Large Space Telescopes

Eduardo do Couto e Silva

SLAC National Accelerator Laboratory

Kavli Institute for Particle Astrophysics and Cosmology

Stanford University

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Vienna, Austria

Outline

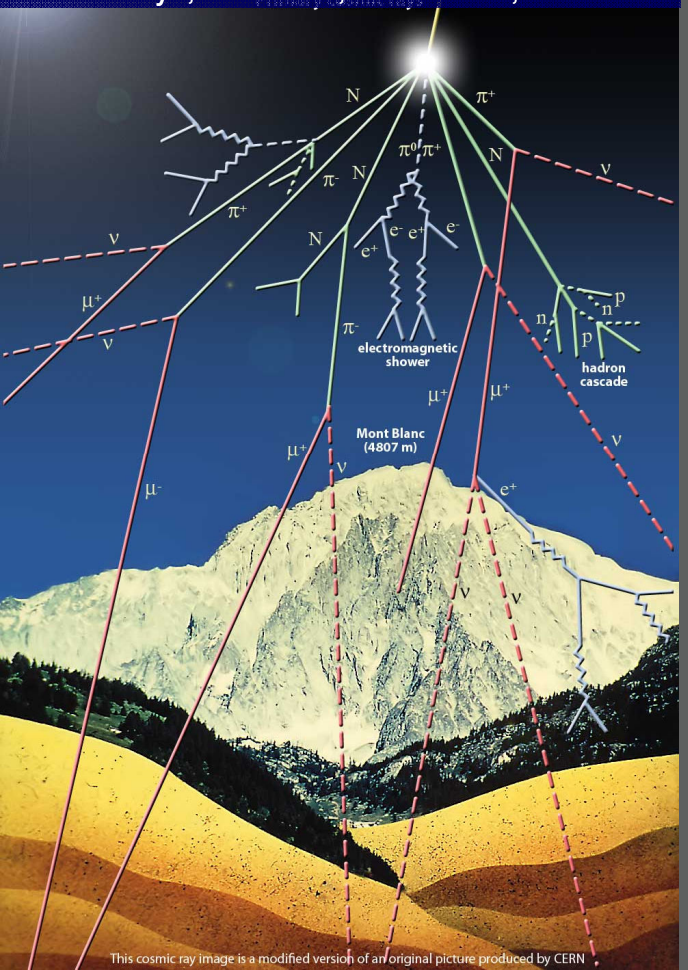
- Introduction
  - Definition of Scope
- Large Focal Plane Arrays (focusing telescopes)
  - Semiconductors
  - Superconductors
- Large Field of View (non focusing telescope)
  - HEP contribution to high energy astrophysics
- Summary

Signals from the Universe

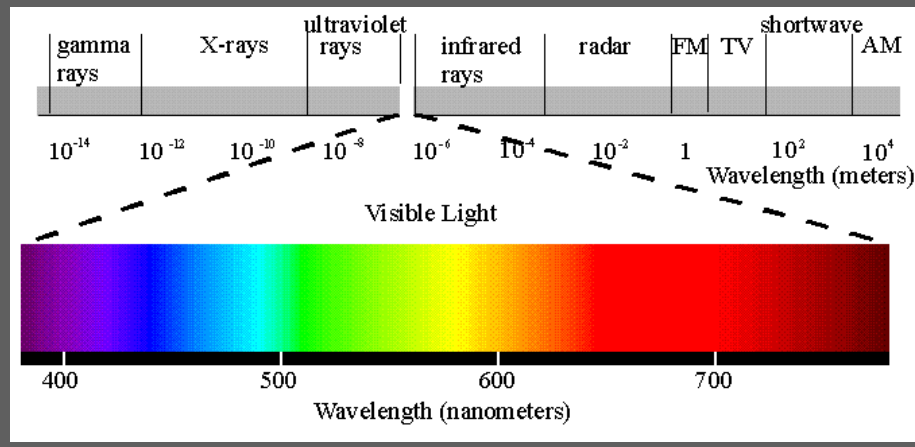
DAFNI, Theopisti; DE ROSA, Gianfranco; MARRODAN UNDAGOITIA, Teresa; PINSKY, Lawrence; SASAKI, Shinichi; YAHLALI, Nadia; ZEHR, Fabien

Particles

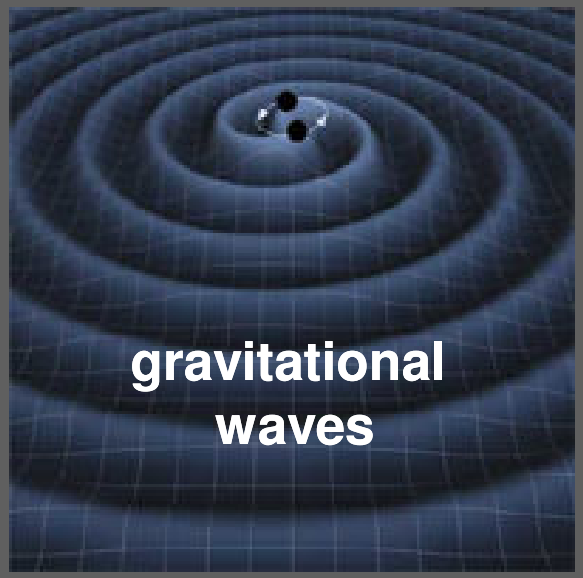
cosmic rays, neutrinos, neutralinos, axions…



GIUBILATO, Piero; UENO, Kazuki; TAKAHASHI,Michiaki



Electromagnetic Radiation

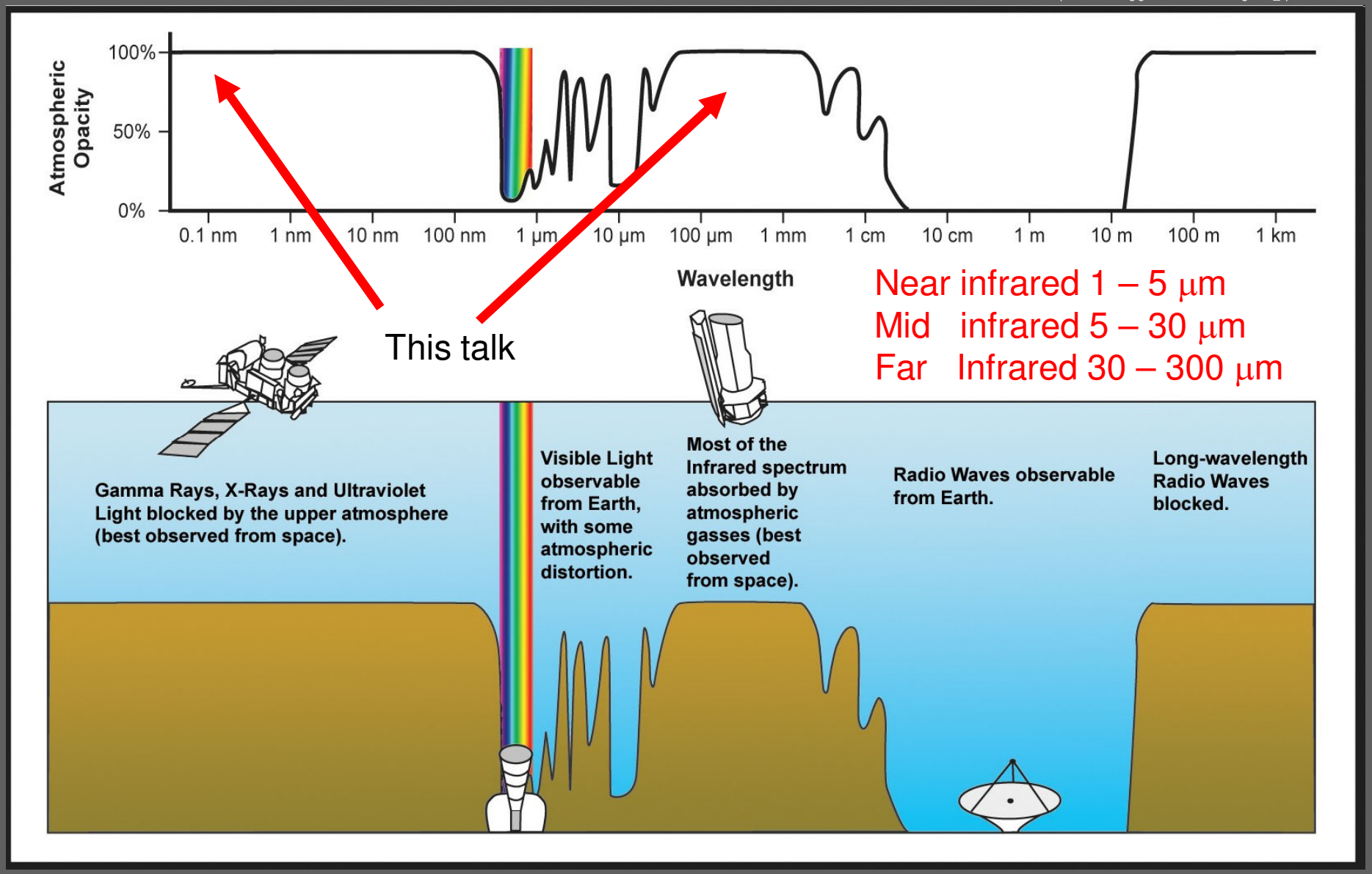


"Perhaps with the exception of detectors from the very highest energy gamma rays, far infrared detectors lag significantly behind all types, and as a consequence this wavelength is comparatively little explored"

M. Ressler et al *Astro 2010 white paper*

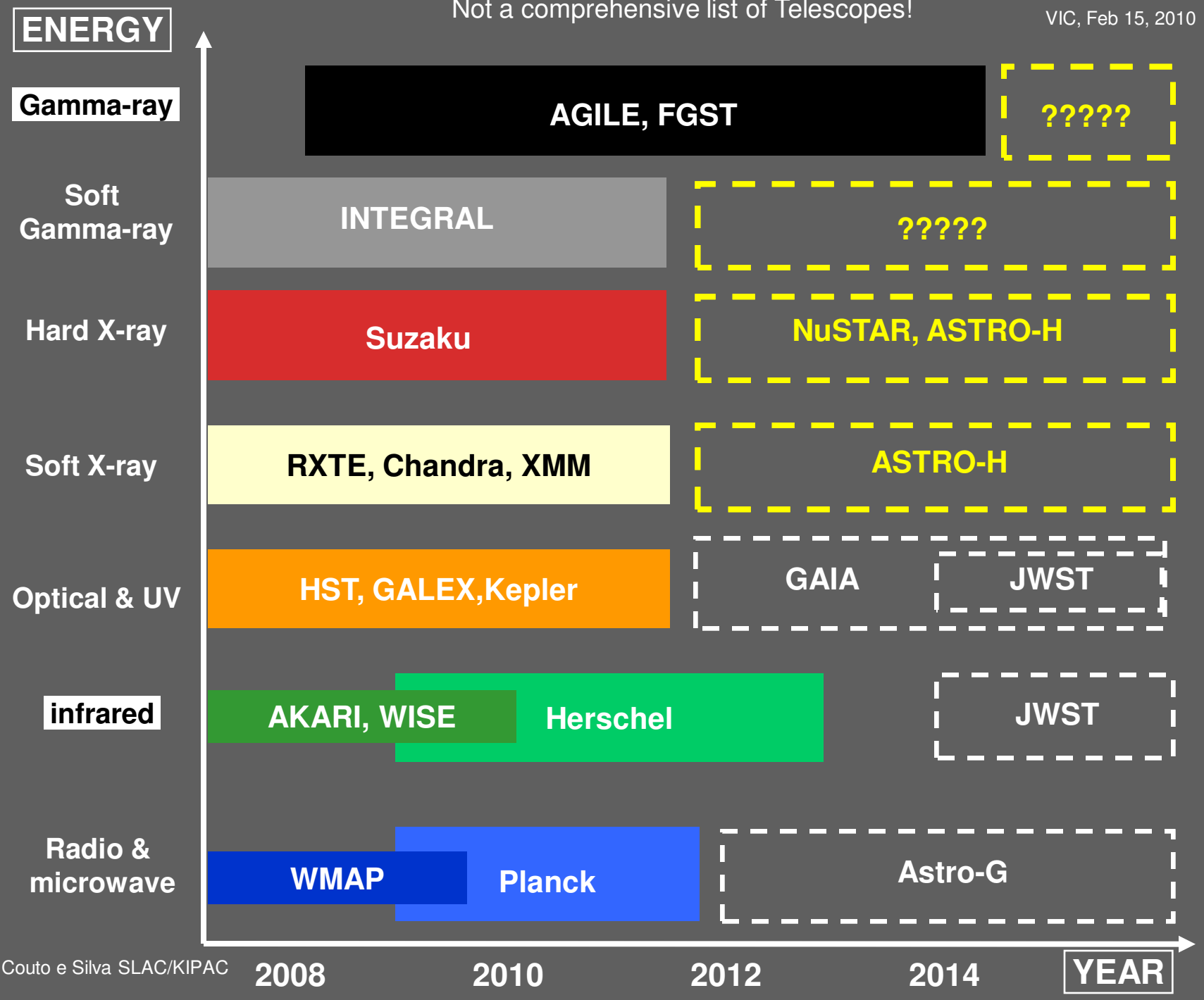
Atmosphere is opaque to certain wavelengths

http://www.tutorgig.com/ed/electromagnetic_spectrum



Not a comprehensive list of Telescopes!

VIC, Feb 15, 2010



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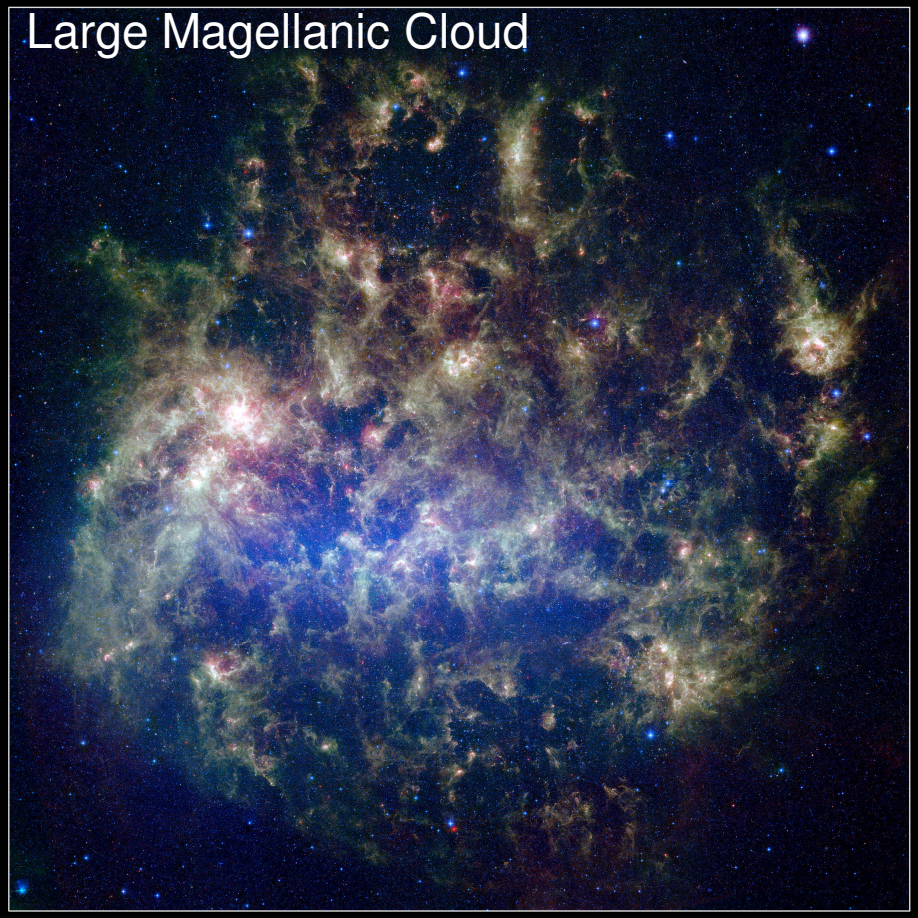
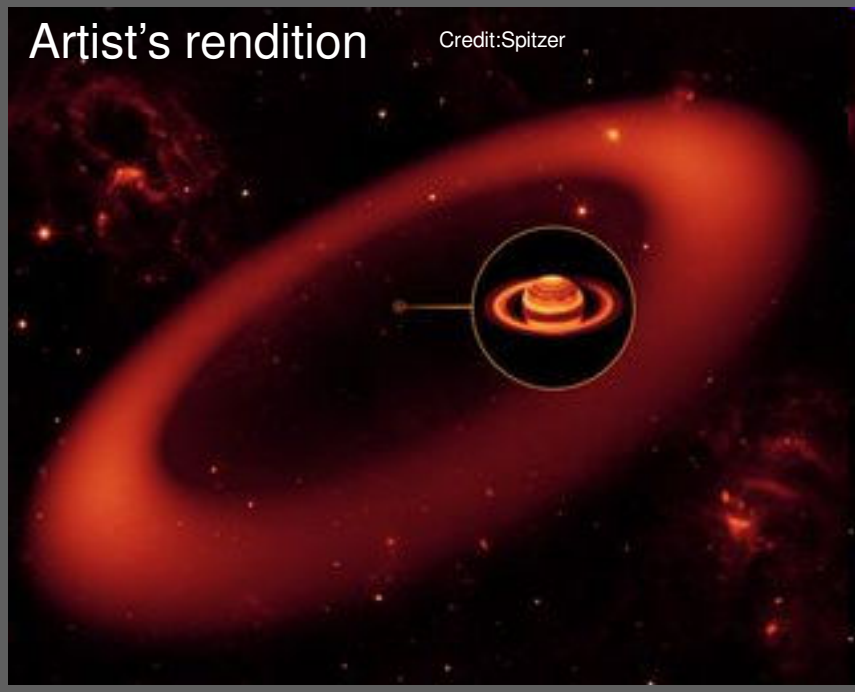
Near and mid Infrared Science (< 30 μm)



HIgh star forming activity



Large ring of dust around Saturn (ring volume can hold 10^6 Earths!)

Early Universe/high redshift
Star and Galaxy Formation
Planetary Systems

What do you mean by Large Space Telescopes?

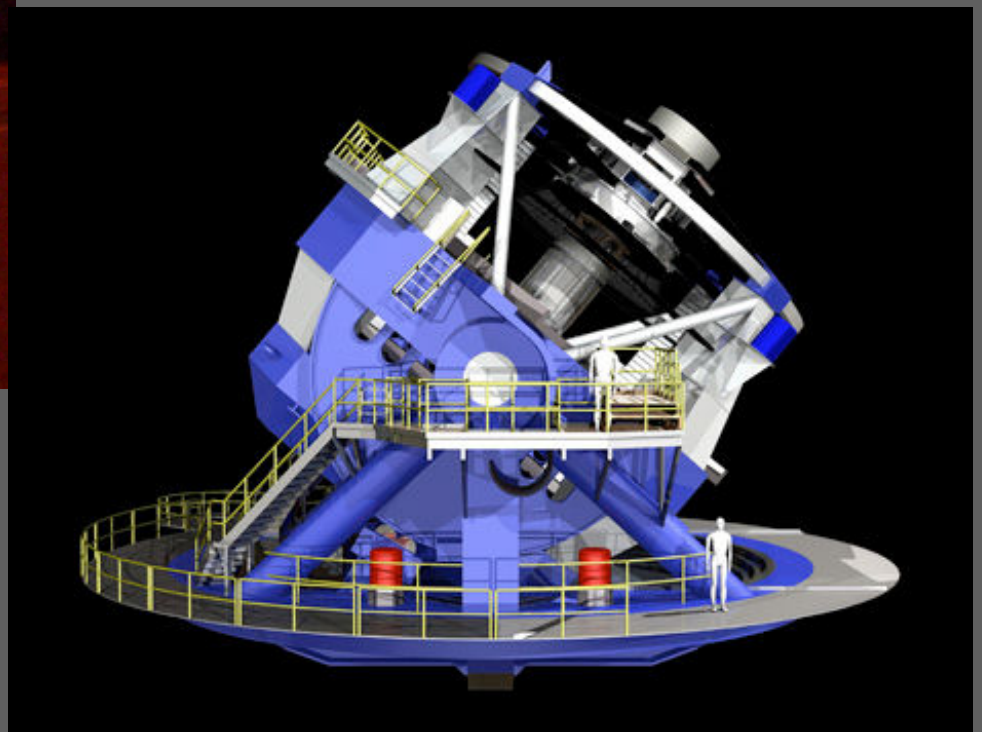
- **Large Mirrors (not discussed in this talk)**
  - **Large Collecting Area**
- **Large Focal Plane Detectors/ Large Field of View**
  - **Large number of pixels**
  - **Large number of multiplexed readout channels**
  - **Large substrate size**
  - **Large Arrays/Mosaics**

State of the art – Optical Focal Plane Array

LSST focal plane array scale model.

