# Recent Topics in Front-End Electronics – Systems Considerations in High Energy Physics and Other Fields


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## Outline

Some Current Systems Issues in High-Energy Physics
Other Applications
- Electron Microscopy
- Fast X-Ray Imagers
- Large-Scale Cryogenic Bolometer Arrays
  - Cosmology
  - High-Resolution Gamma Spectroscopy

Conclusions

# Where are we Going?

ILC: $\mu$m position resolution in vertex detector (1 – 5 $\mu$m)

$\Rightarrow$ ~20 $\mu$m pixels

Jet (multi-track) resolution

Minimal mass (also in “forward” angles!)

$\Rightarrow$ Monolithic pixel devices

(CCDs, MAPs, DEPFETs, multi-tier ICs?)

$\Rightarrow$ Low-mass power distribution, cooling

# Challenges at sLHC

10-fold luminosity + doubled crossing time (25 $\rightarrow$ 50 ns)

Increased radiation damage

Increased multiplicity per crossing (~200 tracks)

$\Rightarrow$ Pattern Recognition

Preliminary Criteria for Detector Lifetime (ATLAS):

Design for 3000 $fb^{-1}$ integrated luminosity

Include 2-fold safety factor

Fluences (ATLAS, 1 MeV neutron equivalent)

| | | |
|---|---|---|
| Pixel system : | r= 5 cm | $\Phi \approx 10^{16}$ $cm^{-2}$ |
| | r= 13 cm | $\Phi \approx 3 \cdot 10^{15}$ $cm^{-2}$ |
| Strips: | r= 38 cm | $\Phi \approx 7 \cdot 10^{14}$ $cm^{-2}$ |
| | r= 70 cm | $\Phi \approx 4 \cdot 10^{14}$ $cm^{-2}$ |

Ionizing Dose: 1 Mrad $\triangleq 3 \cdot 10^{13}$ $cm^{-2}$ $\Rightarrow$ Dose $\approx$ 10 – 300 Mrad

Reduced funding levels $\Rightarrow$ More efficient use of funding

Radiation hardness limited primarily by sensor:

Charge trapping in the sensor $\Rightarrow$ reduced signal

To maintain S/N we can

a) reduce electronic noise

$\Rightarrow$ increased power (front-end power $\propto (S/N)^2$)

and/or

b) reduce sensor capacitance

pixels (material, power, cost)

reduce strip length

$\Rightarrow$ more readout ICs per unit area

$\Rightarrow$ low-mass power distribution, cooling

ICs: Reduce power: SiGe BiCMOS?

Reduce size per cell: multi-layer electronics?

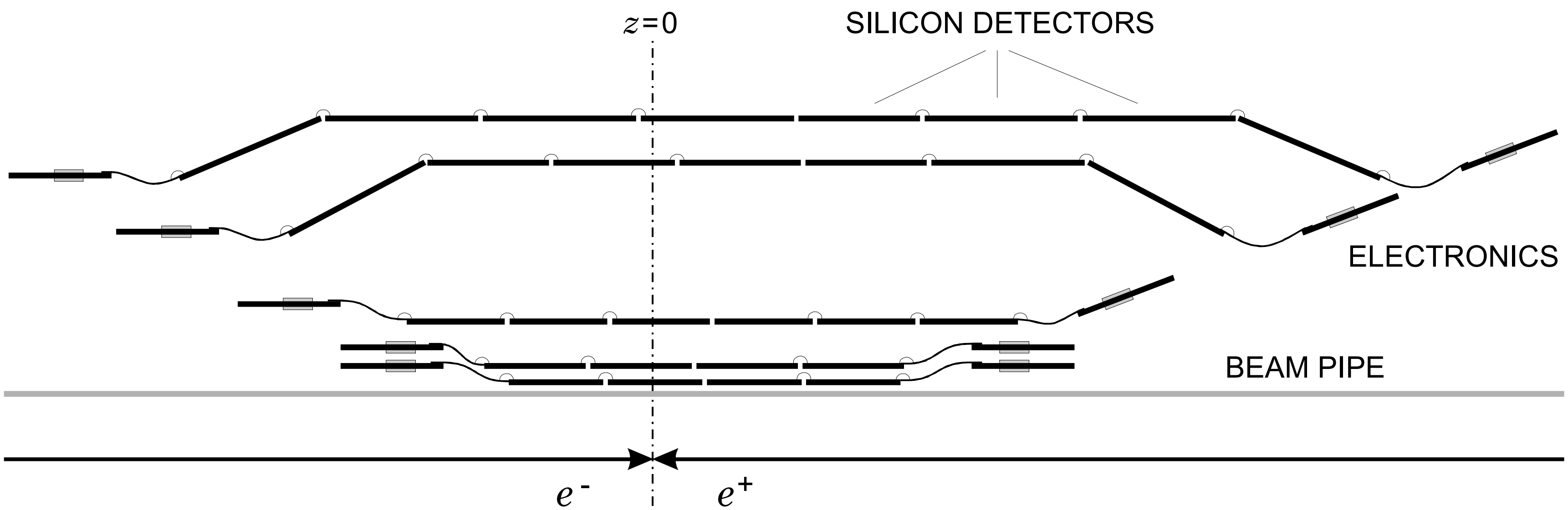
Hybrid pixels allow optimization of sensor and readout, but at the expense material and cost.

Simplifications?

# Major Challenge: Material

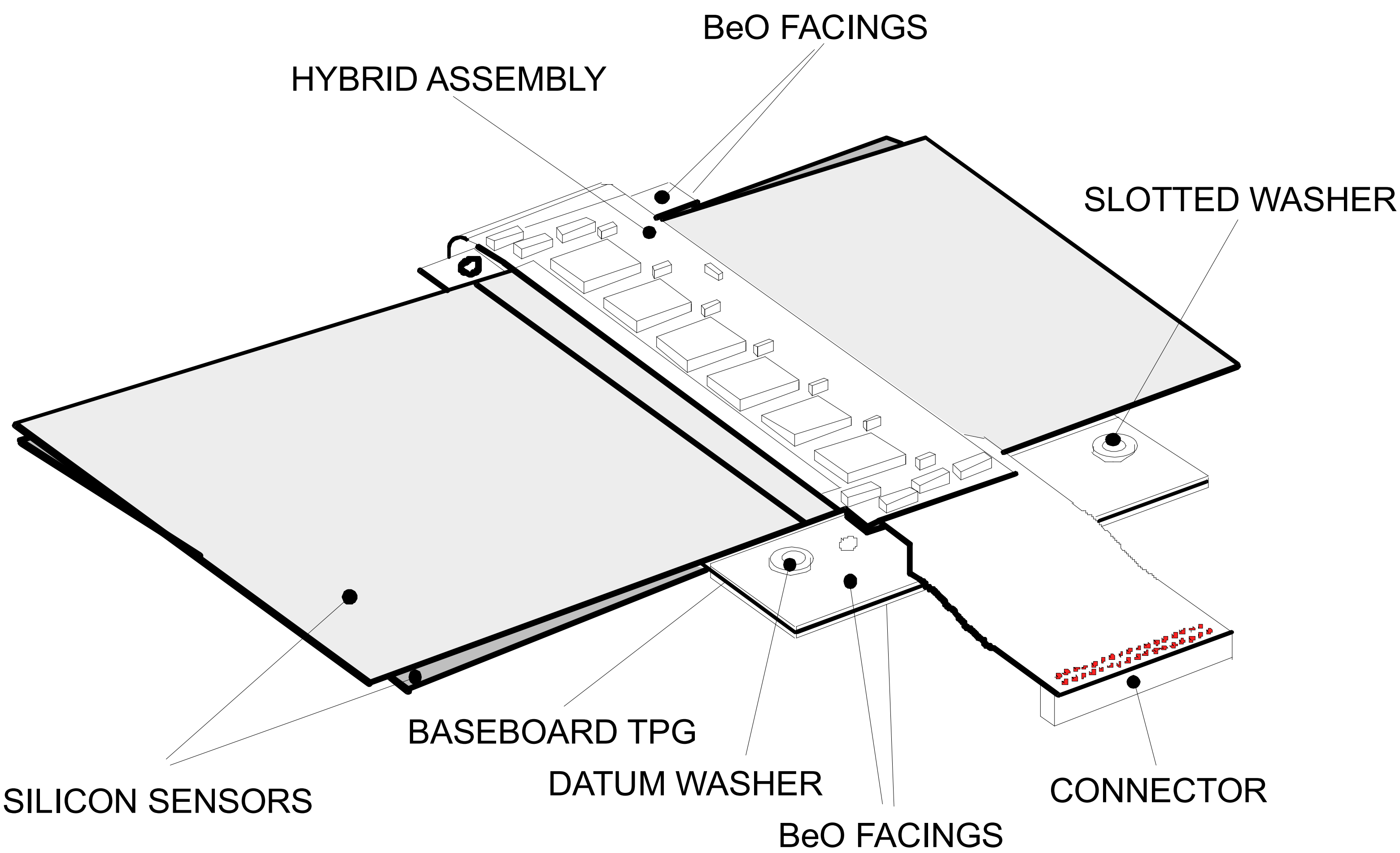
Unlike detectors at $e^+e^-$ colliders where electronics can be placed outside the active region ...

Example BaBar:



... in hadron colliders material is distributed throughout the active volume.

Example: ATLAS strip detector module



# Material in ATLAS Silicon Tracker Barrel

Total material per layer:

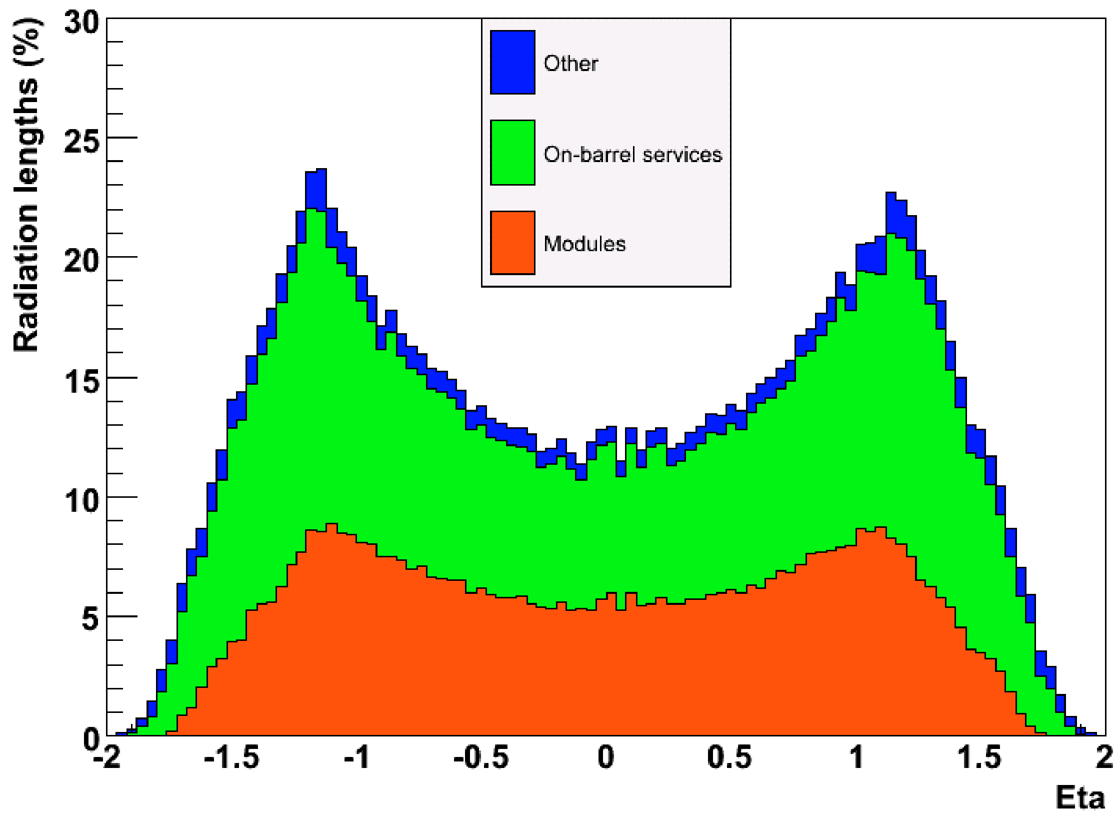
3% $X_0$.

Half is services:

cooling

cabling

carbon fiber support




(see http://www.hep.phy.cam.ac.uk/~cpw1/atlas.html)

| | | |
|---|---|---|
| ATLAS Pixel Detector: | Total (3 layers) | 10.7% $X_0$ |
| | Hybrids + Cables | 1.3% $X_0$ |
| | Support + Cooling | 6.9% $X_0$ |

$\Rightarrow$ Reduce material in cabling and cooling

# Challenge: Increase power efficiency

## Digital circuitry:

Reduced voltage swings and circuit capacitance reduce power consumption

$$P = fCV^2$$

Smaller CMOS feature sizes reduce both the voltage swing $V$ and capacitance $C$, so for a given switching rate $f$ the power decreases.

## Analog front-end:

Equivalent Noise Charge: $Q_n^2 \approx i_n^2 T_S + e_n^2 C_d^2 \dfrac{1}{T_S}$

$T_S$ Shaping Time

$i_n$ Spectral noise current density $i_n^2 = 2eI_{bias}$ $\propto$ strip length

$C_d$ Detector capacitance $\propto$ strip length

$e_n$ Amplifier spectral noise voltage density $e_n^2 \approx \dfrac{1}{g_m}$

in weak inversion depends only on current!
(not feature size)

# Optimization of strip length

Assume reduced signal charge $S_{rad} / S_0$ due to trapping:

Under optimum scaling to maintain signal-to-noise ratio,

input transistor power (≈ preamp power) scales with $(S_0 / S_{rad})^2$.

see Spieler, *Semiconductor Detector Systems*, Ch. 6

Alternative: reduce sensor capacitance

Best to scale strip length by $S_{rad} / S_0$.

Increases number of readout ICs by $S_0 / S_{rad}$, so

increases power by $S_0 / S_{rad}$

- Digital readout power per channel independent of strip length
- Front-end power dominated by input transistor – scales with $\propto C_{strip}^2 \propto L_{strip}^2$

Total power: $$P_{tot} = N_{strip}\left(P'_{analog}L^2 + P_{digital}\right)$$

Number of strips: $$N_{strip} = \frac{A}{p \cdot L}$$ where $A =$ Area and $p =$ strip pitch

$\Rightarrow$ Power per unit area $$\frac{P_{tot}}{A} = \frac{1}{p}\left(P'_{analog}L + \frac{P_{digital}}{L}\right)$$

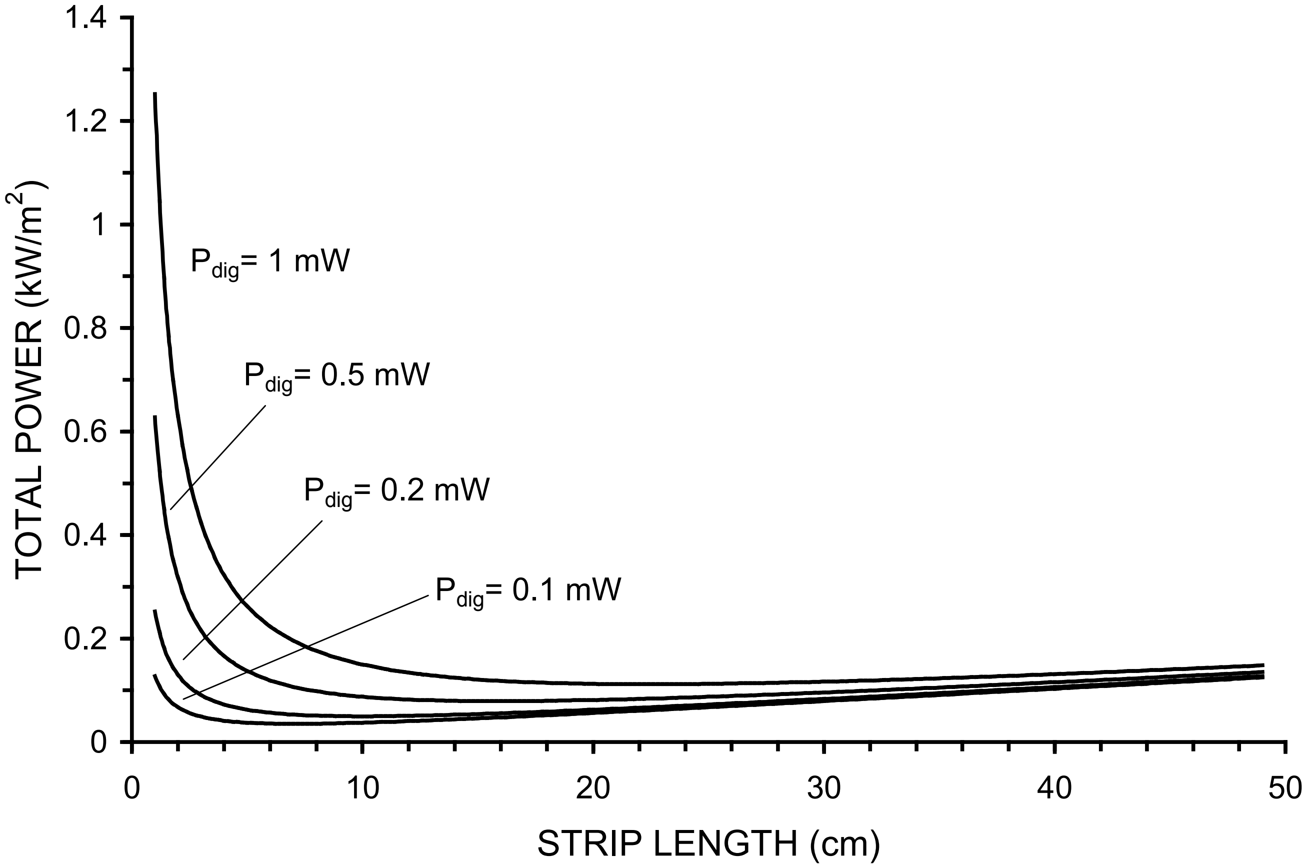
Assume analog power for 10 cm strip length: 0.2 mW
(SiGe design by E. Spencer, UCSC submitted for fab)

For comparison
ABCD chip digital power: 1.1 mW/ch at 40 MHz clock frequency, $V_{DD} =$ 4V
Digital power scales $\propto$ clock frequency and $\propto 1/V_{DD}^2$

Note: max strip length also constrained by occupancy (first science result at LHC!)

# Total Power (kW) per Square Meter vs. Strip Length and Digital Power $P_{dig}$

(strip pitch = 80 μm, analog power 0.2 mW for 10 cm strip length)




- Power increases rapidly at strip lengths below about 3 cm. (Dominated by digital circuitry)
- Important to streamline digital circuitry to reduce its contribution.
  e.g. analyze contributions of individual circuit blocks

# Power Distribution

Both SLHC and ILC require more efficient power distribution schemes than existing designs.

1. Material in ILC critical, so material in power cabling must be minimized.

   Vertex detector requires pixels of ~20 μm size $\Rightarrow$ ~$10^8$ channels.

2. ~10-fold particle flux at SLHC imposes shorter strips in tracker.

3. Deep submicron processes operate at reduced supply voltages

| | | | |
|---|---|---|---|
| Examples: | 180 nm | Logic supply 1.8 V | max |
| | 130 nm | 1.2 V | max |

Voltage drops in power cabling must be well-controlled

Failure of one detector module, for example, must not raise voltage too much.

Key circuit parameters (e.g. transconductance, switching power) define current (not voltage), so current cannot be reduced arbitrarily.

Power conversion circuits allow supply at higher voltage (and reduced current).

