NASA Detector Requirements

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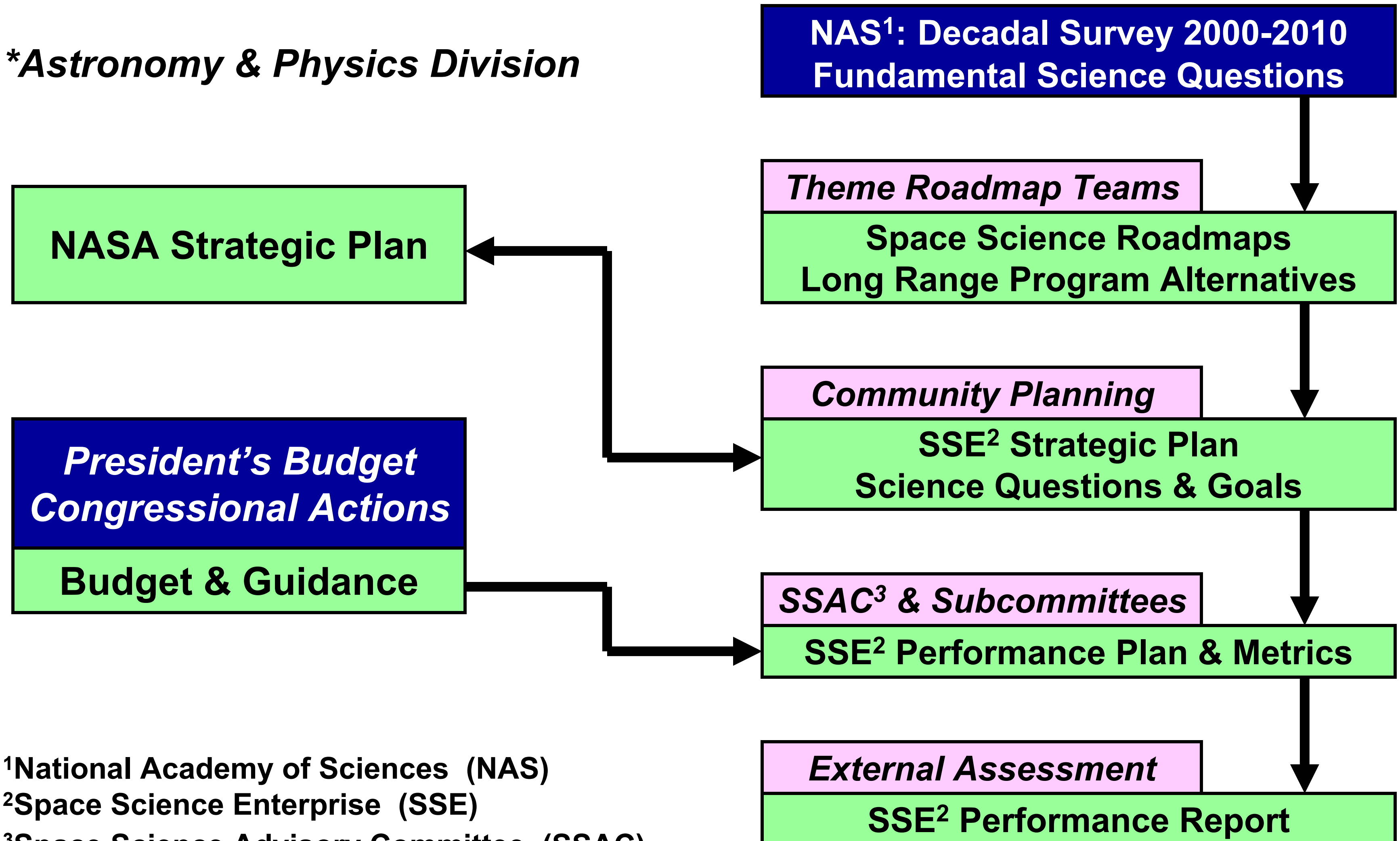
Outline

- NASA Detector Roadmap Process
  - Science Enterprise Roadmaps: Space (SSE) & Earth (ESE)
    - Space Science Themes
      - Astronomical Search for Origins (ASO)
      - Structure & Evolution of the Universe (SEU)
      - Exploration of the Solar System (ESS)
      - Sun Earth Connection (SEC)
- Key Missions and their Detector Requirements
  - Radiation Effects Issues
- Summary of Roadmap & Detector Working Group Conclusions Organized by Wavelength

*Strategic Planning Process: Office Of Space Science (OSS)**

**Astronomy & Physics Division*



[1]National Academy of Sciences (NAS)
[2]Space Science Enterprise (SSE)
[3]Space Science Advisory Committee (SSAC)

