Direct detectors for low background far infrared space telescopes

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Detectors

Detector types

- Current direct detector types for FIR astronomy arrays:
  - Photoconductors
    - Limited to λ<200 μm
    - Require mechanical stress to reach 200 μm
    - "Gap" between 37 and 52 μm
    - Reach NEP ~ 2×10^{-18} at best (doped Germanium)
      - Hard to reach this in space environment
  - Bolometers
    - NTD Germanium
    - High impedance Si detectors
    - Superconducting detectors (TES)

Current state of the art

- The problem

- Current state of the art arrays are:
  - Too noisy
  - Too small
  - (And not ready for space)

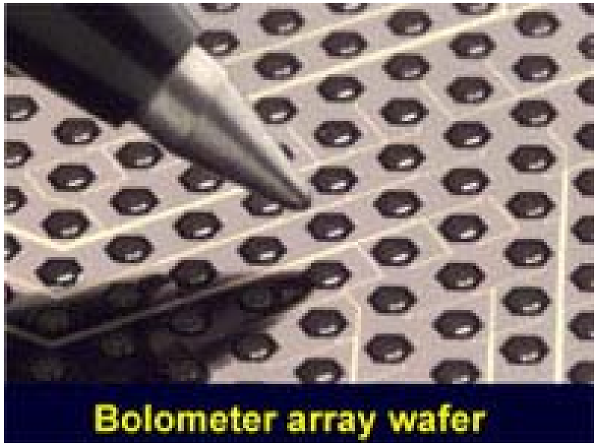
Current state of the art

- Si high impedance detector arrays
  - “CCD” like arrays
  - Currently best NEP ~ 2×10^{-16} $W/Hz^{-1/2}$
  - 16x16 (256) pixel arrays
    - Best predicted results: ~ 7×10^{-17} $W/Hz^{-1/2}$
    - Not good enough for FIRI!

Current state of the art

- NTD Germanium
  - As used in SCUBA, Bolocam, Herschel/SPIRE
  - Can't multiplex with acceptable noise performance
    - So need separate readout chain for each detector
    - Limits practical array sizes to a few hundred pixels

SCUBA focal plane



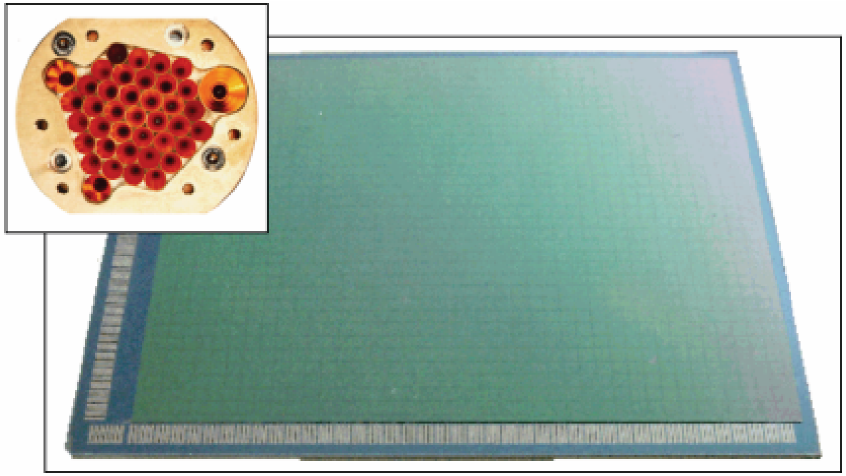
Bolometer wafer (JPL)

Current state of the art

- TES arrays
  - SCUBA-2 made up of 32x40 (sub)arrays
    - Can we make them bigger?
    - Probably, but huge increases not practical
      - Too many wires
      - Too much heat
      - In principle we could have built 5000 pixel arrays for SCUBA-2 out of SCUBA pixels…

