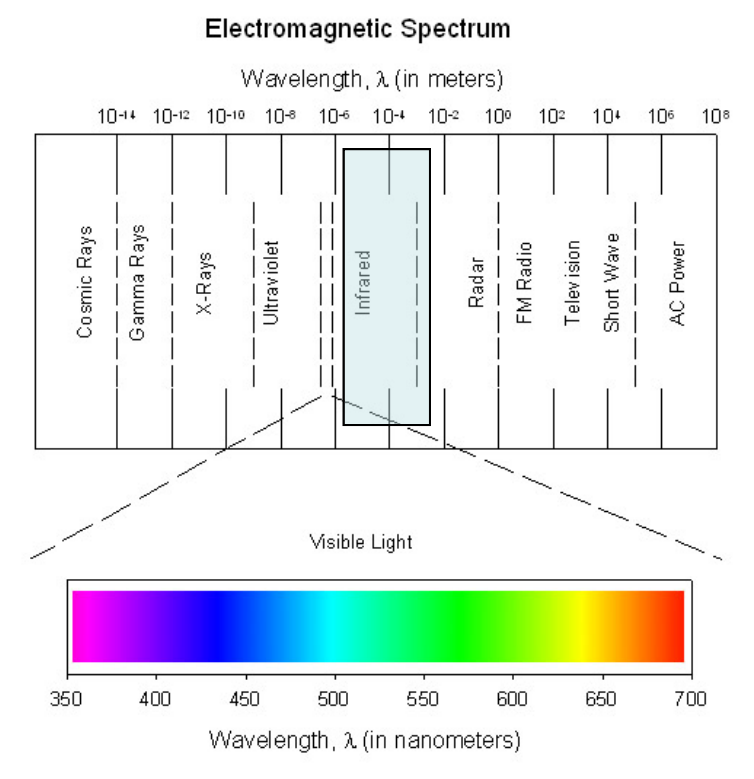
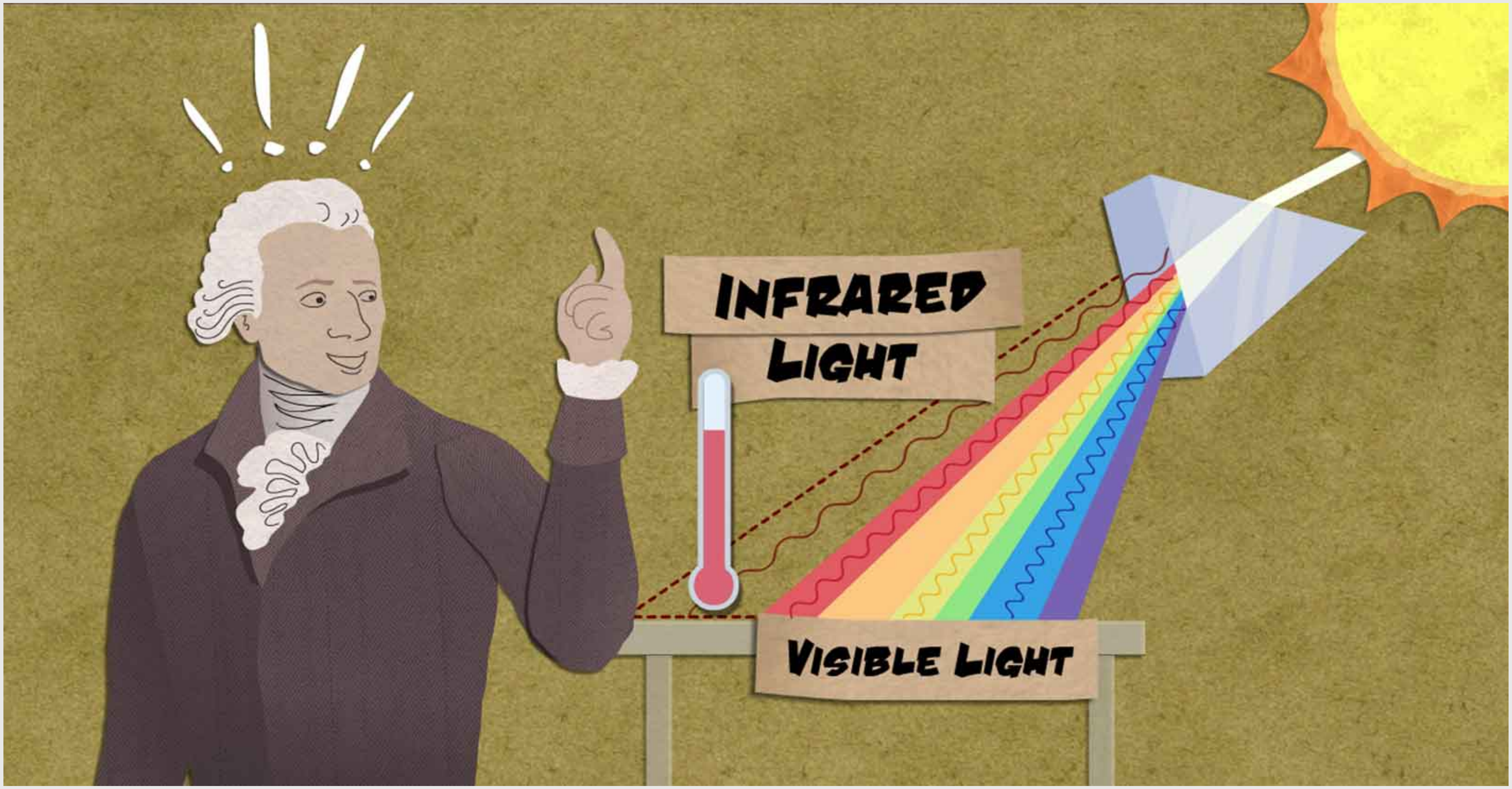
# IR Astronomy

- Eye response goes to 0 at 7500Å
- Silicon bandgap energy of 1.1eV means a hard cutoff in CCD response at 1.1$\mu$
- `near-IR’ : 1$\mu$ - 2.5$\mu$
- `mid-IR’ : 2.5$\mu$ - 25$\mu$
- `far-IR’ : 25$\mu$ - 350$\mu$



