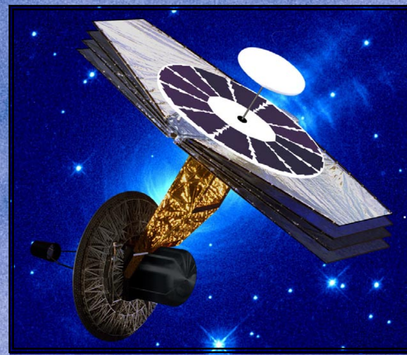


SAFIR:
Single Aperture Far-InfraRed Observatory

Dominic Benford
NASA/GSFC 685 (Infrared Astrophysics)

Introduction

- SAFIR is essentially the same as FAIR, the Filled Aperture Infrared Telescope
- SAFIR can address several fundamental astrophysical problems:
  - Formation of stars and planets in our own neighborhood
  - Coalescence of galaxies in the early universe
- SAFIR is envisioned as a follow-on to NGST, but extended to longer wavelengths. NGST is to HST as SAFIR is to NGST. Size is thus larger still.

Organization

- What SAFIR will do and why
- Where relevant technologies are
- Some development issues

Overall message:

SAFIR needs some advanced technologies

Its needs overlap with other missions

Everything is within reach with reasonable schedule and budget, provided funding for R&D

Motivation

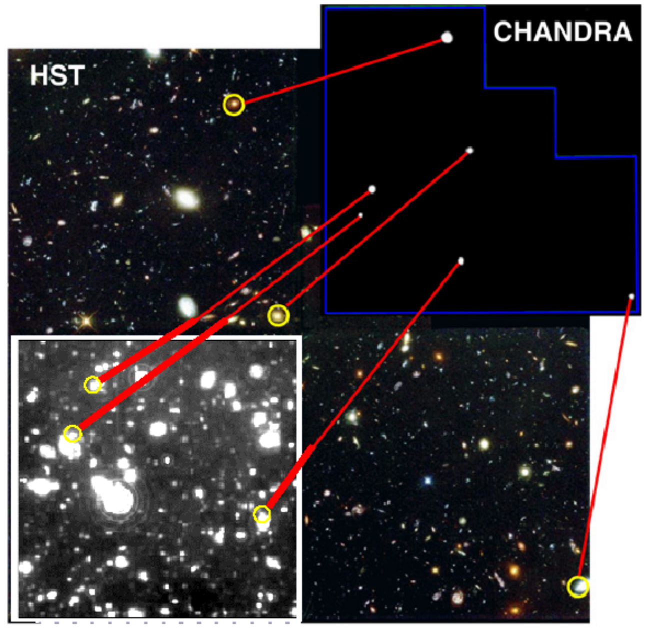
- "SAFIR…will:
  - Study the important and relatively unexplored region of the spectrum between 30 and 300μm.
  - Enable the study of galaxy formation and the earliest stage of star formation by revealing regions too enshrouded by dust to be studied by NGST
  - Be more than 100 times as sensitive as SIRTF or the European [Herschel] mission.
- "The committee recommends SAFIR…
  - The combination of its size, low temperature, and detector capability makes its astronomical capability about 100,000 times that of other missions
  - It [has] tremendous potential to uncover new phenomena in the universe."

– *pages 12, 39 & 110 of Astronomy and Astrophysics in the New Millenium, National Research Council, National Academy Press, 2001.*

SAFIR Science Motivation (I)

<u>Early Galaxies, AGN, and Energy Density</u>

- What happens during the building of galaxies in the early Universe?
- COBE showed that the far-IR/submm energy density in the early Universe is comparable to that in the visible/near infrared.
- What are the relative roles of dust embedded AGNs and starbursts in producing this luminosity?
- Do AGNs at high redshift differ in basic properties from nearby ones?



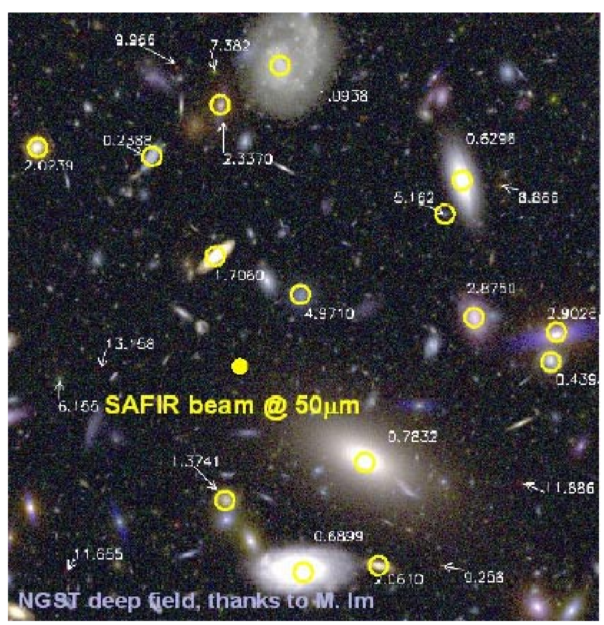
SAFIR Science Motivation (II)

<u>The Emergence of Stars and Galaxies:</u>

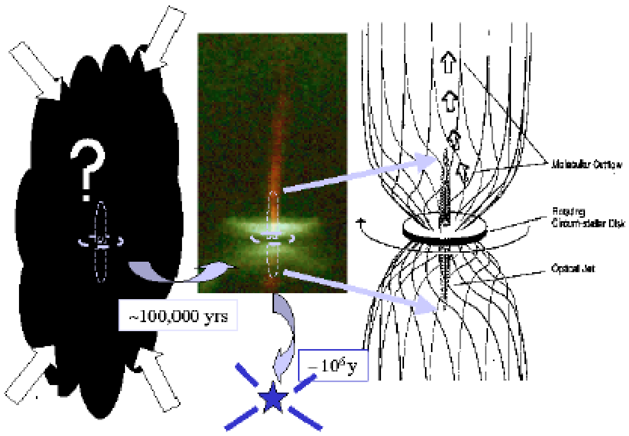
Ultradeep optical images (e.g., HDF) reveal many galaxies too faint to contribute significantly to the COBE-discovered infrared diffuse background.