$\Rightarrow$ reduced current and higher allowed $\Delta V$ allow less material in cabling.

# Powering Schemes

1. Serial connection of detector modules

   Local regulators maintain module voltage with varying loads

   Initiated at Univ. Bonn (see Ta *et al.* NIM A557 (2006) 445).
   Studies at Bonn, RAL, LBNL show little or no degradation of electronic noise using ATLAS pixel and SCT ICs.

2. Local voltage step-down regulators

   a) Pulse-width regulators

   b) Switched charge-pump circuits can operate at high efficiency

      No inductors needed

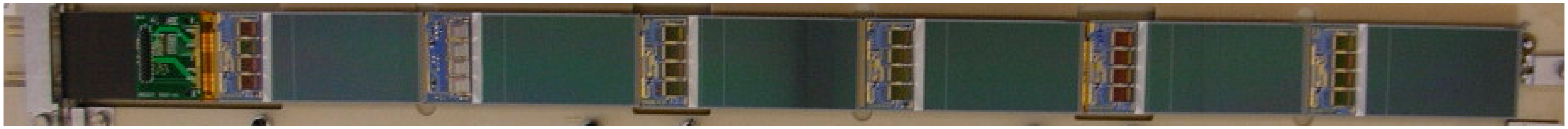
   Switching frequencies often within the passband of the front-end.

3. At ILC the beam duty cycle allows powering off of electronics between pulse trains.

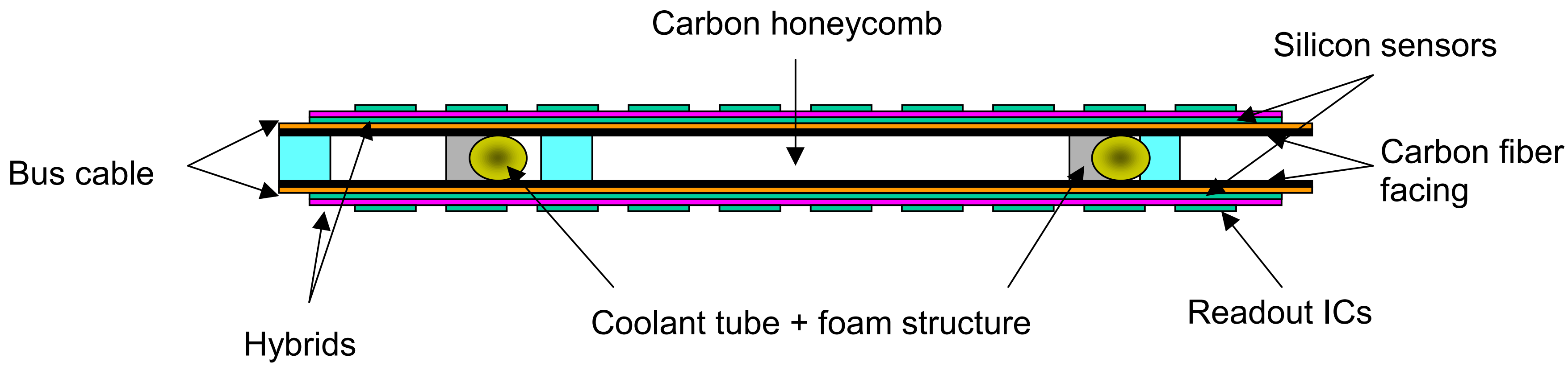
   $\Rightarrow$ forced air cooling probably practical

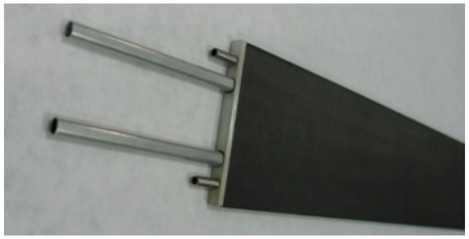
# Module Integration
(ATLAS sLHC: figures courtesy of Carl Haber)

Combining mechanical supports with cooling and wiring can reduce material and simplify assembly.



Cross Section:

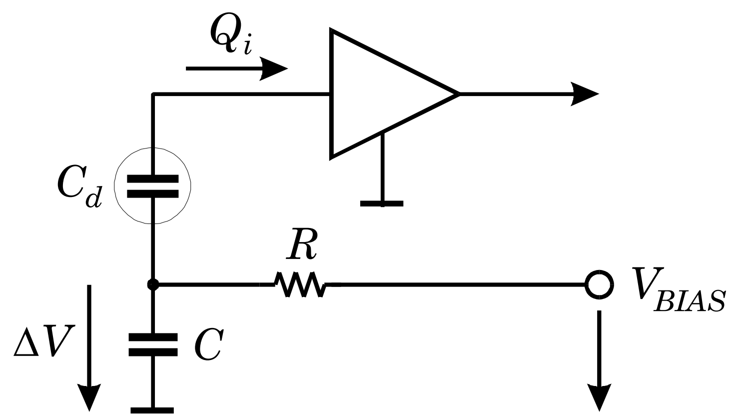


# Pickup

Example: The sensor bias line is a sensitive pickup component.

The preamplifier input is the most sensitive node in the system.




Any disturbance $\Delta V$ on the detector bias line will induce charge in the input circuit:

$$\Delta Q = C_d \Delta V$$

$\Delta V = 10$ μV and 10 pF detector capacitance yield
$\Delta Q \approx$ 0.1 fC – about 600 el or 2 keV (Si).

⇒ Crucial to control pickup on the detector bias line.

# Pickup cont'd

Key design aspects:

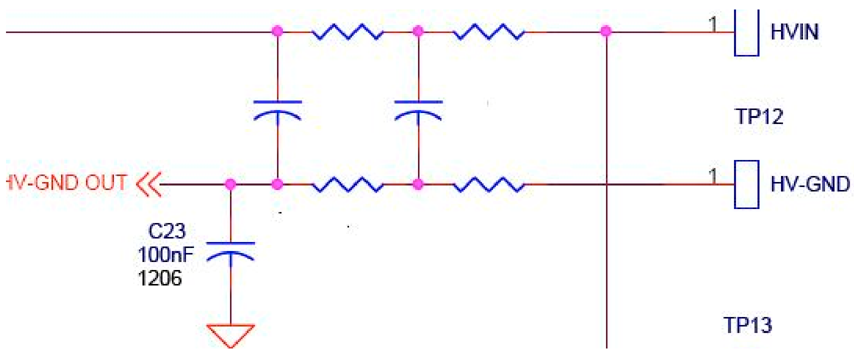
Hybrid shield layer

Local "grounds"

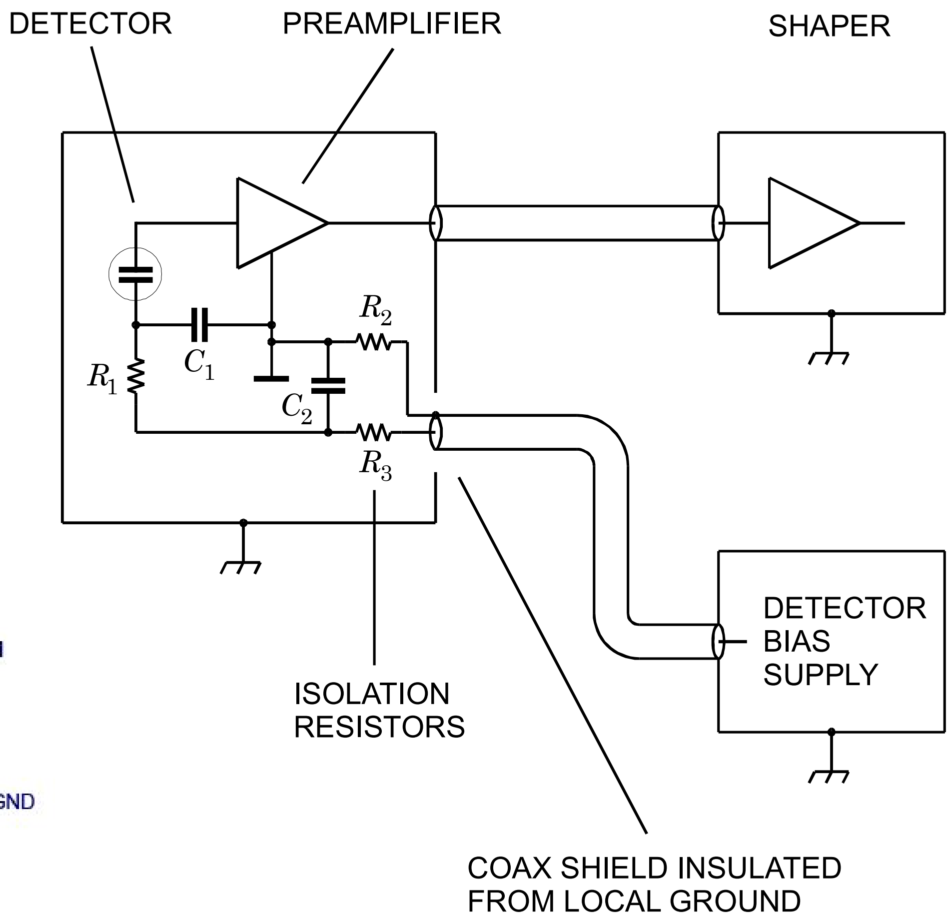
Symmetric HV filter

To minimize material use "self-shielding" techniques:

Both signal and power lines must be treated as balanced feeds, so any pickup becomes a common-mode effect.




Isolation resistors in "discrete" setup:




Resistors in "ground" lead must have the same values as those in the "HV" line.

⇒ 10 modules operated in parallel with good performance.

# Si Pixel Imagers in Electron Microscopy
(courtesy of Peter Denes, LBNL)

Film:

$\Delta$t(exposure-to-image) – minutes-hours-days
Good Modulation Transfer Function
(very small grains), less aliasing (random grain sizer)
Non-linear, low (local) dynamic range

Image plates:

$\Delta$t(exposure-to-image) – minutes-hours-days
Moderate MTF
Wide dynamic range

Phosphor/CCD:

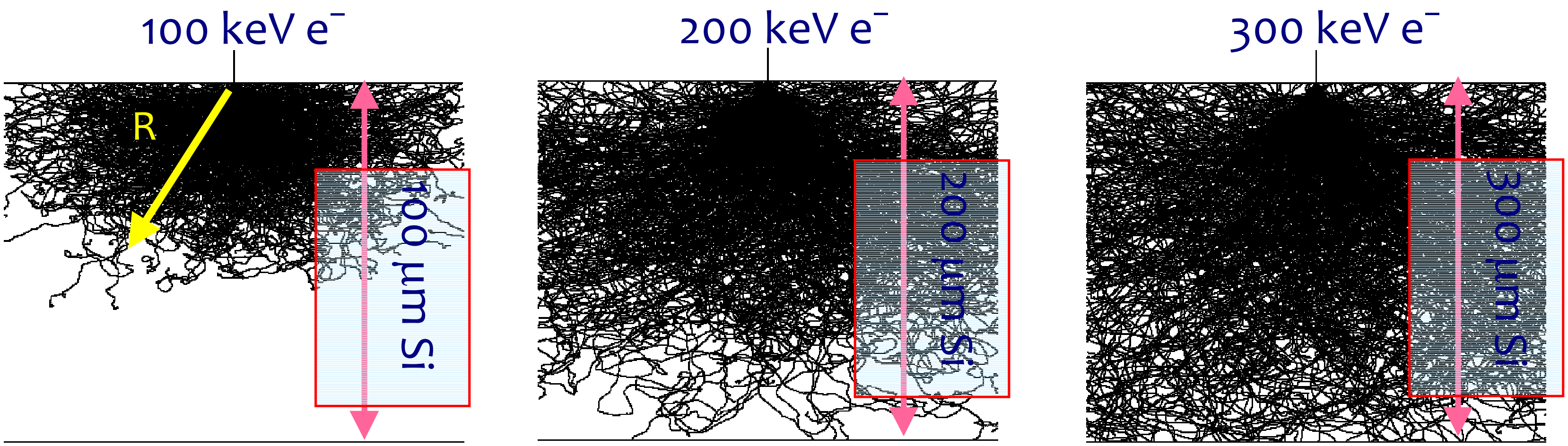
$\Delta$t(exposure-to-image) – seconds
Poorer MTF
Wide dynamic range

To obtain high efficiency with shallow depletion CCDs, a phosphor is used to convert the incident particles to photons.

# Direct Electron Detection in Si

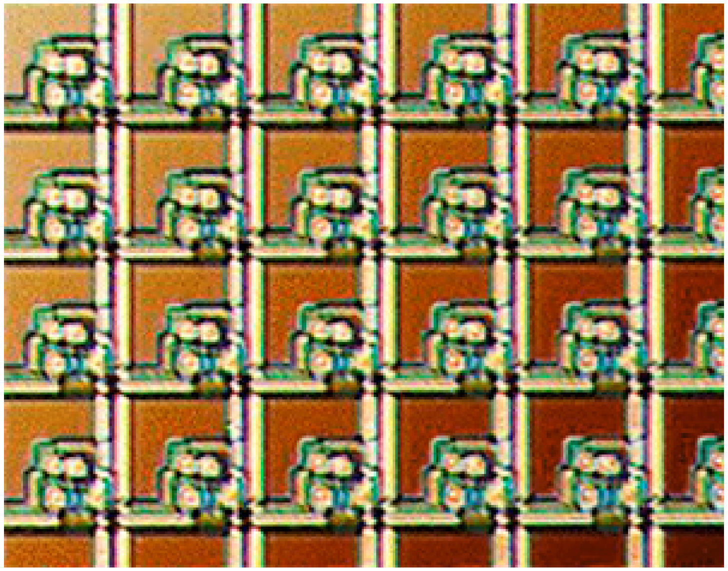
Range (μm) ~ E (keV)

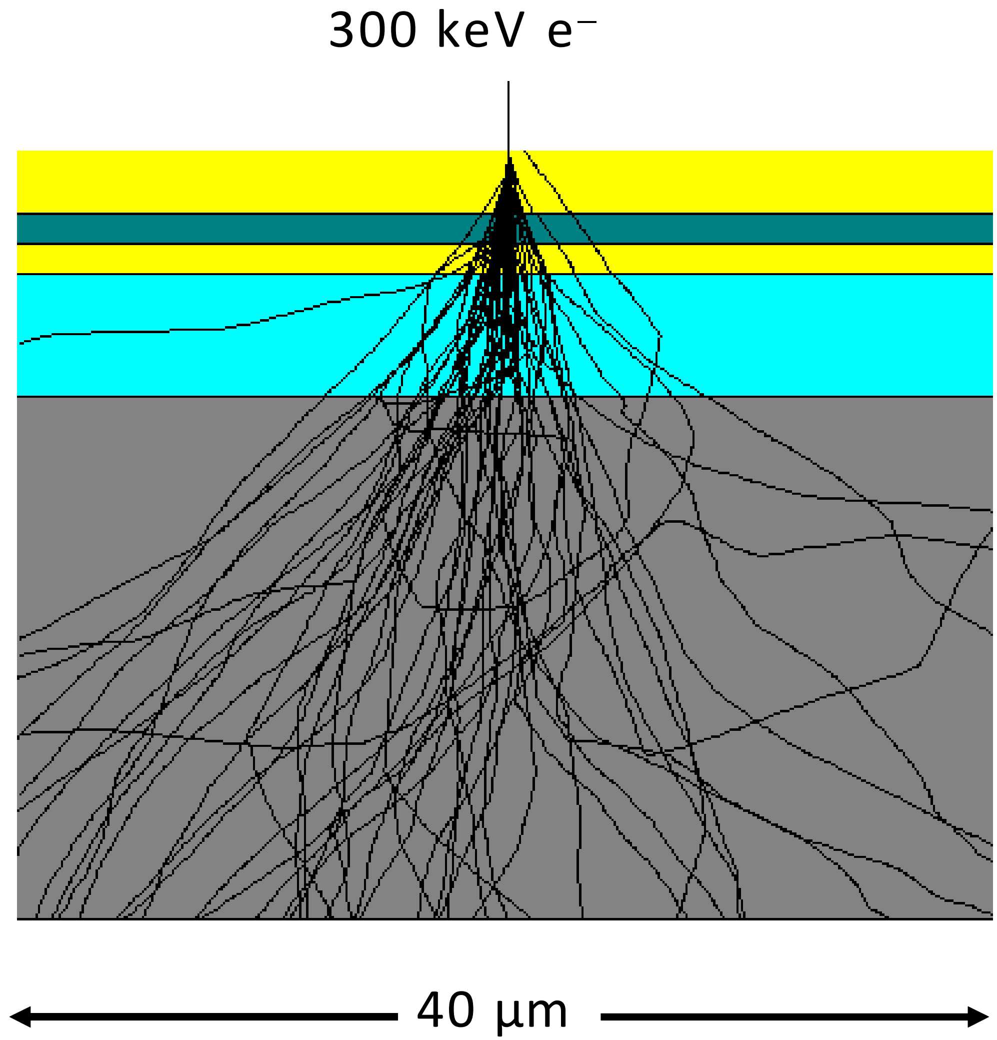
dE/dx ~ 1/E

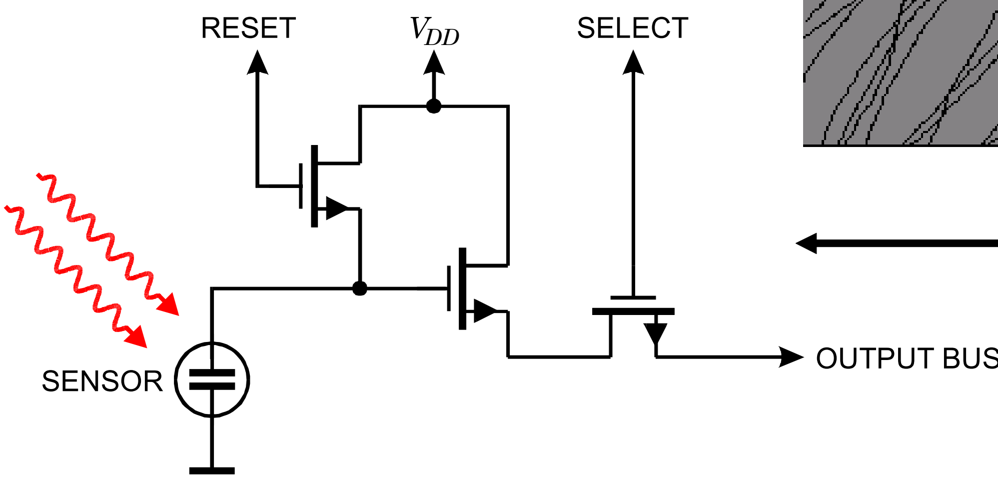



Deep sensitive region ruins position resolution!