**Diagram adapted from <u>Detector Needs for Long Wavelength Astrophysics</u>, Edited by Erick Young, June 2002*

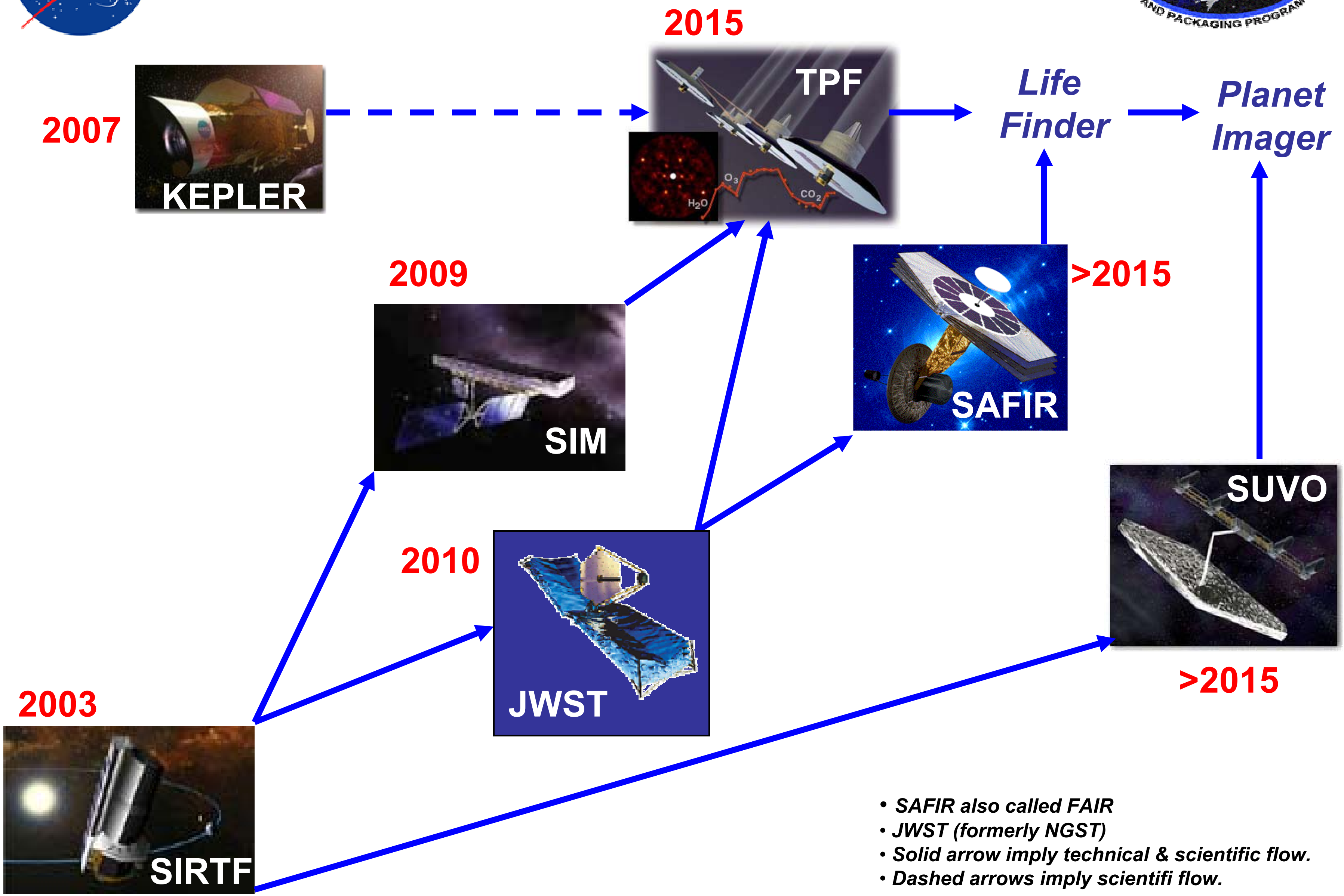
Detector Roadmaps - OSS

- UV / Visible Working Group
  - "UV-Optical Detectors for Space Astrophysics," edited by Chris Blades, 10/2001
- Infrared, Submillimeter, and Millimeter Working Group
  - "Detector Needs for Long Wavelength Astrophysics," edited by Erick Young, 6/2002
- Theme Roadmaps
  - Origins (ASO)
    - View technology roadmap documents at http://origins.jpl.nasa.gov/
  - Structure & Evolution Universe (SEU) Roadmap Investigation
    - View final report & individual Mission responses to the SEU technology roadmap subcommittee questions at http://universe.gsfc.nasa.gov/roadmap/docs/

Detector Funding Challenges

- It is recognized that detectors all too often result in significant cost overruns & schedule delays.
- The bulk of the detector development falls on the shoulders of the cornerstone programs – not just final engineering.
- Other programs (SBIRs, Explorer Technology funds, Research – Office Space Science (ROSS), Space Astrophysics R&A (SARA)) are helpful for the early concept stages.
- Funding of component breadboard validation & subsystem prototypes is difficult, especially >30 μm where commercial & military interest is lacking.
- Large Telescope System Technology Initiative (LTSI)
  - Targets 20-40 m class. Not as yet real, but has a significant detector component.

