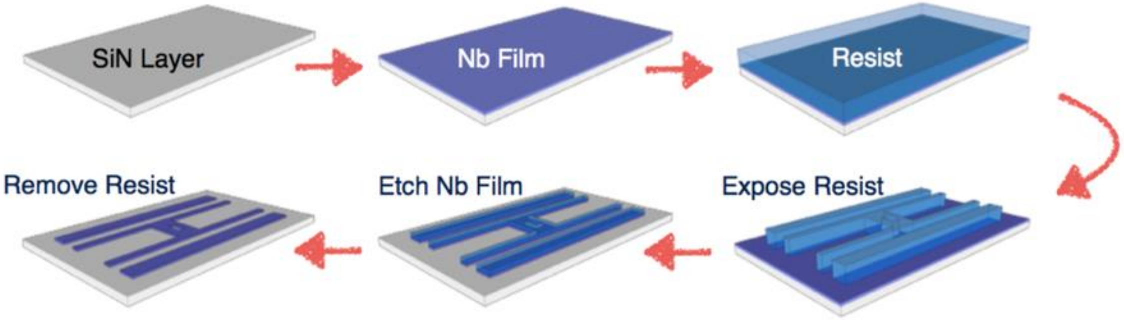
PUTTING THINGS TOGETHER

DEP/LITH/ETCH

Step 1: Deposit material

Step 2: Photolithography

Step 3: Etch

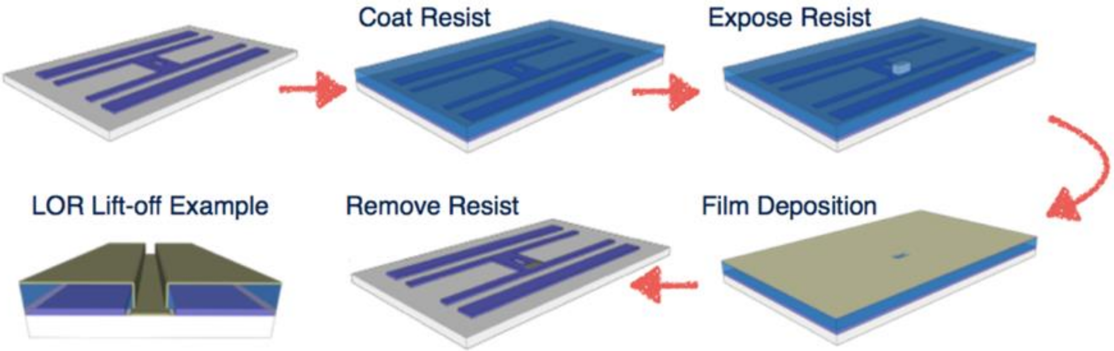


LIFT-OFF

Step 1: Photolithography

Step 2: Deposit material

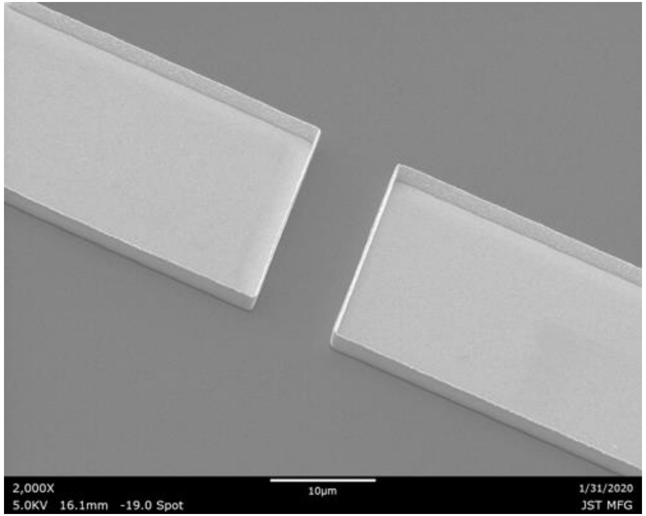
Step 3: ‘Liftoff’ resist and deposited material