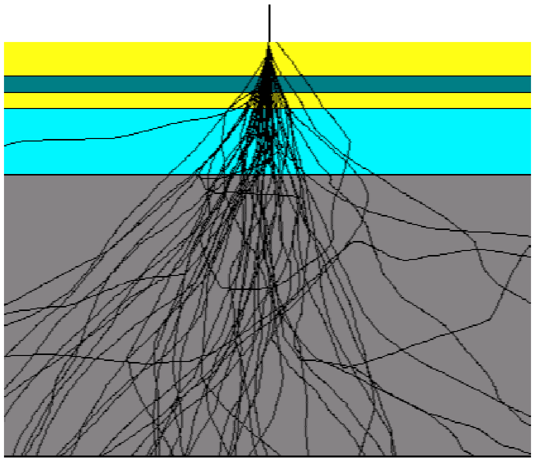
# Monolithic Pixels





# Monolithic Pixels

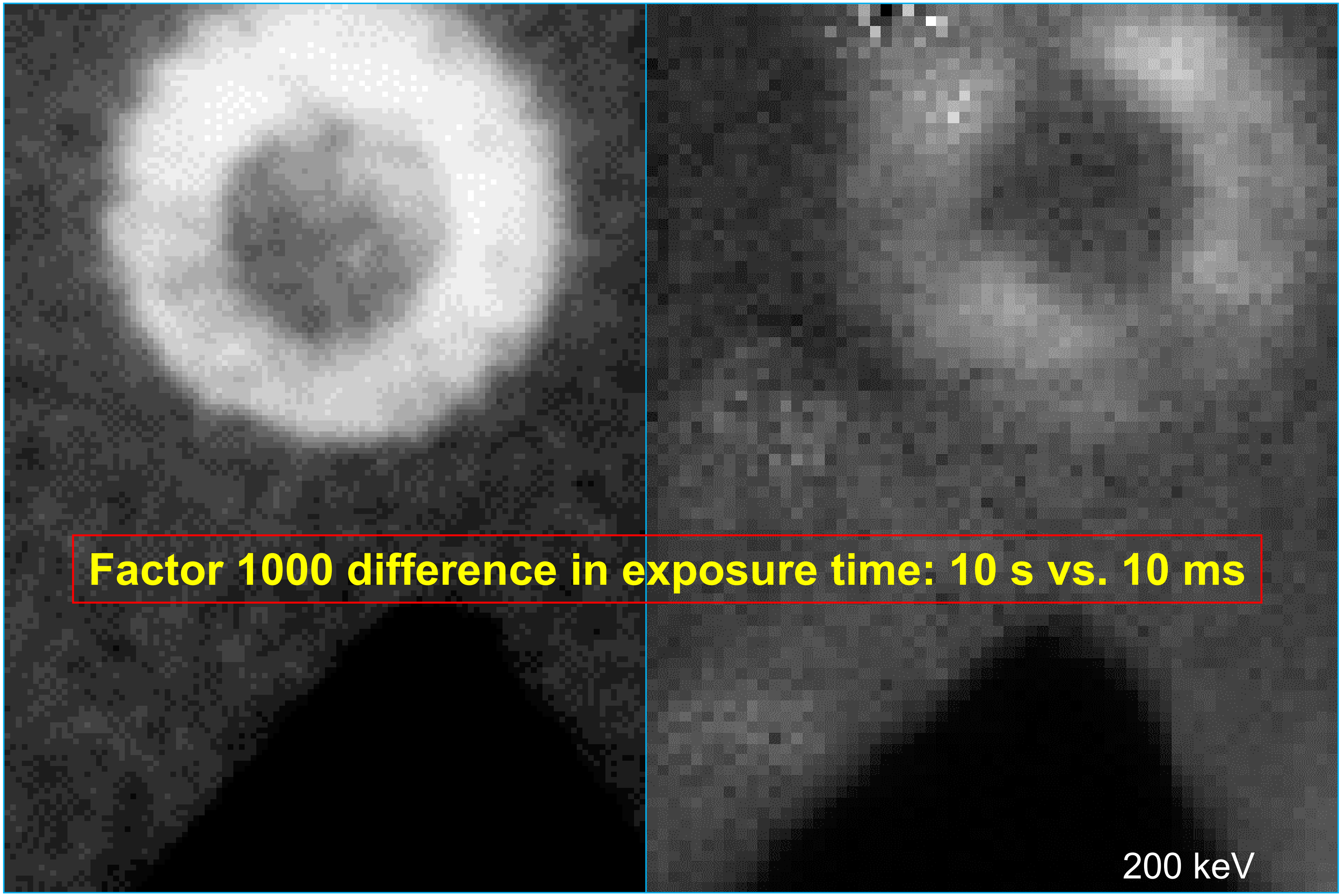


- Essentially all charge collected from thin region
- Detector can be thinned
- Higher energy $\Rightarrow$ better PSF, lower S/N
- Pixels are small (so there can be more of them, but they are less intelligent than hybrid pixels)

But ...

- Radiation damage (~10 rad per exposure)
- Diffusion (because collection region is not depleted)

# Film vs. Silicon

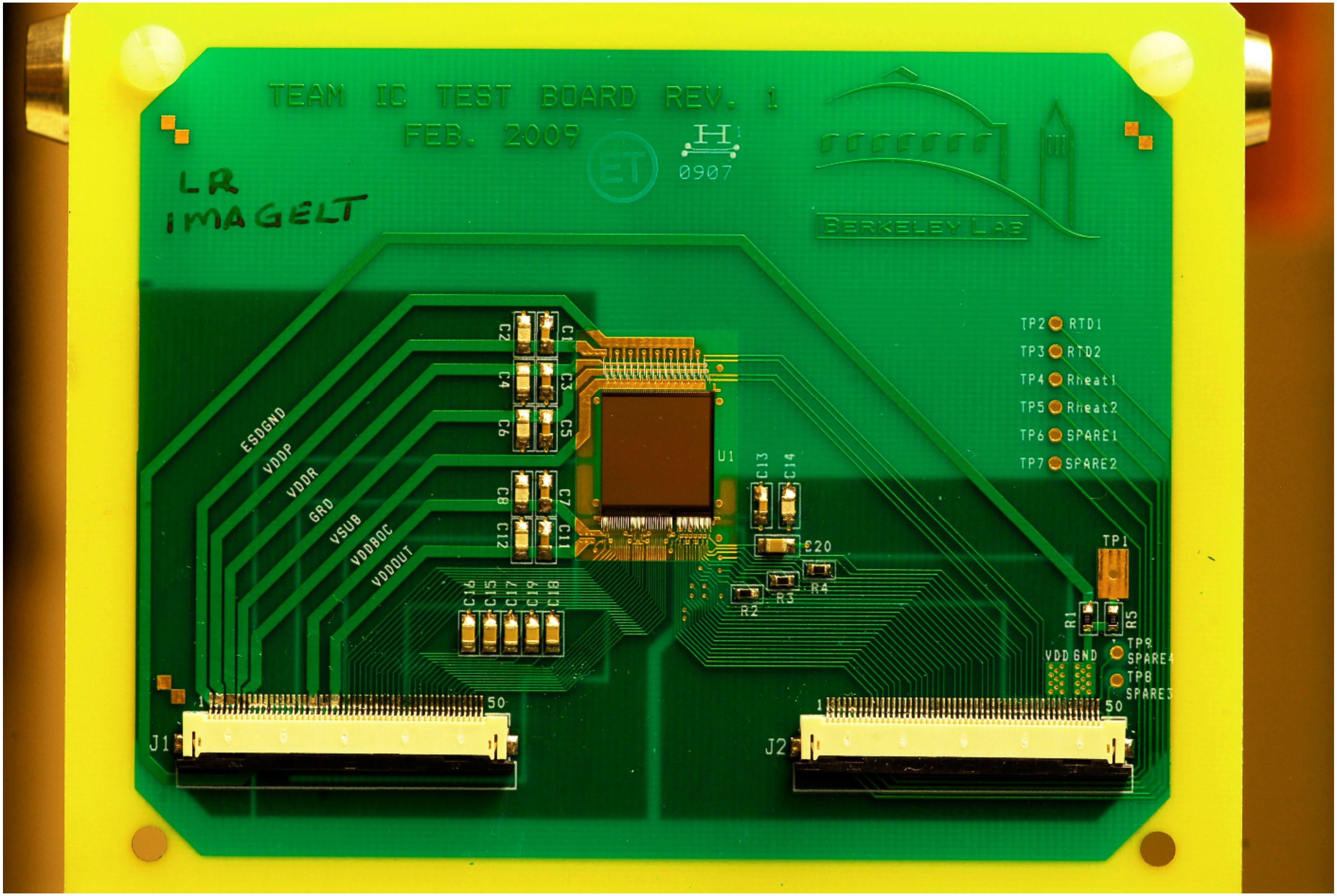


- Same object, photographed with film and silicon (200 keV)
- “Cheerio” is a lithium (aluminum-scandium) core-shell structure (30 nm dia.)
- Film – 10 sec exposure, Si – 10 ms exposure
- 4-fold structure seen in “cheerio” is true!

  Result of inhomogeneous distribution in shell

  “Washed” out in film.

# Large-format, 400 fps detector for TEAM



# Fast CCDs for X-Ray Detection

- "Standard"devices use phosphor, fiber-coupled to CCD
- Deep depletion required for high

  efficiency

  energy resolution

  peak-to-background

- No commercial CCDs

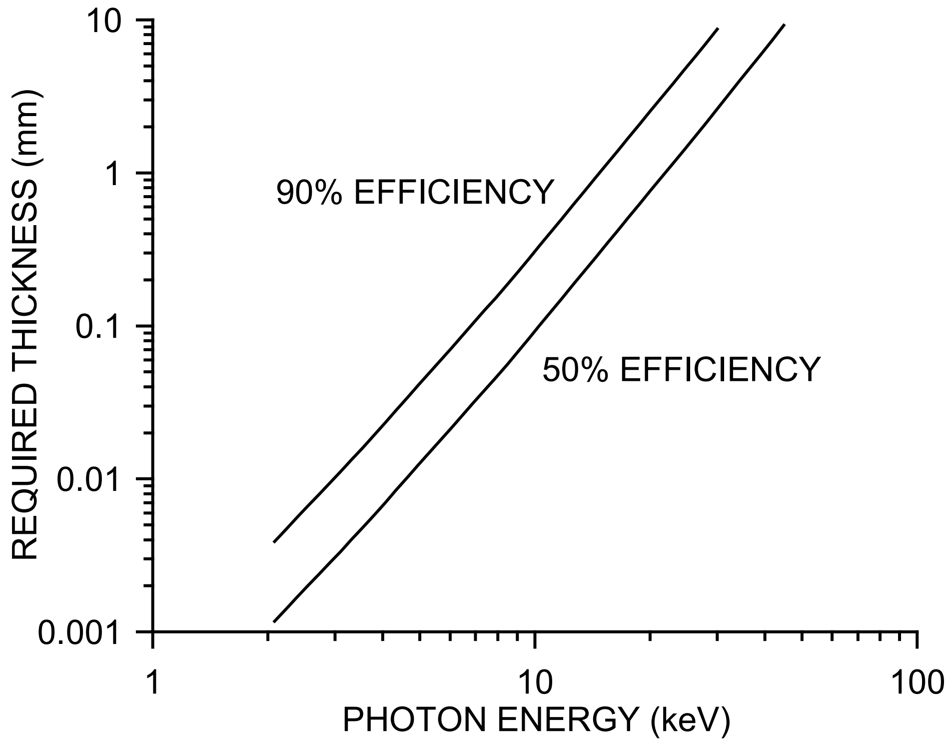
  Full depletion CCDs developed at LBNL

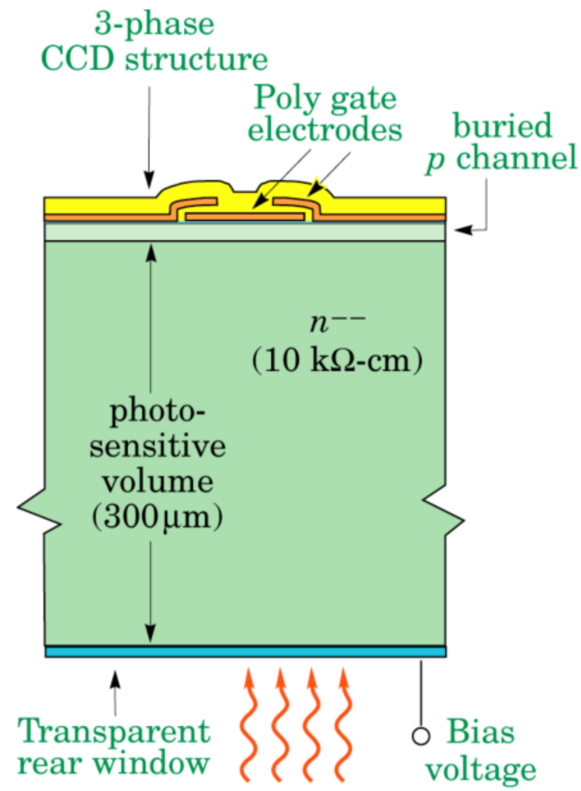
  Up to 650 μm depletion depth

  Decade use in astronomy
  (currently devices for Dark Energy Survey)

# Fully Depleted CCD

- high resistivity $n$-type substrate, fully depleted
- backside illumination
- thin backside dead layer
- 300 μm substrate thickness
  ⇒ 300 μm active thickness
  ⇒ good QE up to λ= 1 μm

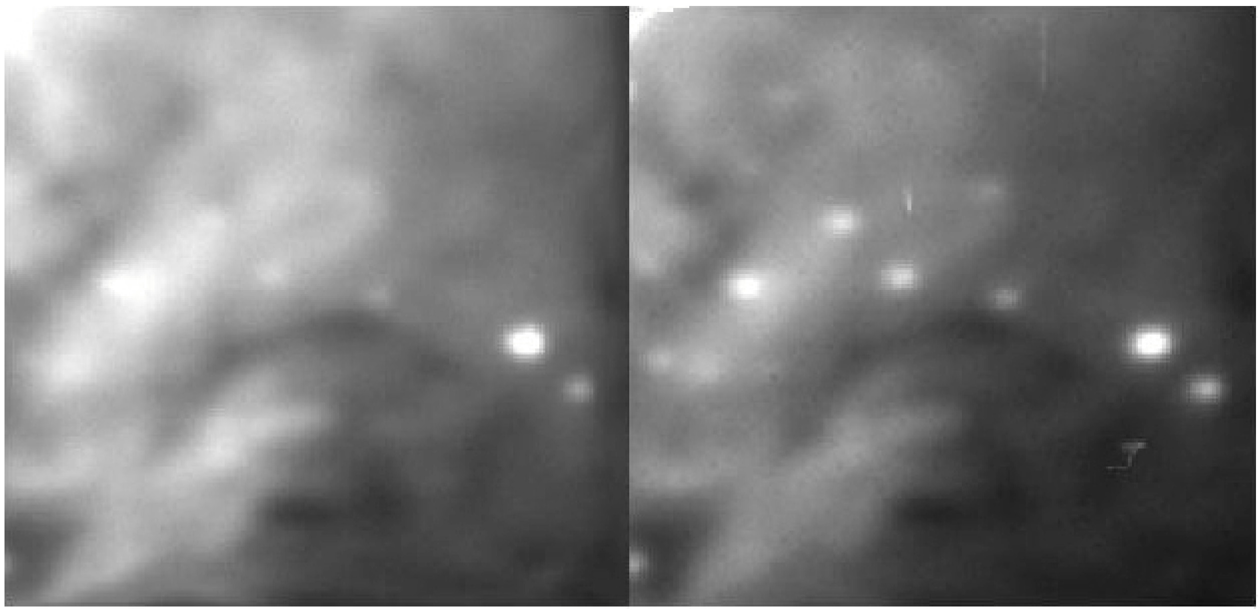



650 μm depletion depth
⇒ ~50% efficiency at 20 keV

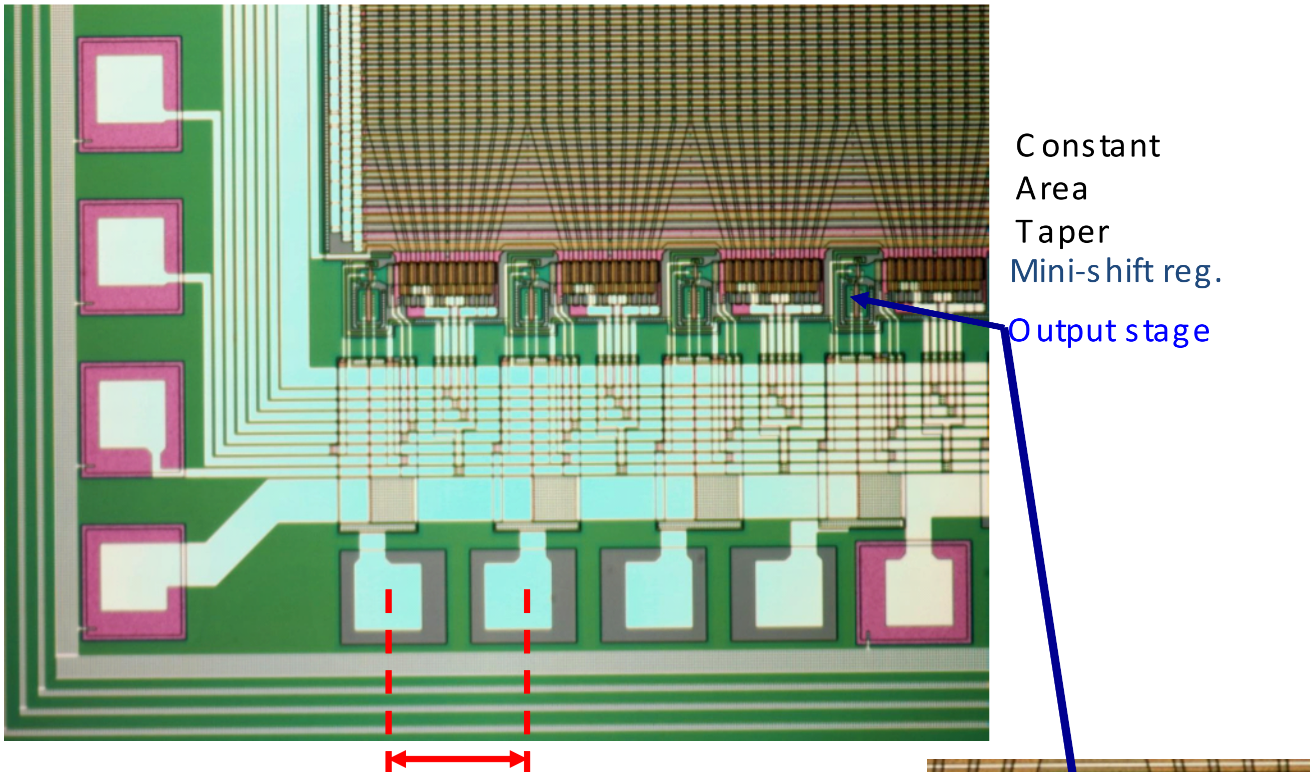
# For astronomy deep depletion extends the red response. Significant since interstellar dust absorbs in the blue.