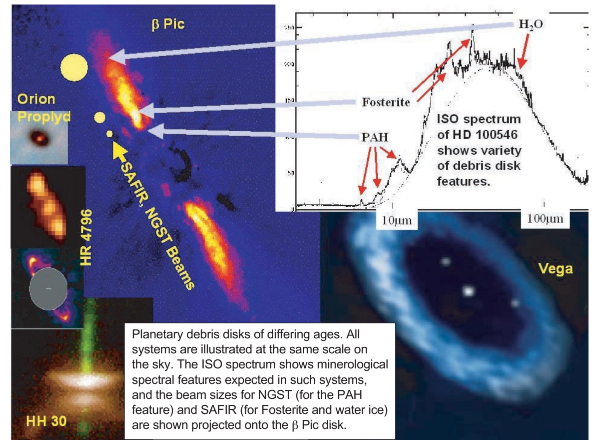
A full understanding of star formation in the early Universe requires that we extend far FIR/submm measurements to these small systems and possible galaxy fragments.

This can best be determined through high sensitivity imaging from 20 to 500µm.



SAFIR Science Motivation (III)





Stars are born in cold interstellar clouds that are so opaque they are undetectable even in the mid infrared (e.g., NGST).

How does the cloud core collapse?
How does subfragmentation occur to produce binary stars?
What are the conditions within protoplanetary disks?
When, where, and how frequently do these disks form planets?

The birth of stars and planets can be probed thoroughly only at FIR/Submm wavelengths where the cloud is transparent.

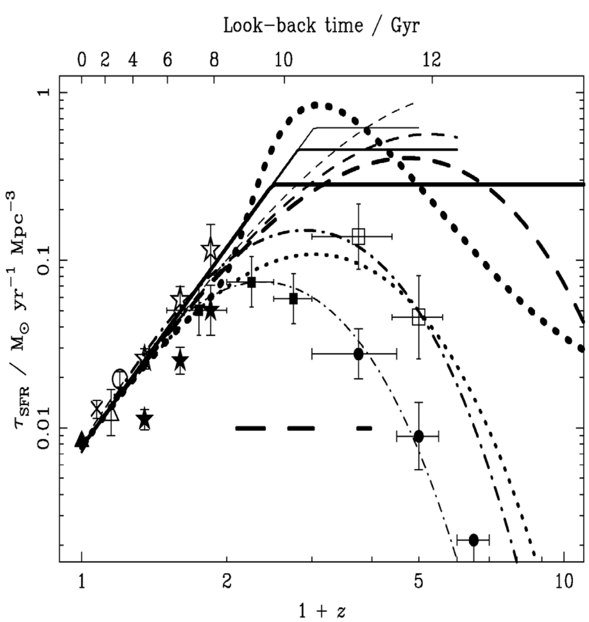
SAFIR Science Motivation (IV)

<u>Chemical and Physical Evolution of Galaxies</u>

• Physical conditions are sensed by varieties of observations: fine-structure lines, molecular lines, continuum

• Far-IR fine-structure lines prominent for most IR bright galaxies
  - trace radiation fields
  - trace gas properties
  - trace abundances
  - dominate gas cooling

• Molecular lines can serve as chemical and physical diagnostics:
  - e.g., high-*J* CO traces shocks
  - e.g., OH, CH, etc. trace chemistry



