(Some) basics of astronomical observations and data processing

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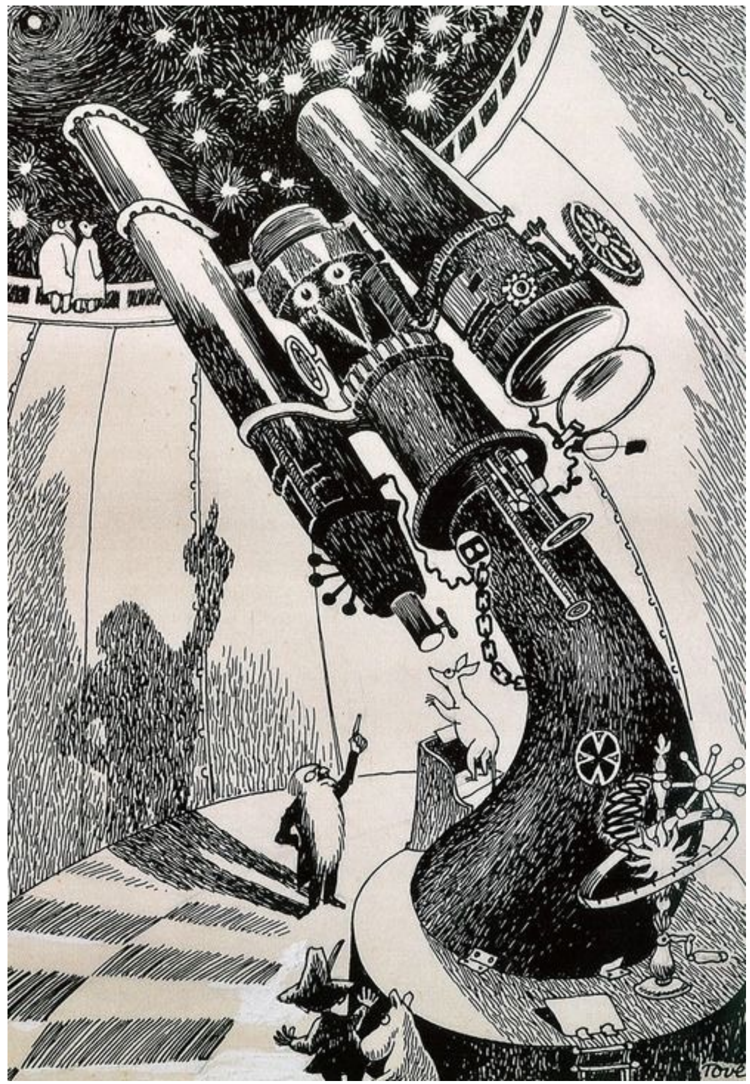
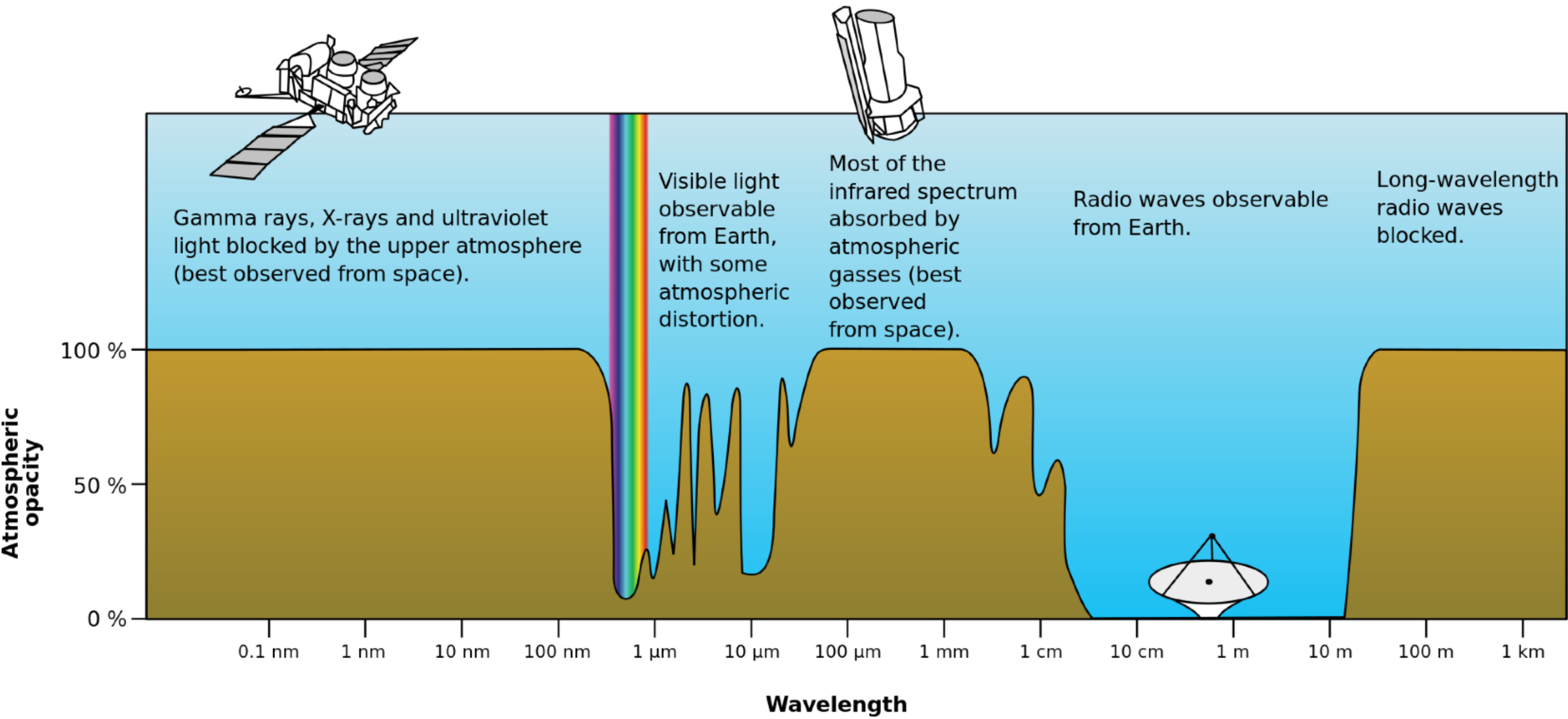


