Kinetic inductance retectors for future optical instruments

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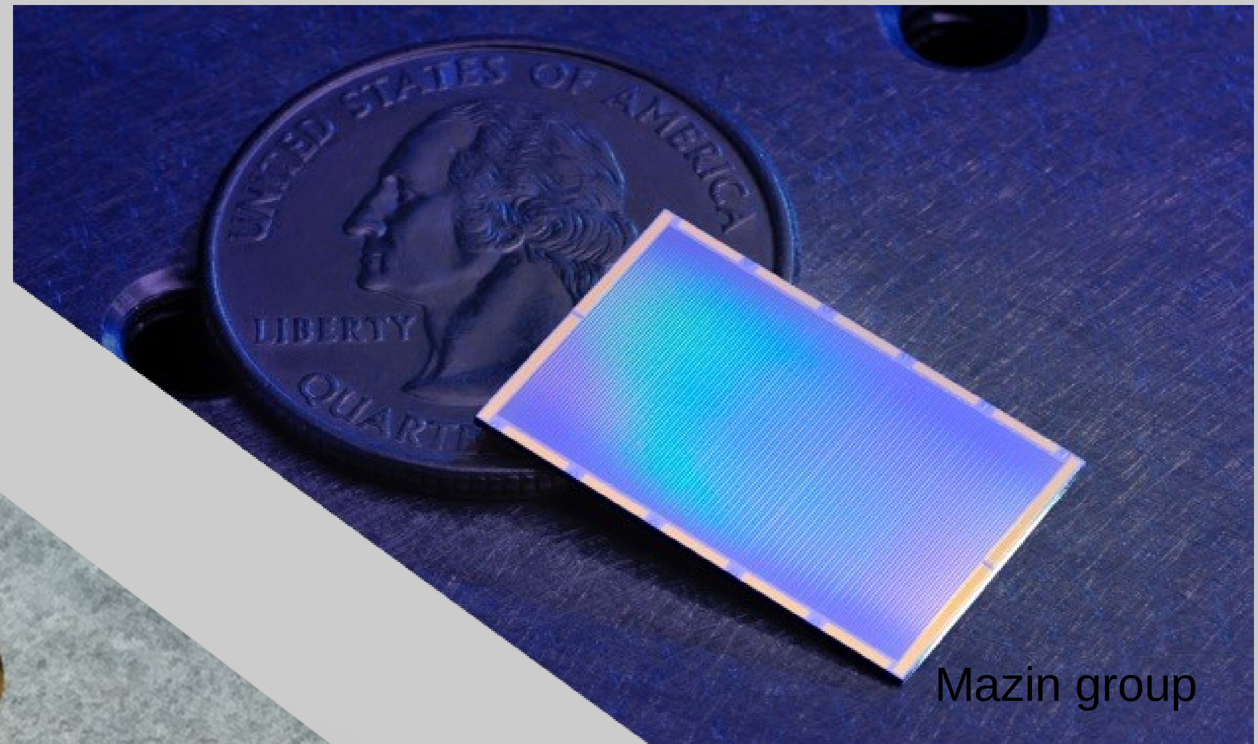
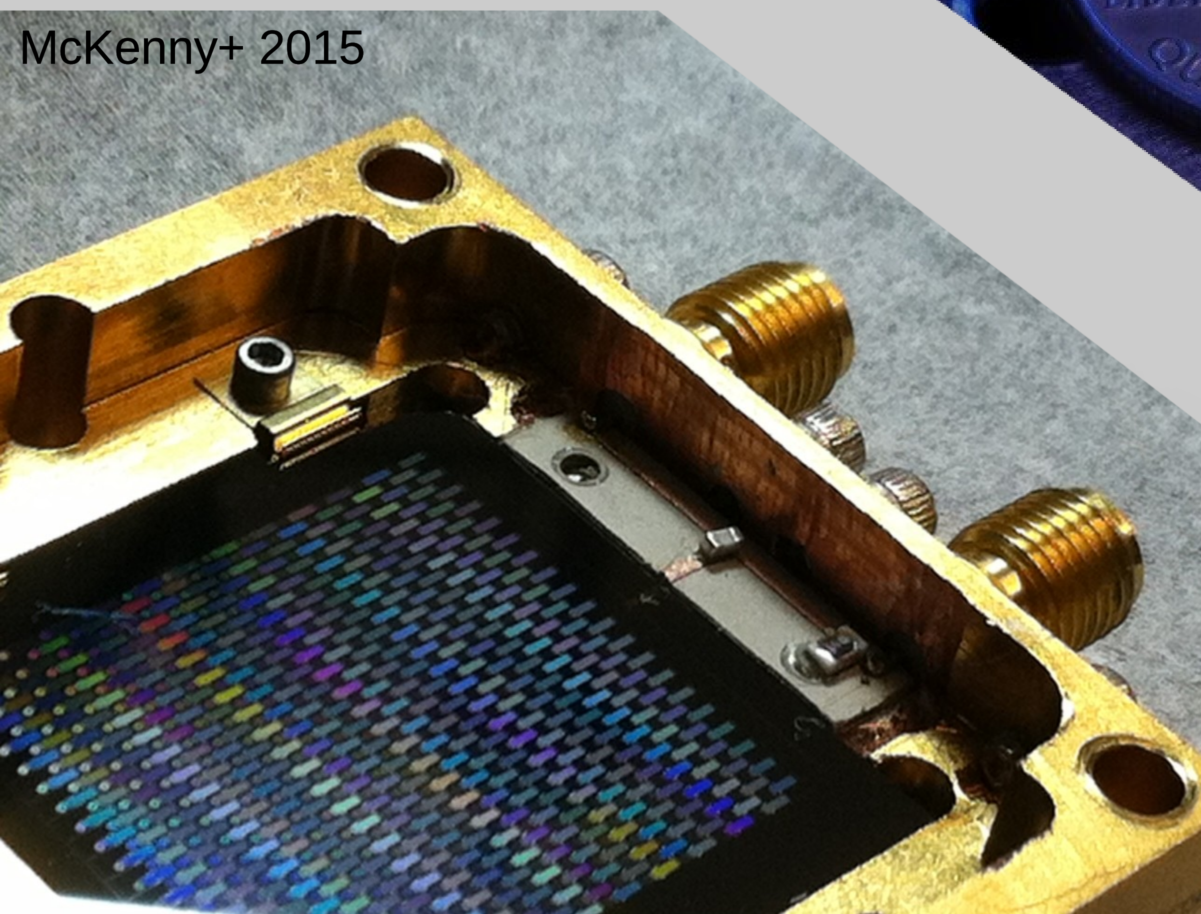


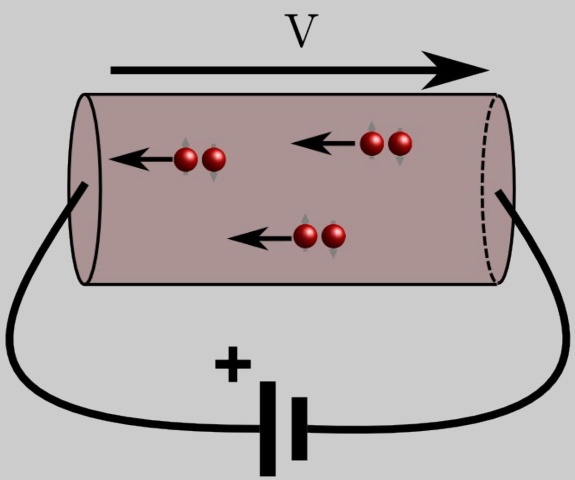


Next Gen LSST workshop

2019-04-11

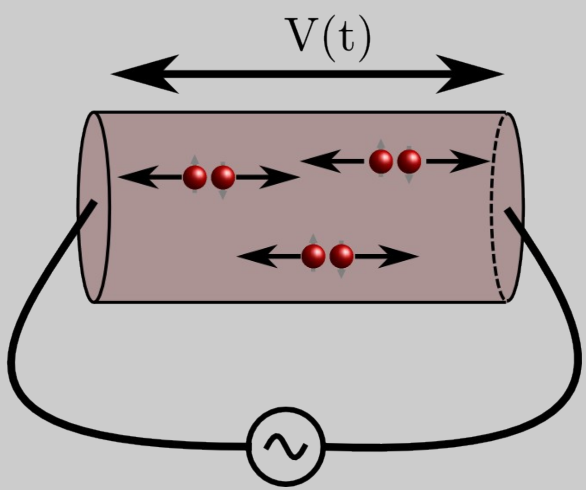
The kinetic inductance effect

The DC case:
- Cooper pairs carry charge without scattering.
- Internal E fields are canceled.



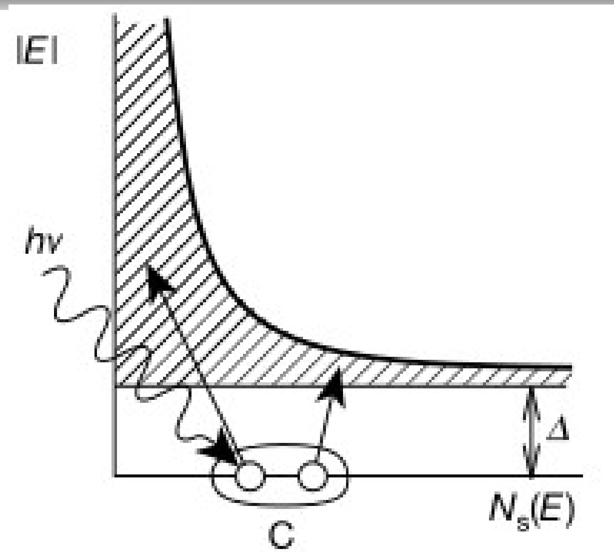
The AC case:
- Cooper pairs have momentum.
- Acceleration leads to a phase shift between I and V.
- This acts like an inductance!