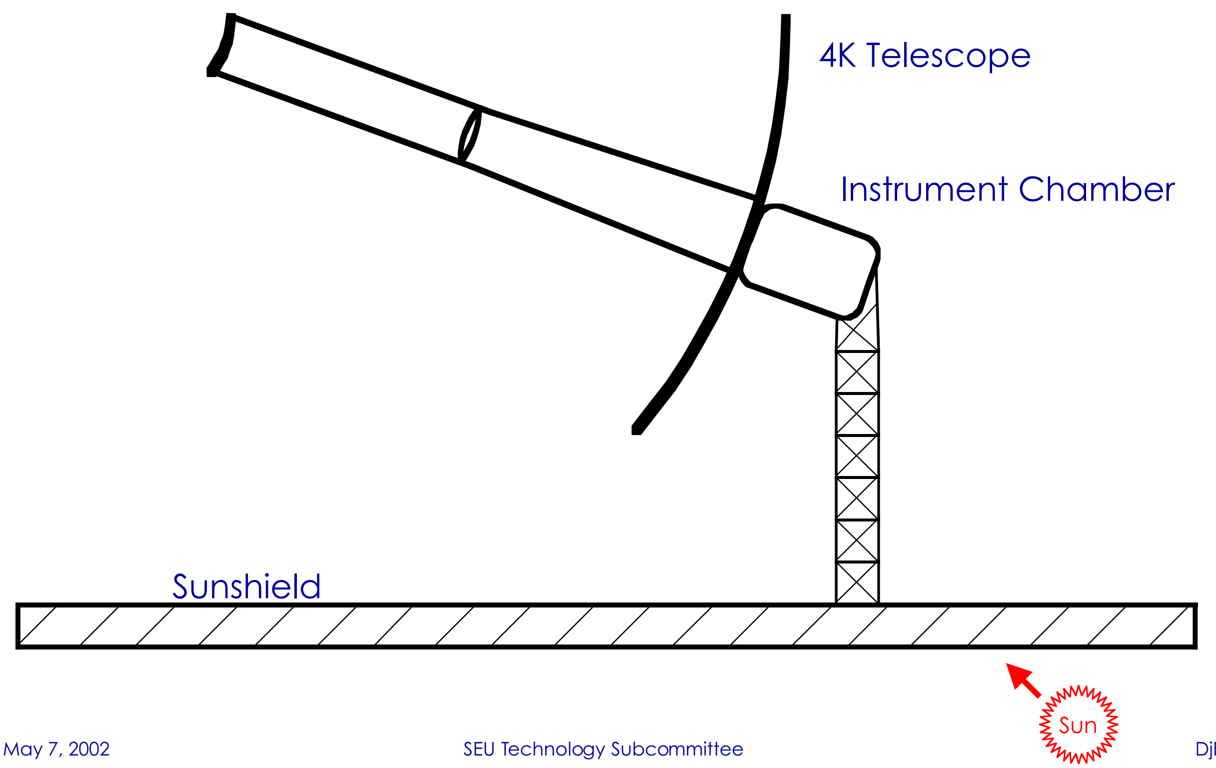
Technologies

Optics

Cryo

Detectors

Cartoon Sketch

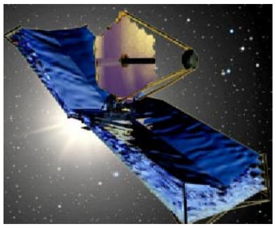


SAFIR vs. NGST

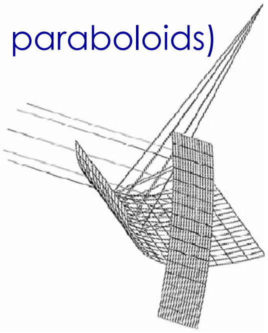
- Thermal:
  - Colder telescope (4K)
  - Stray light below Zodiacal for all wavelengths
  - Cold multiple instrument chamber (MIC)
- Optical:
  - Bigger telescope
  - Coarser: 40µm diffraction limit

Optical Layout Possibilities

- NGST-like (could be sparse)

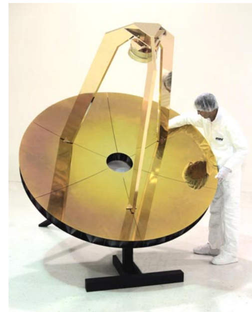


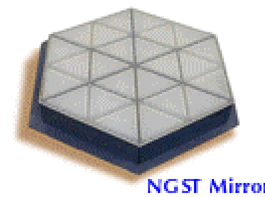
- Off-axis design (long strip mirror, Gregorian)
- DART membrane mirrors (Crossed cylindrical paraboloids)
- Fizeau-style interferometer (strip mirrors)

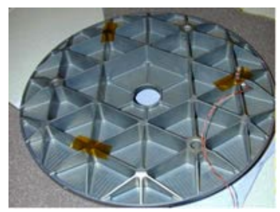


More Exotic Optics

- All-composite
  - COI FIRST/Herschel Demonstrator
- Composite + glass
  - COI NGST demonstrator
- SiC
  - Astrium SOFIA mirror