LIFT-OFF

Step coverage issues – deposited film forms a continuous layer

Fencing– material deposited on sidewalls is left behind



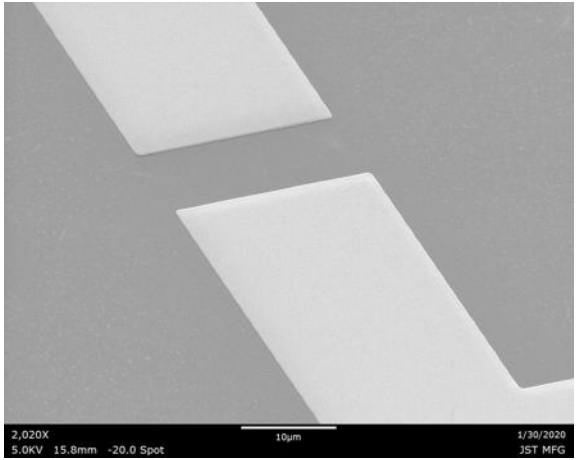
Nearly ‘perfect’ fencing around edges of liftoff pattern

THIN FILM PATTERNING

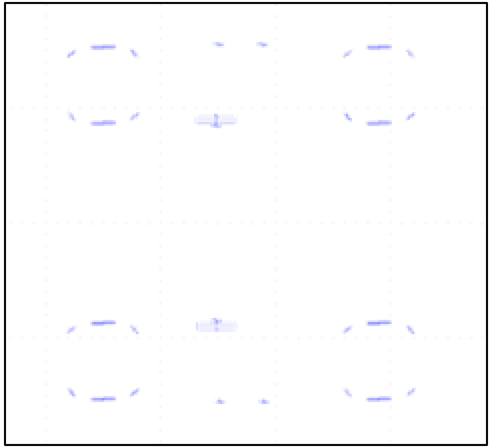
Two layer resist with undercut

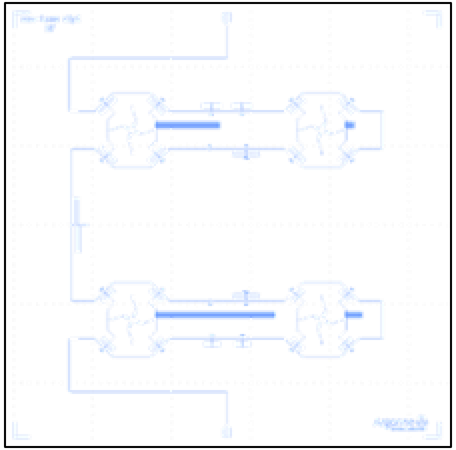
Undercut helps to ‘break’ the film

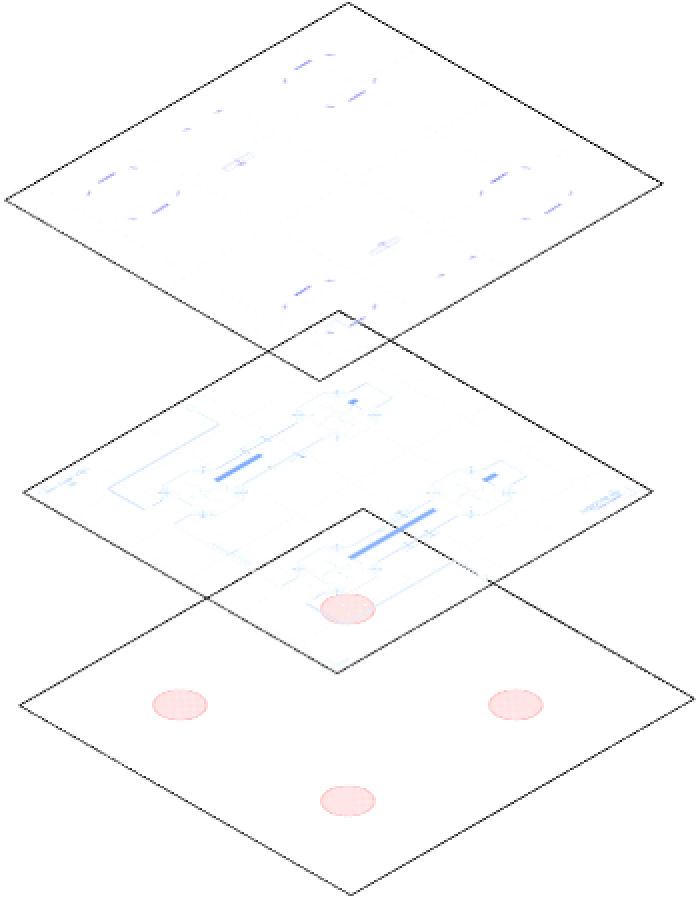
Often see reduced fencing using two layer resist