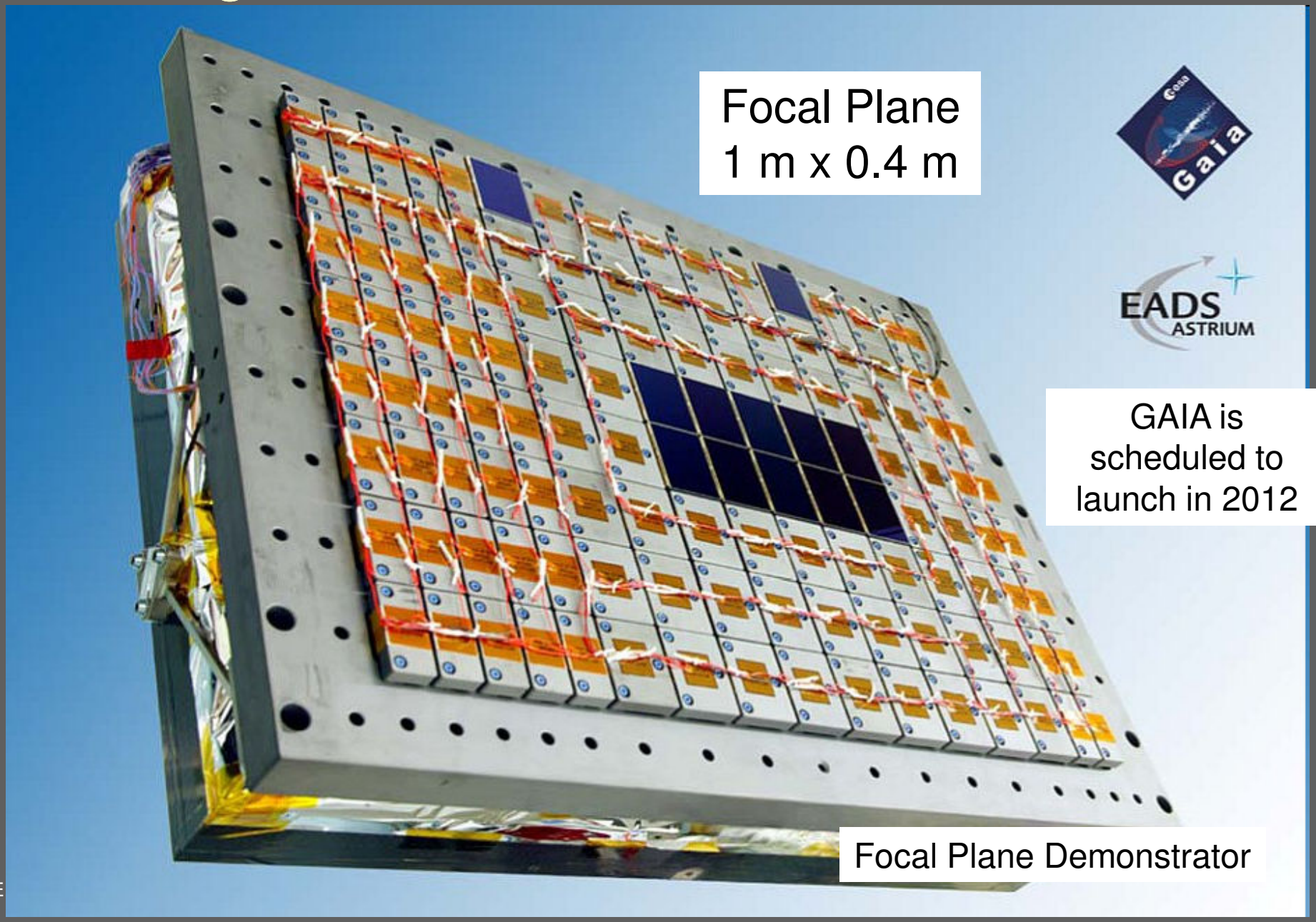
… but on the ground

LSST
3.2 Gigapixels



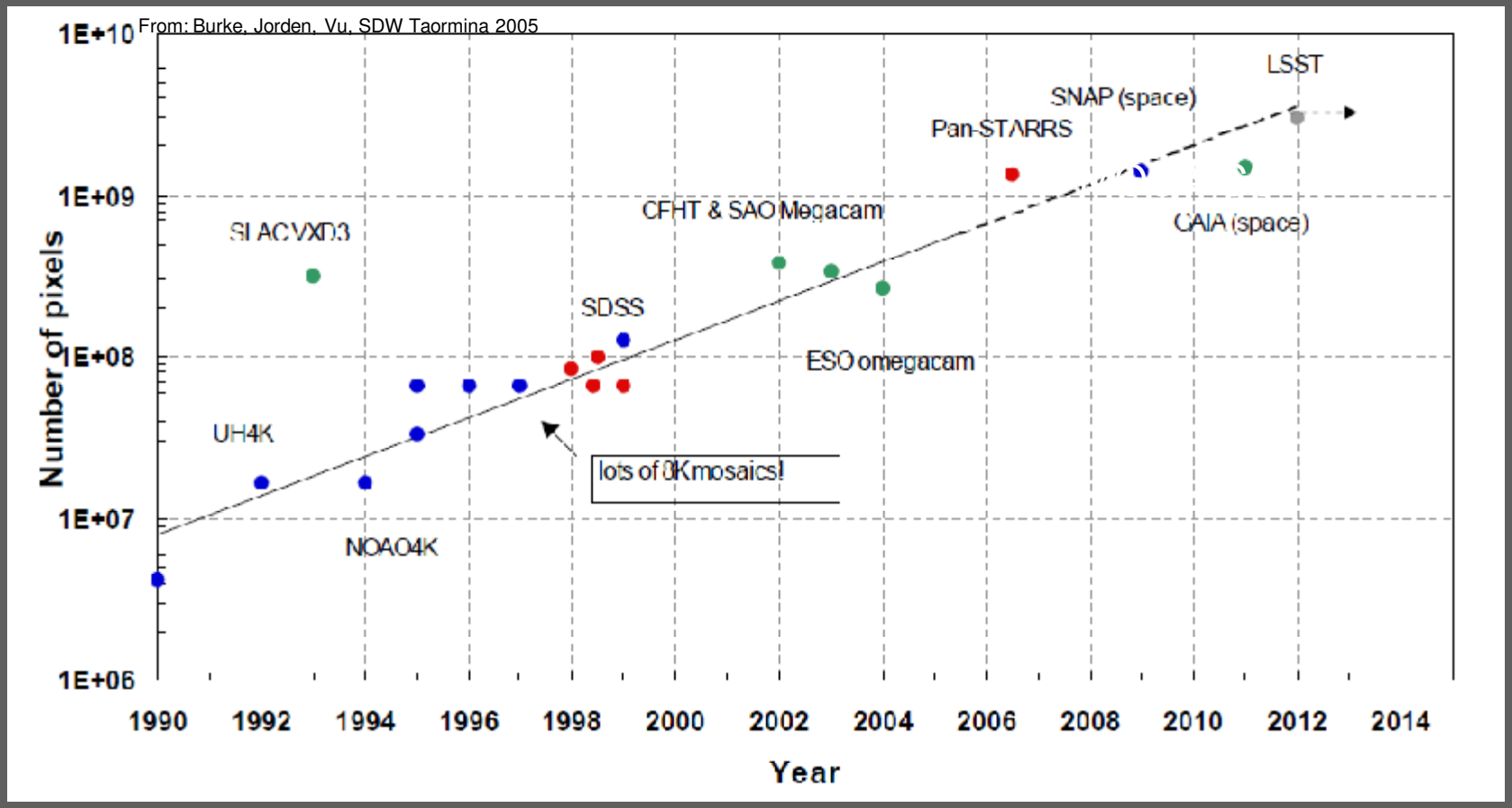
LSST operations planned for ~2015
(dark matter, dark energy etc via
gravitational lensing)

Large Mosaic of CCDs in SPACE – GAIA



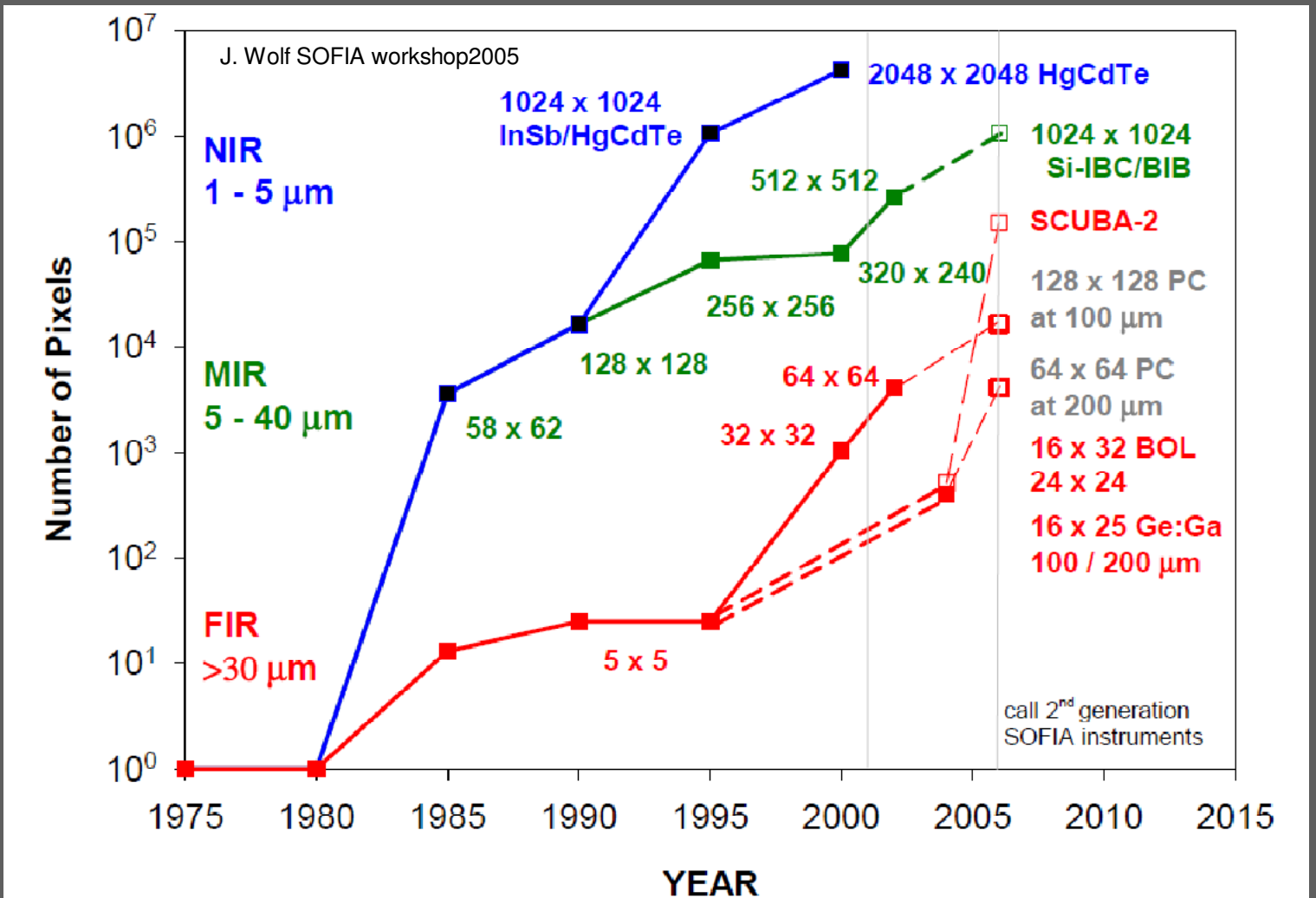
Optical CCDs – The Largest Number of Pixels

CCD Technology is approaching 10^9 pixels (ground and space)



Number of Pixels for Infrared Arrays

For quite a while, far Infrared (> 30 μm) sensors were neither of military nor of commercial interest



Evolution of near IR Arrays (1 to 5 μm)

32x32

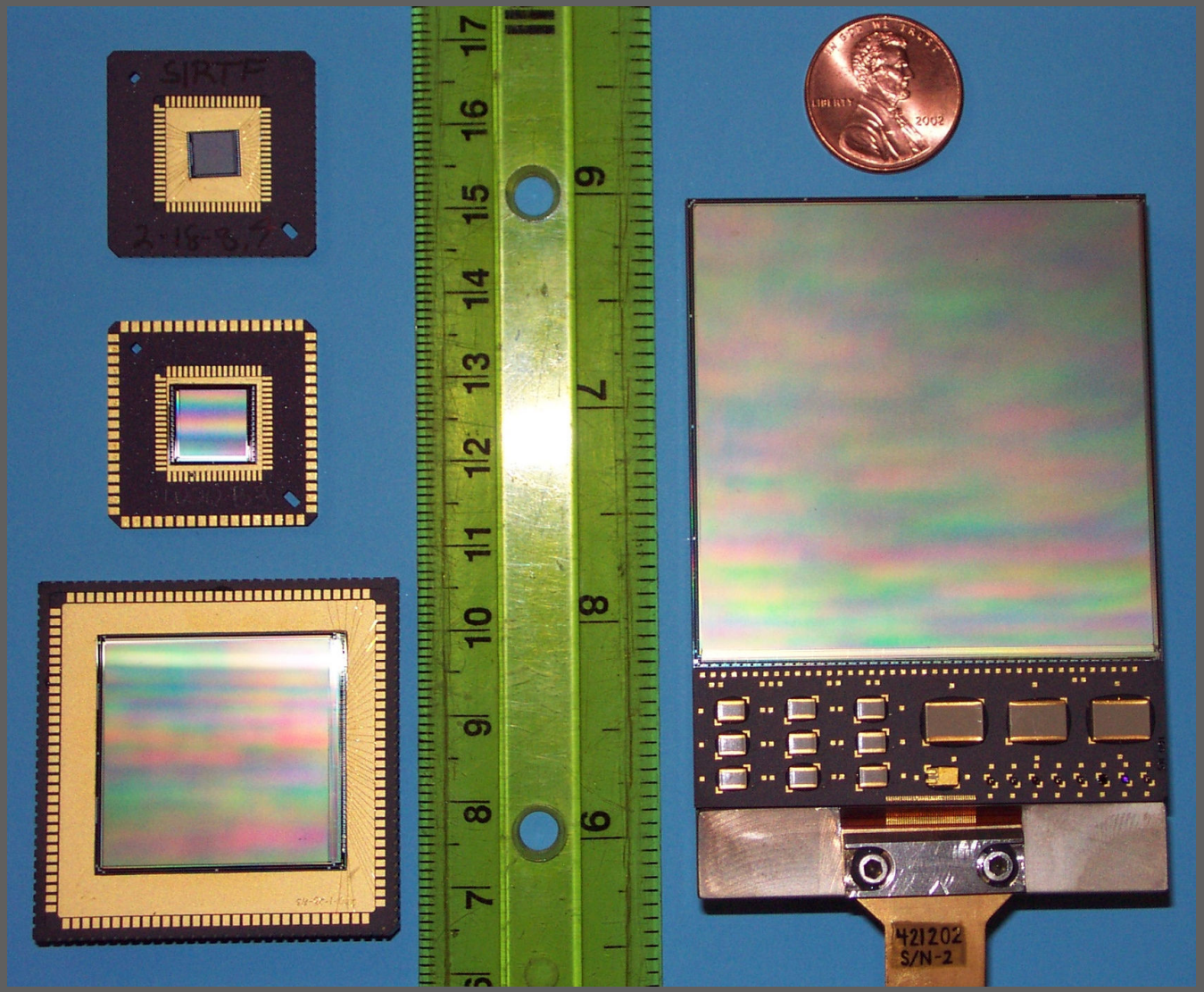
(1983)

58 x 62

(1988)

256x256

(1998)



2048 x 2048

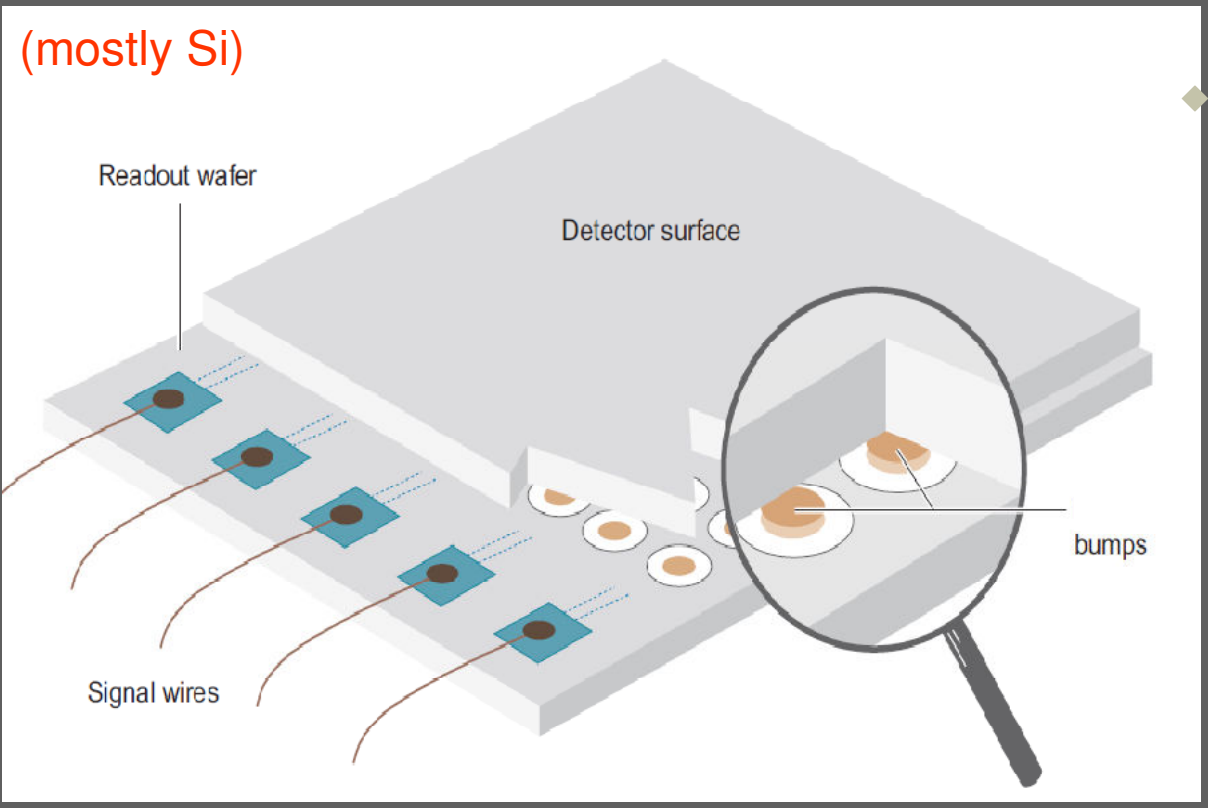
(2008)

Pipher et al.

Slide from Harvey Moseley's talk in LTD13, Stanford 2009

Large Format Focal Planes with Hybrid Arrays

G. Rieke, Annu. Rev. Astron. Astrophys. 2007. 45:77–115



- Technology challenges
  - Large substrates
    - Availability of materials
    - Thermal mismatch
    - Mating forces
  - Closely packed arrays
    - mosaics
  - Smaller pixels sizes
    - Interpixel capacitance
    - diffraction limited

Can hybrids replace CCDs?

"The CCD has provided new possibilities to visualize the previously unseen"

Press Release by the Swedish Royal Academy of Sciences, 2009

- **Excellent Performance**
  - **Low read noise**
  - **Low Dark Current**
  - **Good Linearity**
- **Challenges to overcome in space**
  - **Slow readout**
  - **Large power consumption**
  - **No random access (to pixels)**
  - **Insensitive to time variability in astronomical sources**
    - **exposure and readout are serial**
  - **Radiation in space**
    - **especially at Low Earth Orbit**

Photo by U. Montan

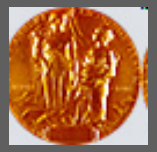
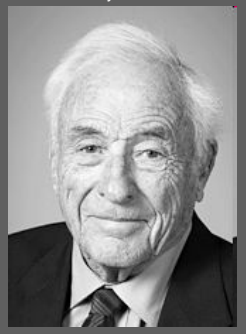


Photo by U. Montan



Willard Boyle

George Smith

Improvements expected with Hybrid technology

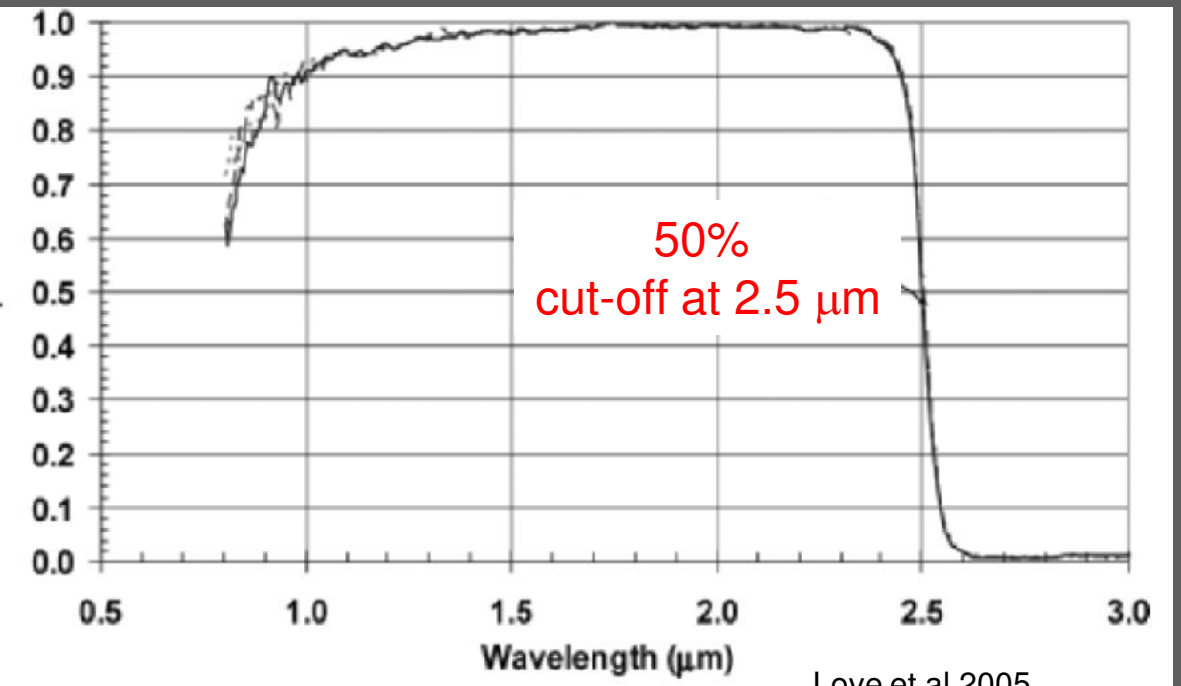
Infrared Hybrid Arrays

- **Single readout amplifier per pixel**
- **High Efficiency**
  - **at short wavelengths**
- **Cryogenic cooling**

"Bandgap Engineering"

The bandgap energy sets the cut-off wavelength

$$\Lambda_{cut-off} = \frac{1.239}{E_{gap}} [\mu m]$$



Love et al 2005

Can not use Silicon!