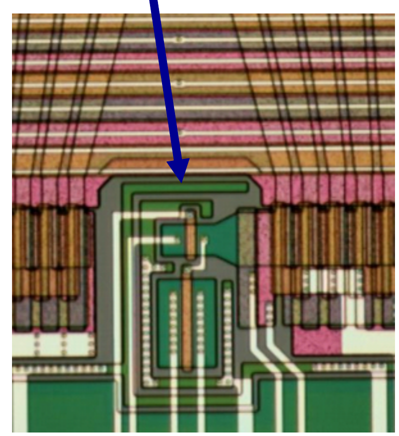
"Conventional" thinned CCD Full Depletion LBNL CCD



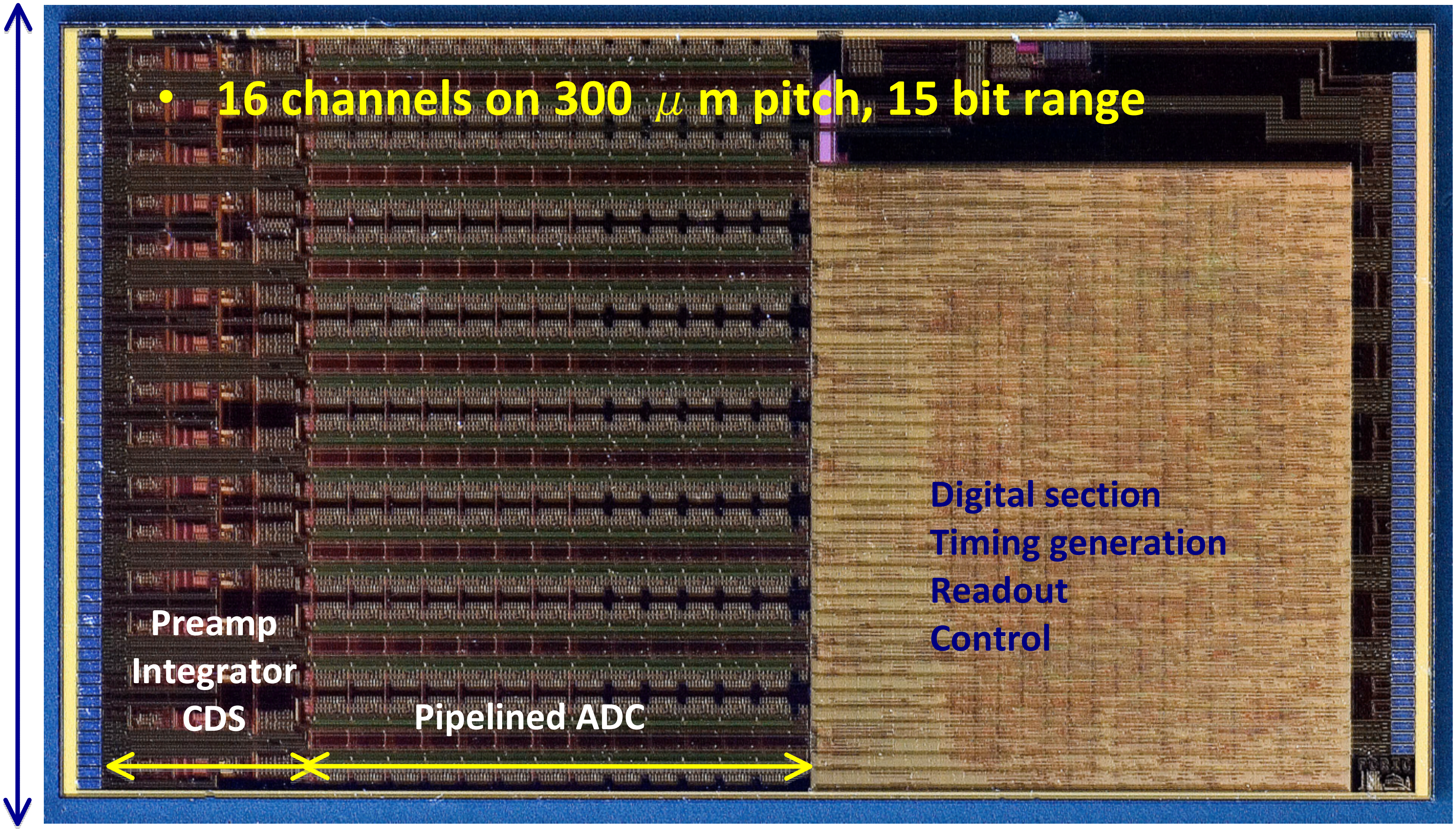
Lick 1m telescope, 4-Dec-1996

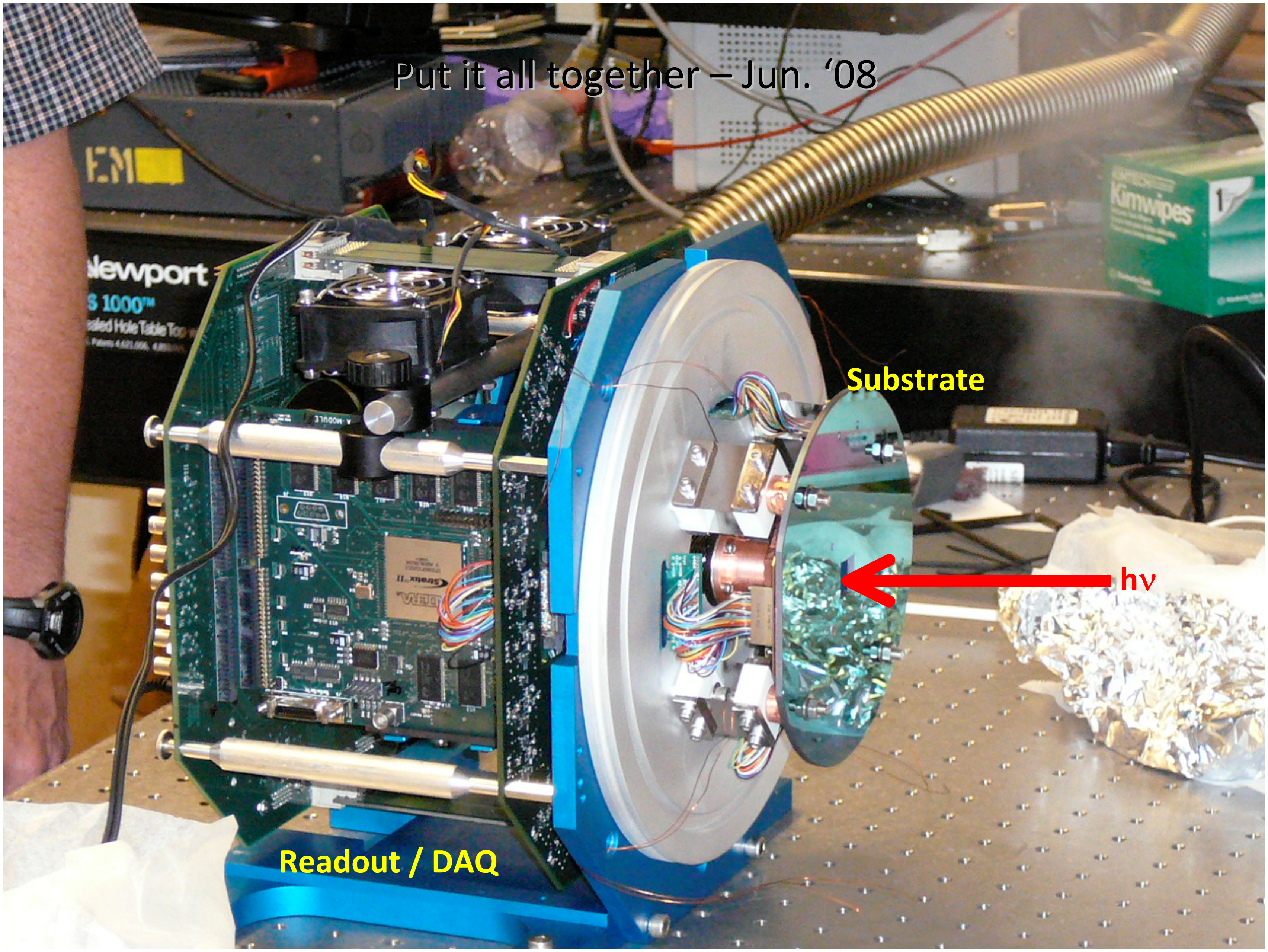
# Multi-Column Readout Increases Readout Rate
(10 columns 30 μm pitch per readout; 16 parallel readouts)



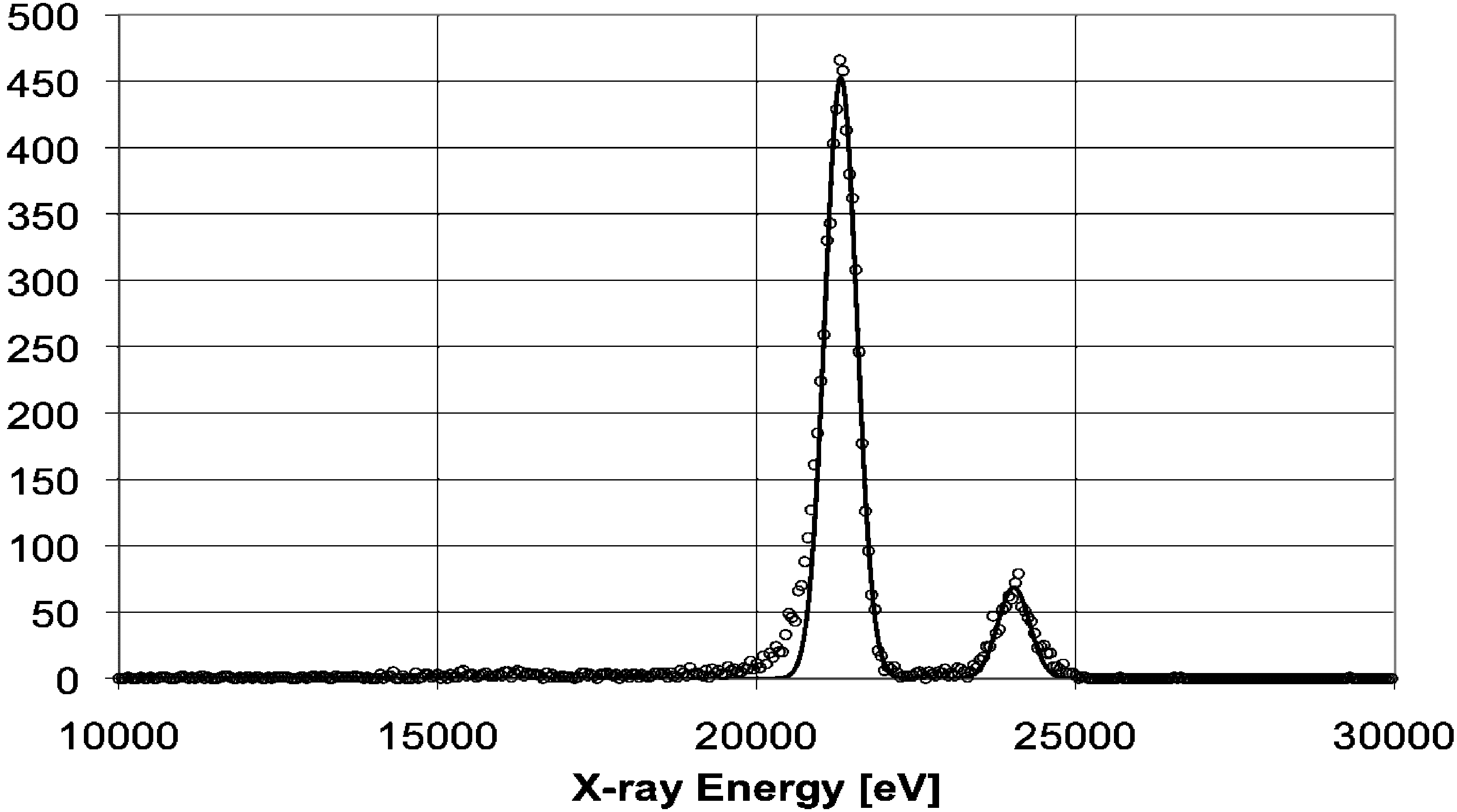
# Operated with custom readout-digitizer IC (250 MHz clock)




Put it all together – Jun. '08
Substrate
hν
Readout / DAQ

# Resolution

In this spectrum $\sigma$= 250 eV, dominated by noise pickup on PCB
Revised PCB has lower noise.



# Large-Scale Cryogenic Bolometer Arrays

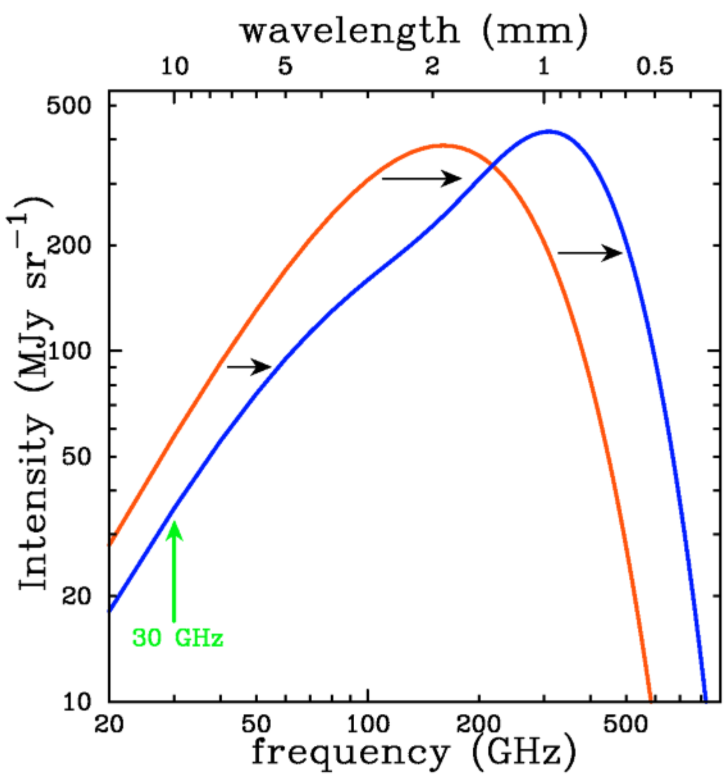
## 1. Cosmology

a) Example: Map evolution of large-scale structure (effect of Dark Energy?):

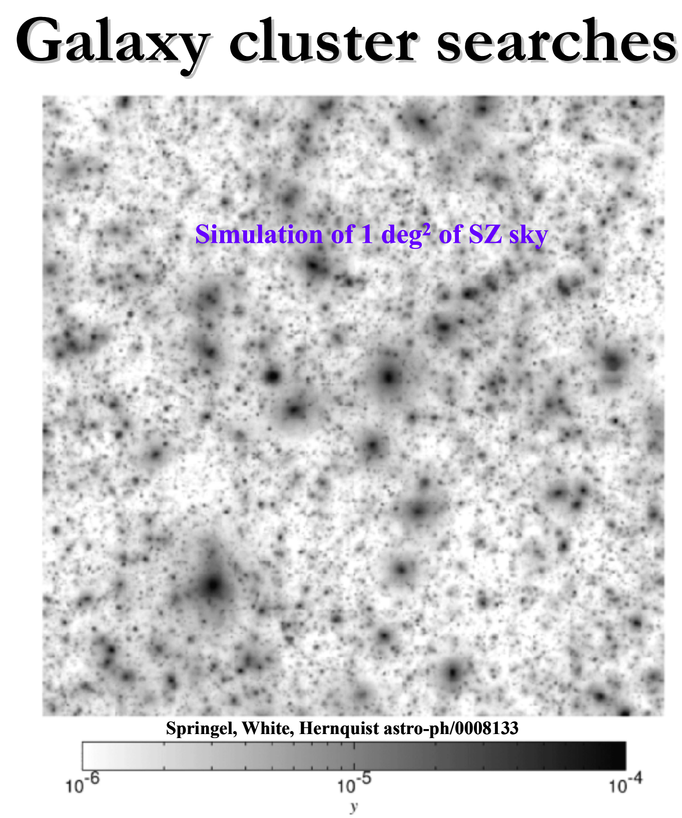
Galaxy cluster search using Sunyaev-Zel'dovich Effect $\Rightarrow\ w,\ \Omega_m$

Inverse Compton scattering: Hot gas in core of galaxy clusters scatters CMB.

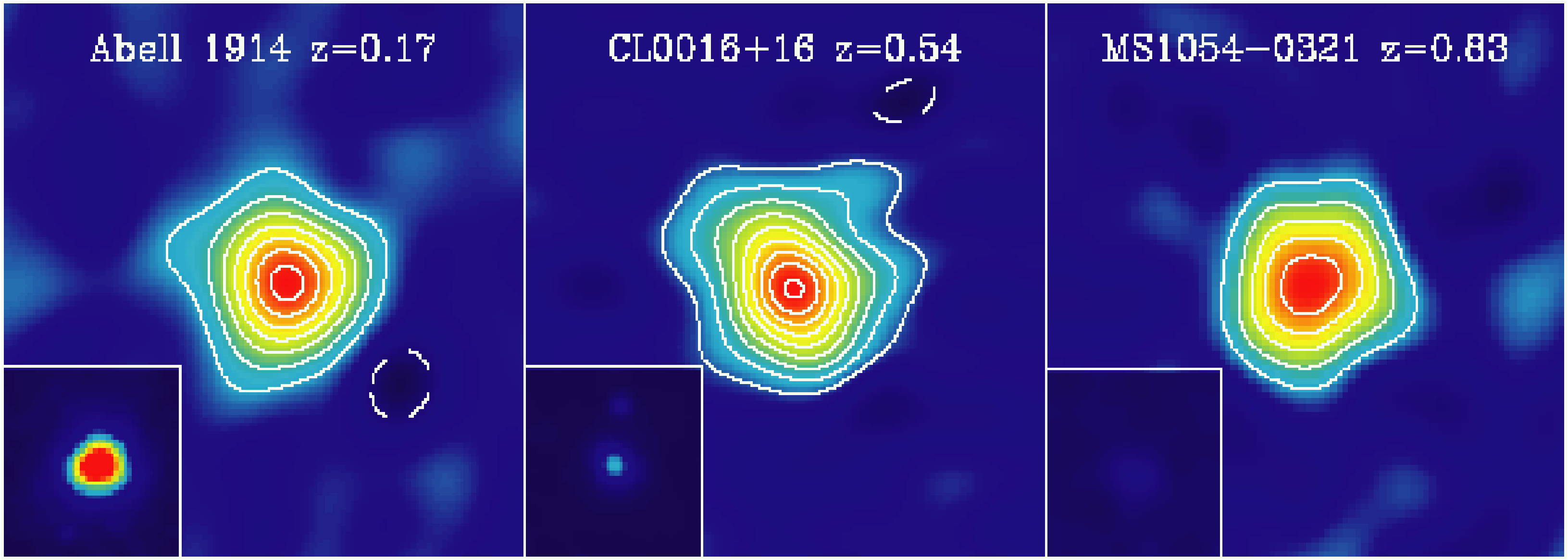
$\Rightarrow$ distorts black-body spectrum – shifts to higher frequencies:




**Clusters appear as dark spots in CMB sky**



SZ signal independent of redshift z




(Holzapfel et al.)

In contrast to x-rays (insets), SZ surface brightness is independent of redshift, so clusters can be seen at any distance.

Optical data needed to determine redshift (coordination with DES – Dark Energy Survey)

**b) Map CMB Polarization**

Detect signature of gravity waves emitted during Big Bang $\Rightarrow$ Energy Scale of Inflation

**Techniques require large-scale bolometer arrays.**

See overview at www-physics.LBL.gov/~spieler "Bolometers and the Big Bang"

# 2. High-Resolution Gamma Spectroscopy

High-rate high-resolution
x-ray fluorescence systems opened a wealth of applications in science and industry.