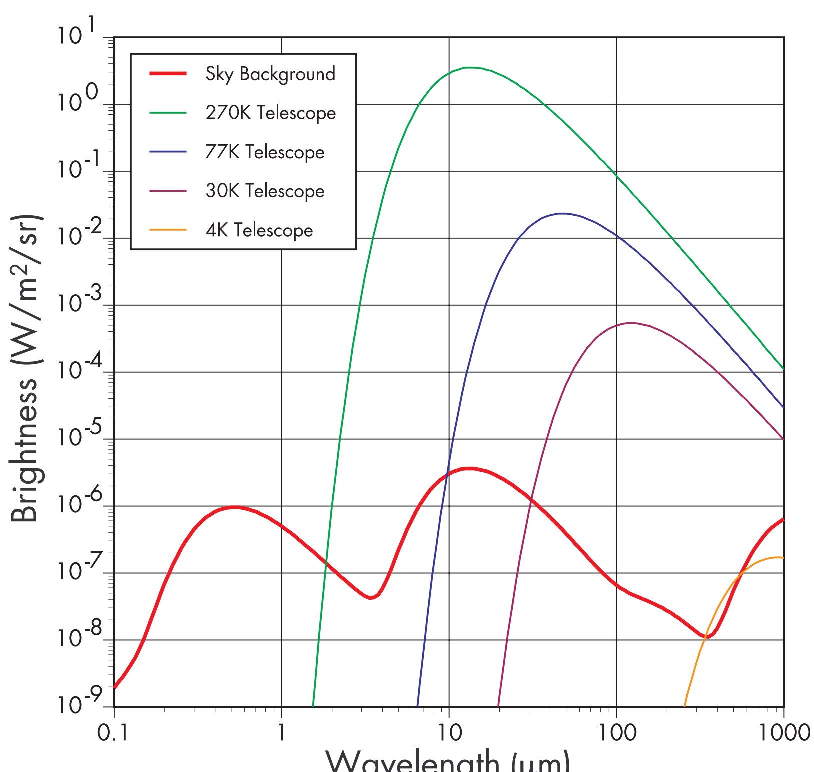






Dark Sky Background

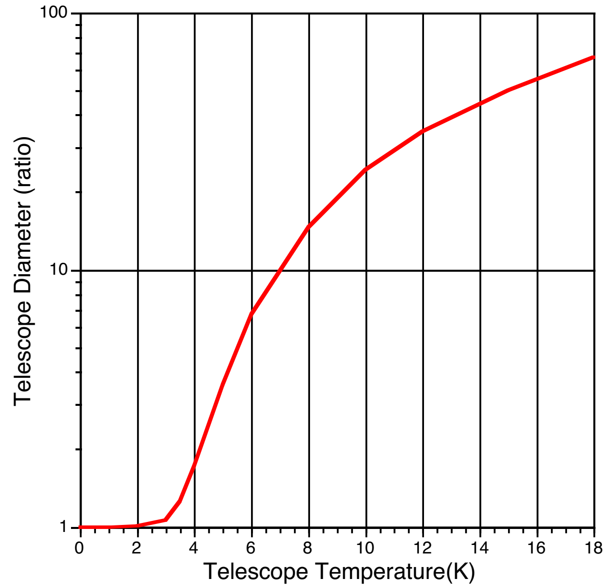
- Combination of background radiation sources at L2 yield darkest sky at 100-600µm.
- Telescope of 5% emissivity must be <4K.
- Across SAFIR range, total power in diffraction-limited beam with 100% bandwidth is ~1fW.



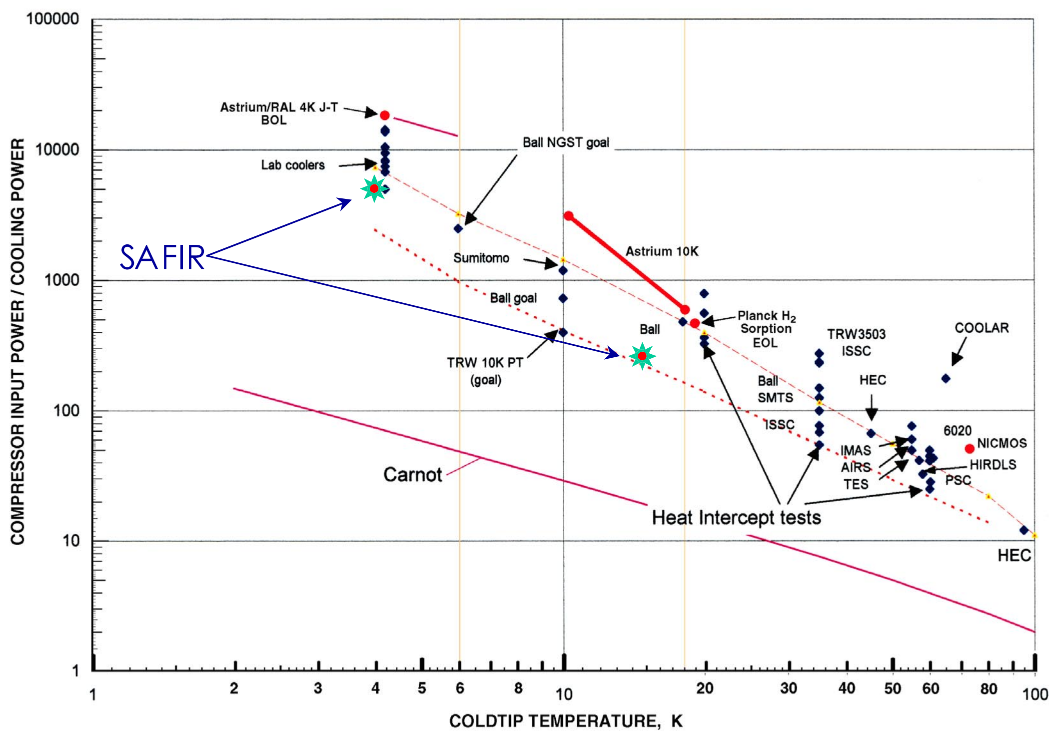
Bigger or Colder?

- You could make the telescope a bit warmer (and therefore noisier), and compensate by making the telescope a bit bigger.

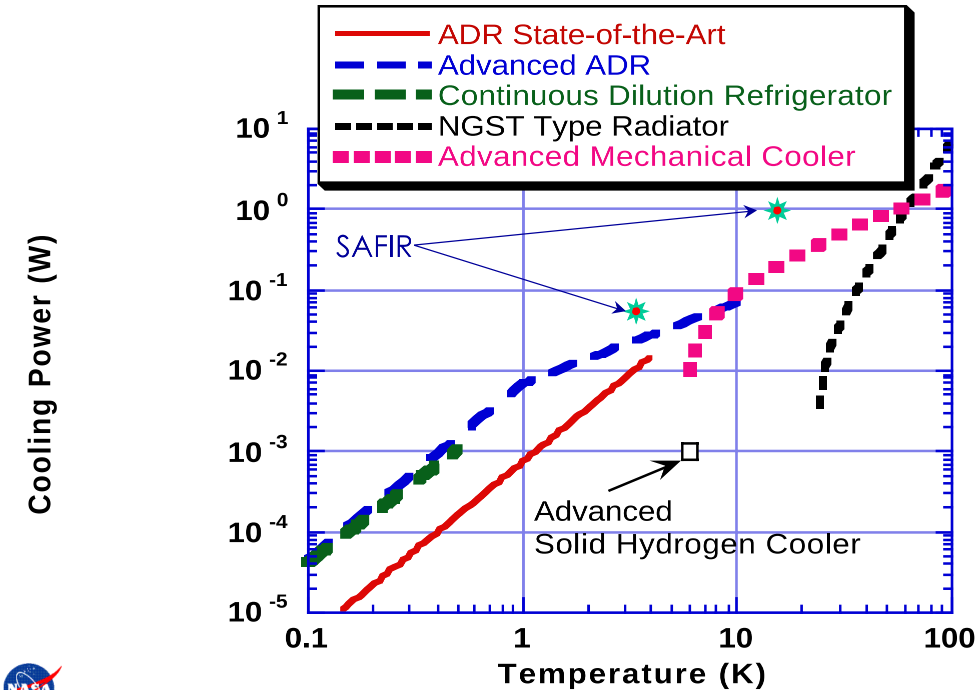
- Calculation shows that you lose really fast as the telescope gets hotter.