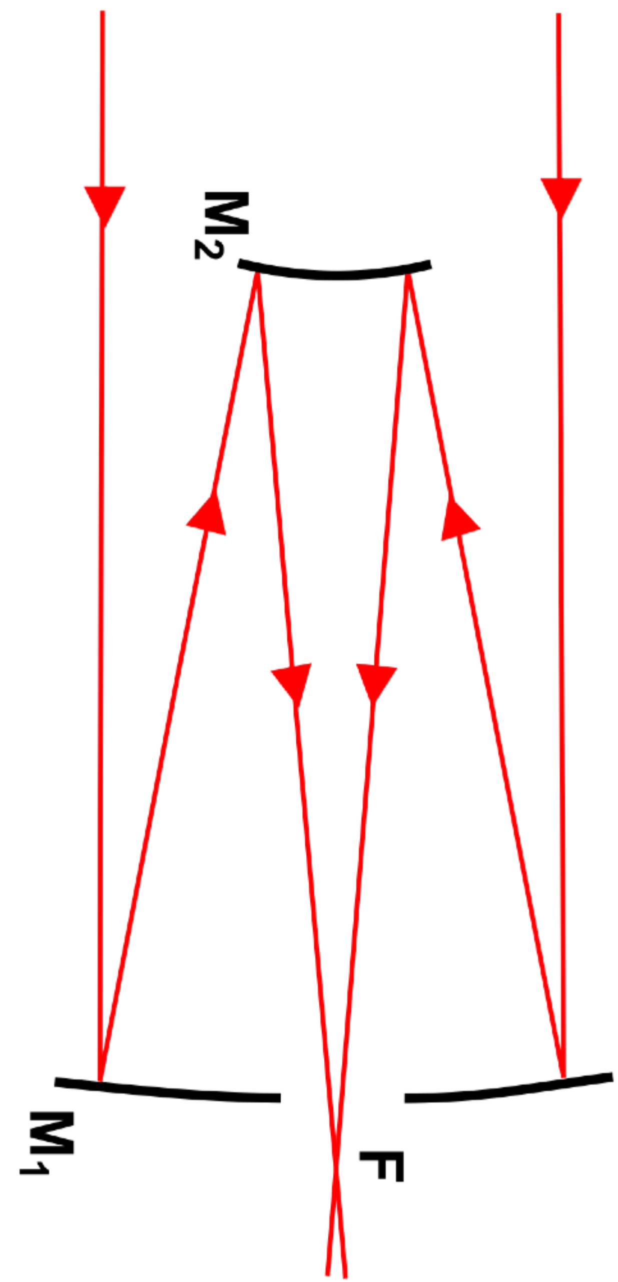
Tove Janson, 1946

Astronomical observations



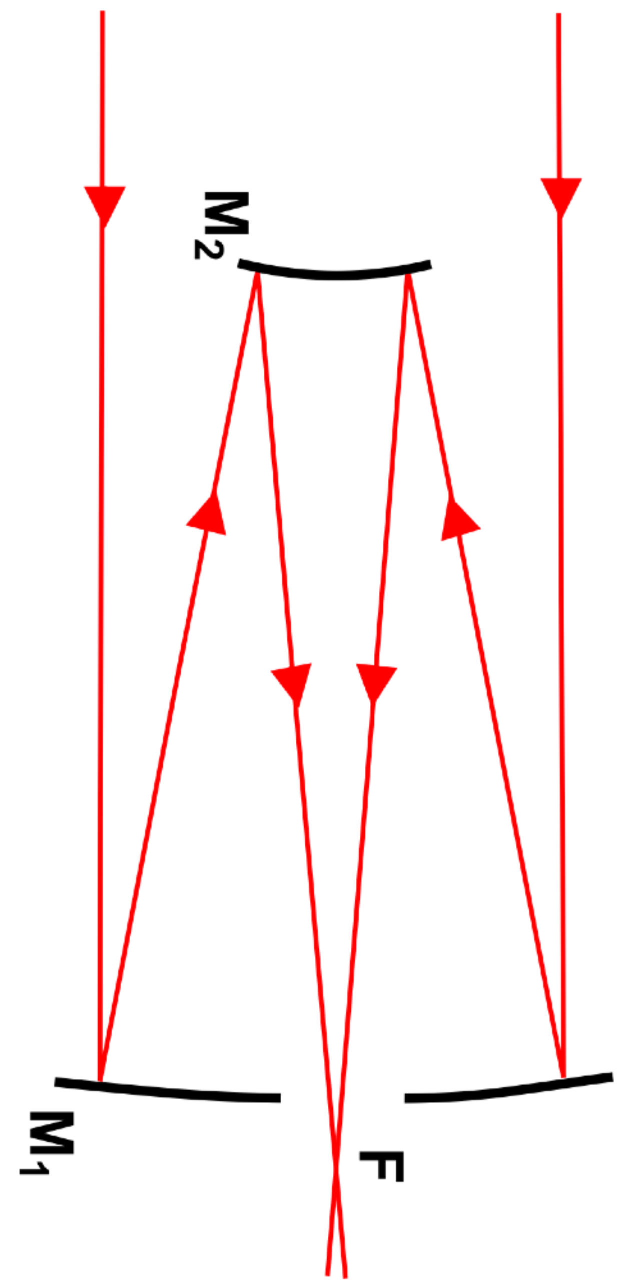
Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