# Herschel discovered near IR

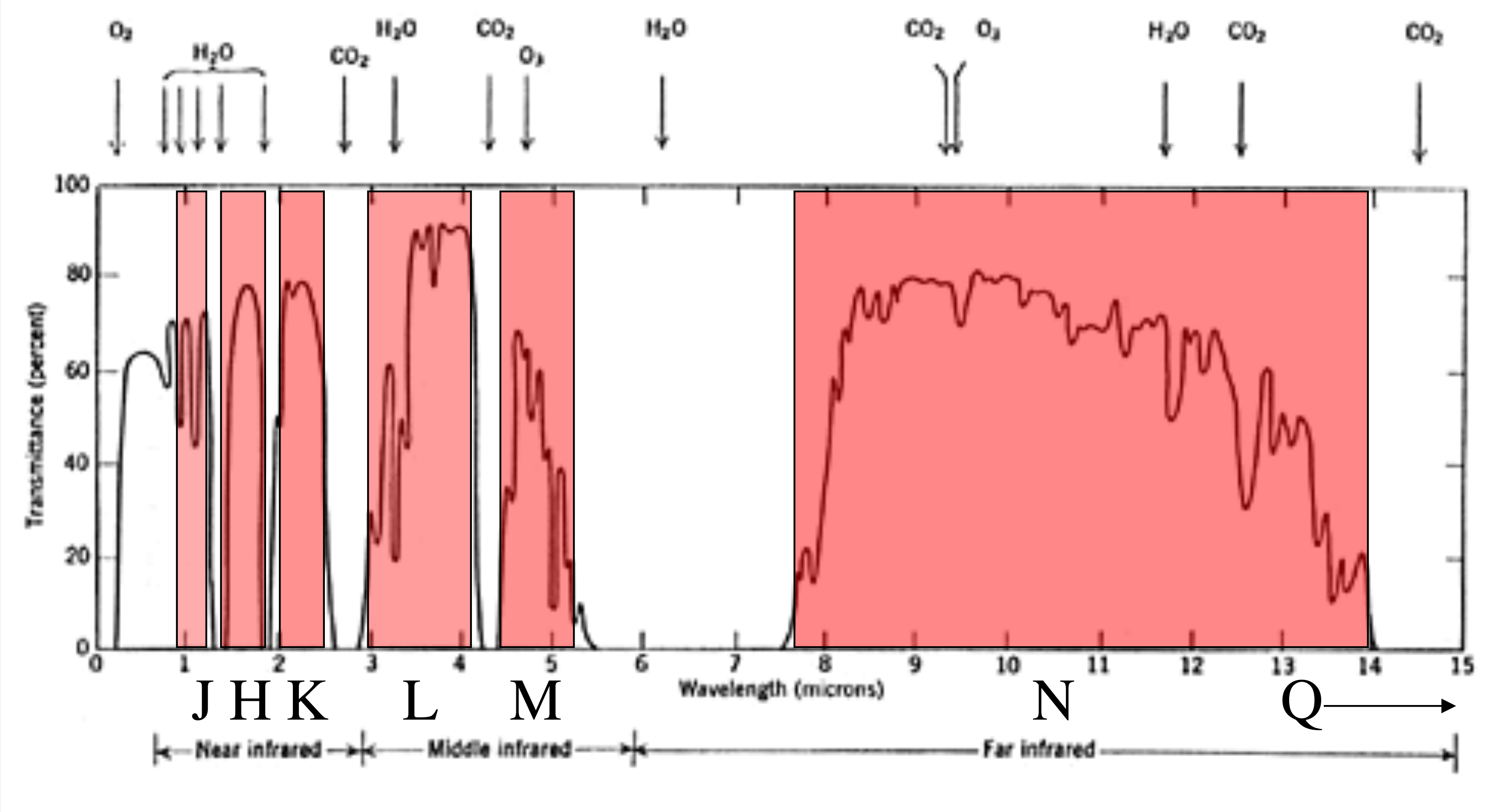


# First patent for IR detector was to detect icebergs and warm ships 1913

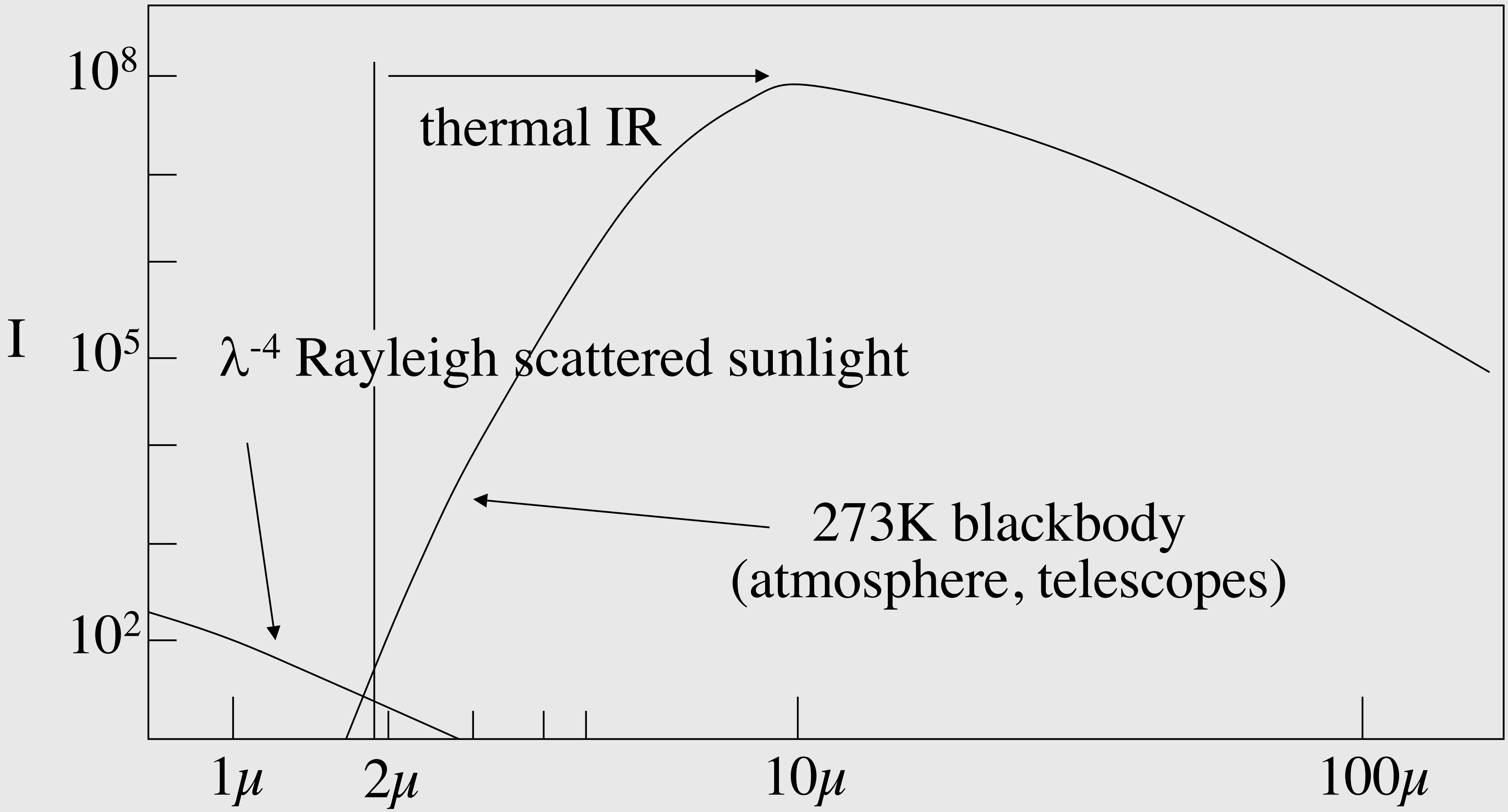
20th Century Fox

# 1947 single diode and scanning mirror was used for IR imaging

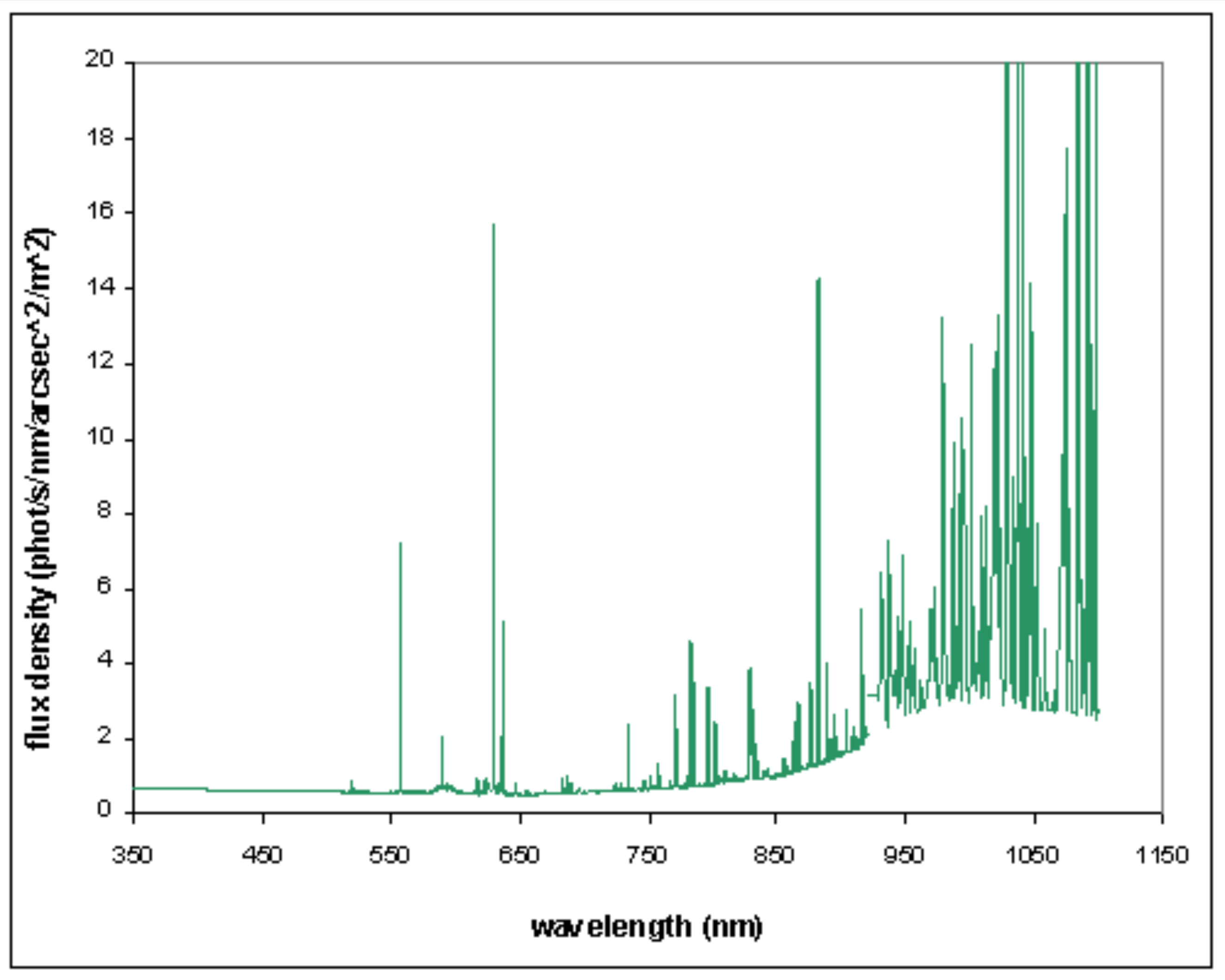
# Atmospheric Windows

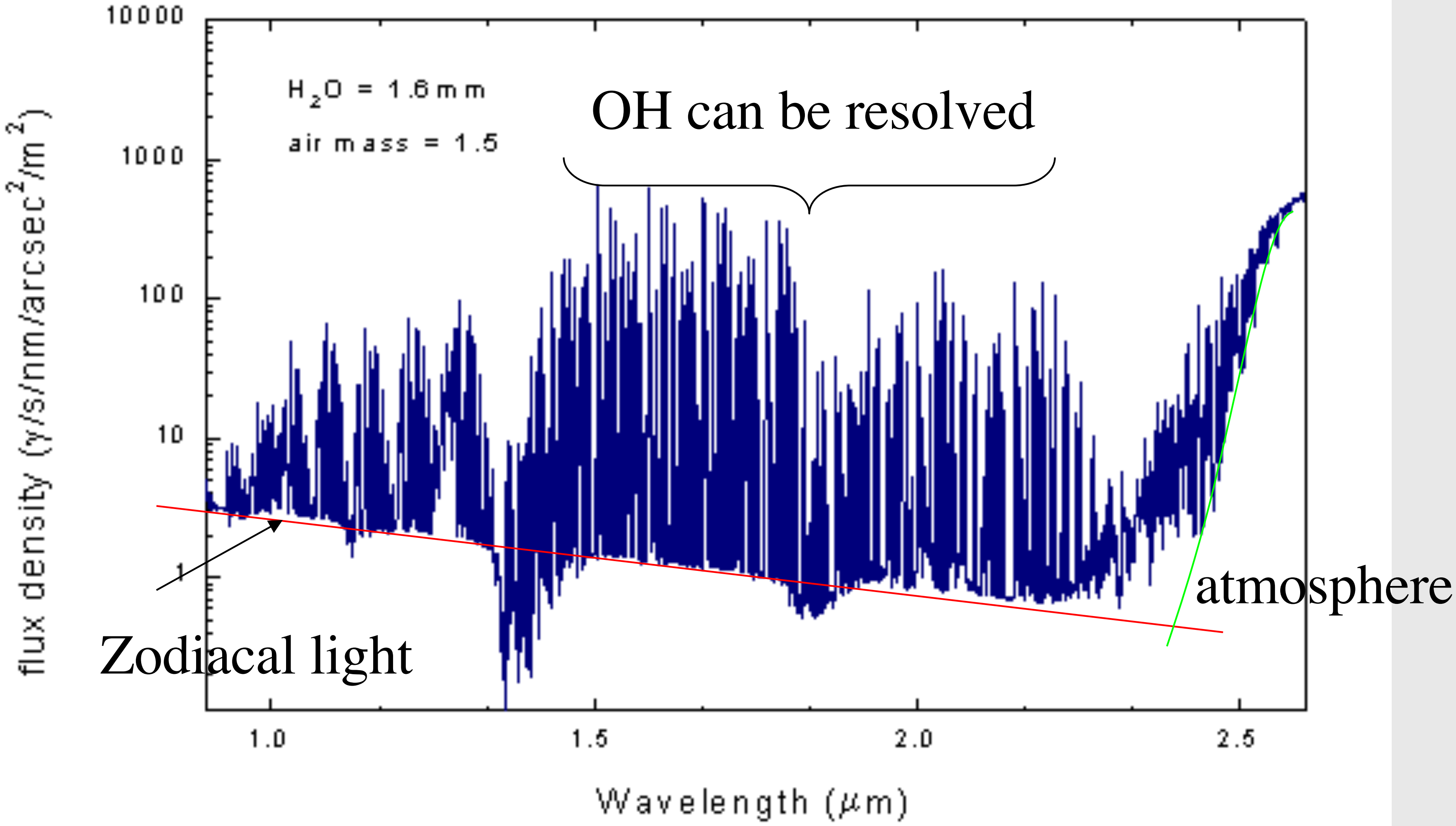


# Backgrounds

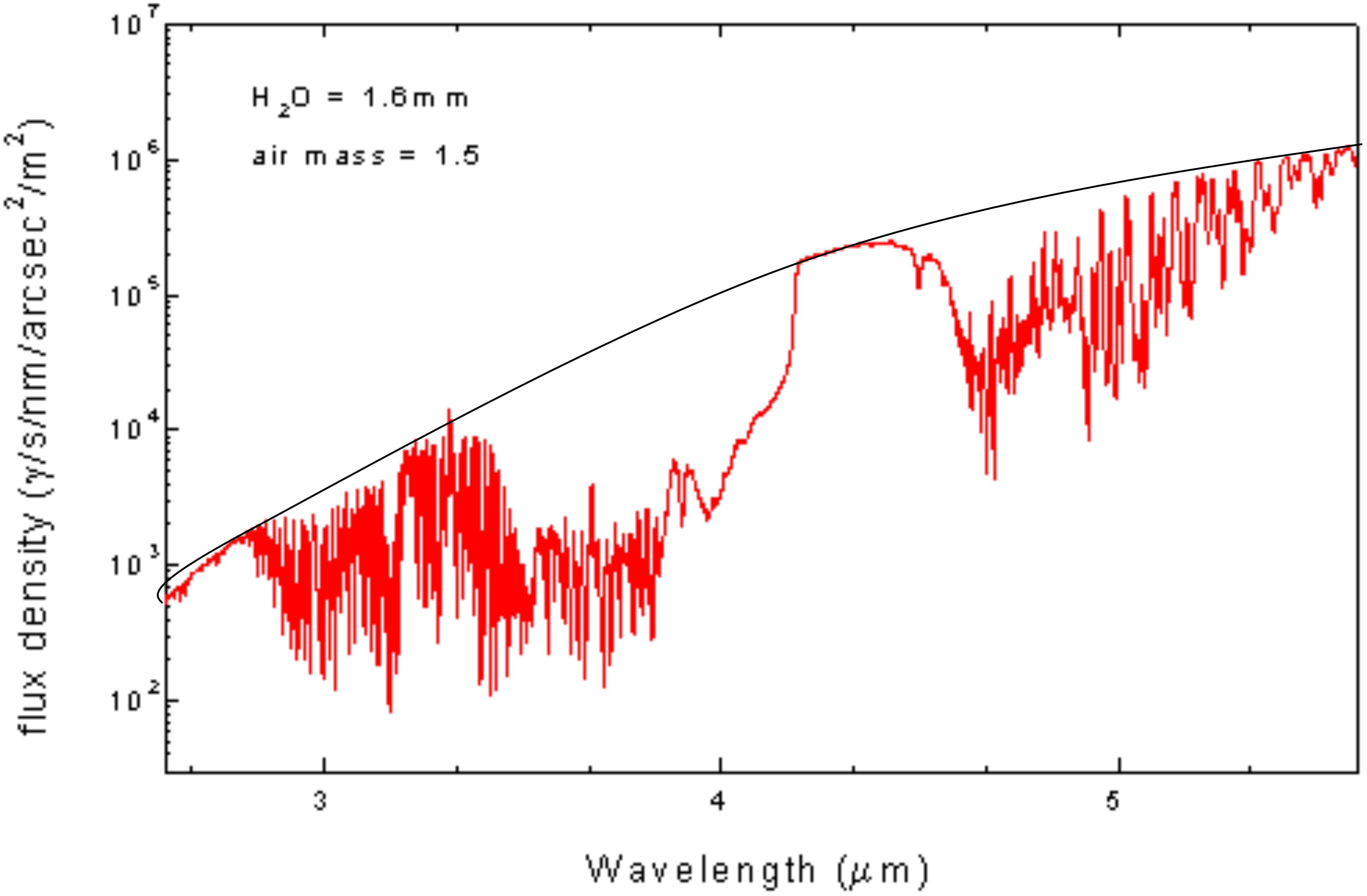


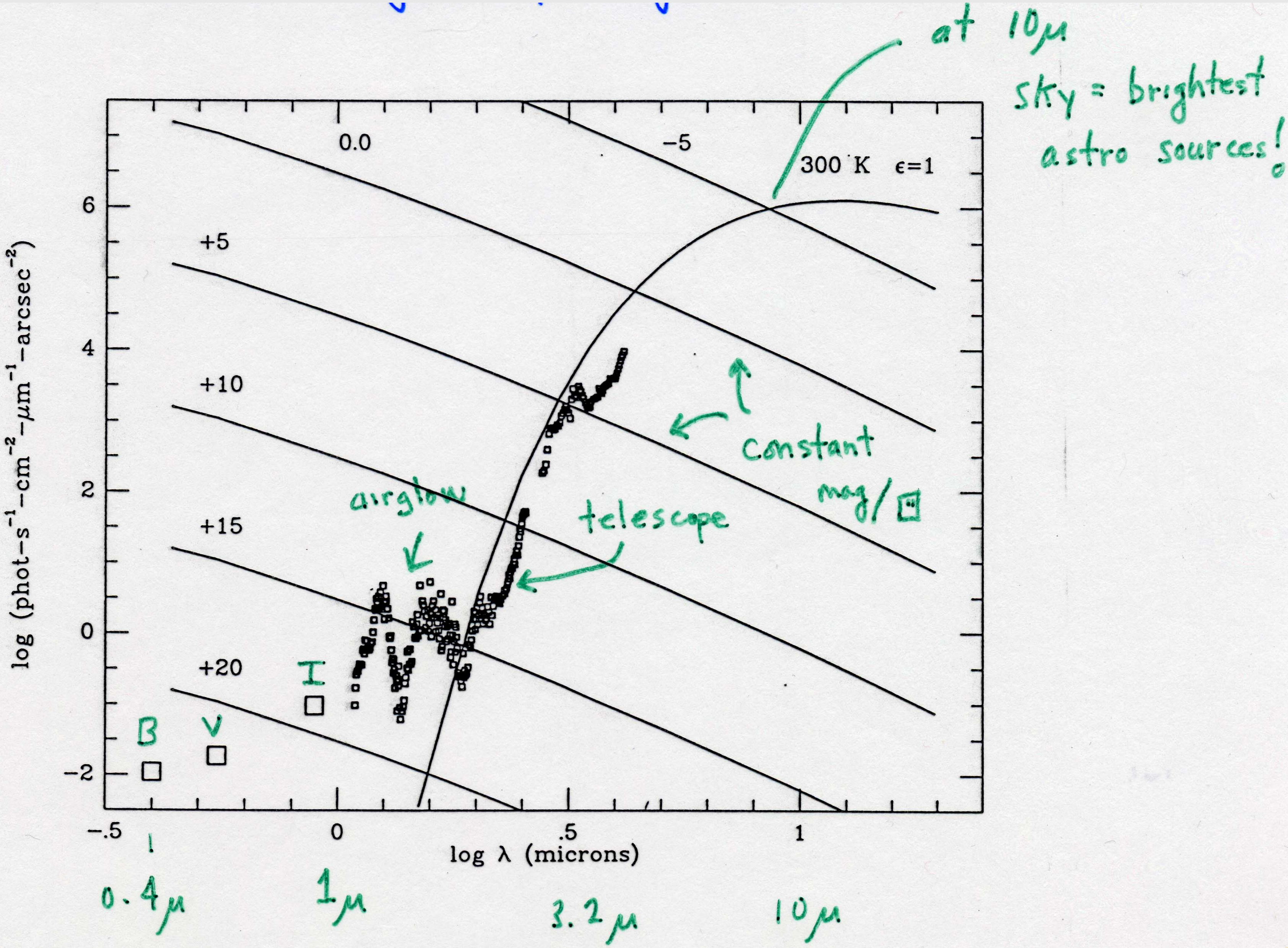
# Backgrounds



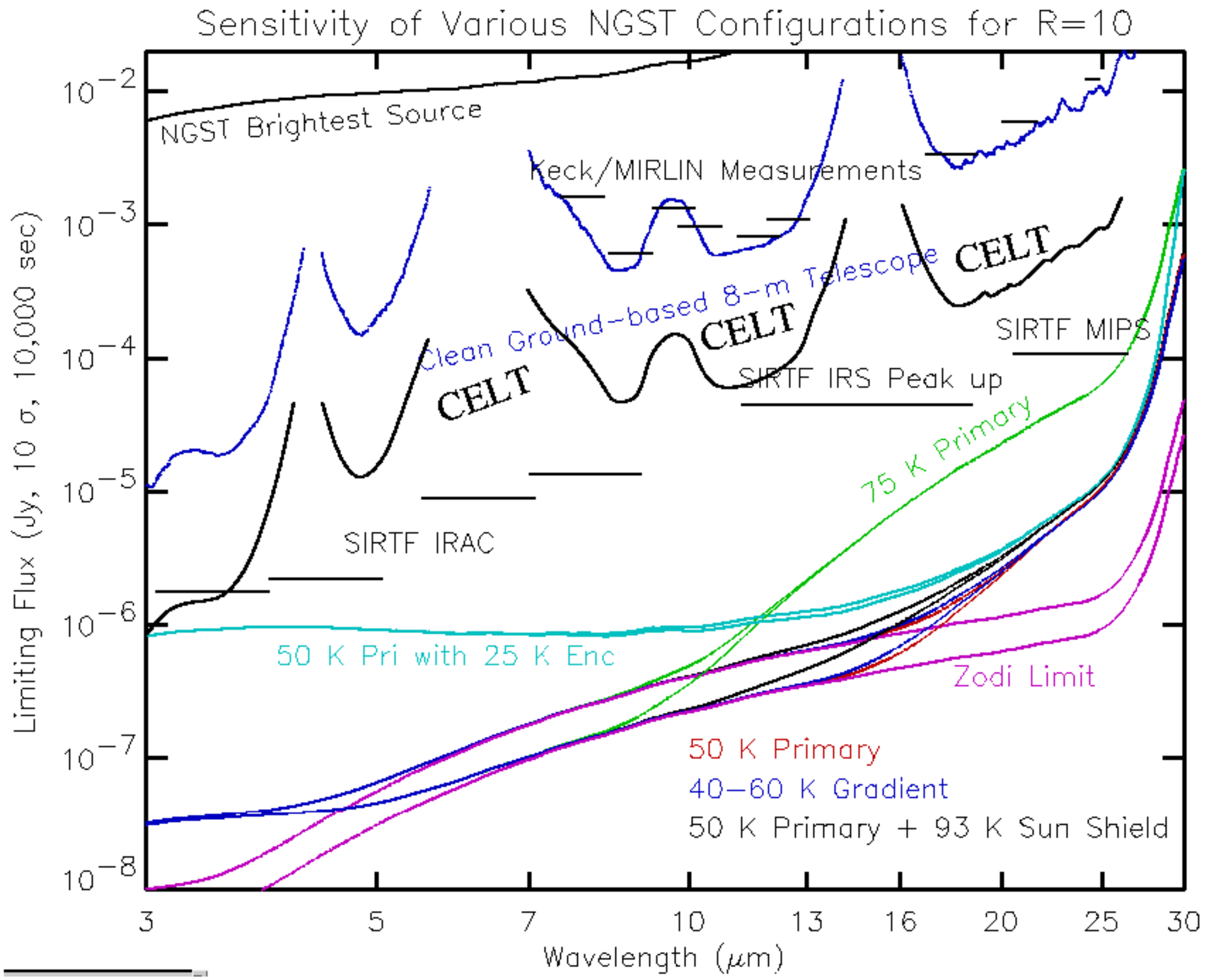

OH can be resolved
H2O = 1.6mm
air mass = 1.5
Zodiacal light