Example:

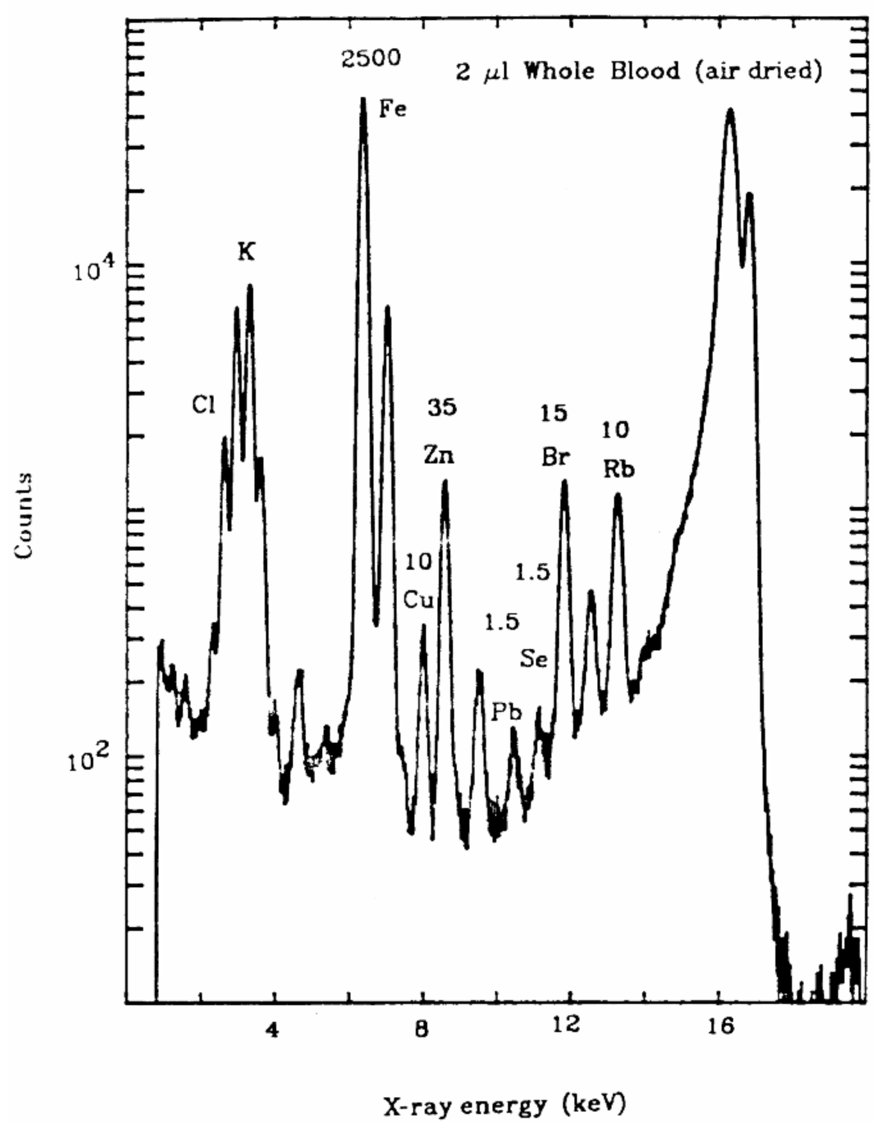
Detection of trace contaminants

Human blood sample prior to introduction of unleaded gasoline:

log scale!

Necessary to measure low intensity peaks adjacent to very strong signals

$\Rightarrow$ Improved by high energy resolution



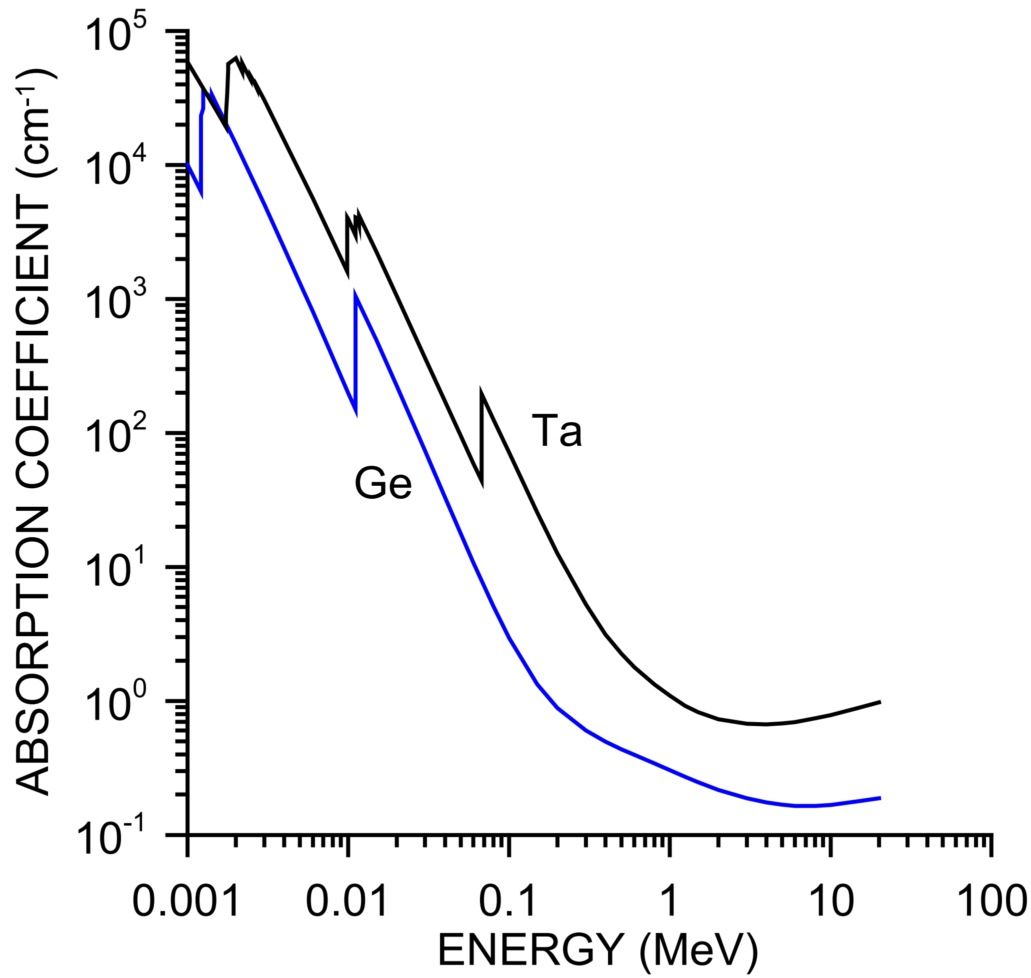
# Quest for Enhanced Energy Resolution

- Improved energy resolution would open many avenues in science, industrial applications, and nuclear non-proliferation.
- Currently, silicon and germanium detectors provide the optimum combination of energy resolution and efficiency at keV and MeV energies.
- High-Z materials would reduce the required sensor size for high full-energy measurement efficiency.
- Although remarkable progress has been made in developing new semiconductor materials and readout techniques that mitigate materials shortcomings, none of them surpass the energy resolution of silicon or germanium.
- Microcalorimeters operating at sub-Kelvin temperatures can provide superior energy resolution, but suffer from small size and rate capability.
- New developments alleviate these problems.
- Different material requirements than in semiconductors extend the range of suitable materials.

Microcalorimeter material requirements differ significantly from semiconductors.

Not necessarily easier, but different requirements open possibilities with different materials, e.g. Ta.

Gamma Absorption Coefficients of Ge and Ta



# Microcalorimeters

- Energy per signal quantum ~meV, rather than ~eV in semiconductors

  Statistical energy resolution: $\sigma_E = \sqrt{kTE_\gamma}$

- In addition fluctuations in number of phonon modes, dependent on heat capacity $C$, so

$$\sigma_E = \sqrt{kT\left[TC(T) + E_\gamma\right]}$$

High resolution requires

- Operation at low temperatures
- Low heat capacity (small sensors + operation at low temperatures)

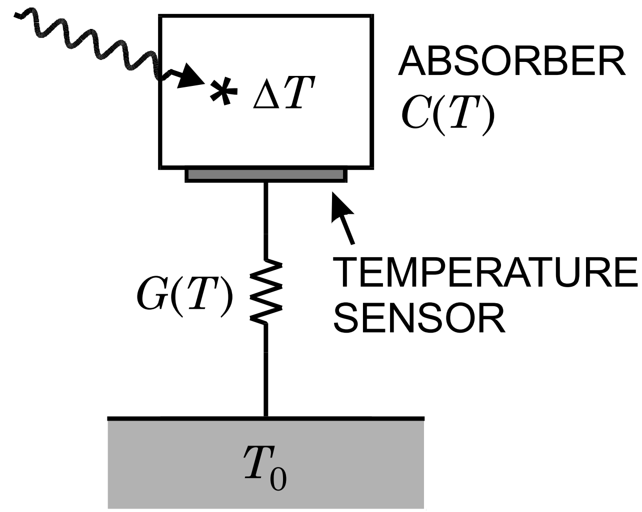
Key developments

- Monolithic integration of large sensor arrays + cryogenic multiplexing

  $\Rightarrow$ increase detection efficiency and rate capability

- Cooling systems that don't require liquid cryogens

# Microcalorimeter Principle




For an absorbed energy pulse

$$\Delta T(t) \propto e^{-t/\tau}$$

where $\tau = C/G$

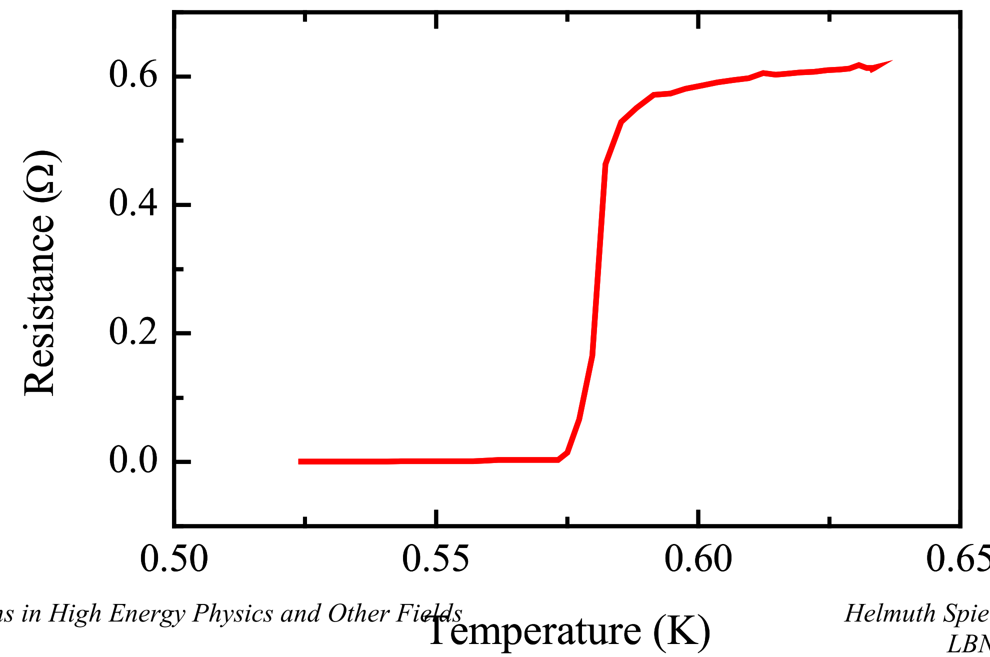
One type of sensor implementation:

Superconducting Transition Edge Sensor (TES)

Thin film superconductor at transition temperature

Bias sensor in transition

small $\Delta T \Rightarrow$ large $\Delta R$



# Electrothermal Feedback

Required power is of order pW, i.e. voltage of order μV
current of order μA

Simplest to bias device with a **constant current** and measure change in voltage

Problem: power dissipated in sensor $P = I^2 R$

Increasing $R \Rightarrow$ Increasing $P \Rightarrow$ Increasing $R \Rightarrow$ Increasing $P$

$\Rightarrow$ **thermal runaway**

When biased with a **constant voltage** $P = \frac{V_b^2}{R}$

Increasing $R \Rightarrow$ Decreasing $P \Rightarrow$ Decreasing $T \Rightarrow$ Decreasing $R$

$\Rightarrow$ **negative feedback**

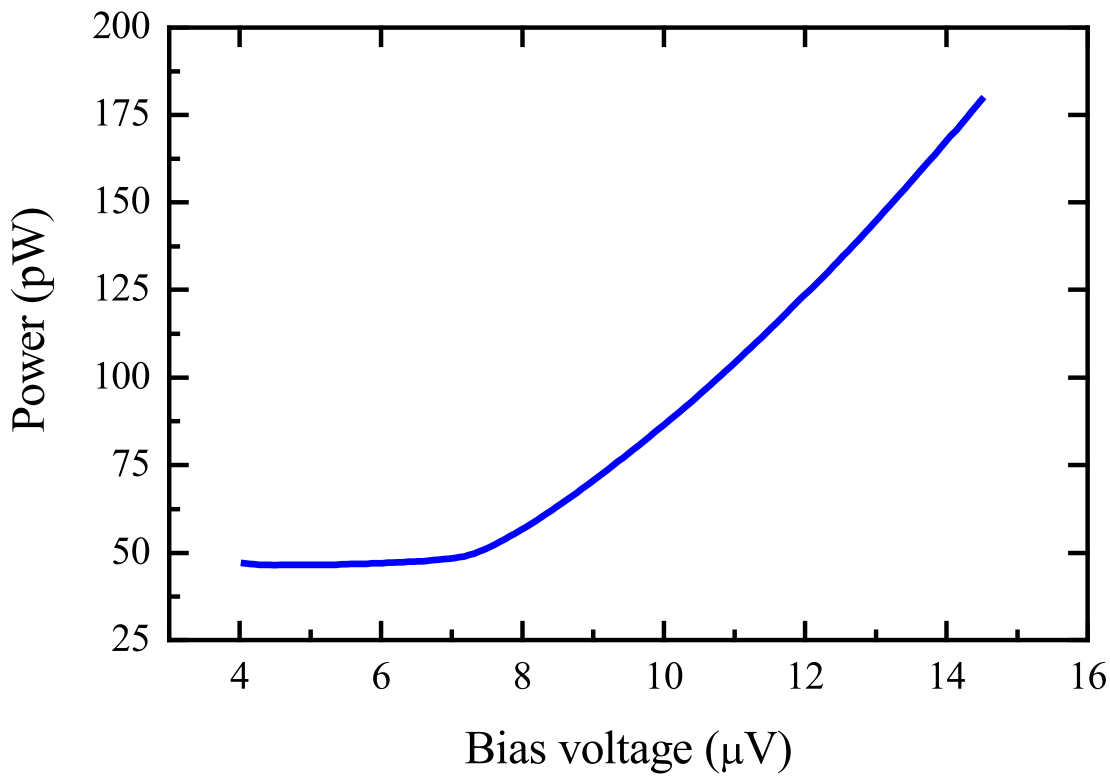
Analogous to fedback op-amps:

Loop gain stabilizes operating point, increases linearity, and bandwidth.

Additional phase shifts can lead to instability.

# Operate with constant voltage bias

⇒ "Constant power operation":

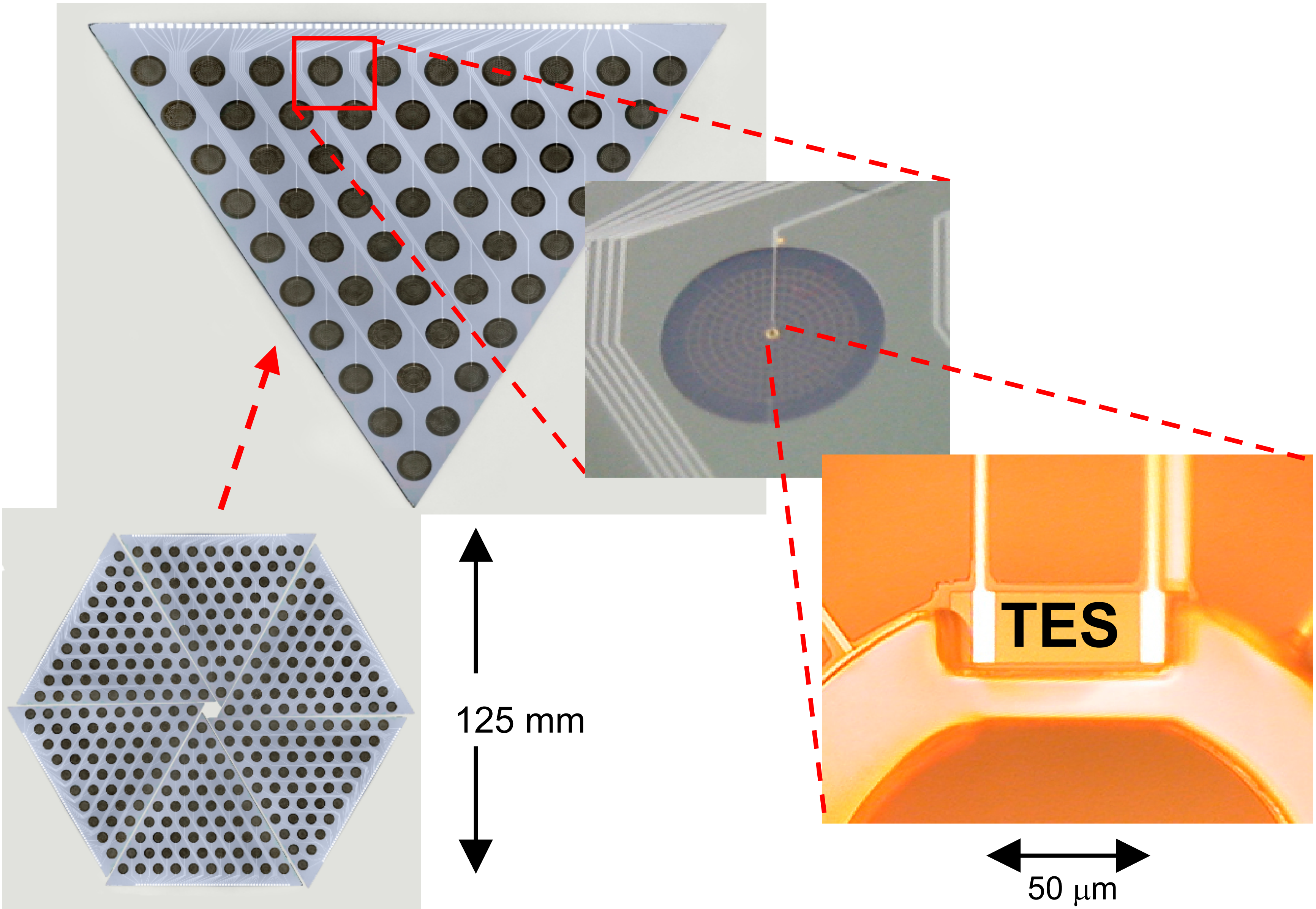



Change in absorbed power is balanced by change in electrical power:

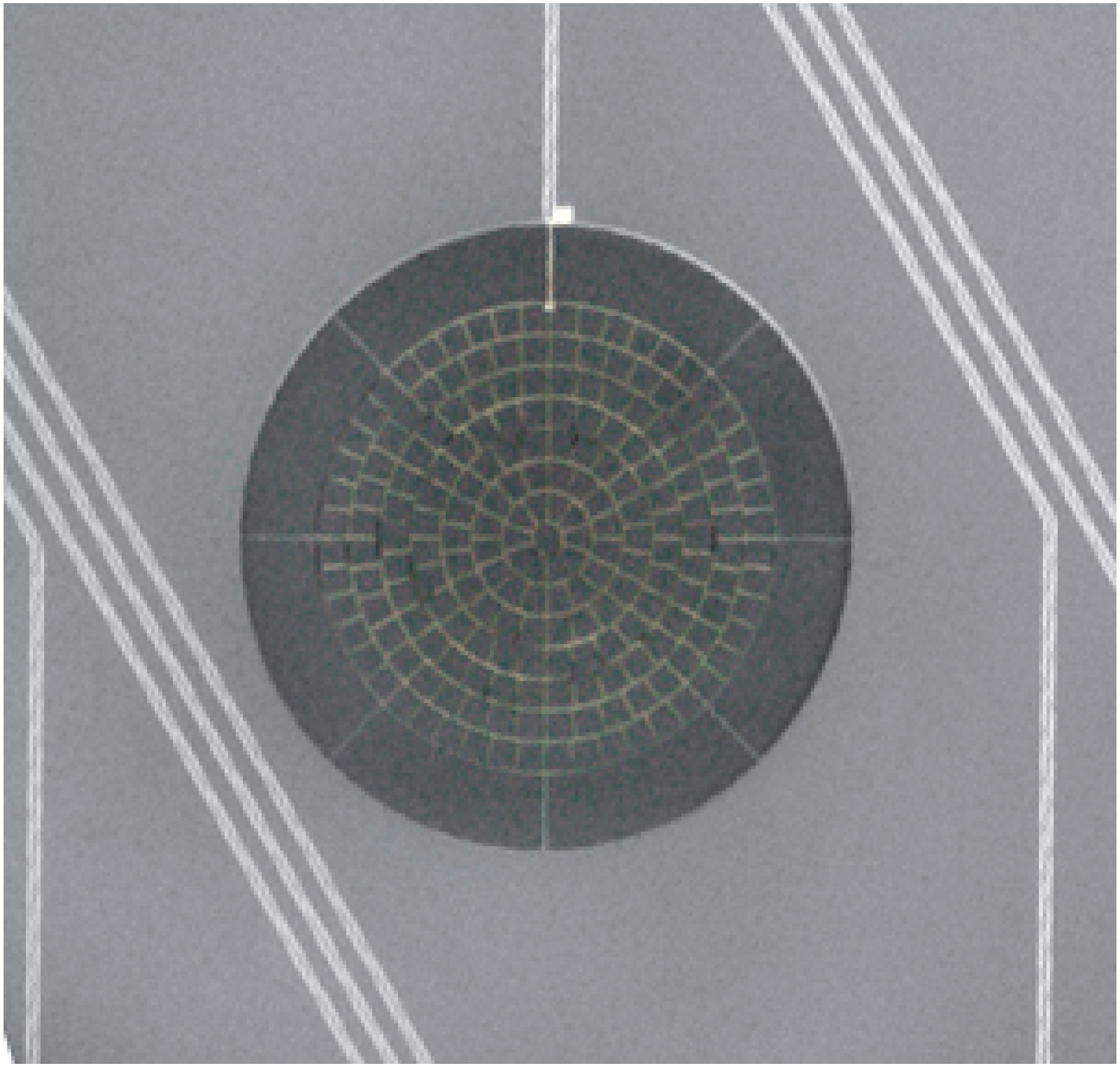
$$\Delta I / \Delta P = 1 / V_{bias}$$

Constant Voltage Bias requires that total resistance in bias loop is much smaller than the bolometer resistance (typ. 1 ohm)

# APEX-SZ Focal Plane



# Close-up of spiderweb bolometer



Key Developments

- Monolithic fabrication of bolometers

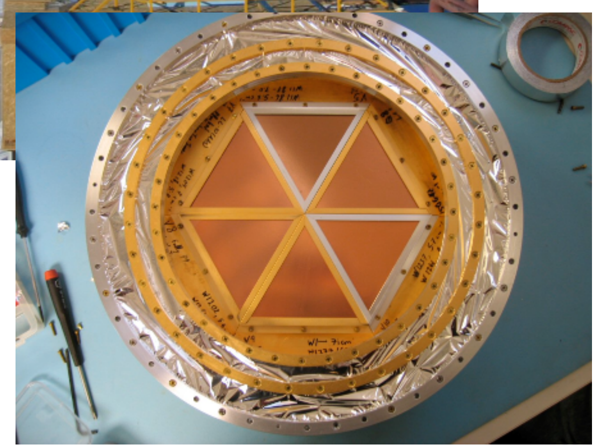
  ⇒ wafer-scale integrated arrays
- Cryogenic multiplexing
  1. Time domain (NIST)
  2. Frequency domain (this work)

     Zero add'l power at cold stage
- Systems in 3rd year of operation:
  1. South Pole Telescope (SPT)

     970 bolometer array
  2. APEX-SZ

     320 bolometer array
- Cryogen-free cooling

  No refilling of liquid cryogens Required



SPT bolometer array

# Principle of Frequency-Domain Multiplexing

1. High-frequency bias (~100 kHz – 1 MHz)

   Each bolometer biased at different frequency

2. Signals change sensor resistance

   ⇒ Modulate current

   ⇒ Transfer signal spectrum to sidebands adjacent to bias frequency

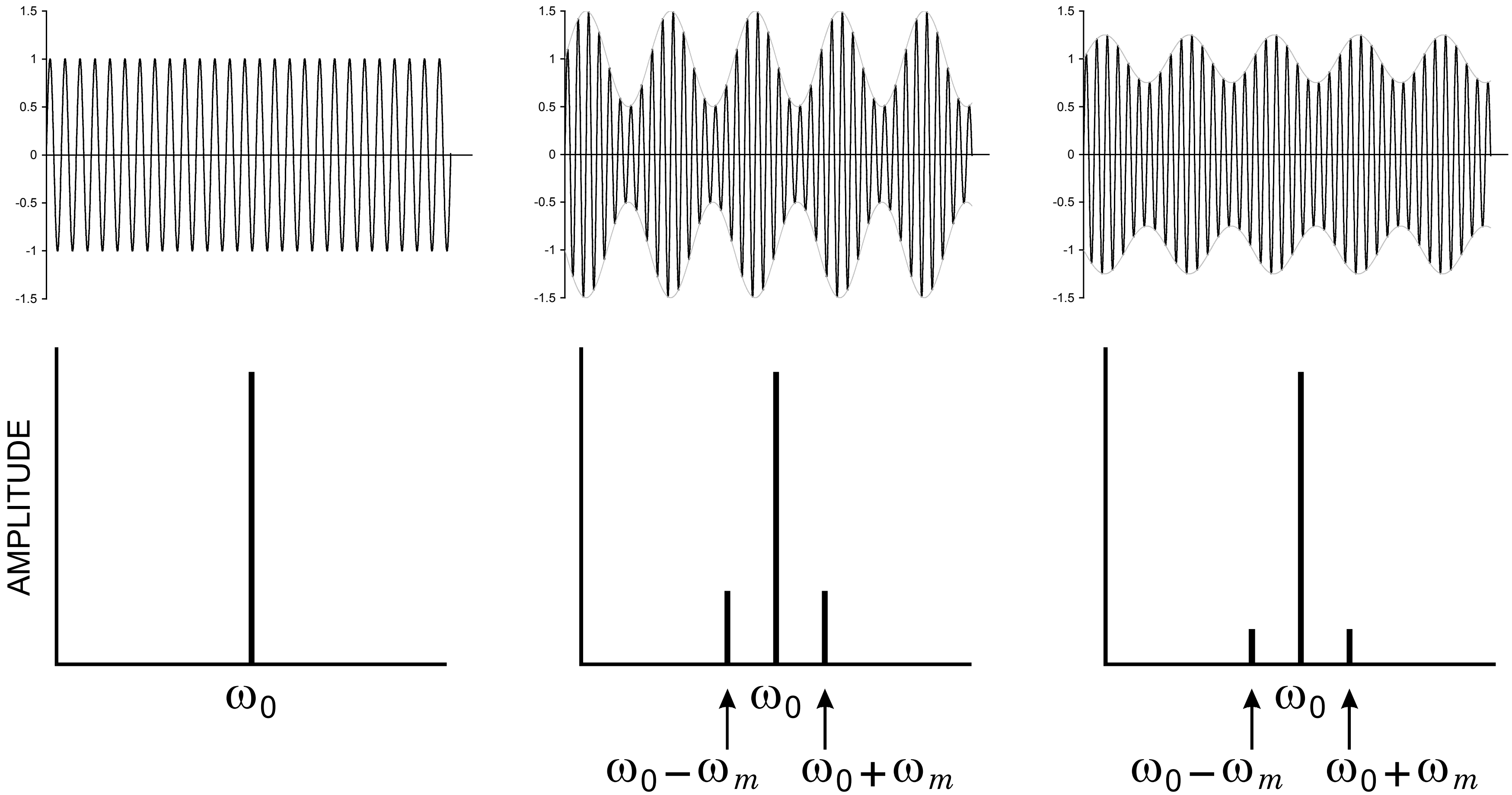
   ⇒ Each sensor signal translated to unique frequency band

3. Combine all signals in common readout line

4. Retrieve individual signals in bank of frequency-selective demodulators

High-frequency bias greatly reduces sensitivity to microphonics.
(no noise increase due to mechanical pulse tube cooler)

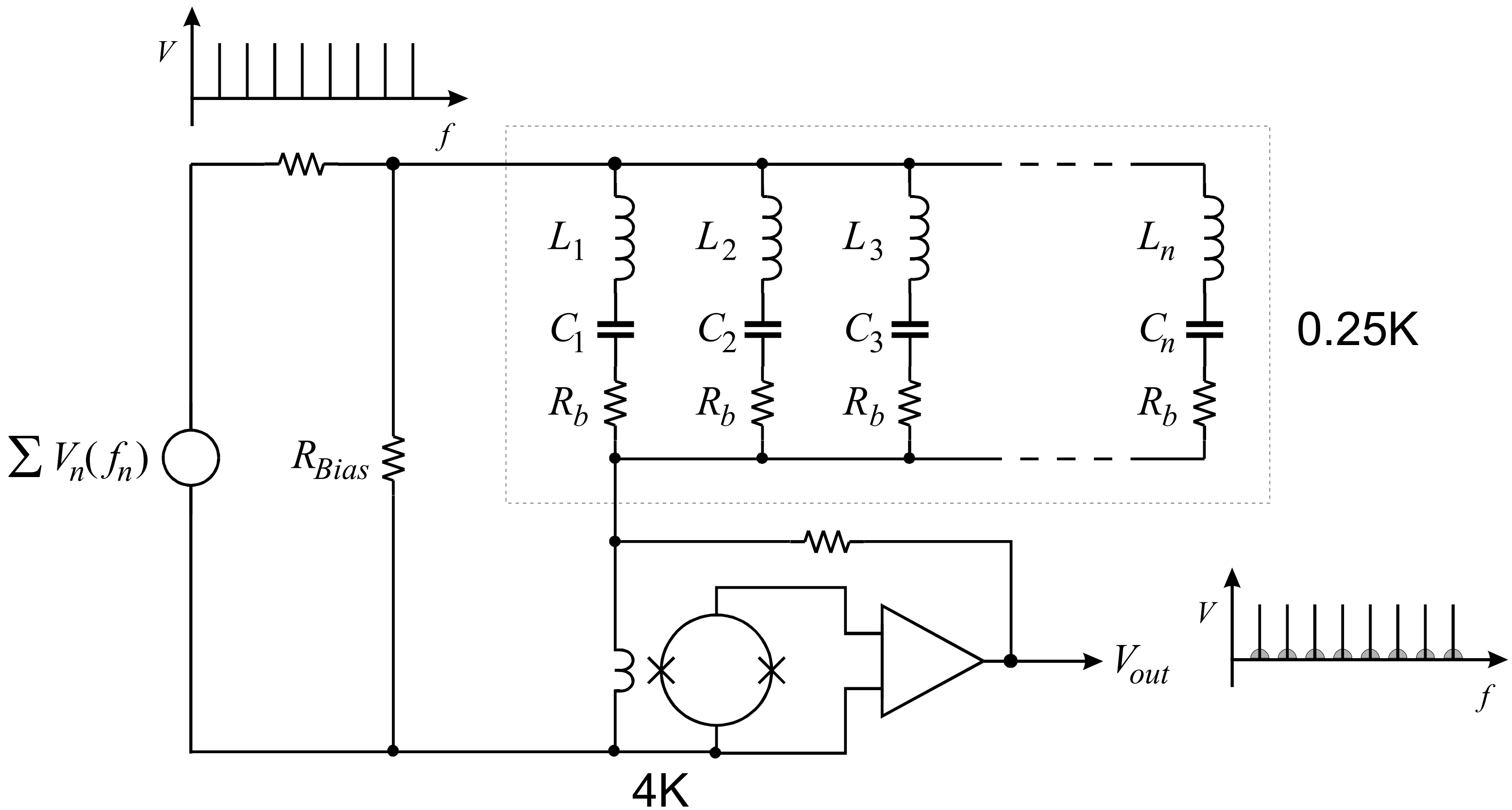
# Modulation Waveforms and Spectra




Carrier amplitude remains constant!

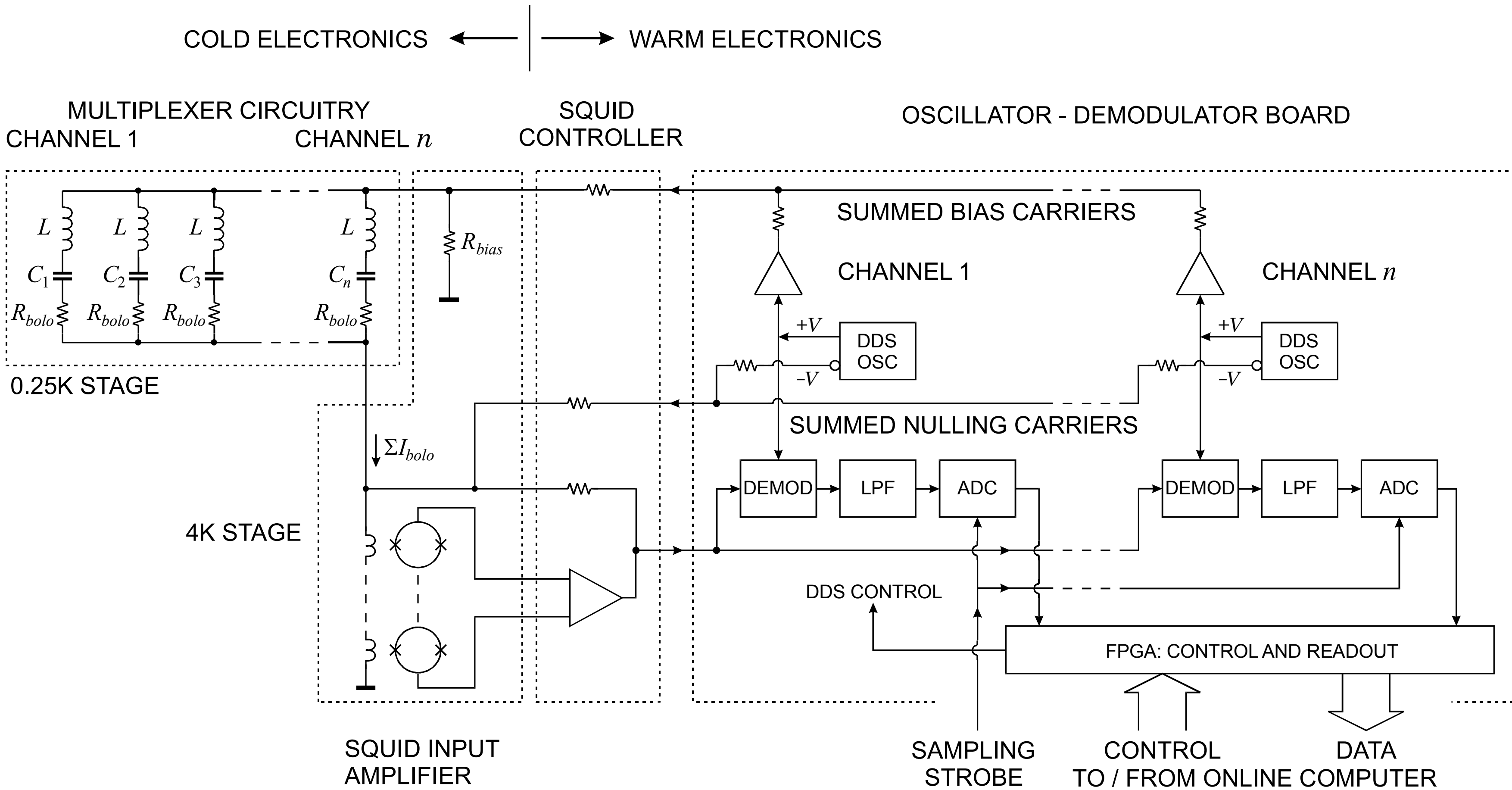
All signal information in the sidebands adjacent to bias frequency.

# MUX circuit on cold stage




- “Comb” of all bias frequencies fed through single wire.
- Tuned circuits “steer” appropriate frequencies to bolometers and limit noise bandwidth.
- Current return through shunt-fedback SQUID amplifier (low input impedance).
- No additional power dissipation on cold stage (only bolometer bias power).

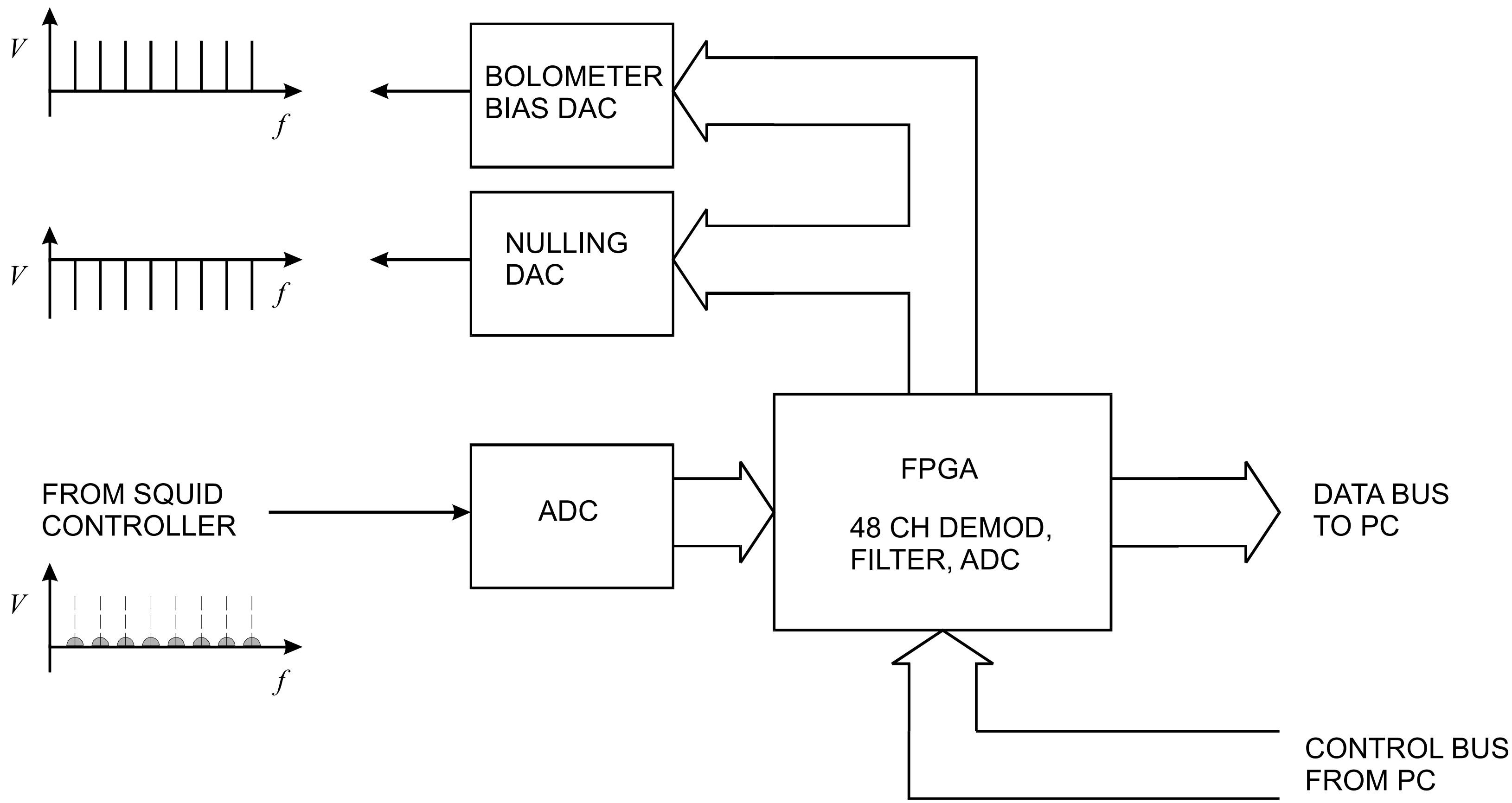
# Readout




Bias frequencies are nulled at SQUID input to reduce maximum signal level.
(does not affect signal, which is only in the sidebands)