Telescopes and astronomical instrumentation



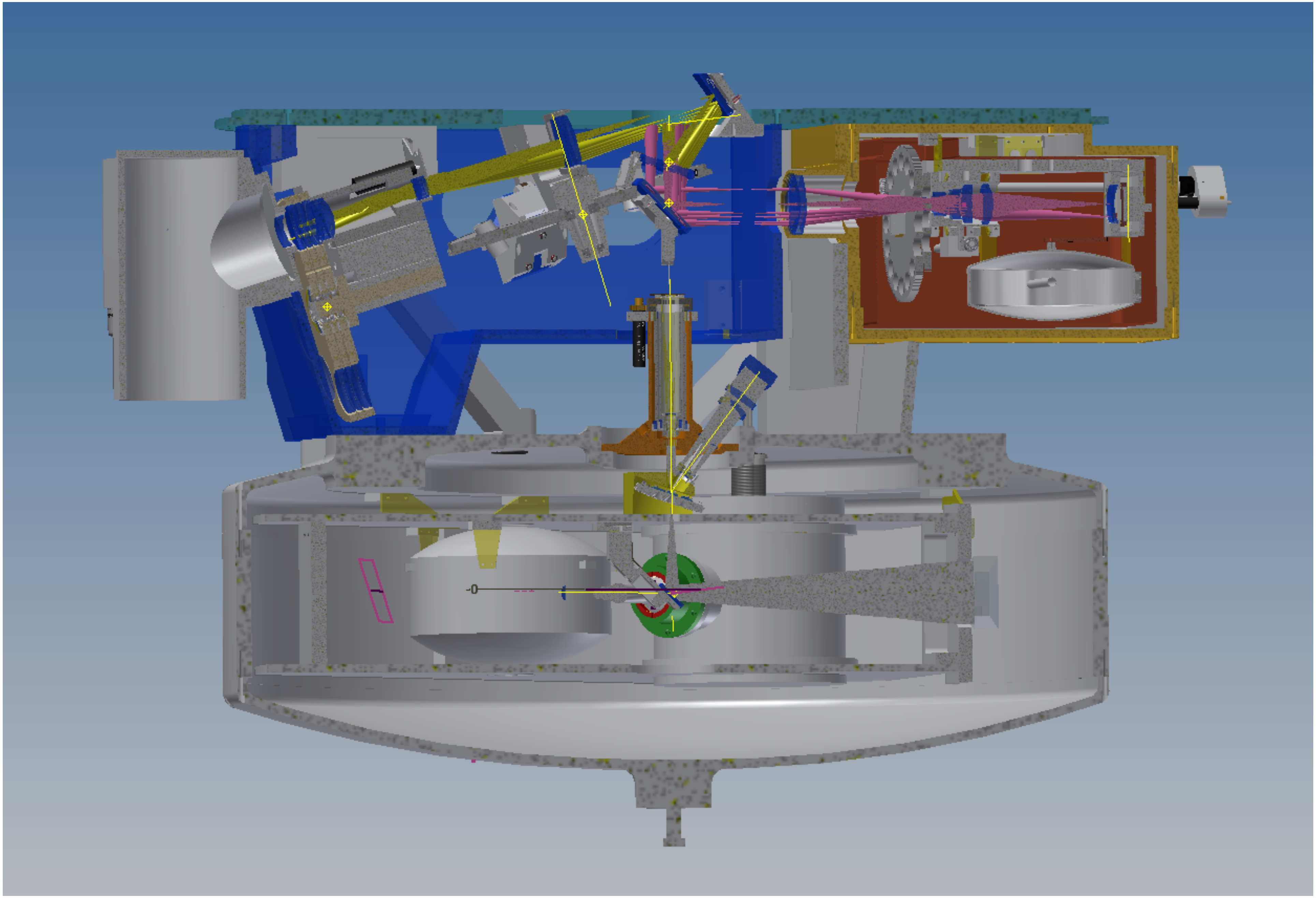
Nordic Optical Telescope, La Palma, Canary Islands