Origins Space-based Missions



Origins Theme Detectors

- SIRTF (1 m class) ***1/9/03 Launch!*** Developed detectors (3 – 180 μm) with sufficient sensitivity in large arrays
- JWST (6 m class)
  - Pushing very low noise performance for large format, small pixel (18 μm) detector arrays in the far visible to MIR (0.6 – 5 μm)
- KEPLER, SUVO, etc. (Likewise DOE-led SNAP, ESA-led GAIA, etc.)
  - Mosaics of high performance, large format CCDs
- TPF (~8 m class IR; 8 m class UV/Optical) TBD architecture.
- SAFIR (~10 m class?; 20-800 μm)
  - MIR & FIR detectors with sufficient sensitivity in large arrays (10^3 - 10^4 pixels @ 600 μm for 10 m telescope)
- SUVO (4 m, or perhaps 8 m class in the UV coupled with TPF)
  - Solar Blind UV detectors with larger formats & higher QE
- Life Finder & Planet Imager : diffraction-limited 20-40 m telescopes
  - Large Format SWIR and MIR arrays

Why the Longer Wavelengths?

NIR	MIR	FIR	Submm	MM
0.6 - 5 μm	5 - 40 μm	>40 μm	200 μm – 1 mm	

- **Direct observation of very distant objects.**
  - **Longer wavelengths penetrate cosmic gas & dust better.**
- **Longer wavelengths also permit earlier (red-shifted) objects to be observed. (UV/optical science with IR technology.)**
- **>80% observed radiant energy of the universe from 40 μm to several MM**
  - **Thermal radiation from the dust in our galaxy**
  - **Red-shifted dust emission from earliest galaxies**
  - **Cosmic Microwave Background (CMB)**

Detector Trends are Science Driven

A scientific observation is reduced to a predicted signal strength and required angular scale, sky coverage & position, etc.

$$T_{obs} \; \propto \; (\text{Sensitivity})^2 / N_{pixels}$$

- **Sensitivity is key but for *broadband imaging*[1] with long wavelength direct detectors we approach fundamental limits**
  - **Background limited by statistical photon fluctuations. (Scattered sunlight & zodiacal thermal emission for $\lambda < 100$ μm.)**
  - **Confusion limit also comes to play when multiple sources lie within a single pixel and add uncertainty to measuring brighter sources.**
- **<u>Driver then becomes larger arrays</u> for maximum reasonable observing time.**
  - **Optical arrays now in use with $>10^7$ pixels but largest FIR array is the 32 x 32 SIRTF photoconductor array. Story is similar from IR to MMwave,**
  - **At 160 μm, SIRTF hits confusion limit in 40 s even in low bkgnd. regions.**

[1] Spectroscopy issues more complex but requires $\sim 10^2$ greater sensitivity.

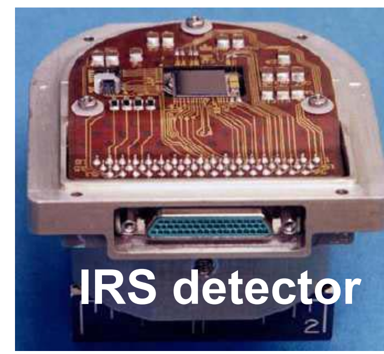
SIRTF Detectors (2003 Launch)

IRAC[1] 4-channel camera with simultaneous 5.12 x 5.12 arcmin images at 3.6, 4.5, 5.8, and 8 μm. All 4 detector arrays are 256 x 256, with 1.2 arcsec pixel size.

256 x 256 InSb at 3.6 & 4.5 μm	Raytheon SBRC
256 x 256 Si:As IBC[4] at 5.8 & 8 μm	Raytheon SBRC

IRS[2] 4 separate modules using backside-illuminated IBC[4] detectors (Boeing)

128 x 128 Si:As at 5.3 - 14 μm	low-res
128 x 128 Si:As at 10 - 19.5 μm	high-res
128 x 128 Si:Sb at 14 - 40 μm	low-res
128 x 128 Si:Sb at 19 - 37 μm	high-res