To go beyond 1.1 μm we need materials with band gap energy smaller than the energy of infrared photons

Infrared Arrays in the 90s (Spitzer Telescope)

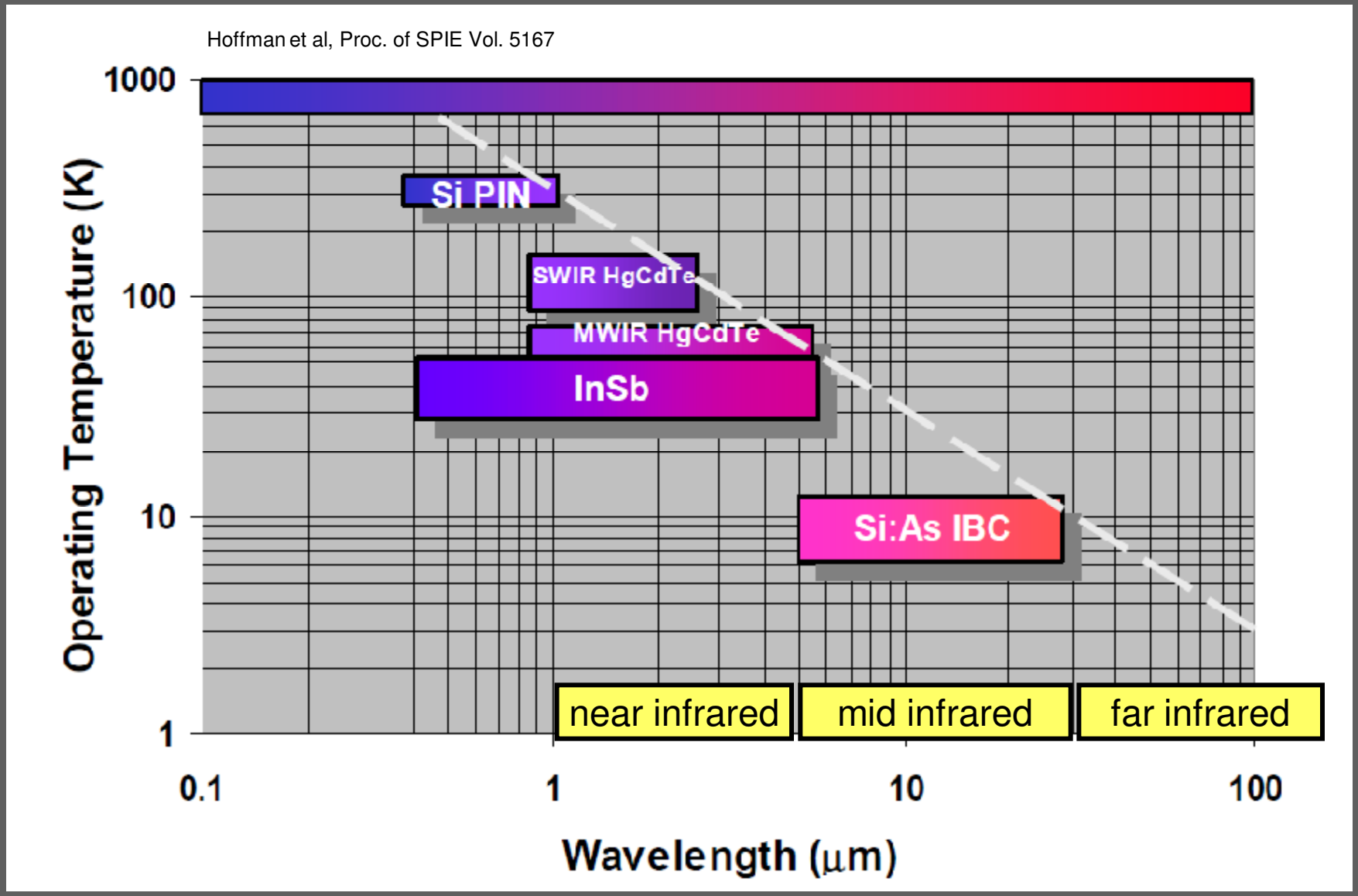
Array Type	Spectral Range (μm)	Pixel Count	Dark Current (e^-/s)	Tempera-ture (K)	Noise (e^-)	Quantum Efficiency
***Spitzer* (2003)**						
InSb	2.8–5	131 072	0.5	15	6.8*	0.86
Si:As IBC	5–26	180 224	2.4	6	6.6*	0.55
Si:Sb IBC	14–38	32 768	<40	4	30*	0.25
Ge:Ga	51–106	1024	156	1.5	92*	0.18
Stressed Ge:Ga	140–174	40	500	1.5	280*	0.15

P. Richards and C. R. McCreigh, Physics Today, Feb 2005

Technology up to 30-40 μm is quite mature and the field is pushing for large arrays

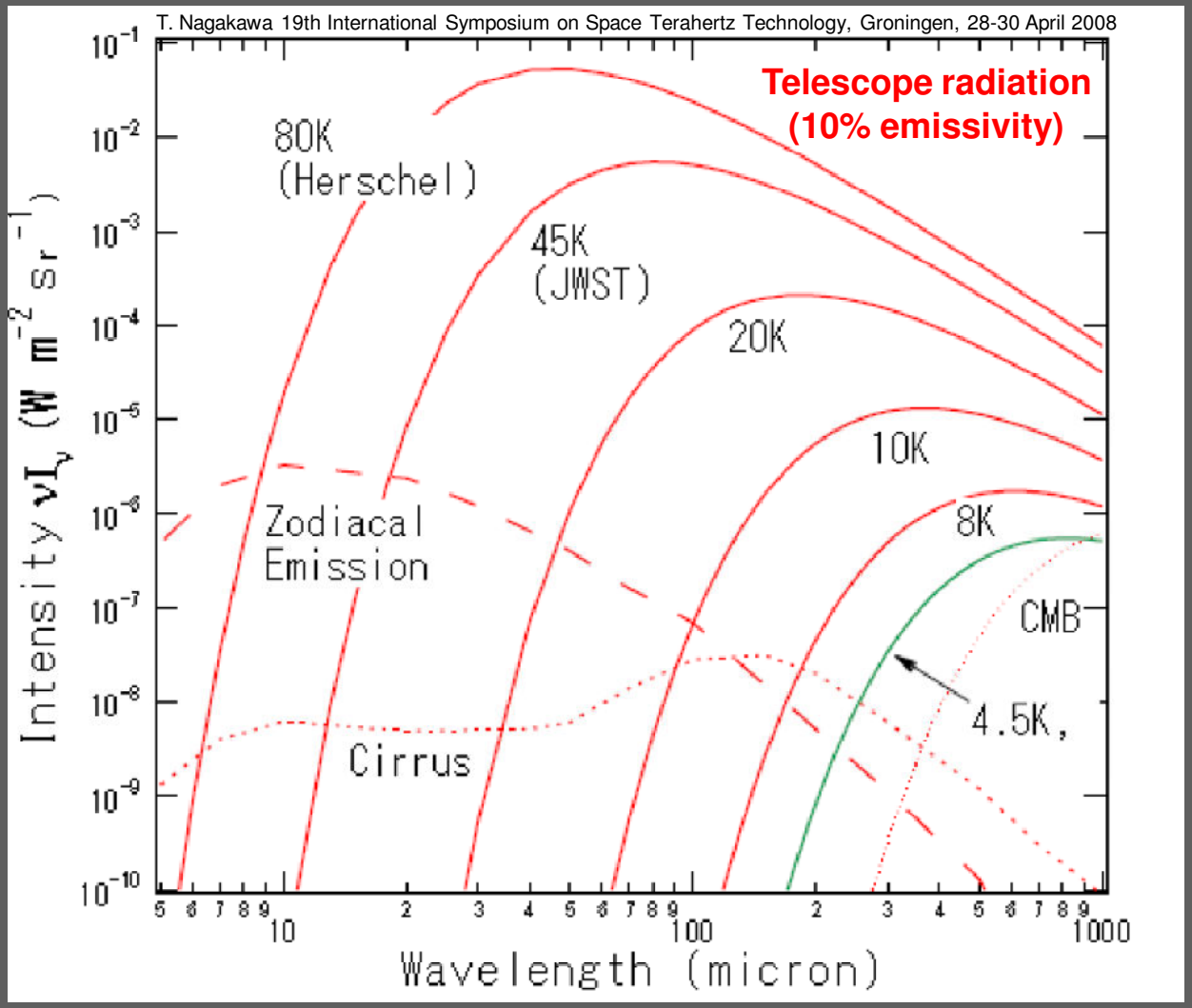
For longer wavelengths (far infrared and beyond) exciting technology developments

Long Wavelengths Require Low Temperatures



Infrared Telescopes must be cooled in Space

Mid infrared | Far infrared | sub-mm



Telescopes as cold as around 5 K are required to achieve natural background-limited observations in the mid- and far-infrared.

Cryogenics is Space is Hard

…but needed for background limited performance

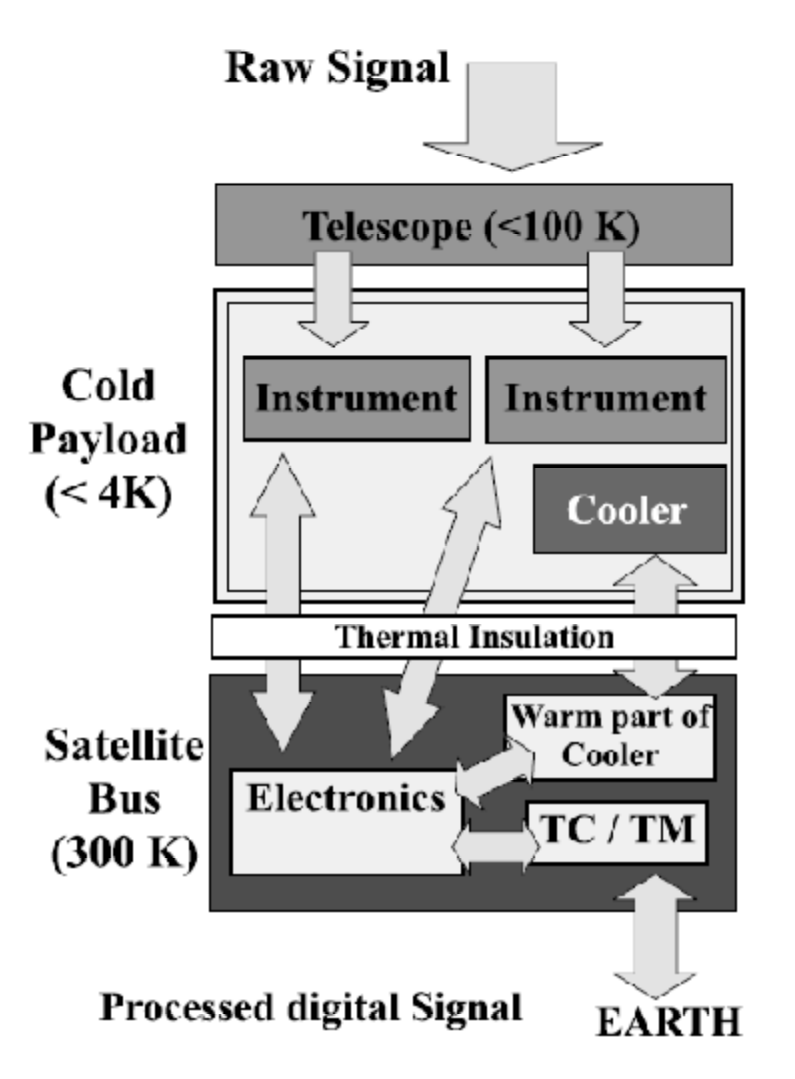
B. Collaudin and N. Rando, *"Cyogenics 40 (200) 797"*

- **T > 40 K**
  - **Radiative cooling**
  - **Space is a 3K heat sink**
- **1 k < T < 40 K**
  - **Liquid He**
  - **Solid Hydrogen**

improvement

Mechanical Coolers
Longer lifetime
Less weight
Less power

- **T < 1 K**
  - **^{3}He, ^{4}He Sorption coolers**
- **T < 100 mK**
  - **Dilution Refrigerator (in 0 g !)**
  - **Adiabatic Demagnetization Refrigerator**



Mechanical Coolers in Operation (AKARI)

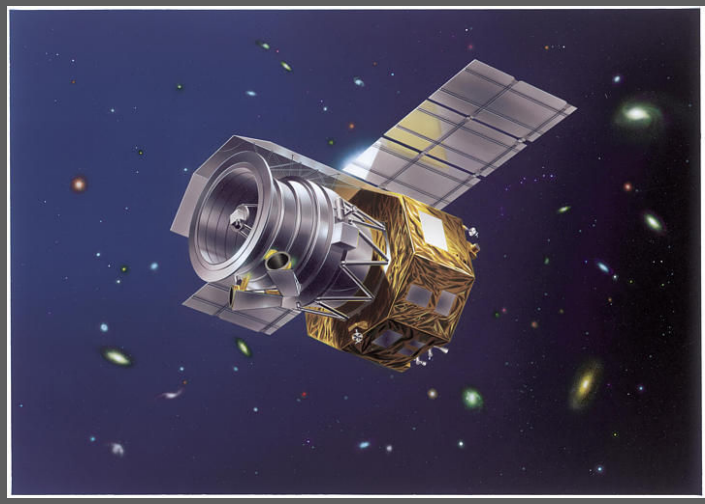
M. Hirabayashi et al, *Cryogenics 48 (2008) 189–197*

Mechanical coolers shield cryogen from higher heat fluxes

- **Liquid He II (170 l or 25 kg)**
  - **superfluid loaded at launch time**
- **Mechanical coolers extended Helium life by 360 days!**
  - **After He is depleted mechanical coolers can still cool down to 30 K**

Measurement of the remaining helium mass

	Days after launch	He temperature rise (mK)	He mass (kg)
#1	20.4	1.08	20.95
#2	77.0	2.78	14.71
#3	135.0	3.14	13.10
#4	379.44	6.54	6.29

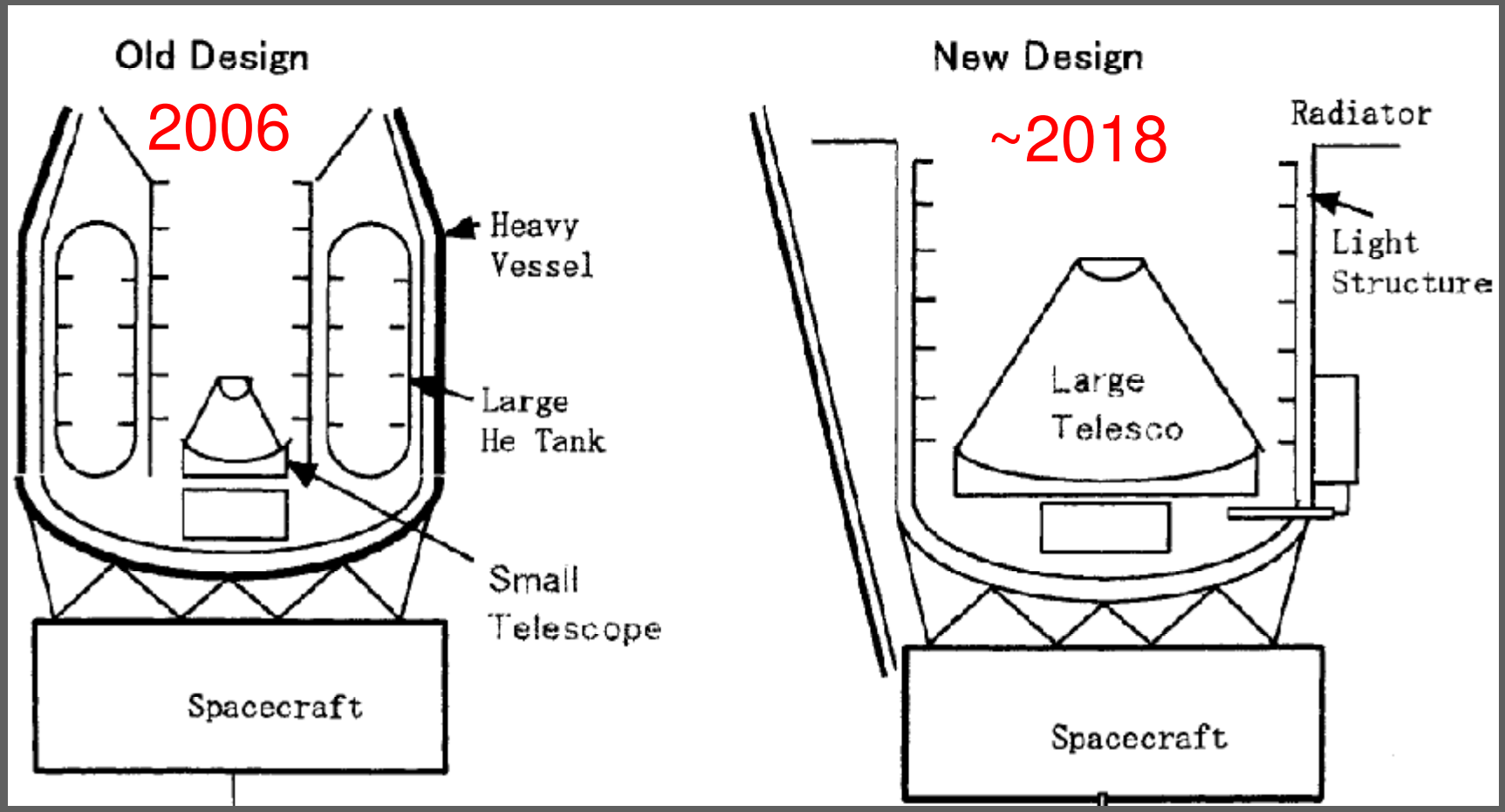


From Aug 2006 until May 2007 AKARI completed the far-infrared All-Sky Survey covering about 94 per cent of the entire sky. Cryogen ran out after that.

Mechanical Coolers: Longer Missions, Larger Telescopes

AKARI
0.7 m mirror diameter
Cryo operations 1.5 yrs

SPICA
3.5 m mirror diameter
Cryo operations 5 yrs



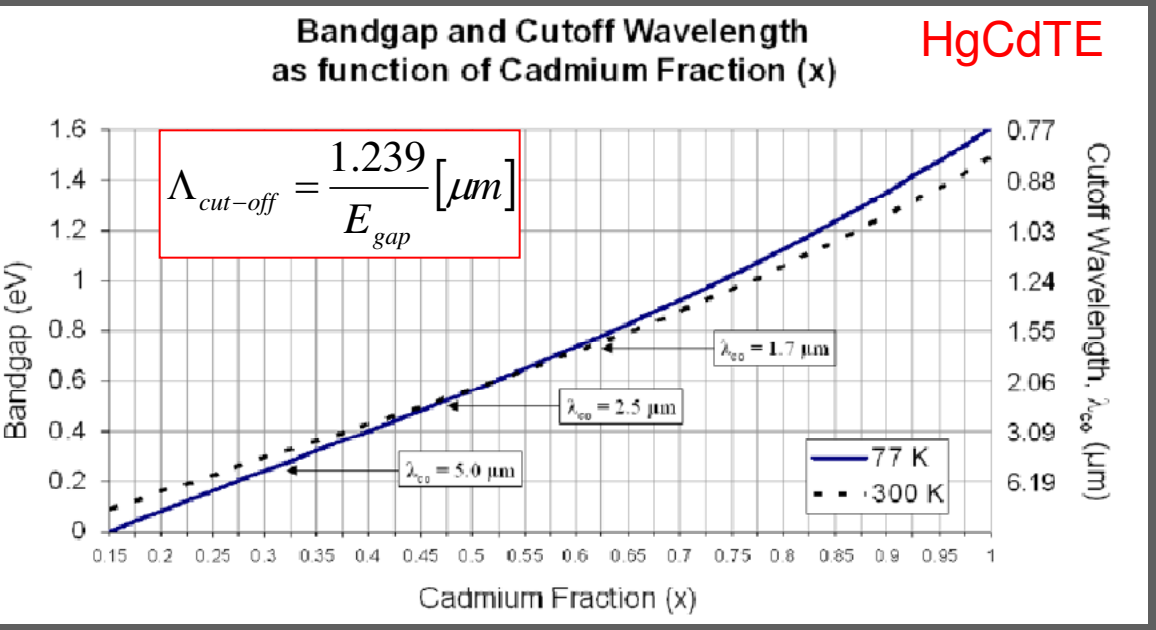
H. Matsuhara SPICAT. Nakagawa et al. / Advances in Space Research 34 (2004) 645–650

Photovoltaic Detectors – pn Junctions

For near and mid infrared detection

Material	E_{gap} (eV)	$\Lambda_{cut\text{-}off}$ (μm^{-1})
Si	1.12	1.1
InSb	0.23 (@77K)	5.4
HgCdTe	tunable	< ~10

- **Lattice Mismatch**
  - **Controlled growth on CdZnTe**
    - a_{CdTe} = 6.48 Å
    - a_{HgTe} = 6.453 Å
- **Thermal Mismatch**
  - **Si = 2.6 10^{-6} /K**
  - **CdTe = 5.3 10^{-6} /K**
- **Molecular Beam Epitaxy**
  - **Major breakthrough**
  - **Reduced dark currents**

