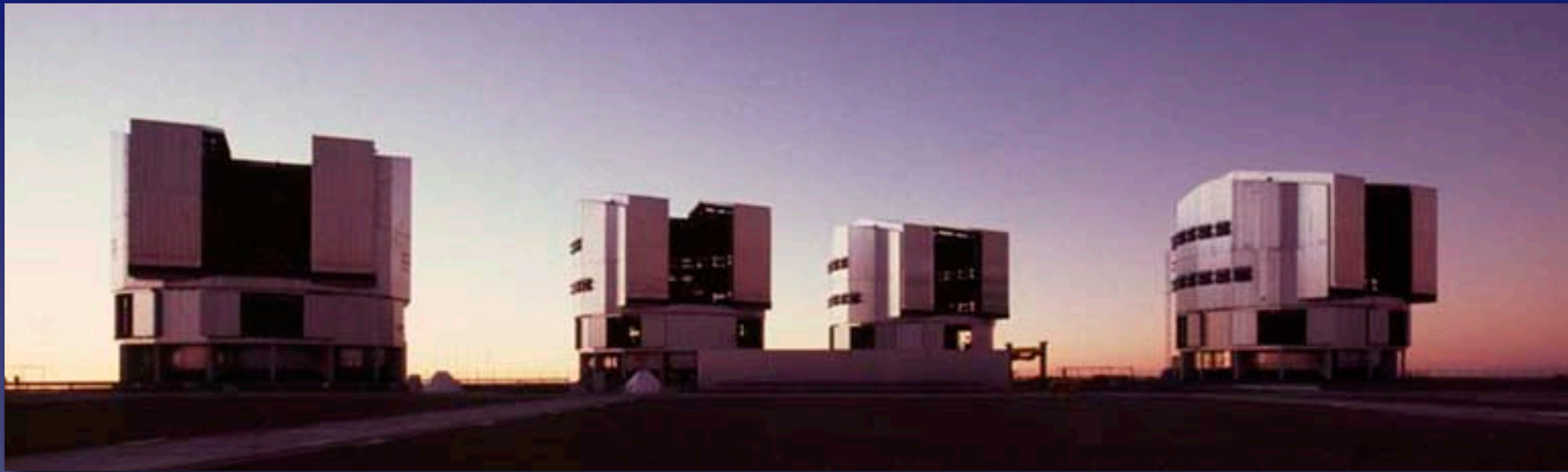


Infrared astronomy: an introduction

Mark McCaughrean
Astrophysics Group, School of Physics
UNIVERSITY OF EXETER

constellation

CONSTELLATION School on Star Formation at Infrared Wavelengths
Osservatorio di Arcetri, Firenze, Italy, May 27 2008

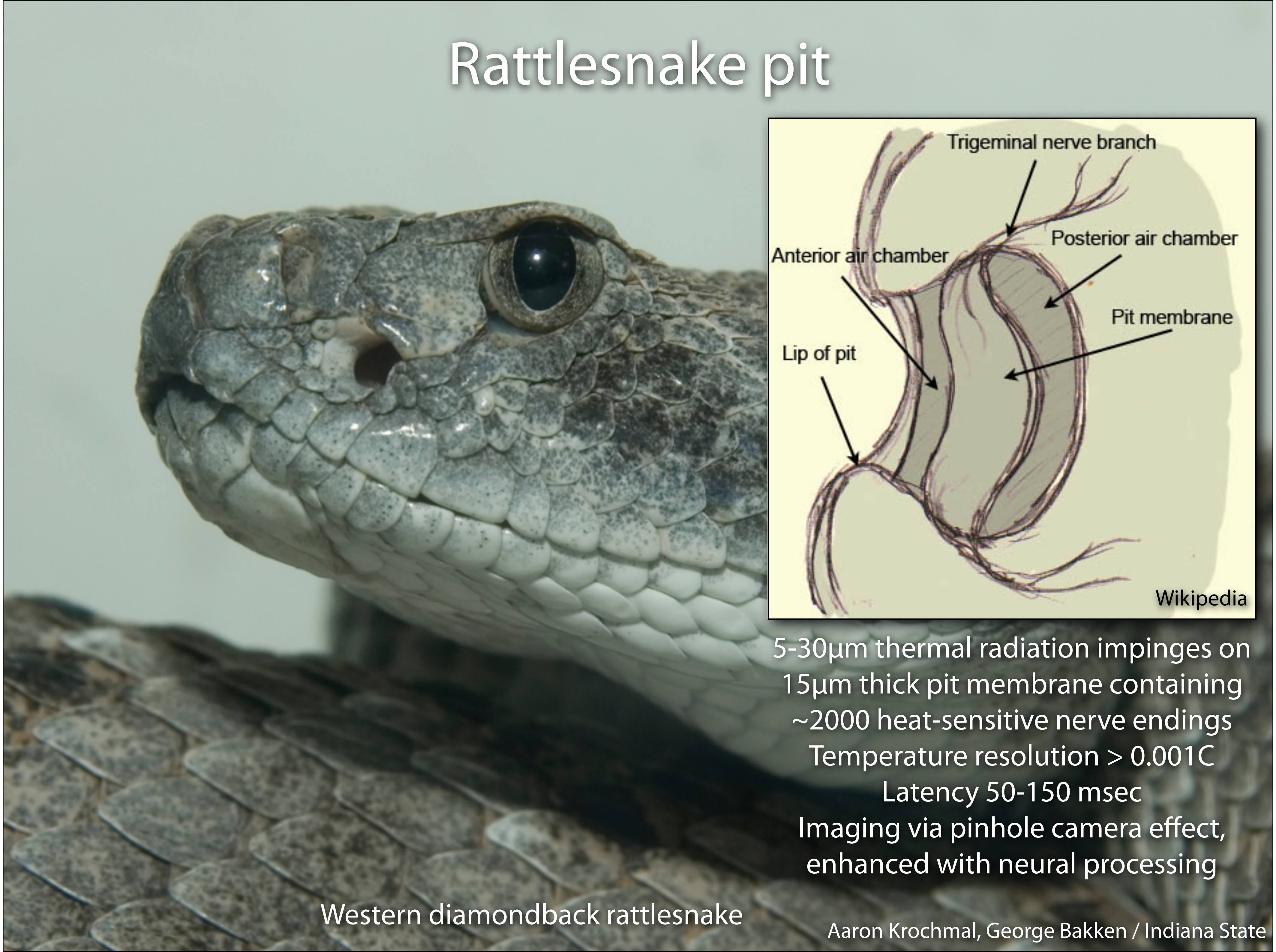
The original infrared observers

Albino rattlesnake

Mark Kostich


Western diamondback rattlesnake
Aaron Krochmal, George Bakken / Indiana State

Rattlesnake pit



5-30μm thermal radiation impinges on
15μm thick pit membrane containing
~2000 heat-sensitive nerve endings
Temperature resolution > 0.001C
Latency 50-150 msec
Imaging via pinhole camera effect,
enhanced with neural processing

Western diamondback rattlesnake

Aaron Krochmal, George Bakken / Indiana State

Rattlesnake nemesis

California ground squirrel

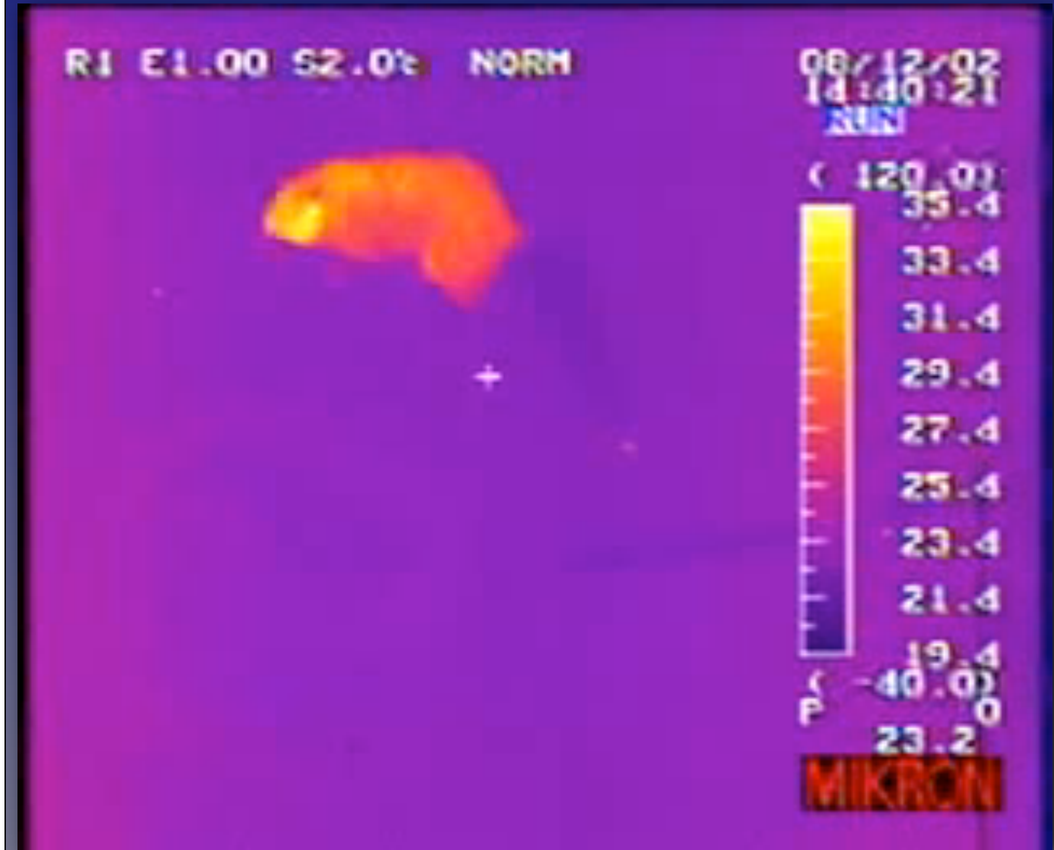
Gregg Elovich

Brave little buggers

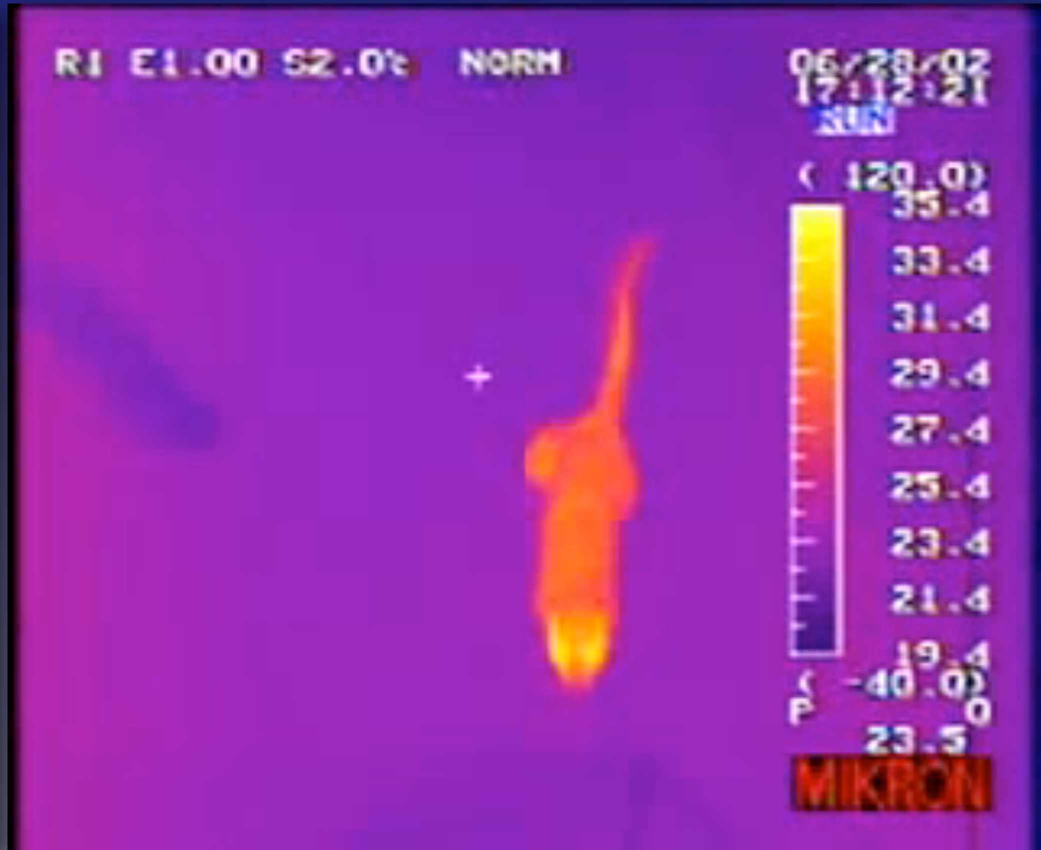
Ground squirrels versus a gopher snake

US National Park Service

But clever too ...



Ground squirrel versus gopher snake
(no infrared sensory organs)



Ground squirrel versus rattlesnake
(member of pit viper family)

Thermal-infrared imaging

Aaron Rundus, Donald Owings / UC Davis / New Scientist

More thermal infrared imaging

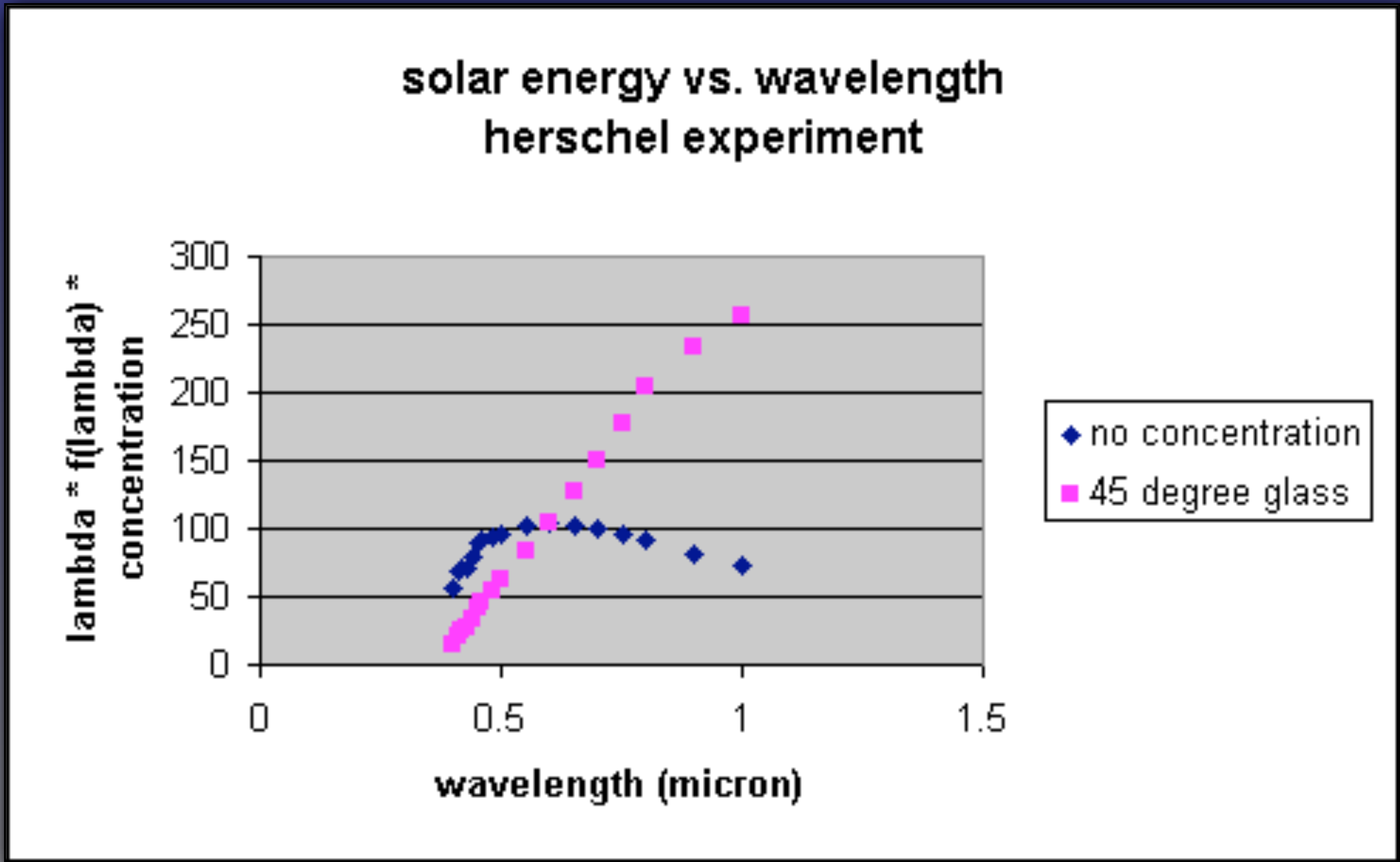
Human discovery of the infrared

- Herschel made discovery serendipitously in 1800
  - Experiment to measure efficiency of filters
  - Dispersed sunlight with prism
  - Used thermometers: basic form of bolometer
- Found peak temperature beyond red end of visible spectrum
  - Said due to “calorific rays”
  - Soon after, Ritter similarly discovered the ultraviolet

William Herschel

Actually, Herschel screwed up

- Peak of solar flux is at ~0.5 μm
- Why did Herschel measure peak at ~1 μm?



Figures due to Tom Chester

Brief history of early infrared astronomy

- 1800: Herschel discovers infrared emission from Sun
- 1856: Piazzi Smyth detects Moon from Tenerife
- 1870: Earl of Rosse measures Moon’s temperature
- 1878: Langley invents infrared bolometer
- 1915: Coblentz, Nicholson, Pettit, et al. measure Jupiter, Saturn, stars, nebulae, using thermopile
- 1960: Johnson establishes first IR photometric system
- 1968: Neugebauer, Leighton make first IR sky survey
- 1974: Kuiper Airborne Observatory enters operation
- 1983: IRAS makes first space IR survey
- 1987: First common-user IR imaging systems

Some physics: black-body radiation

- Definition of “black”
  - “Black” surface absorbs all light at all wavelengths incident upon it
- Definition of “blackbody radiation”
  - To remain thermal equilibrium with surroundings, black surface must then emit just as much energy as it absorbs
  - Spectrum of re-emitted radiation does not depend on spectrum of absorbed radiation
  - Spectrum depends only on temperature of black surface
- Derivation of spectrum non-trivial
  - Attempts by Rayleigh, Jeans, & Wien: ~ right at long λ, grows infinite at short λ; origin of so-called “UV catastrophe”
  - Correct form determined by Max Planck in 1900
  - Required quantised energy $E = h\nu$: beginning of QM

Planck's Law for blackbody radiation

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

Energy emitted
per unit time
per unit surface area
per unit solid angle
per unit frequency
$J\ s^{-1}\ m^{-2}\ sr^{-1}\ Hz^{-1}$

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

Energy emitted
per unit time
per unit surface area
per unit solid angle
per unit wavelength
$J\ s^{-1}\ m^{-2}\ sr^{-1}\ m^{-1}$

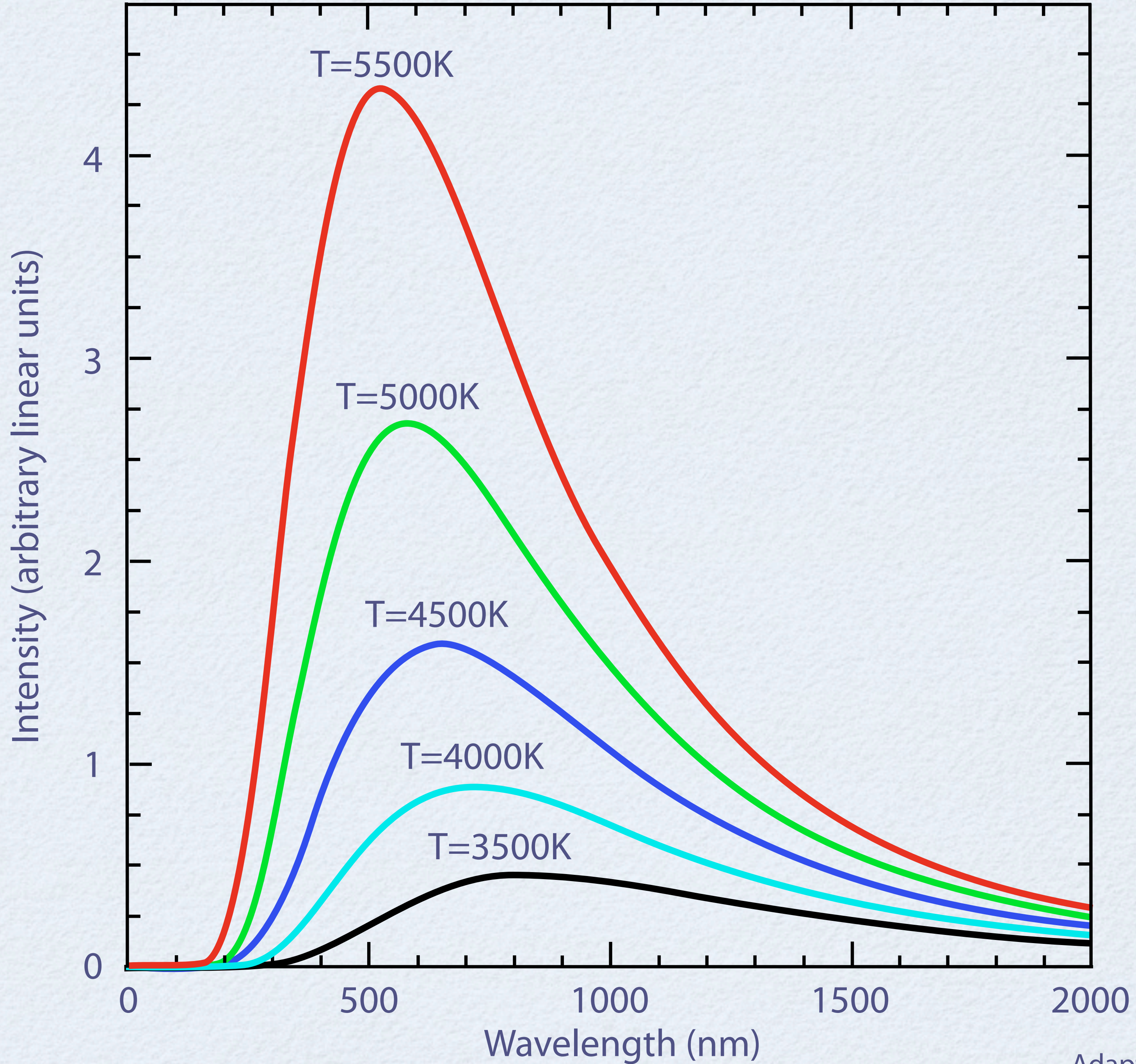
- Note those are only equal in the following form:

$$I(\nu, T)\, d\nu = I(\lambda, T)\, d\lambda$$

- Convert between two forms using:

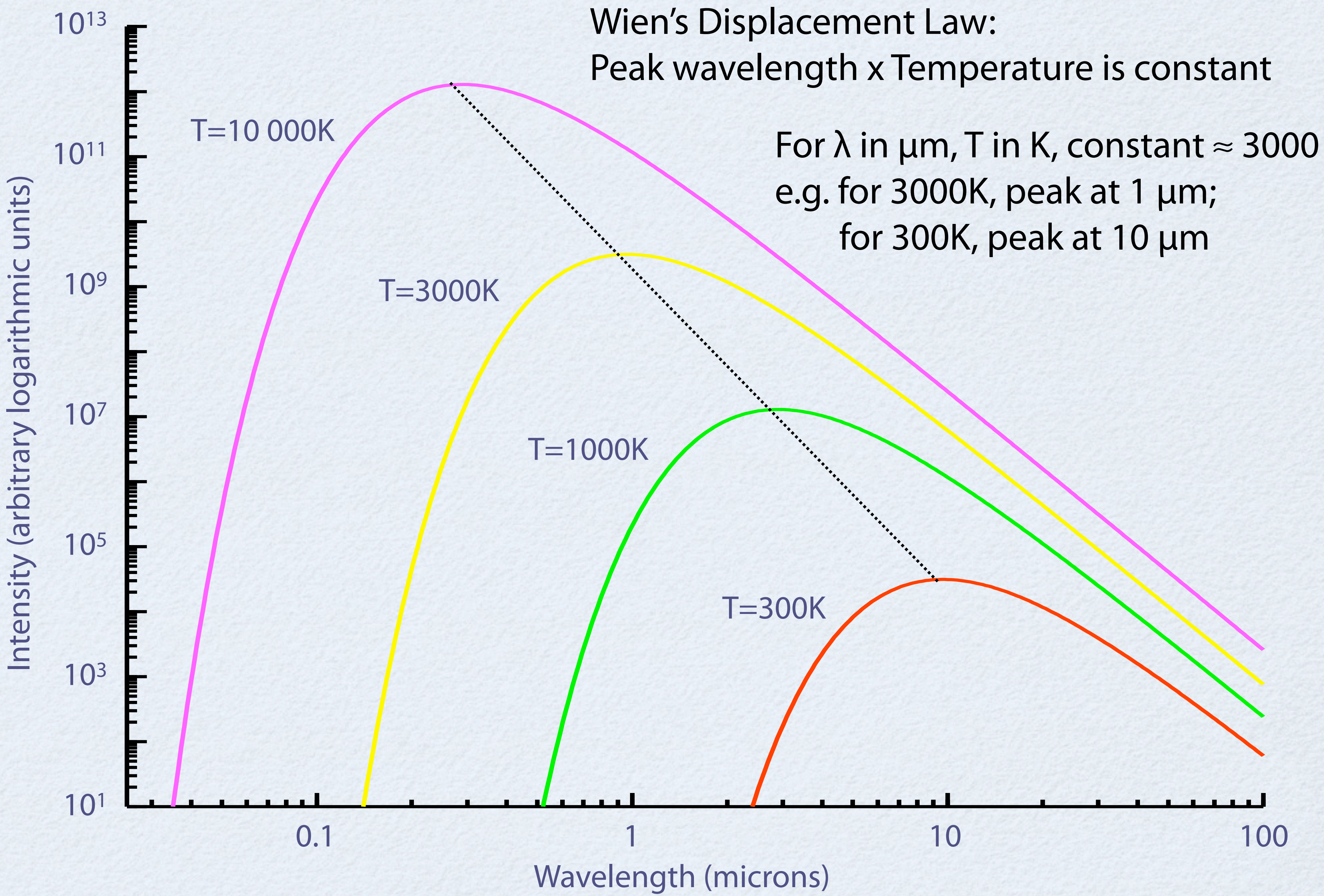
$$c = \nu\lambda \quad \Rightarrow \quad \nu = \frac{c}{\lambda} \quad \Rightarrow \quad d\nu = -\frac{c}{\lambda^2}\, d\lambda$$

Planck’s Law: linear blackbody curves



Adapted from Wikipedia

Planck's Law: logarithmic blackbody curves



Key features of Planck's Law (I)

- Wien's Displacement Law
  - Peak wavelength x Temperature = constant
  - Peak λ (μm) x Temp (K) = 2897.7768 μm K

Important note!
Frequency equivalent:
Peak ν (Hz) x Temp (K)
= 5.879×10^{10} Hz K
But Peak ν ≠ (c/Peak λ)

- Blackbody curves do not overlap
  - Object at temperature T_2 emits more photons (per unit everything) at all wavelengths than object at T_1, if $T_2 > T_1$
- Total power emitted given by Stefan-Boltzmann Law
  - Per unit area, but integrated over all wavelengths, all angles

$$P = \sigma T^4 \quad \text{where} \quad \sigma = \frac{2\pi^5 k^4}{15 c^2 h^3}$$

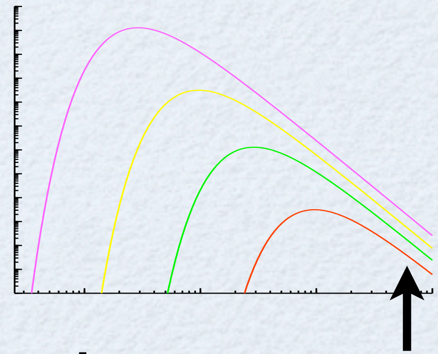
$$= 5.6704 \times 10^{-8}\,\mathrm{J\,s^{-1}\,m^{-2}\,K^{-4}}$$

For object with emissivity ε and total area A:

$$P = \sigma \epsilon A T^4$$

Can often make up for low T with very large A: important!

Key features of Planck's Law (II)



- Long λ behaviour governed by "Rayleigh-Jeans tail"

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1}$$

- For large λ, $hc/\lambda kT \ll 1$
  - $\exp(hc/\lambda kT) \approx 1 + (hc/\lambda kT)$, thus:

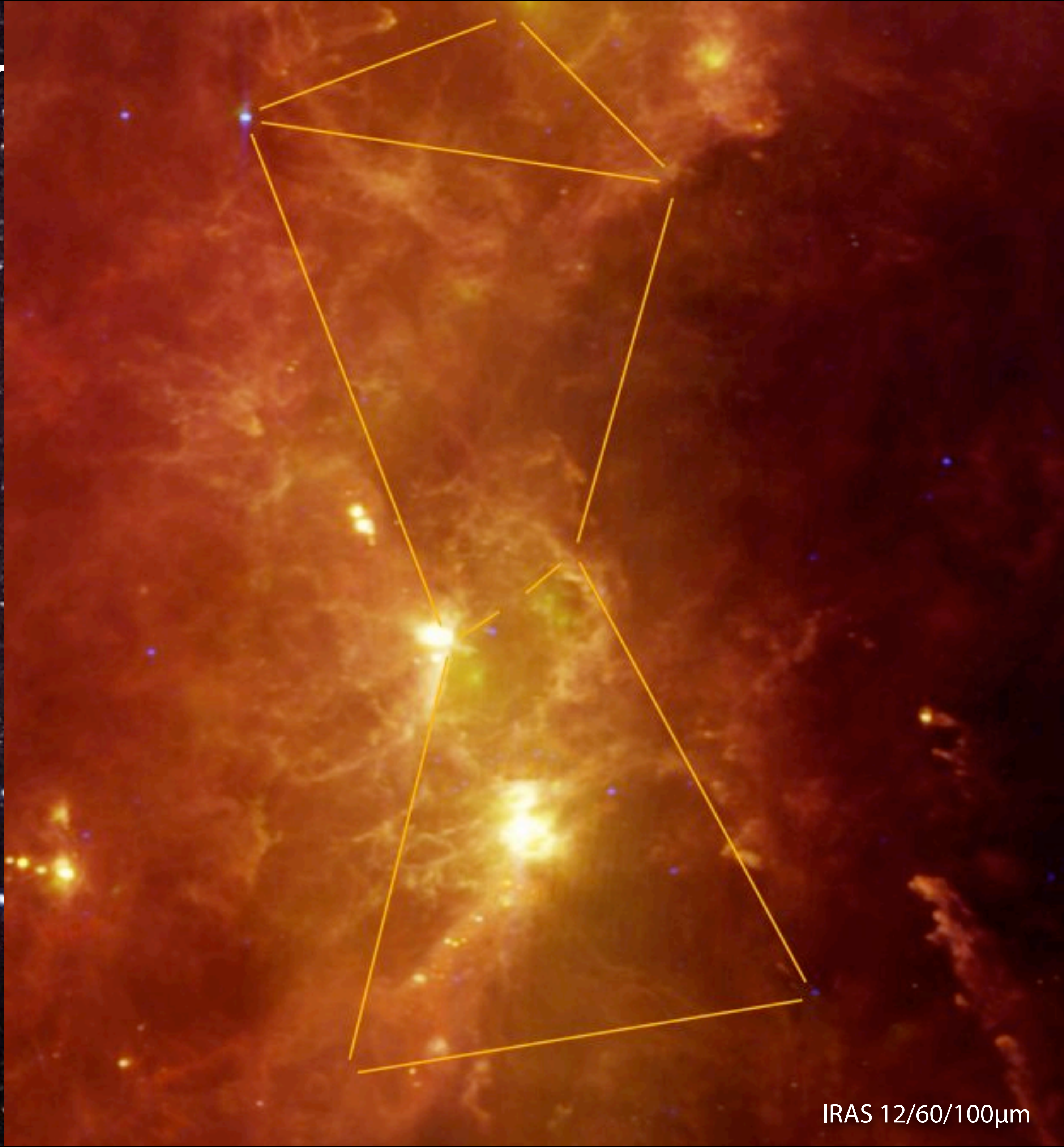
$$I(\lambda, T) \approx \frac{2hc^2}{\lambda^5} \frac{1}{1 + (hc/\lambda kT) - 1} \approx \frac{2hc^2}{\lambda^5} \frac{\lambda kT}{hc} \approx \frac{2ckT}{\lambda^4}$$

  - Therefore, for long-λ, intensity drops as λ^{-4}
  - Often "on the Rayleigh-Jeans tail" in IR astronomy