atmosphere
flux density (γ/s/nm/arcsec2/m2)
10000
1000
100
10
1
1.0
1.5
2.0
2.5
Wavelength (μm)

# Note vertical scales on plots!





at 10μ
sky = brightest
astro sources!

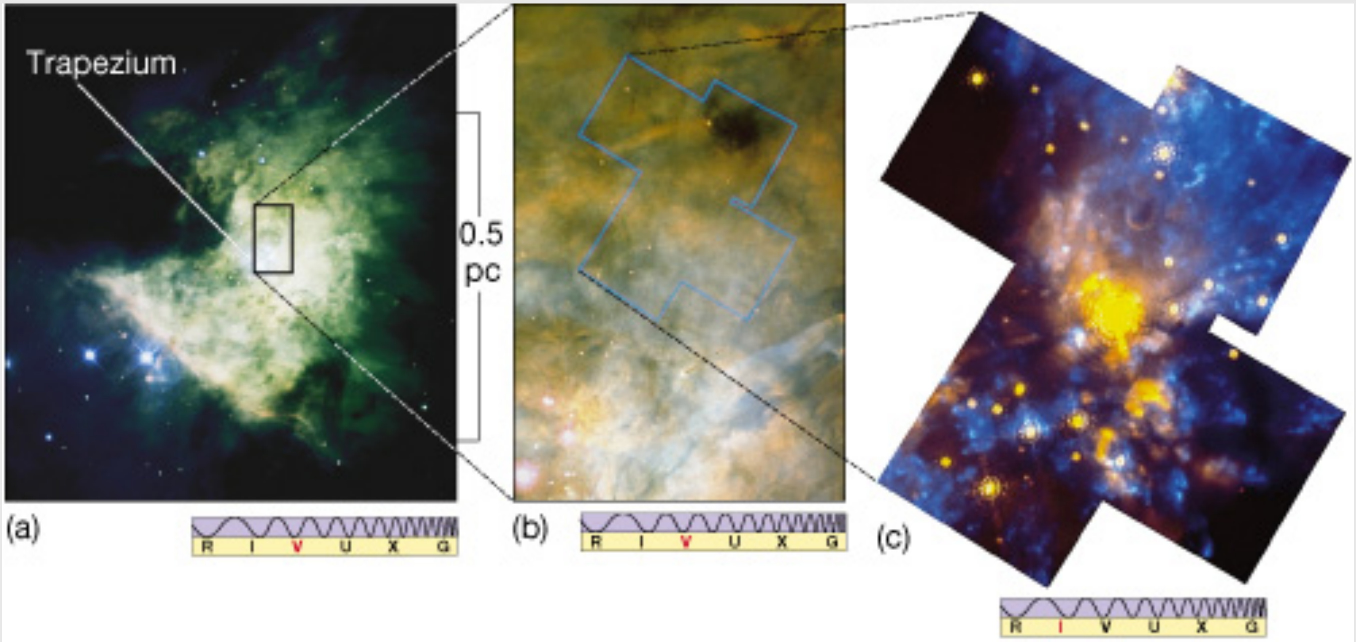

Sensitivity of Various NGST Configurations for R=10
NGST Brightest Source
Keck/MIRLIN Measurements
Clean Ground-based 8-m Telescope
CELT
CELT
CELT
SIRTF MIPS
SIRTF IRS Peak up
SIRTF IRAC
75 K Primary
50 K Pri with 25 K Enc
Zodi Limit
50 K Primary
40–60 K Gradient
50 K Primary + 93 K Sun Shield
Limiting Flux (Jy, 10 σ, 10,000 sec)
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