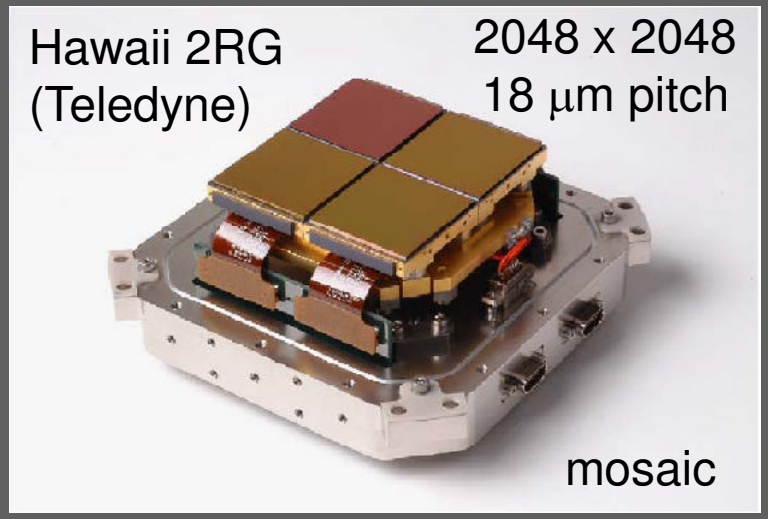


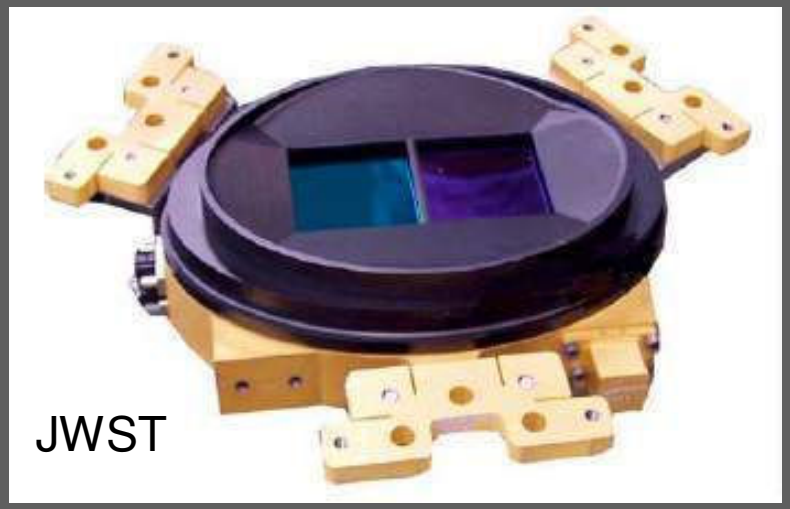
Challenges

Thermal and Lattice mismatches

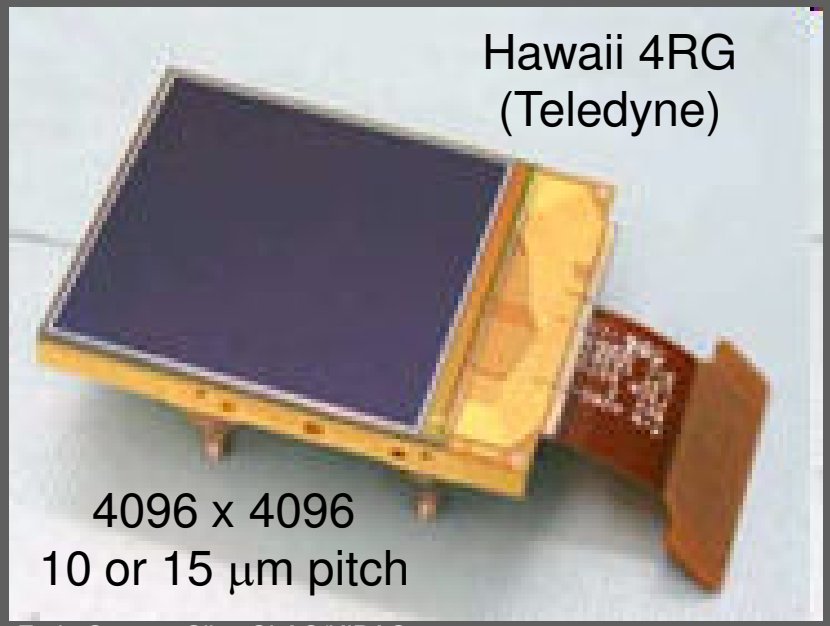
Produce large CdZnTe substrates

HgCdTe for Large Arrays





Mott et al IEEE (2006)



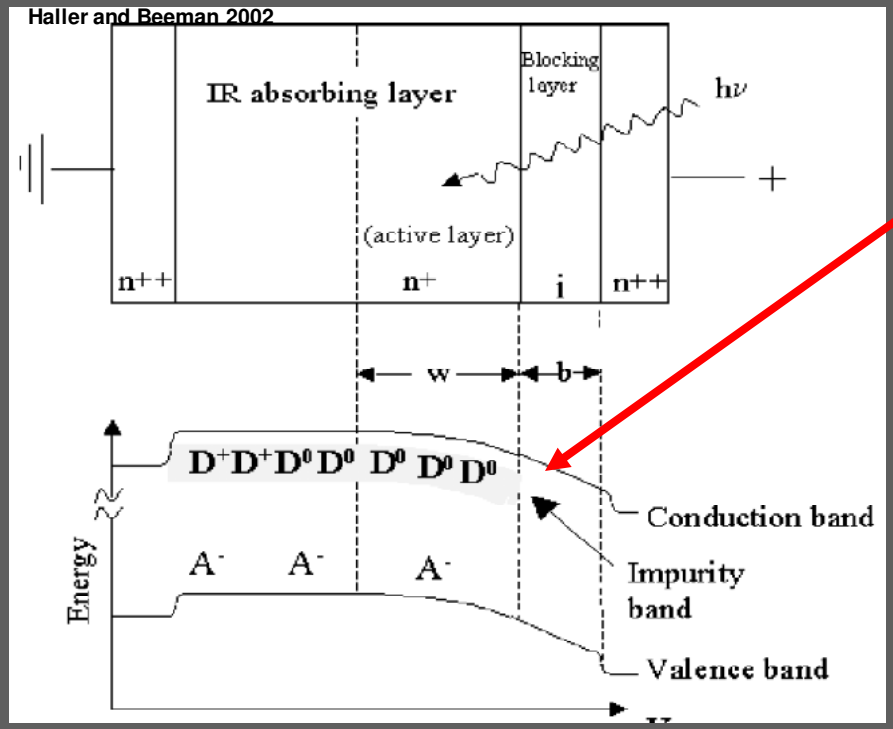
E. do Couto e Silva SLAC/KIPAC

- **JWST- NIRSpec**
  - **Measure 100 objects simultaneously**
  - **1 μm to 5 μm**
- **Large Format small pixel array**
  - **Pixel size of 18 μm x 18 μm**
  - **Each array 2048 x 2048 pixels**
  - **Operating at 36 K**
- **Dark current**
  - **< 0.01 e-/s/pixel**
- **Read noise**
  - **6 e- rms for 1 ks exposure**

Block Impurity Band Detectors (BIB) for MIR

Si or Ge with dopants	$\Lambda_{cut\text{-}off}$ (cm^{-1})
Si:Ga, Si:As, Si:P, Si:Sb	18 - 40
Ge:Ga, Ge:B, Ge:Sb, GaAs:Te	40 - 300

$$\Lambda_{cut-off} = \frac{1.239}{E_{impurity}} [\mu m]$$



- **Thin layer of high purity Si/Ge**
  - **Low dark current (block IR)**
- **Thick heavily doped layer**
  - **High QE (absorb IR)**

Absorption coefficient ~ photoionization cross section x doping concentration
If doping is too high one can have large dark currents (tunneling or hoping)

JWST: Mature Technology Scaled to Large Arrays

Array Type	Spectral Range (μm)	Pixel Count	Dark Current (e^-/s)	Tempera-ture (K)	Noise (e^-)	Quantum Efficiency
***Spitzer* (2003)**						
InSb	2.8–5	131 072	0.5	15	6.8*	0.86
Si:As IBC	5–26	180 224	2.4	6	6.6*	0.55
Si:Sb IBC	14–38	32 768	<40	4	30*	0.25
***JWST* (~~2011~~) (2014)**						
$Hg_{0.55}Cd_{0.45}Te$	0.6–2.3	46 137 344	<0.001	37	5†	0.95
$Hg_{0.70}Cd_{0.30}Te$	2.4–5	20 971 520	<0.001	37	5†	0.95
Si:As IBC	5–28	3 145 728	$\ll$0.1	7	<19†	>0.7

*Read noise only, integrations <200 s. †Total noise, integrations 1000 s.

P. Richards and C. R. McCreigh, Physics Today, Feb 2005

Near and Mid Infrared arrays are well developed

JWST: Mature Technology Scaled to Large Arrays

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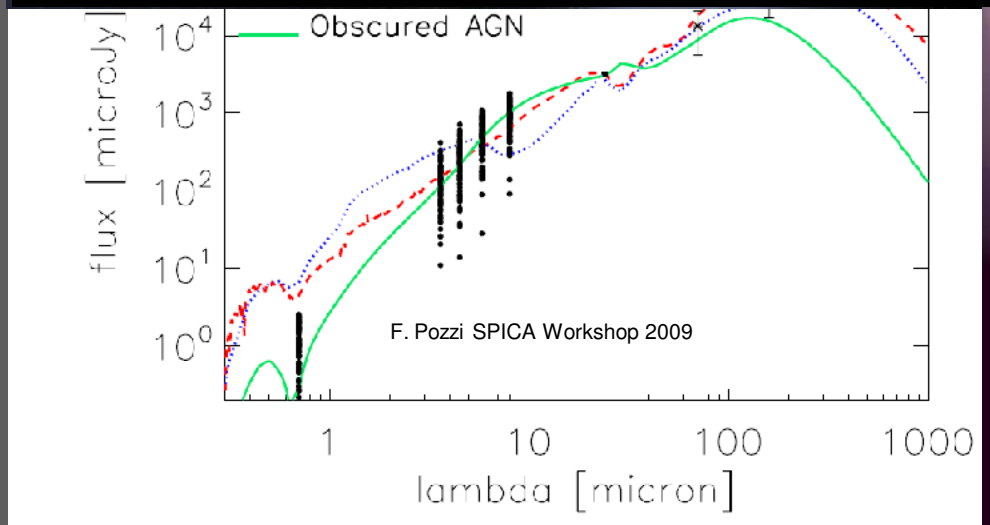
P. Richards and C. R. McCreigh, Physics Today, Feb 2005

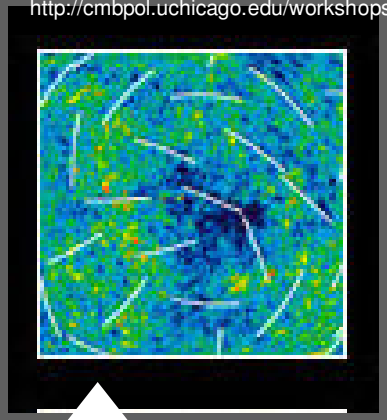
Far infrared arrays

Far Infrared Science and beyond (> 30 μm)

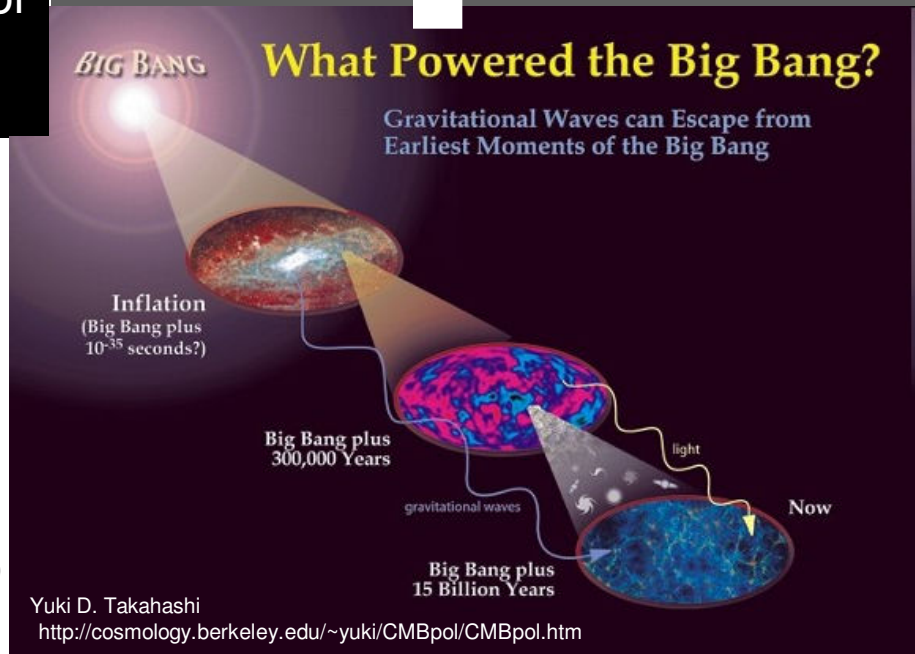
Mass growth of supermassive Black Holes for z >1
(peak of mass growth and star formation)



http://cmbpol.uchicago.edu/workshops.html



CMB Polarization



Yuki D. Takahashi
http://cosmology.berkeley.edu/~yuki/CMBpol/CMBpol.htm

Ge:Ga Detectors for Far Infrared Detection

Arrays have not grown since 90s

AKARI & Herschel are similar to Spitzer

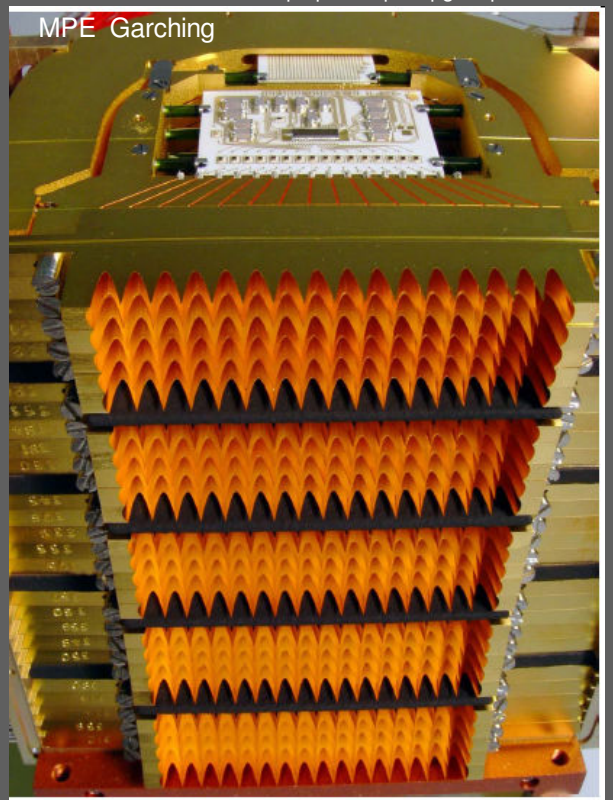
100 -200 μm

- **Unstressed Ge**
  - **E gap ~ 11 meV**
- **Stressed Ge**
  - **large uniaxial stress along 100 direction**
  - **E gap ~ 6 meV**

- **Challenges**
  - **Poor absorption**
    - **requires thick devices (mm)**
  - **Radiation effects in large volumes**
    - **ionizing particles**
  - **Complicated time response**
    - **Hard to calibrate**
  - **Labor intensive**
    - **Assembled by hand**

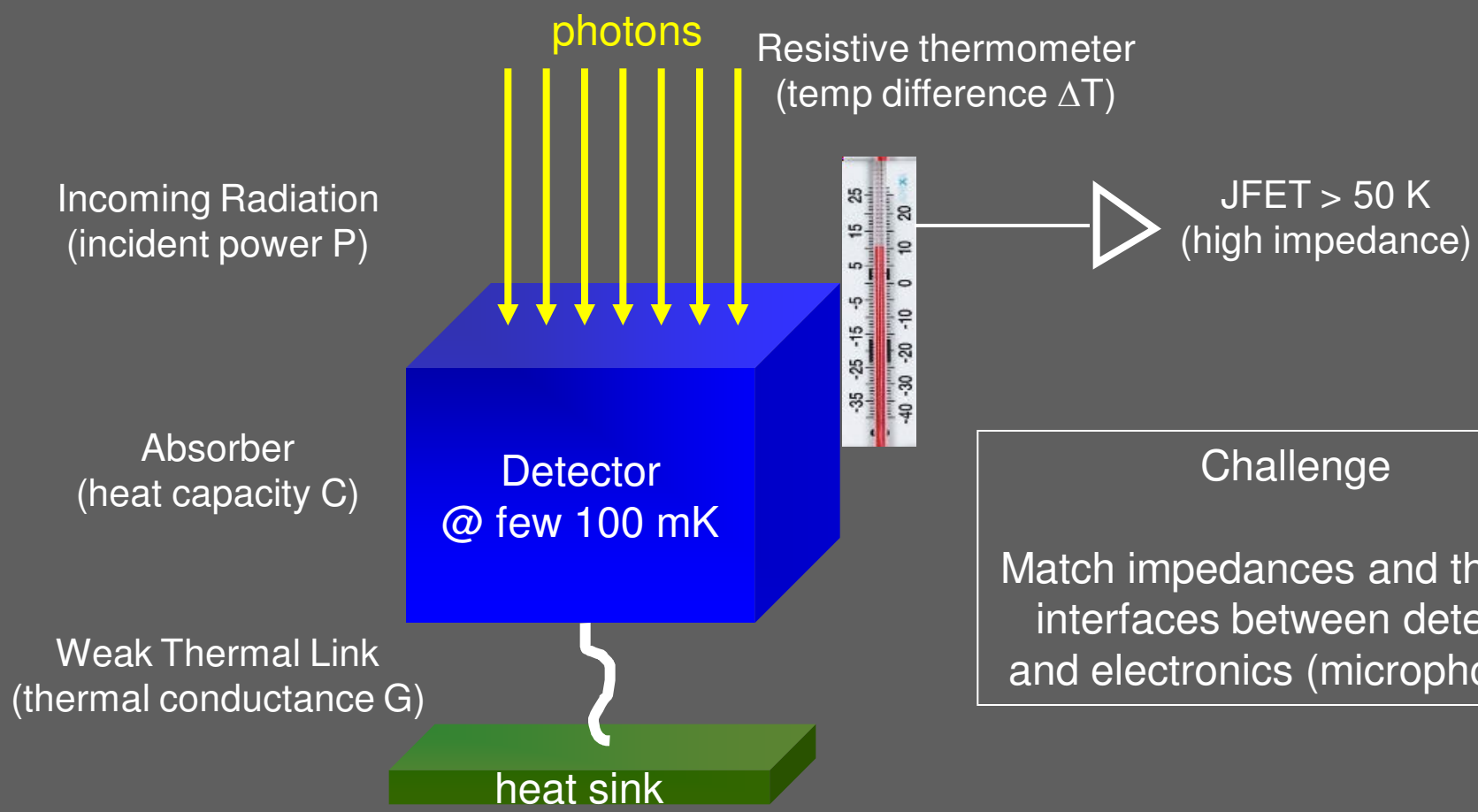
25 x 16 stressed array for Herschel/PACS

http://pacs.mpe.mpg.de/p15n.html



Going beyond Infrared (sub mm- mm): Bolometers

Can't count photons anymore, instead photons are absorbed and <u>thermalized</u> leading to a temperature change

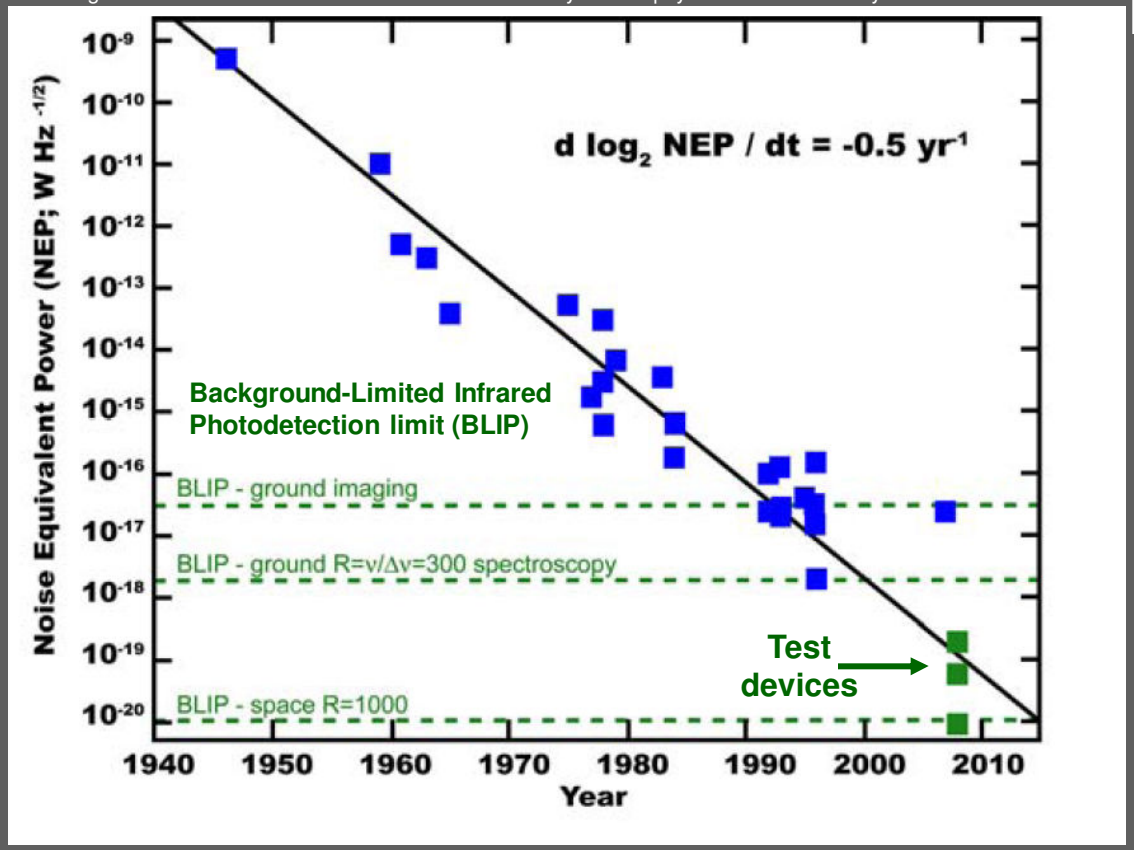


Challenge

Match impedances and thermal interfaces between detector and electronics (microphonics)

Background Limited Performance in Space

M Harwit et al "Far-Infrared/Submillimeter Astronomy from Space Tracking an Evolving Universe and the Emergence of Life Recommendations for The Astronomy & Astrophysics Decadal Survey of 2010"



Must cool optics to reduce thermal emission and cool detectors to reduce noise

Noise Equivalent Power

- **Incident power on pixel that gives output signal corresponding to SNR of 1 into a frequency band of 1 Hz**

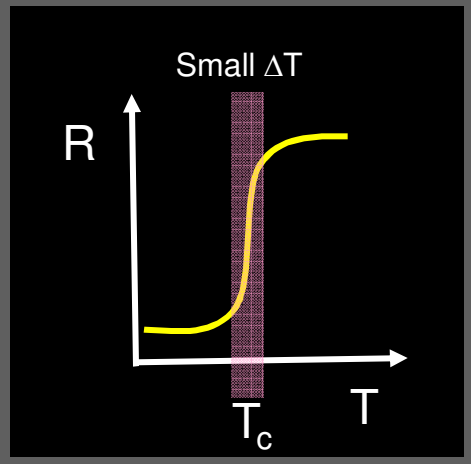
$$NEP = \frac{\sqrt{4kT^2G}}{\eta}\left[\frac{W}{\sqrt{Hz}}\right]$$