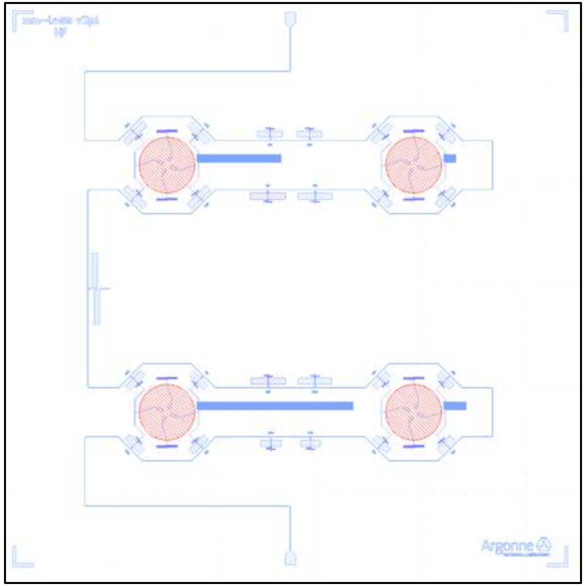


Can also use ultrasonic agitation to try to ‘break’ off fencing





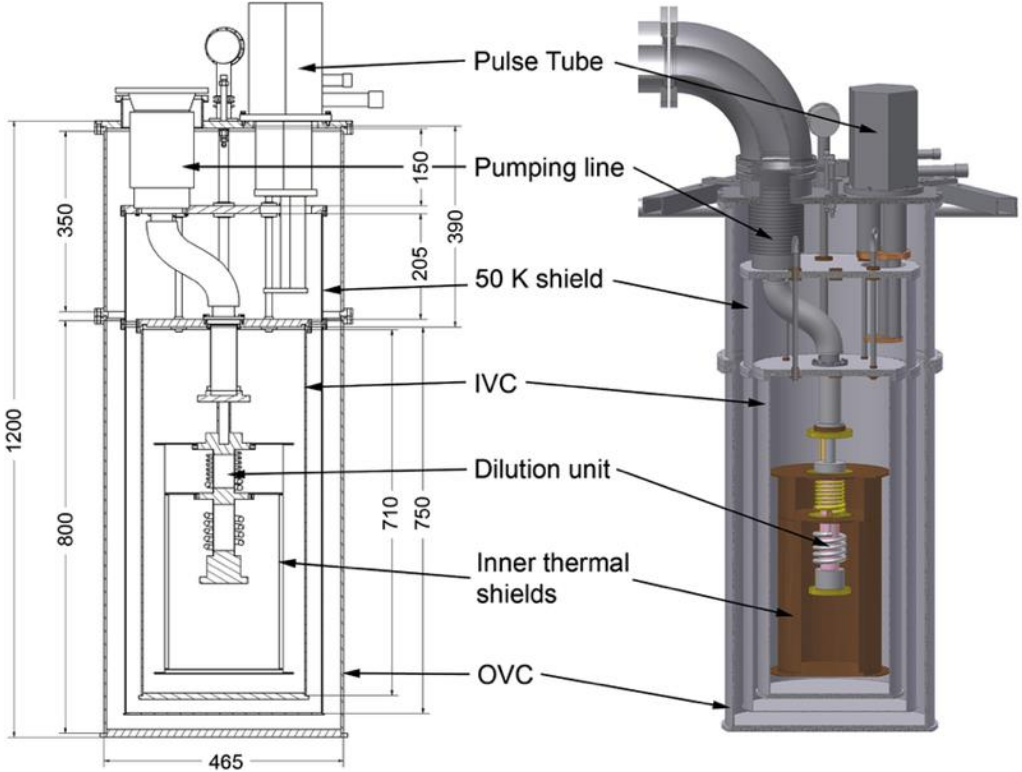


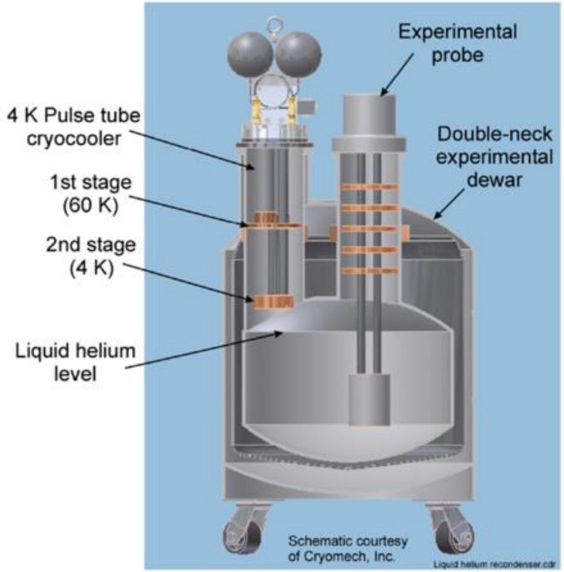


COOLING THINGS DOWN

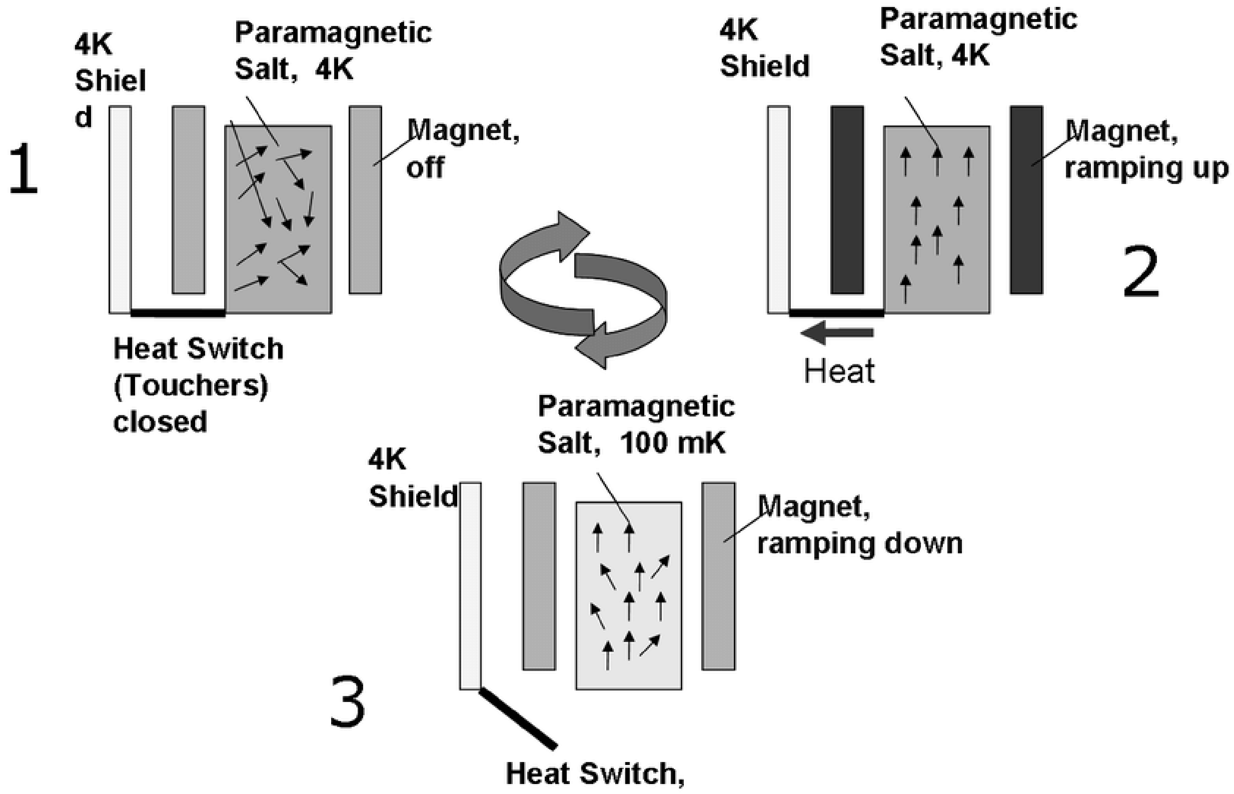
CRYOGENICS