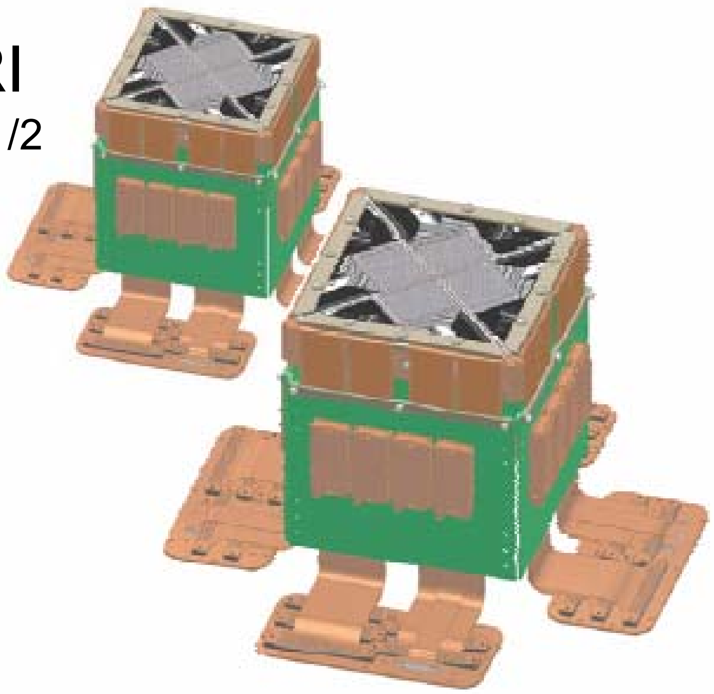
SCUBA individual pixel

SCUBA-2 sub-array (SCUBA array inset)



Current state of the art

- TES arrays
  - Measured optical NEP of SCUBA-2 prototype array:
    - 2.5 x 10^{-17} W/Hz$^{-1/2}$
    - Background limited for JCMT
      - But not good enough for FIRI
      - Need ~ 10^{-19} or 10^{-20} W/Hz$^{-1/2}$



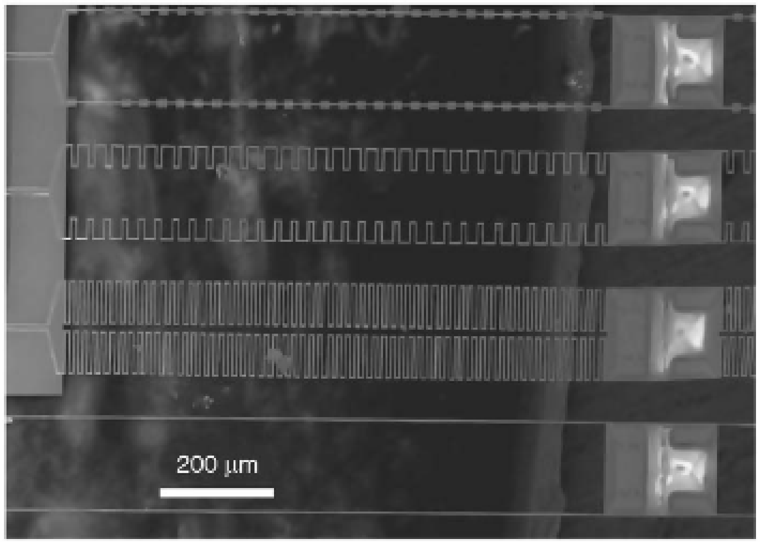
SCUBA-2 detector units

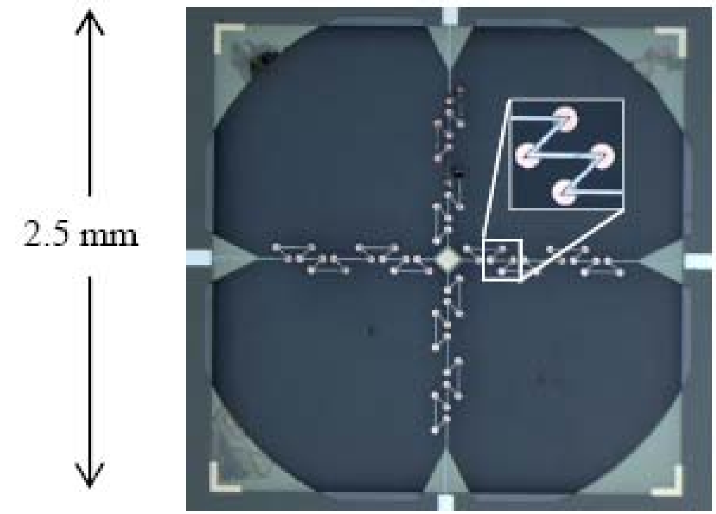
Improvements

- How can we do better?
  - Lowering transition temperature and decreasing thermal conductance (G) helps
    - BUT: can only lower T_c so far (limit to how cold you can get the detectors)
    - Decreasing G is hard to do while still providing adequate mechanical support
    - Run into physical limits: ballistic phonon flow
      - G no longer depends on leg length