Low-temperature astronomical sources

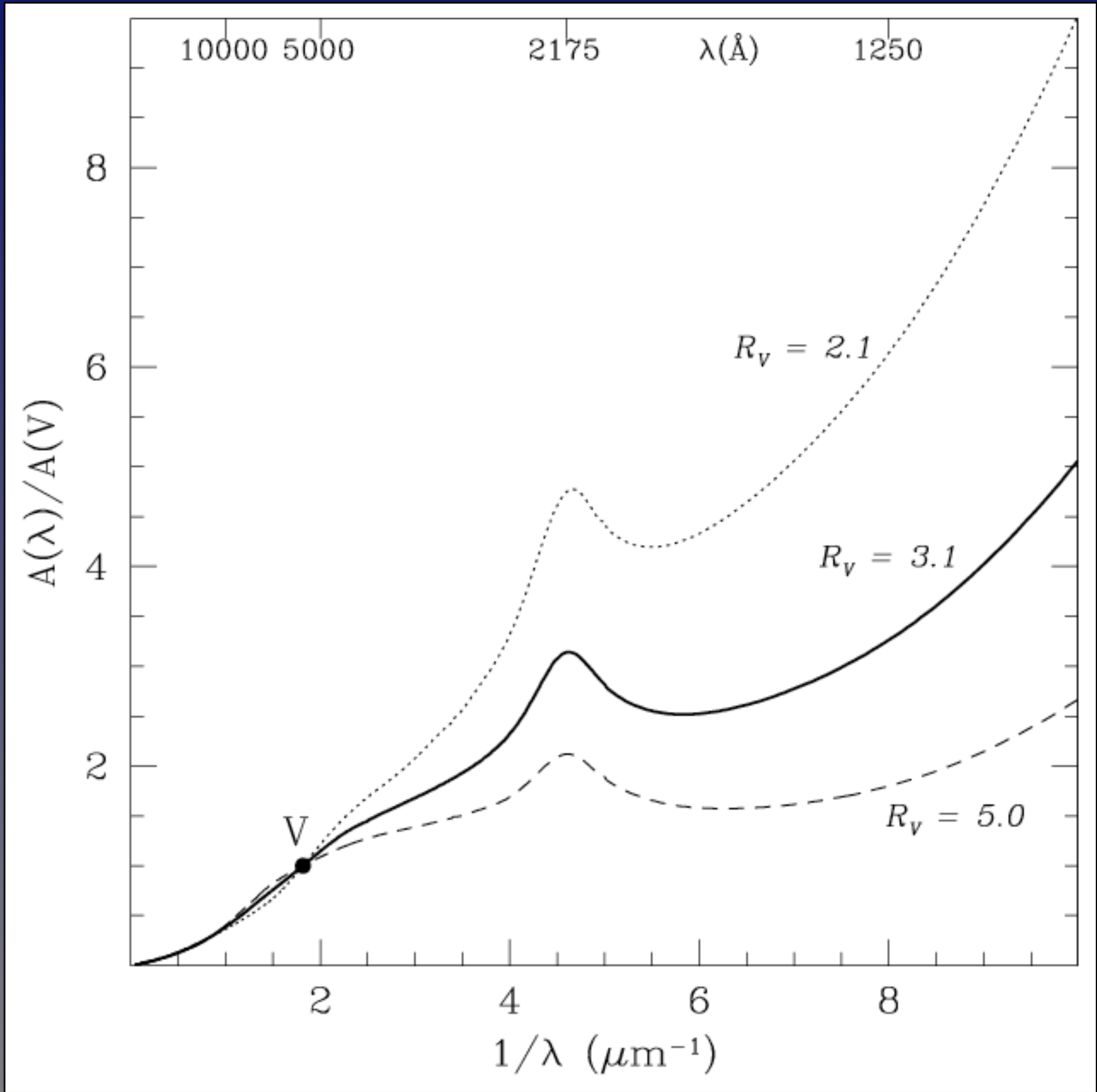
- Bottom end of stellar initial mass function
  - M, L dwarfs T_{eff} typically 3000-1500K, peak ~1-2μm
  - Coolest known T dwarfs ~800K, peak ~4μm
  - More complicated in reality: molecular atmospheres
- Inner regions of circumstellar disks
  - Infrared excess emission, CO bandheads 2-2.5μm
- Terrestrial planet-forming regions in disks
  - Liquid water requires ~300K, ~10μm
- Outer regions of disks
  - Gas depletion due to gas giant formation ~100K, 30μm
- Molecular clouds, prestellar cores dust and gas
  - 100-10K, 30-300μm: connection to sub-millimetre

Or ery




The Orion Nebula star-forming region
Infrared: McCaughrean / VLT / ISAAC

Infrared penetrates dust extinction



Cardelli, Clayton, & Mathis 1989

Dust extinction quantified

- Reduced effects of dust in near- and mid-infrared:

Filter	λ_c	A_λ/A_V
V	0.55	1.000
J	1.21	0.282
H	1.65	0.175
K	2.20	0.112
L	3.45	0.058
M	4.80	0.023
N	10.0	0.052

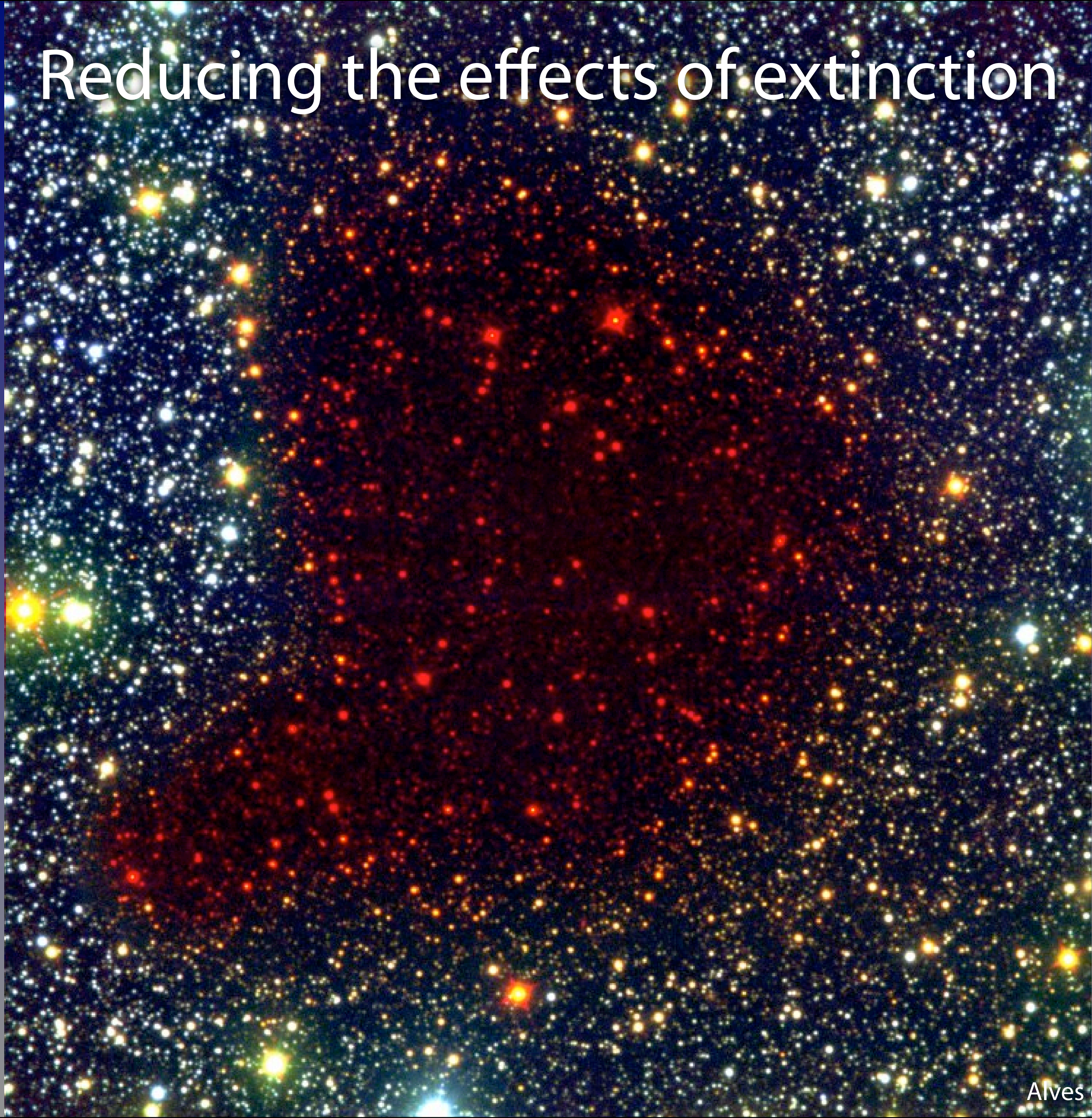
Worked example:

Take extinction of 25 magnitudes at V: dimming by 10^{10}

In K-band, would be 2.8 magnitudes: dimming by 13

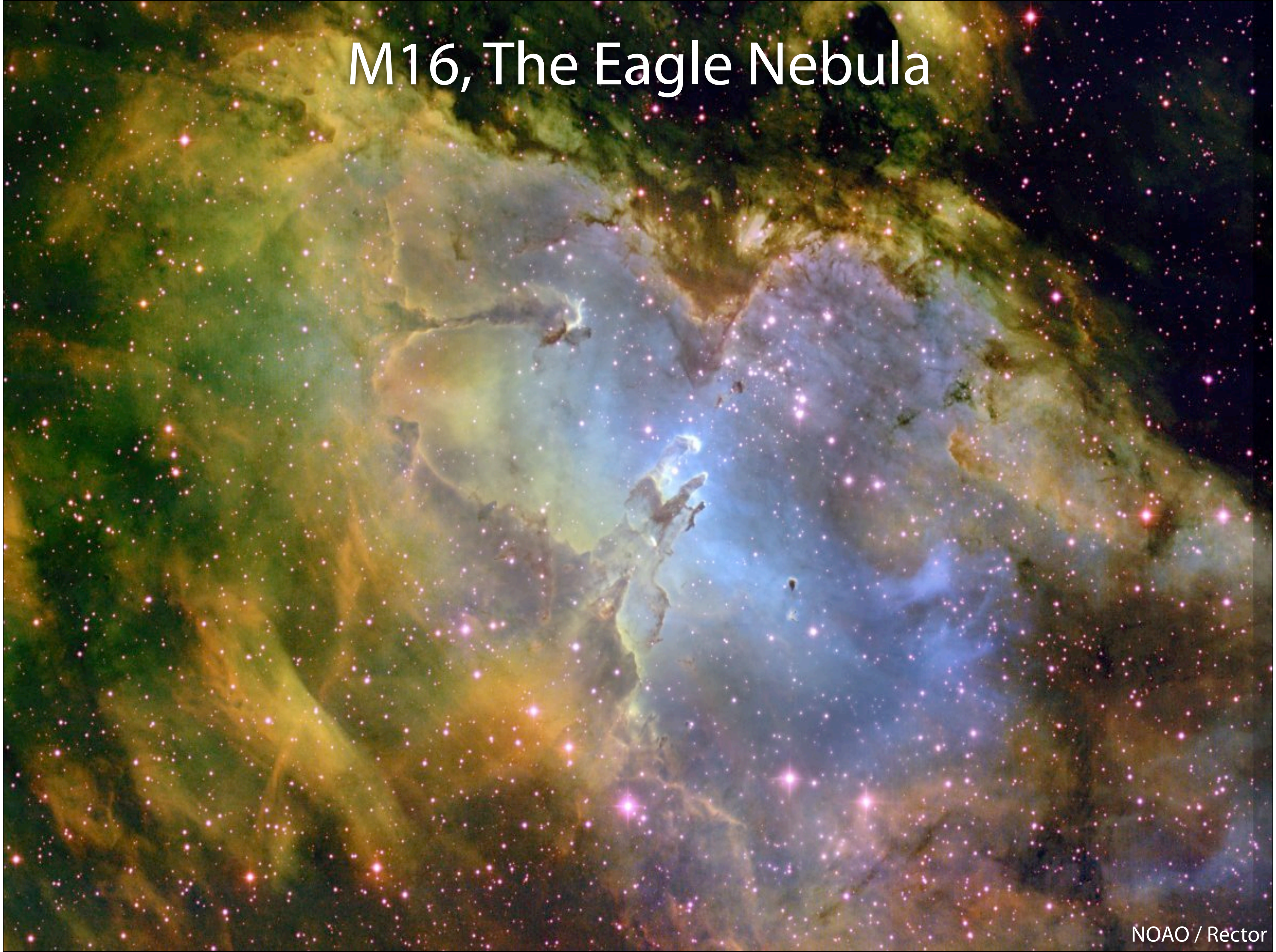
In M-band, would be 0.6 magnitudes: dimming by 4

Reducing the effects of extinction

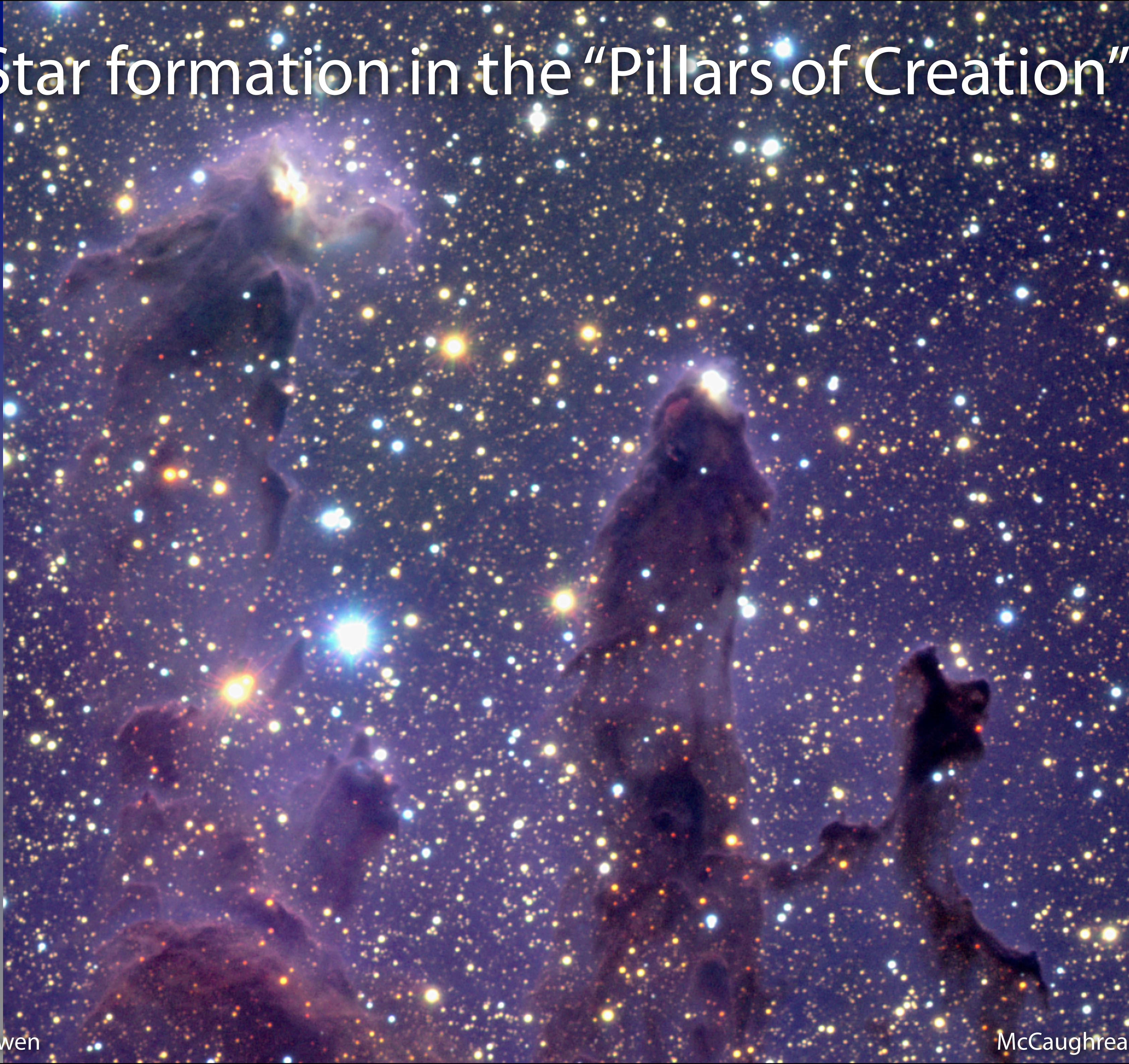


Barnard 68
Optical
+ Infrared

Alves et al. 2001, Nature


M16, The Eagle Nebula
NOAO / Rector

Star formation in the "Pillars of Creation"?



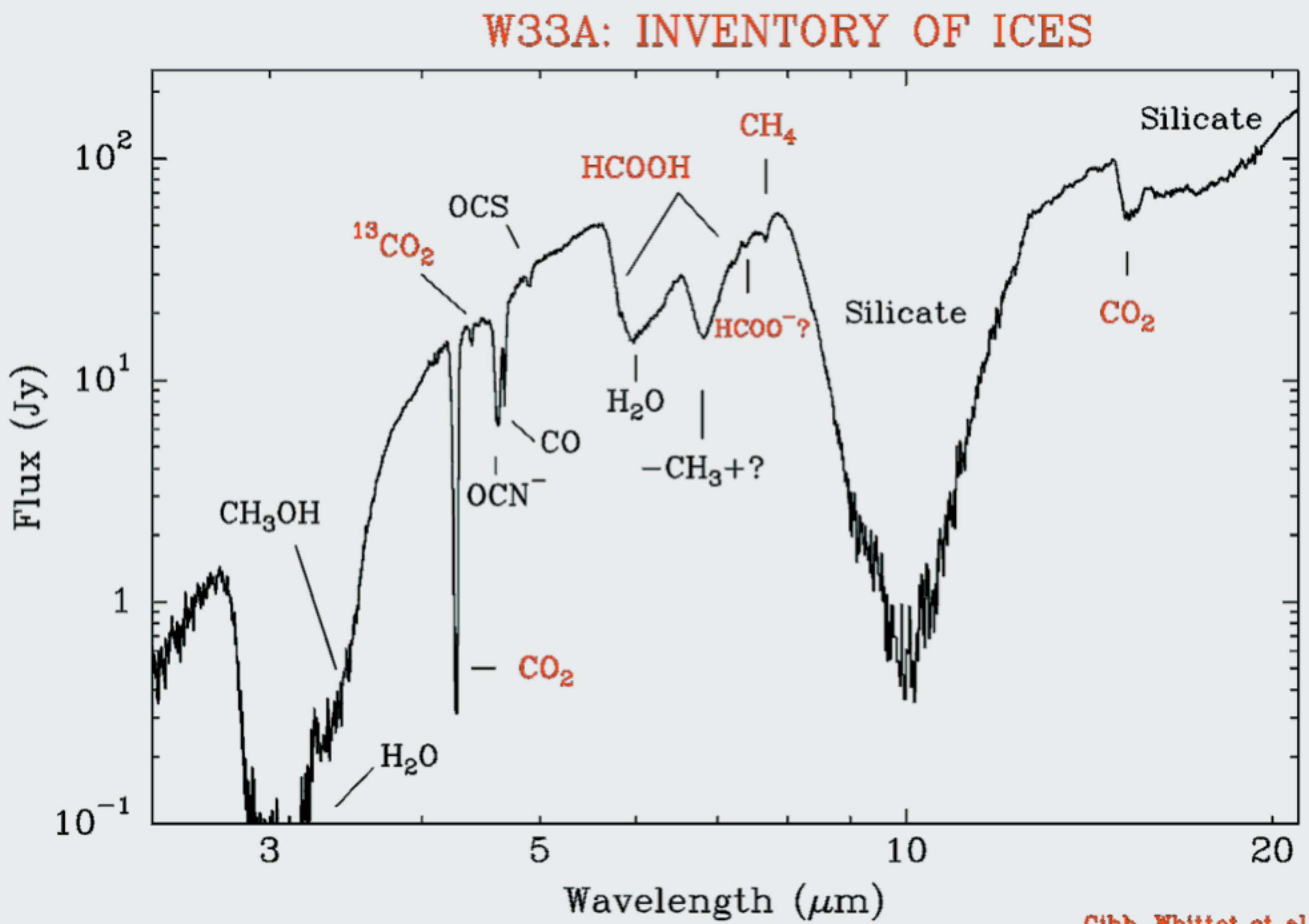
Optical: HST
Hester & Scowen

Infrared: VLT
McCaughrean & Andersen

Line diagnostics and astrochemistry

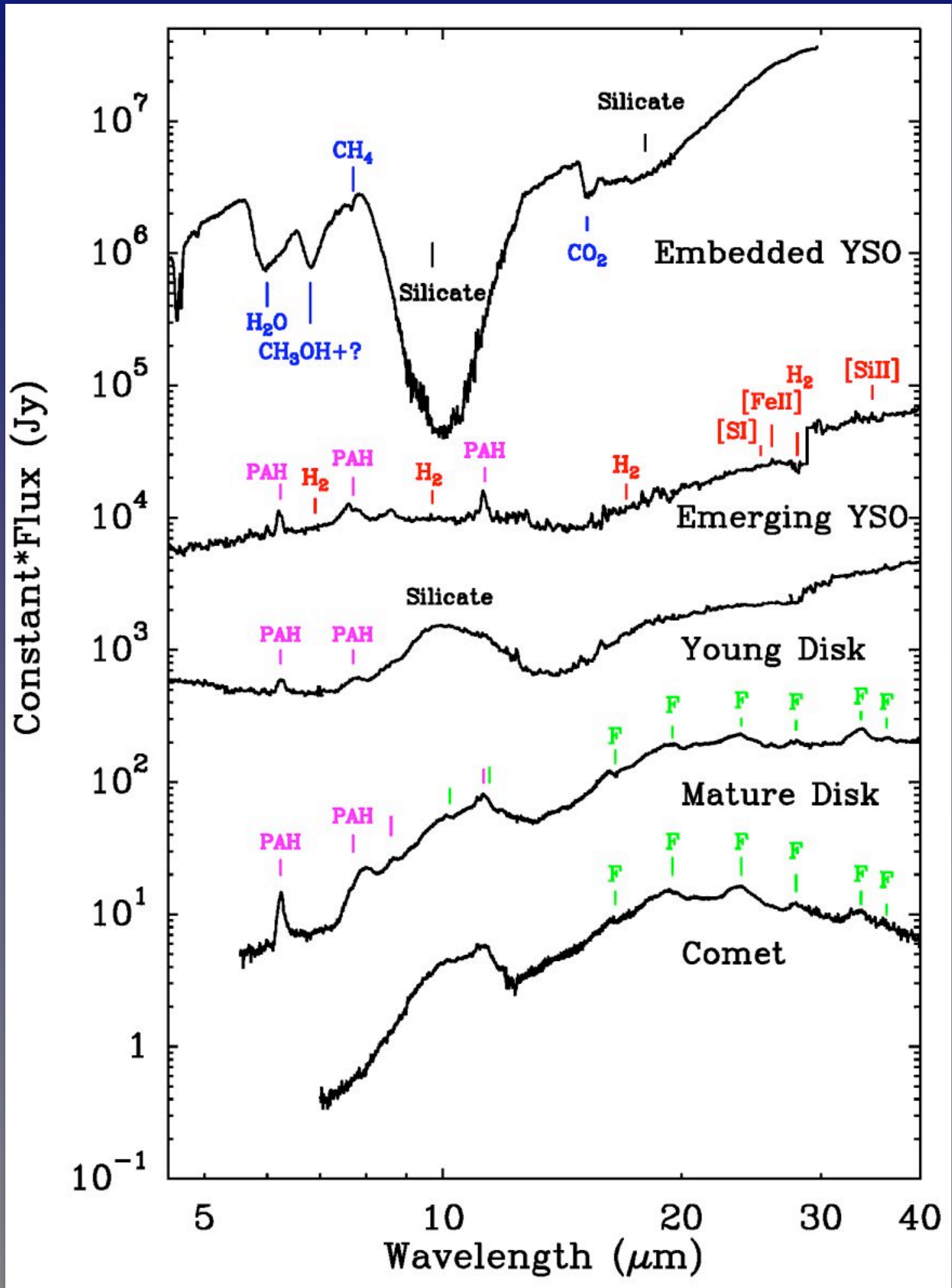
- Molecular absorption bands in stars
  - TiO, VO, H_2O, CH_4, etc.
- Emission lines from ionised nebulae
  - Hydrogen Paschen, Brackett, Pfund series
  - Fe, O, He, Mg, Cr, Si, N, Ca, Ar, Ne, P, C, ...
- Emission/absorption lines in protostars
  - Minerals: SiO, SiC, amorphous/crystalline
  - Ices: CO, H_2O, CO_2, CH_4
  - PAH features: complex C compounds
- Molecular lines
  - Shocked/fluorescent H_2

Ices in and around protostars



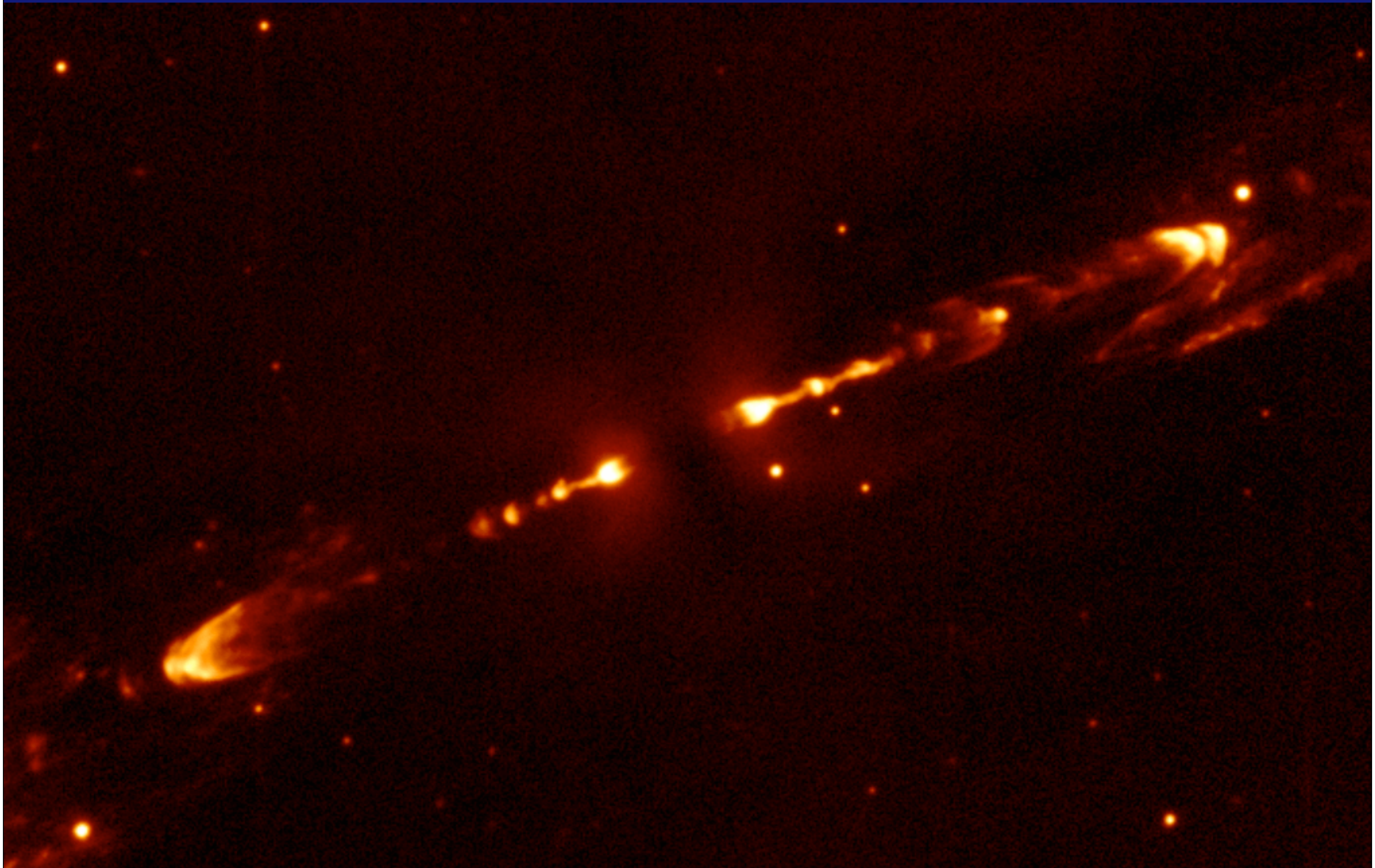
Gibb, Whittet et al. 1999
Schutte et al. 1999

Evolution of circumstellar material



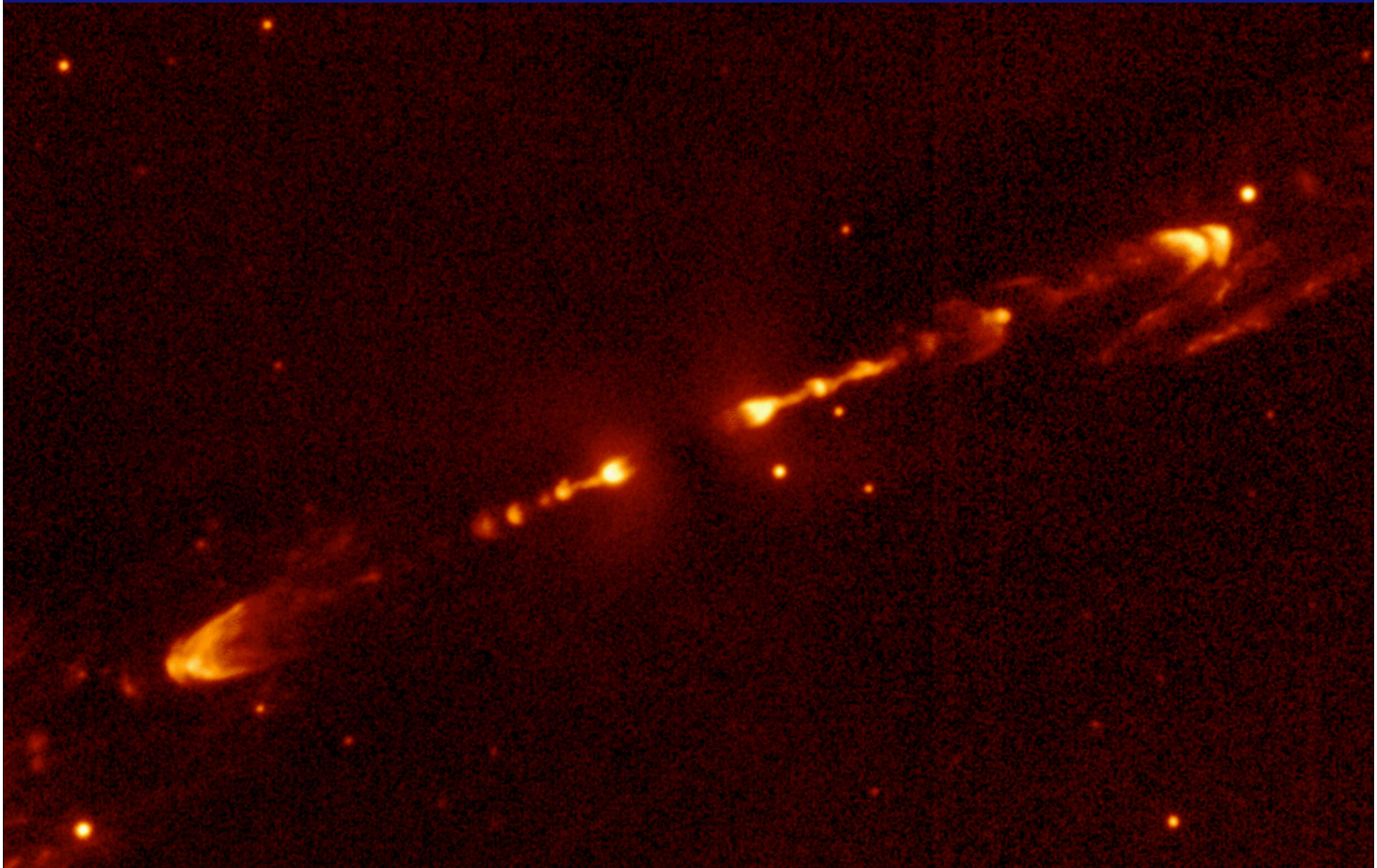
ISO SWS spectra
van Dishoeck

Accretion, outflow, and feedback



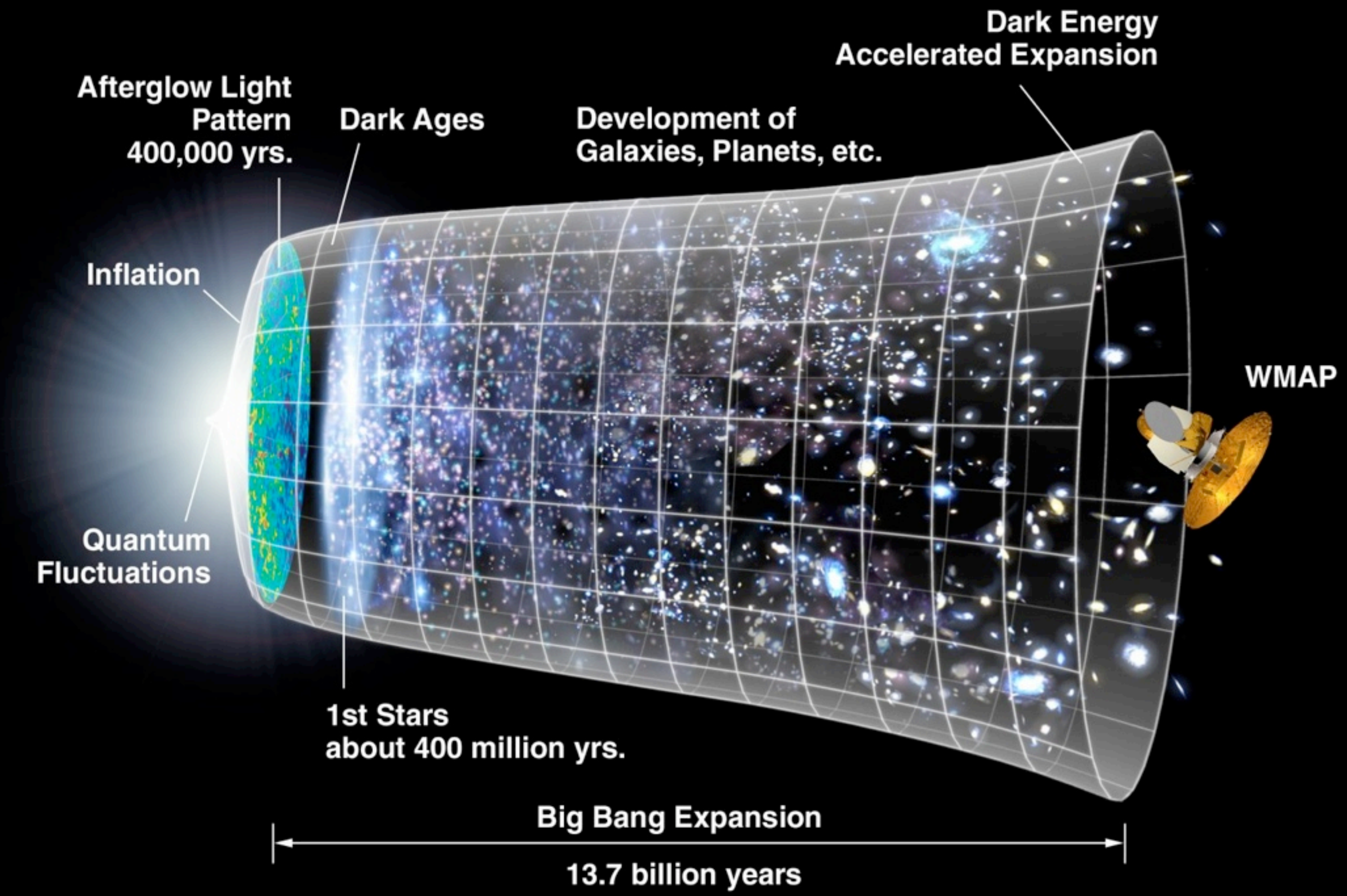
HH212: VLT/ISAAC 6 hours integration time in the 2.12μm H_2 v=1-0 S(1) line (McCaughrean et al. 2002)

Proper motions over seven years



HH212: VLT/ISAAC Oct 2000 - VLT/HAWK-I Jan 2008 (McCaughrean et al., in prep.)