Telescopes and astronomical instrumentation



Nordic Optical Telescope, La Palma, Canary Islands

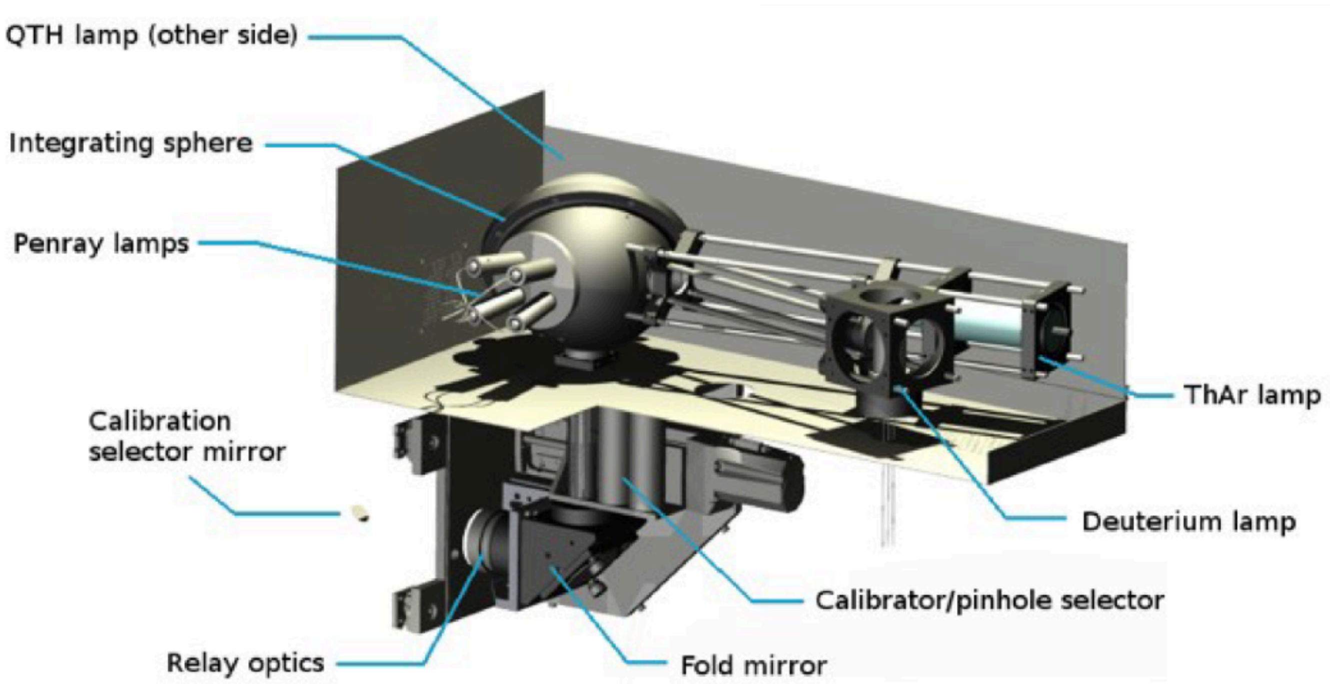
Telescopes and astronomical instrumentation