CRYOGEN FREE



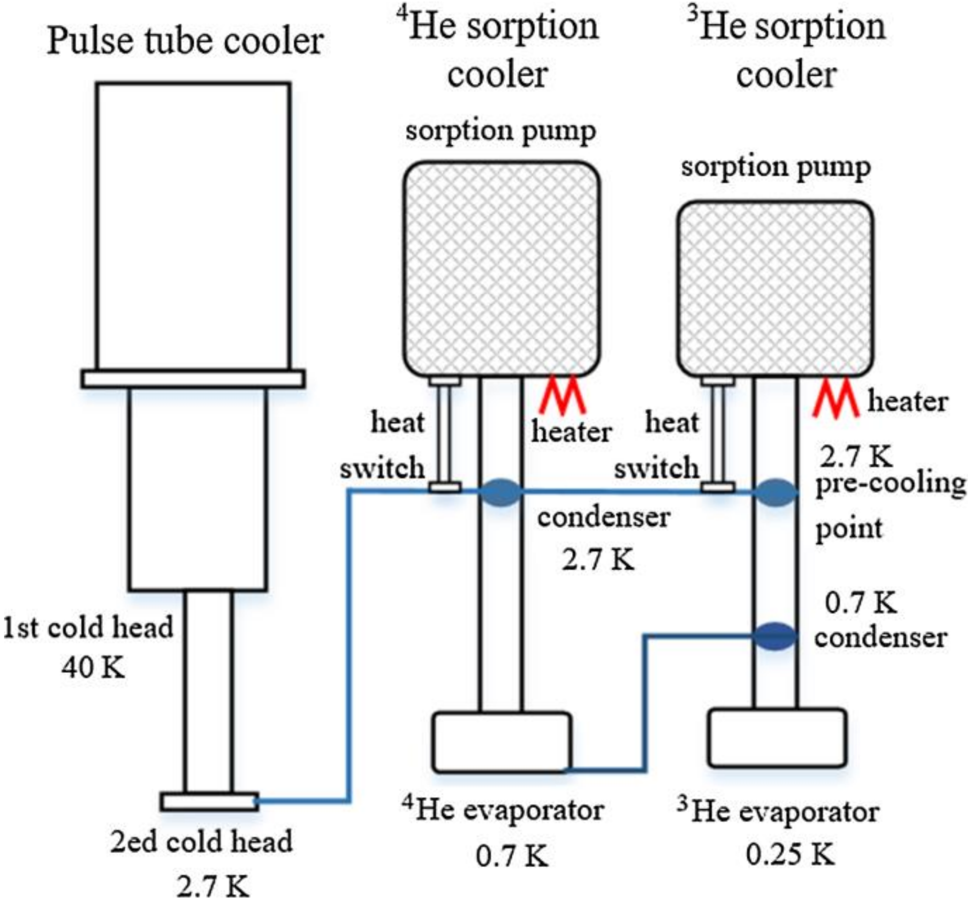


ADIABATIC DEMAGNETIZATION



EVAPORATIVE COOLING

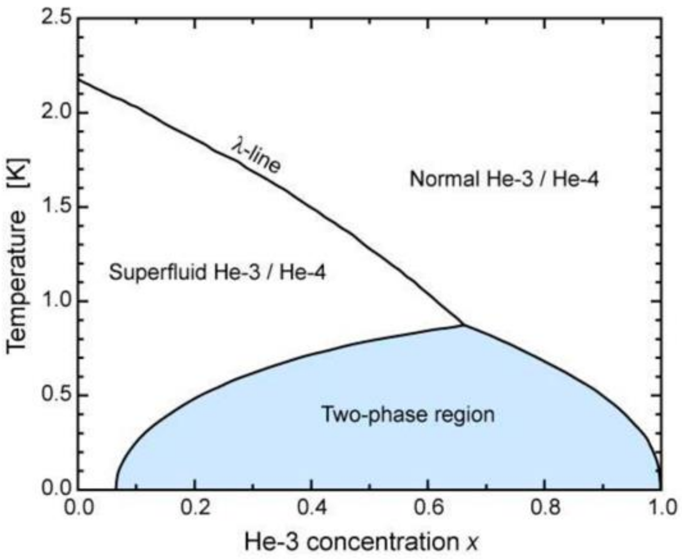
Sorption Fridge

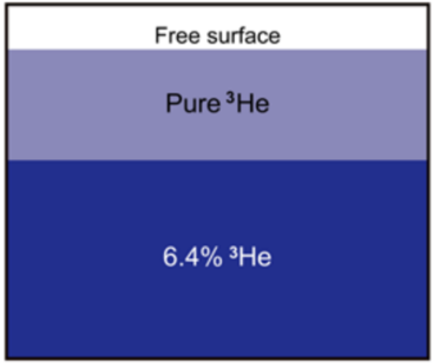


DILUTION REFRIGERATOR

He3/He4 mixture

- Mass difference between He3 and He4 gives a slight preference for He3 to be dissolved in He4
- At sufficiently low temperatures, solubility <100%
- Even at 0K, solubility ~6%
- Below a certain temperature, mixtures separates into two phases
  - — He3 rich
  - — He3 poor (but still has He3)