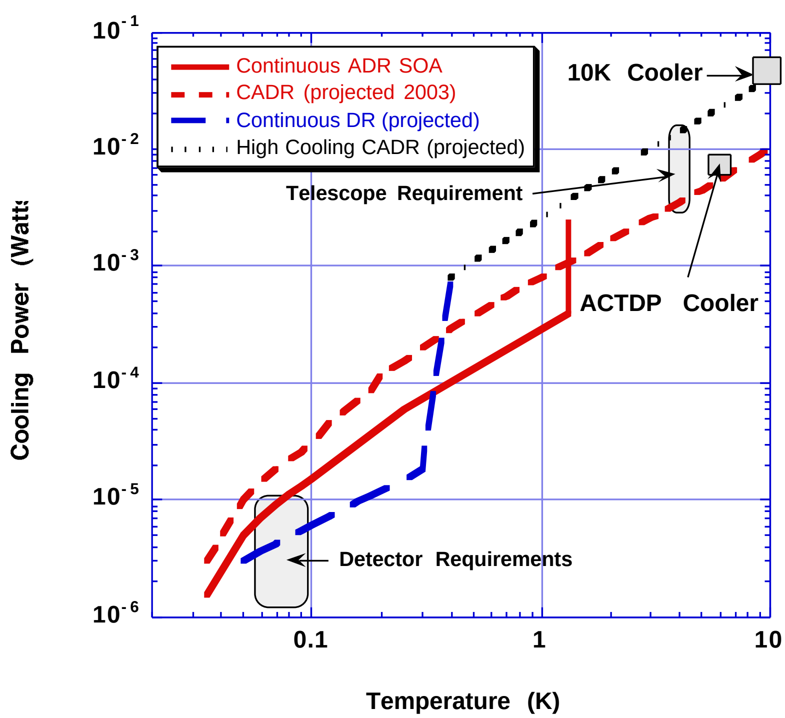
Cooling Power



<100K Cooling

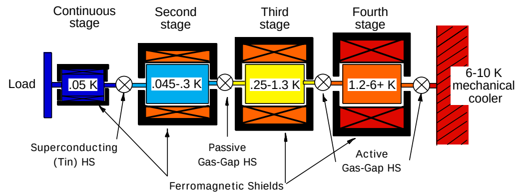


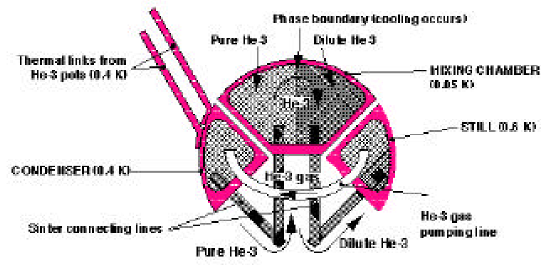
<10K Cooling Status



<1K Coolers

- Continuous (multistage) ADR:
  - Near Carnot efficiency
  - No gravity dependence
  - Can operate from ~10K cooler
  - Intermediate stages can cool telescope/optics
  - Continuous, stable at temperatures down to 0.035K
  - Cons: heavy, require high currents
- Dilution Refrigerator:
  - For same power, can be lighter than ADR.
  - Existing space flight prototypes do not feature continuous operation, have not been operated in zero g, or cannot operate with >4K cooler





SPICA Mission

- Japanese mission
- 3.5m monolithic telescope at 4.5K
- Launch in ~2010
- Similar to SIRTF instrument complement

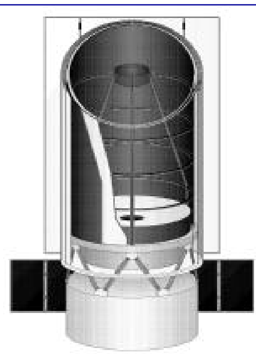


Figure 1. Conceptual design of the SPICA mission with a 3.5 m primary mirror.

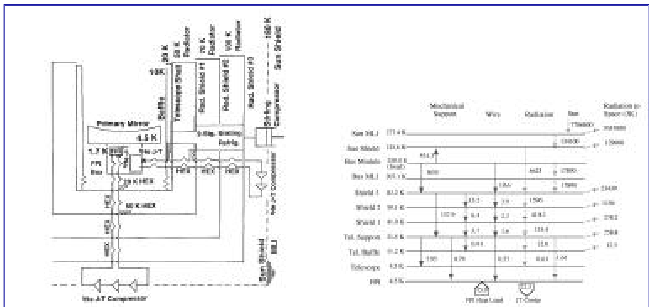


Figure 2. Schematic drawing of the cryogenic system of the SPICA mission. The telescope is enshrouded with multi-layered radiators. One set of a JT cooler (with ^4He) and a two-stage Stirling cycle is used to cool the telescope and some of focal plane instruments to 4.5 K. Another set of a JT cooler (with ^3He) and a two-stage Stirling cycle is used to cool the far-infrared detectors to 1.7 K.