3
5
7
10
13
16
20
25
30
Wavelength (μm)

# Why IR?

- Galactic dust extinction law:

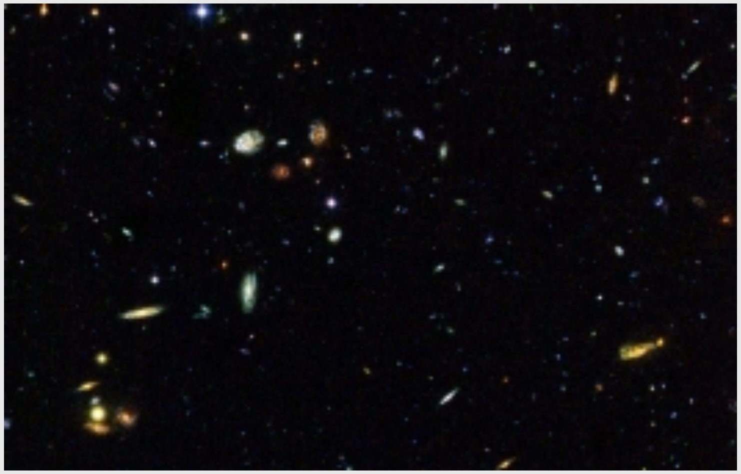
$$k_{2.2\mu} \sim 0.1 k_{0.5\mu}$$

- Cool stuff: $\lambda_{peak}(\text{planck}) = 2898/T\ (\mu)$
  - Cool stars emitted energy peak ~ $1\mu$
  - Giant planets ~ $6\text{-}15\mu$
  - Dust re-radiation ~ $20\text{-}200\mu$



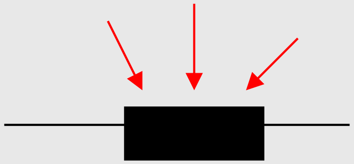
# High-z Universe

- $\lambda = \lambda_0(1+z)$
- @z=1.8 Ca H&K `break' redshifted to J band
- @z=8 L



# Detectors

- Original IR detectors were lead-sulfide, then germanium *bolometers*.