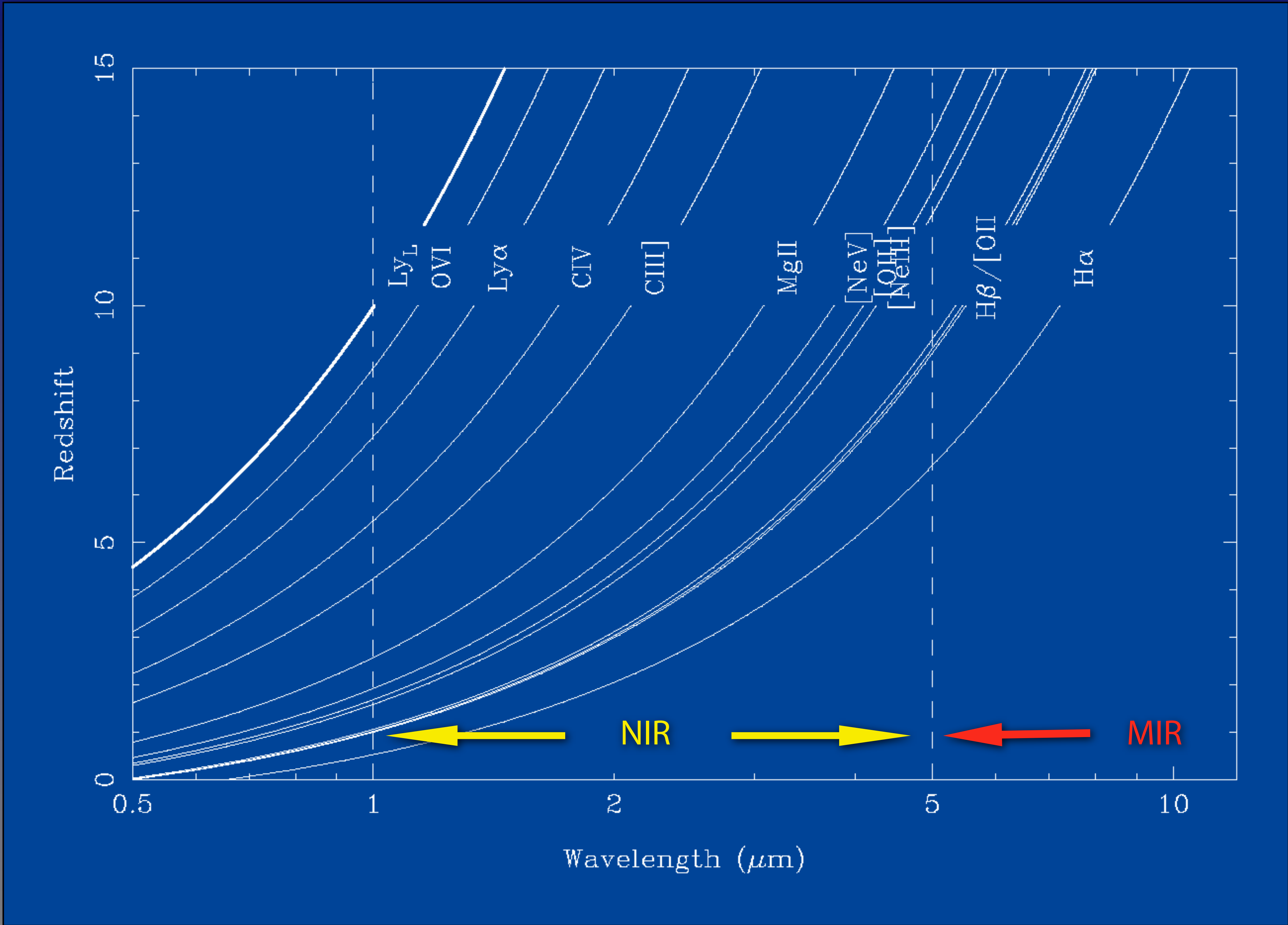
The evolution of the Universe



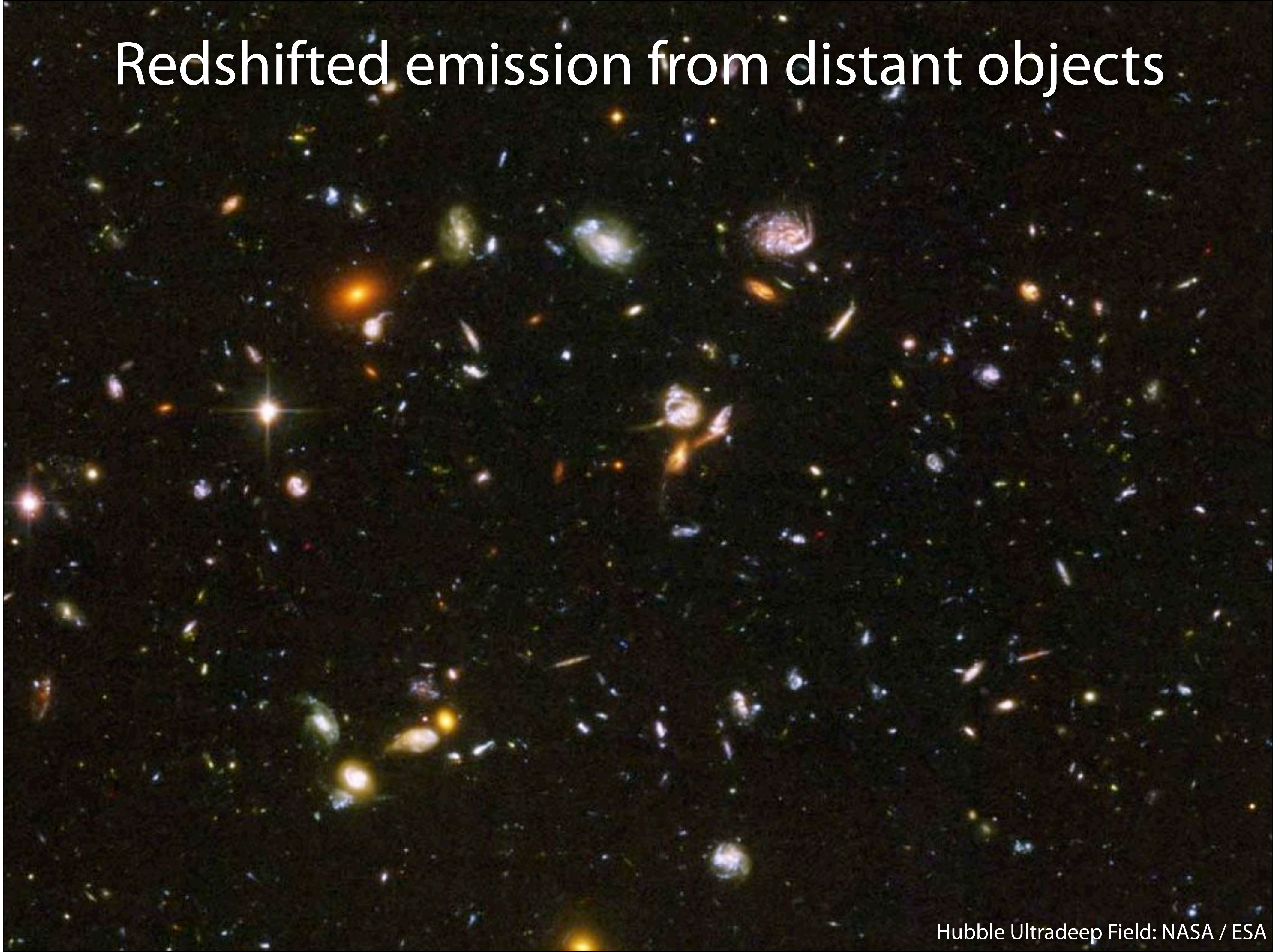
High-redshift astronomy

- Redshift: $\lambda_{obs} = (1+z)\,\lambda_{em}$
- Classical galaxy diagnostics in mid-optical:
  - Hα, Hβ, Ca H & K, 4000Å break, etc.
  - Move to near-infrared at z=2-3
  - Move to thermal-infrared at z=5-10
  - Move to mid-infrared at z=20-30
- Lyα at 1216Å:
  - Moves to near-infrared at z>7
- Cosmic microwave background:
  - Blackbody radiation from ionised plasma at ~3000K
  - Wien's Law says peak should be at at ~1µm
  - But epoch of recombination was at z~1000
  - Should now be at ~3K, so peak at ~1000µm, i.e. 1 millimetre

Redshifted diagnostics



Redshifted emission from distant objects



Hubble Ultradeep Field: NASA / ESA

Boosting sensitivity via gravitational lensing

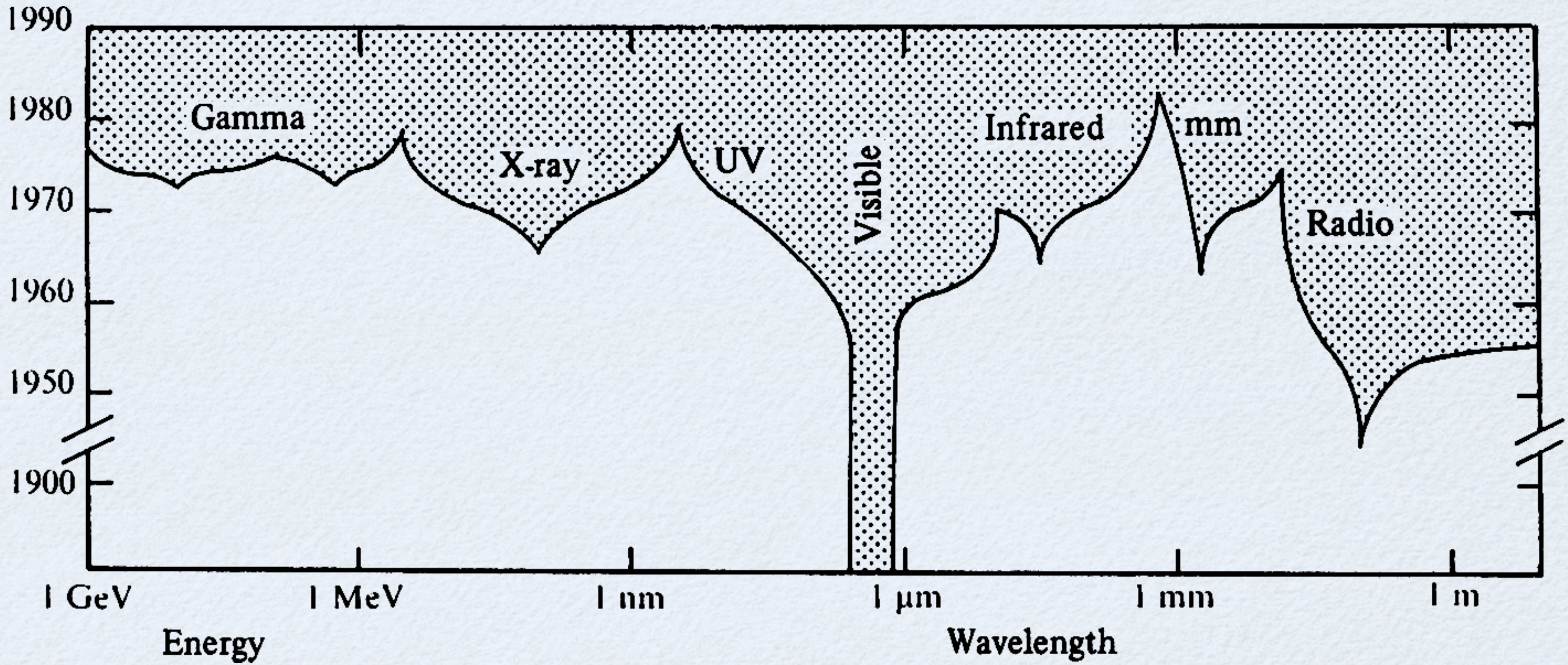
Abell 1689: HST+ACS (g, r, i, z)

NASA / ESA / Benitez et al.

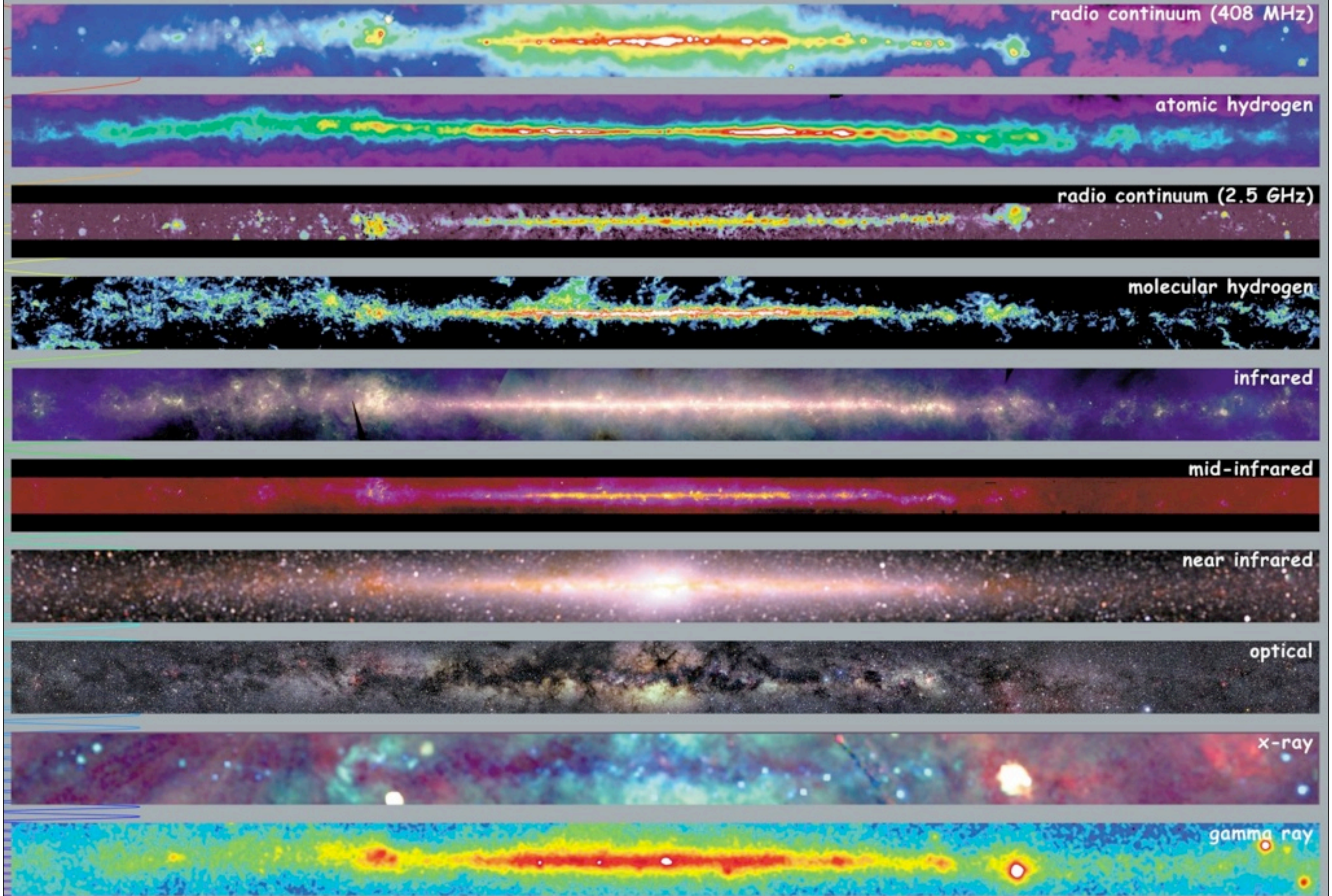
Recap

- Infrared astronomy driven by four factors:
  - Access to low-temperature blackbodies
  - Mitigation of dust extinction
  - Emission and absorption line diagnostics for astrochemistry
  - Galaxies and AGN at high redshift
- First three make the infrared vital for star and planet formation studies
- But infrared astronomy is not that easy
  - Absorption by terrestrial atmosphere
  - Emission by terrestrial atmosphere
  - Thermal background from telescope
  - Unconventional detector technologies
  - Photons "weaker" at longer wavelengths

Opening up the electromagnetic spectrum

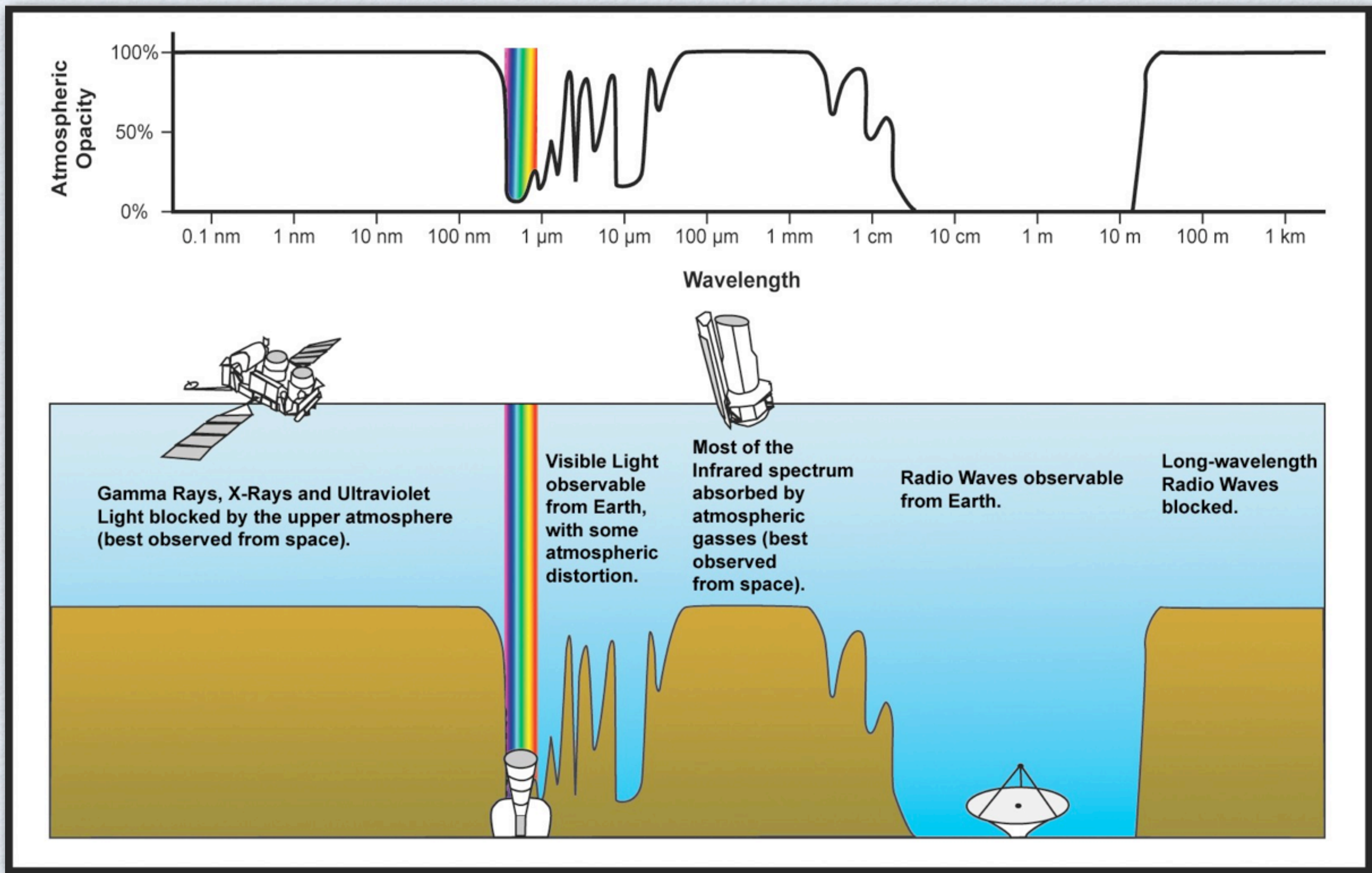


20th century saw entire EM spectrum
from γ-rays to radio made available

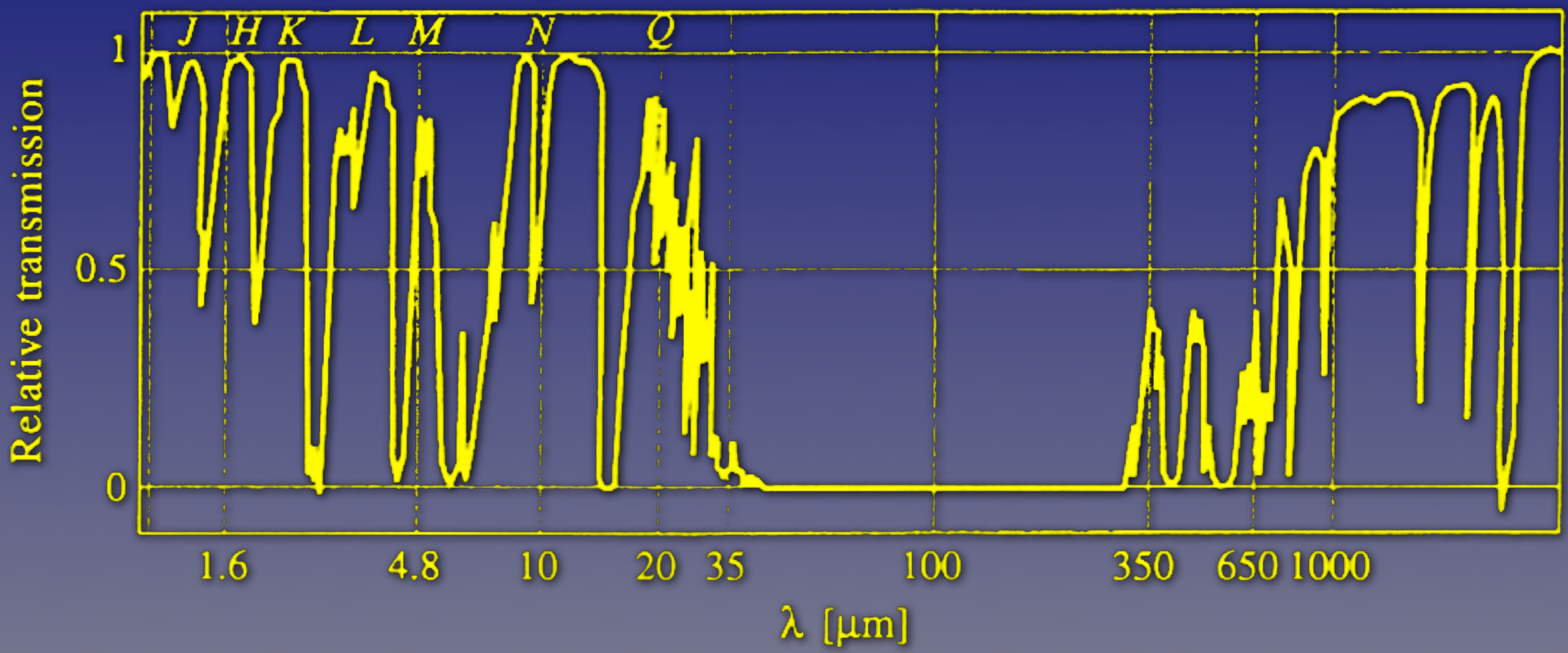


Multiwavelength Milky Way

Atmospheric transmission

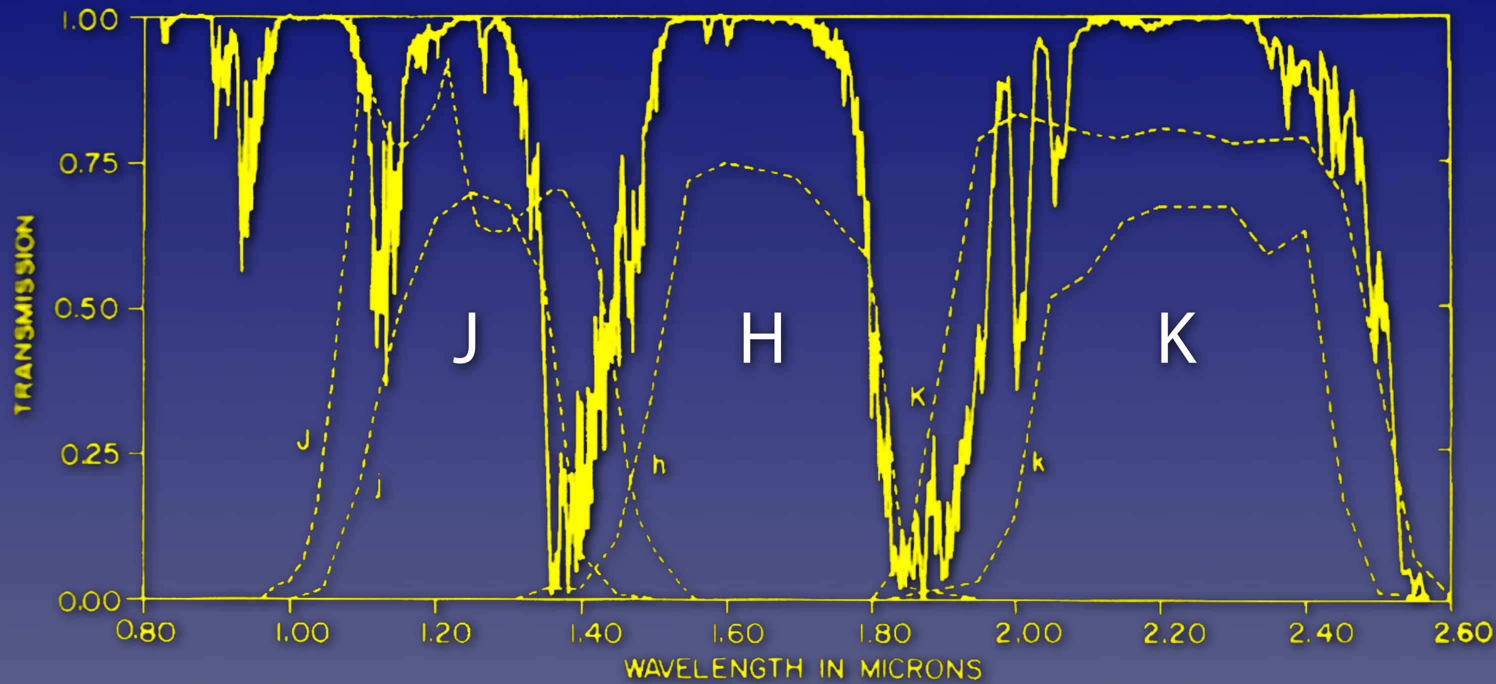


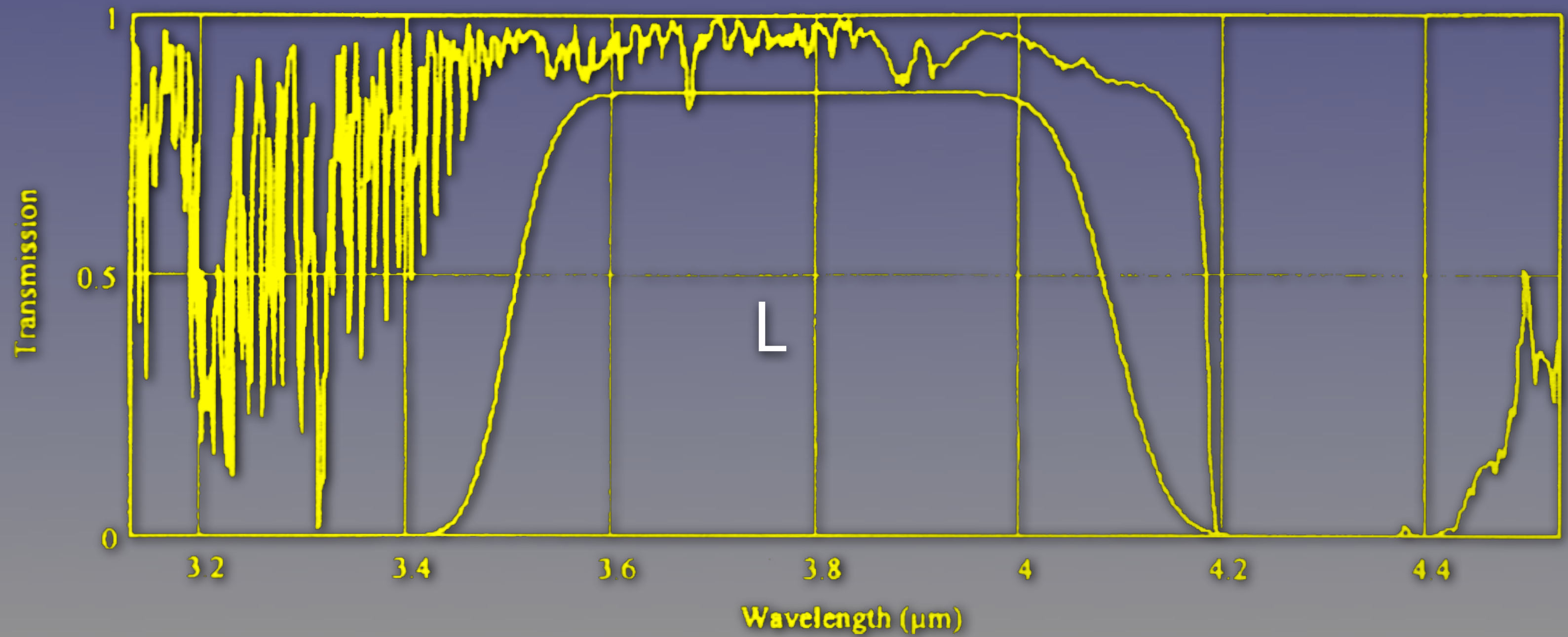
Infrared transmission windows



Léna, Lebrun, & Mignard

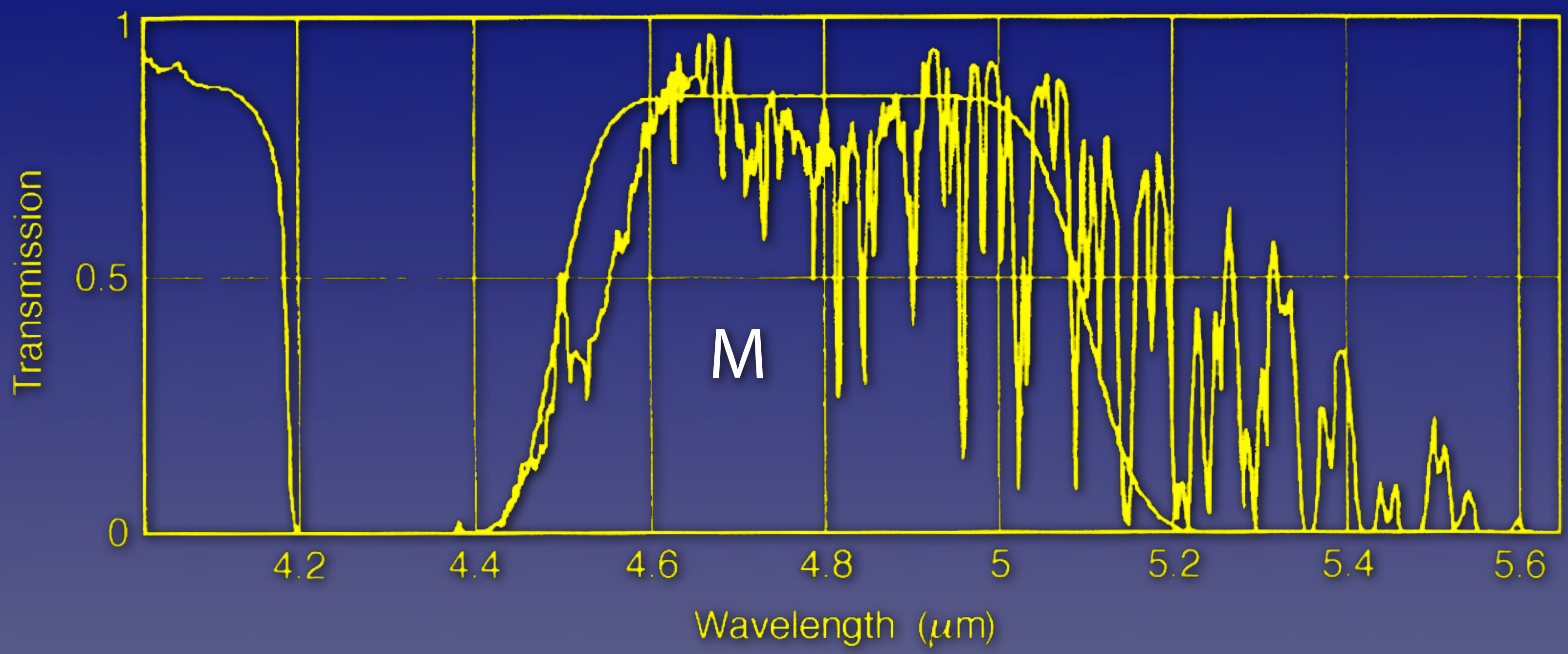
J, H, K, L windows

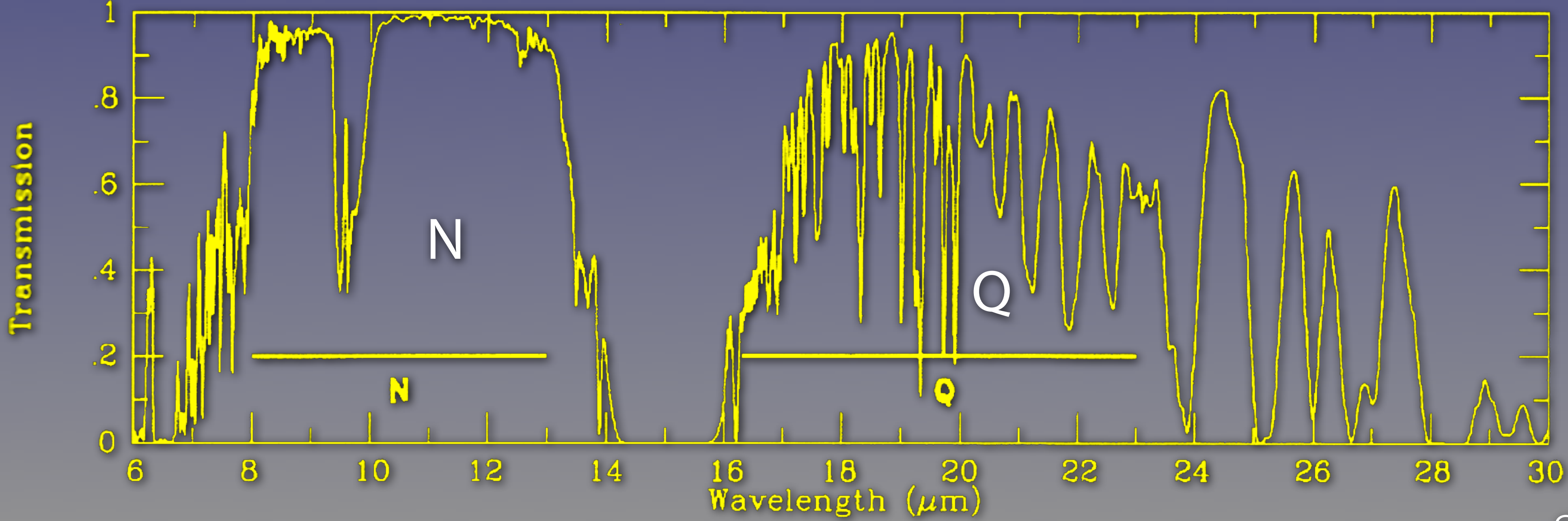




Glass

M, N, Q windows





Glass

Johnson optical-infrared filter system

Filter	λ (μm)	Δλ (μm)	Filter	λ (μm)	Δλ (μm)
U	0.36	0.15	H	1.65	0.23
B	0.44	0.22	K	2.2	0.34
V	0.55	0.16	L′	3.8	0.60
R	0.64	0.23	M′	4.7	0.22
I	0.79	0.19	N	10	6.5
J	1.26	0.16	Q	20	12