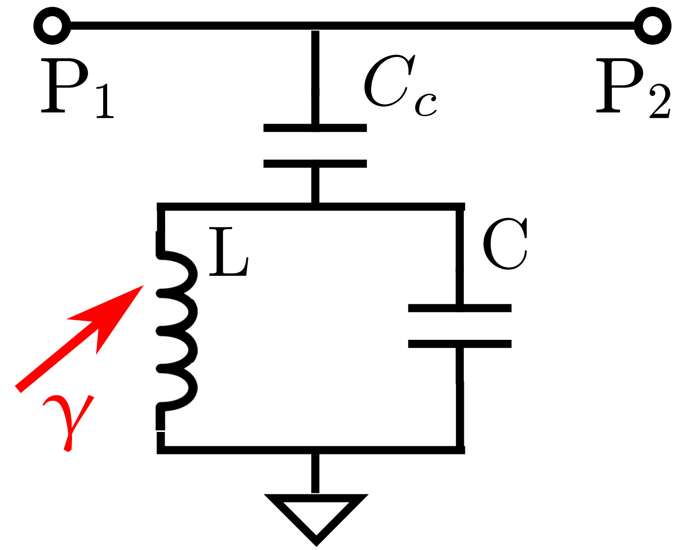
At low temperature:
- To 1st order, L_k is constant.
- To 2nd order, L_k varies linearly with the number of pairs.

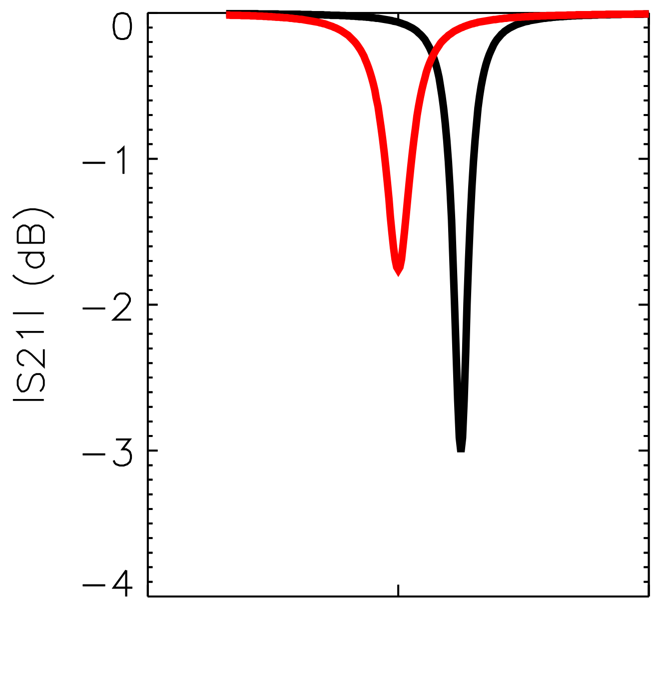


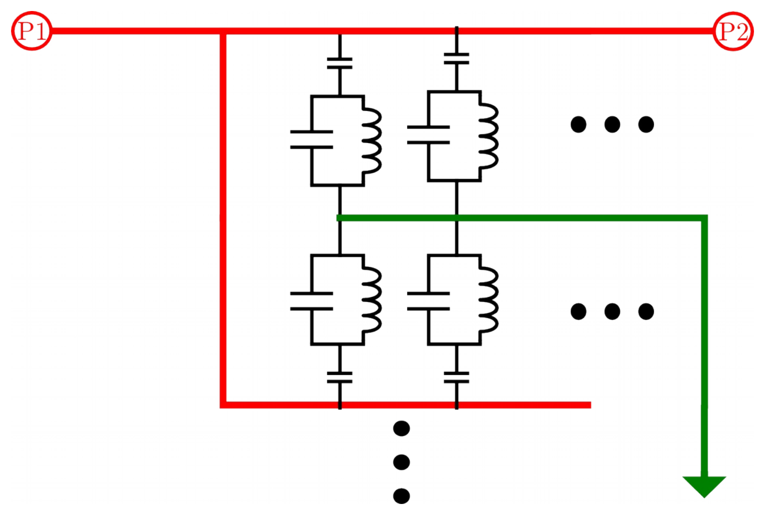
Phase shift leads to E field inside the conductor:
- Non-zero resistance from quasiparticle currents
- R also varies linearly with number of pairs

The kinetic inductance detector: photon absorption breaks Cooper pairs, causes a frequency shift in a microwave resonator.



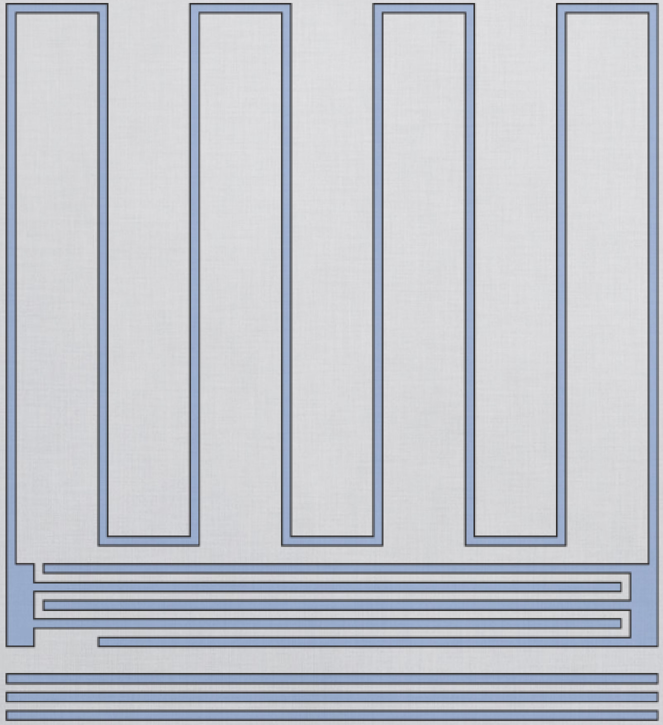


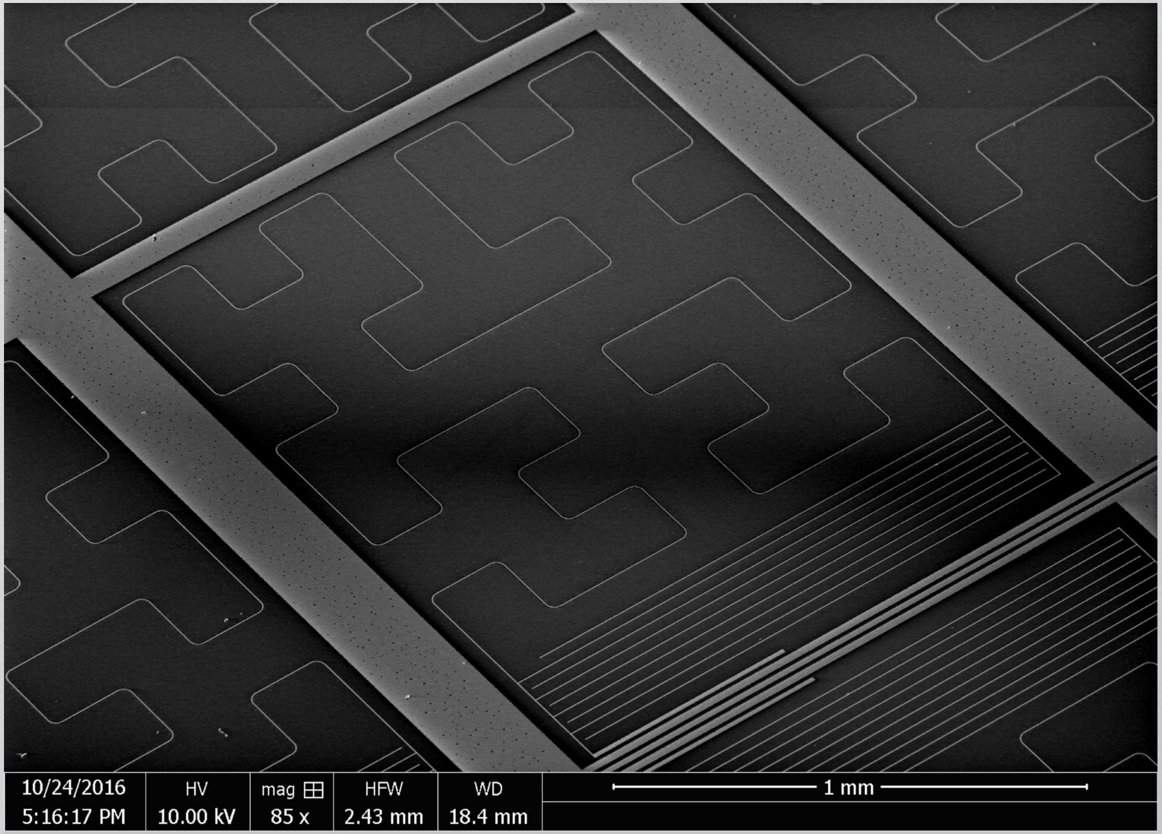




Some figures: Zmuidzinas group

Direct-absorbing lumped-element KID (LeKID): inter-digitated capacitor and meandered inductor