The Nordic Transient Explorer (NTE) being built by the Niels Bohr Institute

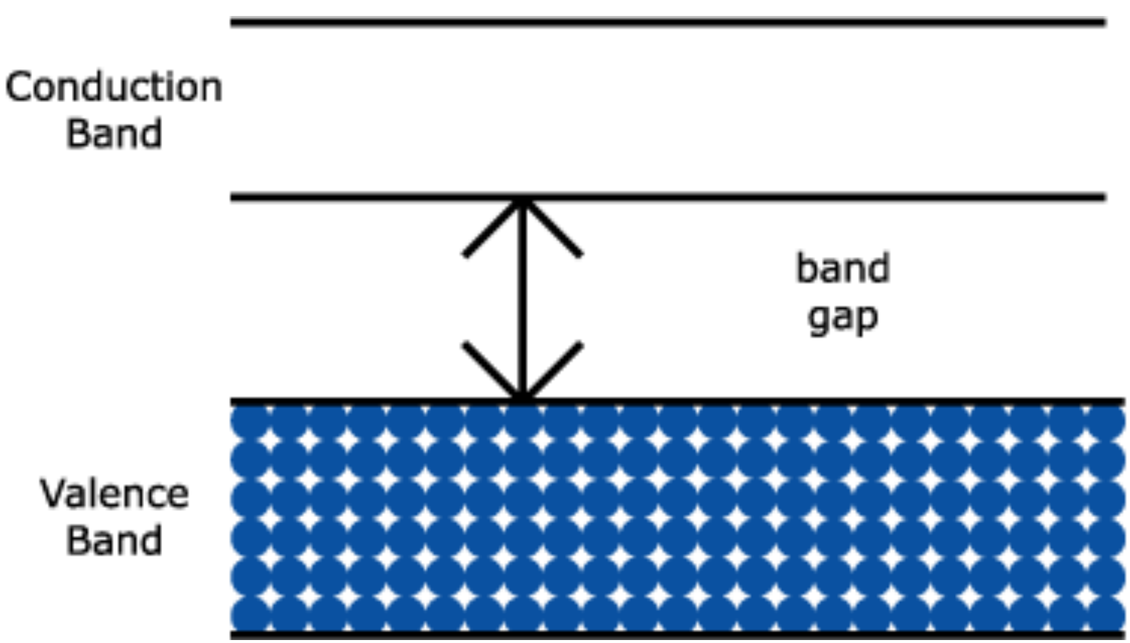
Astronomical instrumentation

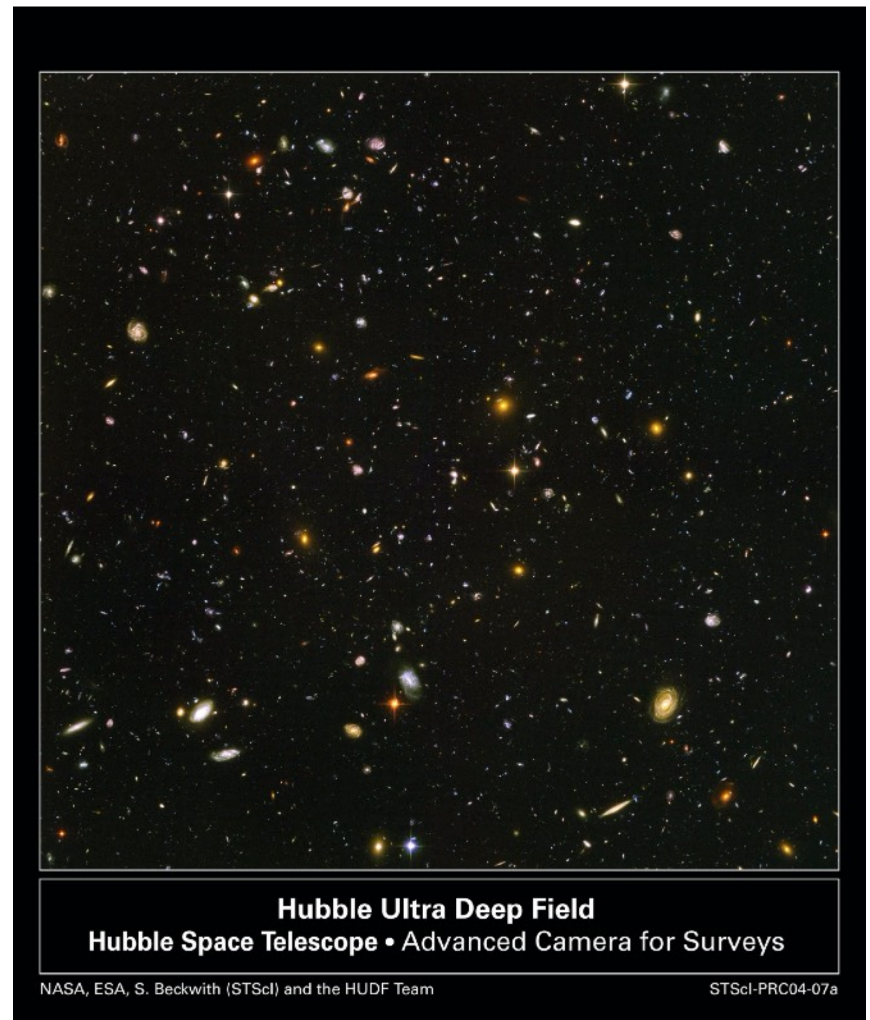
- Astronomical instruments purpose-built by large international consortia
- Instrumentation projects typically require several years for the design and construction as a part of a large group of researchers and engineers
- Cost typically several MEur - can be compensated by the observatories by guaranteed time observations (GTO) time available for the consortium



Basic principles of a charge-coupled device (CCD)

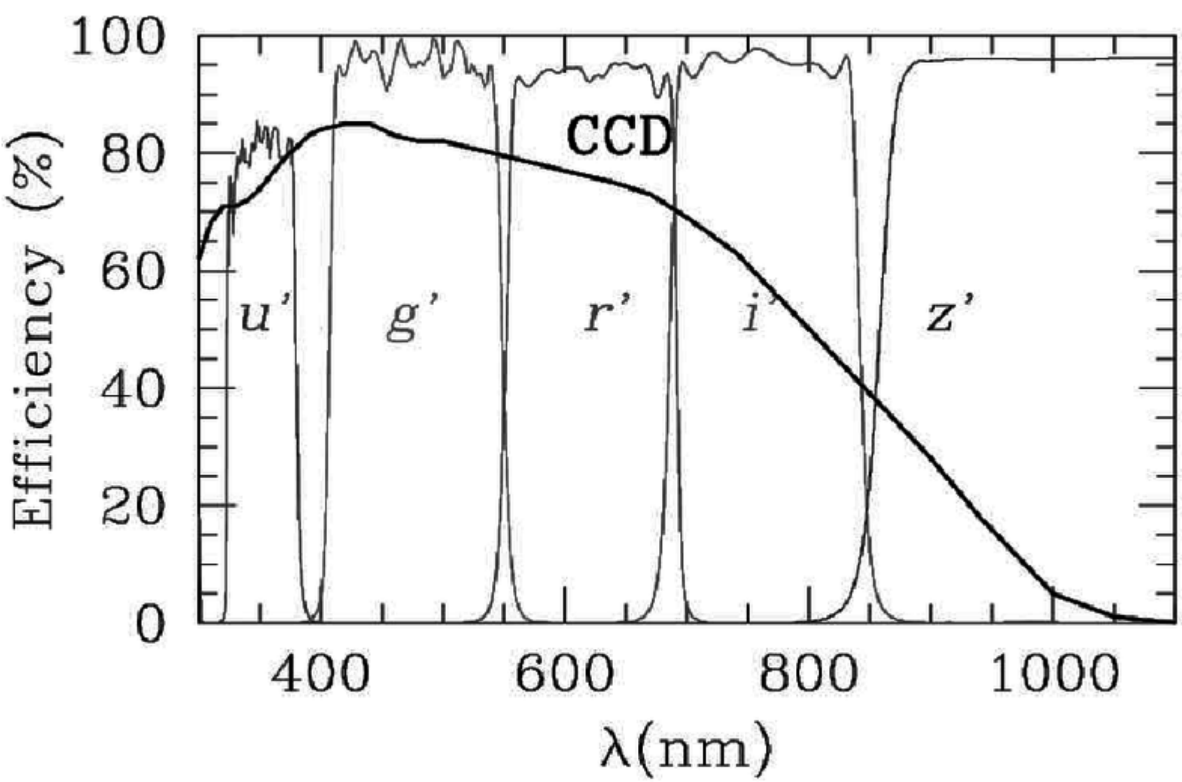
- Photoelectric effect – silicon exhibits an energy gap between the valence and conduction bands
- Incoming photons with a suitable energy interact with the Si atoms and excite valance electrons into the the conduction band
- An electric field applied for capturing the free electrons, this way a CCD detector can collect a large number of photons
- Typical arrays: 2048 x 2048, or 4096 x 4096





Astronomical imaging observations

- Determine the brightness (photometry), positions (astrometry) and structure of astronomical objects, detect new objects
- Use filters to select a certain wavelength range and repeat the imaging in multiple filters to determine the colours of the object
- Use CCD detector (or other semiconductors) to record the light