There are many variations on this basic set, optimised for different sites, detectors, science

Filter	λ (μm)	Δλ (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (W m^{-2} Hz^{-1})	Jansky
U	0.36	0.15	4.19×10^{-8}	1.81×10^{-23}	1 810
B	0.44	0.22	6.60×10^{-8}	4.26×10^{-23}	4 260
V	0.55	0.16	3.51×10^{-8}	3.54×10^{-23}	3 540
R	0.64	0.23	1.80×10^{-8}	2.94×10^{-23}	2 940
I	0.79	0.19	9.76×10^{-9}	2.64×10^{-23}	2 640
J	1.26	0.16	3.21×10^{-9}	1.67×10^{-23}	1 670
H	1.65	0.23	1.08×10^{-9}	9.81×10^{-24}	981
K	2.20	0.34	3.84×10^{-10}	6.20×10^{-24}	620

Sources of background flux

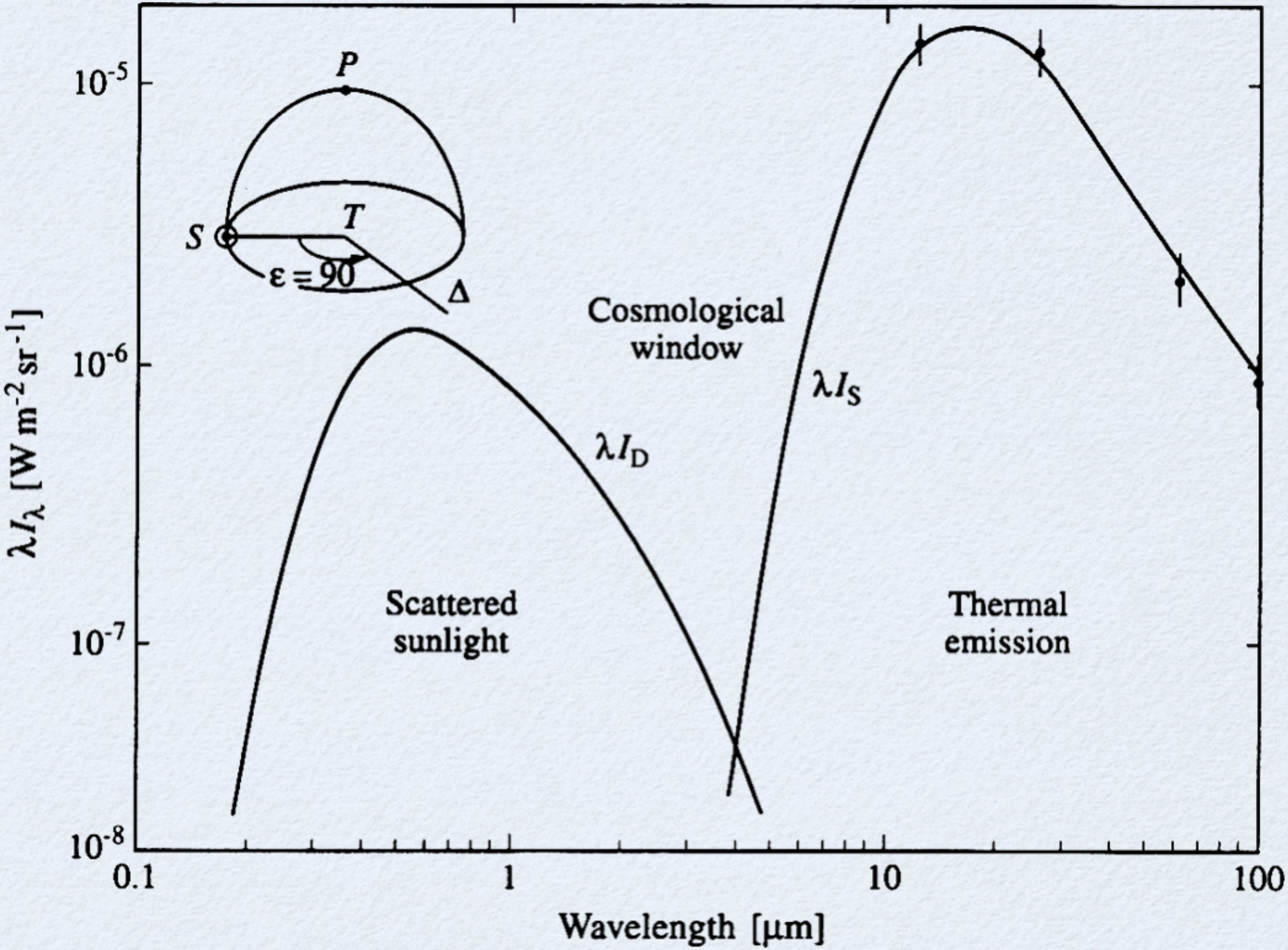
- Several components to background emission
  - All strong function of wavelength
- Telescope:
  - Thermal blackbody emission at ~270-280K
- Atmospheric:
  - Thermal blackbody emission at ~220-230K
  - Scattered moonlight
  - Line emission (Lyα, O_2, OI), OH airglow
- Celestial:
  - Zodiacal dust (scattered sunlight and thermal emission)
  - Unresolved faint stars
  - Infrared cirrus
  - Cosmic microwave background

Zodiacal light

Tony & Daphne Hallas


Gegenschein
Yuri Beletsky / ESO

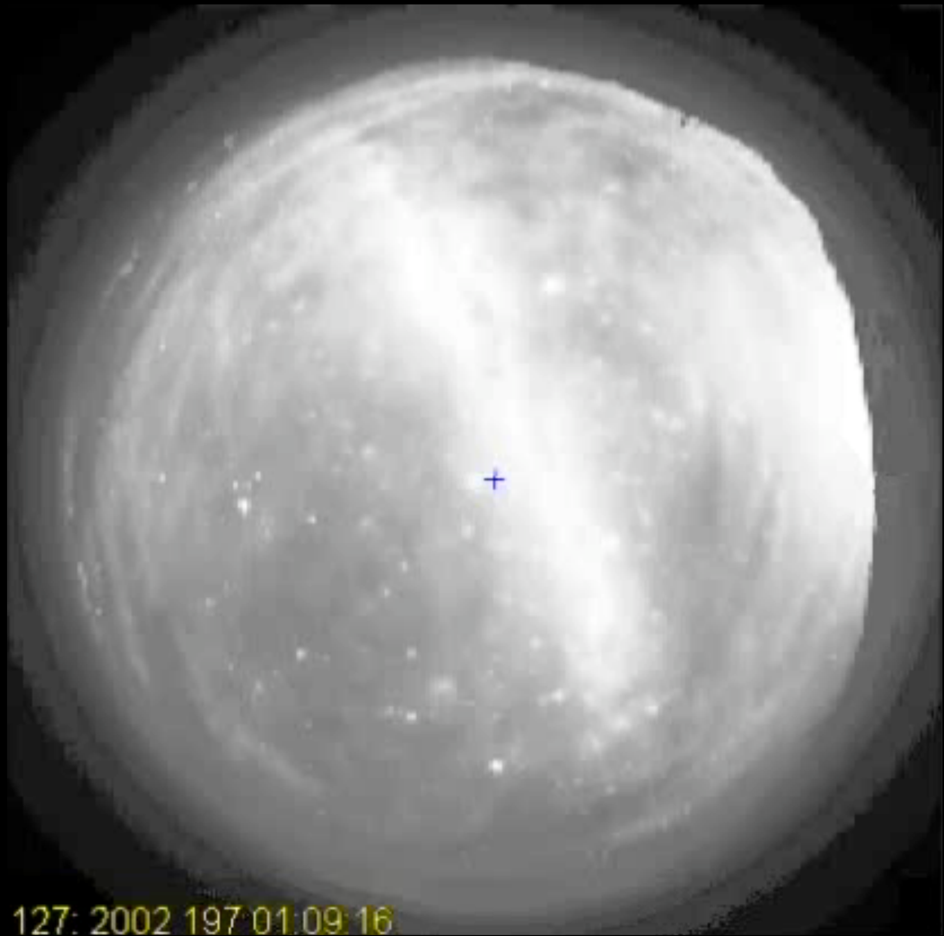
Scattering and emission from zodiacal dust



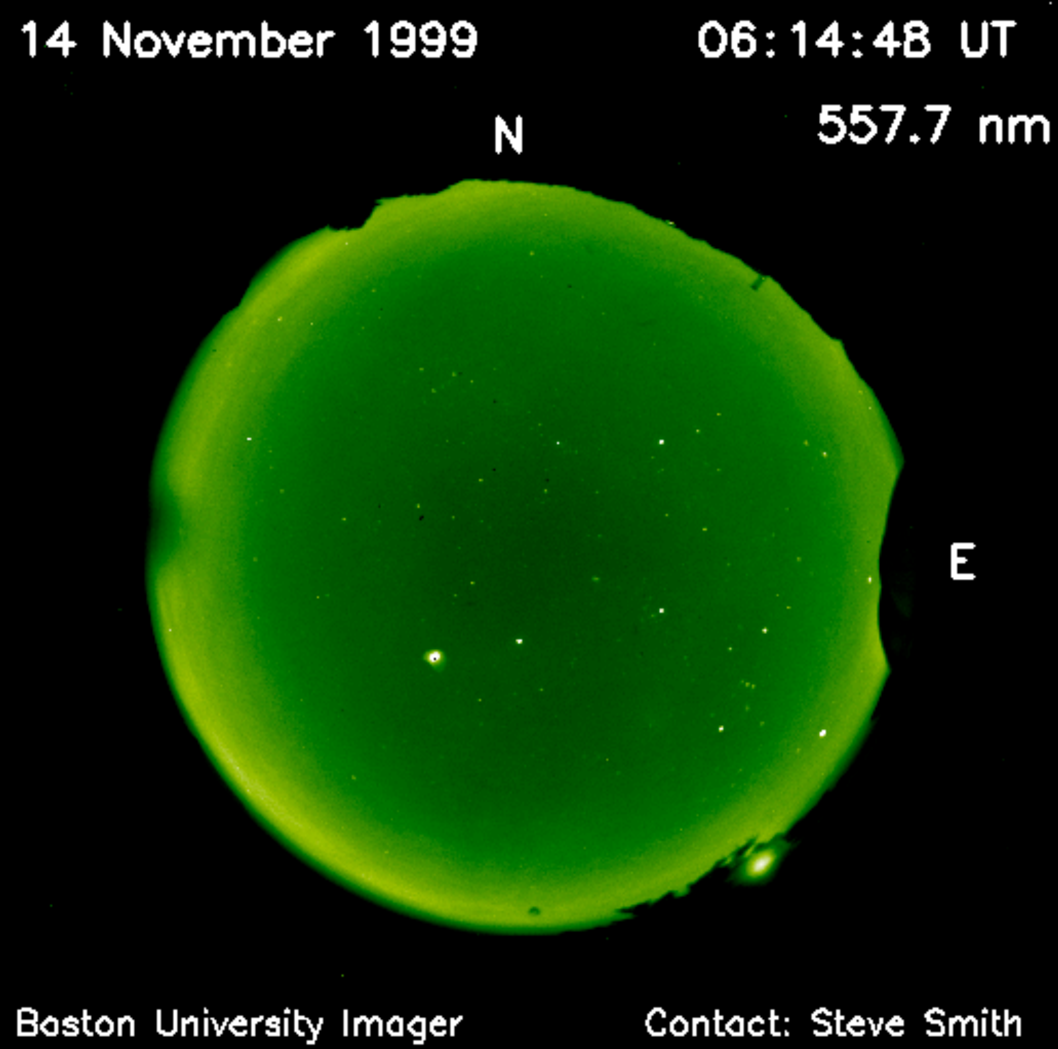
Léna, Lebrun, & Mignard


Gemini-N

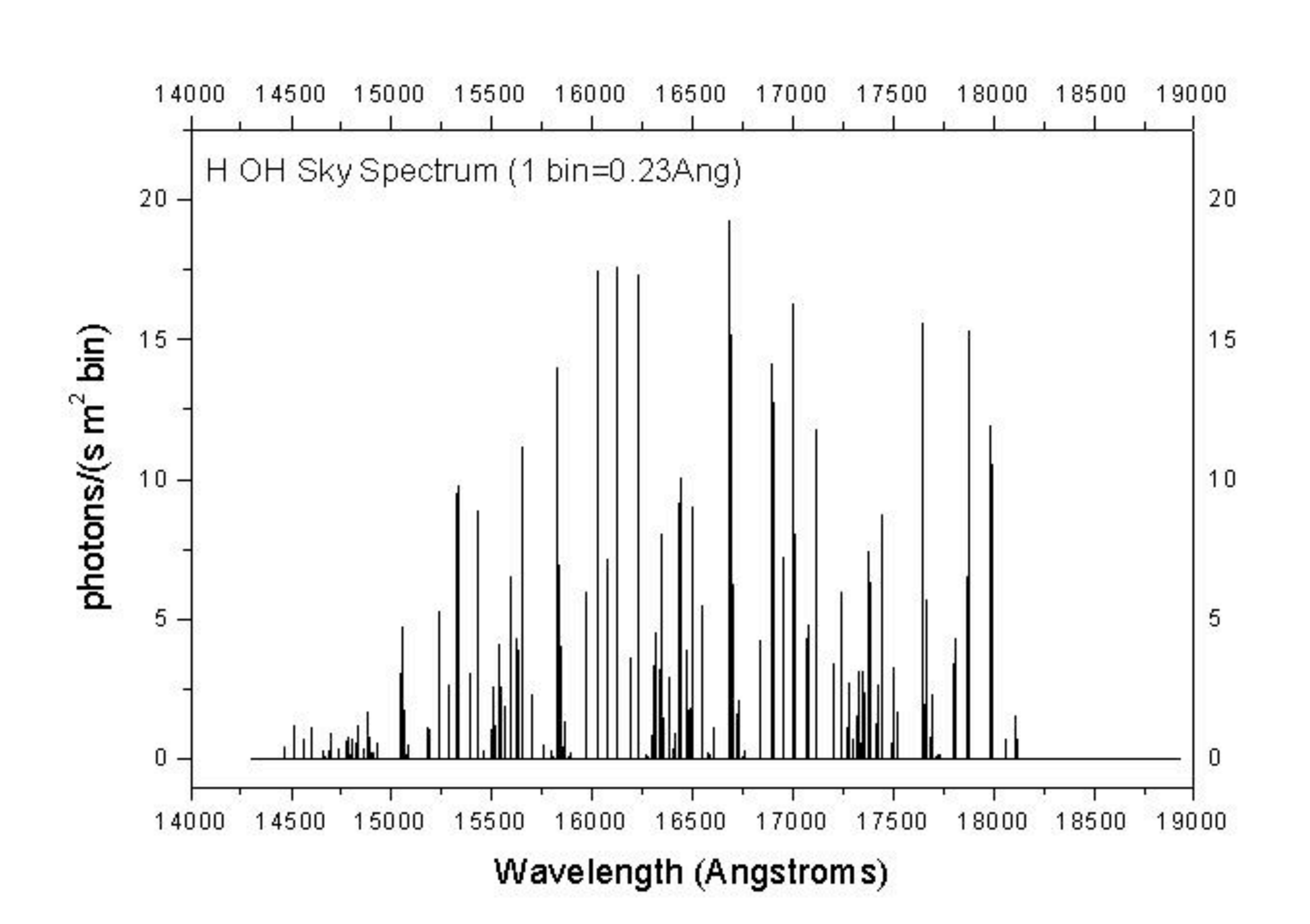
Airglow movies



Antarctic OH airglow movie (2002)