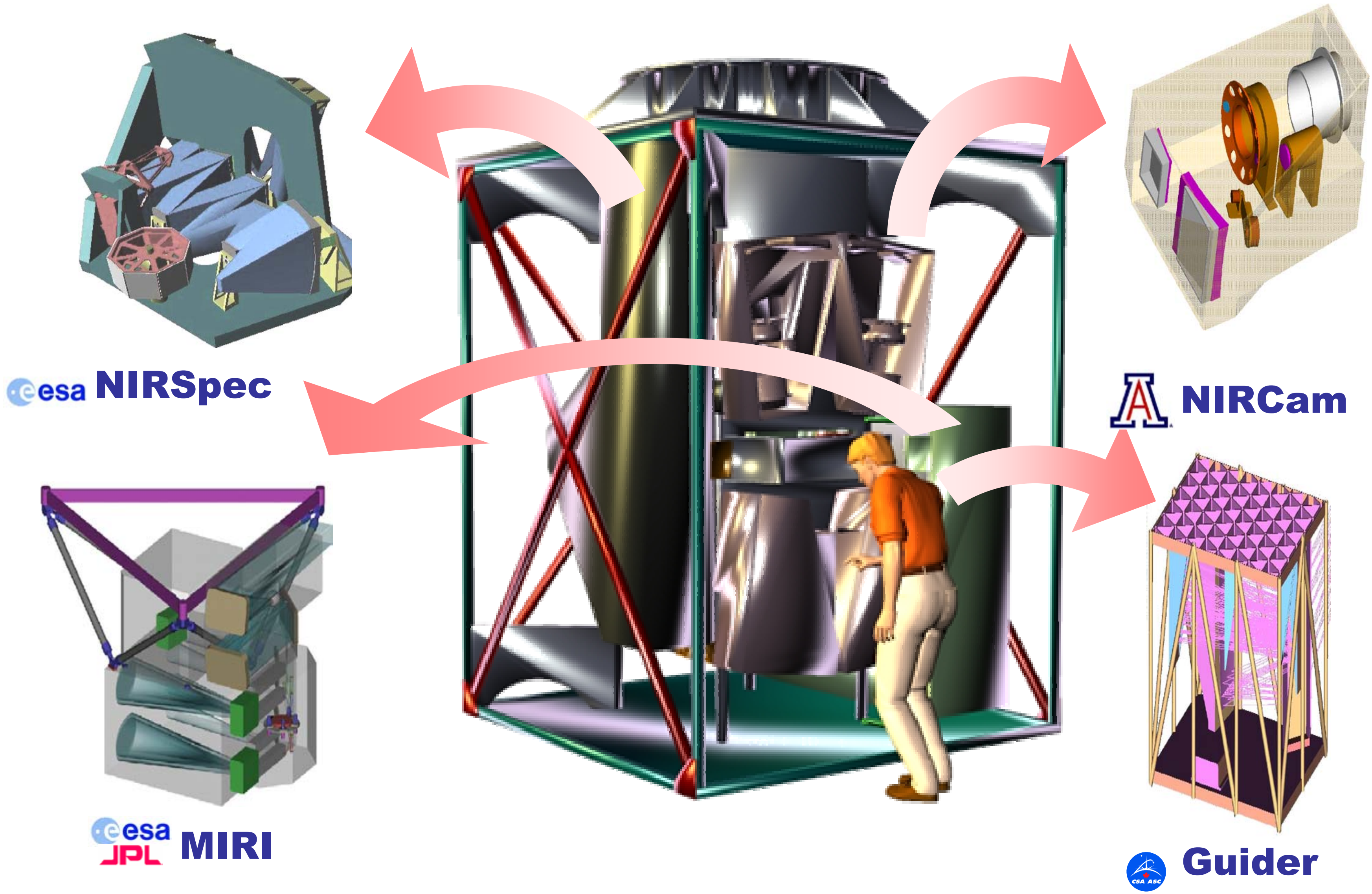


MIPS[3]

Si:As (IBC) 24 μm	DRS
Ge:Ga at 70 μm	Developed & built by MIPS Team
Ge:Ga at 52-99 μm	Developed & built by MIPS Team
32 x 32 stressed Ge:Ga 160 μm	Developed & built by MIPS Team

[1] IR Array Camera, [2] IR Spectroscopy, [3] Multi-Band Imaging Photometer
[4] IBC: Impurity Band Conduction, or BIB: Blocked Impurity Band detectors

JWST Integrated Science Instrument Module (ISIM)



JWST Detector Requirements
5-10 yr. @ L2 (GCR & solar particles)

- **<u>NIR Requirement</u>: Zodiacal background-limited performance for imaging, up to spectral resolution ($\lambda/\Delta\lambda$) of 10 at λ = 2 μm**
  - **<u>Likewise for MIR</u>, except λ = 10 μm**
  - **Detect sources as faint as Mag 33 which implies <1 photon/s at the detector**
- **NIR Specifications**
  - **64 Megapixels with high sensitivity**
    - **4K x 4K Mosaic FPA – 2K x 2K unit Sensor Chip Assembly**
  - **Pixel Noise (1,000 sec): Requirement 10 e^- rms (30-37 °K)**
  - **Quantum Efficiency > 80% for λ from 0.6 to 5 μm**
  - **Major Concerns – Read Noise, Dark Current and Glow**
  - **Other: Full well, Linearity, Persistence, Pixel Pitch, Frame Time,…**

JWST Detector Requirements[1]

- Radiation: <4% pixels out of spec at EOM at L2
  - "Need minimal or no effect on key parameters like responsivity, read noise & dark current."
  - Majority of permanent damage from solar particles.
- Cosmic Ray Upsets[2]: <10% (Goal of <2%) of pixels above total noise specification after a 1000 sec integration in a cosmic ray flux of 5 $s^{-1}cm^{-2}$.
  - Extensive experimental & modeling effort underway to characterize primary proton hits and secondary production in the observatory structure, both prompt and delayed (e.g. activation products).
  - Such "microglitches" have already been a problem for on-orbit IR cameras with much less sensitivity than JWST.

[1] Check http://ngst1.hst.nasa.gov/SearchLib.asp for latest version.
[2] Includes cosmic rays (w/ protons), solar particles & all secondaries!