Resonator-bolometer or thermal KID (tKID): measure thermal pair-breaking

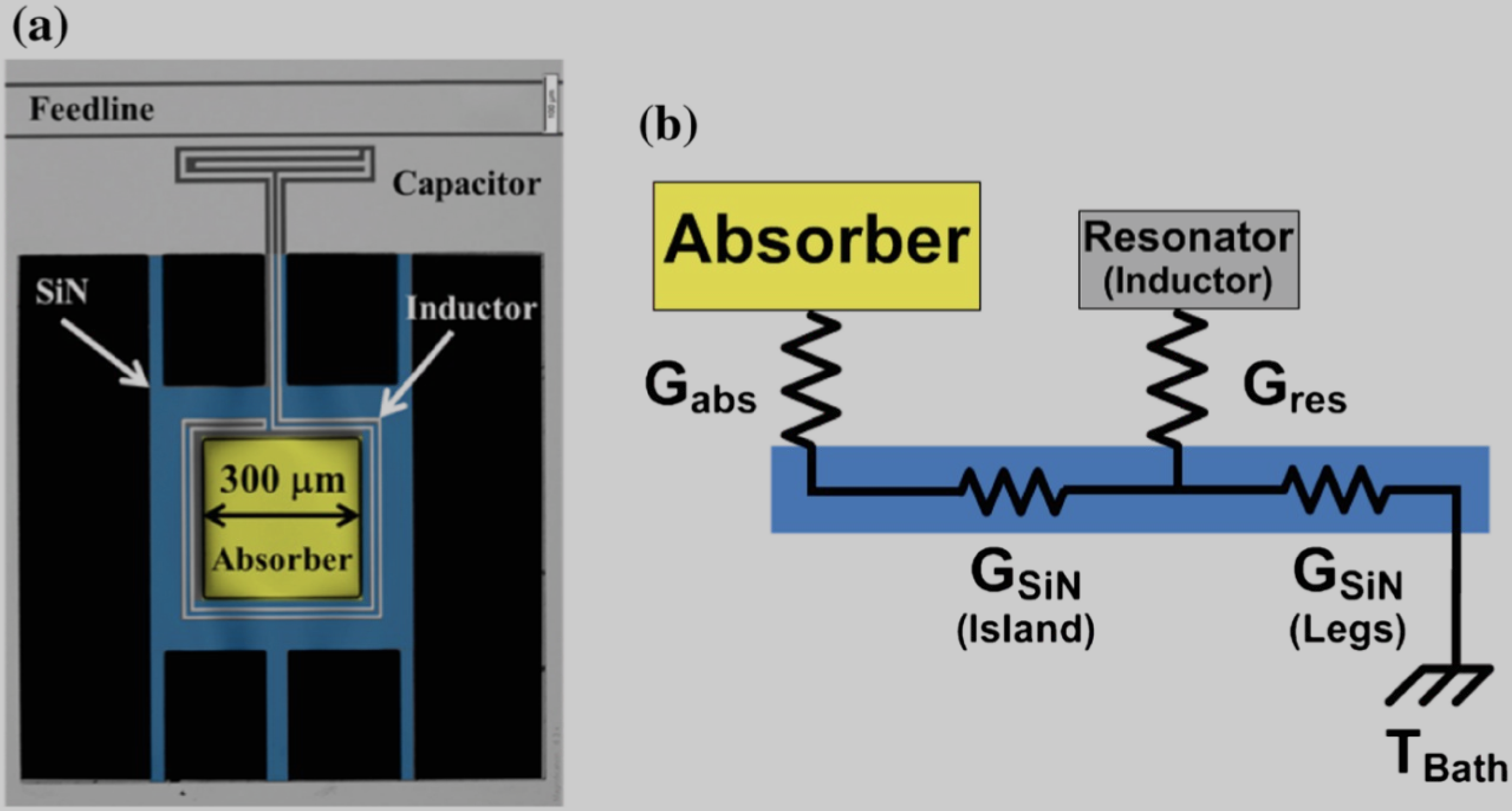
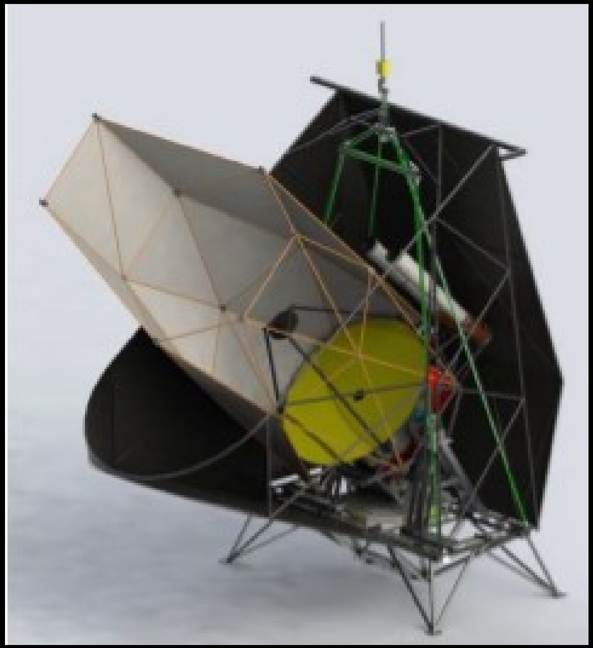
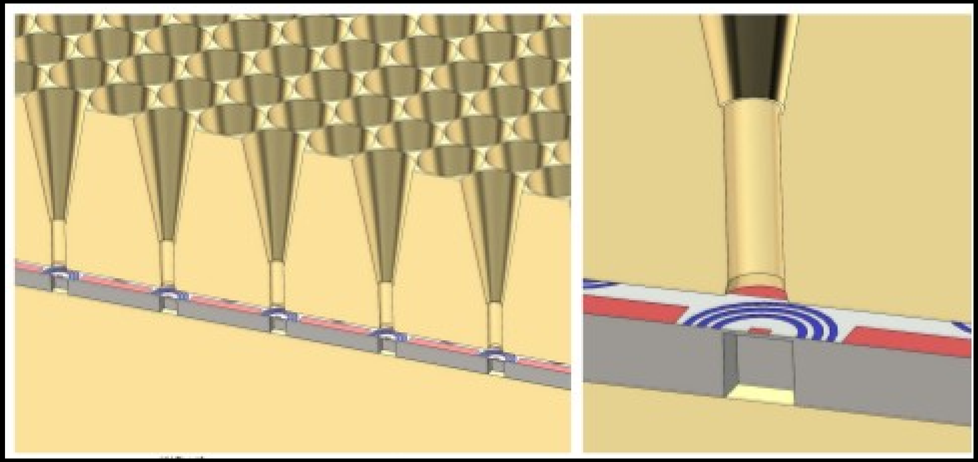


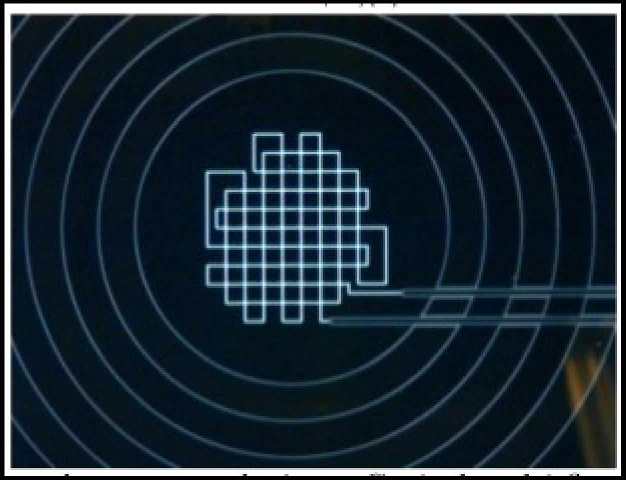
Image from Micelli group, ANL

STARFIRE: the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration

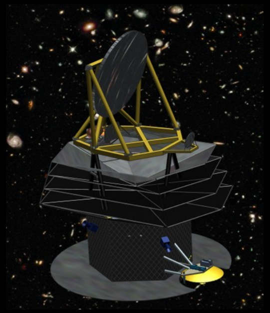
- Baloon, based on BLAST gondola
- IFU grating spectrometer
- 240 to 420 micron
- Direct-absorber KID detectors





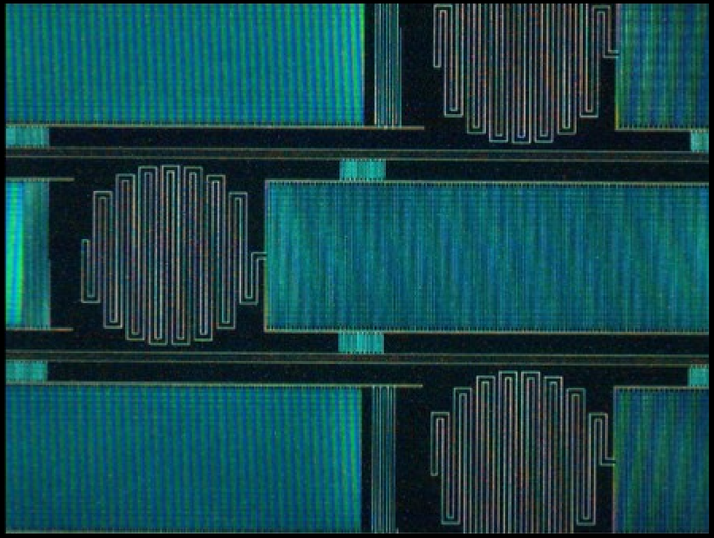


Galaxy Evolution Probe KIDs

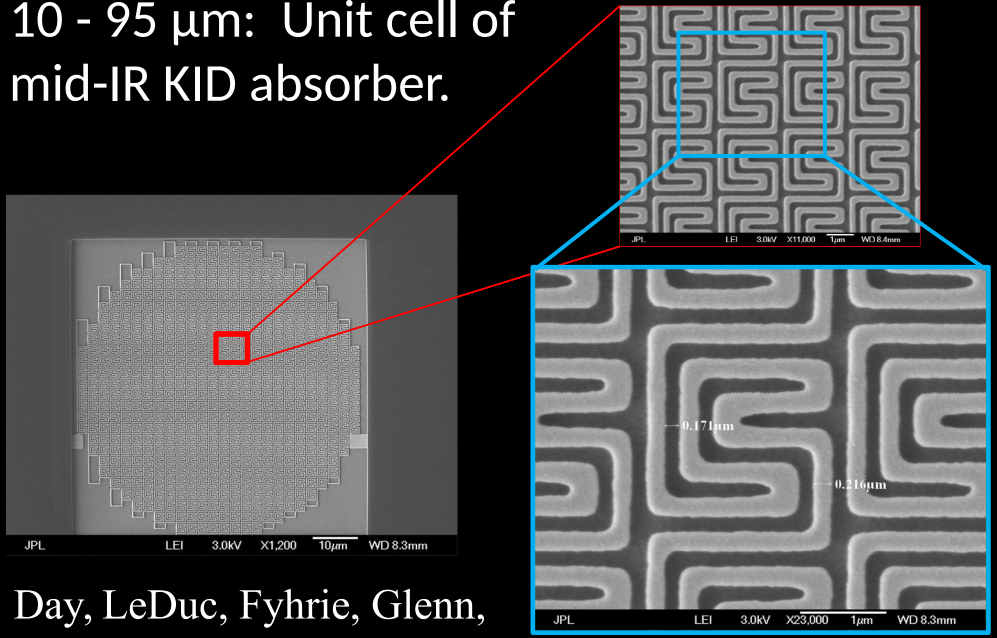


- 50,000 KIDs split evenly between imager and spectrometer
- Why baseline KIDs?
  - Simple architecture, simple cryogenic readout, one focal plane technology for all wavelengths.