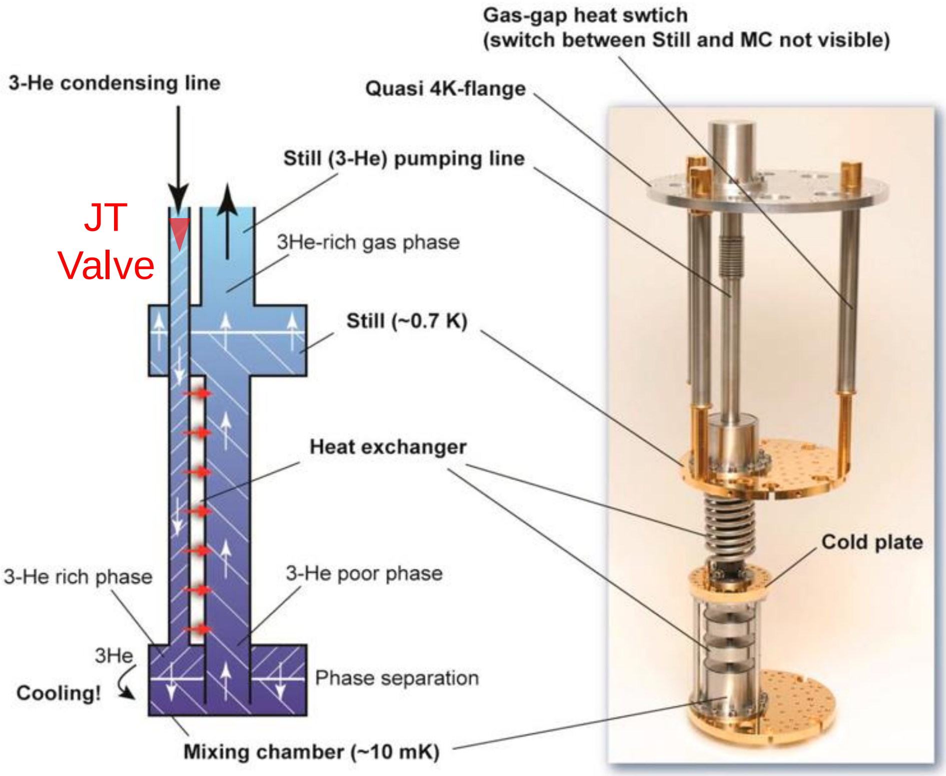


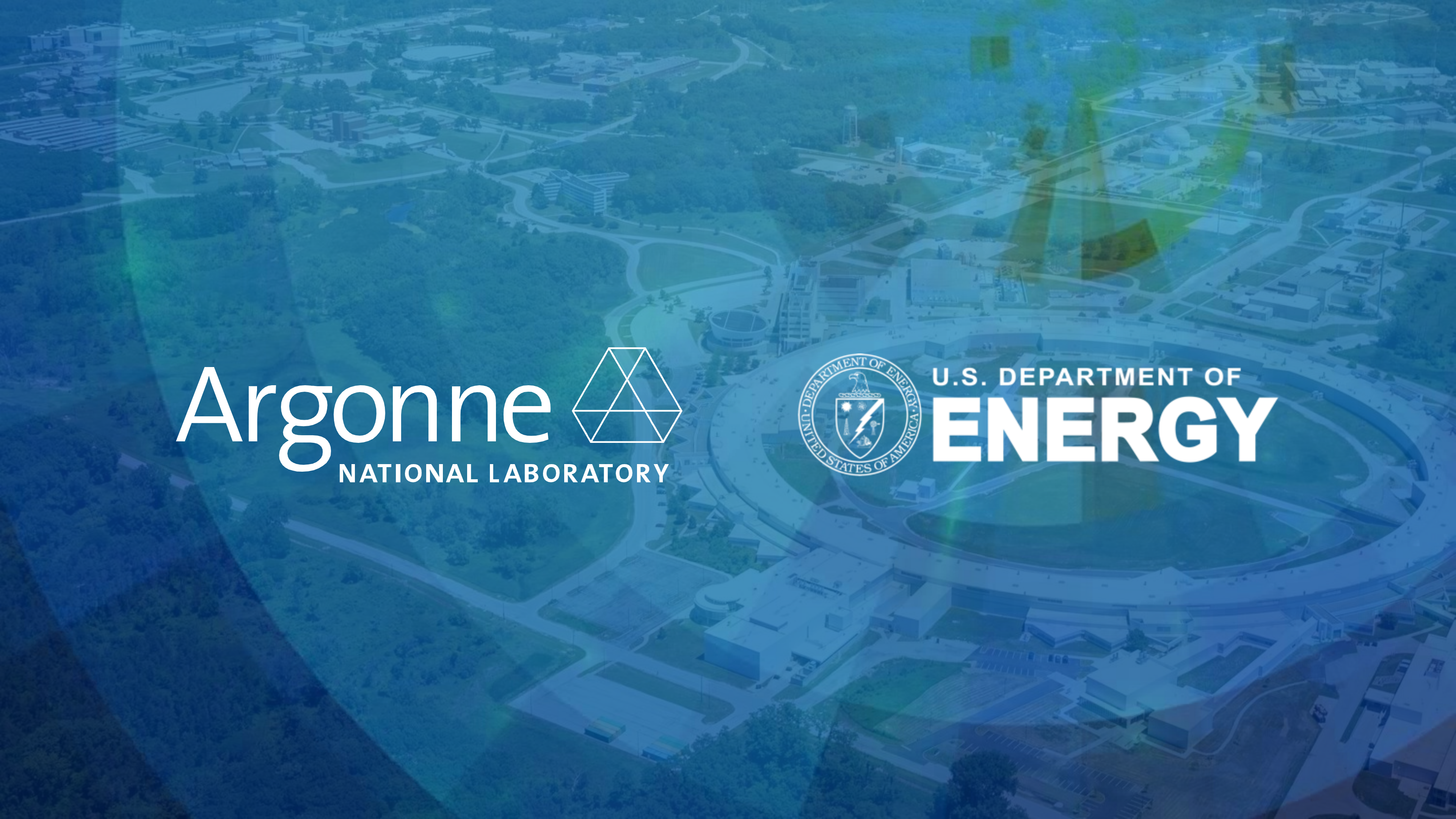


DILUTION REFRIGERATOR

Pumping He3 through He4

- Two chambers: Mixing chamber (MXC) and Still
  - Connect through a small pipe
  - fed near bottom of MXC, below phase separation
- Still heated to higher temperature
  - Evaporates He3 from the liquid in the Still
- Osmotic pressure drives He3 from MXC into Still
- In MXC, He3 “evaporates” from rich phase into dilute phase

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