Detector Funding Challenges

- It is recognized that detectors all too often result in significant cost overruns & schedule delays.
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- Large Telescope System Technology Initiative (LTSI)
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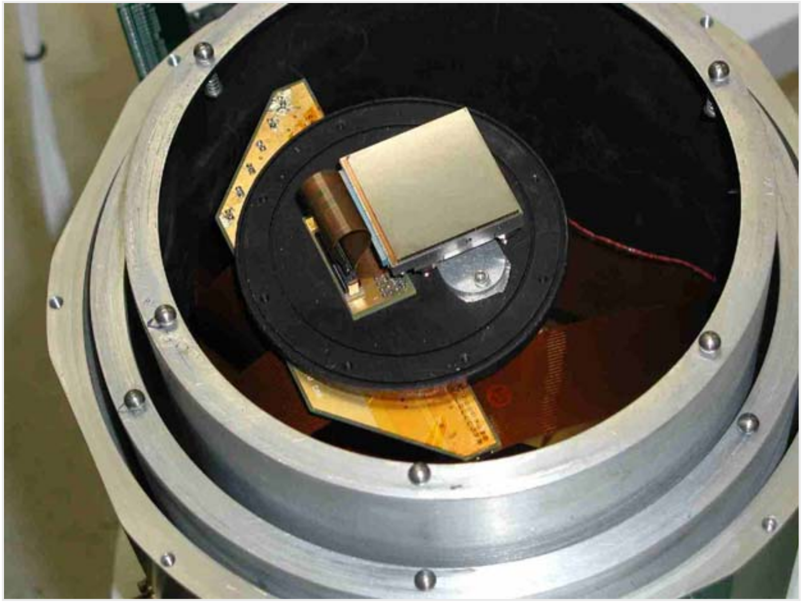
Radiation Effects Characterization

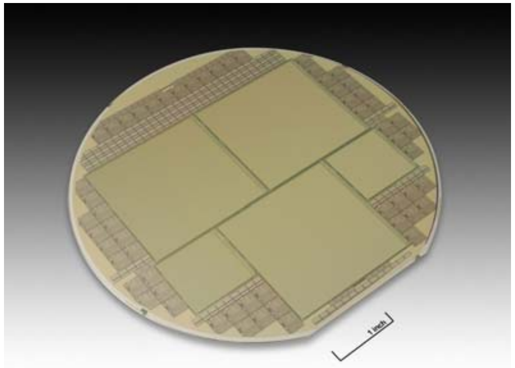
- Radiation effects & Analysis Group at NASA GSFC is teamed with the detector characterization groups to assess radiation effects via experiments & modeling.
  - NASA's Electronic Parts & Packaging (NEPP) Program Electronics Radiation Characterization (ERC) Advanced Sensors project (under NASA's Electronic Parts & Packaging (NEPP) Program) is also collaborating with JWST.
- Proton Testing (very low noise cryo accelerator environment)
  - Proton damage and transient testing (& analysis) of a HgCdTe array (with AFRL) & detector charge collection modeling have provided valuable experience. More experiments in 12/02.
  - Rockwell HgCdTe with H1RG (1k x 1k) proton tested 10/02.
  - Raytheon SB291 ROIC proton tests 12/02.
  - Raytheon InSb with SB291 ROIC to be tested 1Q03.
  - ***Test & measurement fidelity issues are significant!***

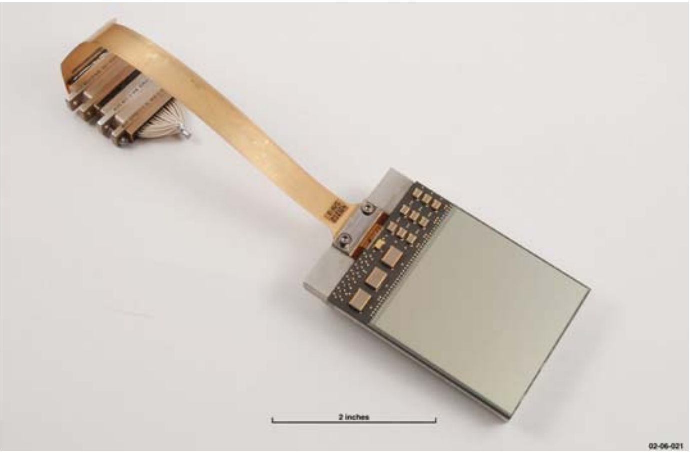
Rockwell/Hawaii 2048x2048 5μm HgCdTe NGST FPA (ARC)

Raytheon/U of R 2K x 2K InSb Detectors (ARC)



In the NGST test dewar ready for test!