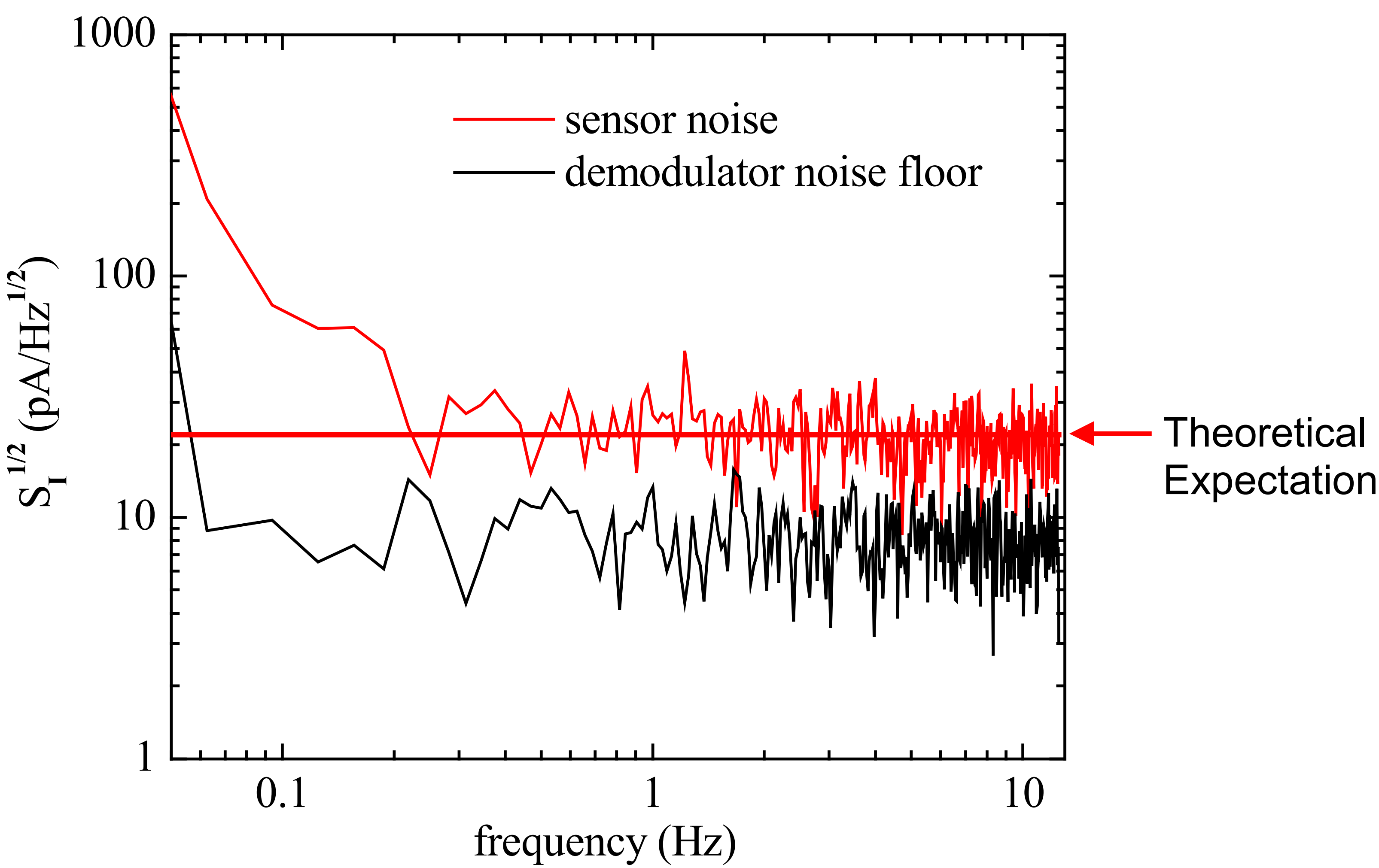
Note: SQUID feedback loop includes room-temperature amplifier.

# Recent improvements in fast ADCs and FPGAs enabled "Fully Digital" Demodulator (Matt Dobbs et al., LBNL/McGill)




- Substantial reduction in power ⇒ Balloon-borne experiments (e.g. EBEX)
- Baseline readout for CMB polarization experiments PolarBear and EBEX (balloon)

# Measured Noise Spectrum in 8-Channel MUX System

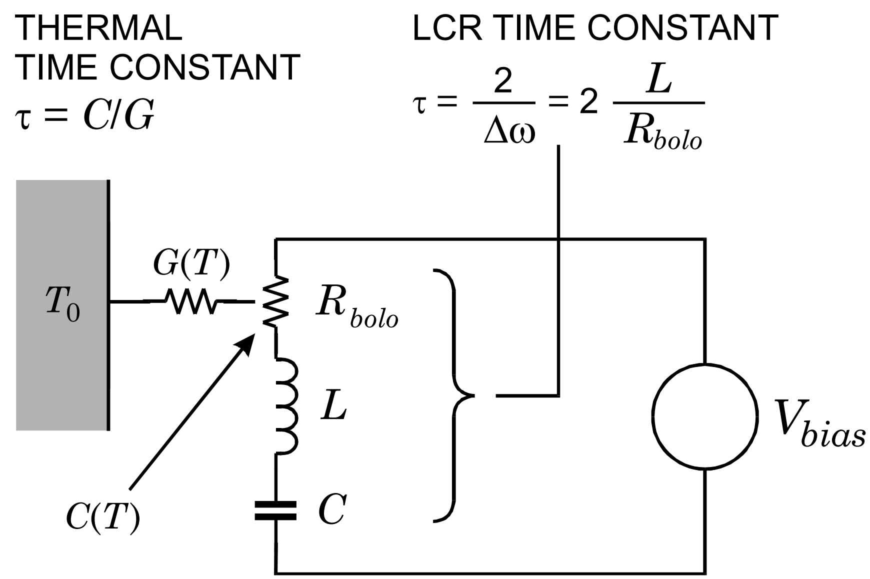



Sensor noise white above 0.2 Hz

(Trevor Lanting)

# Challenges

## Bolometer time constants




Both the bolometer's thermal time constant

$$\tau_{th} = C / G$$

and the time constant introduced by the resonant circuit bandwidth

$$\tau_{LCR} = 2\frac{L}{R_{bolo}}$$

introduce poles and phase shifts into the electrothermal feedback loop.

For a given selectivity (⇒ channel spacing), the bolometer time constant must be sufficiently large to maintain feedback stability.

The bolometer time constant was increased by introducing additional mass (increase $C$). Thermal interfaces introduced additional time constants! Solved in refined design.

Primary challenge: Convincing sensor designers that electronics cannot solve all problems and that bolometers must be tailored to the readout.

# SQUIDs

Superconducting Quantum Interference Devices

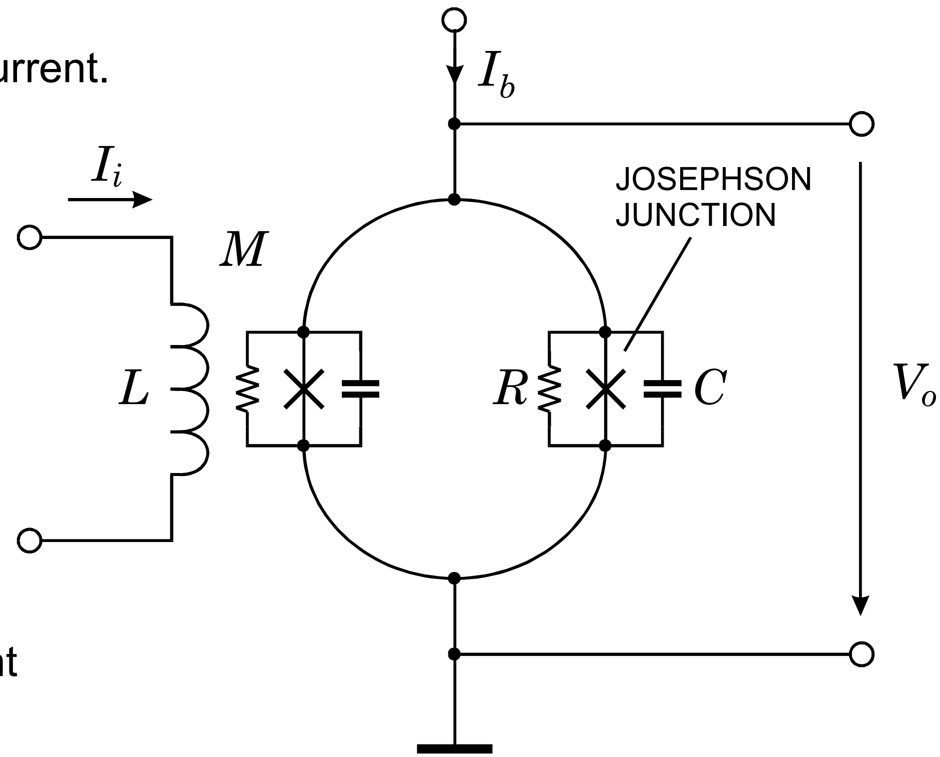
Two Josephson junctions connected in parallel to form superconducting ring:

Two key ingredients:

1. Phase between two tunneling currents in Josephson junction is determined by current.

2. Magnetic flux in superconducting loop is quantized:

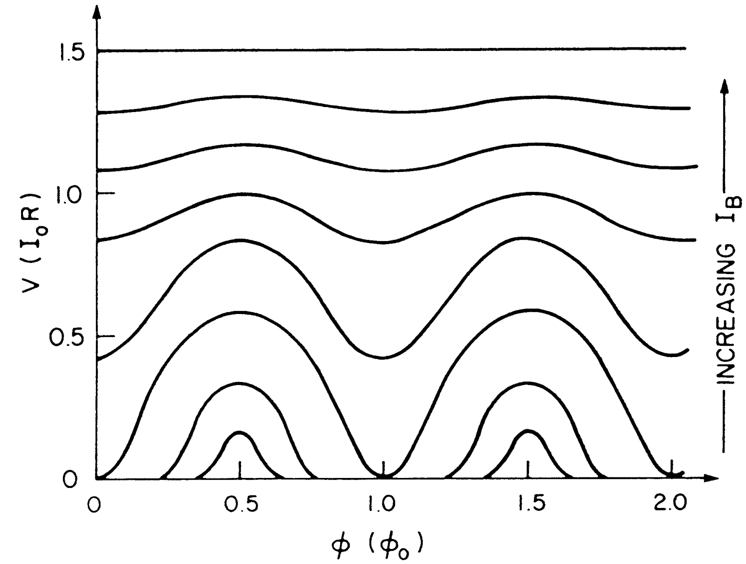
$$\Delta\Phi_0 = \frac{\pi\hbar c}{e} = 2.0678 \cdot 10^{-7}\ \text{gauss cm}^2$$
$$= 2.0678 \cdot 10^{-15}\ \text{Vs}$$




SQUID is biased by current $I_b$.

- Input signal is magnetic flux due to current through coupling coil $L$.
- Output is voltage $V_o$ .

## SQUID Feedback Amplifier




1. SQUIDs have periodic output

   Maximum signals must remain within monotonic range

   Dynamic range extended by

   SQUID array (100 SQUIDs in series) (allows small input inductance)

   Shunt feedback

2. Feedback must be active to maximum bias frequency (~MHz)

   ⇒ High loop gain-bandwidth product of 10s of MHz required

   ⇒ Limits wiring length to maintain phase margin for stability

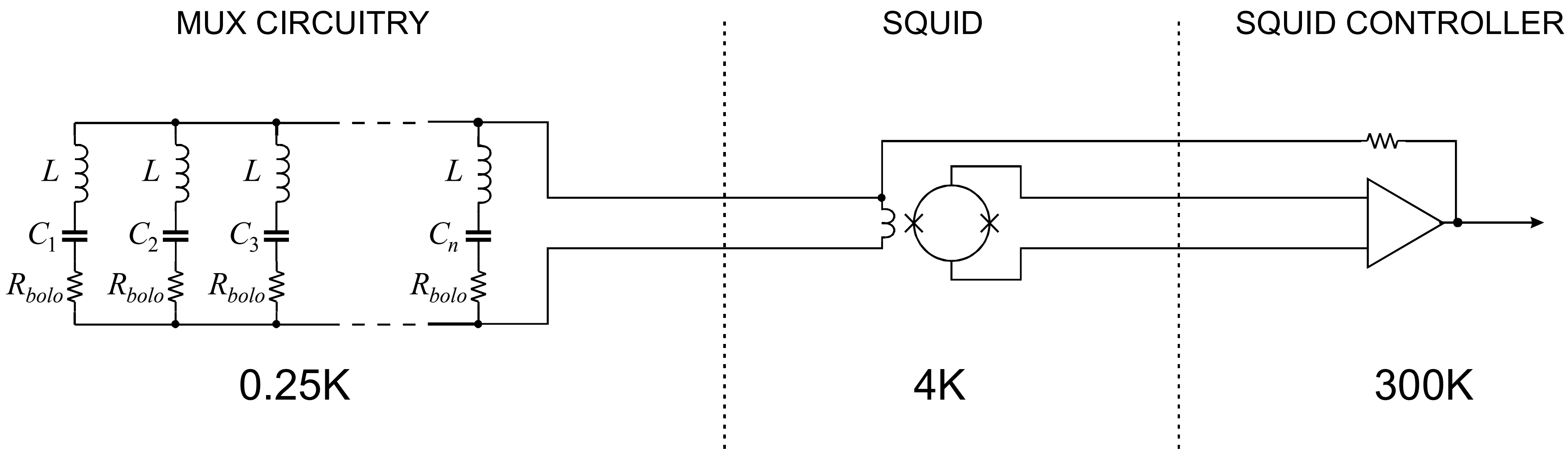
3. In-situ characterization of individual SQUIDs required to determine operating point.

   ⇒ Digitally controlled bias scan and bias point

4. SQUIDs extremely sensitive to high-frequency RF pickup

   ⇒ Digital crosstalk big problem as wide bandwidth connections are required to maintain phase shift in feedback loop.

# Layout of SQUID Feedback Loop

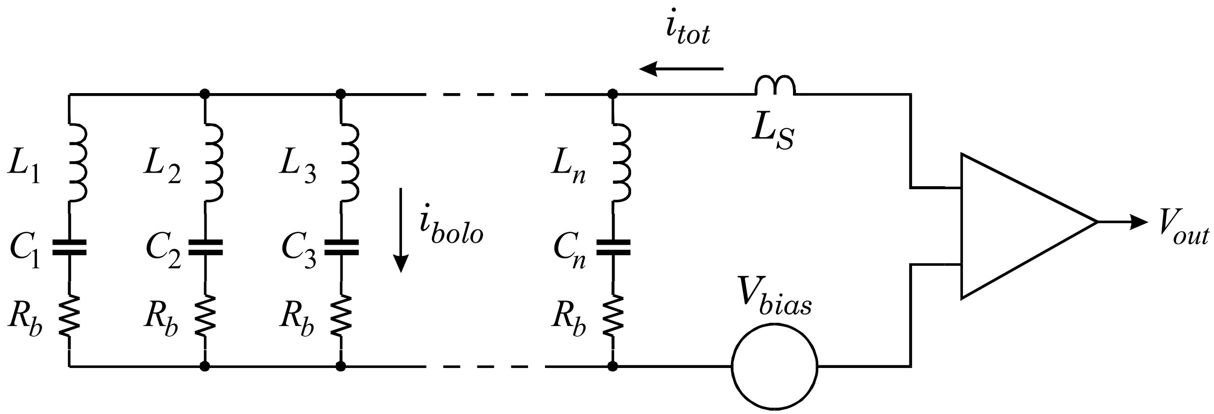



- Shunt feedback lowers input impedance
- Stability against self-oscillation requires control of

  1. Feedback Loop Gain
     Depends on impedance presented by MUX circuitry.
     Caution: textbooks commonly assume infinite source impedance
  2. Loop Phase shift
     Depends on cable length between SQUID and warm electronics.

# Parasitic Inductances and Capacitances

## 1. Series inductance in the wiring between the MUX and the SQUID

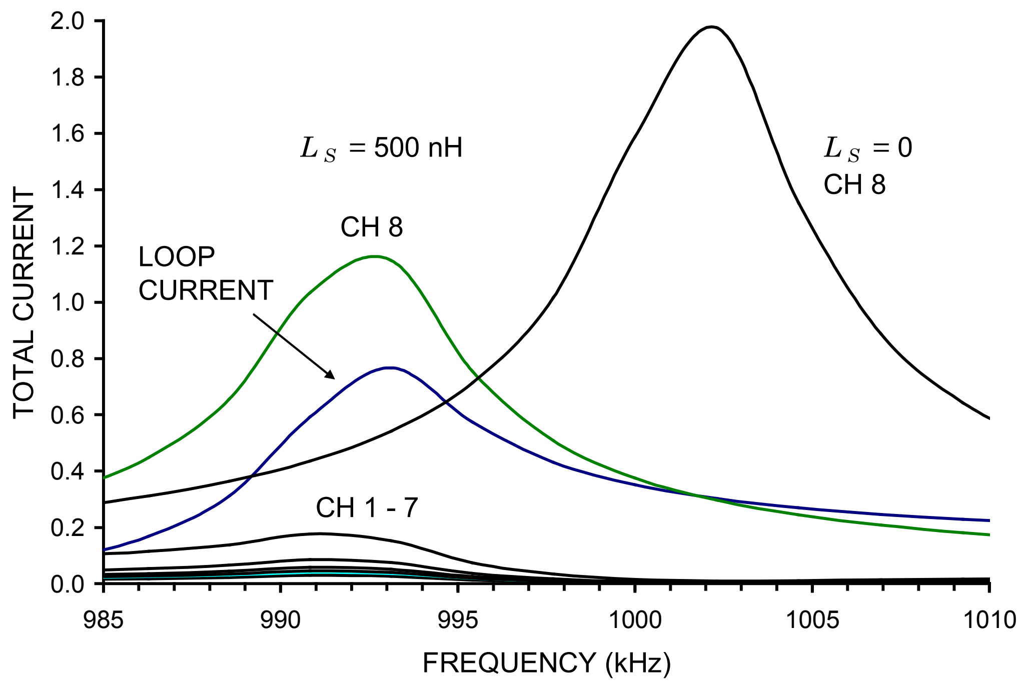



Series inductance introduces shift in current maximum between input loop $i_{tot}$ and bolometer current.

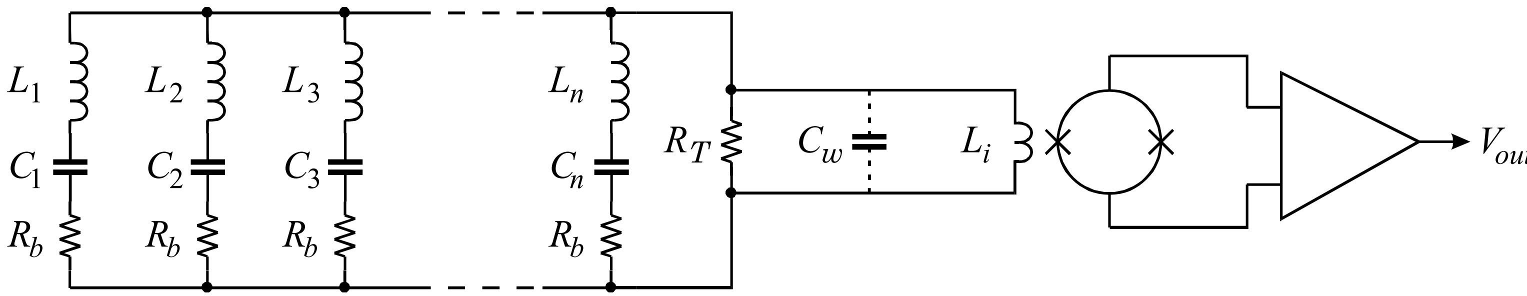
Special tuning procedure required:

Network analysis ⇒
Calculate freq offset

Series inductance also increases bias source impedance and reduces electrothermal loop gain.