Improvements

- Need to do things like this:





- JPL
- NEP 4 x 10^{-19} W $Hz^{-.5}$, predict can improve to 5 x 10^{-20} W $Hz^{-.5}$
- (Kenyon et al, Proc. SPIE 6275 627508)

- SRON/Cardiff
- Preliminary results: predict NEP 6 x 10^{-19} W $Hz^{-.5}$,
- (Mauskopf et al, Proc. IRMMW 2006)

Improvements

- Or:
  - hot electron bolometer – very low G caused by electron-photon decoupling
    - Also very low specific heat (just that of electron gas)
    - NEP ~ 3 x 10^{-19} claimed (Olaya et al, Proc. SPIE 6275, 627506)

Saturation problem

- If background is too high, TES will just stop working (driven above superconducting transition)
  - Different to semiconductor detectors which just degrade in performance gracefully
  - Less than ideal for space mission

- How to get round this?
  - Heat switch (or variable G) link (integrating bolometer)
  - Double Tc bolometer
  - Throw away photons (filter wheel…)

Multiplexing

- And even if you decide you are going to use a TES array, you have another decision to make:
  - Frequency division or time division
    - Jury still seems to be out on this one

Alternatives - STJ

- Superconducting tunnel junction detectors
    - Photoconductors using superconducting energy gap (much smaller than in semiconductors)
    - VERY hard to make arrays

Alternatives - KIDs

- Kinetic Inductance Detectors
  - Like STJs, make use of small energy gap in superconductor
  - Photons absorbed in superconductor produce excitations which change kinetic inductance
  - Very promising
    - Theoretical NEP ~ 10^{-20} W Hz^{-20}
    - Should be able to multiplex large numbers (1000?) of pixels with one readout
      - Multiplexing done at room temperature (cell phone ICs!)
    - Performance degrades with optical loading more gracefully than TESs
    - Fewer fabrication steps, don't require highly complex multiplexer

Alternatives - KIDs

- BUT:
  - Currently immature
    - How long will it take to reach fundamental noise limits?
      - (Took a while for TESs)
      - *CAN* we reach fundamental noise limits?

Other possibilities

- Hot-spot superconducting detectors
- Quantum dot devices
- QWIPs (quantum wells)
- SQPT photoconductor
- Cold Electron Bolometers + quasiparticle amplifier
- Something nobody has thought of yet?
    - (Or haven’t thought of using for astronomy?)

Summary

- Summary of the last 15 slides:

- There are lots of choices that *might* be able to produce suitable detectors

- But which one *will*?

Cooling

Cooling

- Whatever detector technology is chosen, likely to need cooling to at least 300 mK, possibly much lower
  - SCUBA-2 detectors need ~ 60 mK heat sinks

- How do we do this in space?

4-K

- Presumably start with 2 or 4 K platform
  - Traditionally large bucket of helium
    - e.g. IRAS, ISO, Herschel

  - More likely to use cryo-coolers
    - Existing space heritage
    - HFI has mechanical coolers to 4 K
    - Will be used for JWST
    - Development needed,
      - BUT: suitable coolers likely to be available in time
      - Not our biggest problem

300 mK

- 300 mK is reasonably easy
  - Sorption ^{3}He fridge
    - Used successfully on IRTS (1995)
    - Will be used for SPIRE and PACS on Herschel

100 mK

- This is harder
  - Planck dilution fridge (A Benoit and S Pujol)
    - No space heritage, but works upside down on Earth
    - Ran on balloon mission (Archeops)
    - Very low cooling power (few hundred nW at 100 mK)
    - Requires large quantities of ^{3}He and ^{4}He (thrown away continuously)
      - When this runs out: end of mission
      - ^{3}He is a limited resource
        - (Not enough H bombs)

100 mK and below

- Sorption fridge?
  - Recently constructed at Cardiff University
  - Will be used (on the ground) for Clover
  - Requires gravity, but a microgravity version is conceivable

Cardiff University

ADR

- Alternatively, could use magnetic cooling

- No cryogens required (nothing to run out, or leak, no capillaries to plug…)
- Large magnetic fields (not nice for TES detectors; need (heavy?) shielding)
- Traditionally single shot, but continuous ADRs of various designs now being developed (Goddard, Wisconsin)
  - Operated down to 35 mK; 20 mK is possible)