100 - 400 µm: MAKO type LEKID



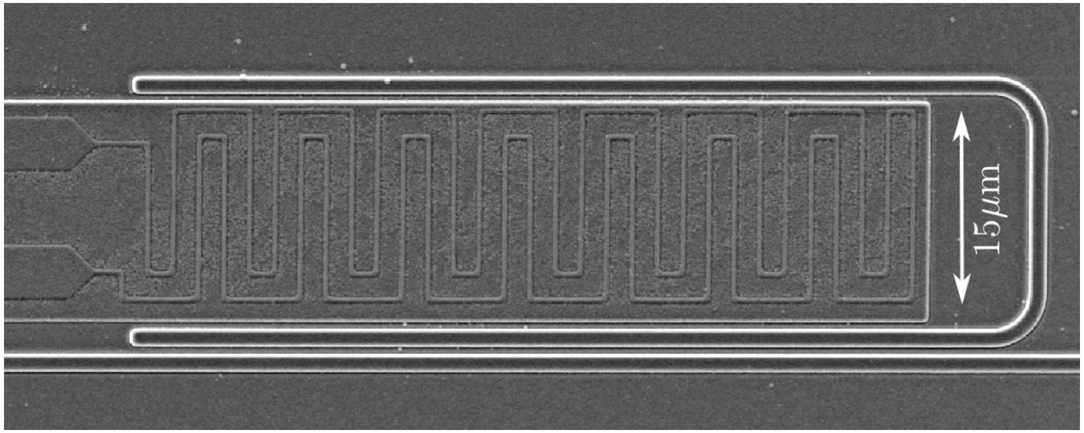
10 - 95 µm: Unit cell of mid-IR KID absorber.

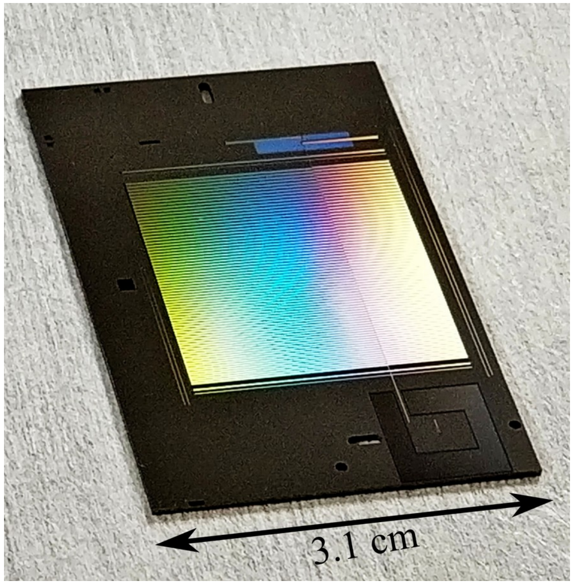


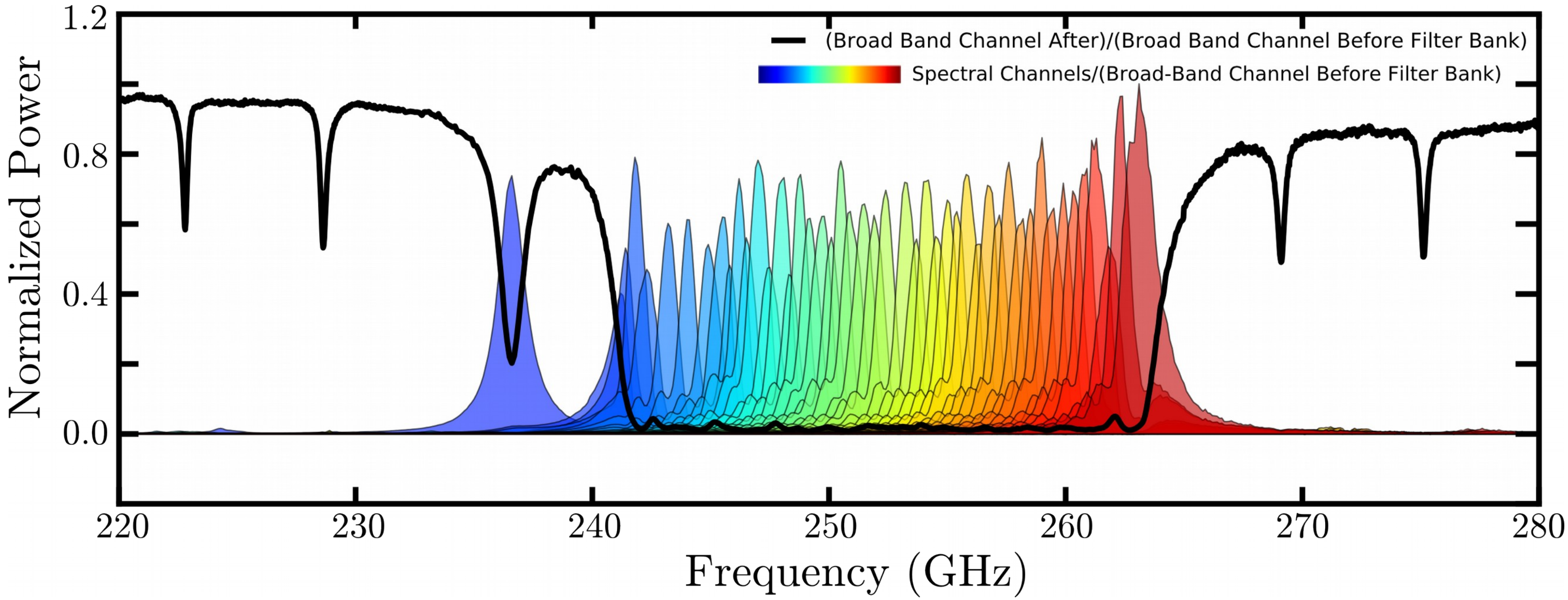
Day, LeDuc, Fyhrie, Glenn, Perido, Zmuidzinas

Technology development plan: MIR KIDs (10 – 100 µm), readout

SuperSpec: an on-chip, R=300 spectrometer covering the 1 mm atmospheric band







Optical MKIDs projects

Mazin (UCSB) group, with FNAL collaborators:

ARCONS:
    2 kpixel demonstration

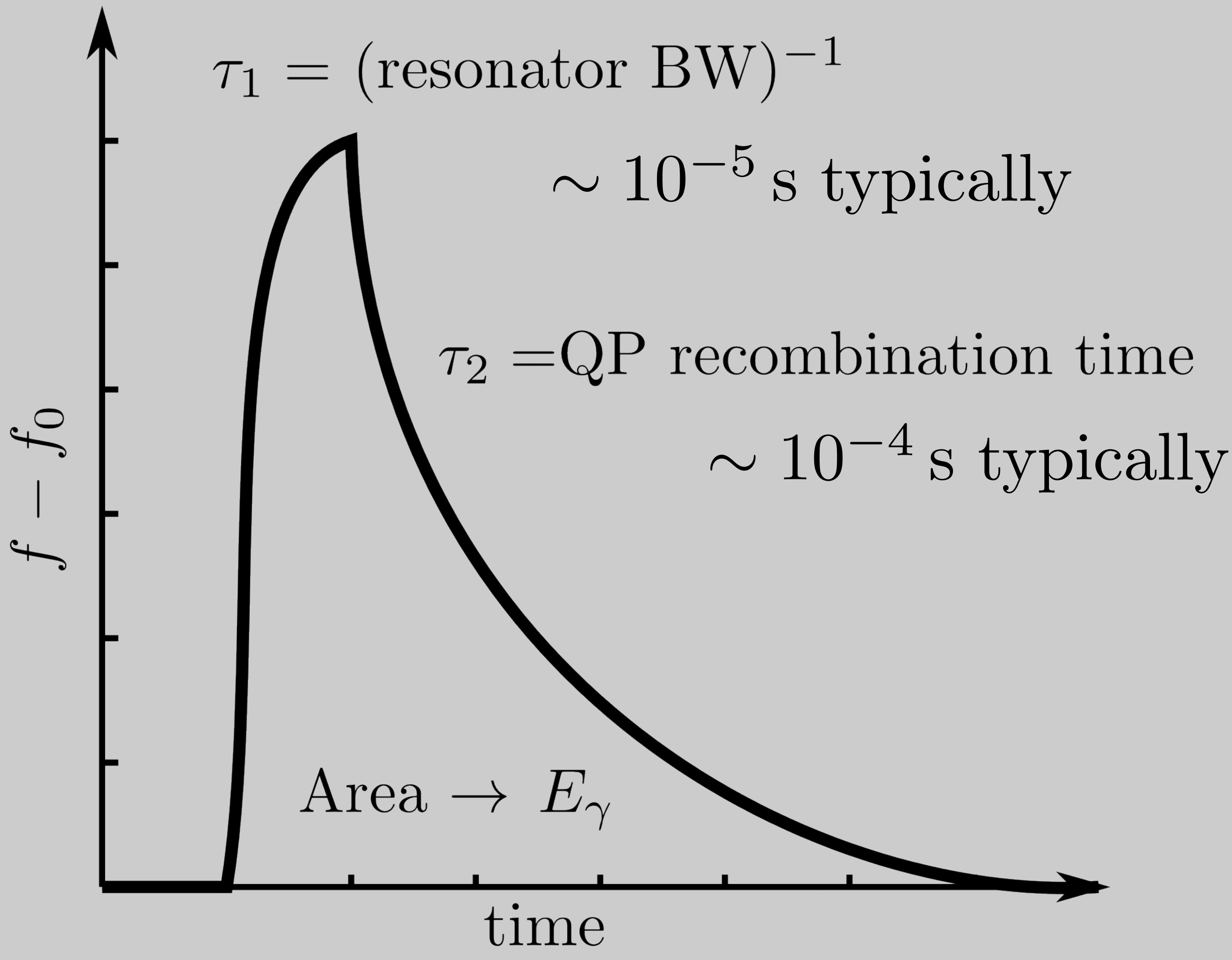
DARKNESS:
    800-1400nm energy resolving camera for speckle-photometry planet hunting