To improve sensitivity

- **Increase quantum efficiency η**
- **reduce thermal conductance G**
- **reduce heat capacity C**
- **operate at low temperatures**

$$\tau = \frac{C}{G}[s]$$

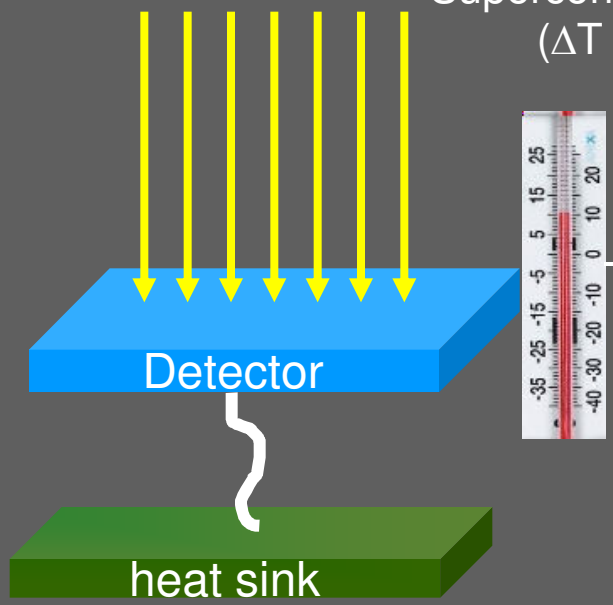
Transition Edge Sensors (TES) Bolometers Superconductors



photons

Superconducting films
(ΔT of mK)

Thin film absorber
(lithography)

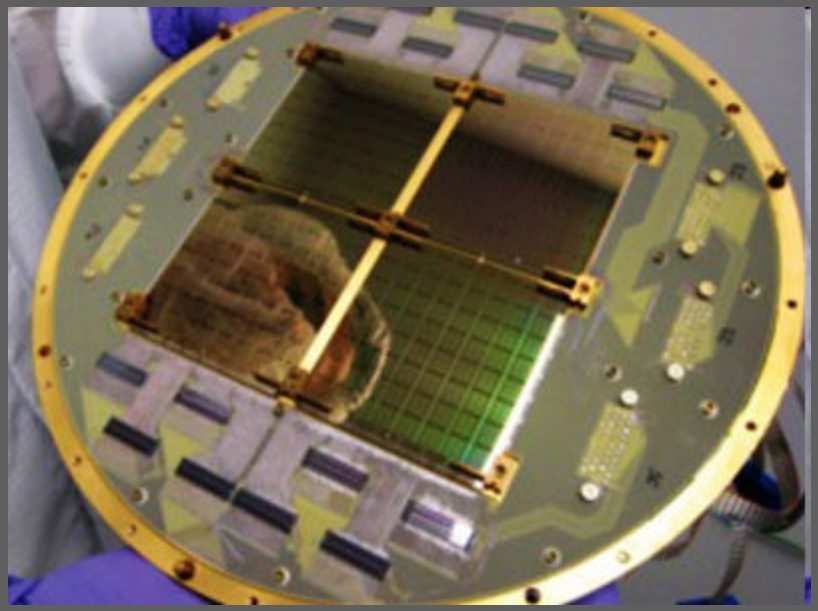


SQUID
(low-impedance
to match low R of TES)

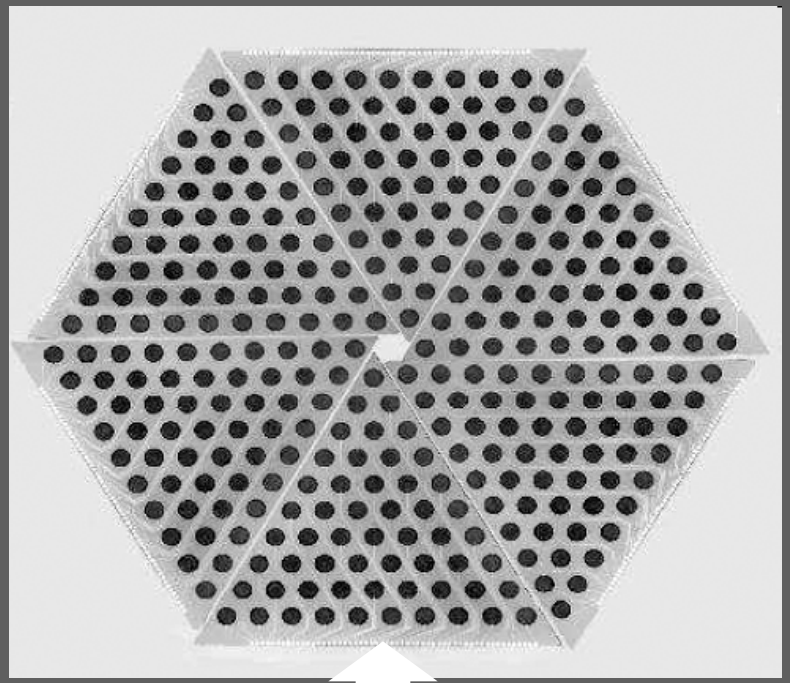
$T_{hs} \sim T_c/2$

Operate at superconducting transition temperatures of a few tens of milikelvin
Biased at constant voltage

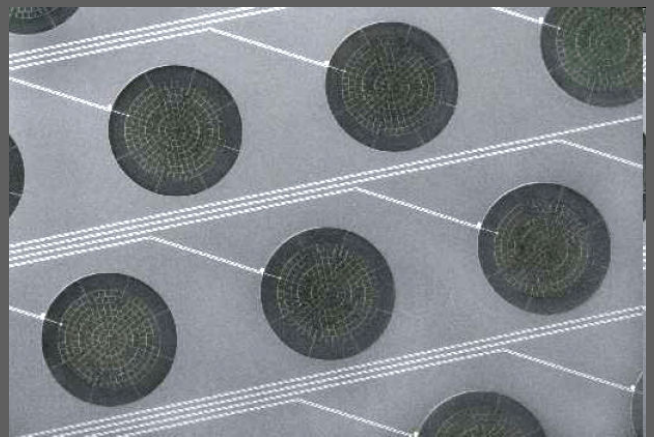
Transition Edge Sensors - Bolometers



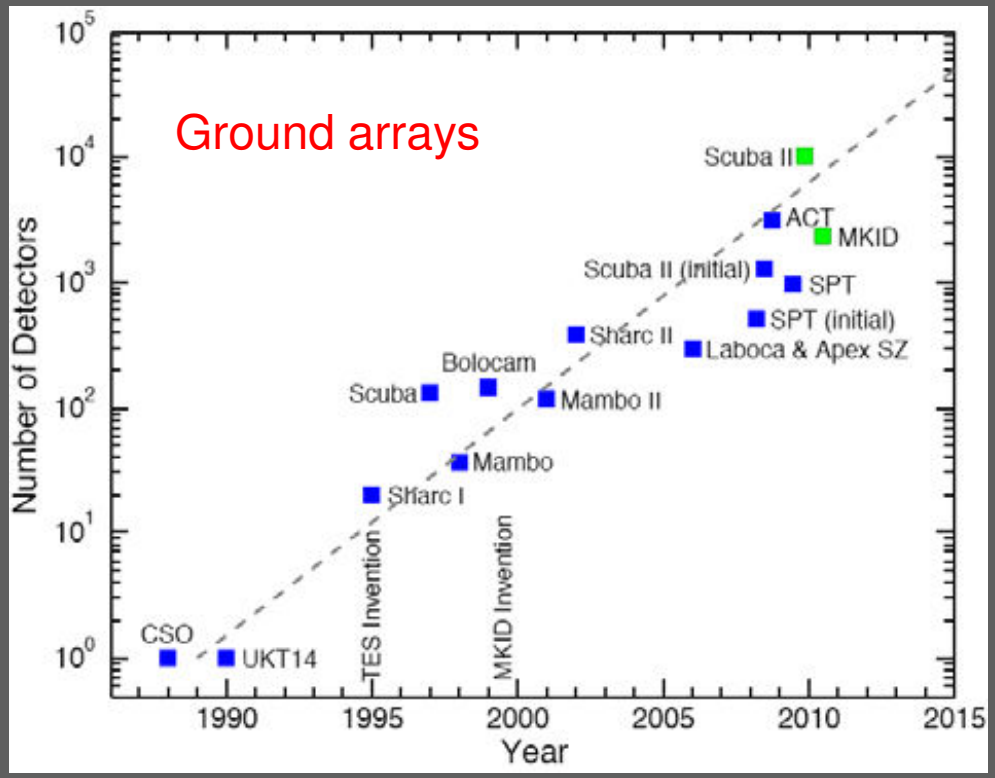
BICEP2 focal plane with 512 polarization-sensitive antenna-coupled bolometers (credit: JPL)



Credit: South Pole Telescope



Bolometers for Long Wavelengths: the Future



J Bock et Astro2010 white paper

Promising Developments

Multiplexed readout below 1 K

Diffraction limited

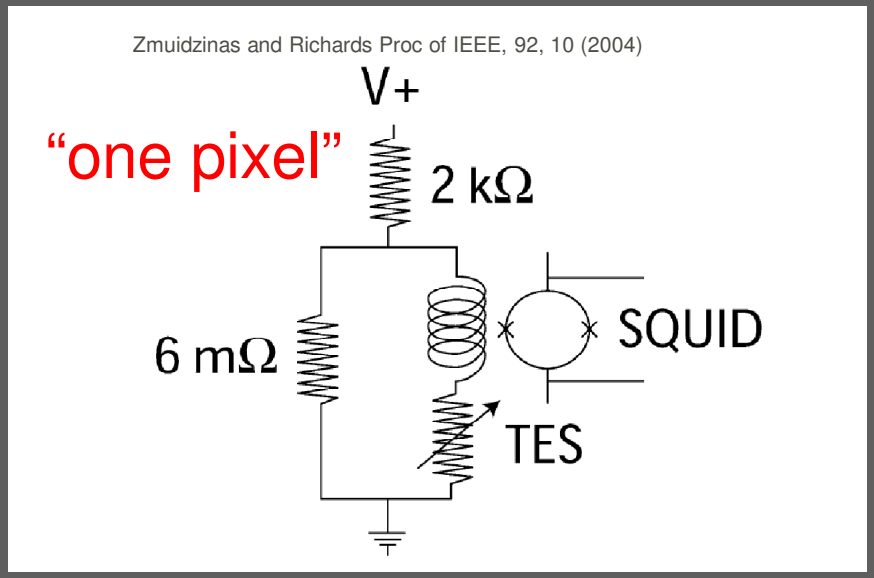
- **Optical CCDs**
  - **10^9 pixels**
- **NIR- MIR photoconductors**
  - **10^{6-7} pixels**
- **FIR sensors & bolometers**
  - **10^{4-5} pixels**

space arrays

Science	Future Opportunities	Requirements		
		NEP [W/√Hz]	τ [ms]	Format
CMB Polarization	Inflation Probe	1-5 x 10^{-18}	1-30	10^4
Galaxy evolution, Star formation, Circumstellar disks	SPICA/BLISS	3-30 x 10^{-20}	100	5000
	SAFIR/CALISTO imaging	3 x 10^{-19}	10	10^5
	SAFIR/CALISTO spectroscopy	3 x 10^{-20}	100	10^5
	SPIRIT	1 x 10^{-19}	0.2	256

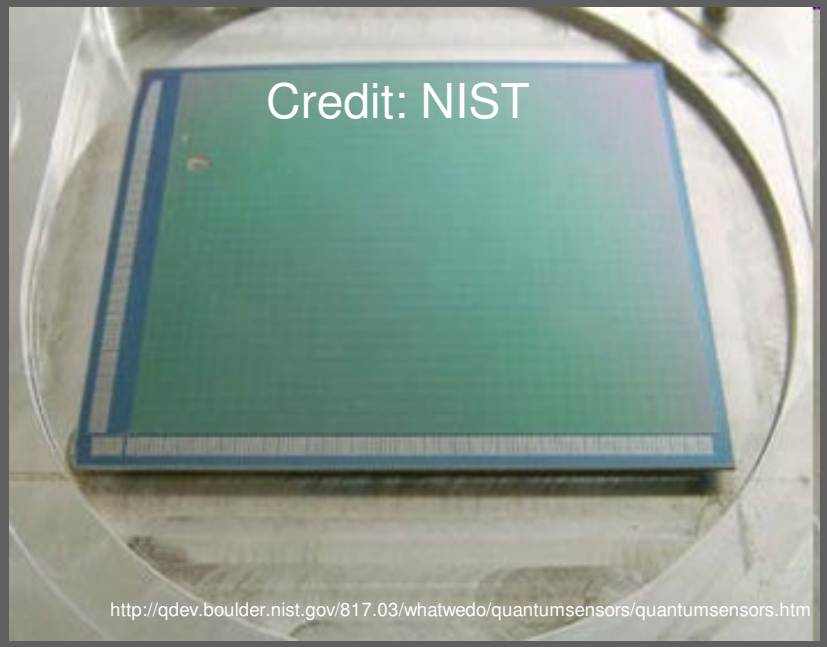
Multiplexed SQUID Readout

SQUIDs are used to read out
TES bolometers
(voltage biased)



- **Low noise**
- **Low power dissipation**
- **Fast readout speed**

- **Two possible MUX schemes**
  - **Time**
  - **Frequency**



SCUBA-2 (ground)

1280-pixel SQUID multiplexer wafer
bump bonded to a
1280-pixel TES bolometer array

Low Power Dissipation

800 B. Collaudin, N. Rando / Cryogenics 40 (2000) 797–819

Table 1
Main characteristics of photon detectors and SQUIDs[a]

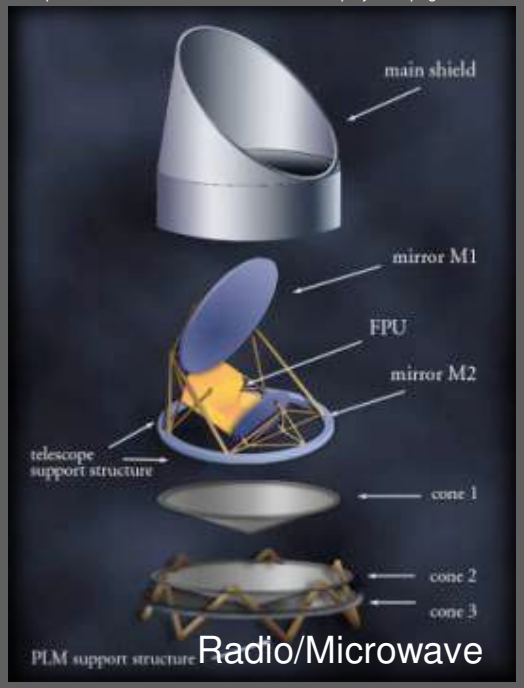
Table is from 10 years ago!

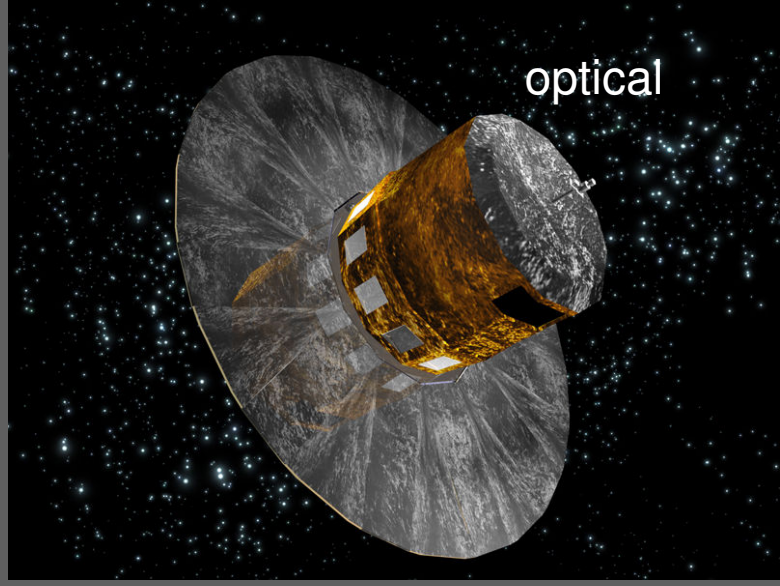
Detector type	Temperature range (K)		Dissipation range (W)		Detector size (pixel and array)		Utilisation
	Min	Max	Min	Max	Pixel (μm)	Array ($n \times n$)	Wavelength
Ge crystal	50	100	0	0	10000	<10	Gamma
CCD	150–200	300	0.1	20	10–30	10^6	X-ray/Vis.
STJs	0.01	1	10^{-9}	10^{-6}	20–50	$<10^3$	X-ray–UV–Vis.–NIR
μ-Calorimeters	0.05	0.3	10^{-12}	10^{-11}	100	<100	X-ray
TESs	0.05	0.3	10^{-11}	10^{-9}	100	<100	X-ray–UV–Vis.–NIR
Photo-conductors – NIR	30	100	0.01	0.02	30–50	10^6	NIR
Photo-conductors – MIR	2	20	0.01	0.02	50–100	$<10^4$	MIR
Photo-conductors – FIR	1	2	0.001	0.003	50–100	$<10^3$	FIR
Sub-mm bolometers	0.1	0.3	10^{-9}	10^{-8}	100–500	$<10^2$	Sub-mm
SQUIDs (LTS)	1	4	10^{-12}	10^{-11}	na	na	Read-out/accelerometer

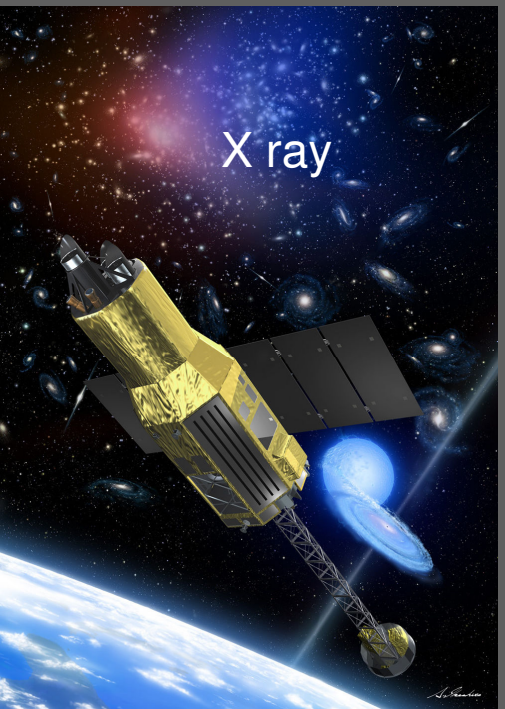
[a] na: Not approved.

TES Bolometers and superconducting detectors dissipate very little power, require very low temperatures and can be used at other wavelengths

http://www.astro.cardiff.ac.uk/research/instr/projects/?page=nir



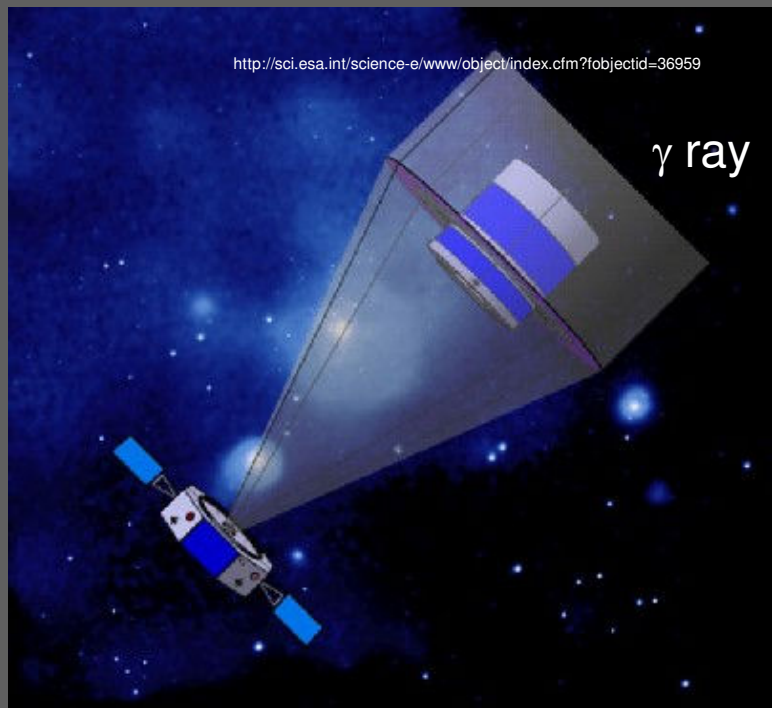




Focal Plane Telescopes

There are specific requirements at different wavelengths

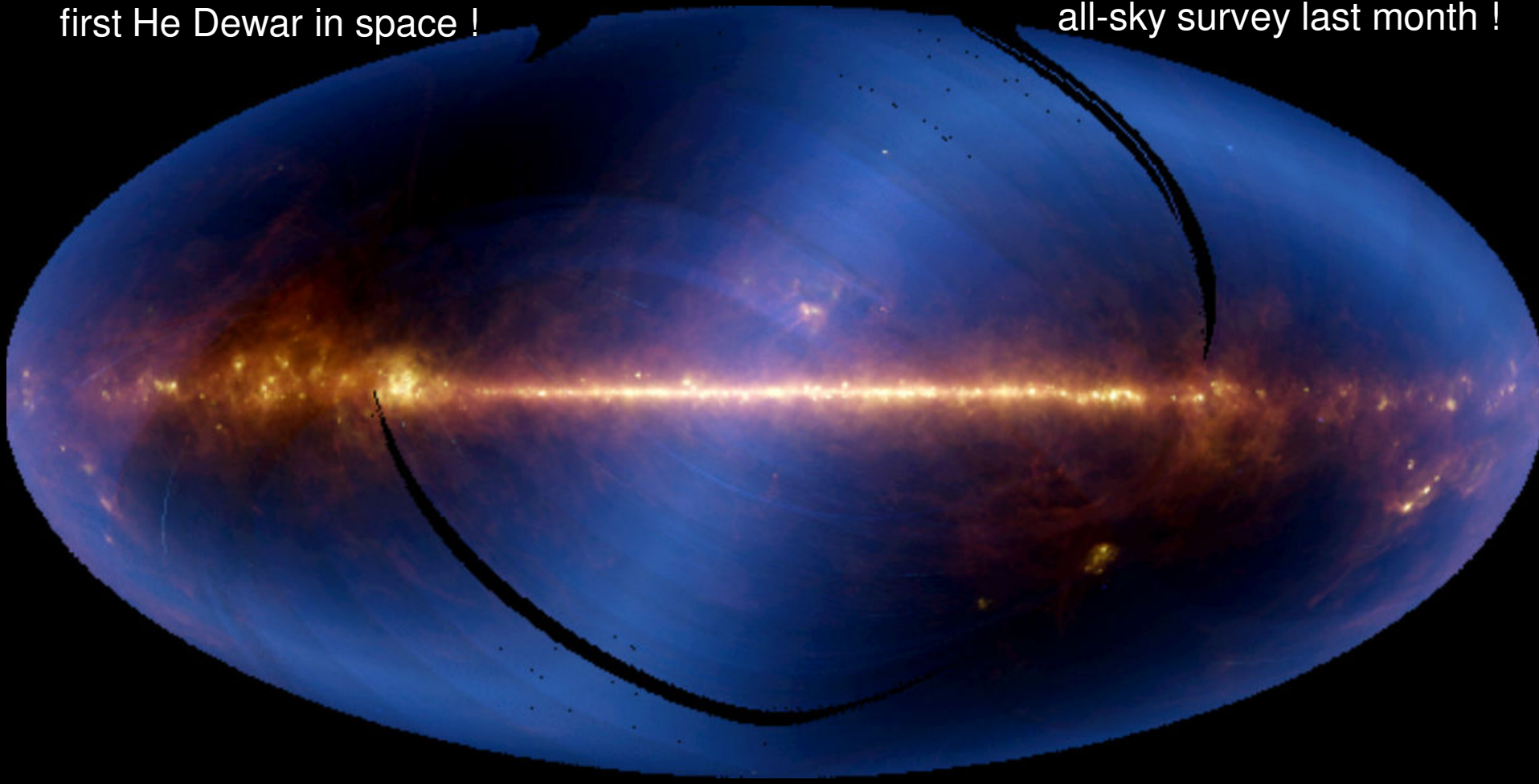
The higher the energy the harder it is to focus light



All-sky Survey in Infrared: a Tour de Force

6 months of pointings,
first He Dewar in space !