Photoconductive: resistance a very sensitive function of T. Ran at liquid helium temperatures (4K).

- 1980’s the first photo-diode (CCD-like) detectors became available with semicondutors that had smaller bandgaps than silicon

larger dark currents!

| Material | wavelength($\mu$) | $T_{operate}$ |
|---|---|---|
| Si | $<1.1\mu$ | 160K |
| HgCdTe | $0.8 - 5\mu$ | 65K |
| InSb | $1 - 5.6\mu$ | 35K |
| SiAs | $6 - 27\mu$ | 10K |

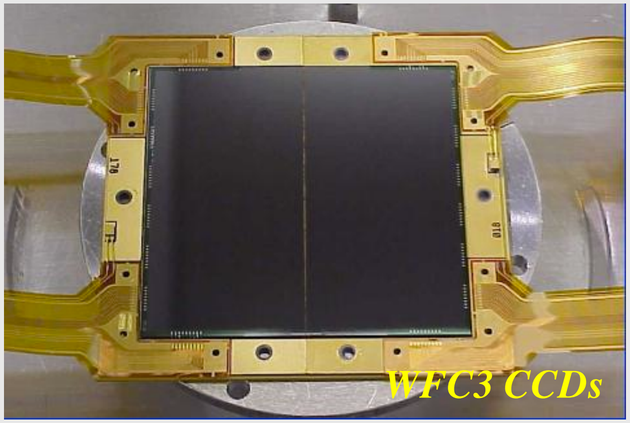
As the bandgap decreases, the dark current goes up at given thermal energy (~ kt) so need to run at lower temperature

# Modern (2019) near-IR detectors

- Charge-transfer devices (CCD) hard to build out of IR detector materials
- So, use photo-sensitive layer on top of readout layer (silicon) or MUX. Each pixel has its own amplifier
- Connect the two layers pixel-by-pixel with iridium bumps (“bump bonded”)
- Can readout signal multiple times
- Honeywell, Rockwell, Raytheon, Teledyne

# Common detector types for the visible through mid-IR

## CCD

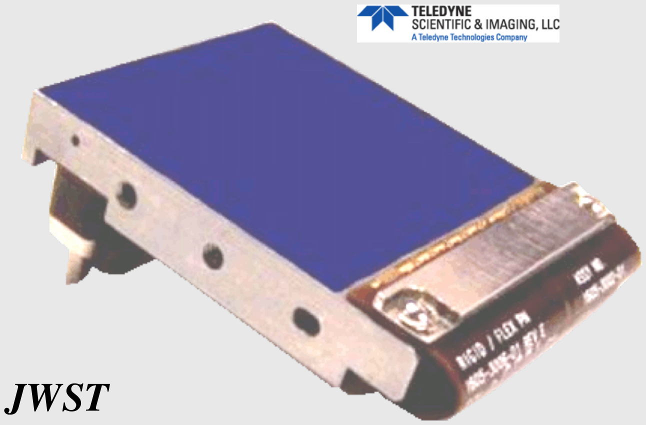

*WFC3 CCDs*

- $\lambda \sim 250 - 1050$ nm
- Intrinsic Si photoconcuctor
- Photons collected and charge read out in same piece of silicon
- During readout, charge physically moves from one pixel to the next
- Usual readout is correlated double sampling
- Because charge moves, on-chip binning is possible

## Hybrid detector arrays

- Photon collection separated from readout
  - Optimized detector layer collects charge
  - Optimized readout integrated circuit senses charge in place (it does not move like in a CCD)
- Multiple non-destructive reads typically used to beat down read noise and integrate through cosmic ray hits

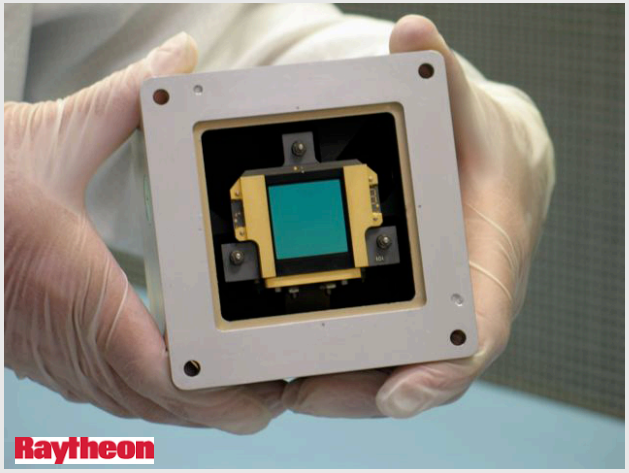
### Near-IR array



***JWST NIRSpec H2RG***

- $\lambda \sim 1.7$ to $> 5\ \mu$m
- Intrinsic HgCdTe or InSb photoconductor
- NICMOS, IRAC, WFC3, JWST NIR instruments

### Mid-IR array



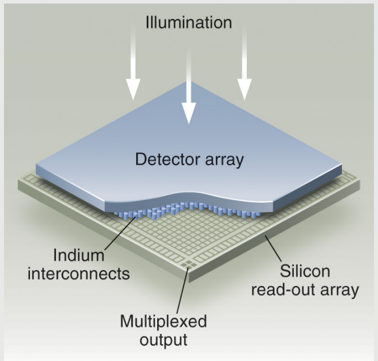
***JWST MIRI***

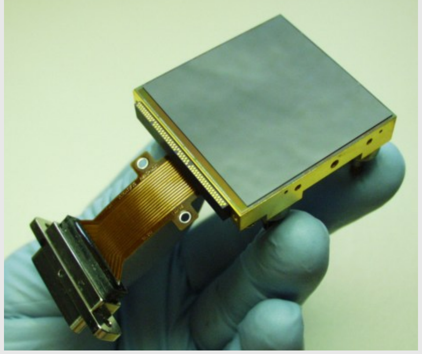
- $\lambda \sim 5 - 28\ \mu$m
- Extrinsic (intentionally doped) Si:As photoconducor (other dopants are possible for longer wavelength response)
- IRAC and JWST/MIRI

# JWST's H2RGs are part of the Teledyne HxRG family

H: HAWAII: HgCdTe Astronomical Wide Area Infrared Imager
x: Number of 1024 (or 1K) pixel blocks in x and y-dimensions
R: Reference pixels
G: Guide window capability

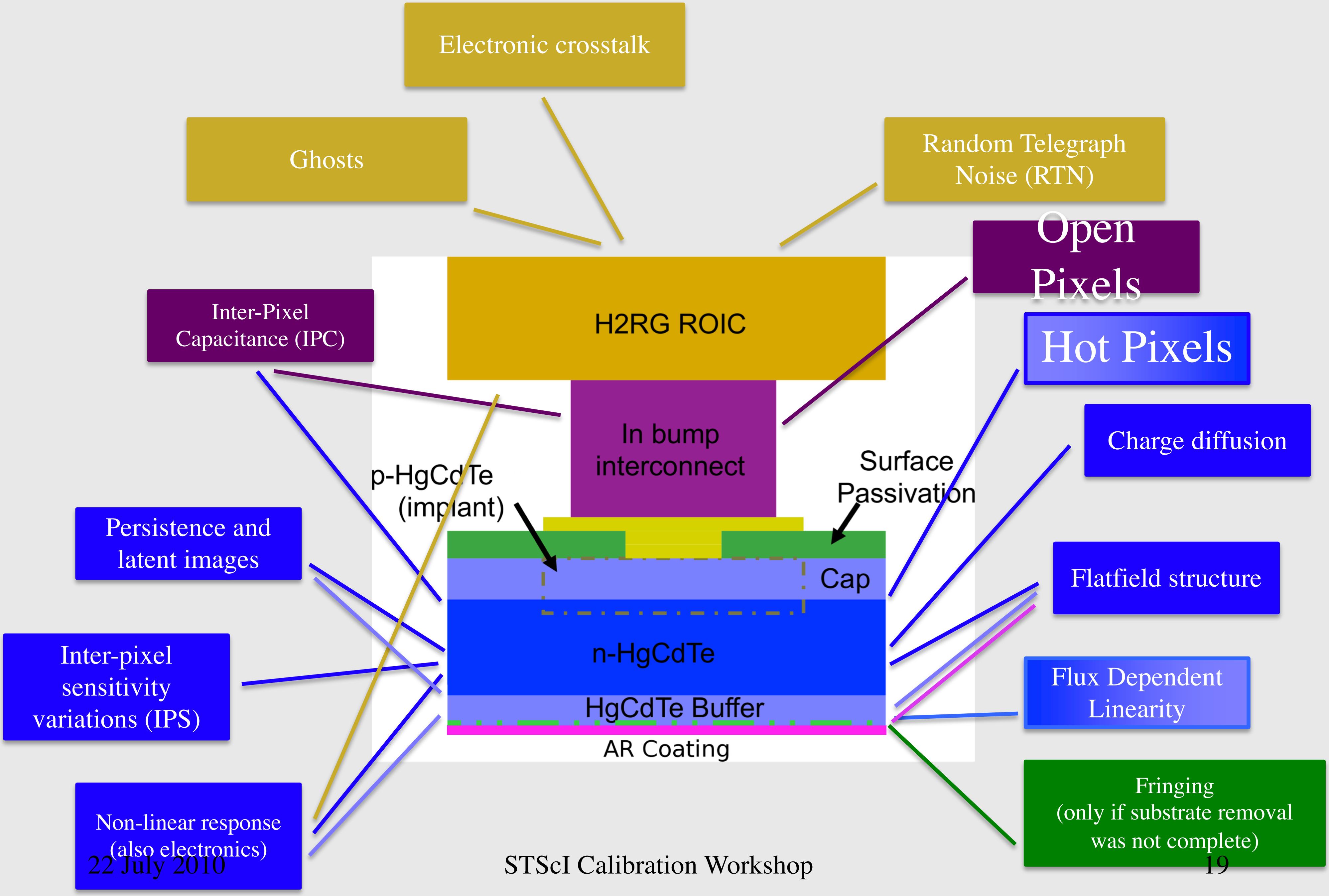
- ➔ Substrate-removed HgCdTe for simultaneous visible & infrared observation
- ➔ Hybrid Visible Silicon Imager; Si-PIN (HyViSI)