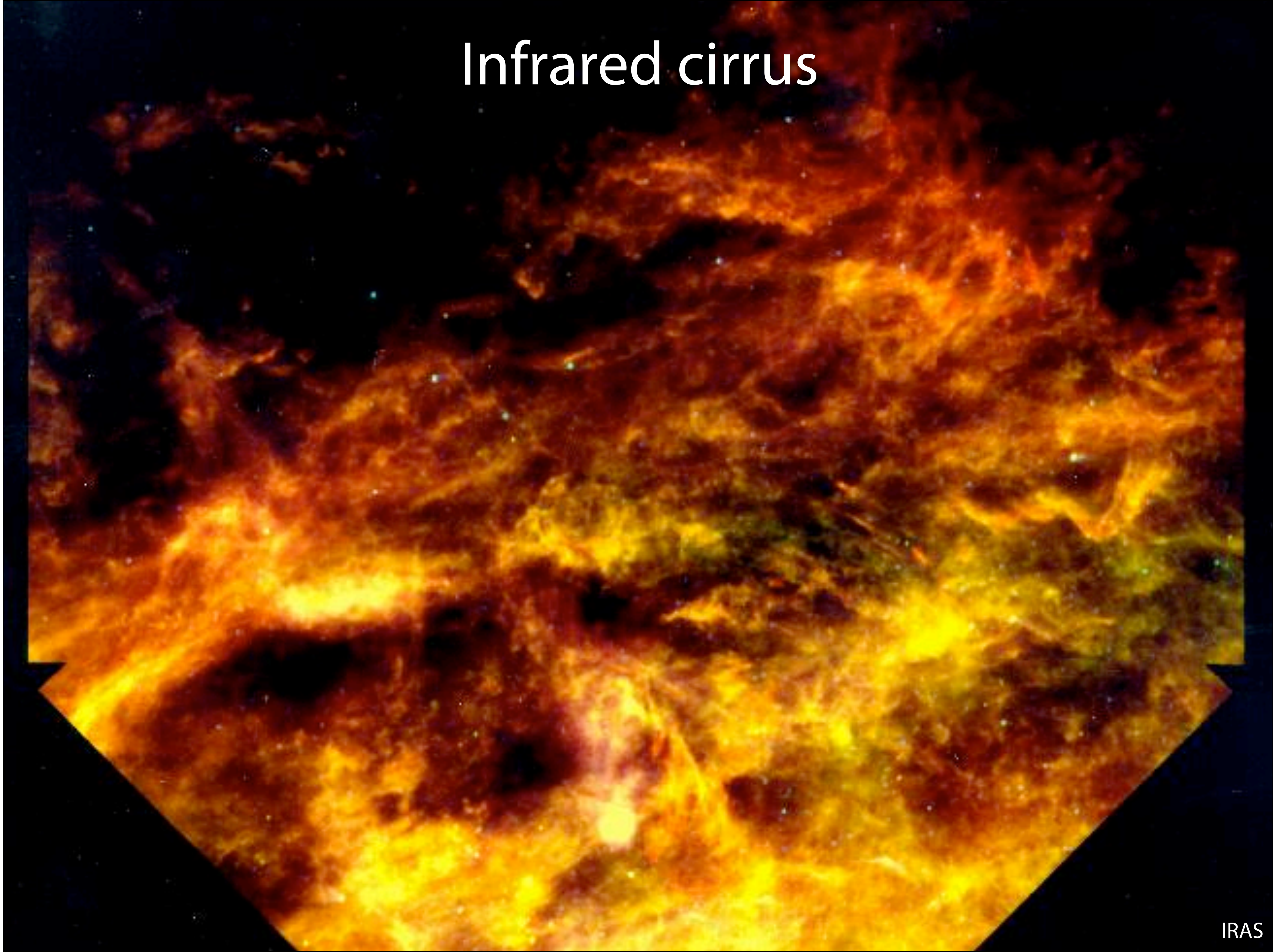


Near-infrared OH airglow



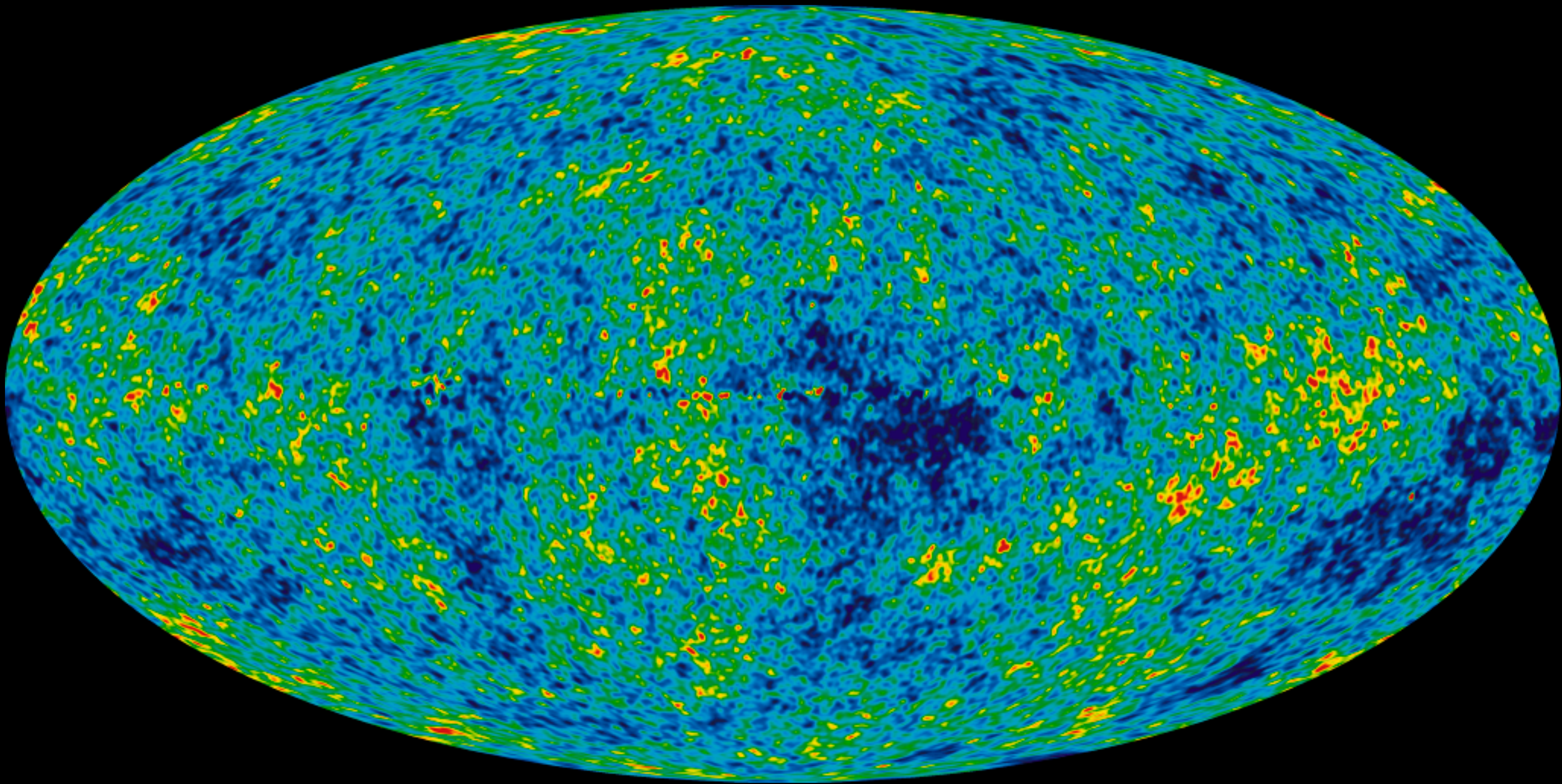
Ennico / COHSI

Infrared cirrus



IRAS

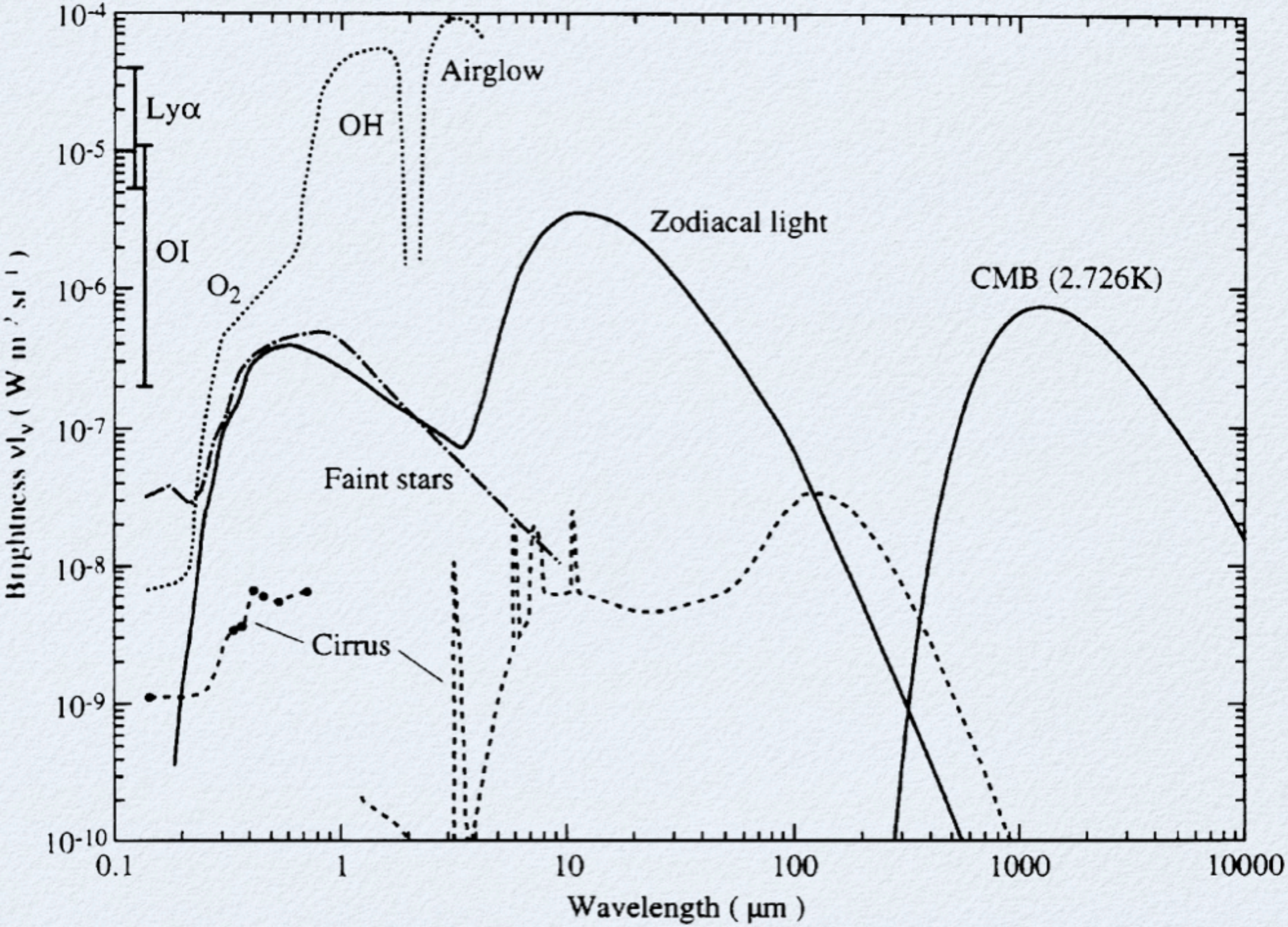
Cosmic microwave background



Aitoff projection showing temperature fluctuations in CMB

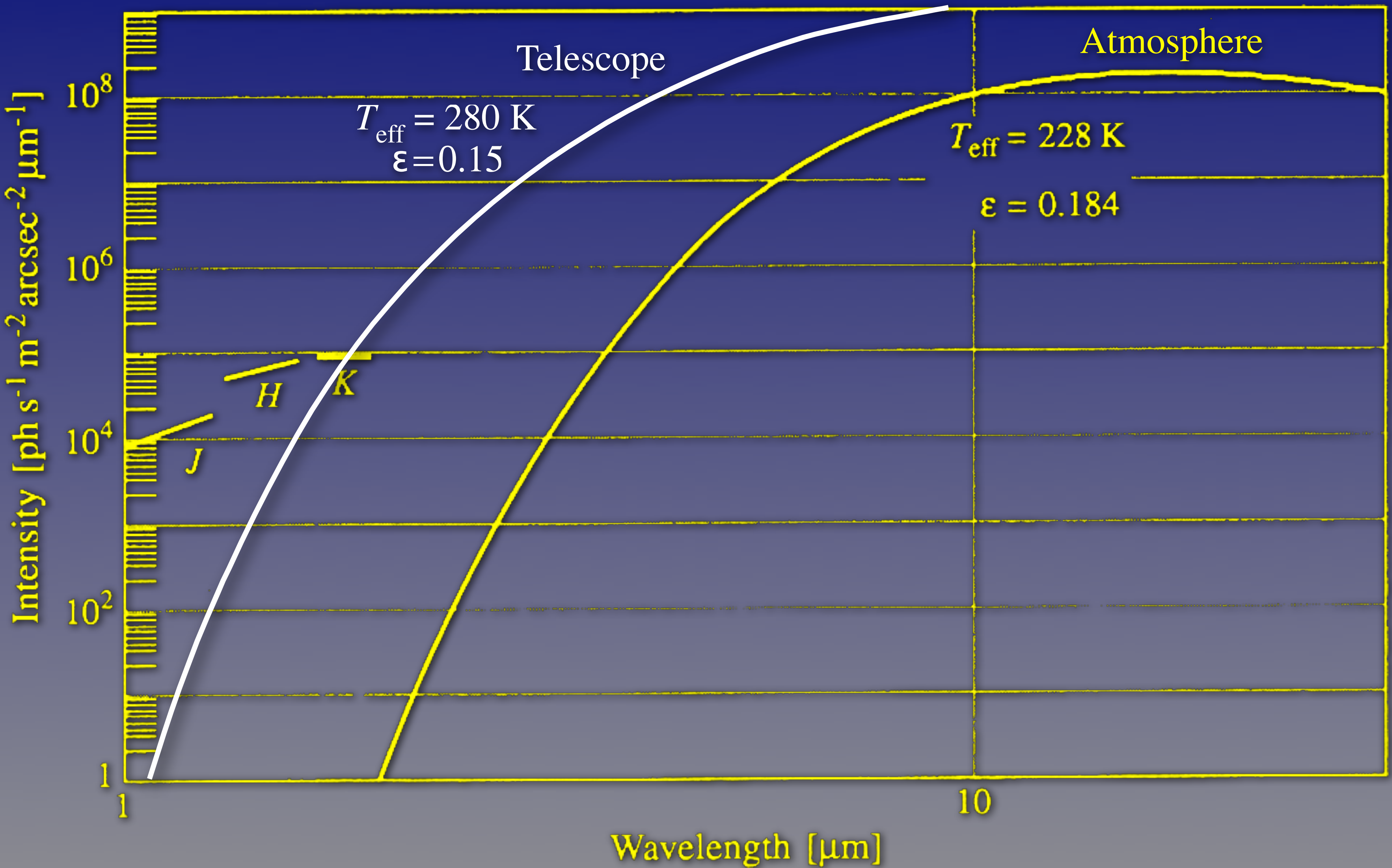
NASA / WMAP

Sky background spectrum



Glass / Leinert / COBE

Importance of telescope thermal emission



Léna, Lebrun, & Mignard

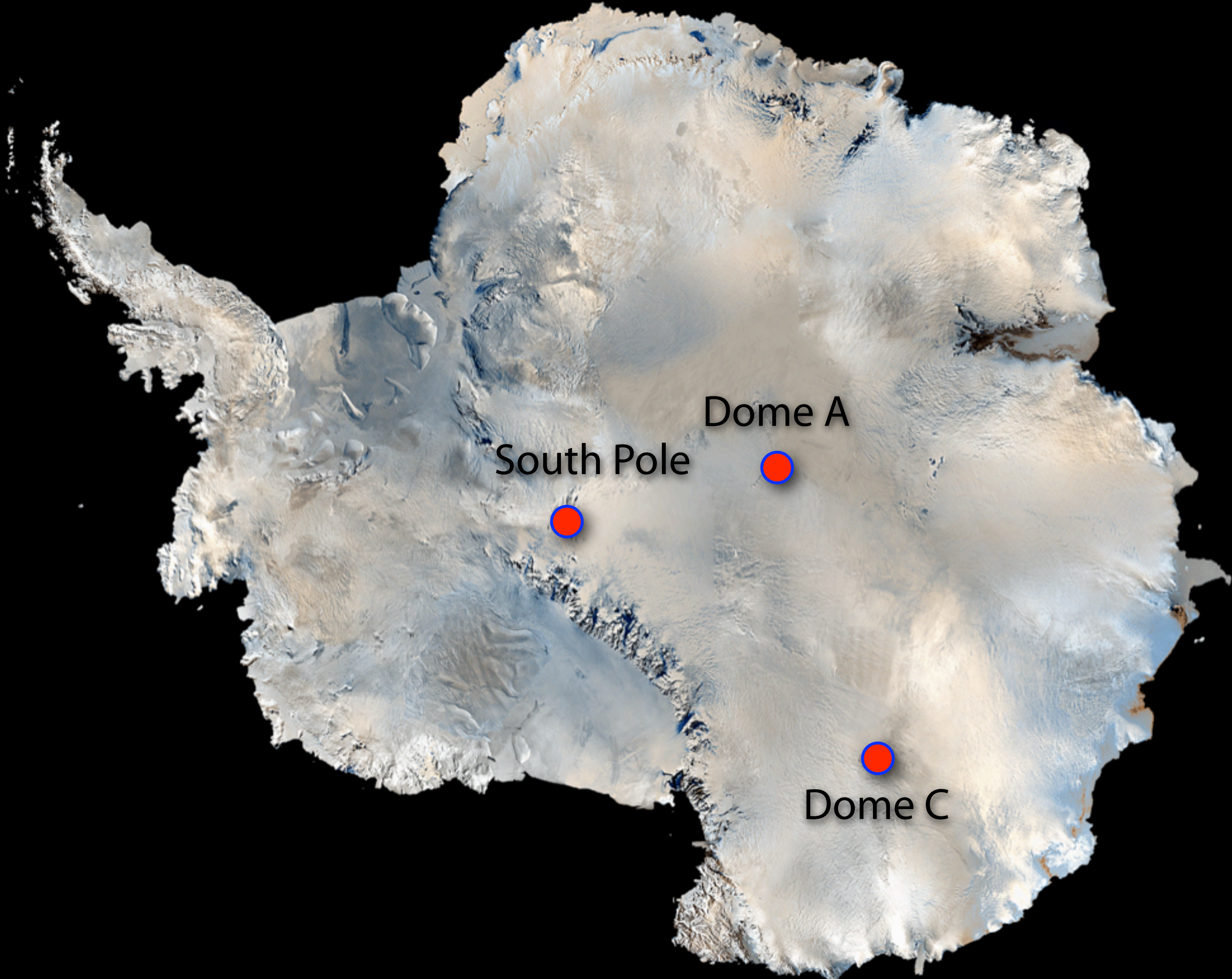
Everest as seen from the ISS

Mauna Kea in the Pacific Ocean

Wainscoat

Cerro Paranal in the Chilean Atacama desert

Antarctica: the coldest continent on Earth



Concordia Station, Dome C, Antarctica

IPEV / PNRA / Dargaud

Airborne infrared astronomy: SOFIA

NASA / DLR

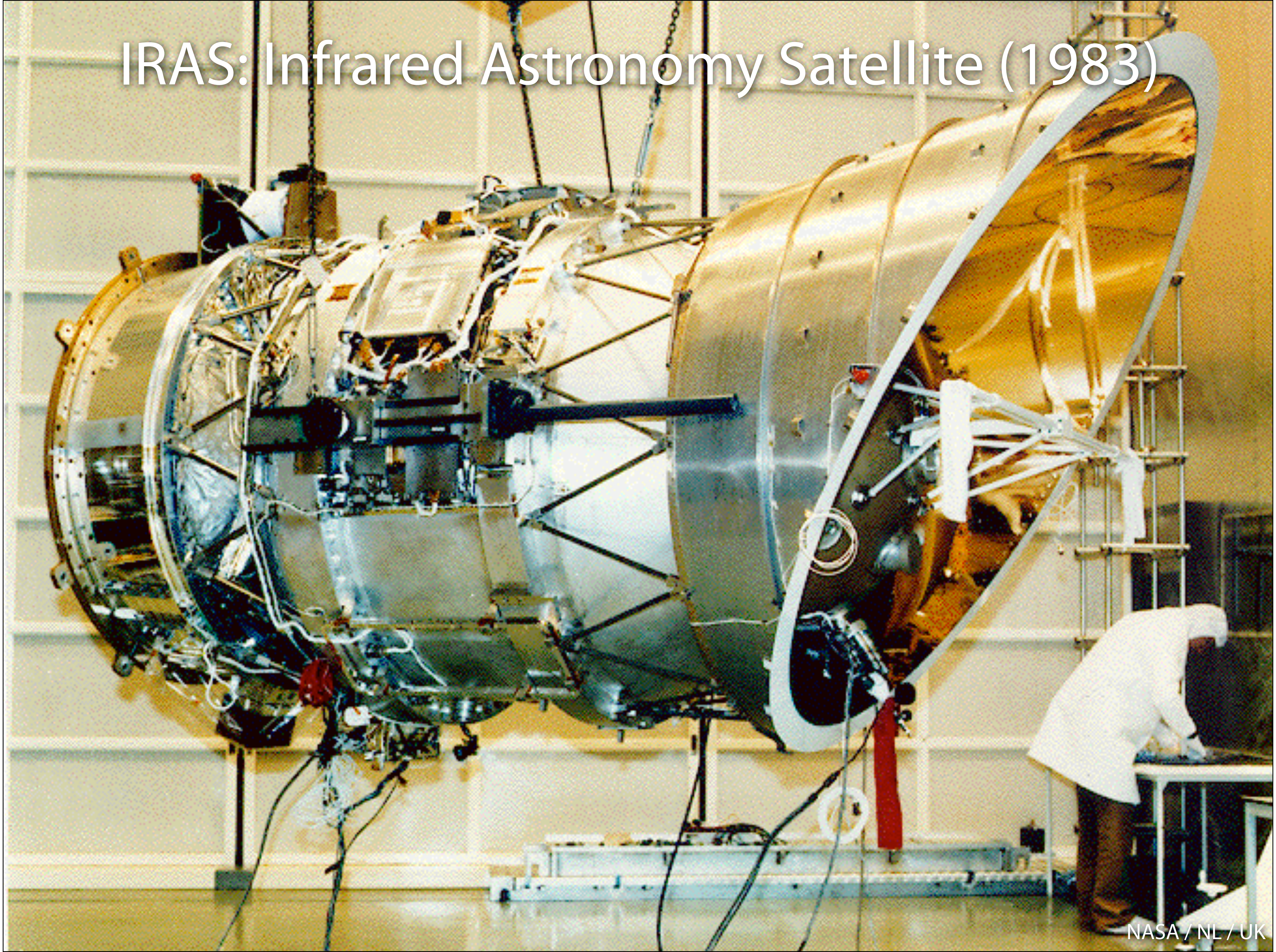
Infrared astronomy in space

- Get above the atmosphere
  - Eliminate thermal/non-thermal sky emission: lower background
  - Eliminate seeing: achieve diffraction-limited resolution
  - Eliminate absorption: equal access to all wavelengths
- How to reduce telescope thermal background?
  - Any object at ~1AU from Sun will have ~ same temperature as Earth, minus ~20K-worth of greenhouse effect
  - HST actually actively heated to keep mirror at room temperature
- Solutions
  - Move further away from Sun: temperature at 5AU ~ 120K
  - Cool entire telescope/instrument package with cryogens
  - Use sunshield to passively cool telescope

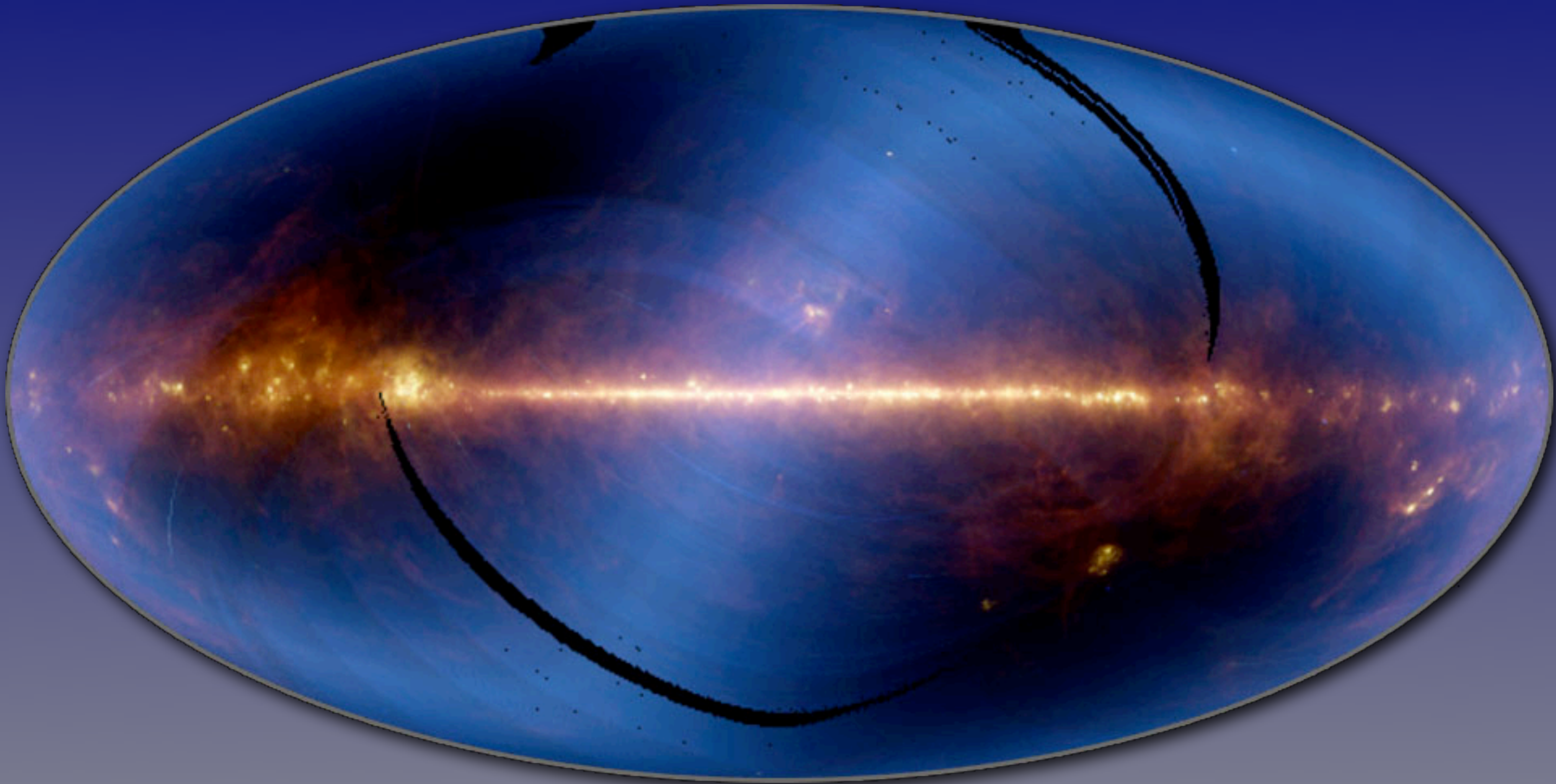
A brief history of IR space astronomy

- Early days
  - AFCRL/AFGL survey rocket flights
- The first orbiting space infrared survey
  - IRAS
- The first orbiting space infrared observatory
  - ISO
- Subsequent infrared missions
  - IRTS, HST/NICMOS, MSX, Akari, Spitzer
- The future of space infrared astronomy
  - HST/WFC3, Herschel, WISE, JWST, (Darwin/TPF, SAFIR, FIRI, ...)
- (Excludes many other IR missions:
  - COBE, WMAP, ODIN, SWAS, SL-2, WIRE, solar system ...)

IRAS: Infrared Astronomy Satellite (1983)



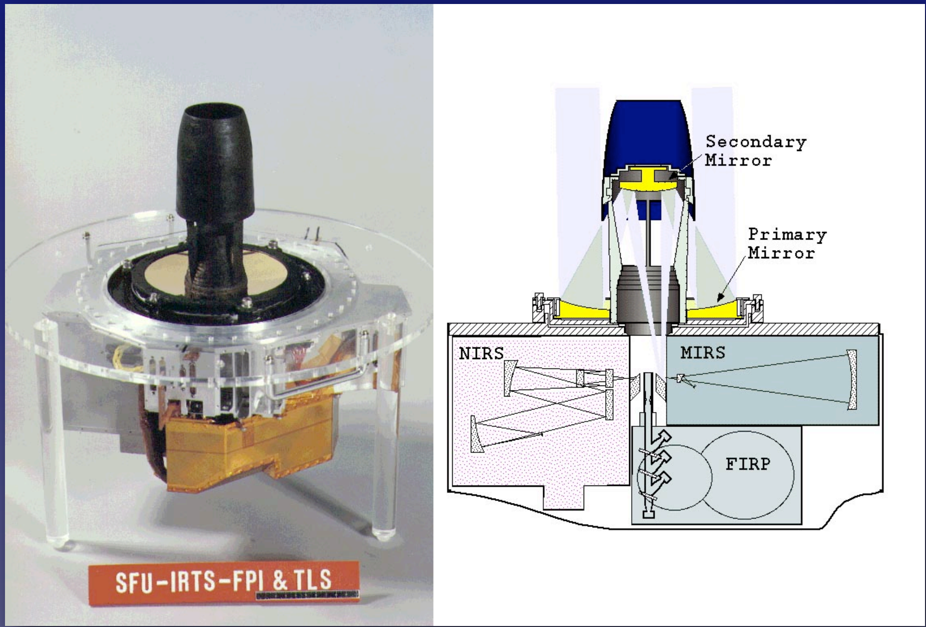
IRAS (almost) all-sky survey

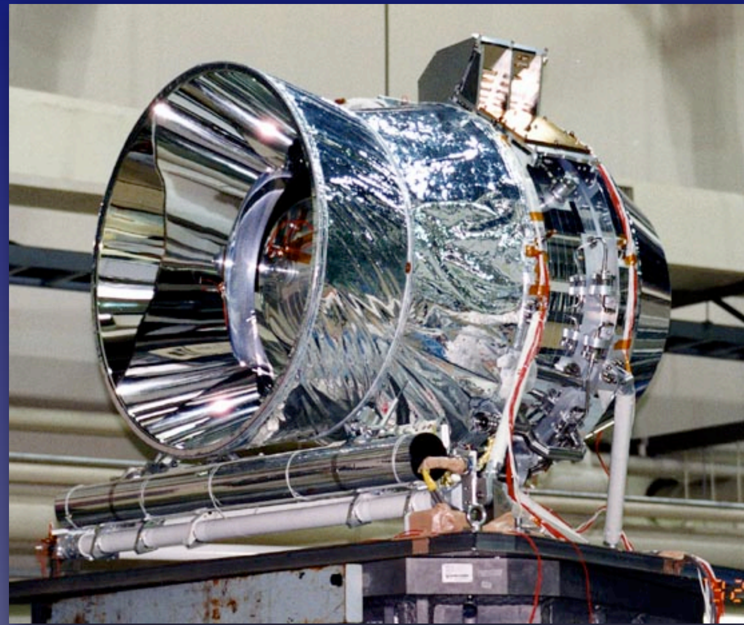


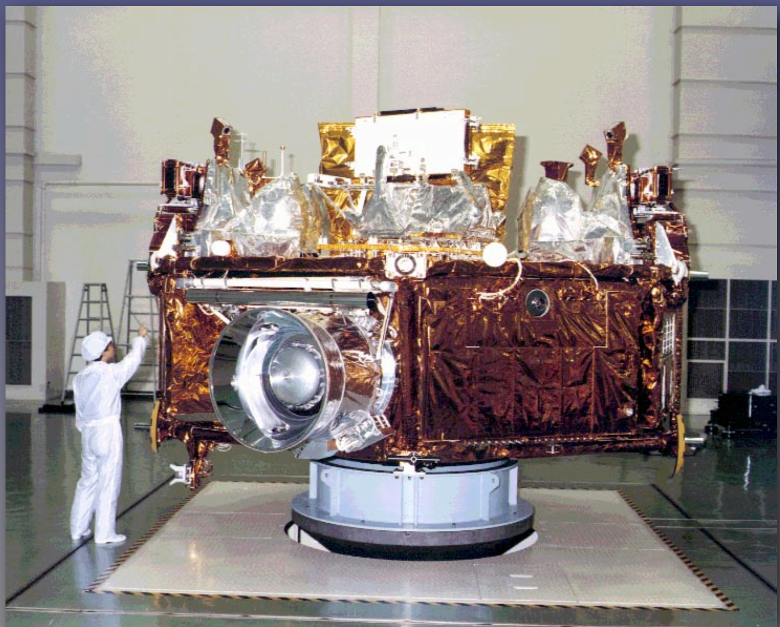
NASA / NL / UK

- Yellow-red horizontal strip is the galactic plane
- Blue S-shaped feature is the ecliptic

IRTS: Infrared Telescope in Space (1995)

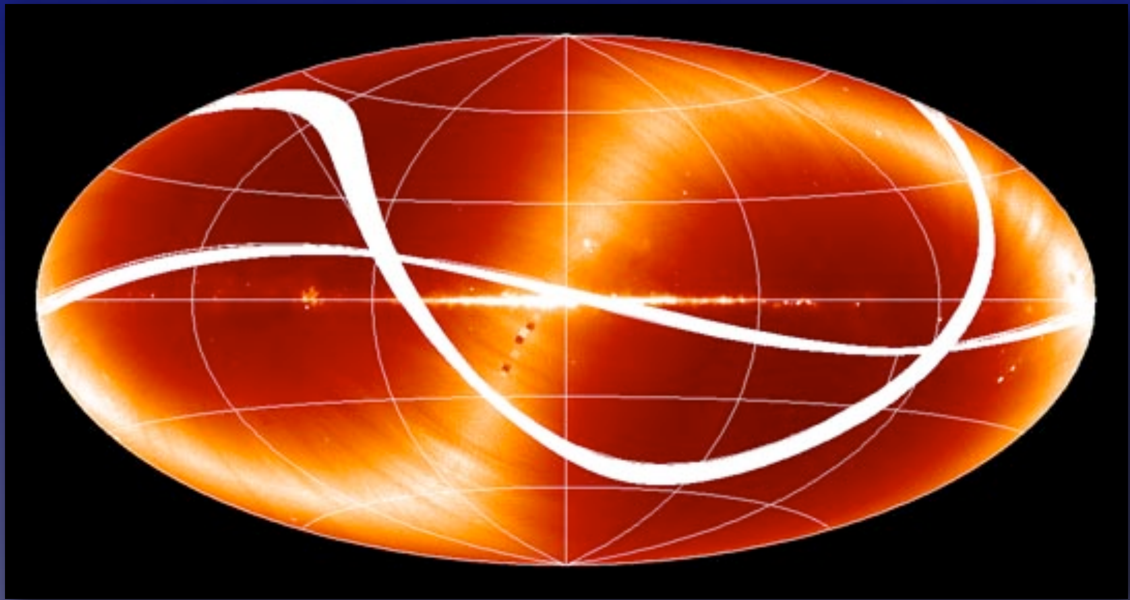


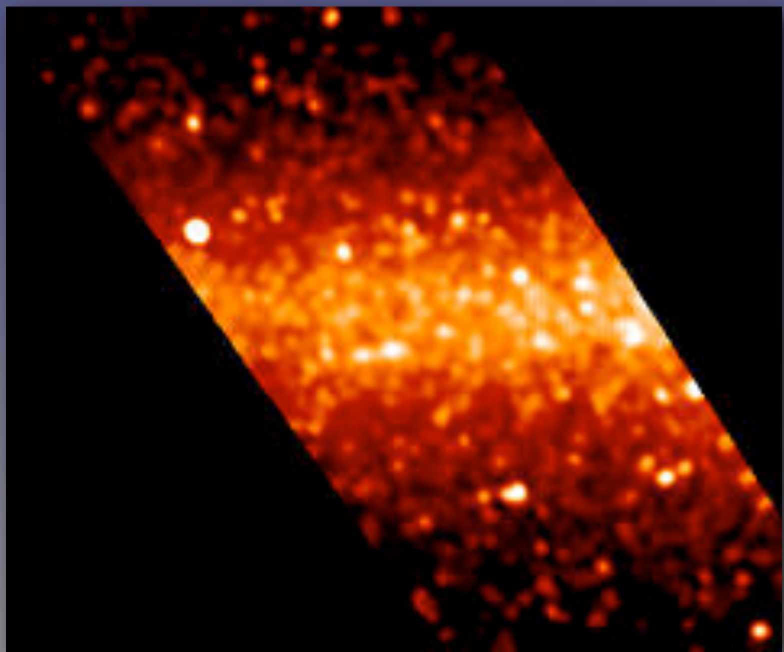


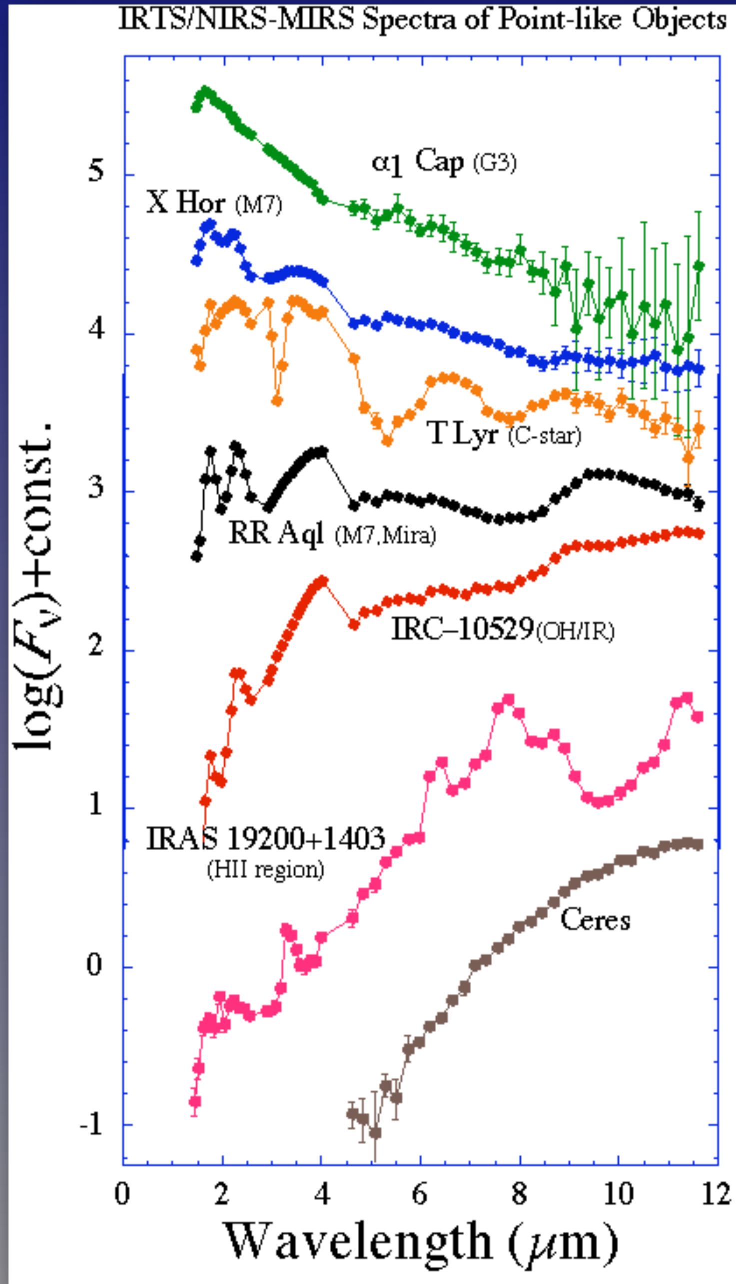


JAXA

IRTS survey coverage and results

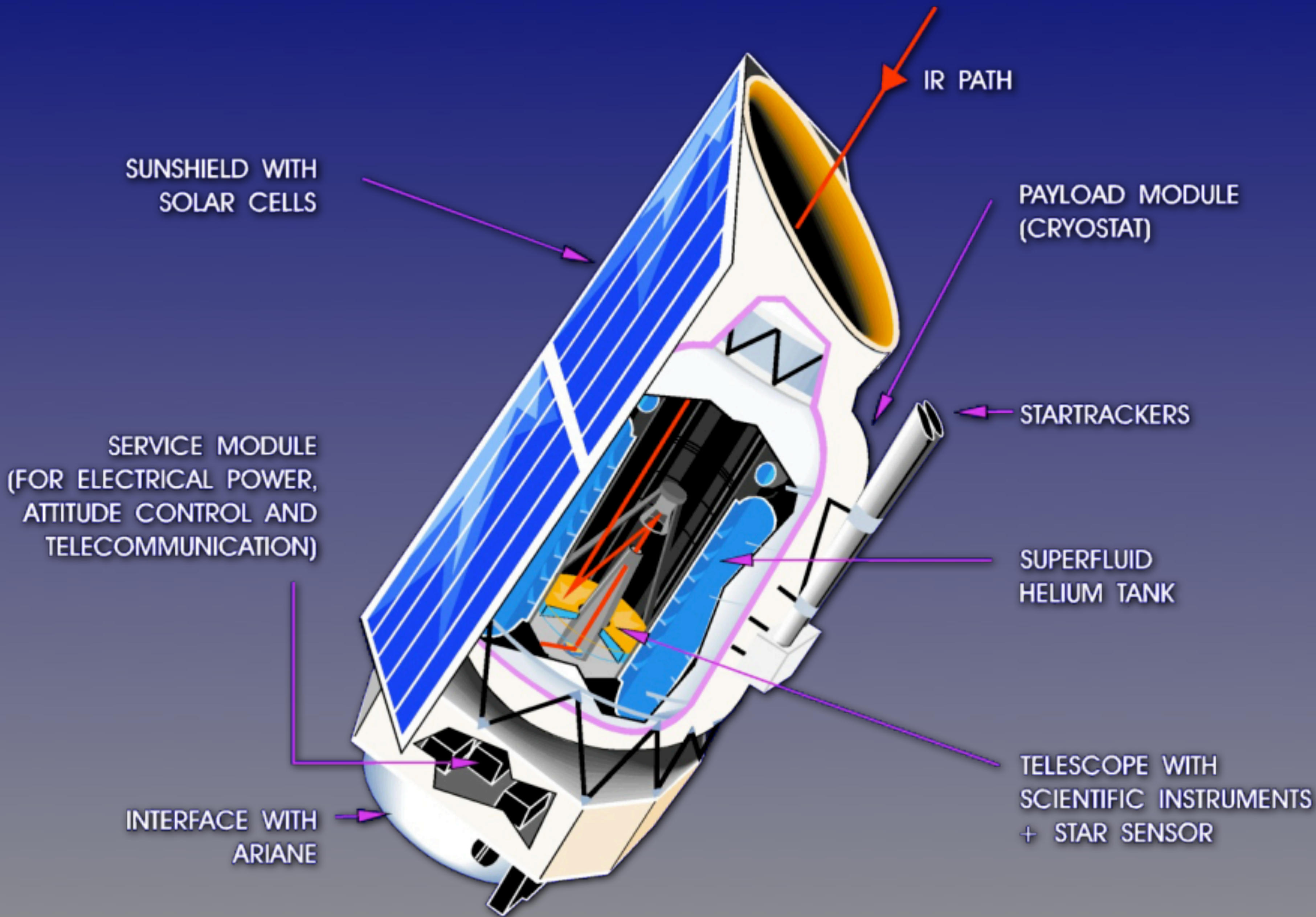






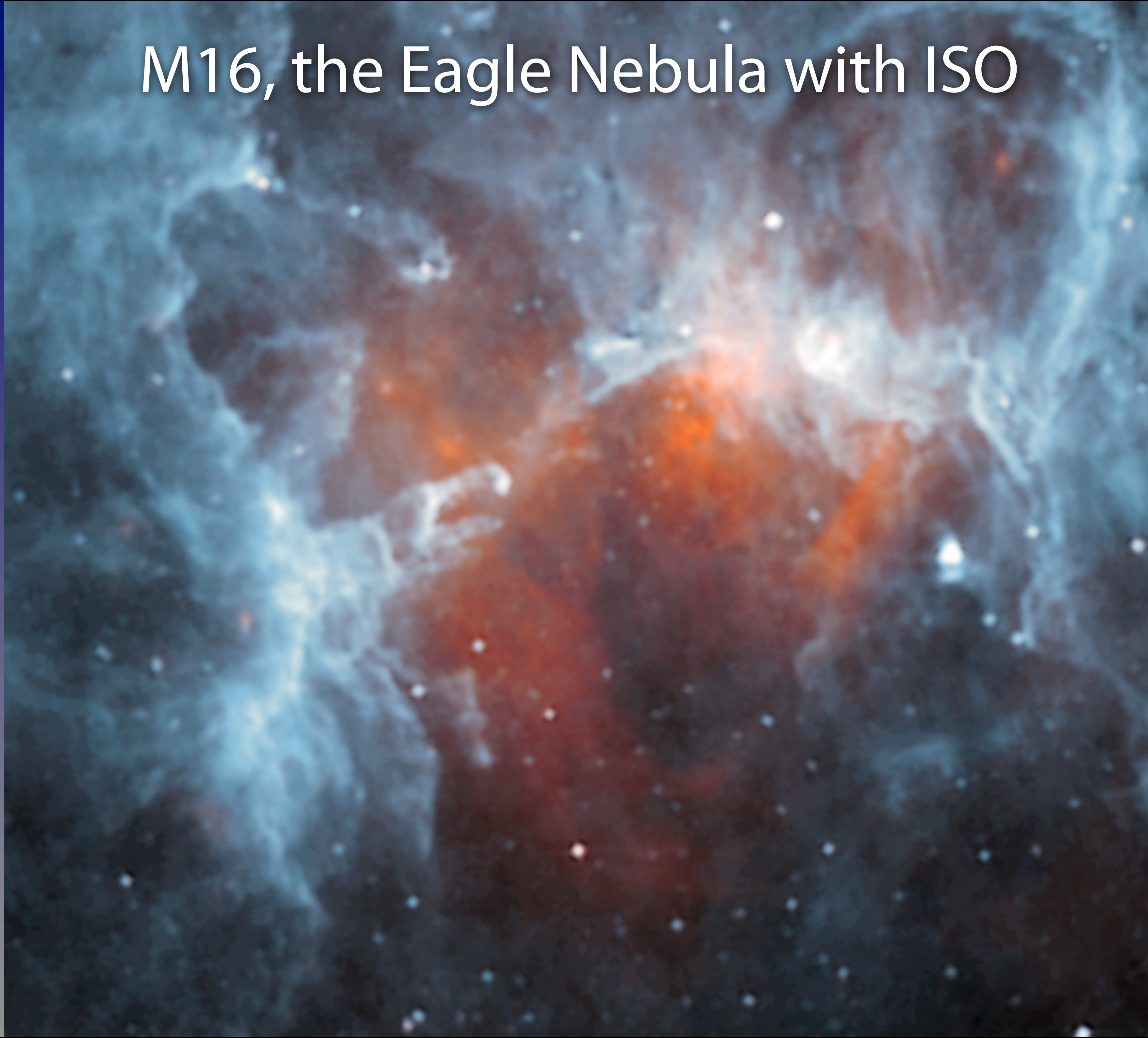
JAXA

ISO: Infrared Space Observatory (1995)