- (Brief) space heritage:
  - Flew on XRS on ASTRO-E2
    - Operated successfully in the few days before the helium was lost

Combinations

- Mini ADR with ^3He or ^4He fridge?
    - (Wisconsin, ESI group)

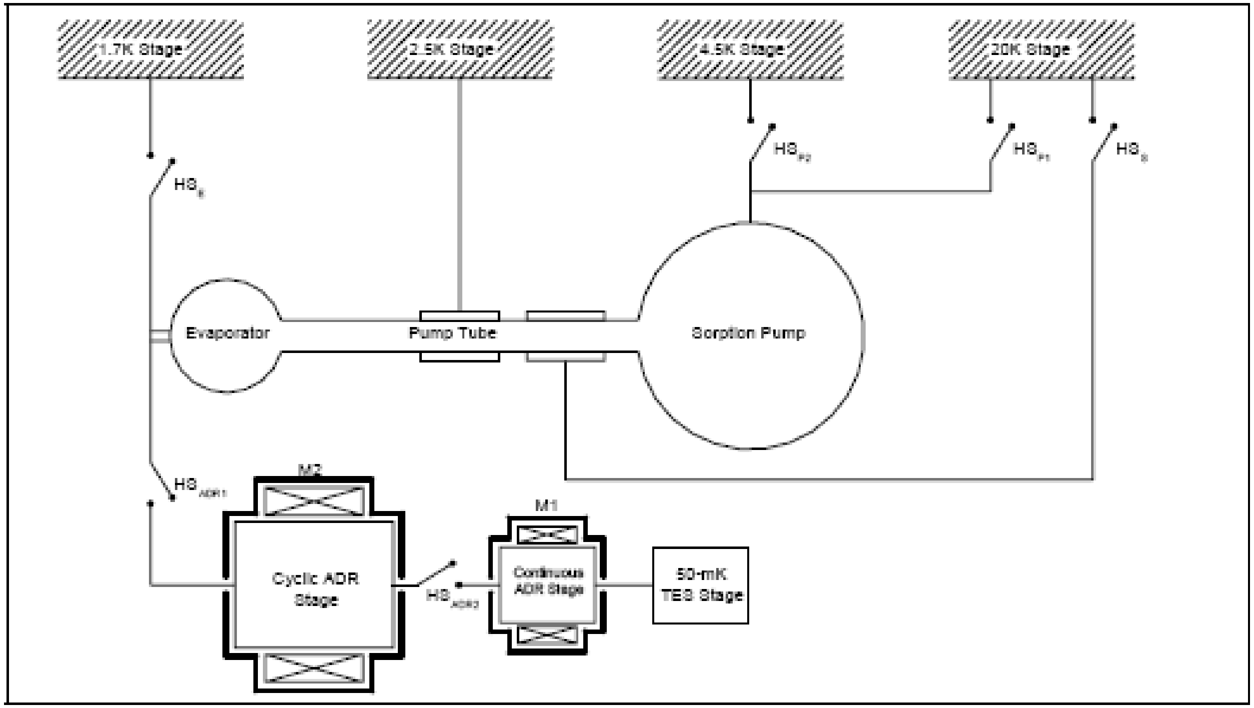


Figure 8 – Conceptual layout of a hybrid ADR – Sorption Cooler system suitable for ESI.

Griffin et al, Proc. SPIE 6275, 62750E

Cryogenic system

- Will have to transfer heat from detectors to coolers, and from coolers to higher temperature stages

- It's not likely to be straightforward
    - SPIRE, PACS and HFI have complex cryogenic systems
    - SCUBA-2 is maybe more representative
        - Very complex cryogenic system
        - Meets specs, but only at the expense of a lot of hard work on design and plenty of overengineering

- Cryogenic system HAS to work
    - Almost certainly won't be able to entirely use existing measurements and methods
    - Some R&D almost certainly required (as with SPIRE, HFI, SCUBA-2)

Summary

- Detectors are a problem!
  - What we need doesn't currently exist
  - It's not even clear which of many direction we should be going in

- Cooling detectors won't be easy either

- Likely cooling solutions *do* exist
  - Have to choose from many options, and develop full cryogenic system around them

- Detectors and detector cooling are key issues for making FIRI plausible