| Name | Format (# of Pixel) | Pixel Pitch ( m) | # of Outputs | Institutions, Observatories, and Programs Using HxRG Arrays |
|---|---|---|---|---|
| **H1RG** | 1024×1024 | 18 | 1, 2, 16 | Wide-field Infrared Survey Explorer (WISE)<br>Orbiting Carbon Observatory (OCO)<br>Development Programs in Astronomy & Earth Science |
| **H2RG** | 2048×2048 | 18 | 1, 4, 32 | James Webb Space Telescope (JWST) - NIRCam, NIRSpec, FGS<br>Joint Dark Energy Mission (JDEM)<br>Astronomy institutions and observatories: Calar Alto, Caltech, CFHT, ESO, ESTEC, Gemini, GSFC, IRTF, ISRO, IUCAA, JHU-APL, Keck, LBNL, LMU, MIT, MPIA, MPS, OCIW, Penn State, RIT, SALT, SAO, Subaru, TATA, U. Arizona, UCLA, UC Berkeley, U. Hawaii, U. Rochester, U. Toronto, U. Wisconsin<br>Space surveillance applications |
| **H4RG-10** | 4096×4096 | 10 | 1, 4, 16, 32, 64 | Joint Milli-Arcsecond Pathfinder Survey (J-MAPS)<br>Development Programs in Astronomy |
| **H4RG-15** | 4096×4096 | 15 | 1, 4, 16, 32, 64 | In Development, first on sky telescope test in 2011 |

# Some calibration “gotcha’s” and where they might originate in the sensor chip assemblies (SCA)



Electronic crosstalk

Ghosts

Random Telegraph Noise (RTN)

Open Pixels

Inter-Pixel Capacitance (IPC)

Hot Pixels

Charge diffusion

Persistence and latent images

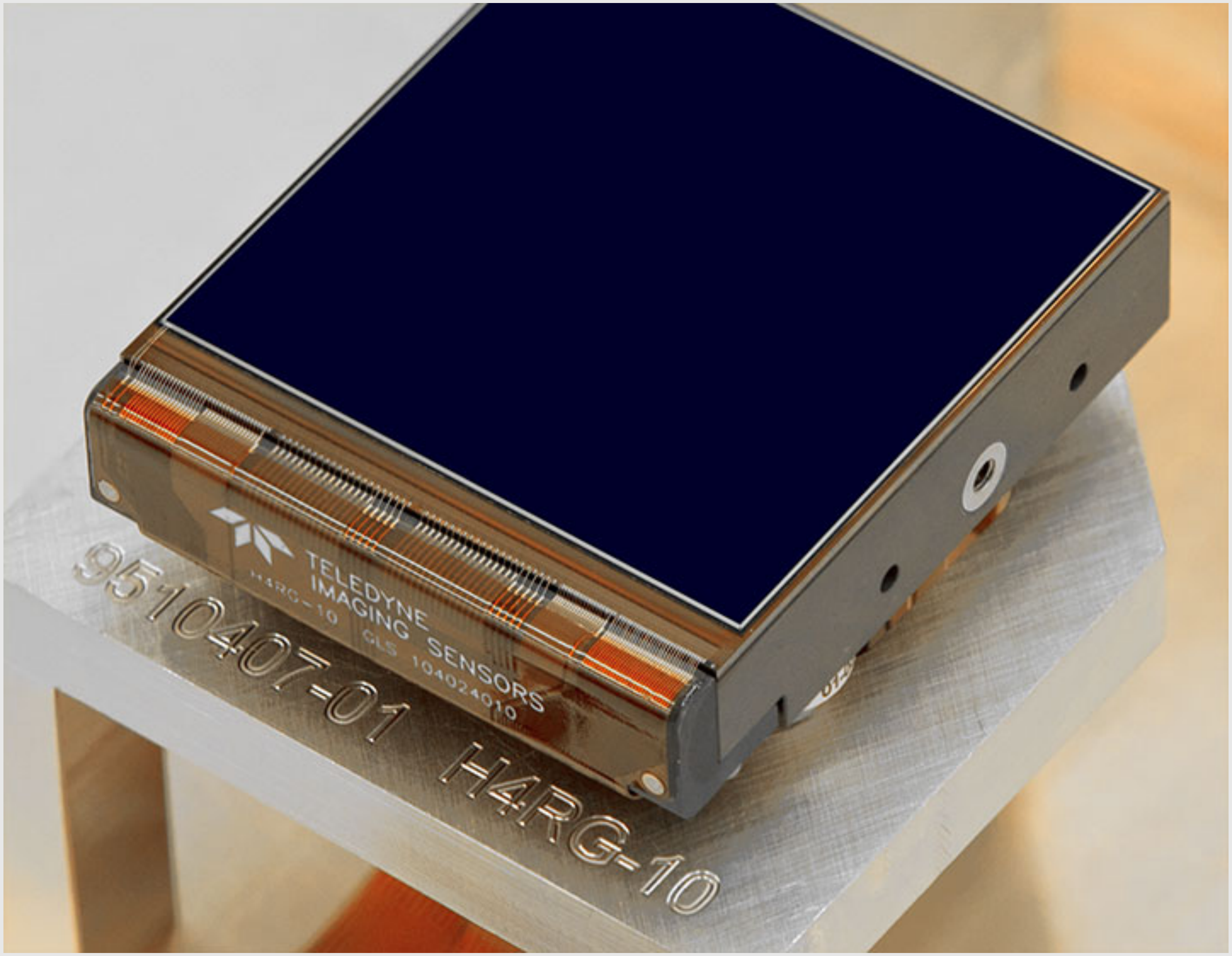
Flatfield structure

Inter-pixel sensitivity variations (IPS)

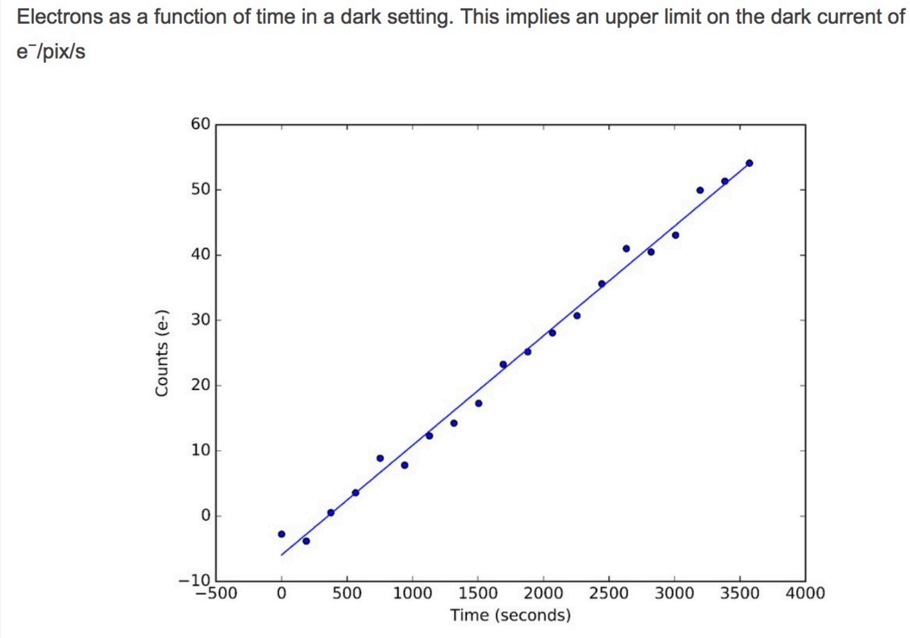
Flux Dependent Linearity

Fringing
(only if substrate removal was not complete)