MEC:
    R~10 IFU for Subaru

Future instruments: KRAKENS, Picture-C

More details on optical projects at the end of the talk.

KIDs as single photon detectors



Ultimate resolving powers and Fano factors

In Silicon, the energy gap is around 1.1 eV → an optical photon generates a few quasiparticles.

In a 1K superconductor, the gap is 3e-4 eV → an optical photon generates hundreds of qps.

How well can you measure the energy?

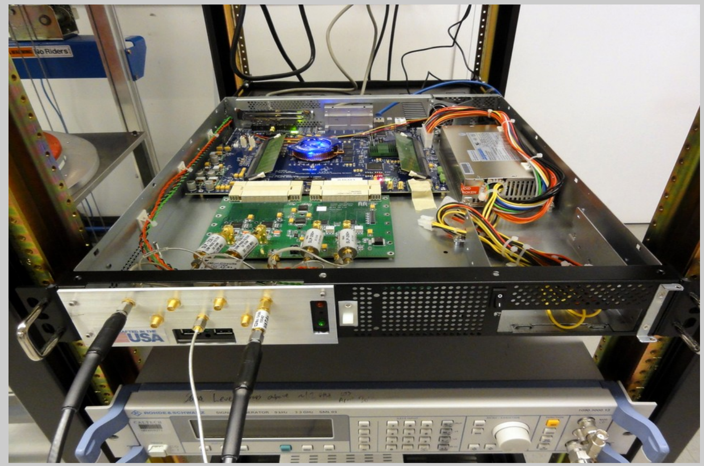
Naive approach: $N/\sqrt{N} \sim 1000$

Less naive approach: $2.35\ \sqrt{F_w/E} \sim 200$

Even less naive approach: today, 16. Eventually, 50.

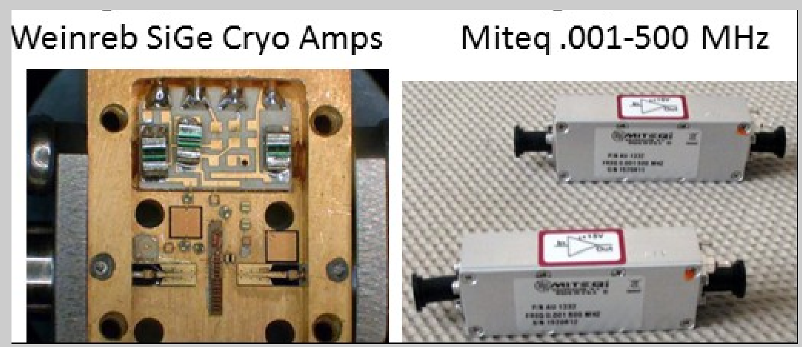
A complete system:

Sub-K fridge with
microwave coax



CASPER-ROACH
open-source
FPGA board

Low noise cryogenic
amplifiers

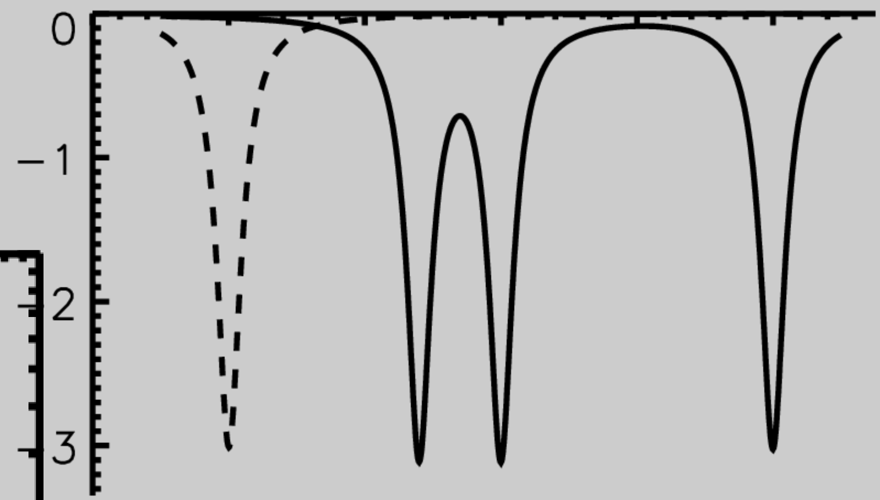


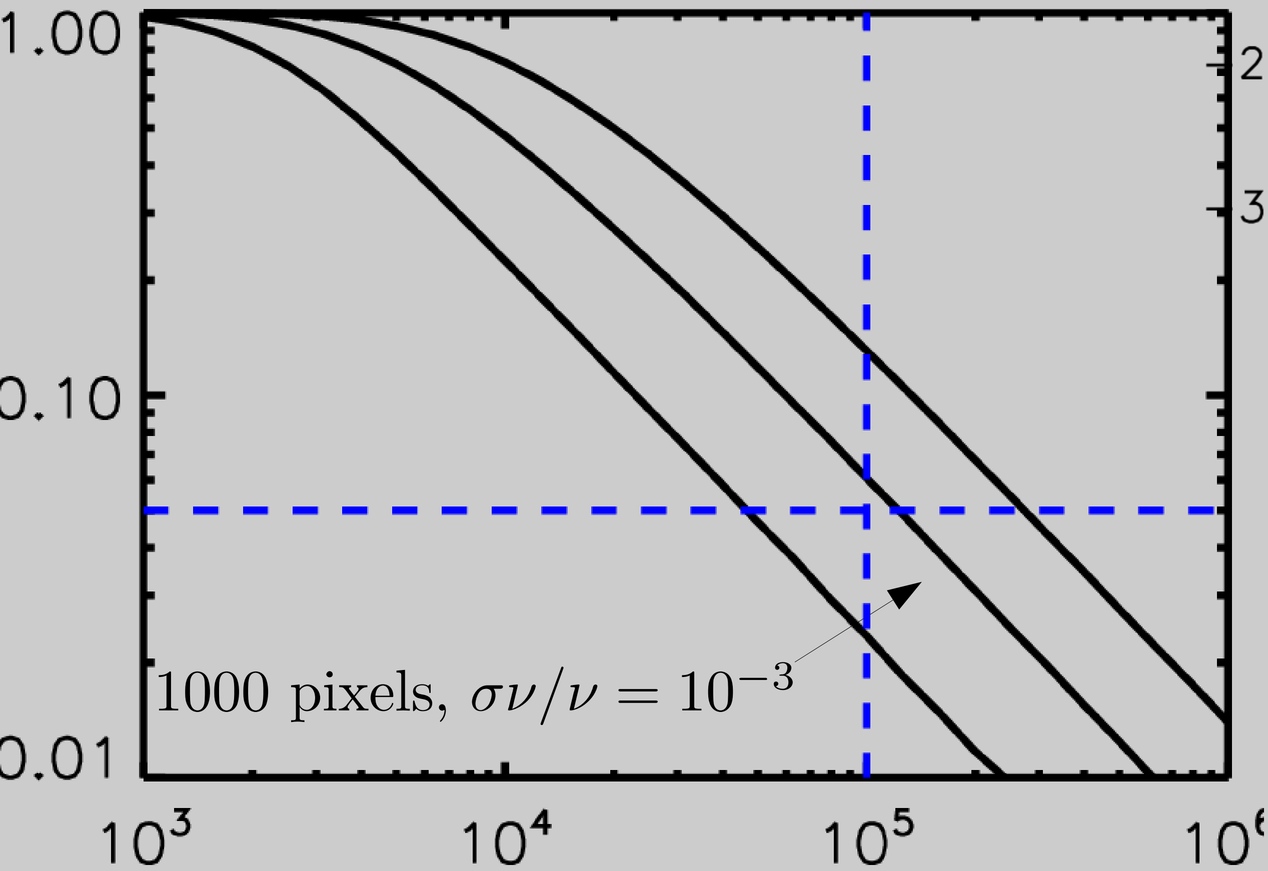
<u>Readout:</u> Today, $10/pixel with off-the-shelf hardware
→ $1/pixel with custom boards and large orders