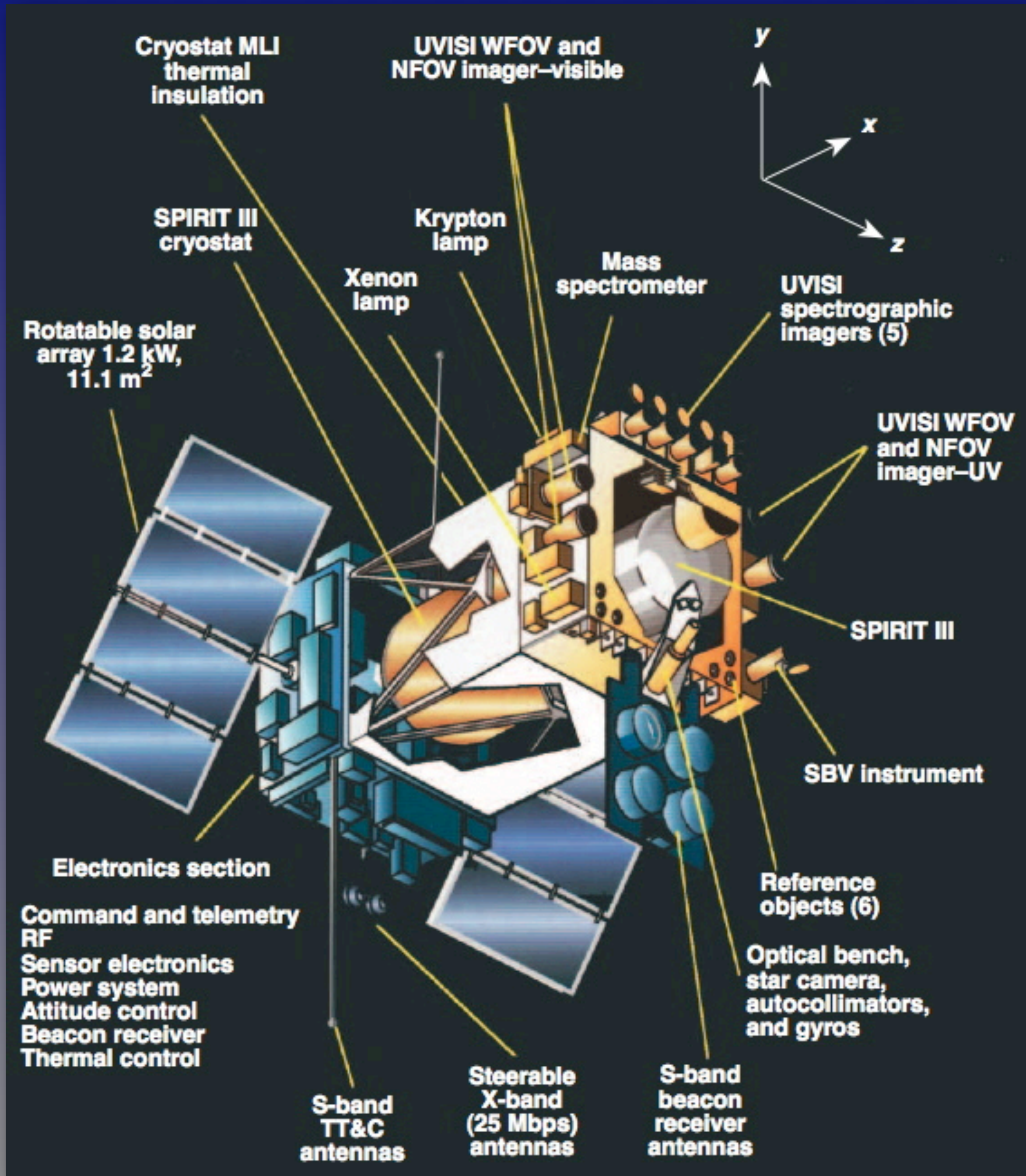
ESA

M16, the Eagle Nebula with ISO



ESA

MSX: Mid-Course Space Experiment (1996)



US BMDO

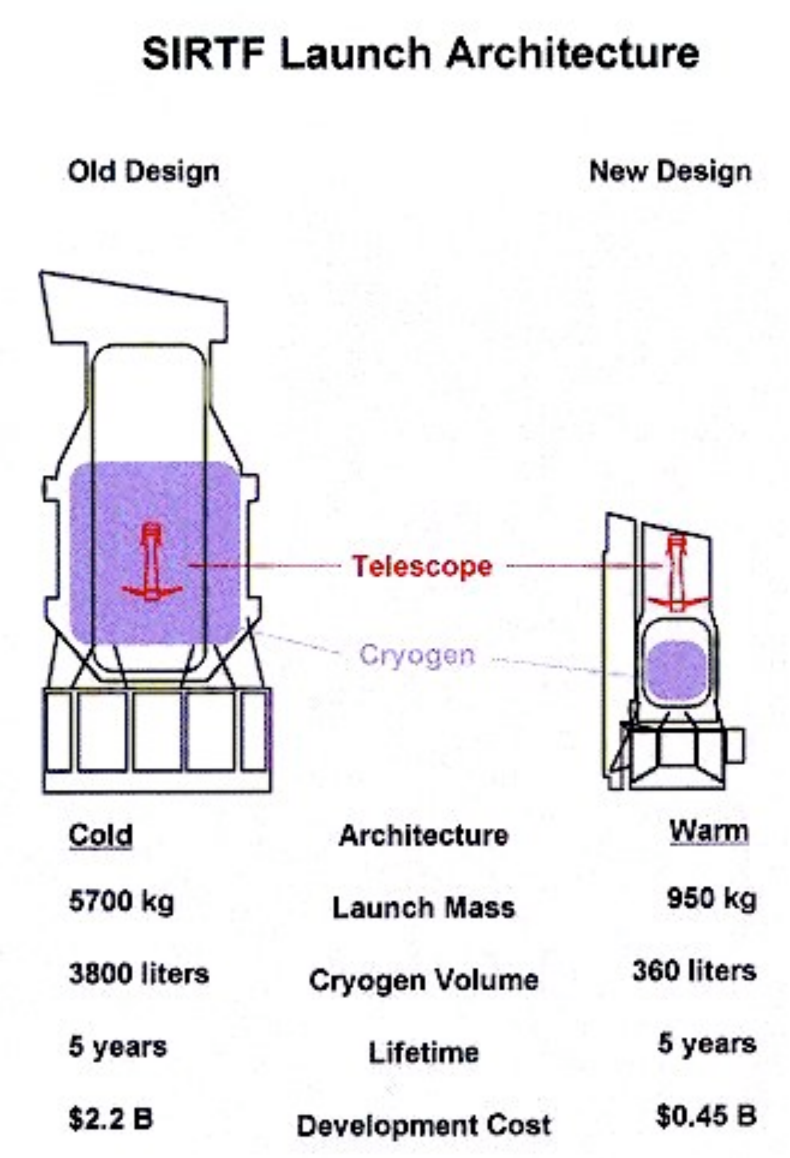
Galactic centre with MSX

HST NICMOS (1997)

Orion Nebula & Trapezium Cluster

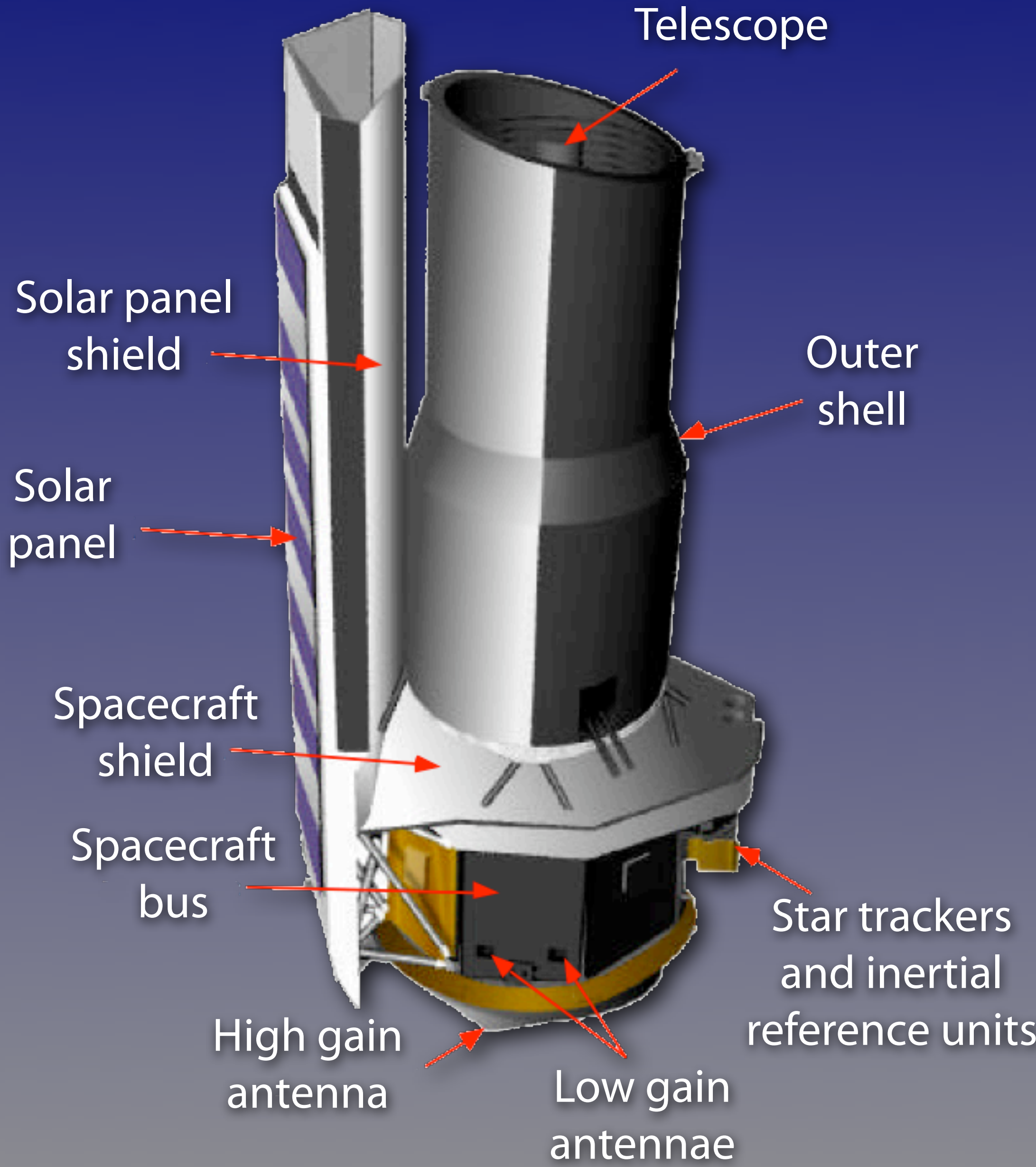
Luhman et al. / NASA / ESA

Spitzer Space Telescope (2003)



SIRTF Launch Architecture

Cold	Architecture	Warm
5700 kg	Launch Mass	950 kg
3800 liters	Cryogen Volume	360 liters
5 years	Lifetime	5 years
$2.2 B	Development Cost	$0.45 B

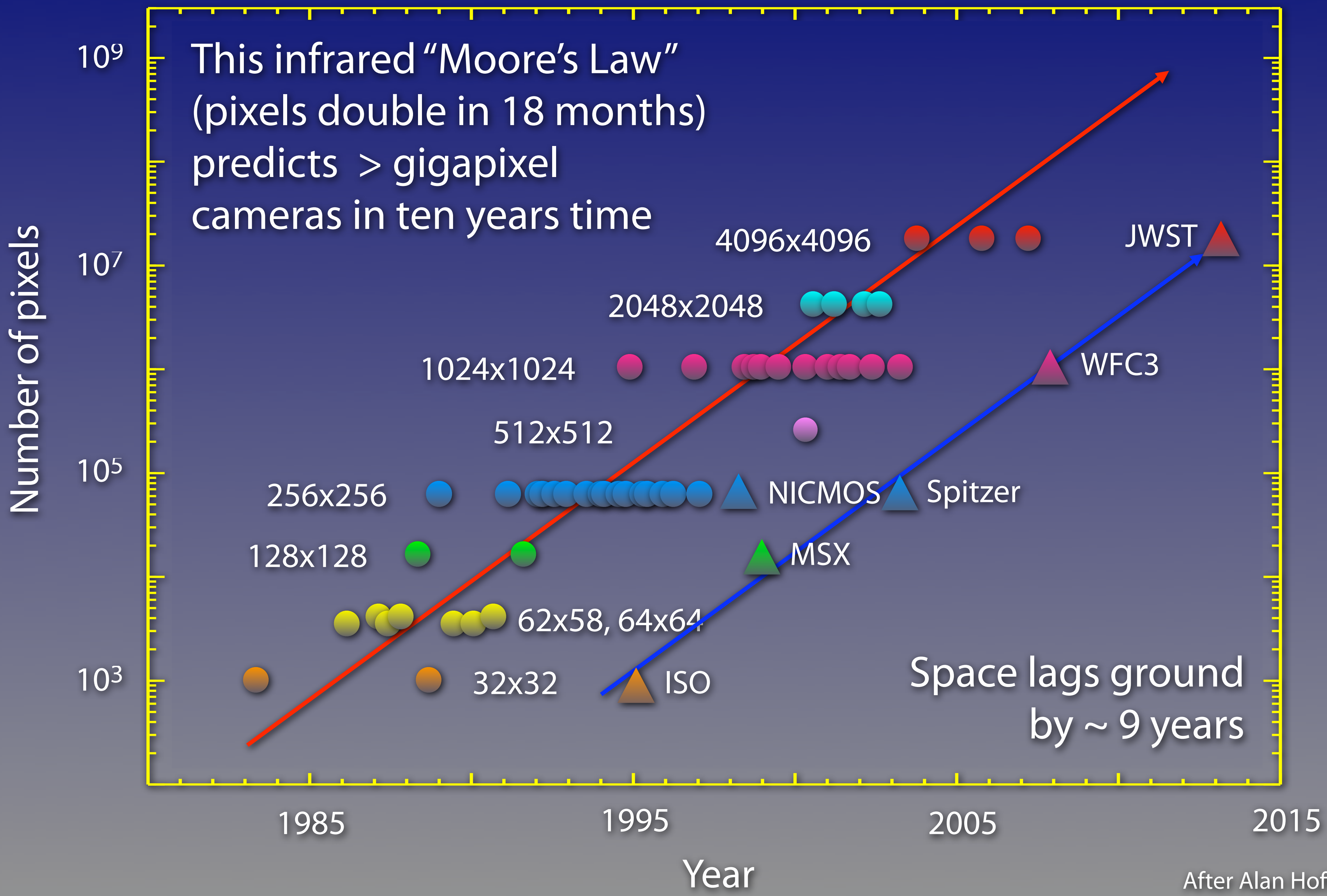


NASA

Herschel Space Observatory (2009)

ESA

The role of infrared array detectors

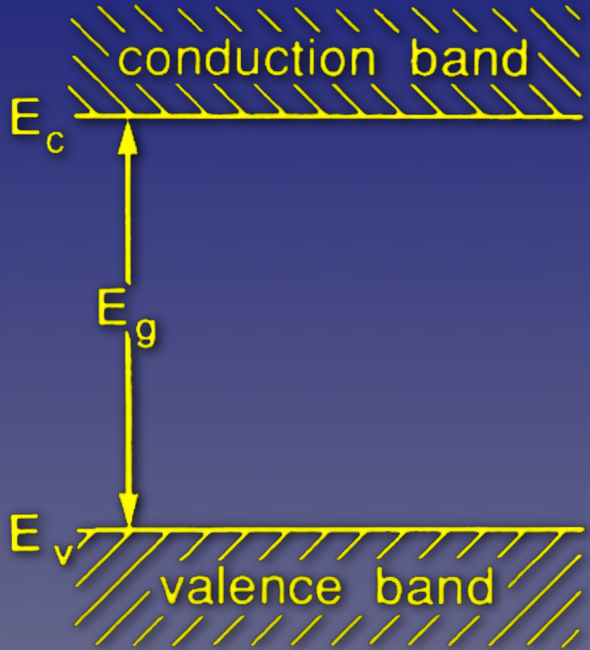


After Alan Hoffman

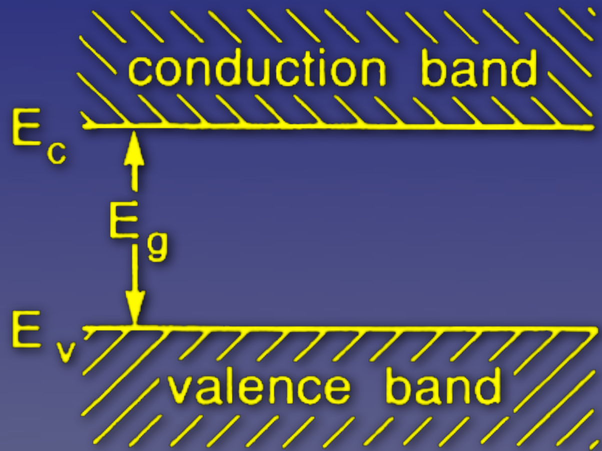
Basic techniques for detecting IR photons

- Aim: convert incoming photons into electrical signals
- Photoconductors (0.3-30μm):
  - Photons generate electron-hole pairs in semiconductors
  - Electrons move to conduction band
  - Electrons swept by electric field and measured
- Bolometers (30-1000μm):
  - Photons heat bulk material (semi- or superconductor)
  - Temperature change induces change in electrical properties
- Heterodyne systems (100-1000μm):
  - Mix incoming electromagnetic waves with local oscillator
  - Detect amplitude of beat signal at much lower frequency
  - Low noise electronics then used to amplify signal
  - Coherent detection: preserves phase → interferometry

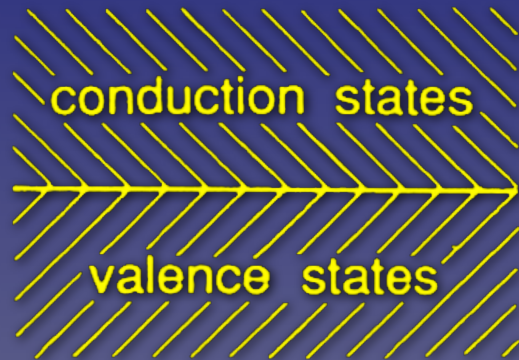
Energy band diagrams



Insulator
$E_g > 3.5\text{eV}$



Semiconductor
$0\text{eV} < E_g < 3.5\text{eV}$



Conductor
$E_g = 0\text{eV}$

$1\text{eV} = 1.602 \times 10^{-19}\text{ J} \approx 1.24\mu\text{m}$

Rieke

Detector materials in the Periodic Table

Ia	IIa	III b	IV b	Vb	VIb	VII b	VIII			Ib	IIb	III a	IV a	V a	VI a	VII a	0
1 H													↓				2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 ir	78 Pt	79 Au	80 **Hg**	81 Tl	82 **Pb**	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac															

- Typical semiconductors used in photoconductors include:
  - Group IV: Ge, Si
  - Group III-V: GaAs, InAs, InSb
  - Group II-VI: CdS, CdTe
  - Group IV-VI: PbS, PbSe, PbTe

Rieke

Intrinsic semiconductor properties

Material	Bandgap (eV)	Cutoff (µm)
CdS	2.4	0.5
CdSe	1.8	0.7
GaAs	1.35	0.92
Si	1.12	1.11
Ge	0.67	1.85
$Hg_xCd_{1-x}Te$ (x=0.554)	0.5	2.5
PbS	0.42	2.95
InSb	0.23	5.4
$Hg_xCd_{1-x}Te$ (x=0.8)	0.1	12.4

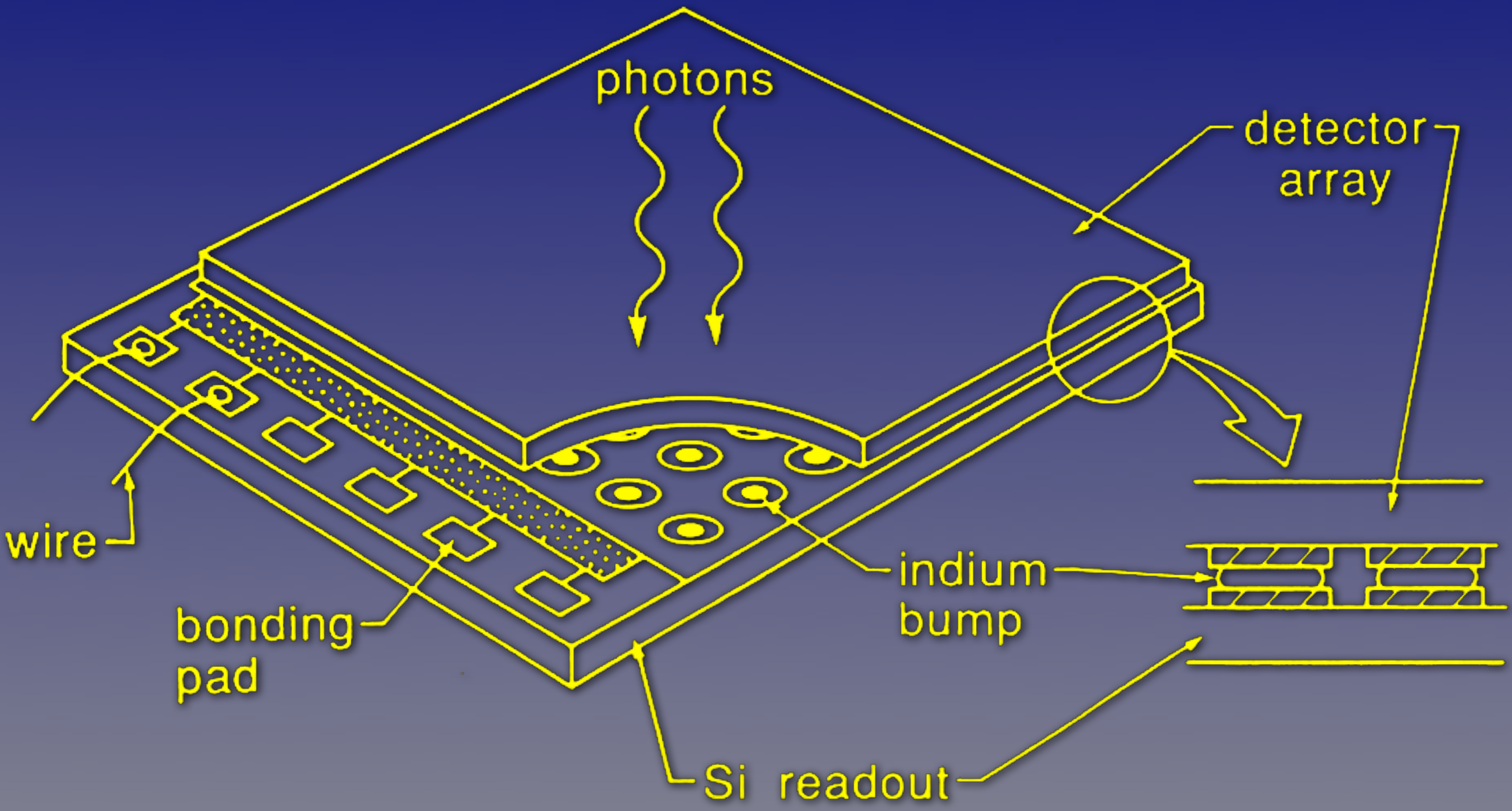
Extrinsic semiconductor properties

Material	Bandgap (eV)	Cutoff (μm)
Si:In	0.16	7.9
Si:Ga	0.072	17.2
Si:As	0.054	23
Si:Sb	0.043	29
Si:As (BIB)	0.041	30
Si:Sb (BIB)	0.031	40
Ge:Ga	0.011	115
Ge:Ga (stressed)	0.0062	>200

Infrared arrays

- Until early 1980s, only single element IR detectors
- Silicon microelectronics techniques widespread
  - Spinoff was CCD detectors
  - But IR semiconductors techniques not so well developed
- Answer: hybrid infrared arrays
  - Use IR semiconductor for detection layer
  - Use Si multiplexer for charge storage and measurement
  - Interface two mechanically via metal interconnects
- IR material must backside illuminated
  - Detector material must be thin
  - Historically done via mechanical polishing
  - Now done via molecular beam epitaxy onto substrate

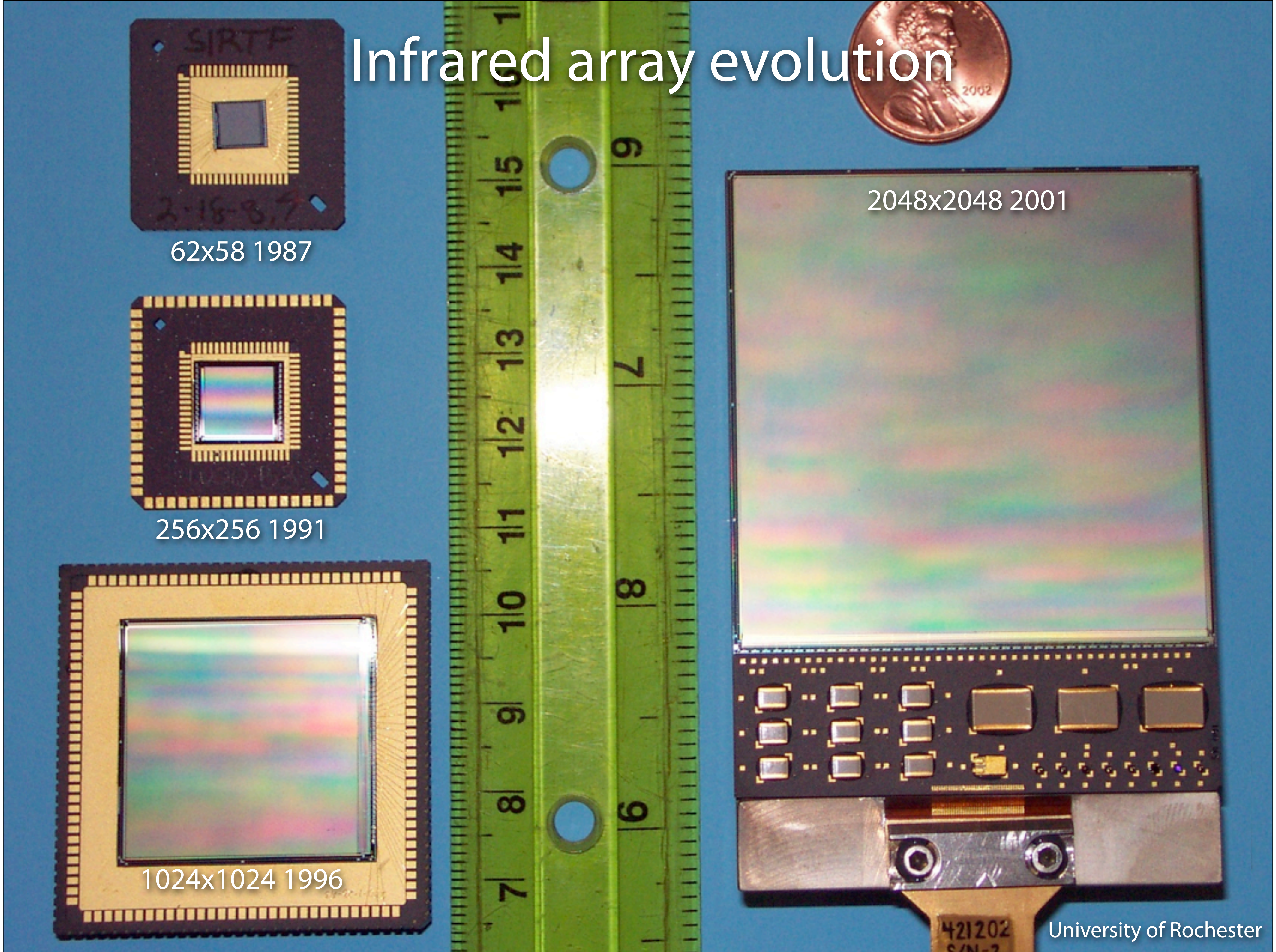
Schematic hybrid infrared array

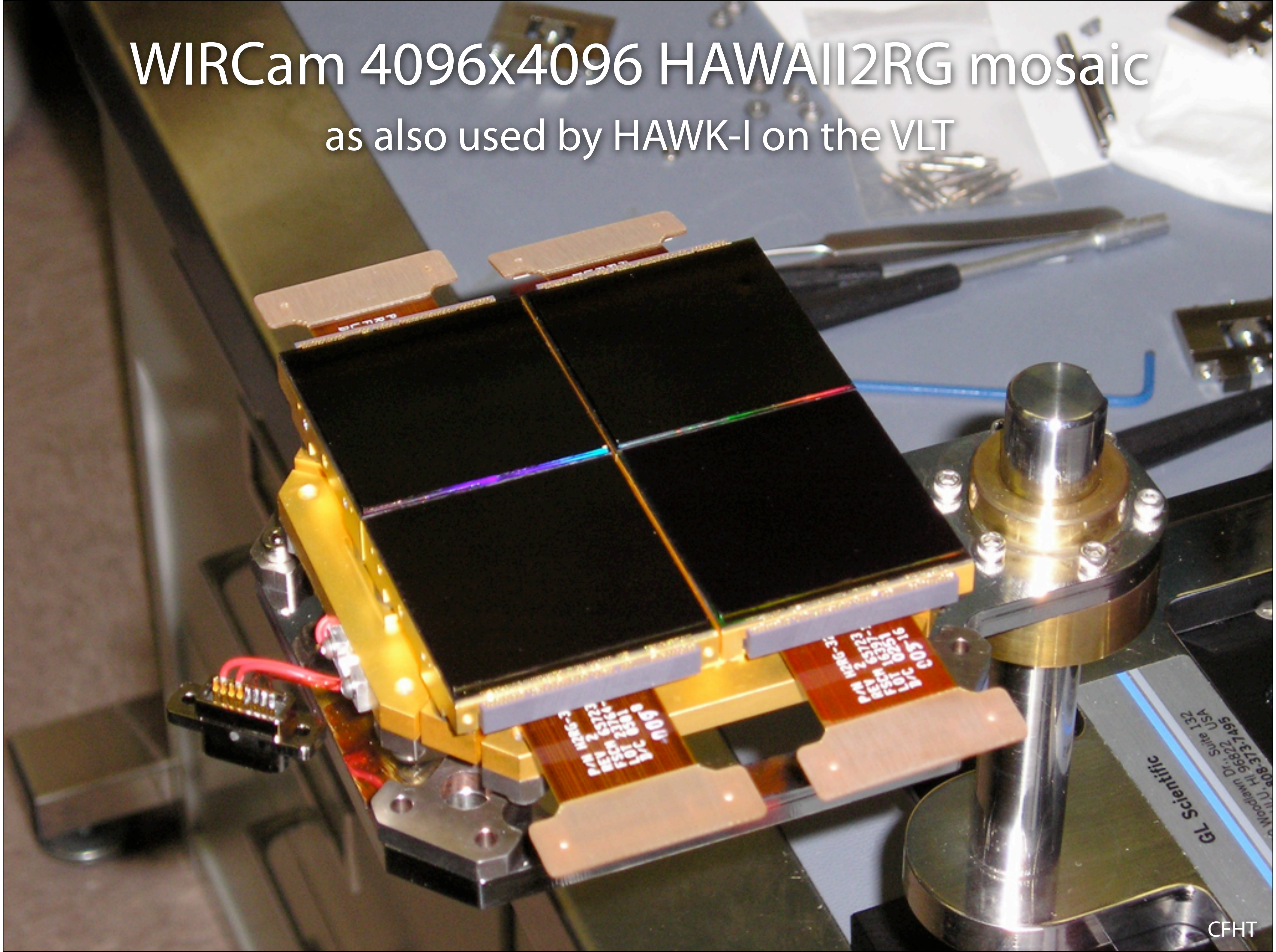


Detector array layer deposited on transparent substrate e.g. sapphire

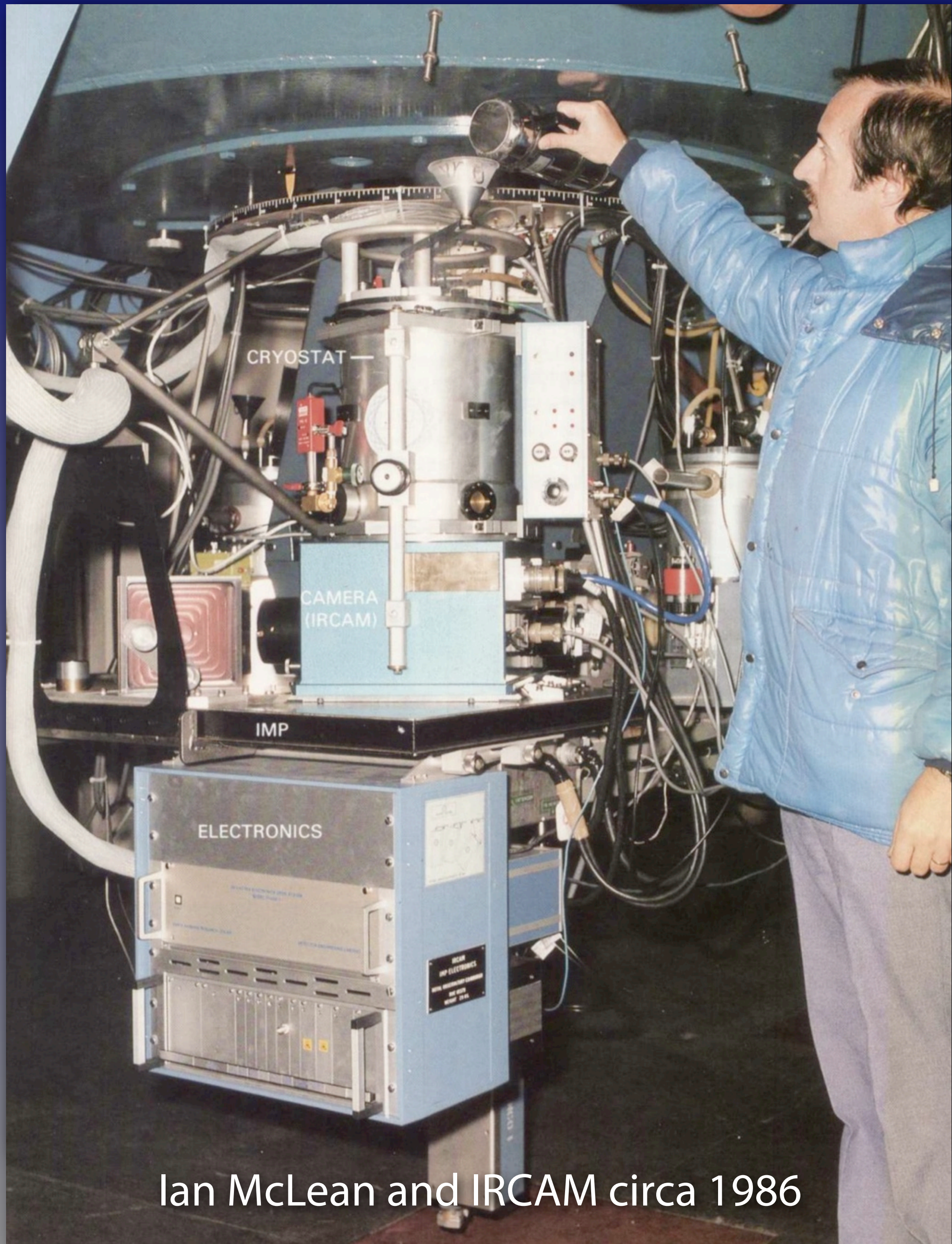
Rieke

Infrared array evolution




WIRCam 4096x4096 HAWAII2RG mosaic
as also used by HAWK-I on the VLT
GL Scientific
CFHT