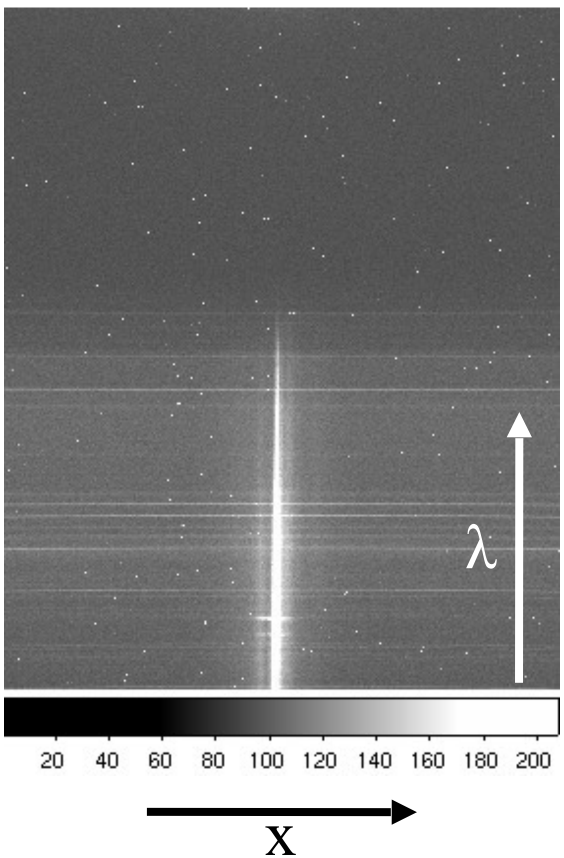


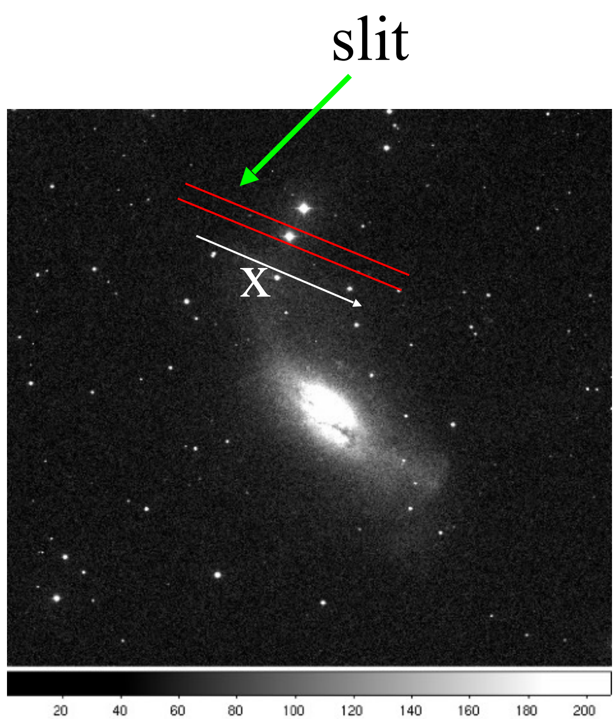
The Cosmic Bird

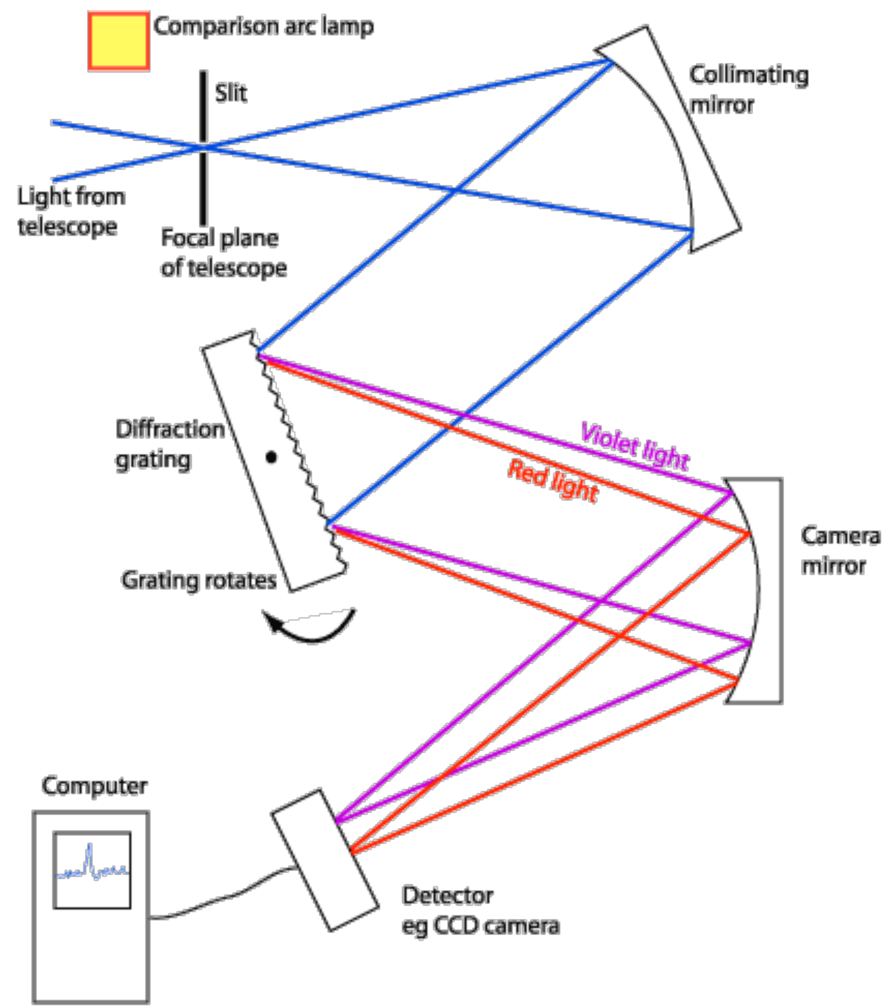
ESO Press Photo 54a/07 (21 December 2007)