Multiplexing density / yield trade off

MUX density dominated by resonator collisions

Higher Q, better uniformity → more channels





$$f_i = f_0 x^i + \delta_i \qquad \sigma = \sqrt{\langle \frac{\delta_i}{f_i} \rangle}$$

$$\text{Collision} \equiv f_i - f_j \leq 5 Q_i f_i$$

Figure based on Zmuidzinas internal memo

Fundamental sensitivity limits

$$\mathrm{NEP}^2 =$$

$$(\text{photon Poisson})^2 + (\text{photon Bose})^2$$

$$+(\text{recombination noise})^2$$

$$+1/R \cdot (\text{amplifier noise})^2$$

$$+1/R \cdot (\text{TLS Noise})^2$$

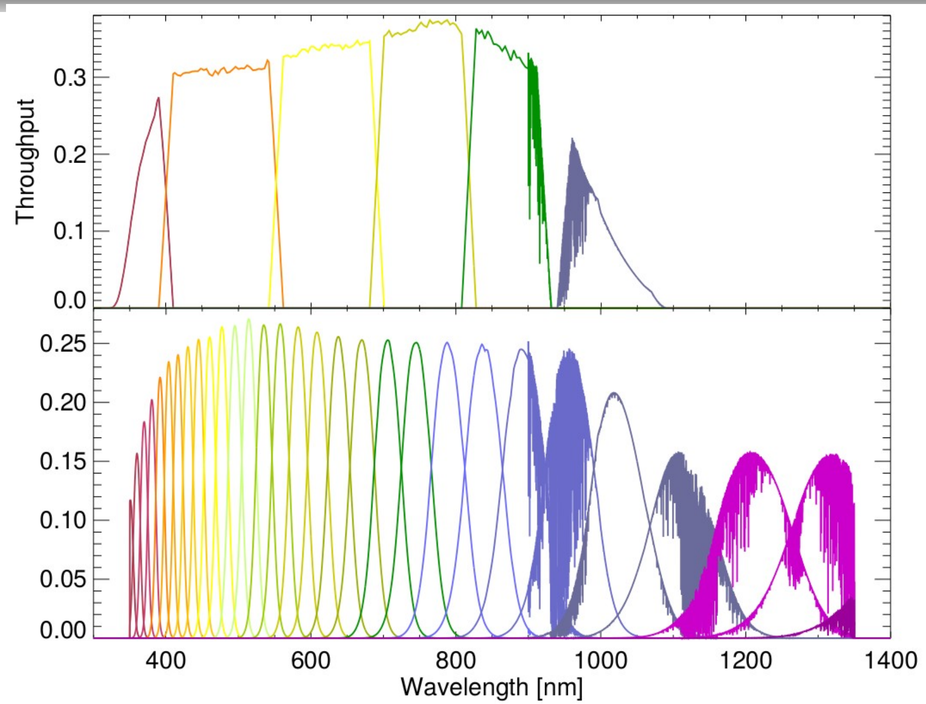
$$+\ (\text{small terms})$$

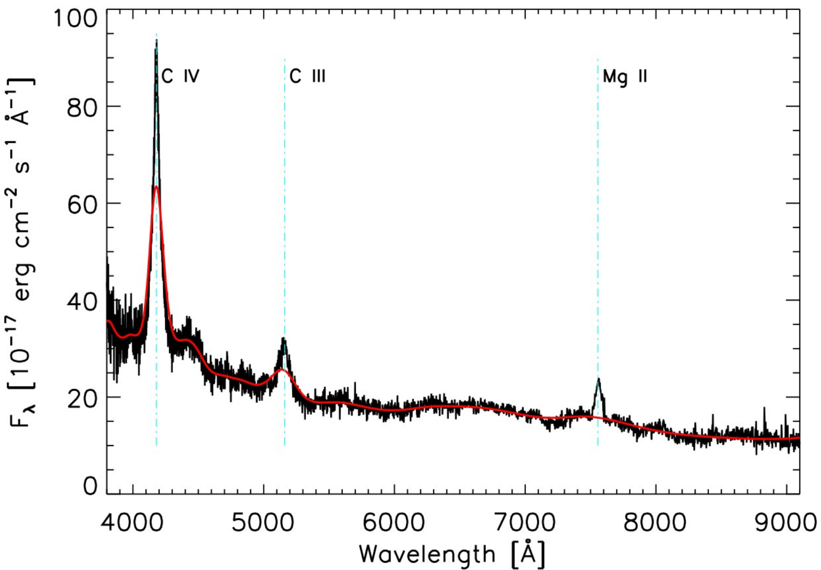
Background limit for all detectors

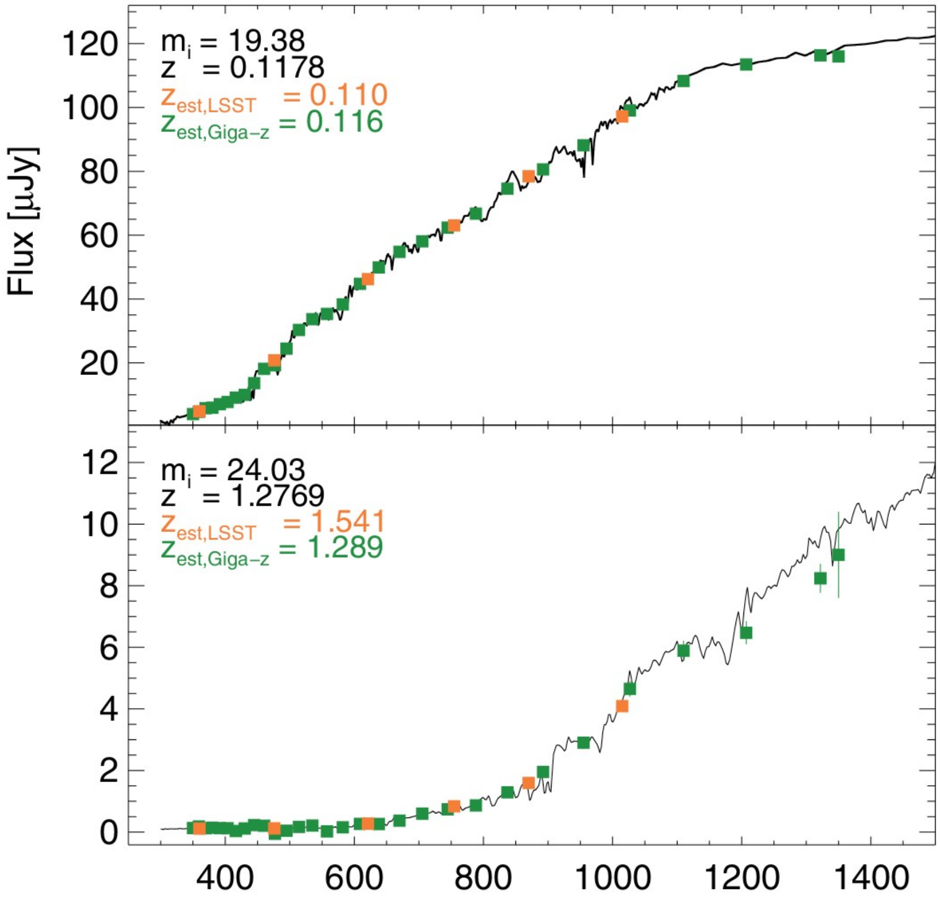
All pair breaking detectors.
For ground based CMB case:
$\sim (\text{photon Poisson})^2$

$\sim f(\nu_{\text{readout}}, Q, V_{\text{inductor}}, T_{\text{c}})$

Application #1: low resolution spectroscopy for large scale optical surveys and followup