Large Format Far-IR Detector Development

- Seek rare objects hence need to cover a lot of sky
  - Survey speed requires improved QE & larger formats
- Large Format Semiconducting Bolometer Arrays (384 pixels!)
- Superconducting Transition Edge Sensor (TES) Bolometers
  - Astronomical application with SQUID multiplexers, detector-noise limited multiplexed readout & novel antenna-coupled designs demonstrated for scalability
- Photoconductors
  - SIRTF demonstrated Ge:Ga: 32x32 @ 70 μm & 2x20 @ 160 μm
  - Ge-based arrays don't work >200 μm (and must be stressed for ~100 – 200 μm operation)
  - Si:As BIB (or IBC) arrays exist for MIR (6 - 40 μm in astronomy)
- Novel ultrasensitive sensitive detectors of interest
  - Superconducting tunnel junctions with RF-SET, antenna-coupled hot electron TES bolometers & kinetic inductance detectors
- Heterodyne receivers (Coherent detection)

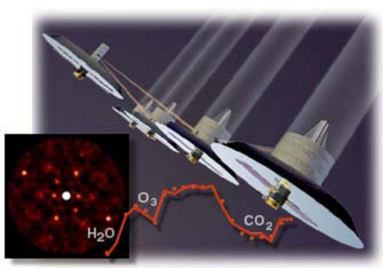
Single Aperture FIR Observatory: SAFIR

- **SAFIR (>2015; 10 m class at 20 – 600 μm)**
  - **Seeks rare objects hence needs to cover a lot of sky**
    - **Survey speed requires improved QE & larger formats:**
      - **128x128 array with NEP[1] ~3 x 10^{-19} W/√Hz**
      - **64x64 array with NEP ~3 x 10^{-20} W/√Hz**
- **Superconducting TES bolometer**
  - **Can be made in large arrays with low power operation**
  - **Small mass, volume, and cryogenic system complexity**
  - **Very sensitive and fast**
  - ***Not as mature as other technologies***
- **Semiconducting bolometer**
  - **Well-established**
  - ***Cryo-electronic assembly can be more complex***
  - ***Not easily multiplexed***

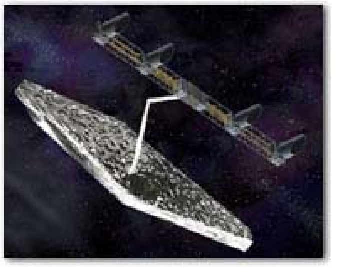
1 Noise Equivalent Power (NEP): The power falling on 1 detector to produce a S/N = 1
Note that some sources quote a requirement of 10-21 W/√Hz.

Terrestrial Planet Finder (TPF)

- **Selected 2 of 60 architectures (5/02), to select one in ~2006.**
- **IR Nulling Interferometry (large arrays of sensitive FIR detectors)**
- **UV / Visible Coronagraph *(TPF + SUVO??)***
  - **Photon-counting microchannel plate (MCP) detector arrays**
    - **Large format (in area & pixel count), low background, zero read noise, long wavelength rejection, radiation tolerance, R.T. operation**
    - **Revitization with advent Si MCP that can serve as substrate for high QE photocathodes. Capability for larger formats & production yield. Novel readout technology also being explored.**
  - **AlGaN arrays are exciting and have commercial & DoD interest but dark currents are many orders of magnitude too high…**

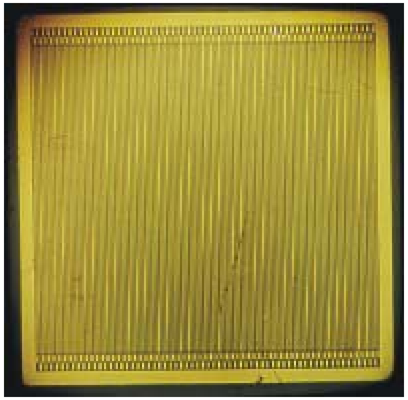


- ***UV Observatory detector working group is considering technology paths for next UV/Optical Telescope.***



SEU Constellation-X (~2009 Launch)

- Array of X-ray telescopes to look at black holes, galaxy formation & missing baryonic matter.
- Hard X-ray Telescope (HXT) at 6-40 keV!
  - CdZnTe or CdTe arrays
  - Series of stacked Silicon strip detectors is being evaluated as a backup technology



CdZnTe

- X-ray Calorimeter Array (1-10 keV)
  - 32x32 superconducting transition edge sensor (TES) microcalorimeter with NEP ~3 x 10^{-18} W/√Hz
    - Need simultaneous readout of all pixels, single photon detection
    - Both far-IR & X-ray communities are interested, a plus.
    - Could be pathfinder for LF if funded sufficiently.

SEU Constellation-X, cont.

- <u>Gratings / CCD Arrays</u> (0.25 - 1 keV)
  - Investigating MIT-LL resistive-gate CCD with enhanced low energy efficiency in a front-illuminated CCD
    - Development on hold.
  - MIT-LL Event-driven CCDs (signal charge is sparse)
    - Gen I: 512 x 512 out of fab; Gen III: planning 3k x 4k

Si-based Detector Arrays

- CCD
  - Wide variety of very high performance large format CCDs for applications in X-ray and UV/Visible, therefore a critical technology to push in foreseeable future.
  - Radiation sensitivity is an important problem, especially charge transfer efficiency (CTE) degradation. (Also hot pixels, increased dark current, transients.)
- APS
  - No CTE issue, and opportunity for highly integrated, low-power operation.
  - Dark current levels, uniformity, reset noise, etc. remain issues.
- CMOS Hybrid
  - Promising technology in development. (e.g. Rockwell)
- CID
  - Again, no CTE issue, but less performance. One manufacturer.
- Viability of technology base is a great concern.