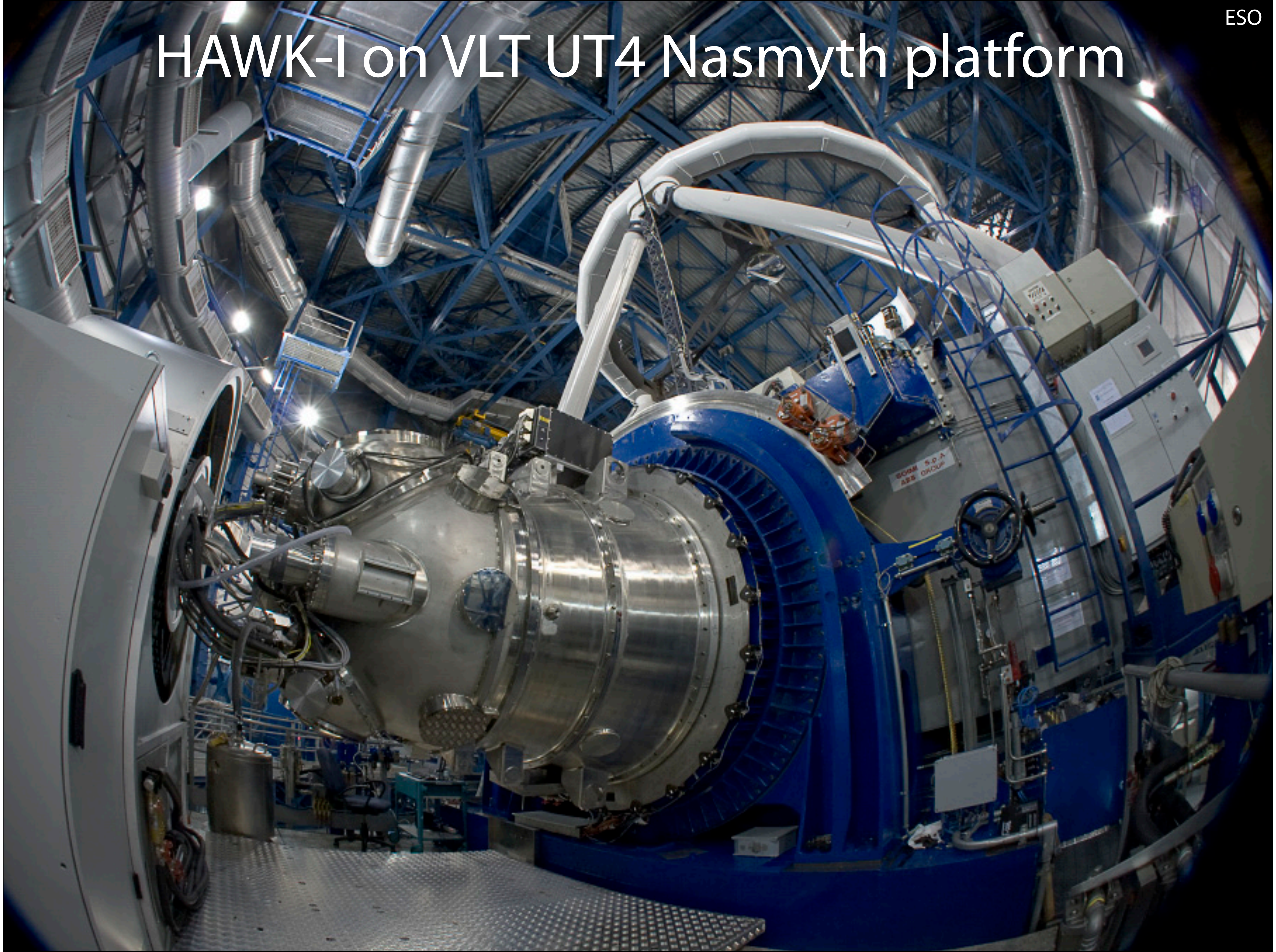
Men and their magnificent machines



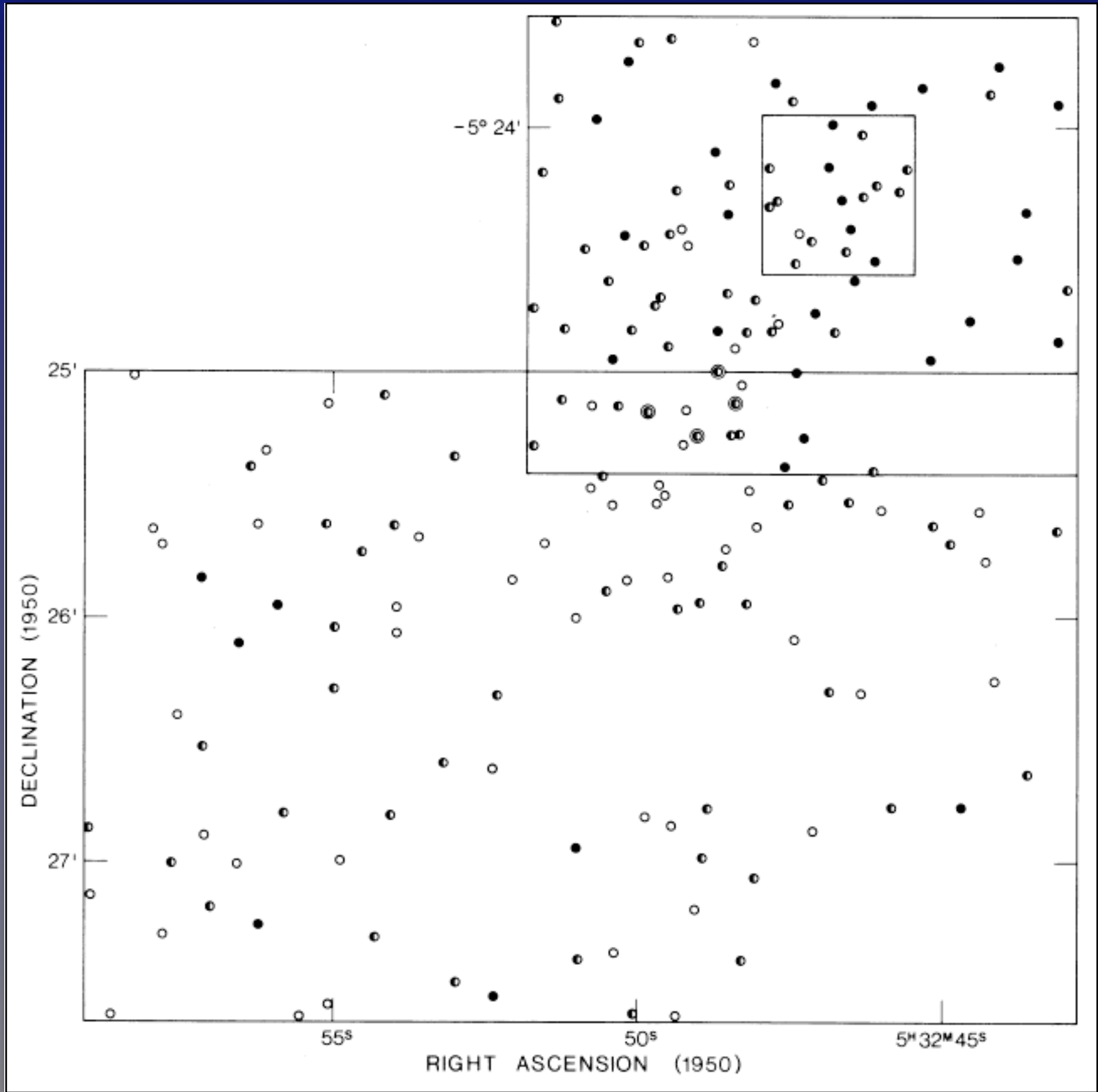
Ian McLean and IRCAM circa 1986

ESO

HAWK-I on VLT UT4 Nasmyth platform



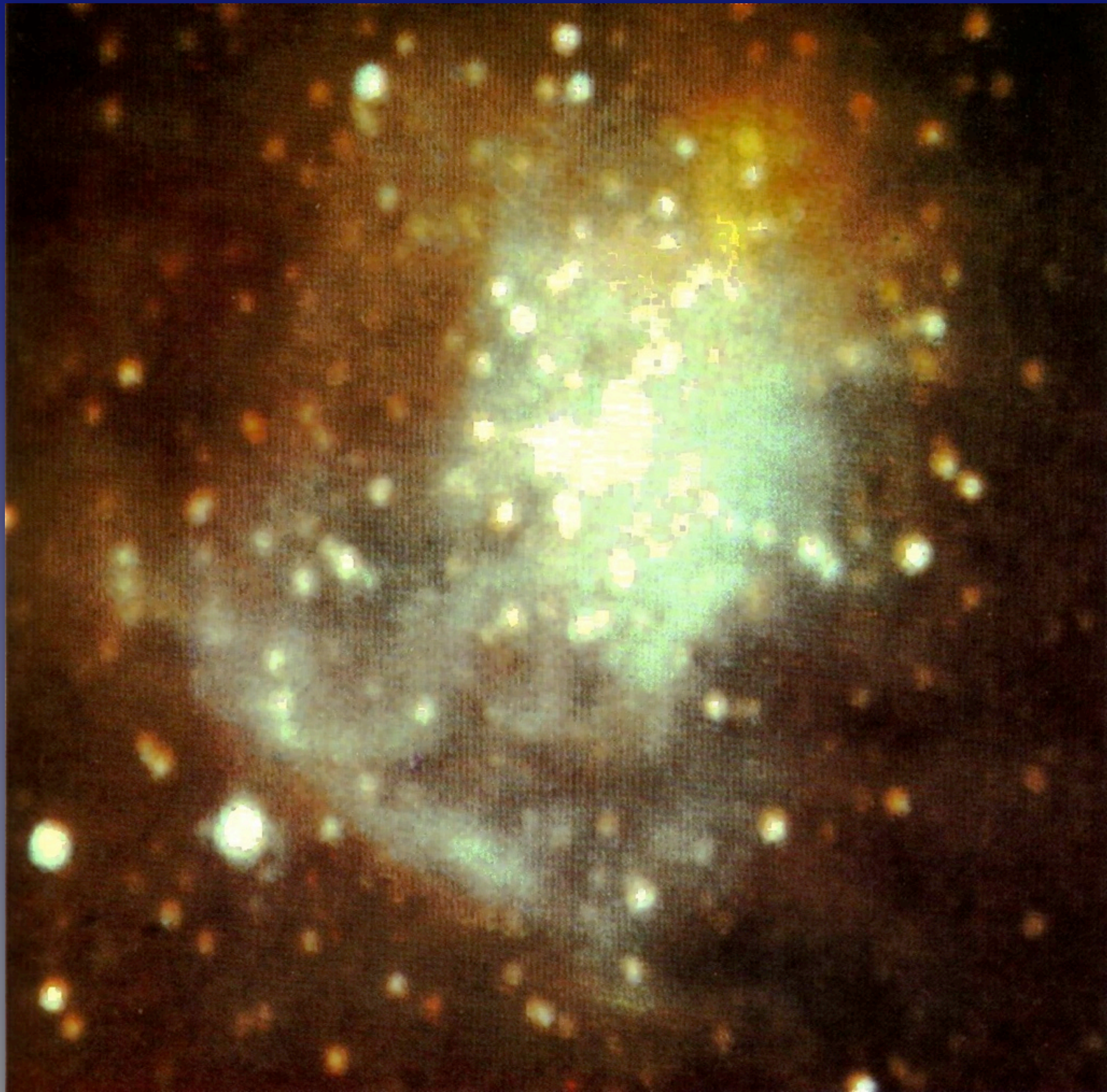
Orion single-element mapping survey



UKIRT / 2.2 microns / 5 & 3.5 arcsec beams / tens of sources

Lonsdale, Becklin, Lee, & Stewart 1982

Single-element detector raster image



AAT+IRPS / JHK bands / 2 arcsec pixels, 2 arcsec seeing / ~200 sources

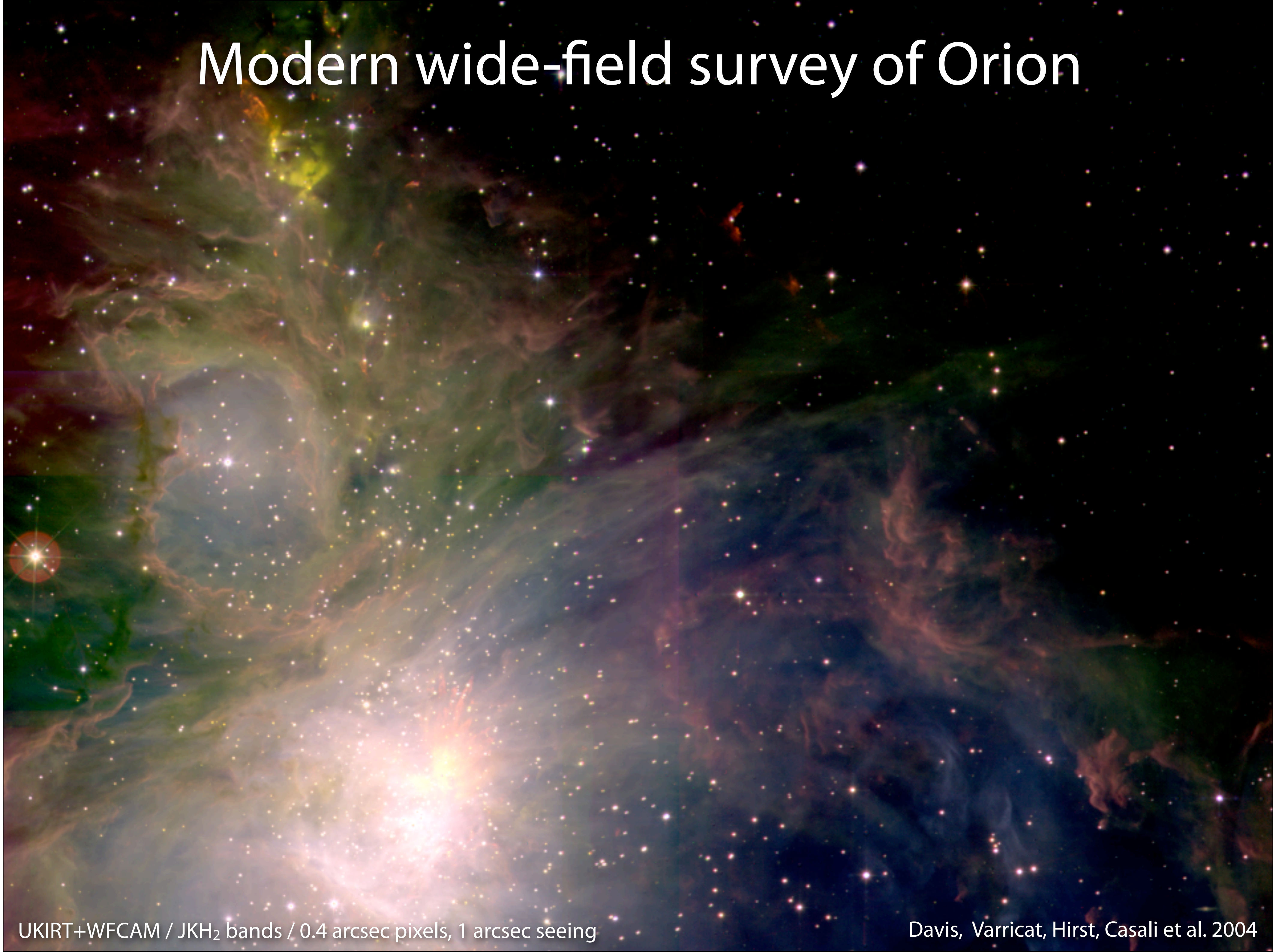
Allen, Bailey, & Hyland 1984, S&T

First IRCAM imaging mosaic of Orion

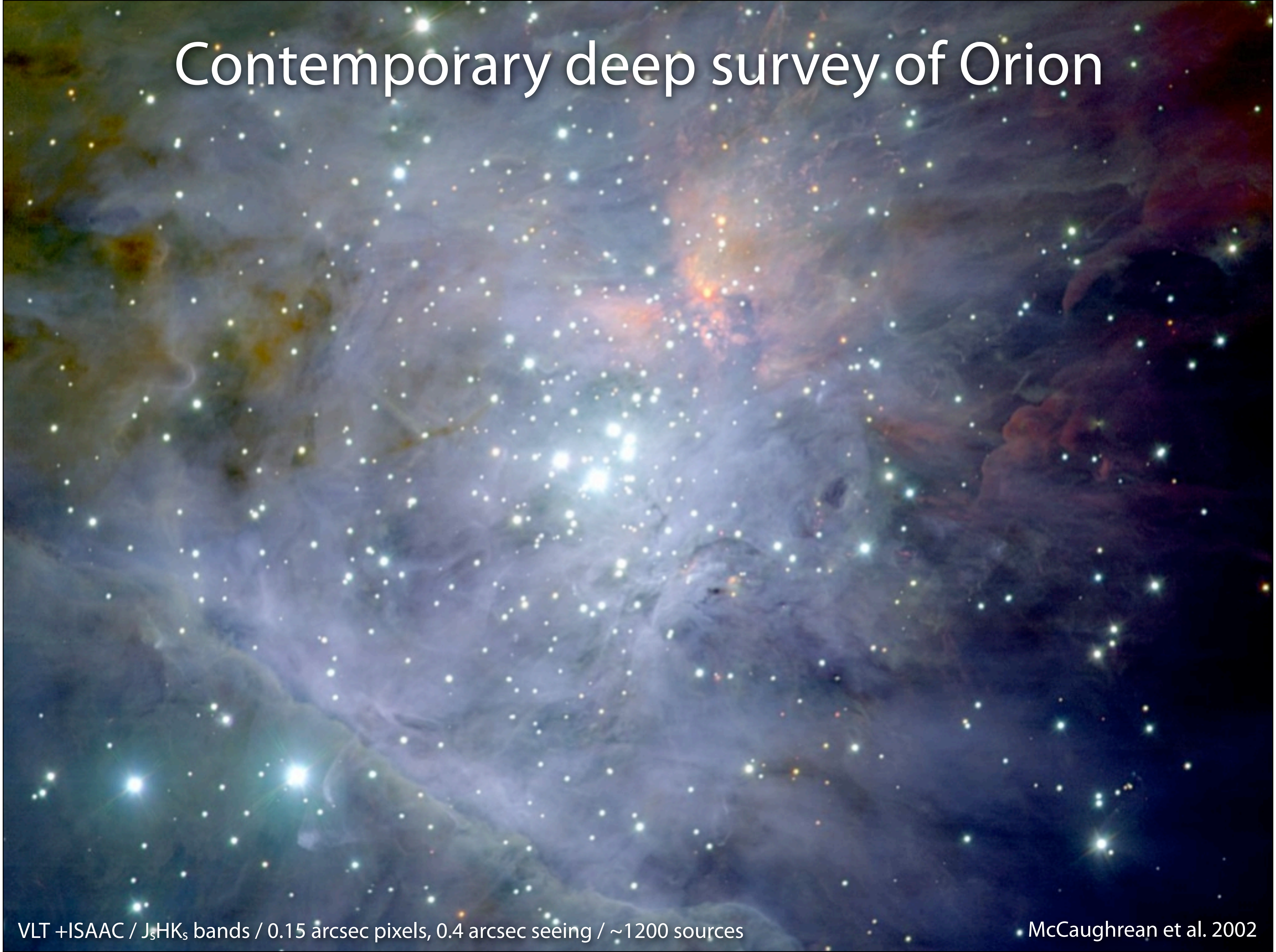
UKIRT+IRCAM / K band / 0.6 arcsec pixels, 2 arcsec seeing / ~400 sources

McCaughrean 1988, PhD thesis

Modern wide-field survey of Orion



Contemporary deep survey of Orion



VLT +ISAAC / $J_s H K_s$ bands / 0.15 arcsec pixels, 0.4 arcsec seeing / ~1200 sources

McCaughrean et al. 2002

Back to physics: Poisson distribution (I)

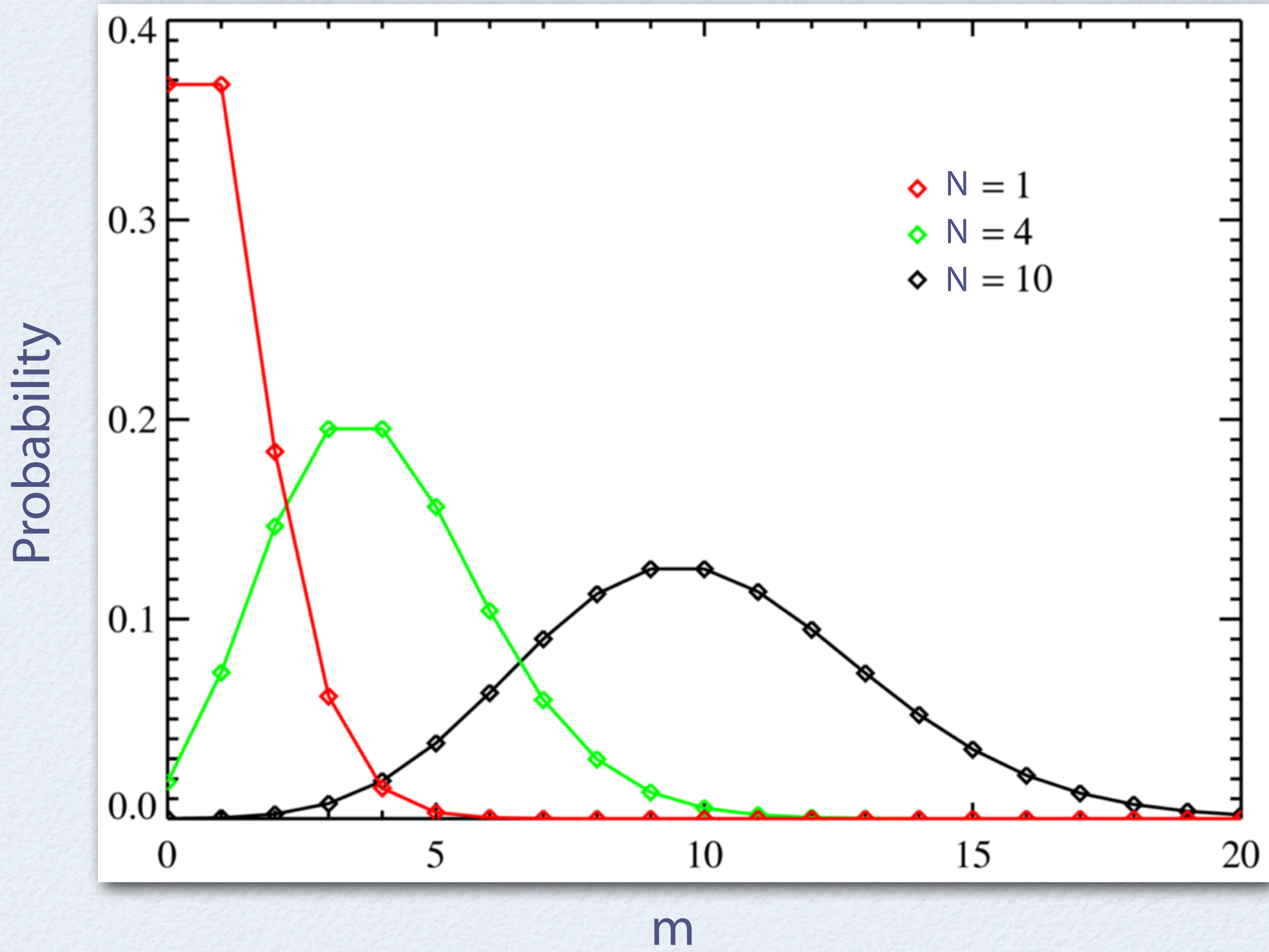
- One of many contributions by Poisson to mathematics
  - Later work by Ladislaus Bortkiewicz, based on statistics of number of soldiers kicked to death by horses annually
- If mean expected number of discrete events (arrivals) in given time interval is N, then probability of there being exactly m occurrences is:

$$f(m; N) = \frac{N^m e^{-N}}{m!}$$

  - m must be non-negative integer (0, 1, 2, ...)
  - N must be positive real number
  - Derivation non-trivial: many available

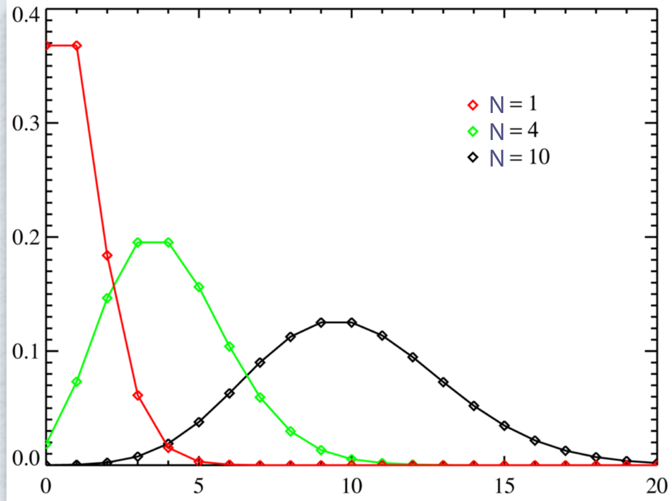
Siméon-Denis Poisson
(Wikipedia)

Poisson distribution (II)



Adapted from Wikipedia

Poisson distribution (III)



- Key features:
  - m can only have integer values
    - Lines joining values for illustration only
  - m cannot be negative (obviously)
  - Thus distribution is lop-sided for small N
  - More symmetric for large N
  - For our purposes, N is almost always large (>10)
- For large N, distribution is ~ normal with variance = N

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-x^2}{2\sigma^2}} \quad \Rightarrow \quad f(m) \approx \frac{1}{\sqrt{2\pi N}} e^{\frac{-m^2}{2N}}$$

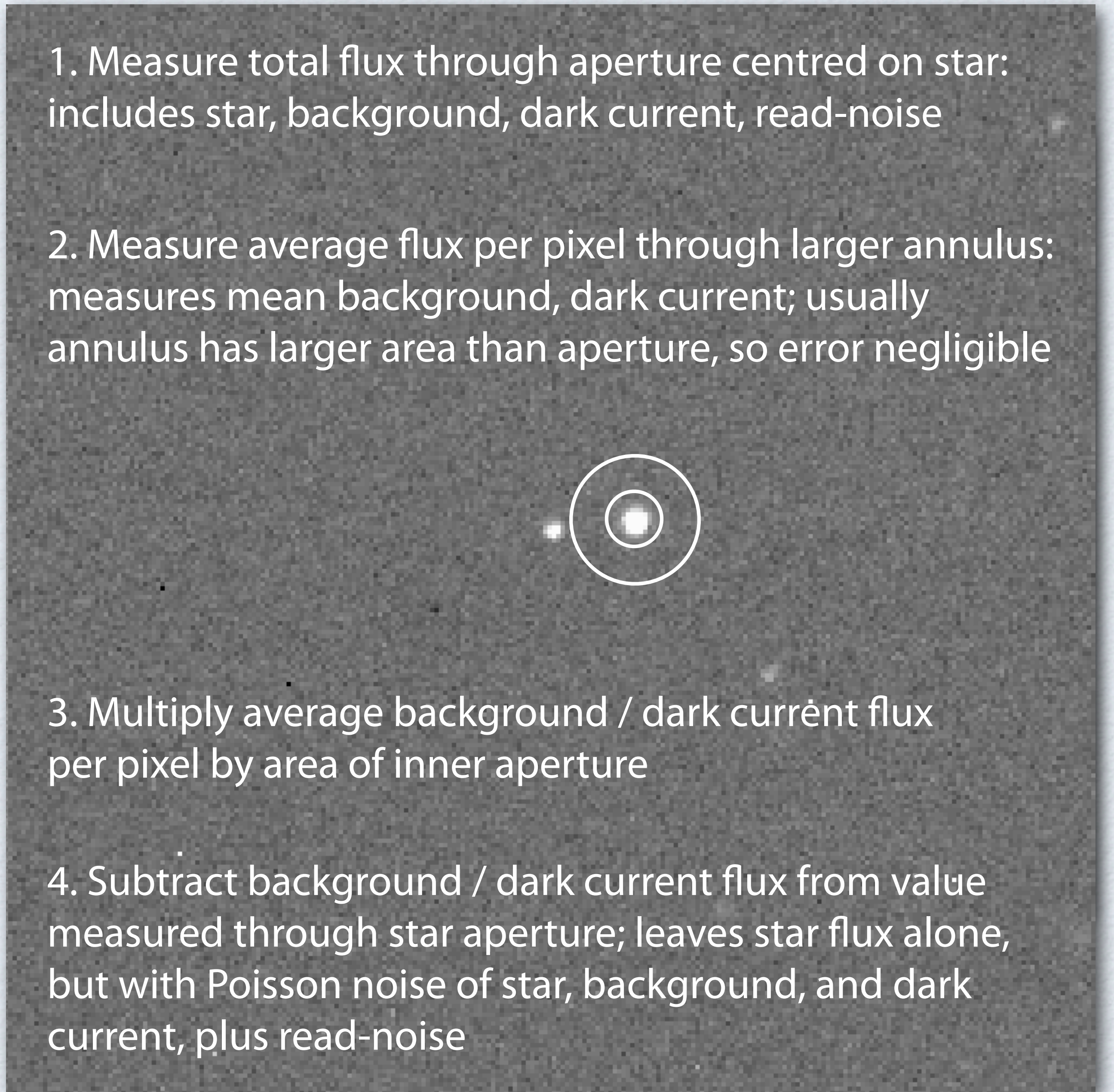
Normal distribution — Poisson distribution for large N

- Variance = σ^2, thus standard deviation σ (or "noise") of a Poisson distribution with mean counts $N = \sqrt{N}$

Poisson distribution (IV)

- Important!
  - Poisson statistics apply to the individual uncorrelated events actually registered in given time window
- Basic infrared array detector operation
  - Incoming photon flux impinges on a pixel
  - Some fraction converted into electrons
  - Proceed to collect electrons for given integration time
  - Cumulative charge creates voltage on pixel
  - On read-out, voltage converted to counts by A/D converter
  - Counts may be coadded over large number of integrations
- At which point do Poisson statistics get applied?
- Answer:
  - Number of electrons collected per integration time