Astronomical spectroscopic observations

• Determine the flux density as a function of wavelength (spectral energy distribution, spectral lines, physical conditions, velocities etc.)
• Use a mask with a narrow aperture (slit) to cut the 2D image to 1D
• Use a diffraction grating (or a grism) to disperse the incident light beam into spectrum
• Spectrographs use an imaging device (CCD) to record the dispersed light



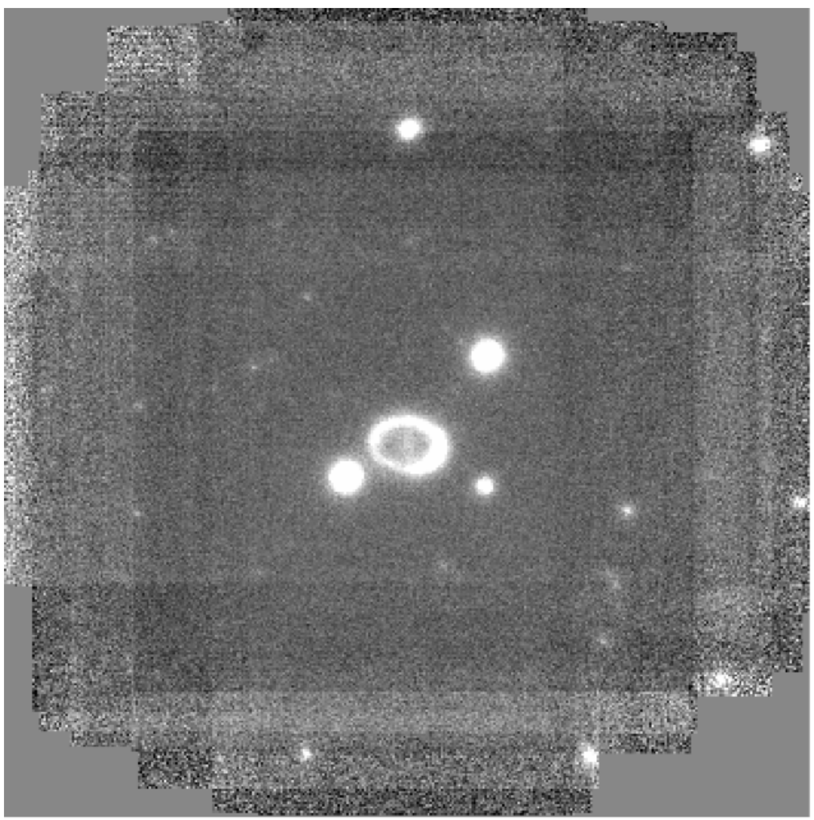




Astronomical data format

Flexible Image Transport System (FITS)

- Standard format in astronomy > 30 yr
- ASCII header with keyword/value pairs
- Pixel data without any compression
- Multidimensional arrays for 3D+ cubes
- Not proprietary / open format, large number of viewers, editors, libraries
- Adopted by the Vatican Library for the long-term digital preservation of material



Downloads — mattila@tuorla12-astro: ~ — more naco_img_jitter_0002.fits — 80×...