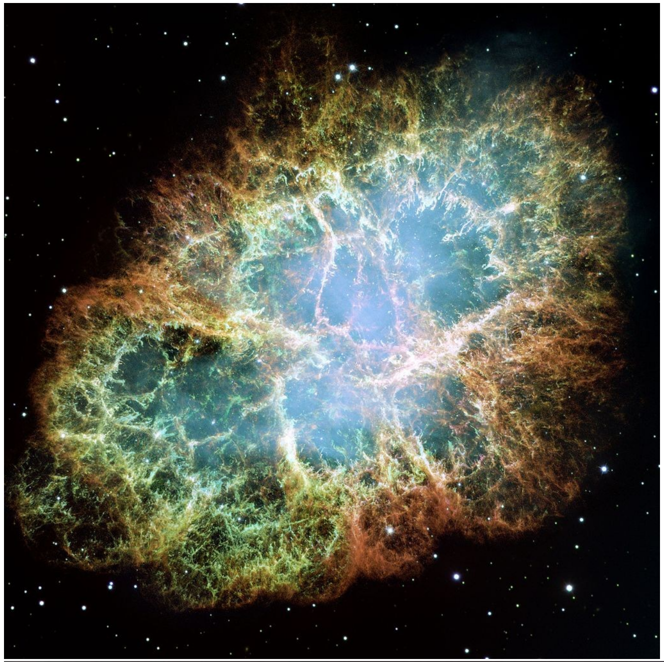


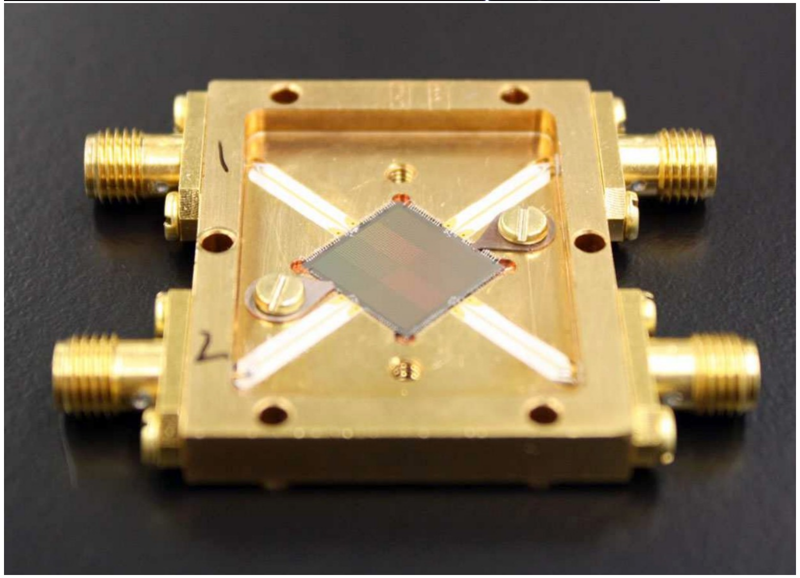


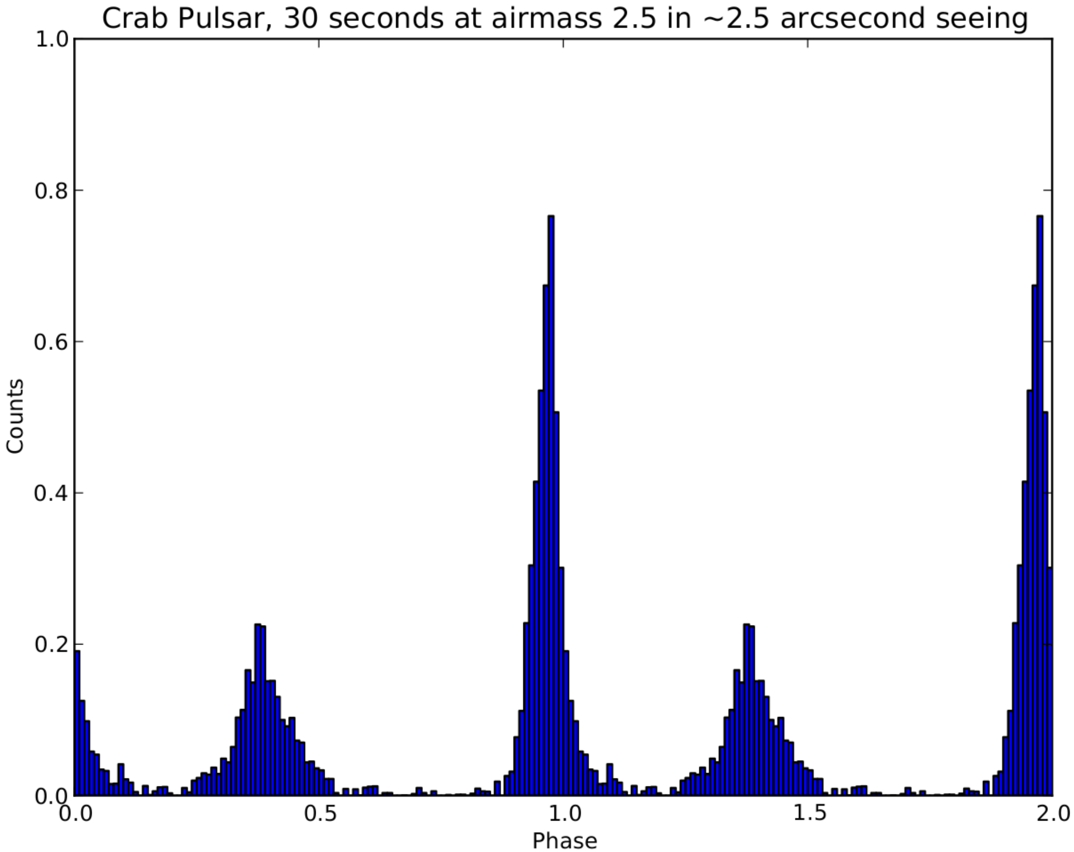


Figures from Marsden+ 2013

Application #2: time resolved astronomy

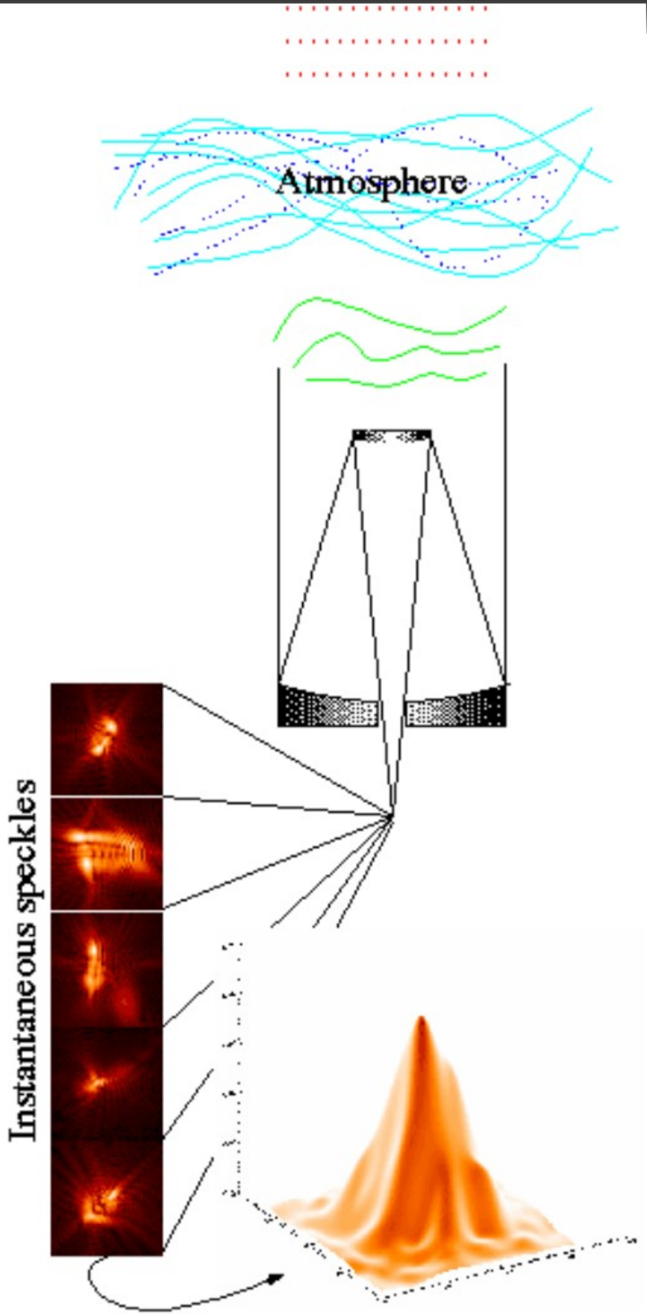


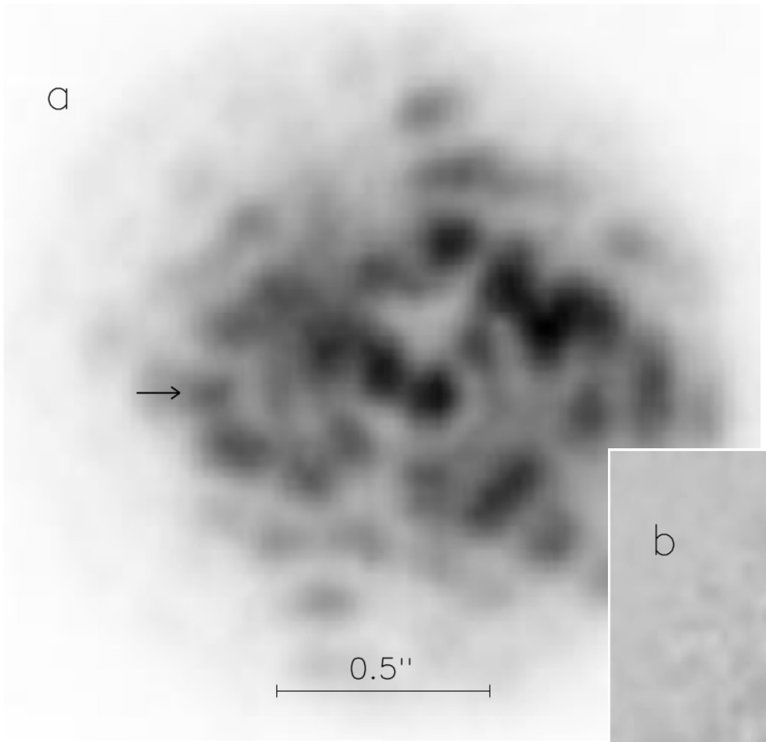


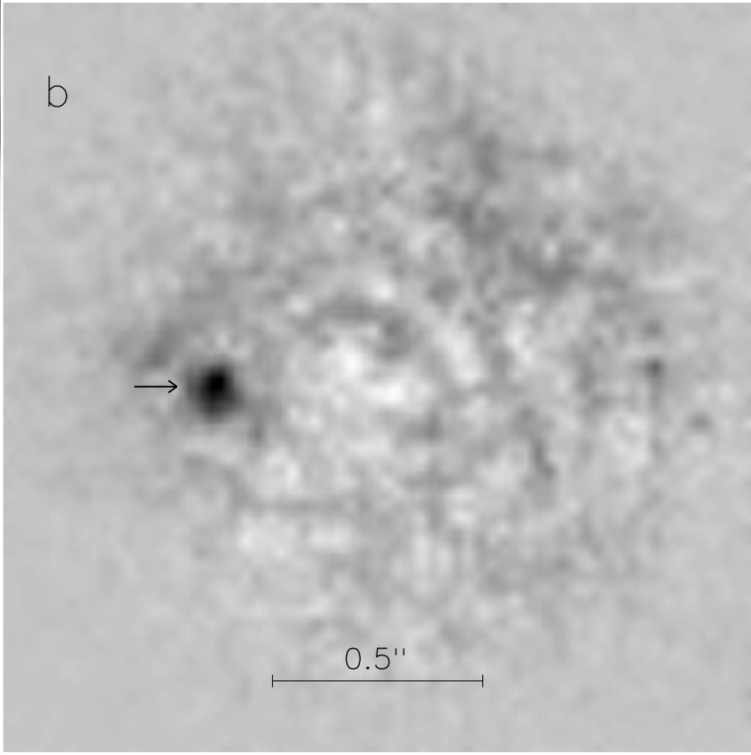


Optical enhancement of the Crab Nebula.
ARCONS MKID camera
Mazin Group, 2011

Application #3: speckle techniques



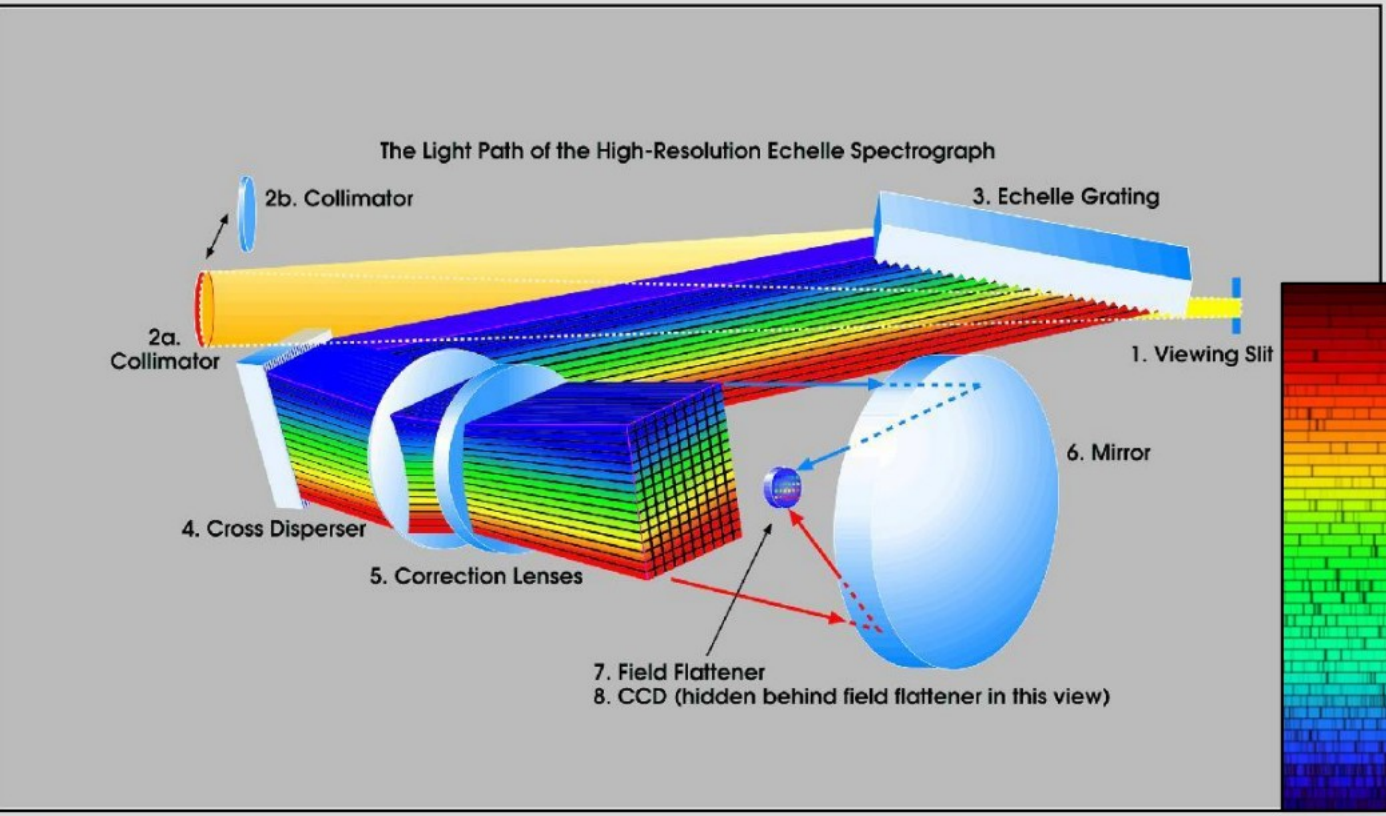


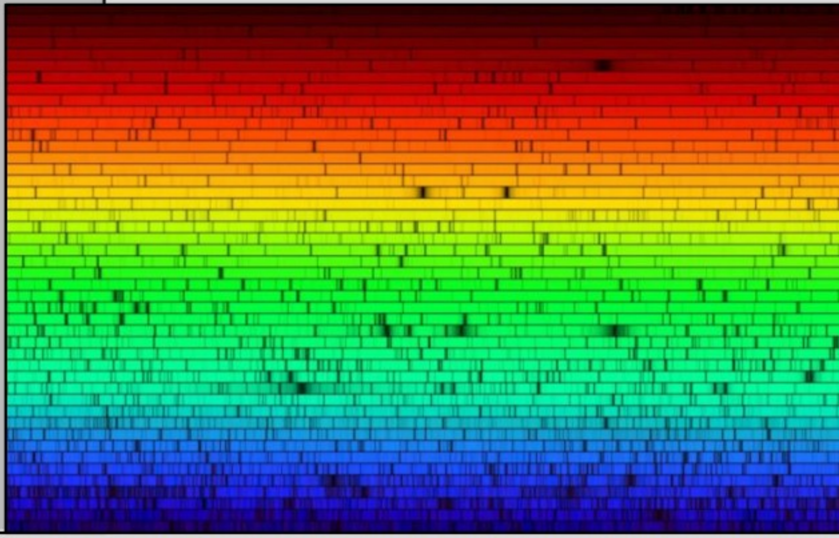


Images: Olivier Lai (CFHT)
& Boccaletti+ 2000

Application #5: order sorting following high-resolution dispersive spectroscopy

- Grating disperses incident light into diffraction orders
- A Cross disperser separates orders spatially
- CCD imager





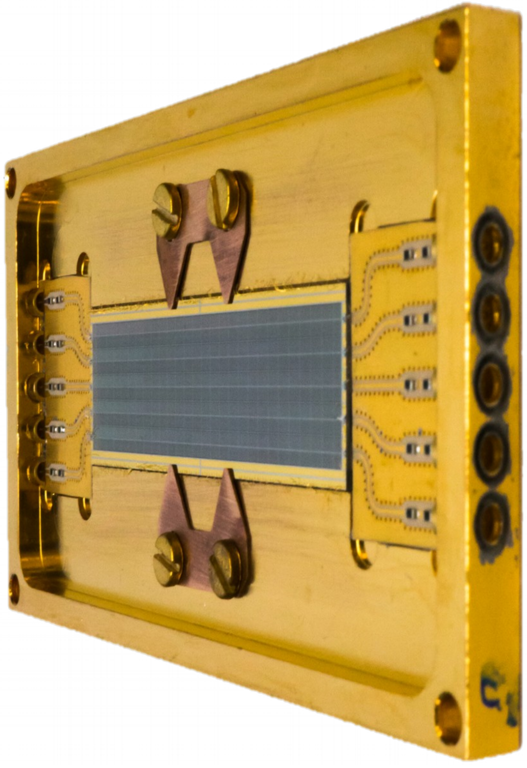