Application to signal-to-noise calculations



1. Measure total flux through aperture centred on star: includes star, background, dark current, read-noise

2. Measure average flux per pixel through larger annulus: measures mean background, dark current; usually annulus has larger area than aperture, so error negligible

3. Multiply average background / dark current flux per pixel by area of inner aperture

4. Subtract background / dark current flux from value measured through star aperture; leaves star flux alone, but with Poisson noise of star, background, and dark current, plus read-noise

Calculating astronomical S/N (I)

- Stellar flux: F photons s^{-1} m^{-2}
- Stellar aperture area: M pixels
  - πR^2 where R is radius of aperture in pixels
- Background flux: G photons s^{-1} m^{-2} $pixel^{-1}$
  - Assume well-measured over large annulus; assume error-less
- Dark current: I_D e^- s^{-1} $pixel^{-1}$
  - Negligible for imaging; can be important in spectroscopy
- Read-noise: R_N e^- $pixel^{-1}$
  - Typically measured in calibration experiment
- System throughput η
  - Detector QE x (optical & atmospheric transmission)
- Integration time: t seconds
- Diameter of telescope: D m; Area A m^2

Calculating astronomical S/N (II)

- Measured stellar signal (in e^-) in stellar aperture:

$$S = \eta \mathrm{AFt}$$

- Measured background signal (in e^-) in aperture:

$$B = \eta \mathrm{AGMt}$$

- Measured dark current signal (in e^-) in aperture:

$$D = I_D \mathrm{Mt}$$

- Total signal (in e^-) giving rise to Poisson noise:

$$S + B + D = [\eta A(F + GM) + I_D M]\, t$$

Calculating astronomical S/N (III)

- Poisson noise due to star, background, dark current:
  - Simply √ of total signal

$$= \sqrt{[\eta A(F + GM) + I_D M]\, t}$$

- Read-noise over stellar aperture (e^- RMS):
  - Uncorrelated pixel-to-pixel: adds in quadrature over no. pixels

$$= \sqrt{M} R_N$$

- Total noise added in quadrature:
  - Standard way of adding uncorrelated noise terms

$$= \sqrt{[\eta A(F + GM) + I_D M]\, t + M R_N^{\,2}}$$

Calculating astronomical S/N (IV)

- Therefore, signal-to-noise:

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{[\eta A(F + GM) + I_D M]\,t + M R_N{}^2}}$$

- When F is large (bright star; "source noise limited" case):
  - Background, dark current, and read-noise terms negligible

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{\eta AFt}} = \sqrt{\eta AFt}$$

  - Thus doubling S/N requires:
    - 4 x integration time
    - 4 x collecting area

Read-noise limited case

- Full signal-to-noise:

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{[\eta A(F + GM) + I_D M]\, t + M R_N{}^2}}$$

- When F and G small (very low background):
  - Stellar & background shot noise, dark current terms negligible

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{M} R_N}$$

  - e.g. narrow-band imaging of faint sources or spectroscopy
  - Here, doubling S/N requires:
    - 2 x integration time
    - 2 x collecting area
    - 2 x smaller R_N

Background-limited case

- Full signal-to-noise:

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{[\eta A(F + GM) + I_D M]\, t + MR_N{}^2}}$$

- When F is small but G large (bright background):
  - Stellar shot noise, dark current, read-noise terms negligible

$$\frac{S}{N} = \frac{\eta AFt}{\sqrt{\eta AGMt}} = \sqrt{\eta At}\,\frac{F}{\sqrt{GM}} = \frac{S}{\sqrt{B}}$$

  - Typical for broad-band imaging of faint sources
  - Here, doubling S/N requires:
    - 4 x integration time
    - 4 x collecting area
    - 4 x lower background

The case for big, cold telescopes

- For faint sources in the background-limit, we have:

$$\frac{S}{N} = \sqrt{\eta A t}\frac{F}{\sqrt{GM}} \quad \Rightarrow \quad t = \left(\frac{S}{N}\right)^2 \frac{1}{\eta A}\frac{GM}{F^2}$$

- Thus time required to reach some given sensitivity

$$\propto \frac{1}{A} \quad \Rightarrow \quad \propto \frac{1}{D^2}$$

  - and $\propto GM$

- Thus maximising sensitivity of telescope requires:
  - Maximising telescope diameter D
  - Reducing background G as much as possible
    - i.e. get above atmosphere and make telescope cold
  - Reducing number of pixels M covered by source
    - Equivalent to reducing area covered by each pixel on sky

Reducing the area subtended by source

- Have assumed constant image size (FWHM θ)
  - ~ true for seeing-limited observations
- What happens if θ is made smaller by factor of 2?
  - Can make pixels smaller by factor 2
  - Reduces area of pixel by factor 4
  - Collect same amount of starlight from point source
  - But only 1/4 of background
- In background-limited case

$$\frac{S}{N} = \frac{S}{\sqrt{B}} \quad \Rightarrow \quad \frac{S}{N} \propto \frac{1}{\theta}$$

  - and $t \propto \theta^2$
  - Thus improving spatial resolution reduces integration time required for point sources

Impact of improved spatial resolution

- If diffraction-limited resolution can be achieved:
  - Using adaptive optics on ground or going into space
  - Dependence of image size θ on telescope diameter D and wavelength λ:

$$\theta\text{ (radians)} = 1.22\,\frac{\lambda\text{ (metres)}}{\text{D (metres)}} \quad\Rightarrow\quad \theta\text{ (arcsec)} = 0.25\,\frac{\lambda\text{ (microns)}}{\text{D (metres)}}$$

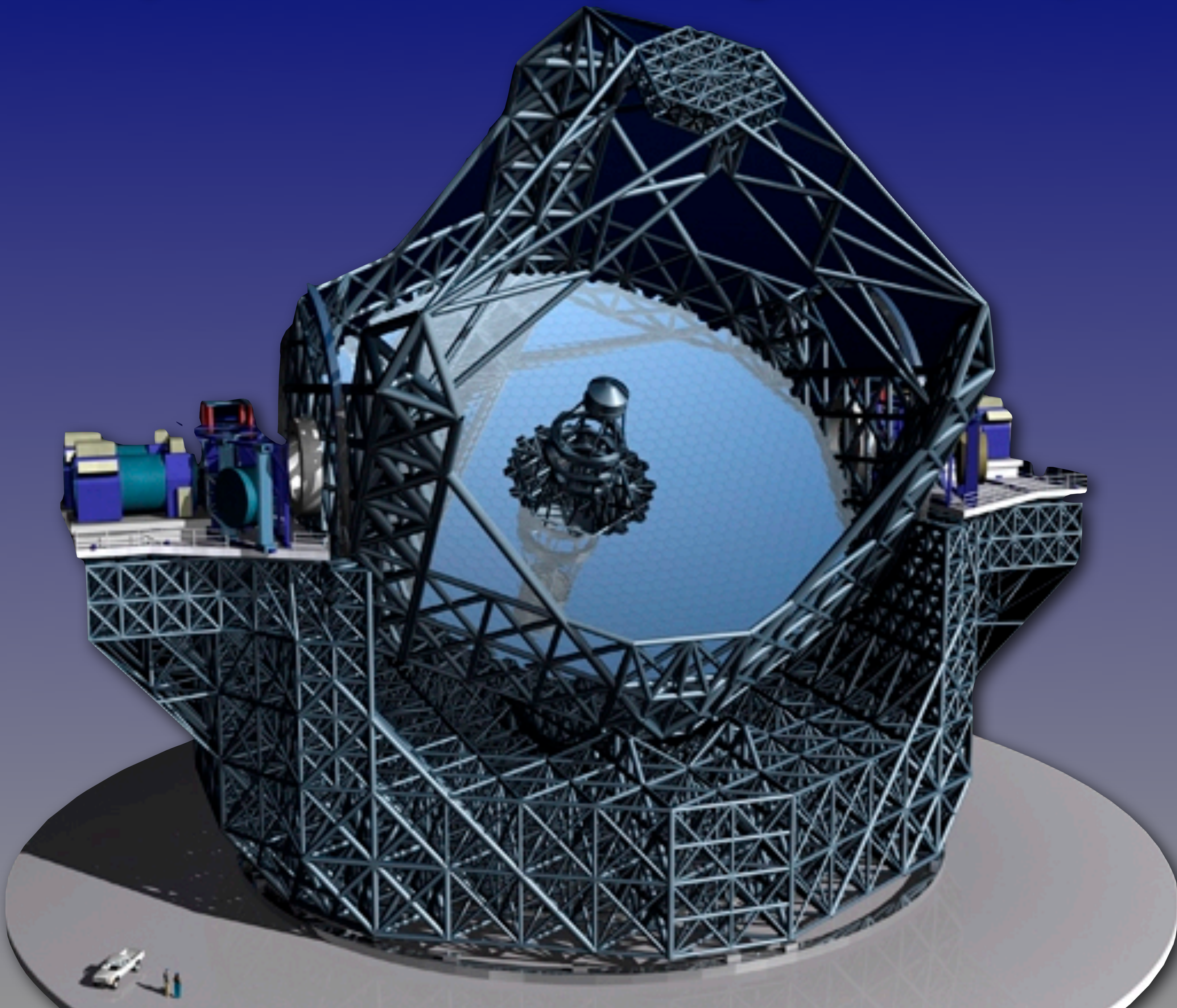
- Thus $\theta \propto \frac{1}{D} \quad\Rightarrow\quad \theta^2 \propto \frac{1}{D^2} \quad\Rightarrow\quad t \propto \frac{1}{D^2}$

- Therefore, combined time required to reach given S/N:
  - For diffraction-limited, background-limited point source

$$t \propto \underbrace{\frac{1}{D^2}}_{\text{Diffraction limited}} \times \underbrace{\frac{1}{D^2}}_{\text{Background limited}} \quad\Rightarrow\quad t \propto \frac{1}{D^4}$$

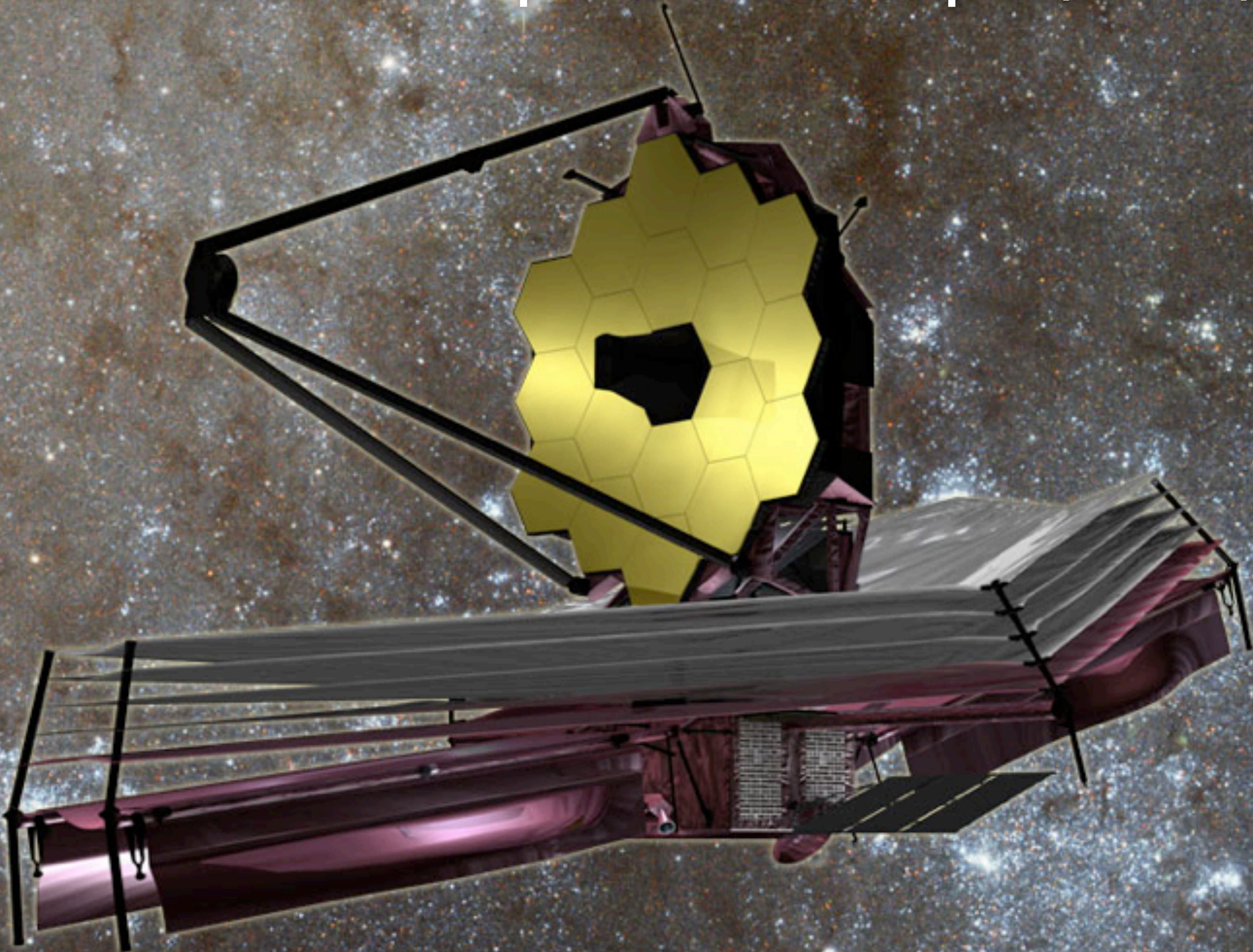
Thus big telescopes good, big cold telescopes better!

European Extremely Large Telescope



ESO

James Webb Space Telescope (2013)

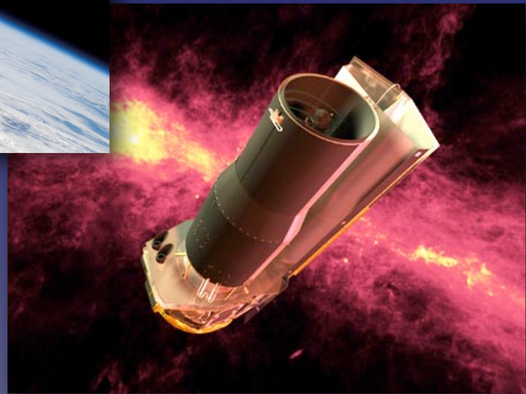


NORTHROP GRUMMAN
Space Technology

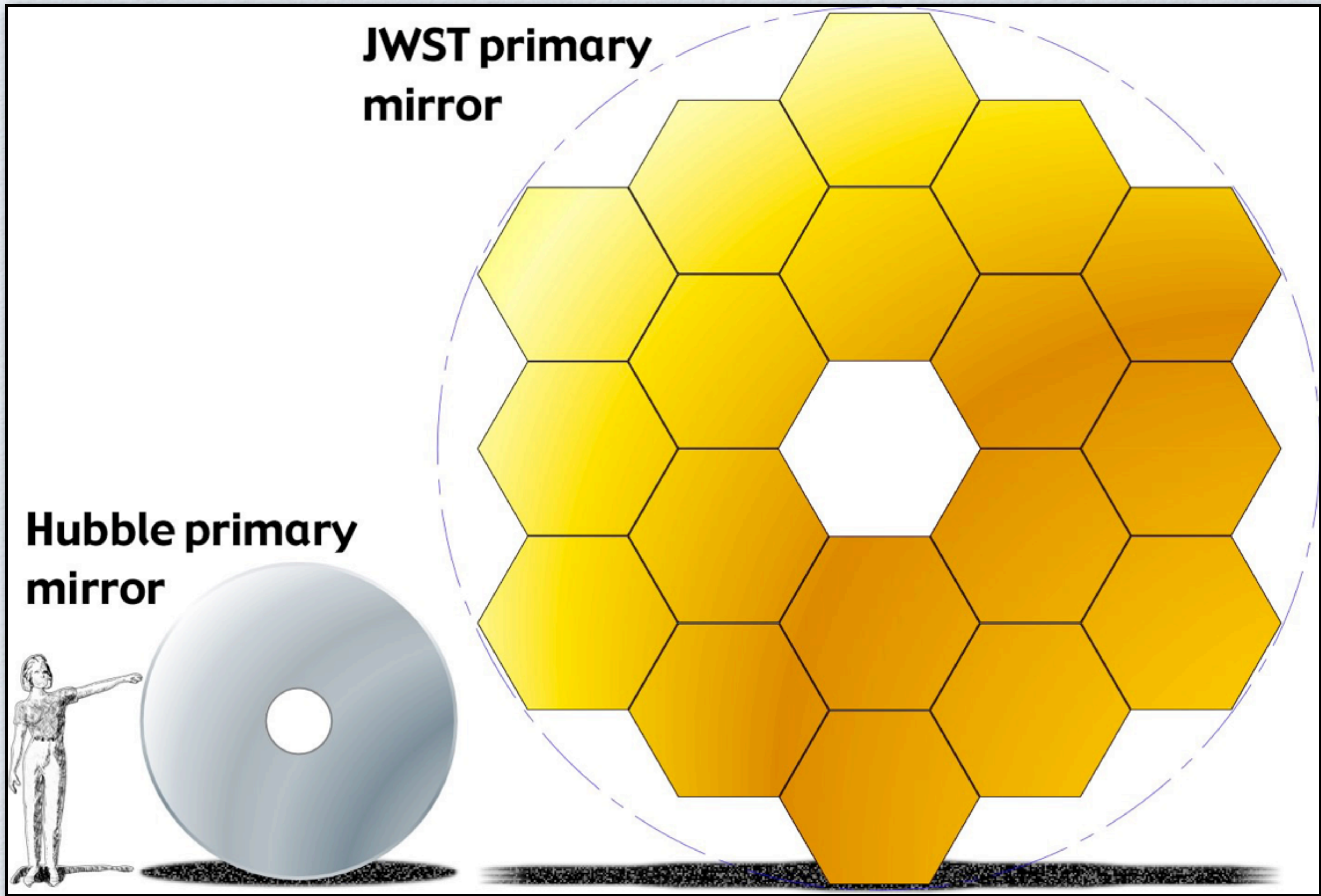
An overview of the JWST

- 6.5m deployable primary
- Diffraction-limited at 2μm
- Wavelength range 0.6-28μm
- Sun-Earth L2 orbit
- 4 instruments
  - 0.6-5μm wide field camera (NIRCam)
  - 1-5μm multiobject spectrometer (NIRSpec)
  - 5-28μm camera/spectrometer (MIRI)
  - 1-5μm fine guidance sensor / tunable filter imager (FGS/TFI)
- Passive cooling of telescope to <50K
- NIRCam/NIRSpec/TFI passively cooled to 30K; MIRI actively to 7K
- 5 year lifetime requirement, 10 year goal
- June 2013 launch on Ariane 5 ECA
- Total budget (NASA, ESA, CSA, incl. 5 years operations): $5 billion

Natural successor to HST & Spitzer

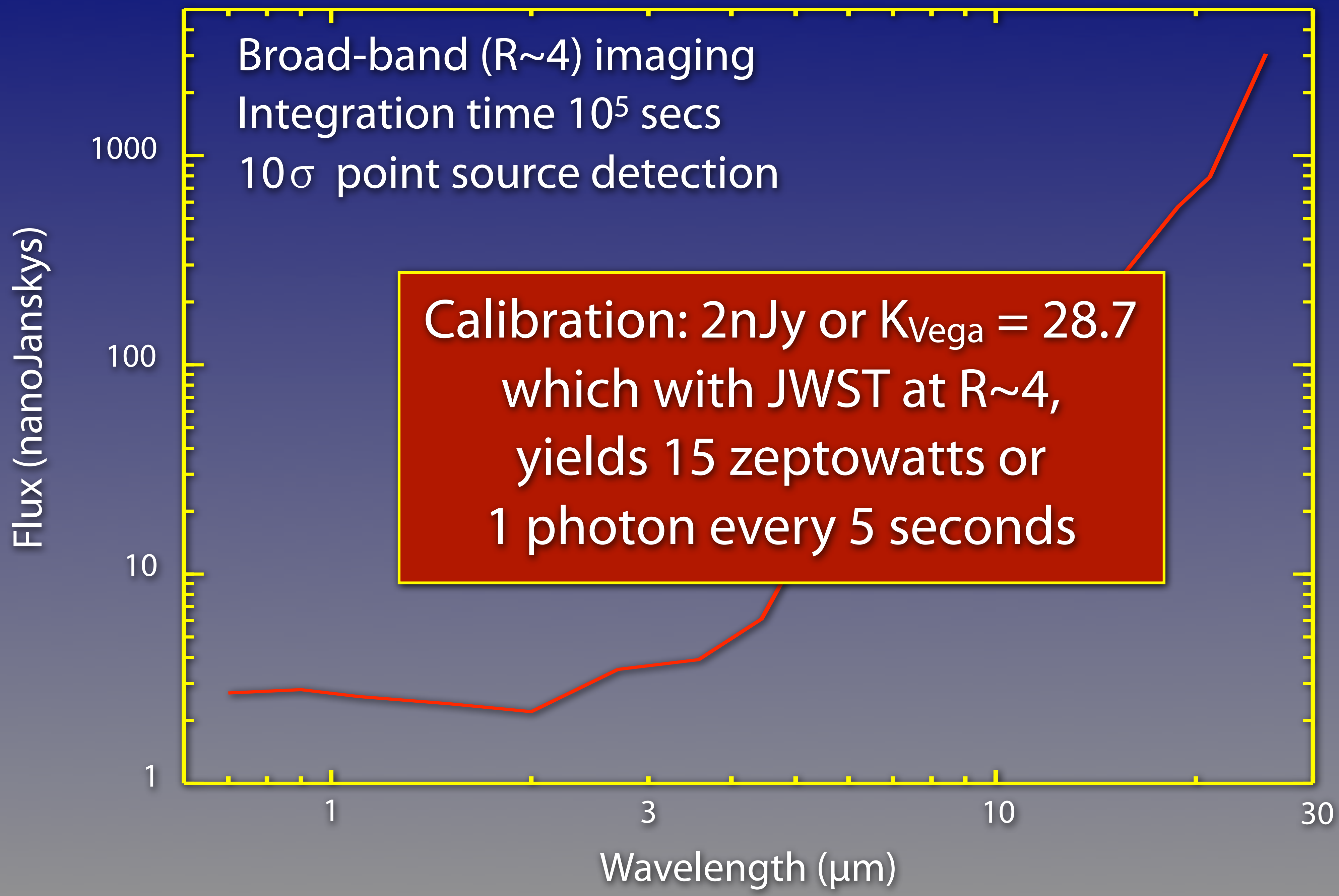


JWST: 7x area & 2.5x resolution of HST



NASA / STScI

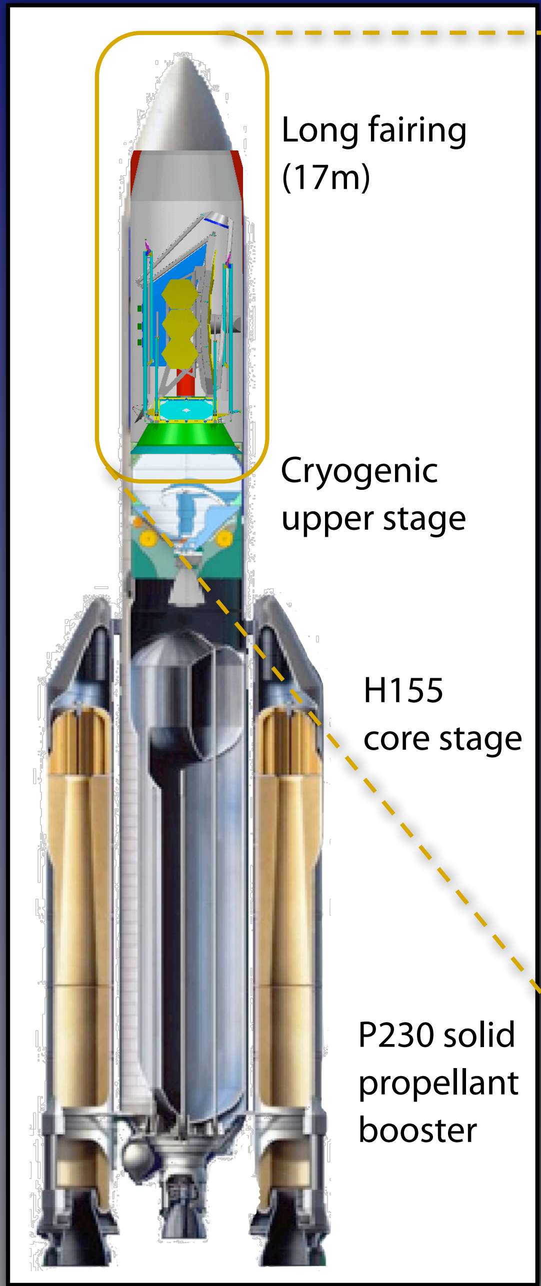
The extraordinary sensitivity of the JWST

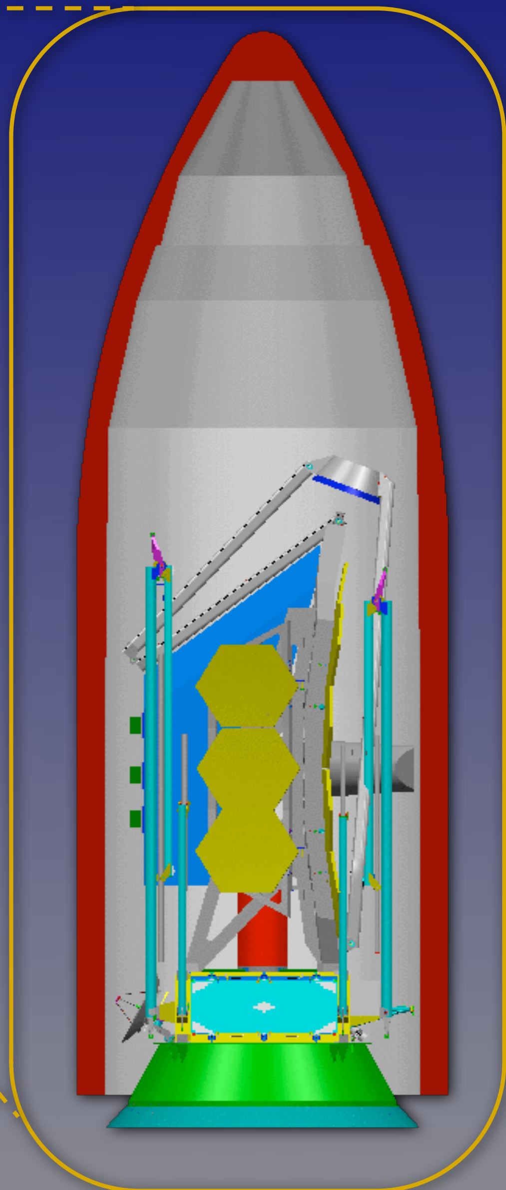


JWST star and planet formation goals

- Trace deeply embedded phases of star formation
  - Clouds → cores → protostars
- Investigate extreme ends of the Initial Mass Function
  - Formation and impact of massive stars
  - Substellar IMF to planetary masses
- Examine the epoch of planet building
  - Development of protoplanets in young disks
- Follow astrochemical evolution
  - Processing of gas, dust, & ice in cores, protostars, & disks
- Extend isolated paradigm to clustered, competitive star formation in a wide range of environments
  - Good match to goals of CONSTELLATION

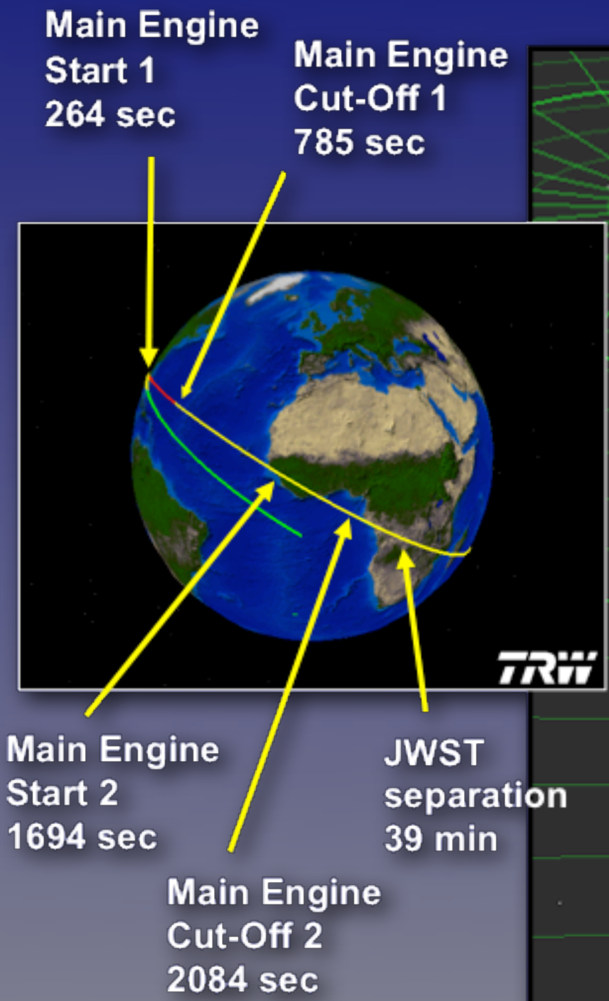
Ariane 5 ECA launch from Kourou to L2

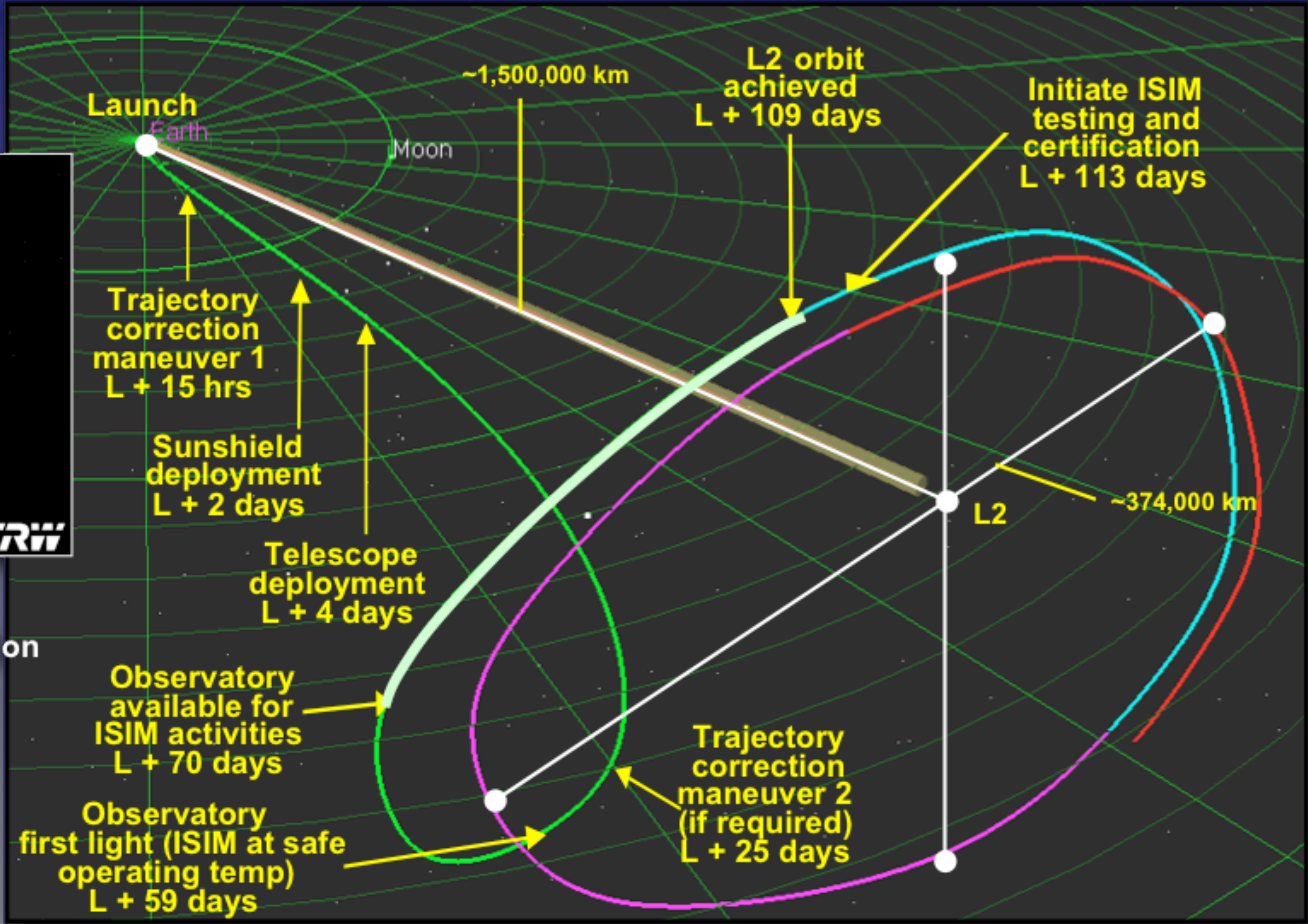




Stowed configuration

Trajectory to L2





JWST

JAMES WEBB SPACE TELESCOPE

2008 Spacecraft Deployment Animation

NASA

NORTHROP GRUMMAN

Summary

- Key questions to be answered in star & planet formation
  - What is the origin of the stellar mass distribution? Is it universal?
  - What is the impact of feedback locally and globally?
  - How do disks turn into planetary systems?
- Infrared astronomy has a key role to play
  - Greatly improved IR (& mm) sensitivity & spatial resolution needed
- Fortunately, the next decade will bring those resources