The WISE telescope
with better sensitivity began
all-sky survey last month !



Map of 96% of the sky at 12, 25, 60 and 100 μm
(Credit : IRAS team)

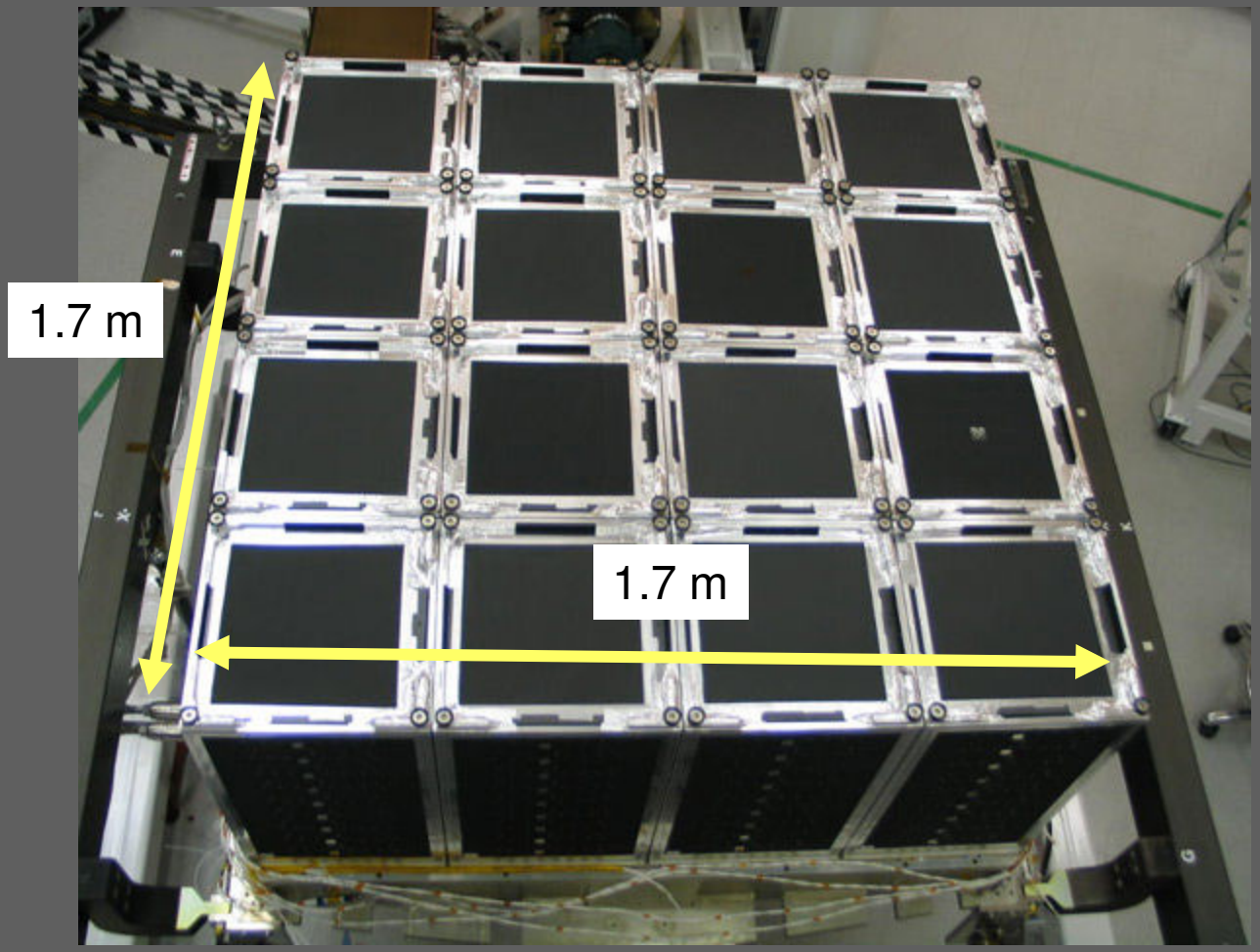
Example of Large Array in all Sky-survey mode

not in Infrared but in high energy gamma rays

- **Large Mirrors?**
  - **No, we cannot focus these high energy photons**
  - **use active shield to reduce backgrounds**

- **Large ~~Focal Plane Detectors~~ Field of View**
  - **Large number of pixels**
    - **~ 10^6 "pixels"**
  - **Large substrate size**
    - **6 inch Silicon substrates**
  - **Large number of readout channels**
    - **Multiplexing, low noise and fast readout**
  - **Large Arrays**
    - **Large "Mosaic" of 1.7 x 1.7 m**

4 by 4 array for gamma ray detection

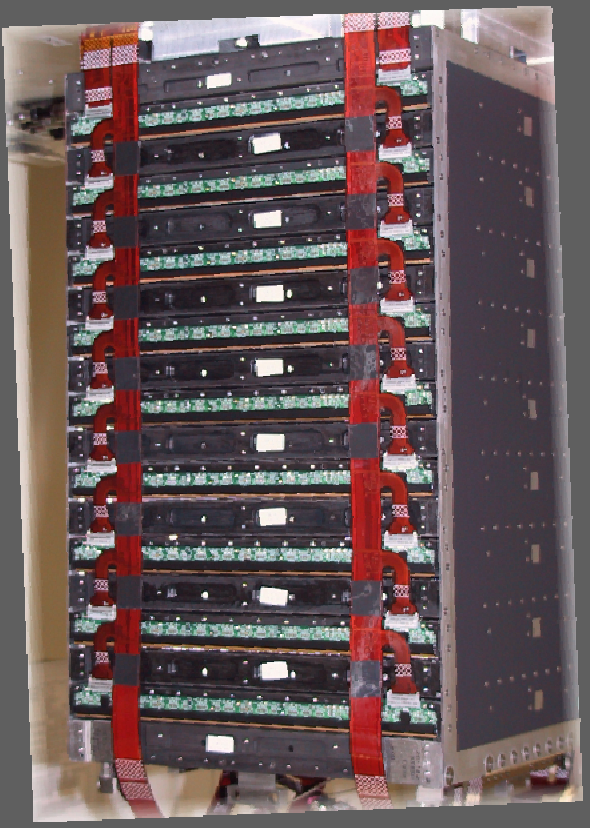


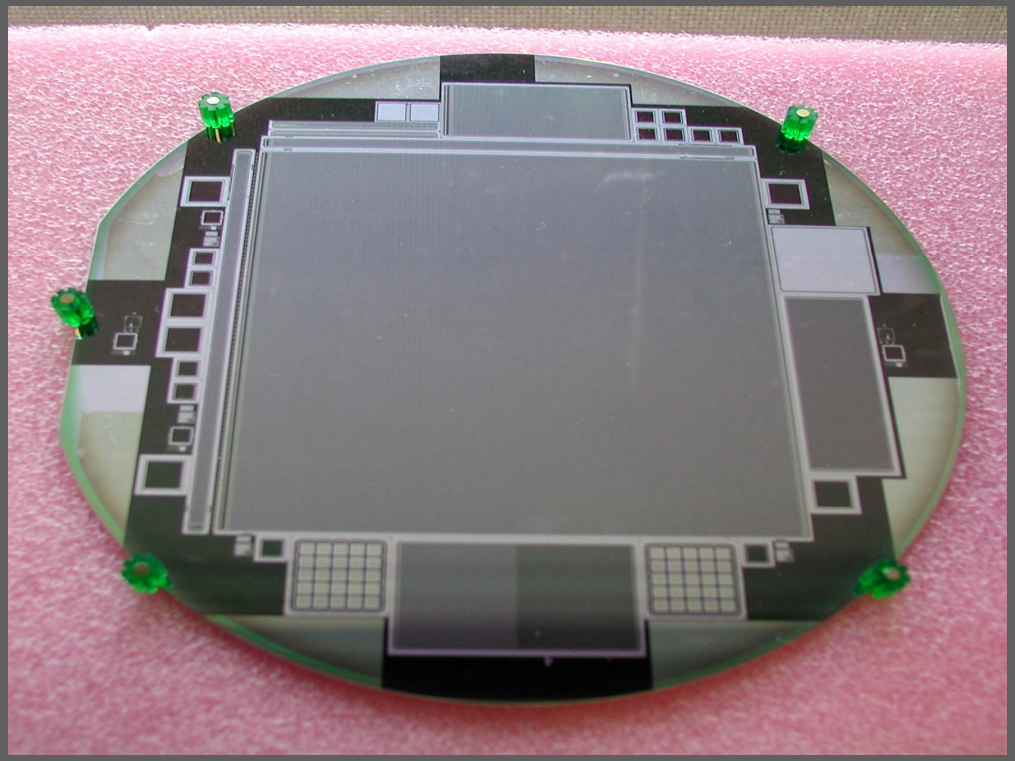
Large Area Telescope of FGST (formerly known as GLAST)

Fermi Large Area Telescope: Breakthrough from HEP

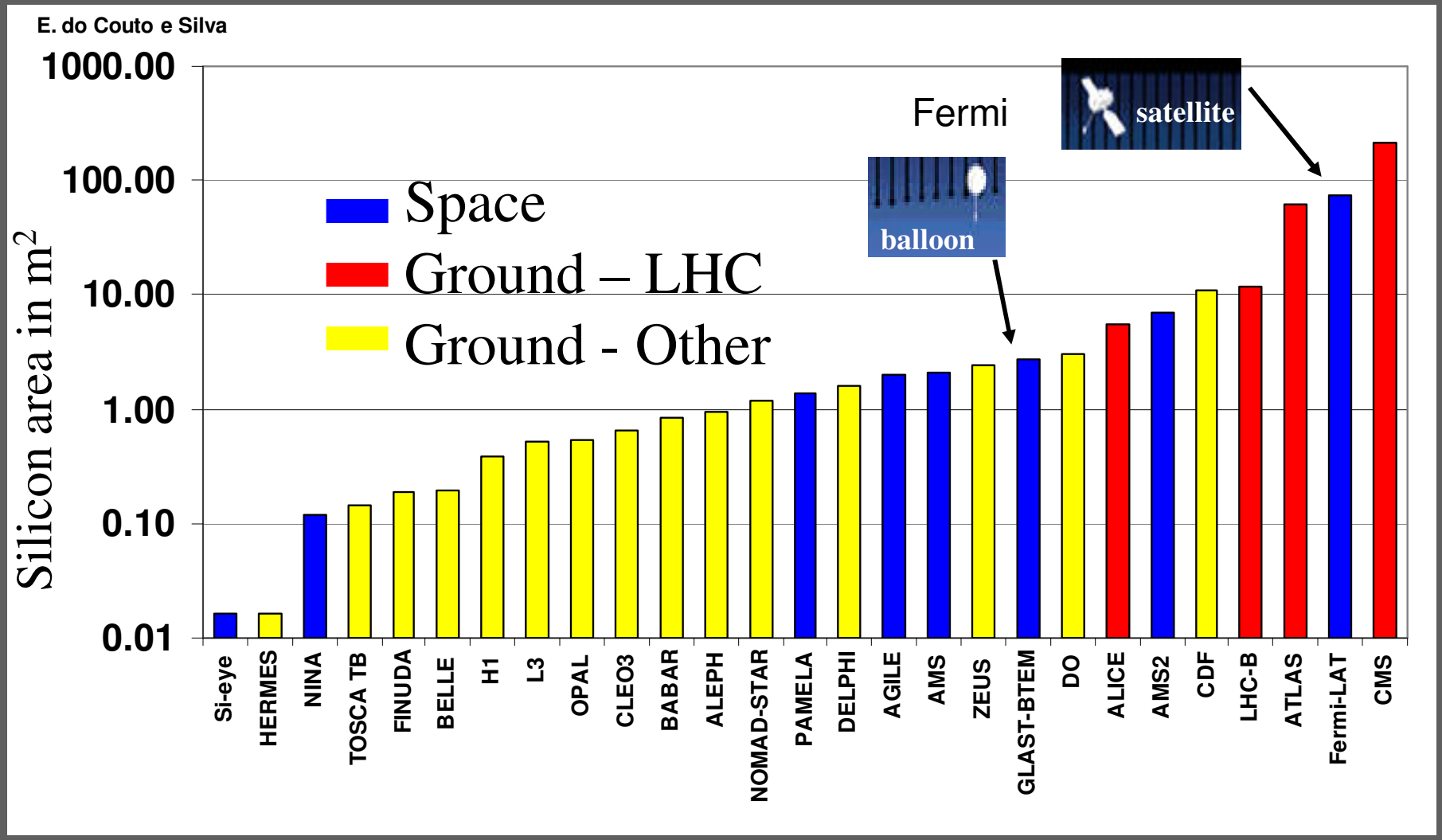
1996: Kamae and Ohsugi presented to HPK the challenges of Fermi LAT

Dimensions: from 3 cm x 6 cm (4 inch) to 9 cm x 9 cm (6-inch)
Dead channels: from few % to 0.08%
Leakage current: from 50 nA/cm^2 to 2.5 nA/cm^2
Silicon tracker area: from ~ 1 m^2 to 80 m^2