Figure 3. Heat flow (unit: mW) diagram of the SPICA mission cooled by radiation and cryogenic coolers. Black arrows show the heat flow by conduction and shaded arrows show the heat flow by radiation. We assume a structure of the conceptual design (Figure 1)

Images courtesy of Takao Nakagawa

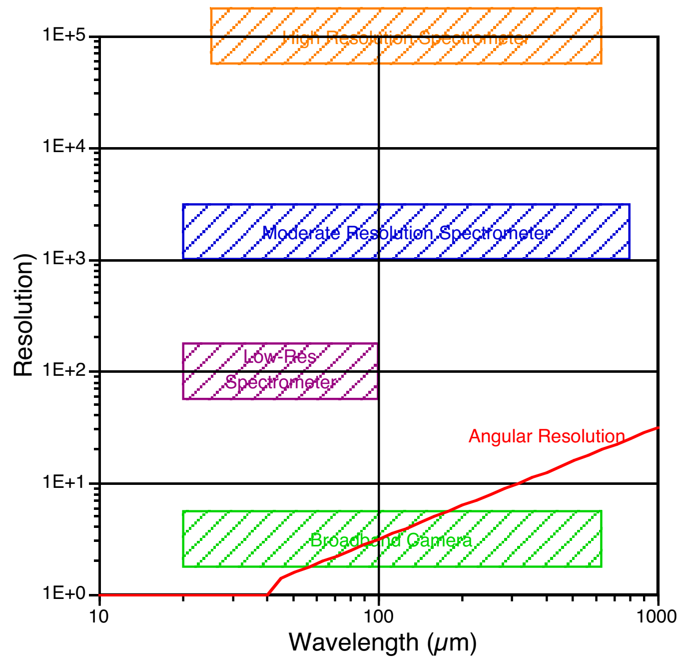
Instrument Complement

Broadband Camera:
- Spectral resolution of R~5
- Covering 20 to 600 microns
- Will probably require bolometers

Low resolution spectrometer:
- Spectral resolution of ~100
- Covering 20 to 100 microns
- Could use bolometers or photoconductors

Moderate resolution spectrometer:
- Spectral resolution of ~2000
- Covering 20 to 800 microns.
- Requires very sensitive detectors

High resolution spectrometer:
- Spectral resolution of ~1,000,000
- Covering 25 to 520 microns,
- Will probably require heterodyne mixers

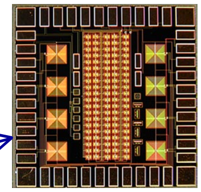


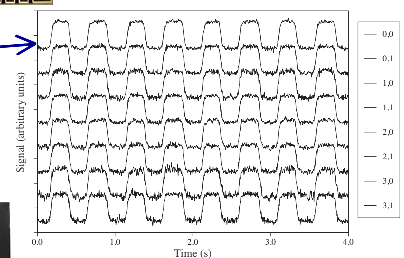
Detector Options

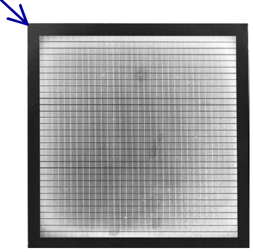
- Superconducting transition edge sensor (TES) bolometer:
  - Can be made in large arrays
  - Operates at low power
  - Small mass, volume, and cryogenic system complexity
  - Very sensitive and fast
  - *Not as mature as others*
- Semiconducting bolometer:
  - Well-established
  - Typically more complex cryo-electronic assembly
- Photoconductors:
  - Limited wavelength range
  - Some funny effects

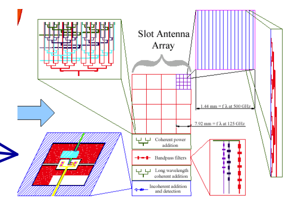
Superconducting TES Bolometers

- Irwin (1995) suggested a stable bias configuration that increases sensitivity
- Lee et al. (1996) made TES bolometer
- Bock et al. (1998) showed TES bolometer for space application
- Chervenak et al. (1999) made SQUID multiplexer
- Benford et al. (2000) demonstrated multiplexed detection of infrared light
- Gildemeister et al. (2000) built a 32x32 mechanical structure
- Staguhn et al. (2001) demonstrated detector-noise-limited multiplexed readout
- Benford et al. (2001) demonstrated astronomical application of TES bolometers with SQUID multiplexers
- Bock, Hunt (2002) show novel antenna-coupled bolometer designs