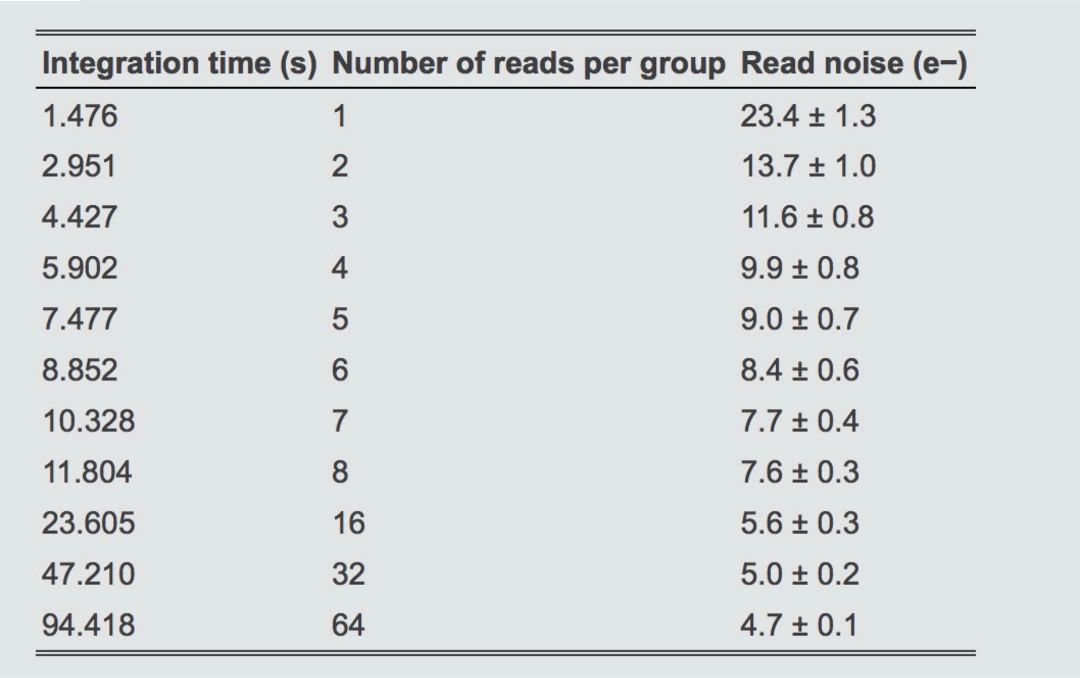
Non-linear response
(also electronics)


TELEDYNE
IMAGING SENSORS
H4RG-10 GLS 104024010
9510407-01 H4RG-10

# Teledyne Hawaii-RG series is current standard HgCdTe



Electrons as a function of time in a dark setting. This implies an upper limit on the dark current of <.021 e⁻/pix/s



| Integration time (s) | Number of reads per group | Read noise (e−) |
|---|---|---|
| 1.476 | 1 | 23.4 ± 1.3 |
| 2.951 | 2 | 13.7 ± 1.0 |
| 4.427 | 3 | 11.6 ± 0.8 |
| 5.902 | 4 | 9.9 ± 0.8 |
| 7.477 | 5 | 9.0 ± 0.7 |
| 8.852 | 6 | 8.4 ± 0.6 |
| 10.328 | 7 | 7.7 ± 0.4 |
| 11.804 | 8 | 7.6 ± 0.3 |
| 23.605 | 16 | 5.6 ± 0.3 |
| 47.210 | 32 | 5.0 ± 0.2 |
| 94.418 | 64 | 4.7 ± 0.1 |

- 1k x 1k, 2k x 2k, 4k x 4k pixels (18$\mu$)
- Long-wave cutoff can be tuned by CdTe mix (1.7$\mu$ - 5.5$\mu$)
- QE >85% from ~0.85$\mu$ - 5.5$\mu$

# Hawaii-2RG: linearity

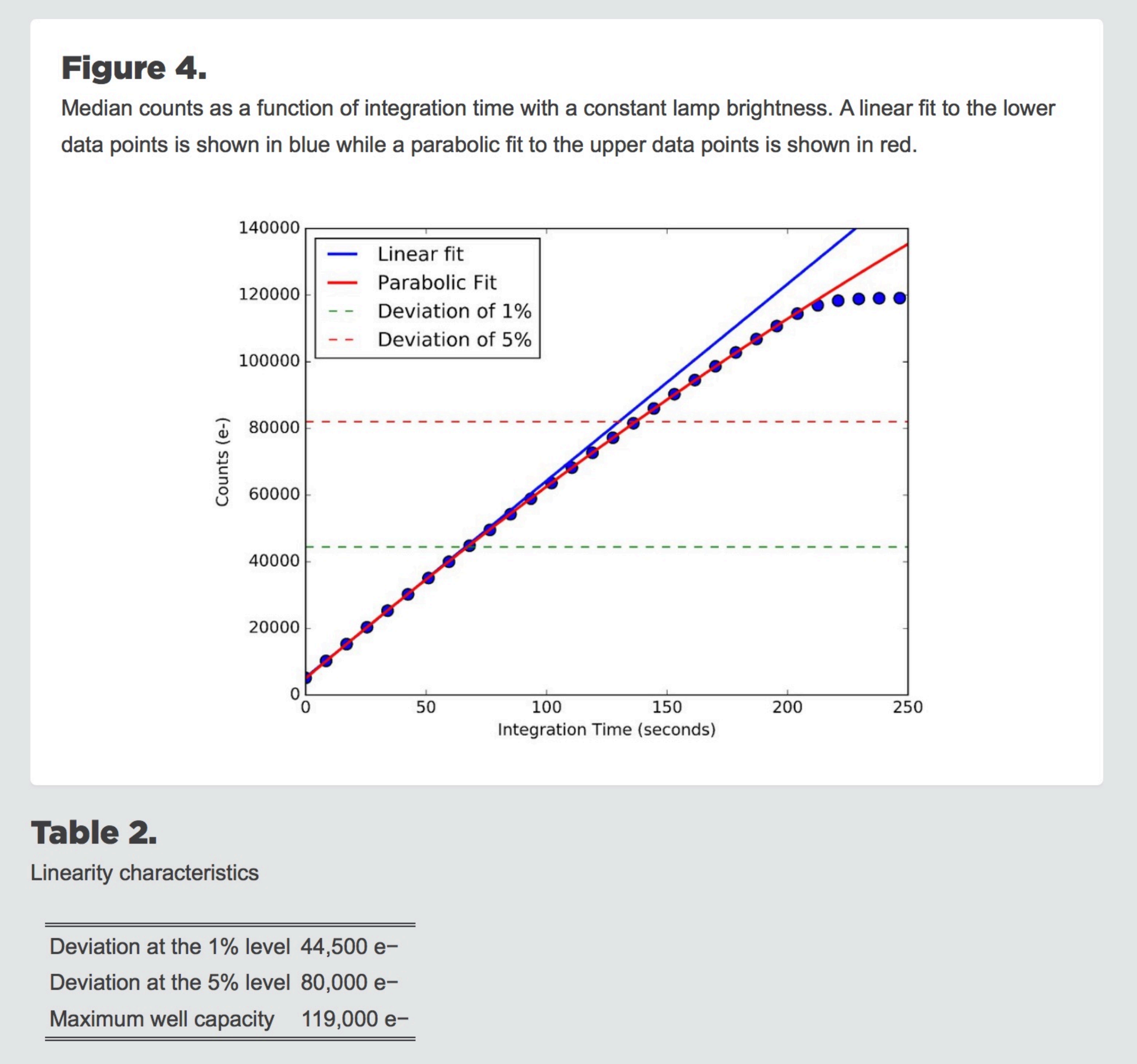


**Figure 4.**

Median counts as a function of integration time with a constant lamp brightness. A linear fit to the lower data points is shown in blue while a parabolic fit to the upper data points is shown in red.

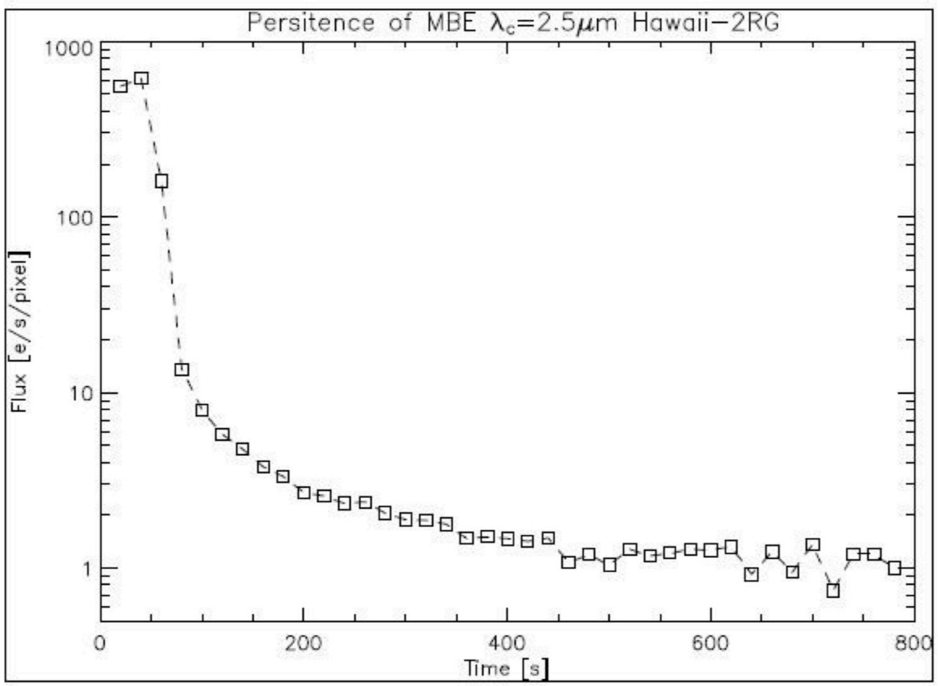
**Table 2.**

Linearity characteristics

| | |
|---|---|
| Deviation at the 1% level | 44,500 e− |
| Deviation at the 5% level | 80,000 e− |
| Maximum well capacity | 119,000 e− |