CCD Mosaics

- CCD array size continues to grow beyond 4k x 4k
  - Can fully sample the working field of view of 8-10 m telescopes but plans for 25 – 100 m telescopes & high resolution cameras on the ground.
- Growth in mosaics accompanied by more complex controller systems able to handle multiple readout channels.
  - Power, heat & cost challenges in space
  - ASIC controllers are being used
  - Hybrid imaging technologies using bump bonding to couple CMOS circuitry to a CCD-based array (JPL, MIT)

[1] Clampin, "Space Astrophysics Detectors & Detector Technologies", June 2000.

Future Missions with Mosiacs

- Supernova Acceleration Probe SNAP (2 m)   (DOE-led)
  - GigaCAM – billion pixel imager using 4-side abuttable high resistivity LLNL p-CCDs & 2k x 2k Rockwell NIR HgCdTe devices.
    - Heavy leverage from NASA HST WFC3 1k x 1k 1.7 μm array and JWST 2k x 2k format ROIC development.
  - Mosaic of 36 2k x 2k HgCdTe NIR and 36 3.5k x 3.5 K p-CCDs
- Kepler (1 m)   Mosaic of 42   2.2k x 1k n-CCDs
- ESA-led GAIA   Mosaic of 200   4k x 2k n-CCDs
- SUVO (4 – 8 m)
  - Requires a minimum of 16k x 16k. 4k x 4k CCD development by HST ACS ‘surprisingly difficult’ so plan a mosaic.

Hardening CCDs is a Challenge

- **Incremental hardening techniques of n-CCDs**
  - **Multi-phase pinned (MPP) operation, formats that minimize the number of parallel transfers (e.g. ACS requested a 4k x 2k CCD from SITe), clever readout schemes, cooling, mosaics.**
    - **Efficacy of some good ideas such as the 'notch' has been demonstrated but can be elusive.**
    - **Other tricks such as filling traps in advance of a target can be effective in some cases, but are not a given.**
  - **p-CCDs may provide a X3 improvement in CTE radiation performance, based on an E2V prototype device.[1]**
    - **Further efforts, including gettering and notch techniques are being pursued by DTRA (SBIR with Full Circle Research), and programs at Berkeley (e.g. SNAP).**

[1] Hopkinson, IEEE Trans. Nucl. Sci., Vol. 46, Dec. 1999.

CCD Lessons Learned

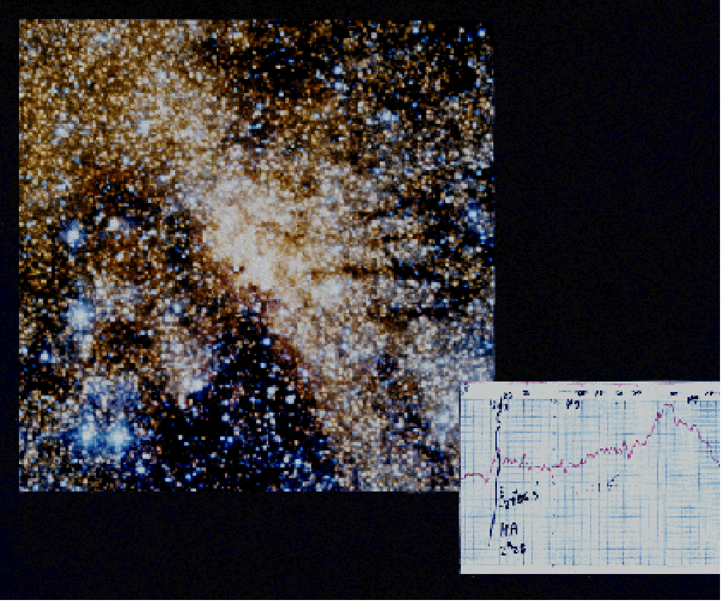
- Hubble Space Telescope (HST) Experience
  - Wide Field Camera 2 CTE has decreased 15 – 40% from 1991-1999, depending on the sky background level. (Heavily shielded LEO)
    - The key scientific observations tend to be degraded first.
  - Hot pixel growth rates require monthly anneals that consume 10% of the observing time on the HST instruments (STIS, WFC2, ACS).
  - We are currently studying this effect on ACS (SITe 2k x 2k) through on-orbit CTE and hot pixel characterizations, and through ground-based studies on the Wide Field Camera 3 (E2V CCD43) to be launched in 2004. We have no idea why ~0 °C annealing is effective!
- The sensitivity of CCDs to radiation is ***extremely*** application dependent. LEO can be a challenge!
  - Likewise, this leads to significant ground test fidelity issues. For ex., What is the appropriate CTE measurement technique for a given on-orbit application?