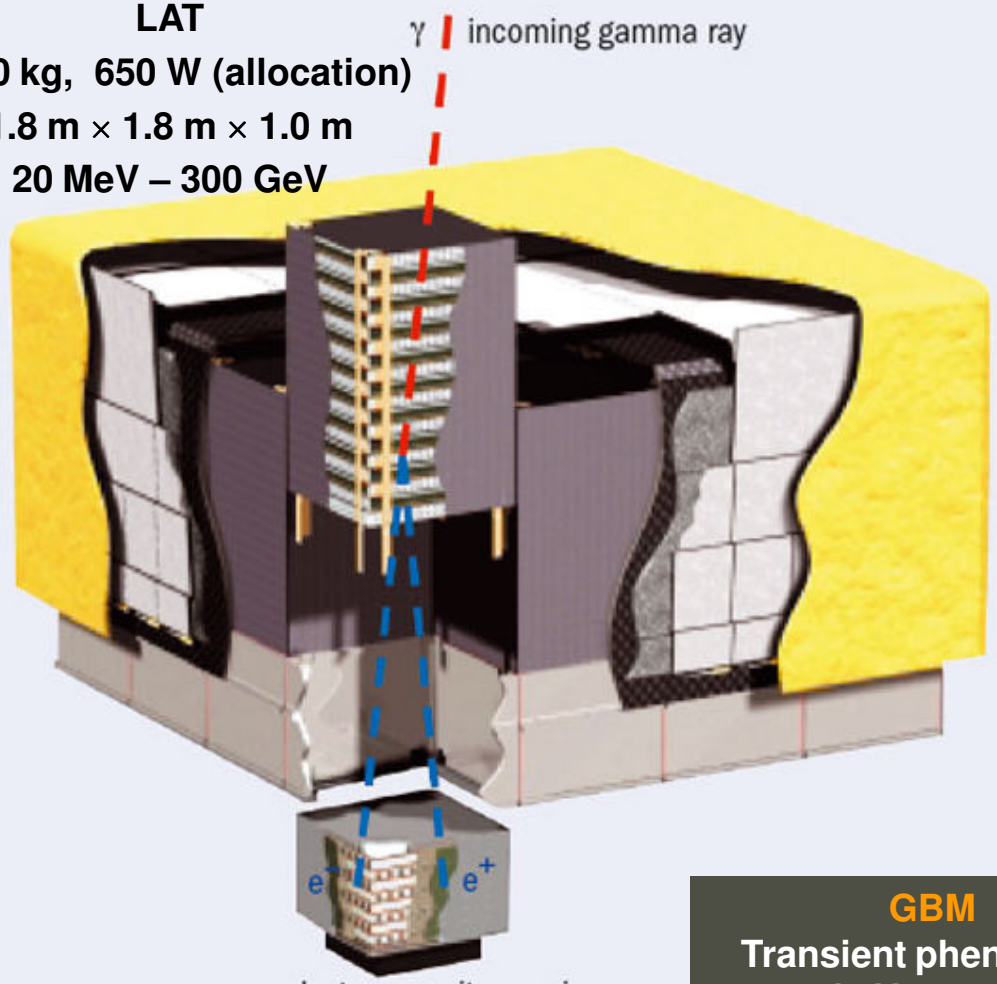
Silicon microstrip: robust technology

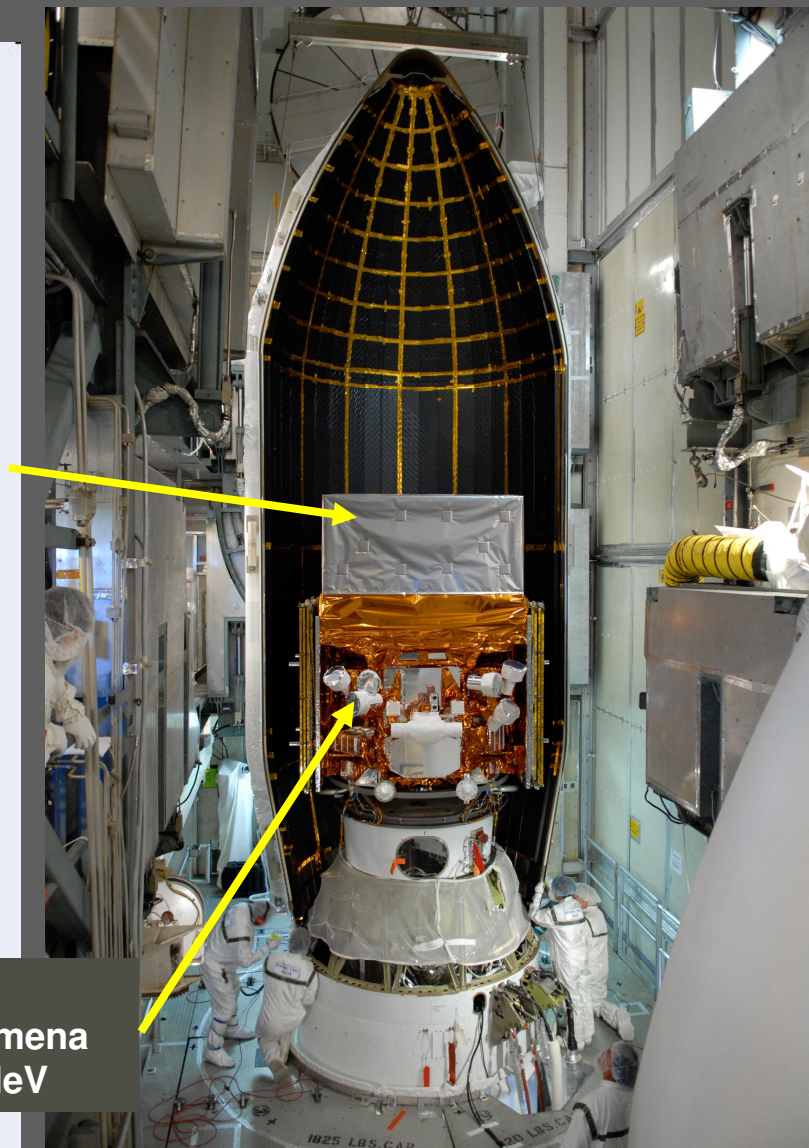


Fermi Gamma ray Space Telescope

Fermi measures direction, energy, flux and arrival time of γ

LAT
3000 kg, 650 W (allocation)
1.8 m × 1.8 m × 1.0 m
20 MeV – 300 GeV





GBM
Transient phenomena
~8 keV to 40 MeV

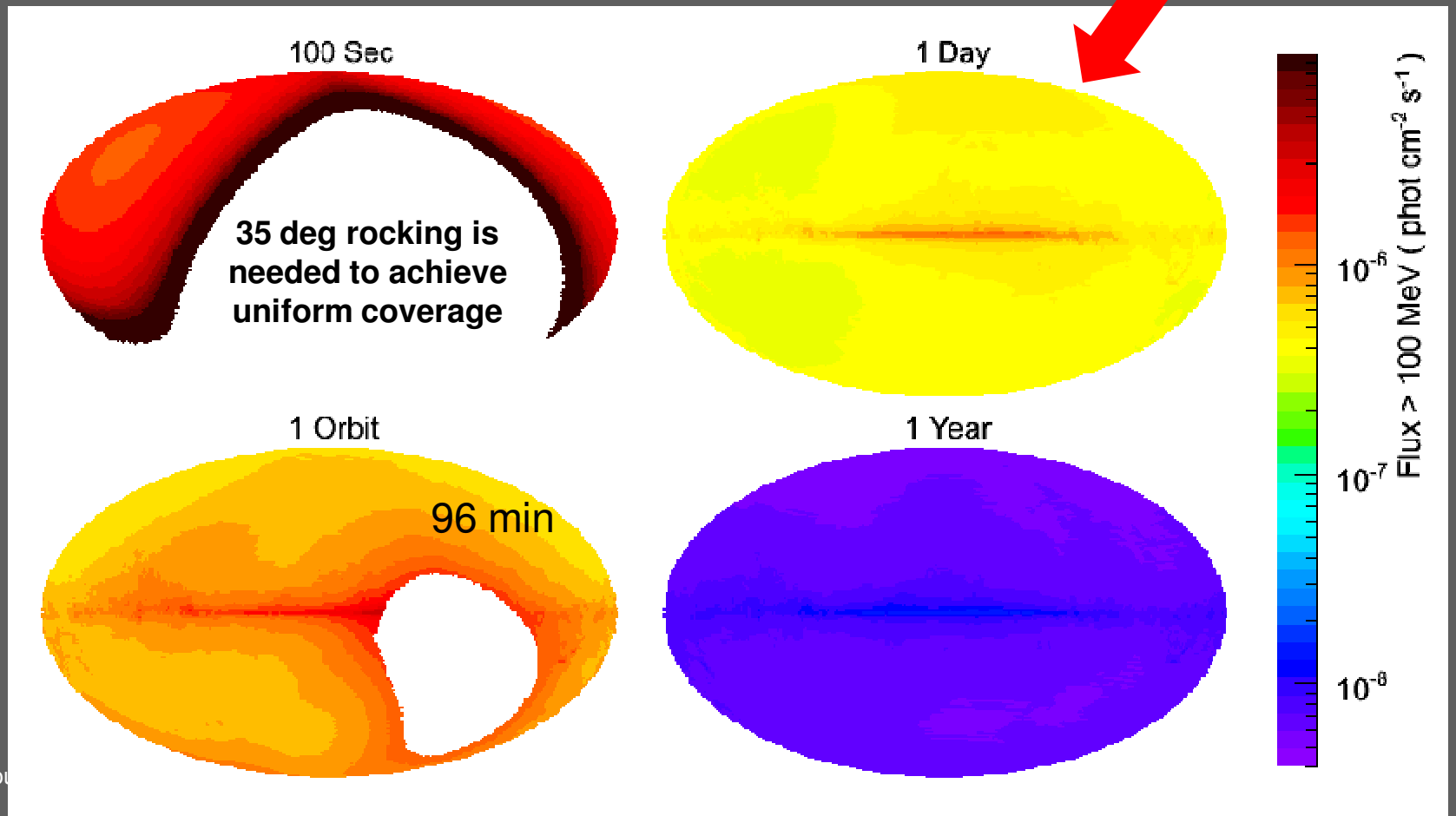
Huge Field of View and Large Area

Variability provides an extra handle for source identification

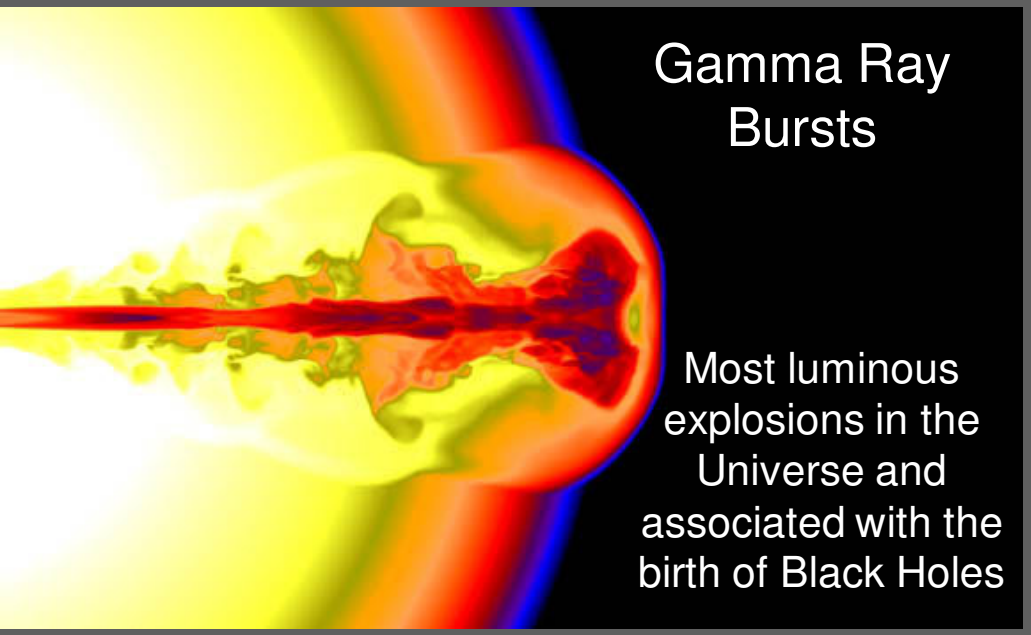
Observes 20% of the sky at any instant (sky survey)

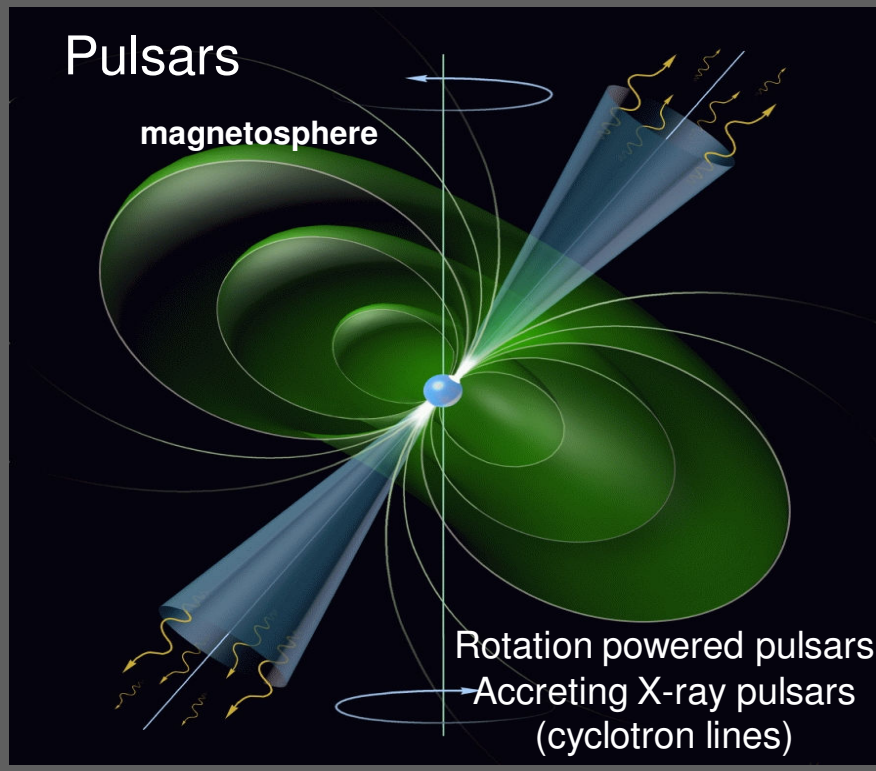
exposes all parts of sky for ~30 minutes every 3 hours.

No need for pointing,
no tour de force
it is a large array!!



Relativistic Outflows

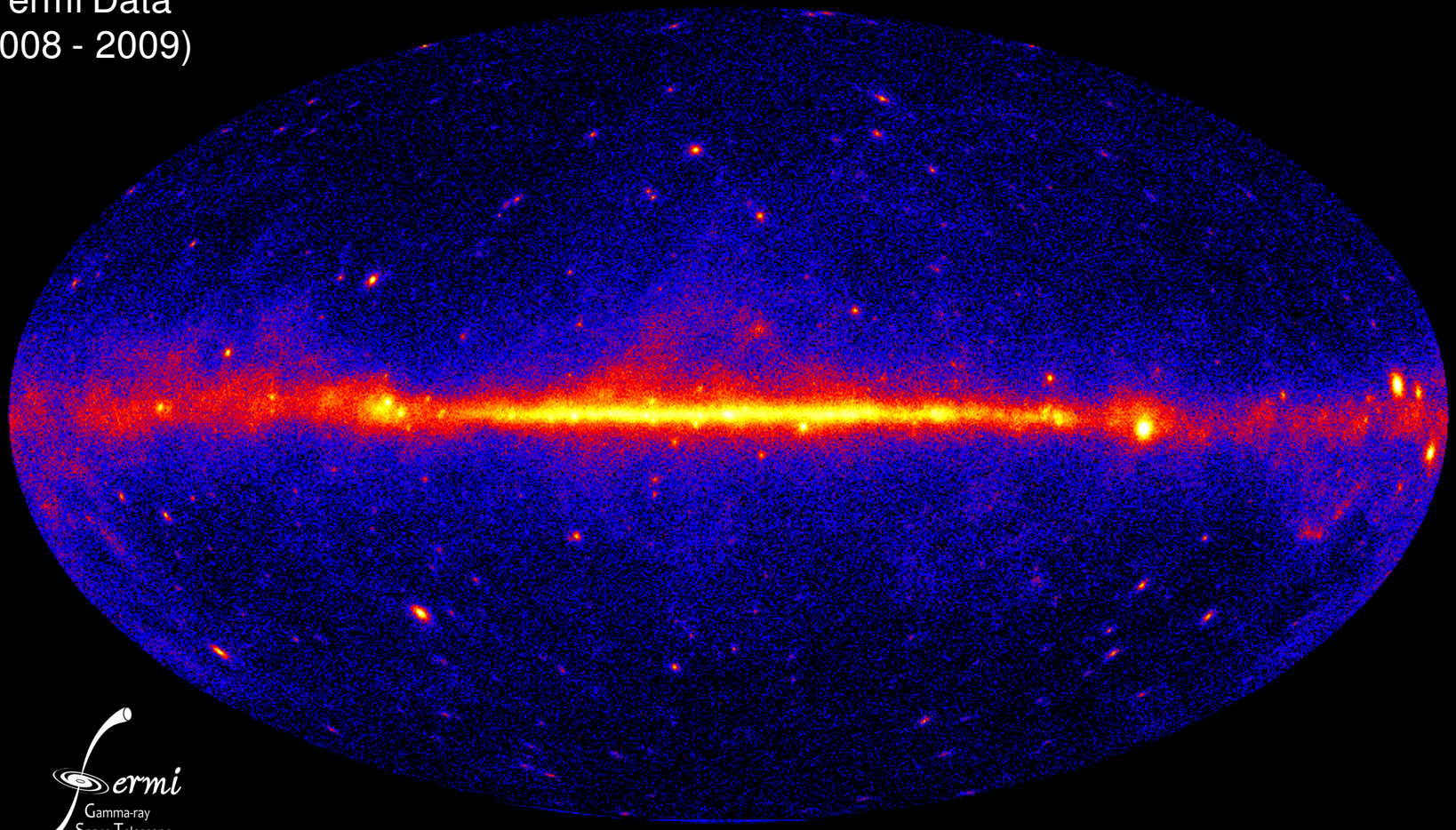




Gamma ray emissions exhibit large time variability

All Sky Survey in gamma rays

Fermi Data
(2008 - 2009)

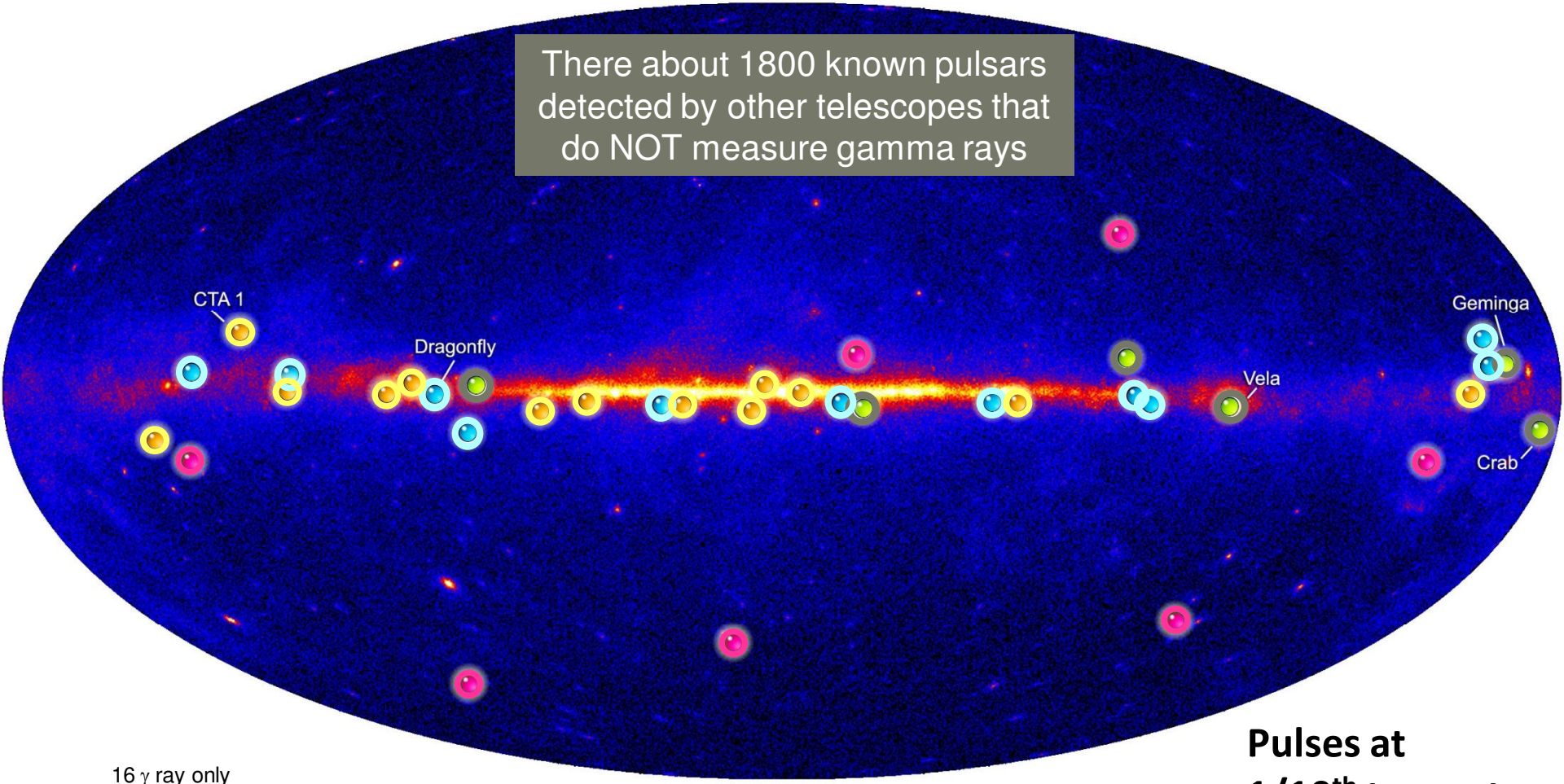


The diffuse emission is a tracer of interstellar gas, provides information about cosmic ray spectra and intensities and may contain signatures of new physics

Fermi LAT: The Beginning of a New Era for γ Ray Pulsars

In one year Fermi identified almost 10 times more pulsars than EGRET
these are ~40% of the bright sources at low latitude

There about 1800 known pulsars detected by other telescopes that do NOT measure gamma rays



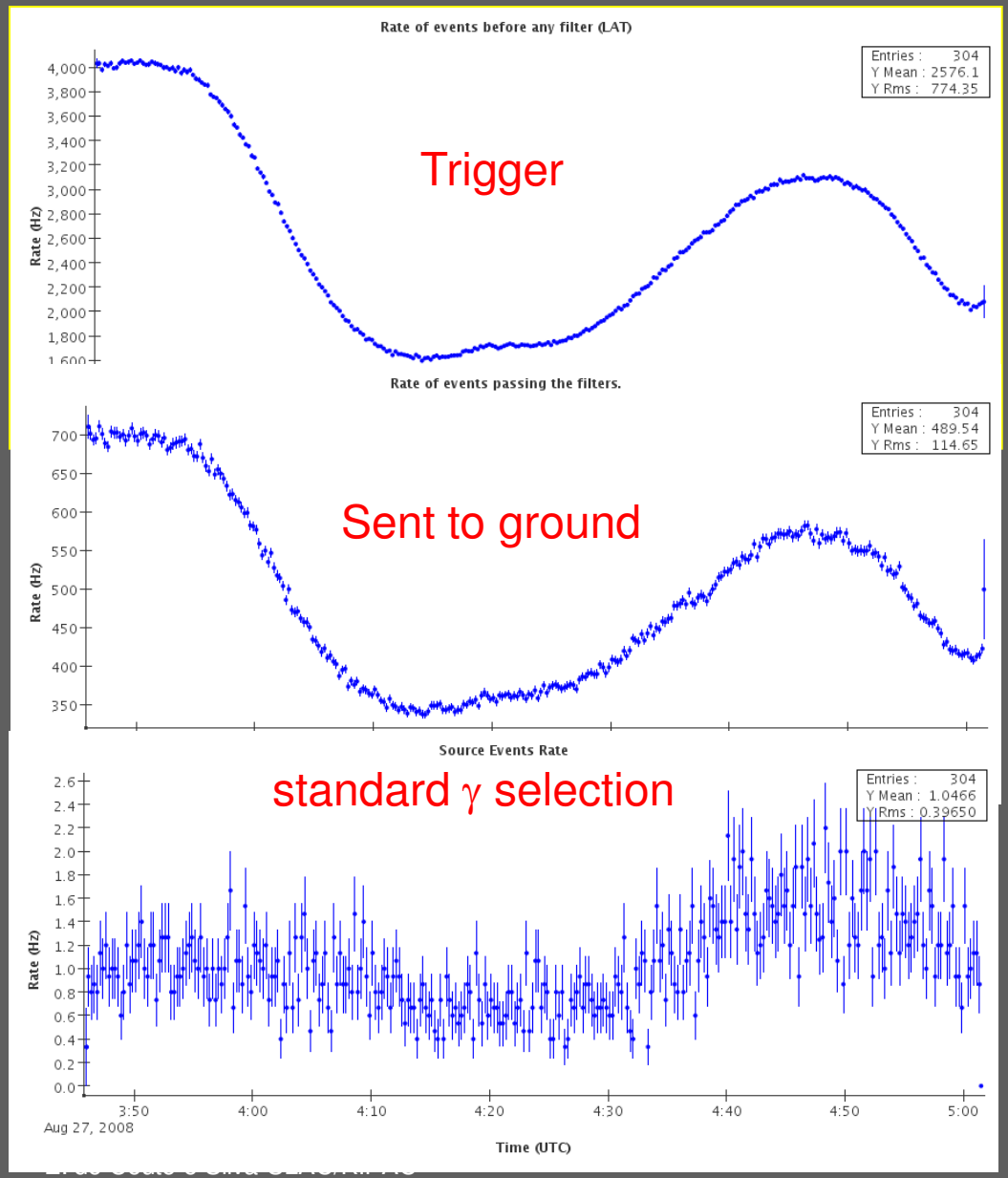
16 γ ray only
From blind searches (Aug 09)

Fermi Pulsar Detections

12 New pulsars discovered in a blind search
7 Millisecond radio pulsars
13 Young radio pulsars
6 Pulsars seen by Compton Observatory EGRET instrument

Pulses at 1/10th true rate

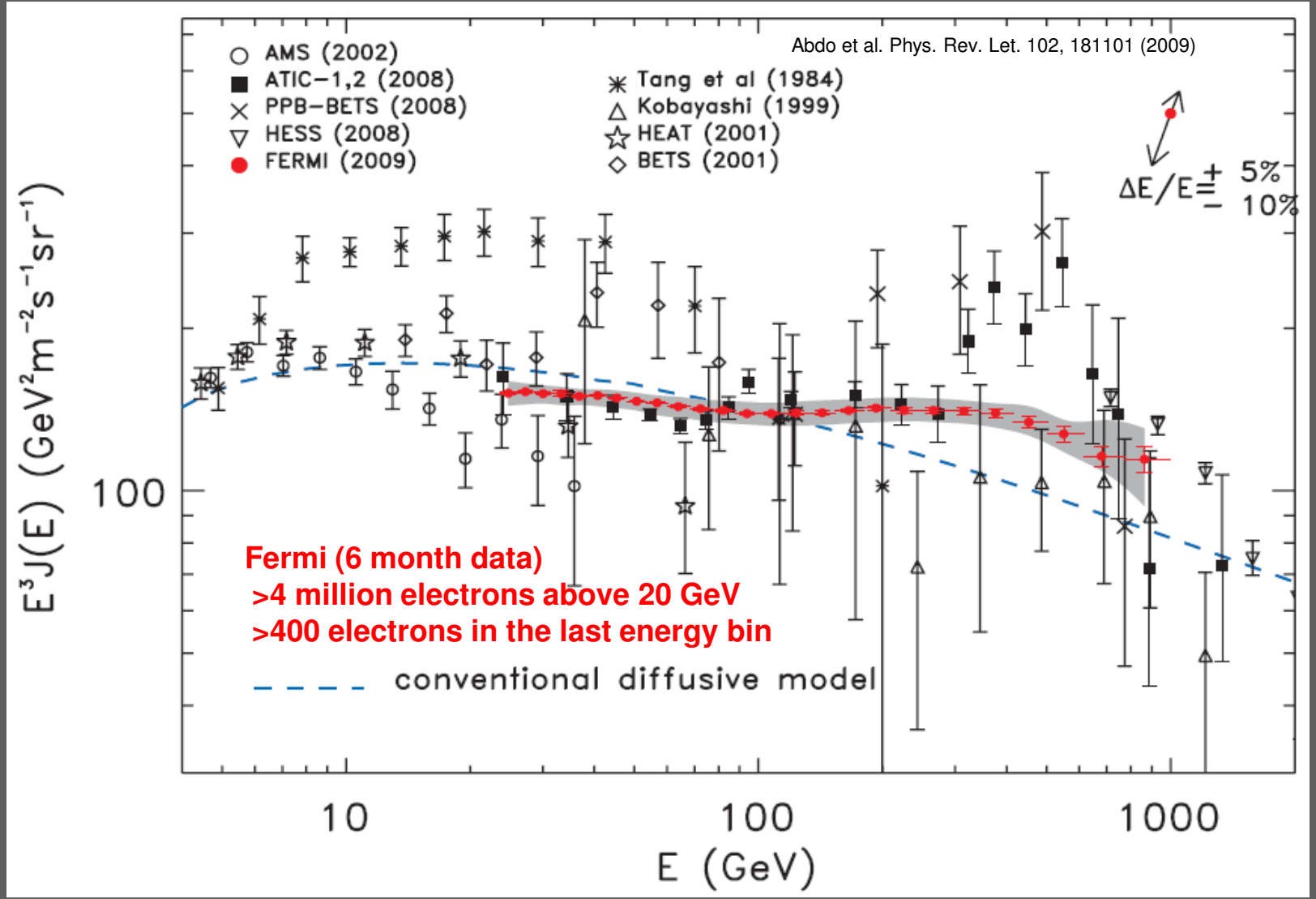
Rates During Science Operations



- **Average input rate**
  - **~ 2500 Hz**
- **Downlink rate (sent to ground)**
  - **~ 450 Hz**
- **γ rates (after event selection)**
  - **~ few Hz**
- **Can we use the background to do relevant science?**

Fermi LAT High Energy e+/e- Spectrum

no prominent spectral features between 20 GeV and 1 TeV
significantly harder spectrum than inferred from previous measurements



Pulsars?
Dark Matter?