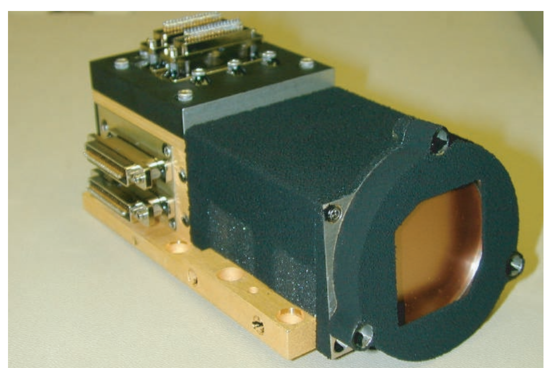


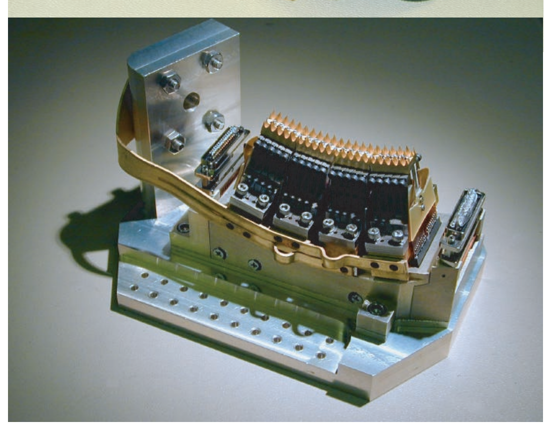




Photoconductors

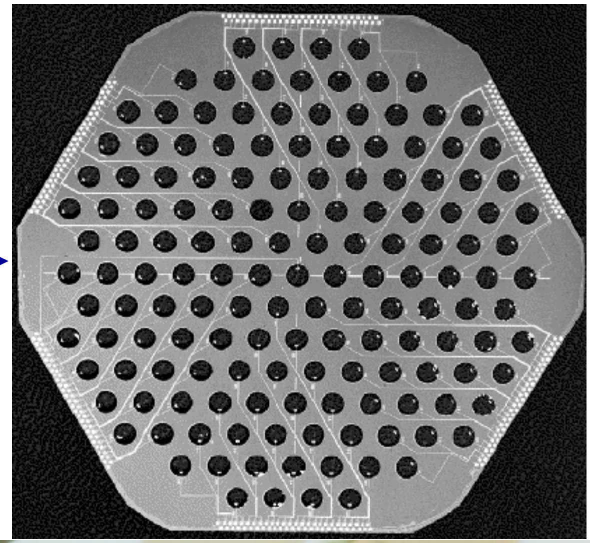
- SIRTF demonstrated 32x32 Ge:Ga array for 70μm and 2x20 Ge:Ga for 160μm
- Ge-based arrays don't function at >200μm (and have to be stressed to work there…)
- (Si:As BIB arrays for <40μm)

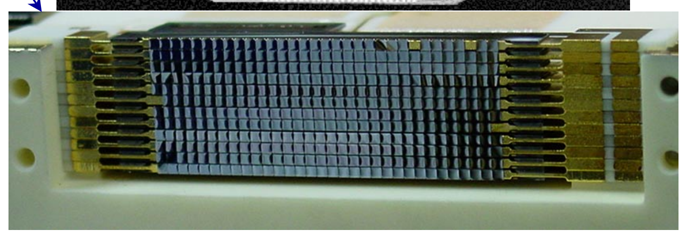




Semiconducting Bolometers

- State-of-the-art:
  - BOLOCAM array
  - HAWC array

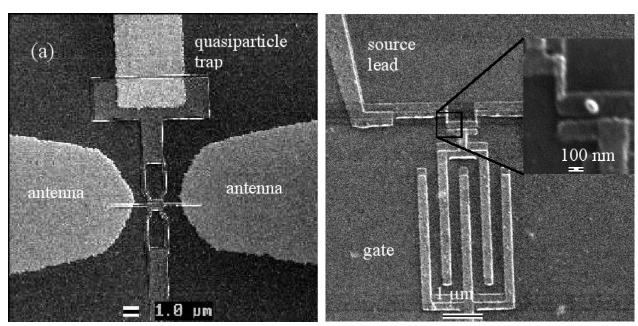


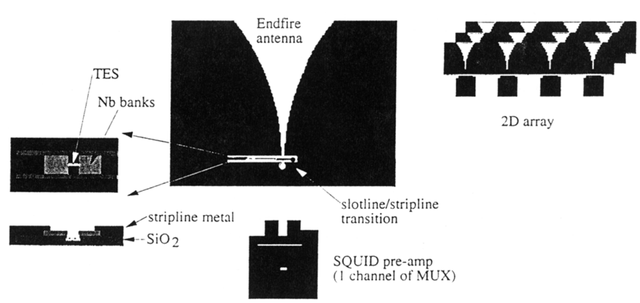


- To be used on Herschel
- Not easily multiplexed

Very Sensitive Detectors

- STJ with RF-SET
  - (Yale/GSFC)
- Antenna-coupled hot electron TES bolometers
  - (NIST)
- Kinetic Inductance detectors
  - (Caltech/JPL)

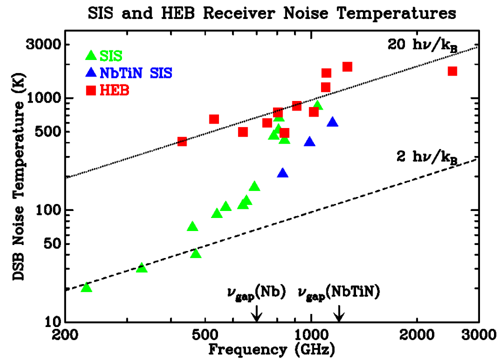


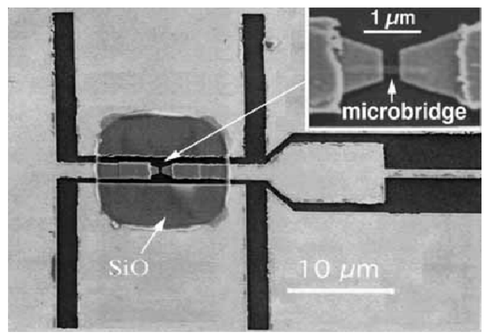


Heterodyne Receivers

- SIS junctions near quantum limit
- HEBs operate at higher frequencies

- Need to improve performance & tunable range
- Need broadband LOs
- Need compact backends





Leveraging Detectors

- SAFIR will require:
  - 128x128 array of detectors with NEP of ~$3\cdot10^{-19}$ W/√Hz
  - 64x64 array of detectors with NEP of ~10^{-20} W/√Hz
- Constellation-X is developing:
  - 32x32 array of detectors with NEP of ~$2\cdot10^{-18}$ W/√Hz

- Bahcall figure of merit:
  - Detectors characterized by #pixels/sensitivity^2
  - Doubling time is ~1 year.
  - Continuum array requires 9 years
  - Spectroscopy array takes 18 years

Technology Challenges

- Cooling a large telescope to 4K (and detectors to ~0.05K).
- Detectors with sufficient sensitivity, in large format.
- Deployable cryogenic telescope of 10m class.
- Adequate testing facilities for components & integrated systems.

Development Issues

What technologies should be developed?

Where can these developments be leveraged?

How do we validate them?