HIRES at Keck Telescope - http://www2.keck.hawaii.edu/inst/hires

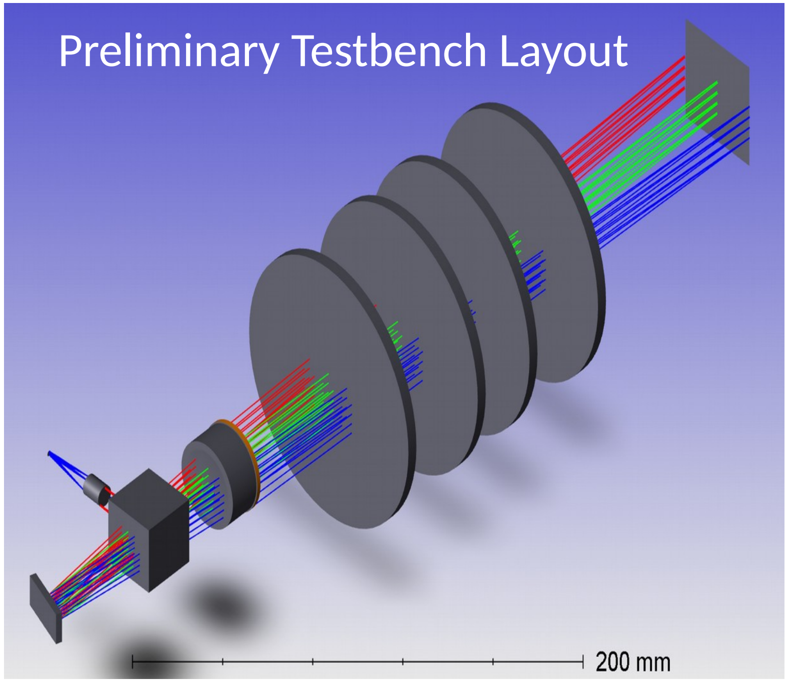
http://www.vikdhillon.staff.shef.ac.uk/teaching/phy217/instruments/phy217_inst_echelle.html

Slide from Sumedh Mahashabde, Oxford, KIDSpec collab.

MKIDs for Spectroscopy

- MKIDs can sort echelle orders
  - No read or dark noise even into the near-IR (think faint!)
- No cross disperser
  - Compact, high throughput
- Long linear arrays of MKIDs are pretty easy
  - 5 x 2k arrays now @ 20 µm x 2 mm pitch
  - 60 x 8k eventually
- R~3k – 5k testbed
  - 50 – 100 k eventually
- Data Hungry (LSST-MSE):
  - ~23TB/fiber@S/N 30
  - 175PB night





Next few slides from the J. Bailey, UCSB

Hafnium MKIDs: moving from R~10 to R~50

- We are now testing MKIDs from Hafnium (Hf) with T_c~450 mK, τ_{qp} = 80 µs, and parametric amplifiers