## 2. Resonance formed by SQUID input inductance and wiring capacitance




Low-inductance wiring increases capacitance. Compromise required.

⇒ Resonance well within feedback loop gain-bandwidth product.

⇒ Damp resonance by termination resistor $R_T$ .

Constraint: Must be large compared to amplifier input impedance.

# 3. Parasitic Resonances

1. Additional resonances due to distributed capacitance of spiral inductors in MUX circuit. (10 – 20 MHz)

2. Multiple series resonant circuits connected in parallel also form parallel resonances.

   When a bolometer goes superconducting, the associated parallel resonance assumes such a high $Q$ that the resonant impedance and phase shift lead to self-oscillation at a frequency close to the series resonance.

   $\Rightarrow$ Requires

   - uniformity of superconducting transition temperatures
   - stable control of bias levels

   Can be suppressed by damping resistor $R_T$.

Parasitic resonances lead to self-oscillation because SQUIDs require a high bandwidth feedback loop to

- extend SQUID's maximum signal capability over full range of bias frequencies,
- reduce SQUID's non-linearity over full range of bias frequencies (intermodulation of bias carriers generates spurious signals)

## Why eliminate SQUIDs?

- Suppression of RF pickup/digital crosstalk to SQUID major challenge in prototyping.
- Regular retuning required (added electronic functions required).
- Changes in temperature cause significant changes in SQUID characteristics.
- Limited signal capability requires feedback at MUX frequencies (~MHz) well beyond signal bandwidth (~kHz).
- Eliminating SQUIDs would greatly simplify design and operation.

## Assessment of amplifier noise temperature points towards alternatives.

The noise temperature is the temperature for which the thermal noise of the source resistance is equal to the amplifier noise.

$$T_N = \frac{e_n i_n}{2k},$$

where $e_n$ and $i_n$ are the amplifier's input voltage and current noise densities

## 1. SQUIDs

The noise temperature of optimized SQUIDs in the He temperature range is typically

$$T_N \approx \frac{f}{10^8 \text{ [Hz/K]}}$$

so at 1 MHz $T_N \approx$ 10 mK.

## 2. Bipolar Transistor

$$T_N = \frac{T}{\sqrt{\beta_{DC}}}$$

excludes room temperature operation

BJTs not functional at required temperature

## 3. JFETs and MOSFETs

At the relevant temperatures the channel noise capacitively coupled to the gate dominates the input current noise.

$$T_N \approx T\omega \frac{g_m}{I_D} \frac{L^2}{\mu}$$

MOSFETs provide

1. Low temperature operation ($T =$ 4K)
2. Small channel lengths $L$
3. High $g_m / I_D$ (reduces power requirements)

Practical MOSFETs should provide $T_N <$ 50 mK at 1 MHz and room temperature.

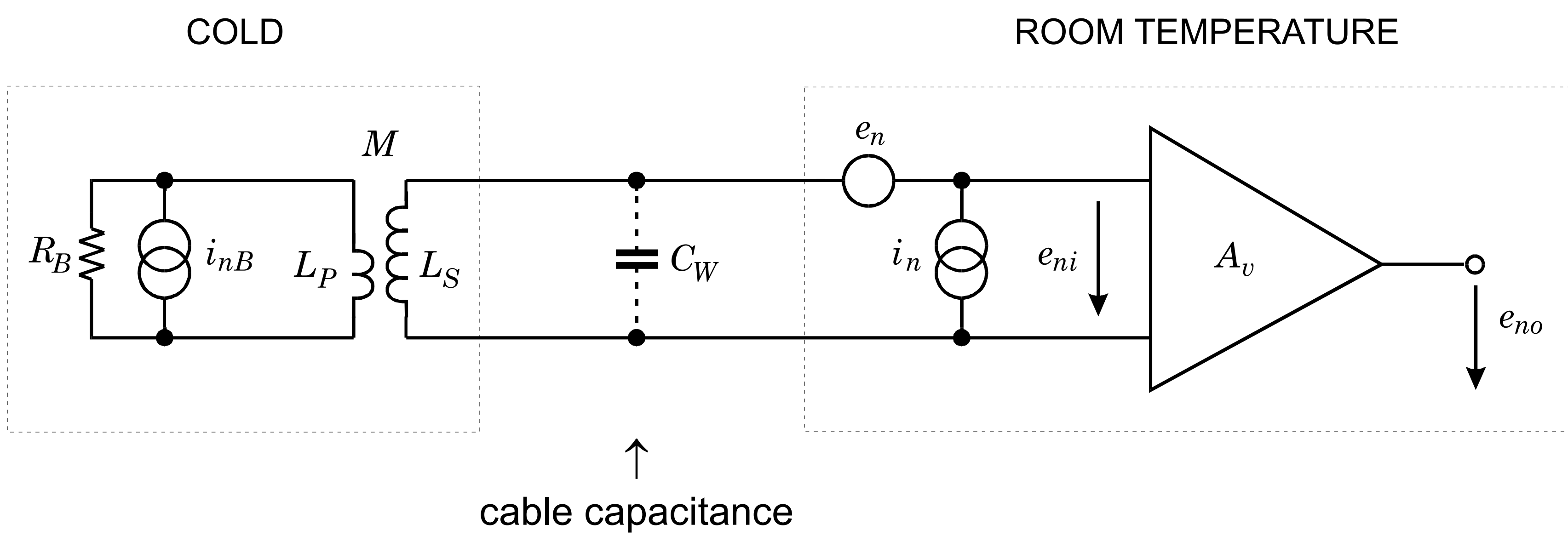
However ...

MOSFET noise matching requires high source resistance (voltage signal)

$\Rightarrow$ Input transformer required

Would this configuration work?

Superconducting transformer on 4K stage to reduce wire resistance (thermal noise).



Bolometer noise at transformer secondary: $e_{niB} = \mathbf{i}\omega M i_{nB}$

Must override amplifier noise voltage $e_{niB} > e_n$, so $M > \dfrac{e_n}{\omega i_{nB}}$

Typical values: $\omega = 10^7$

$e_n = 1 \text{ nV}/\sqrt{\text{Hz}}$

$i_{nB} = 10 \text{ pA}/\sqrt{\text{Hz}}$ $\Rightarrow$ $M > 10\ \mu\text{H}$

Primary impedance $X_P = \omega L_P$ must be much smaller (<10%) than the bolometer resistance to maintain voltage bias.

$R_B = 1\ \Omega$ $\Rightarrow$ primary inductance $L_P \le 10$ nH

Since $M = \sqrt{L_P L_S}$, secondary inductance $L_S > 10$ mH

Maximum frequency is limited by the resonance formed by wiring capacitance and $L_S$.

Assume wiring capacitance of 25 pF (50 cm from 0.25K to 300K): resonance at 300 kHz

Increase frequency: $\omega = 10^8$ $\Rightarrow$ primary inductance $L_P \le 1$ nH

$M > 1\ \mu\text{H}$ secondary inductance $L_S > 1$ mH

mH inductors not compatible with monolithic integration (spiral inductors)
+ self-resonances in MHz regime.

First Pass Summary

Increasing frequency reduces transformer size

Reduce capacitance at transformer secondary

$\Rightarrow$ place transformer adjacent to amplifier

$\Rightarrow$ minimum capacitance set by amplifier (MOSFET) input capacitance

$\Rightarrow$ Superconducting transformer to reduce resistance (thermal noise)

$\Rightarrow$ Transformer and MOSFET at 4K

Practical monolithic transformers: Spiral inductors with $L_S < 100\ \mu\text{H}$

Desirable to reduce secondary inductance to increase resonant freq.

Mutual inductance can be maintained by increasing primary inductance.

$$M = \sqrt{L_P L_S}$$

Can constant voltage bias be maintained with

transformer's primary impedance > bolometer resistance?

# External Electrothermal Feedback

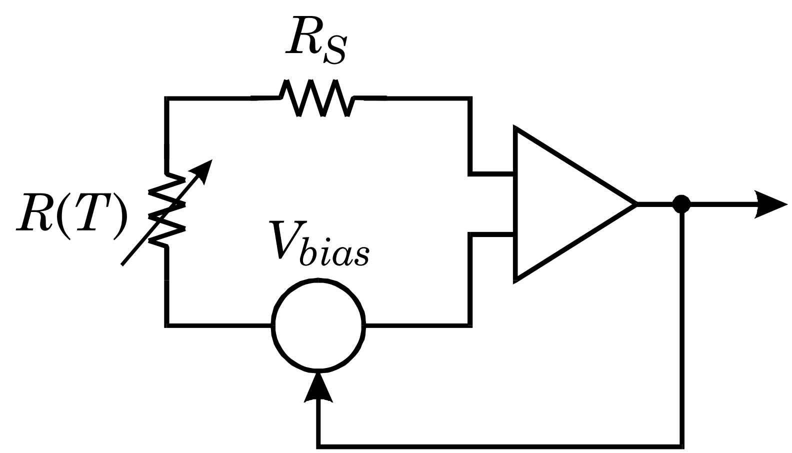
For constant voltage bias the change in temperature vs. signal power

$$\frac{\Delta T}{\Delta P_S} = \frac{\dfrac{1}{G + \mathbf{i}\omega C}}{1 - \dfrac{V^2}{G + \mathbf{i}\omega C}\dfrac{dG_B}{dT}} = \frac{A_0}{1 - A_L}$$

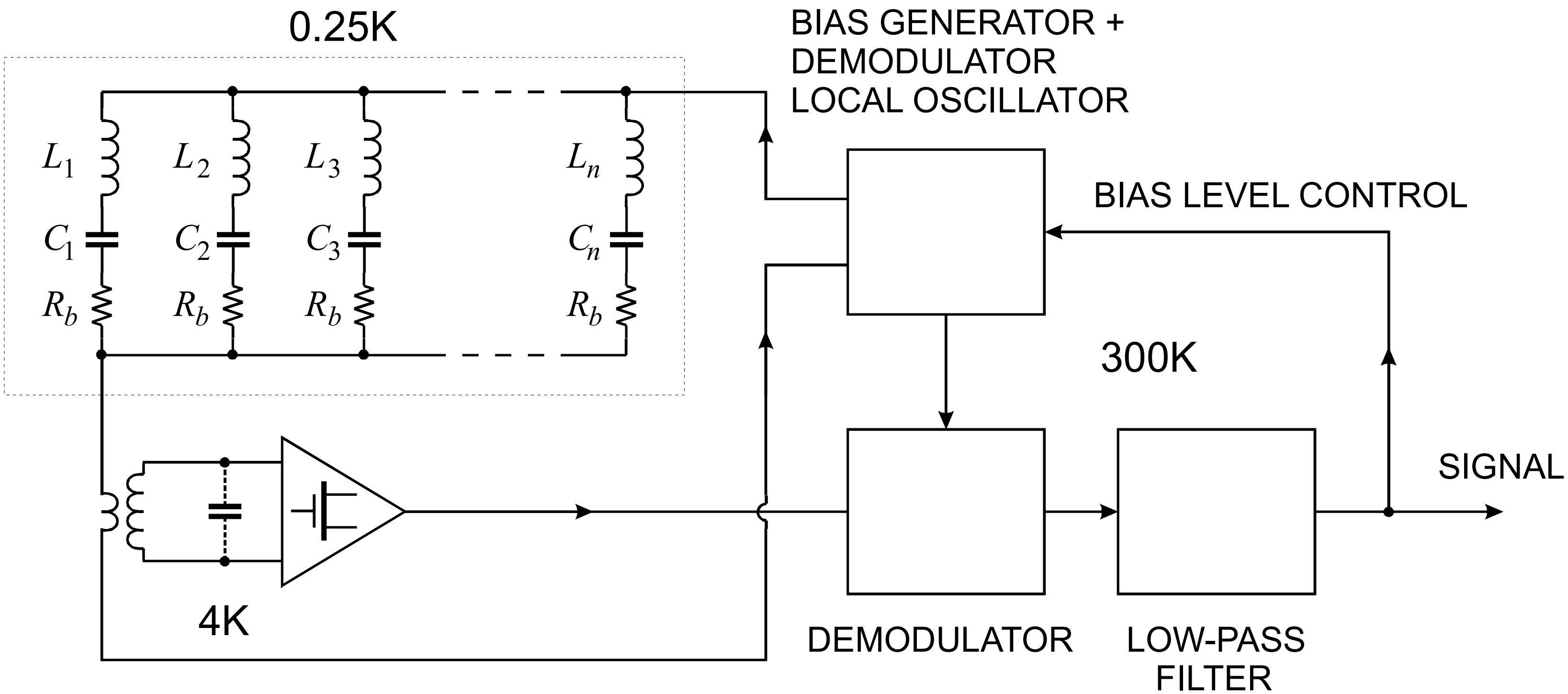
as in a feedback amplifier ( $A_0 =$ amplifier open loop gain, $A_L =$ loop gain).

Instead of controlling the bolometer's heat flow only by the thermal link, the bias power can be electronically controlled.

Even with a significant series resistance in the bias loop, this allows adjustment of the bias to maintain constant voltage across the bolometer.



# Implementation with digital demodulator

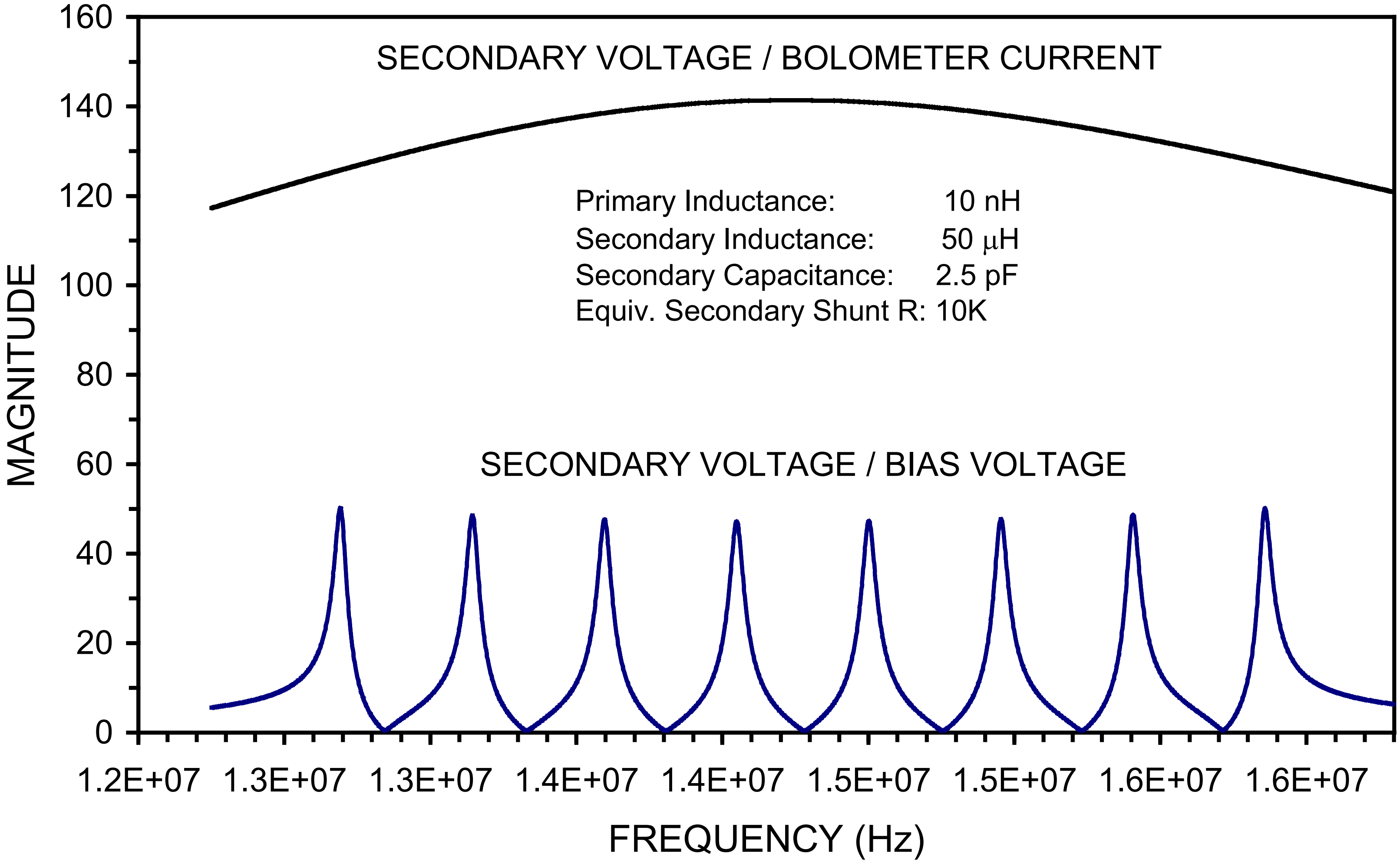



The low-pass filter suppresses components from the neighbor channels.

It adds a pole in addition to the $LC$ filter in each bolometer leg, so its cutoff must be sufficiently high.

This places an additional limit on the channel spacing, but higher bias frequencies increase frequency range for MUXing.

# Simulated MOSFET MUX Performance:
## 3.2 MHz BW (<10% noise degradation) allows 32 ch with 100 kHz spacing




MOSFET amplifier with local feedback to reduce input resistance.
Alternative configurations provide greater bandwidth with add'l design constraints.

## Microcalorimeter Summary

- Large-scale microcalorimeter arrays increase efficiency and rate capability.
- Monolithic integration and cryogenic multiplexing make this practical.
- Robust readout systems essential – eliminate SQUIDs.
- External electrothermal feedback loop allows practical monolithically integrated transformers.
- MOSFETs on high-resistivity silicon fabricated at LBNL have demonstrated improved noise and low power at 4K.
- In contrast to SQUIDs, MOSFETs provide reproducible operation with well-controlled operating points.
- Operation in 10 – 30 MHz regime reduces size of inductors and capacitors.
- Detailed simulations indicate that this could indeed work,
  but the devil is in the details – needs more effort!
- No funding at LBNL for further development
  (“no overlap” with DOE Office of HEP program)

  Feel free to follow up!

# Conclusion:
# Novel developments require understanding of all relevant components and their interactions.

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*In engineering it is legitimate to do the right thing for the wrong reasons.*

*Functionality Counts!*

Works for established techniques

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Works for established techniques

*In science it is legitimate to do the wrong thing for the right reasons.*

*Understanding Counts!*

Obviously we'd like to combine the best of both.

For new concepts and unexplored regimes
we must approach "engineering" topics as scientists.

# Challenges

- No “silver bullets”!
- Systems design is crucial in advanced detectors.
- Many details interact, even in conceptually simple designs.
- It is essential to understand key aspects and their interactions.
- Key front-end issues don’t require detailed electronics knowledge of circuits, but understanding of basic underlying physics is essential.
- Broad physics education required.

  U.S. physics departments commonly do not recognize the scientific aspects of instrumentation R&D.

  Many developments are essentially technician efforts, so the simplistic perspective doesn’t accept that novel developments require a scientific approach.

  Emphasis on theory and mathematical techniques neglects understanding of physics and how to apply it to undefined multidimensional problems.

- Opportunities for other countries to do much better!