Key UV / Visible Detector Challenges

- **UV / Visible**:
  - We enter "billion pixel missions" requiring large volume fabs at the same time the CCD industry is meeting competition from APS & CMOS technologies.
  - Specialized CCDs (e.g. QE improvement in NUV (200 – 400 nm) and the FUV (100 – 200 nm)
    - UV imaging with CCDs remains a challenge due to their high QE in visible, low UV flux levels & low sky backgrounds
- **UV**:
  - Solar Blind UV detectors with larger formats & higher QE
  - Current missions use photocathodes (PC) with MCP intensifiers with various readouts.
    - In the near & mid term PC/MCP/RO technology must be pushed
    - Emerging Si MCPs promise for larger formats & production yield
  - Other technologies: Electron Bombarded CCDs (EBCCDs), AlGaN, GaN or SiC arrays, as well as panchromatic technologies such as delta-doped CCDs, energy-resolving STJs & TESs.

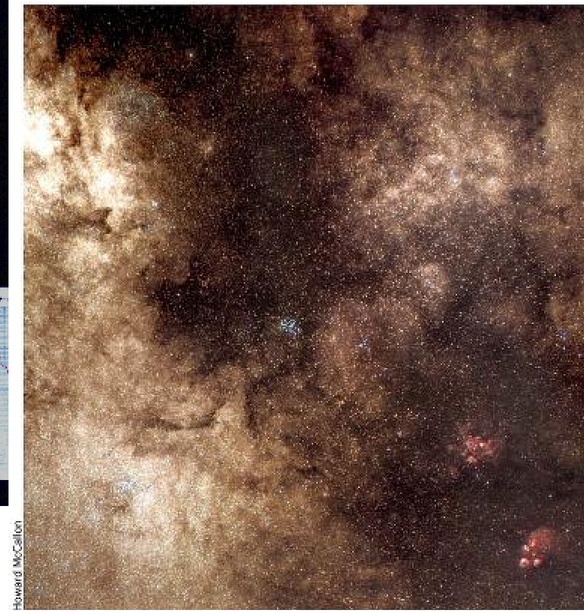
Longer Wavelength Detector Challenges

- IR, Submm & millimeter wave working group recommends 'detector czar' to see balanced and sustained support to maintain or advance key capabilities with vendors.
  - Longer wavelengths have no military or commercial interest.
- Photoconductors: Arrays of 1024 pixels exist out to 120 μm using CMOS ROIC technology adapted from shorter wavelengths. Need to generally expand formats.
  - Si ROIC is critical for large formats, and NASA has unique deep-cryogenic CMOS processing needs.
- Develop Ge or GaAs IBC detectors (possibly out to 400 μm) in large formats.
- TES bolometers should be producible in large arrays, and development of SQUID multiplexers & system architectures will be key.
- Semiconducting bolometers with individual JFET amps perform well but difficult to scale. Monitor Herschel large format arrays mated to MOSFET readouts.
- Other : Monitor energy-resolving/photon-counting STJ & TES that may emerge in the NIR, as well as bandgap engineered devices.



Single PbS Detector, 1967
PtSi NIR Mosaic, early 1990s

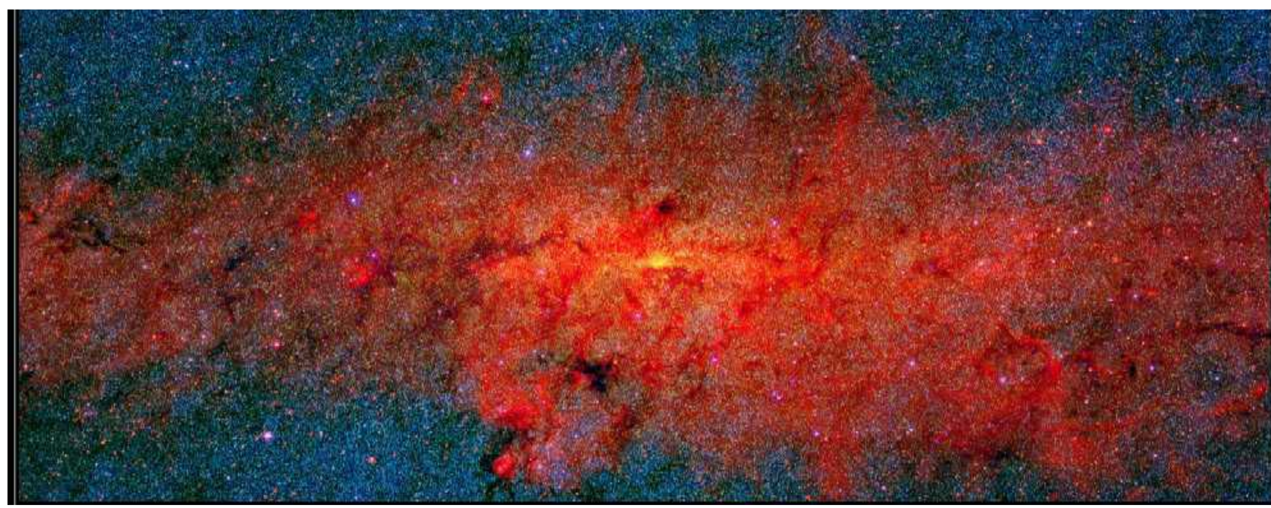
~ 1995



Visible

2MASS @1.25 μm & 2.17 μm*

The Galactic Center



2 MASS + Midcourse Space Experiment (MSX) @ 11 μm

**2MASS is 2 μm All Sky Survey*