Milestones for Success

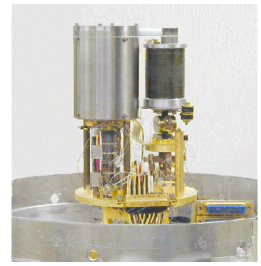
- Cryocoolers:
  - Develop higher power, lower temperature, and higher efficiency for the 4K-30K cold end.
  - Flight demonstrations like MAP for radiative cooling
  - Flight ADR on Astro-E II
  - Development of continuous ADR from ~10K stage
- Detectors:
  - Demonstrate continuum sensitivity in the lab (10^{-19} W/√Hz)
  - Demonstrate spectroscopic sensitivity in the lab ($3 \cdot 10^{-21}$ W/√Hz)
  - Demonstrate array formats working at 32x32
  - Demonstrate architecture scalable to 128x128

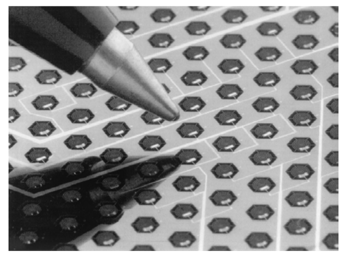
Milestones for Success (II)

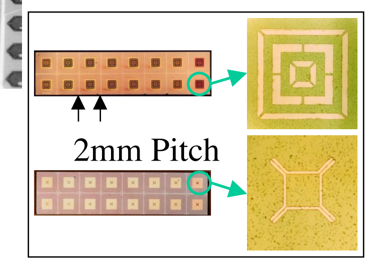
- Optics:
  - NGST architecture as a proof-of-principle
  - Studies of other options for lighter weight and/or lower cost
  - Work out deployment, alignment
- Testing:
  - Big vacuum chambers
  - Cryogenic test chambers
  - Optical testing for far-IR wavelength optics
  - Detector testing in relevant environments

Flight-like Demonstrations

- Cryogenics:
  - Some cooler (probably ground tested) able to yield similar temperature and scalable power with same technology
  - CADR demonstration (soon)
- Detectors:
  - Herschel bolometers
  - Con-X microcalorimeters
  - Demonstration of more sensitive detectors







Venue for Flight Demonstrations

- It's hard to test many of these technologies in a relevant environment (temperatures, gravity, size)

- Detectors - particularly for spectroscopy - cannot be tested astronomically except on a cryogenic space telescope

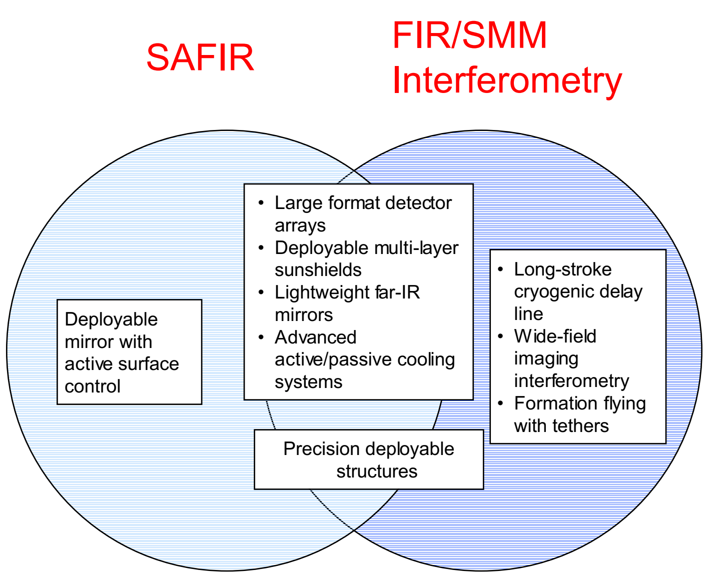
A larger class of Explorer mission - "BigEx" could permit riskier technologies to be flown earlier

Cross-Pollination

- Cryocoolers for ~4K are under development for many missions:
  - CMBPOL
  - X-ray Spectroscopy missions
- Detectors - superconducting TES bolometers:
  - CMBPOL candidates
  - Con-X microcalorimeters
    - The common interest between the far-IR and the X-ray regime in these detectors makes them a very attractive technology.
- Deployable telescope
  - NGST is developing the first large, deployable, cryogenic telescope.
  - Possible that SUVO might be interested

Related Issue: Interferometry

- One possible implementation of SAFIR would be a Fizeau interferometer
- Shared technologies for fixed-boom interferometry:
  - Deployed structure
  - Metrology/control



Technology Needs

- Cryogenic cooling:
  - Radiative to ~30K
  - Refrigerators to ~6K (optics @4K)
  - Refrigerator <1K (detectors ~0.1K)
- Lightweight, large optics:
  - Larger than NGST
  - Lighter than NGST
  - Colder than NGST

  But less demanding figure!
- Support structures:
  - Deployable optics
  - Deployable sunshade
  - Low thermal conductance S/C-to-telescope support
- Detectors:
  - Wavelengths 20-600μm
  - Large format direct detector arrays (1k-10k pixels)
  - Coherent receivers
- Infrastructure:
  - Manufacturing capability
  - Testing Facilities
  - Flight Heritage: MAP, SIRTF, NGST, Herschel, SOFIA (& suborbital), Con-X

When all is said and done...

- SAFIR is a high priority mission for the astronomical community. It could launch in ~2015.
- Before this happens, some technologies will need further development
- NGST, Con-X, and others will help this development.
- Detectors tend to drive capability; nobody else will make them. Build them first.

When all is said and done...

- Cryogenics:
  - 4K refrigerator ACTDP
  - Continuous ADR or zero-g dilution fridge
- Optics:
  - Lightweight, large, cryo-compatible telescopes
- Detectors:
  - Advance superconducting bolometer arrays to necessary sensitivity
  - Enlarge bolometer array architectures towards kilopixels
  - Increase tunable bandwidth (mixer & LO) for heterodyne systems
  - Push on novel, ultrasensitive detector technologies