“ Infrared arrays have caused an even greater revolution in infrared astronomy than CCDs have for optical astronomy”

I. McLean, Exp. Astro. 14 25-32 (2002)

SUMMARY

- **Mechanical coolers are promising technology for space telescopes**
  - **Extend mission lifetime, reduce weigh and power**
- **Near and mid infrared arrays are mature for use in large focal planes**
  - **Semiconductor bandgap engineering**
  - **Moderate cooling above 1 K**
- **Exciting technology advances for far infrared and sub-mm arrays**
  - **Superconducting detectors**
  - **Multiplexed readout schemes**
  - **Cooling well below 1 K**
- **Telescopes with a large field of view are providing high scientific return**
  - **Silicon microstrip detectors from HEP enabled all sky survey in gamma rays**

Acknowledgments and Credits

Thanks to Manfred[2] and the VIC 2010 organizing committee for providing me with the challenge and the privilege to speak in this venue.

I am indebted to S. Kahn (SLAC/KIPAC/Stanford) for suggesting the main theme

Thanks to S. Church and her group (Stanford), in particular J. Lau and K. Thompson for their valuable input and material provided. Thanks to my colleagues at SLAC/KIPAC/Stanford for comments and suggestions that improved this talk: T. Kamae, R. Partridge, P. Kim, R. Resch, Y. Uchiyama, B. Cabrera and P. Brink.

Below is a list of resources I used to prepare this talk:

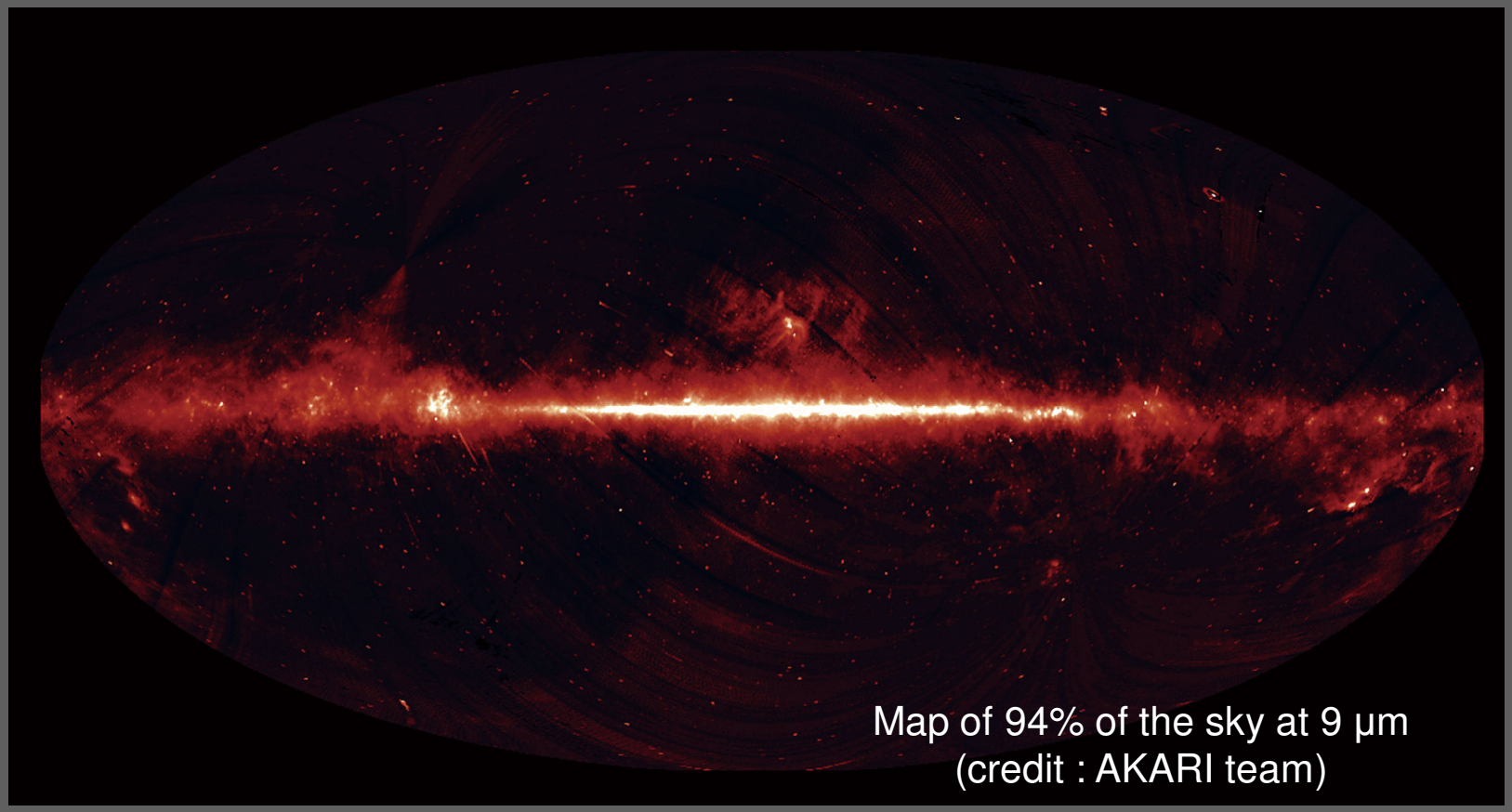
•P. Richards and C. R. McCreigh, *Physics Today, Feb 2005*
•P. Richards, J. Appl. Phys 76 (1), 1 Jul 1994
•G.H. Rieke, Annu. Rev Astron. Astrophys 2007, 45-77-115
• J. Zmuidzinas and P. Richards, *Proc of IEEE vol 92, no 10. oct 2004*
• I.S. McLean, *Experimental Astronomy 14: 25-32,2002*
• G. Finger et al, *NIM A 565 (2006) 241-25*
• B. Collaudin and N. Rando, *"Cyogenics 40 (200) 797"*

White papers for the Astro 2010 US Decadal Review

• W. Holmes et al, *"Cooling systems for far infrared telescopes and Instruments"*
• M, Ressler et al, "*Development of Large Format Far Infrared Detectors"*
• J. Bock et al," *Superconducting Detector Arrays for Far Infrared and sub-mm Astrophysics"*
• *NASA,ESA and JAXA websites for their corresponding infrared and sub-mm missions*

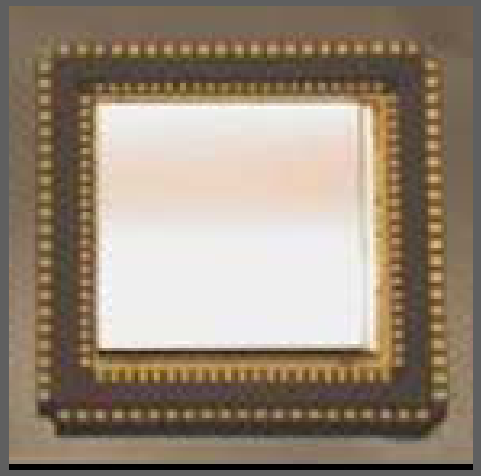
Back up slides

AKARI : First year Catalogue



Map of 94% of the sky at 9 μm
(credit : AKARI team)

Wide-field Infrared Survey Explorer (WISE)



FIRST LIGHT!

Constellation of Carina (thousands of stars)
Area is three times the size of the moon.
8s exposure
blue (3.4 um), green (4.6 mm), red (12 mm)

- 1024×1024 detector arrays
- Si:As
  - 12 μm and 23 μm
- HgCdTe
  - 3.3 μm and 4.7 μm

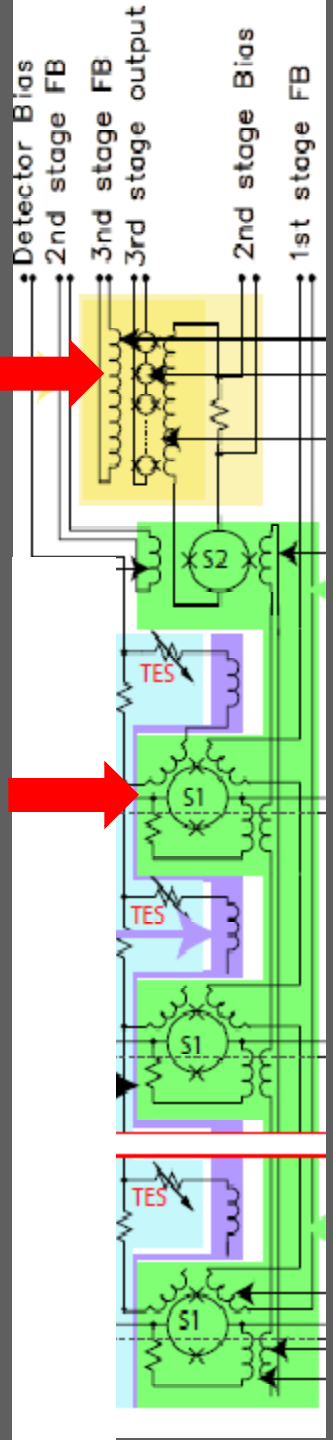
Image credit: NASA/JPL-Caltech/UCLA

Time Multiplexing (NIST)

The output of each column is amplified by an array of SQUIDs

SQUIDs switch TESs and read out the signal

Must minimize the number of wires!

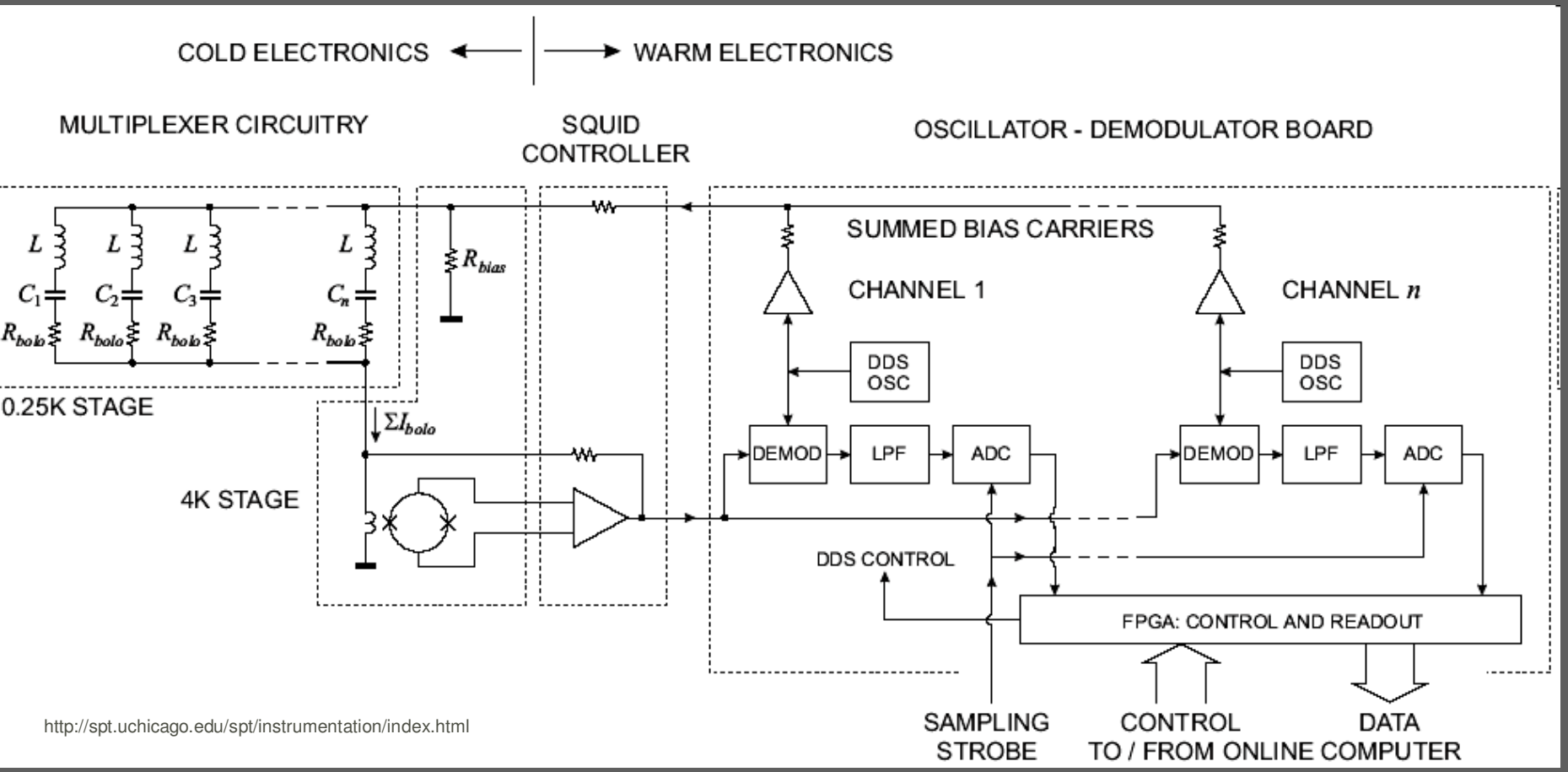


- **Stage 1 SQUIDs (S1)**
  - **are coupled to TES**
  - **are configured in a column**
- **Multiplexed readout**
  - **S1 address lines**
    - **are wired in series (for each row)**
      - **reduce number of lines**
  - **S1 turn on**
    - **sequentially**
    - **keep other S1s in a superconducting state**
      - **… no noise no power!**
  - **S1 output signal**
    - **sum signals in a column**
    - **route single output signal per column to S2 SQUIDS**

South Pole Telescope – Frequency Domain MUX

Example from a ground base telescope

1 SQUID per module not per detector (TES)

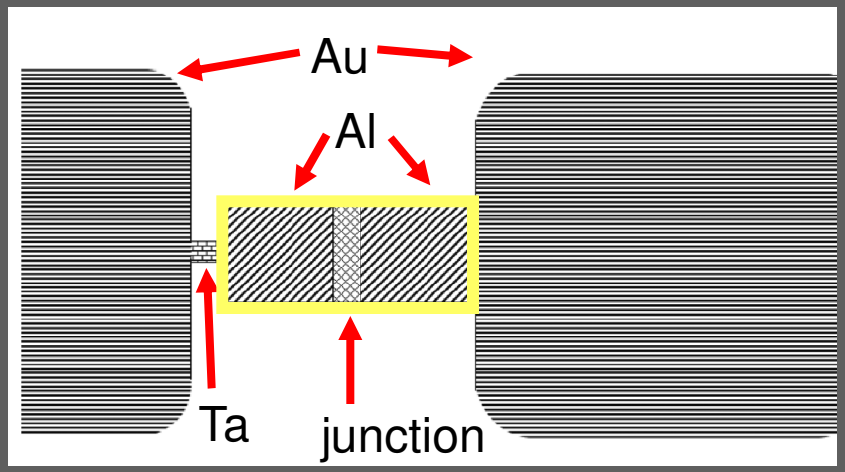


http://spt.uchicago.edu/spt/instrumentation/index.html

TES are biased with sinusoidal voltage (Each TES has a different frequency)
Amplitude modulated signals are read out by a single SQUID and recovered.

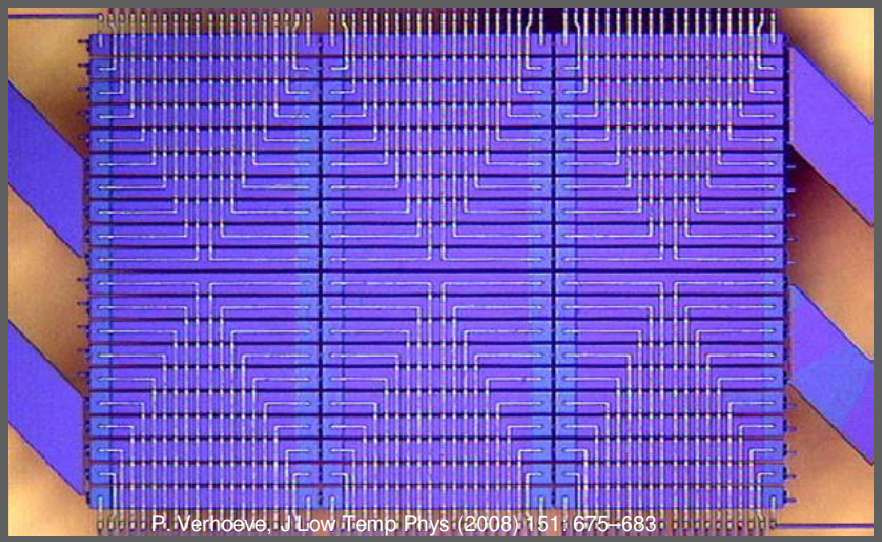
Future Developments: Superconducting Junctions

- Energy Gap
  - Semiconductor ~ eV
    - e/h pairs
  - Superconuctor ~ meV
    - quasiparticles



V. Savu et al, IEEE Trans. App. Superconductivity Vol 17, No 2, Jun 2007

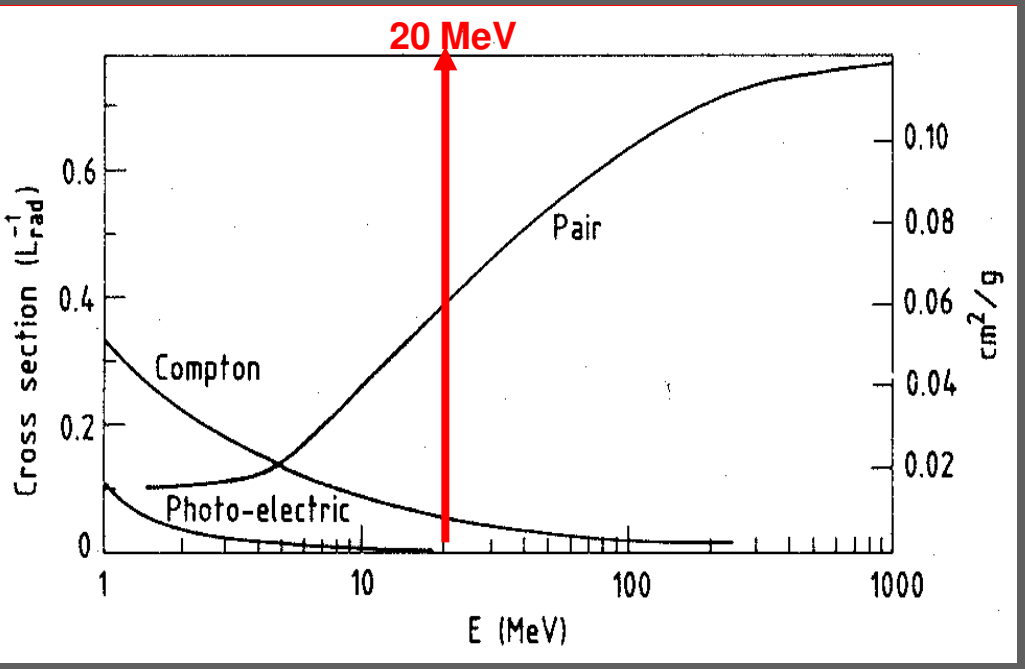
- Characteristics
  - Energy resolution
    - 10 x better than semiconductors
  - Not so low temperatures as TES
    - ~300 mK
  - …but large arrays and mulltiplexing are still in development



P. Verhoeve, J Low Temp Phys (2008) 151: 675–683

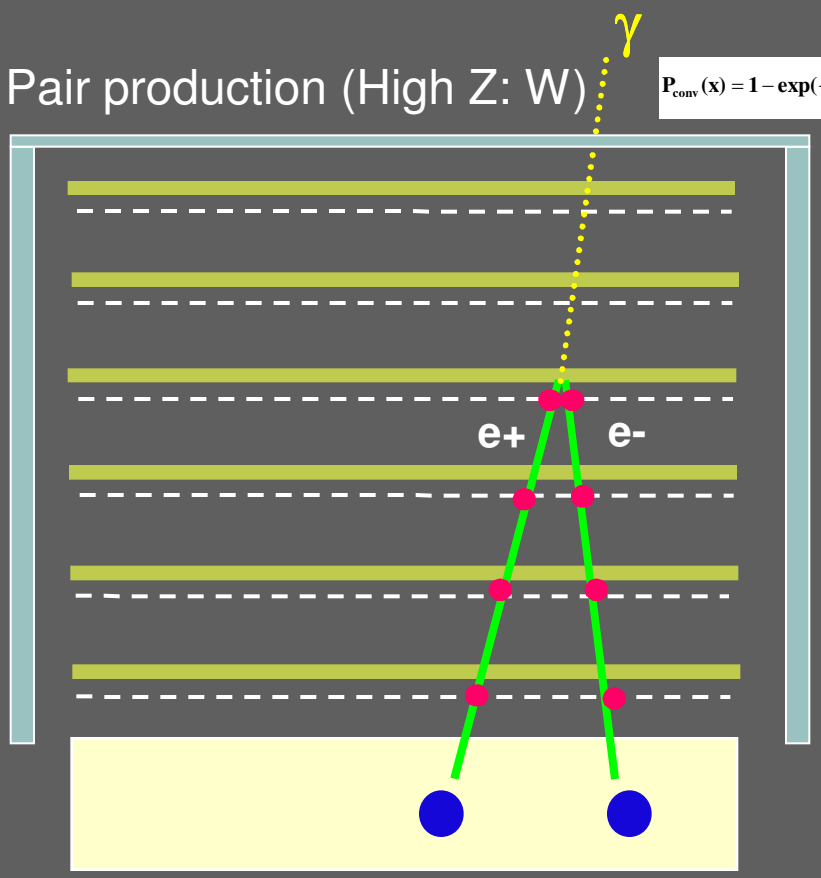
High Energy γ Ray Telescopes

- **Short wavelength**
  - **Radiation cannot be focused**
- **Cross section increases ~ 20 MeV**
  - **Pair production dominates**



Pair production (High Z: W)

$$P_{conv}(x) = 1 - \exp\left(-\frac{7}{9}\frac{x}{\chi_{Mat}}\right)$$



$$A_{eff} \cong A_{Geo} \cdot P_{conv} \cdot \varepsilon_{Ana}$$