# Hawaii-2RG: Persistence

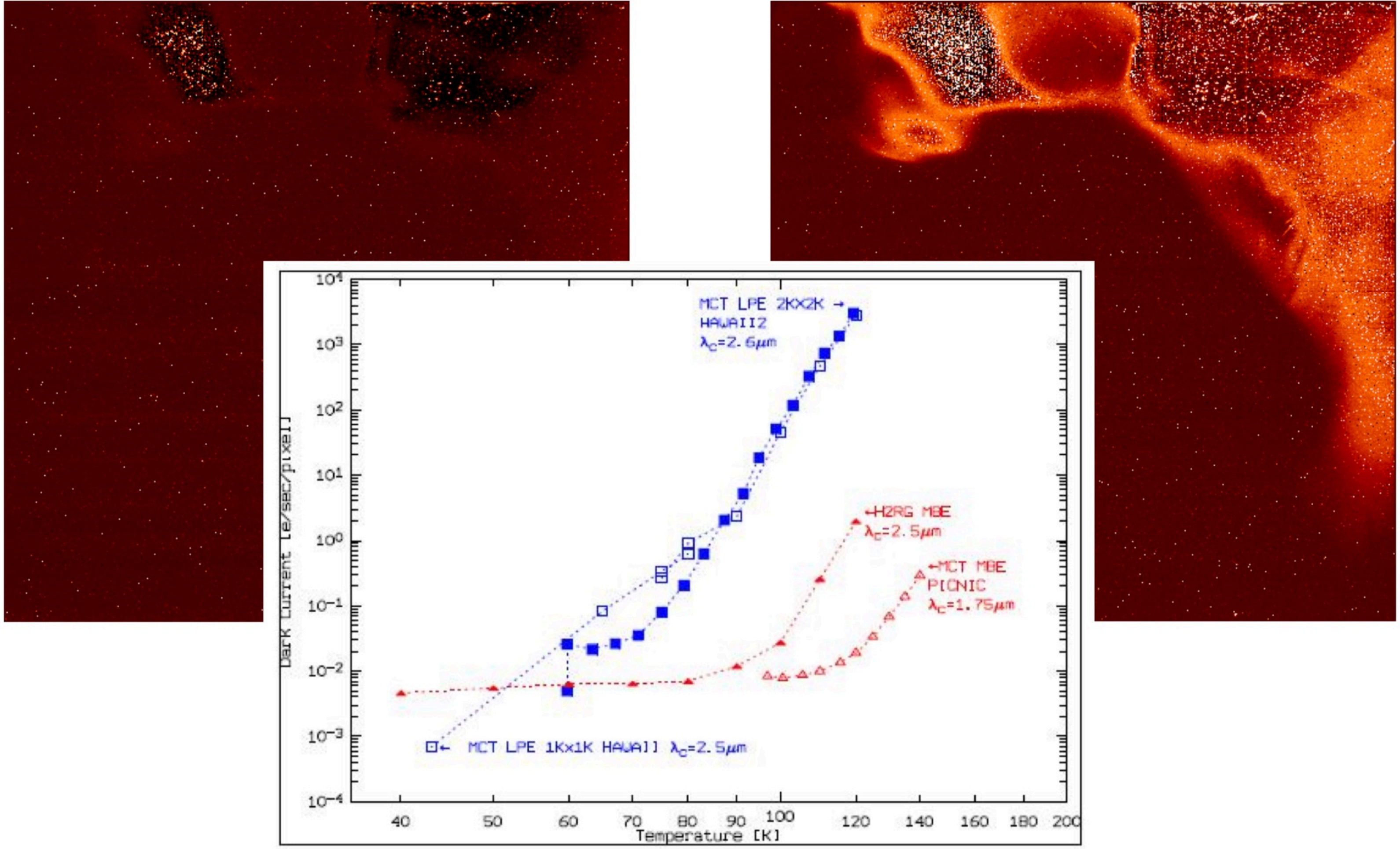
**HAWAII-2: Persistent Images = f(t)**



Persistence of Hawaii-2RG MBE array in J band. Detector integration time 20 s.

# Hawaii-2RG: Messy

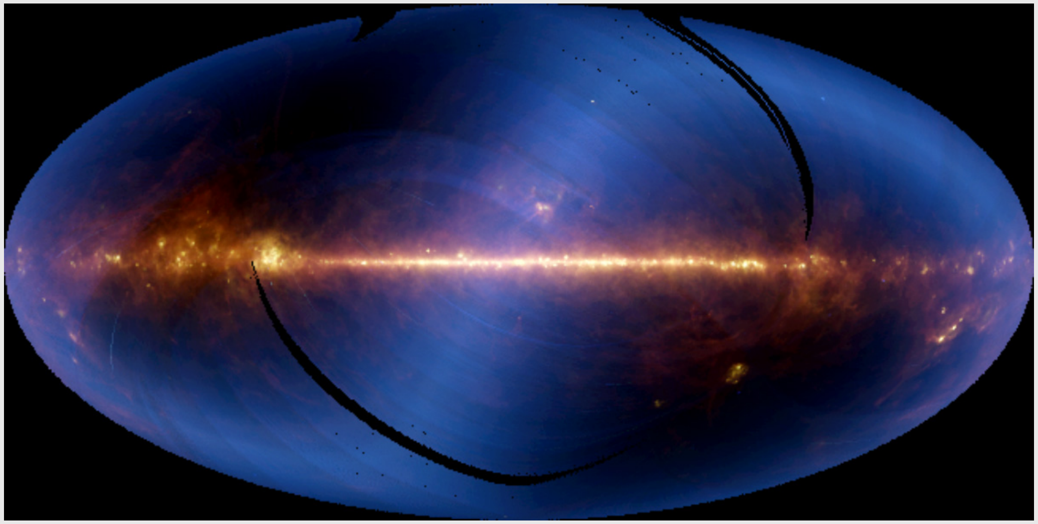
## HAWAII-2: Global Dark Current Maps = f(T)



Dark current maps for T=40K (left) and T=80K (right); $t_{int}$ = 11′

# Space is cool

- IRAS 1983
- ISO 1995
- Spitzer 2003
- WISE 2009
- Kuiper
- SOFIA

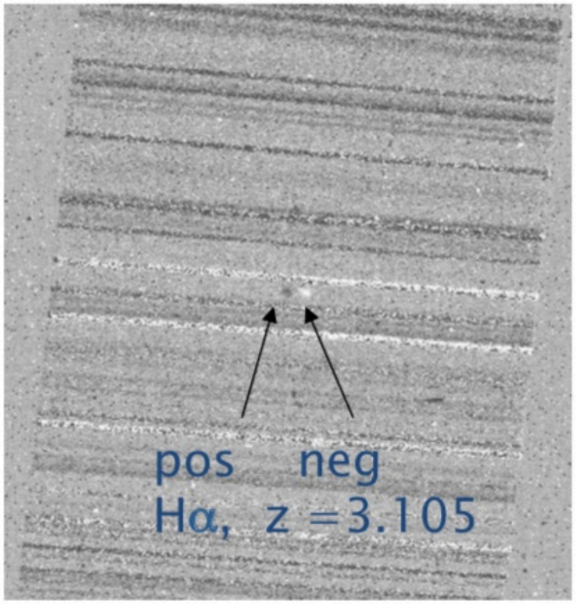


# Special considerations for IR observing

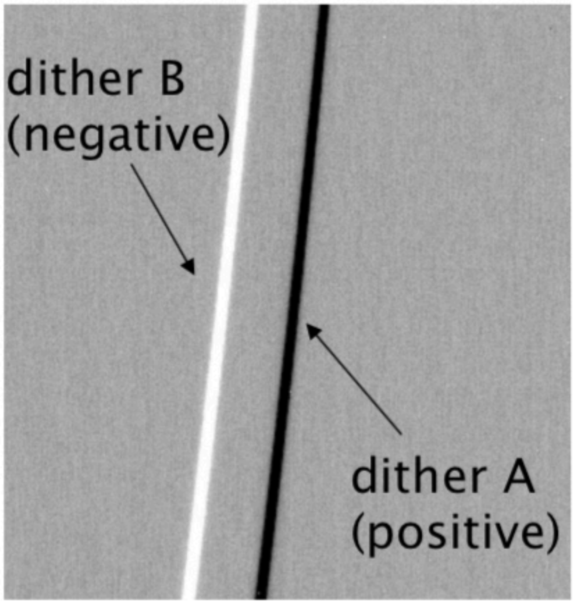
- Hardly any!
- Chopping/dithering (highly variable background)
    - Subtracts off sky (background)
- Backgrounds are enormous: avoiding saturation requires lots of short exposures
- Don’t ignore detector dark/readout noise
- Telescope designers be careful
    - Baffling
    - Cold pupils
    - Underfilled secondaries

# Example from Keck/NIRSPEC at R ~ 2000

Single long (900 sec) exposure on a high-z galaxy (note all the cosmic rays and the dominance of night sky emission lines)



Subtracted pair of images (note pos. & neg. images and both the sky residuals and the doubling of cosmic ray effects)



Difference of two short exposures of a standard star (note how cleanly sky subtracts and the lack of cosmic ray hits)