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                  -32 / number of bits per data pixel
NAXIS   =                    2 / number of data axes
NAXIS1  =                 1471 / length of data axis 1
NAXIS2  =                 1473 / length of data axis 2
EXTEND  =                    T / FITS dataset may contain extensions
COMMENT   FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT   and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
DATE    = '2015-11-29T21:32:04' / file creation date (YYYY-MM-DDThh:mm:ss UT)
EXPTIME =                  90. / Integration time
AIRMASS =                   1. / Averaged air mass (Recalculated)
ALARM   = '        '           / Active alarm(s), if any.
ORIGIN  = 'ESO-PARANAL'        / European Southern Observatory
TELESCOP= 'ESO-VLT-U4'         / ESO Telescope Name
INSTRUME= 'NAOS+CONICA'        / Instrument used
OBJECT  = 'SN1987A_Ks'         / Target description
RA      =                  83. / 05:35:27.9 RA (J2000) pointing (deg)
DEC     =                 -69. / -69:16:11.1 DEC (J2000) pointing (deg)
EQUINOX =                2000. / Standard FK5 (years)
RADECSYS= 'FK5     '           / Coordinate reference frame
MJD-OBS =               55479. / Obs start 2010-10-10T08:12:44.708
DATE-OBS= '2010-10-10T08:12:44.7081' / Observing date
UTC     =               29563. / 08:12:43.000 UTC at start (sec)
LST     =               17185. / 04:46:25.545 LST at start (sec)
PI-COI  = 'UNKNOWN '           / Name(s) of proposer(s)
OBSERVER= 'UNKNOWN '           / Name of observer
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DATAMD5 = 'd4a2475e9288771a5e941cb4e84e2c58' / MD5 checksum
PIPEFILE= 'naco_img_jitter.fits' / Filename of data product
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HIERARCH ESO OBS OBSERVER = 'UNKNOWN ' / Observer Name
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HIERARCH ESO OBS PROG ID = '086.D-0713(D)' / ESO program identification
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HIERARCH ESO TEL AIRM START = 1. / Airmass at start
HIERARCH ESO TEL ALT =     44. / Alt angle at start (deg)
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HIERARCH ESO TEL AMBI PRES START = 741. / Observatory ambient air pressure q
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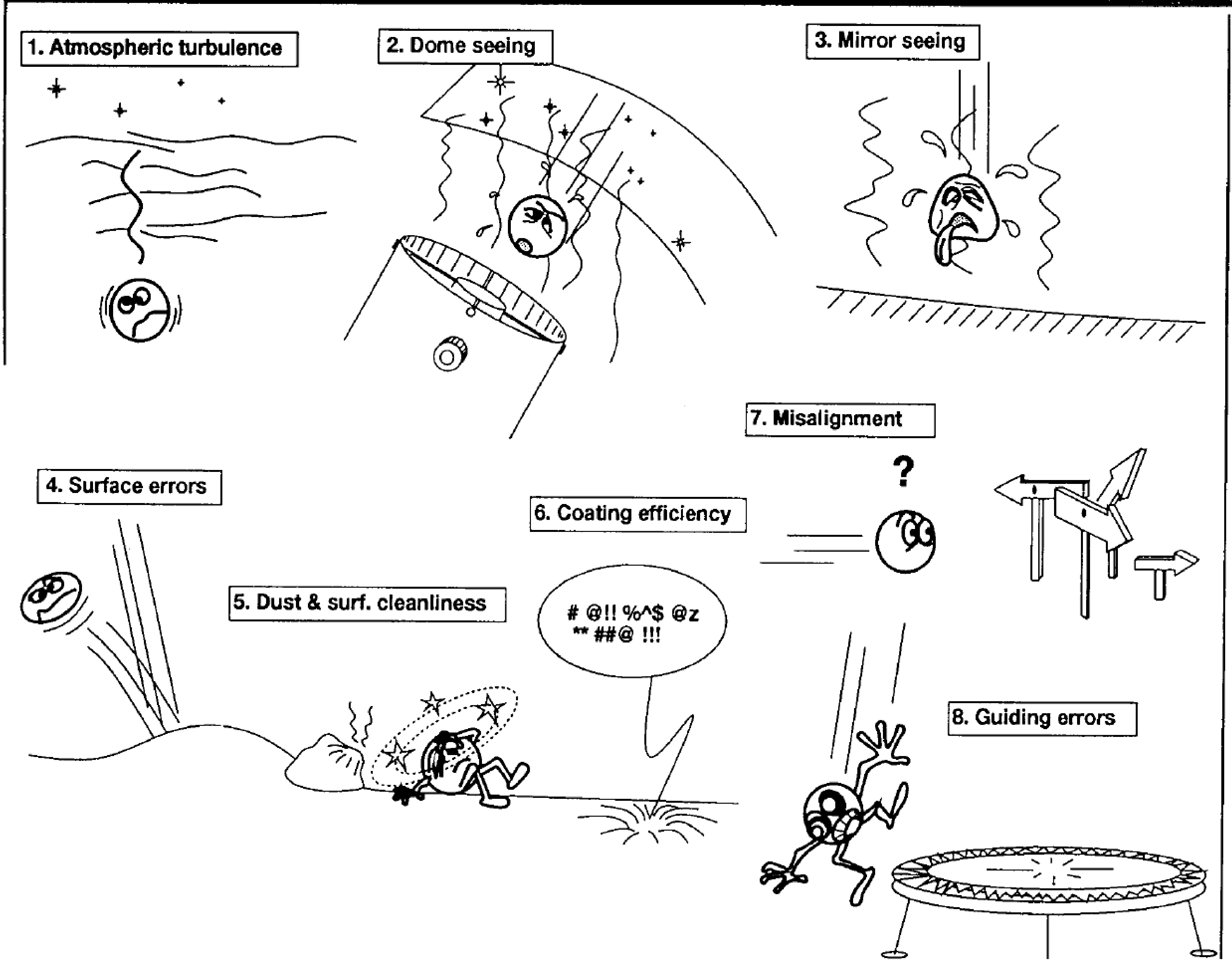
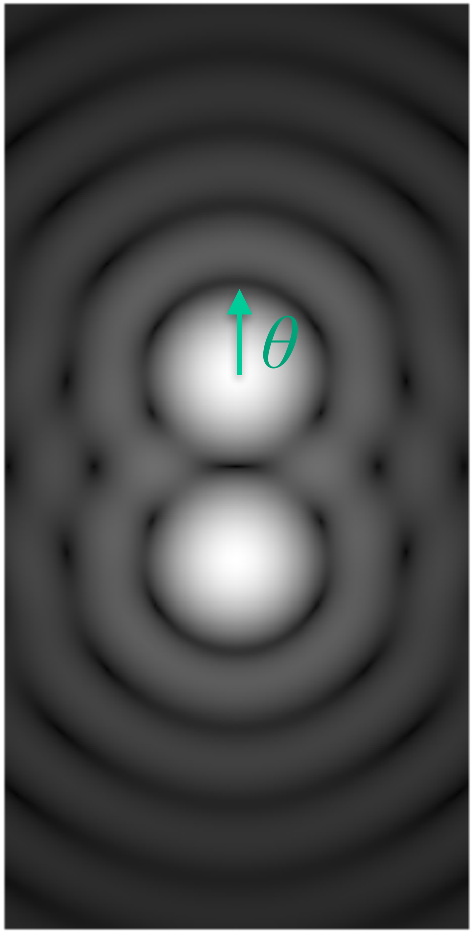
The quality and calibration of astronomical observations

THE HAZARDS OF A PHOTON'S LIFE



well resolved



$$F(u,v) = \mathrm{FT}\{f(x,y)\}$$

i.e.,

$$F(u,v) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y) \exp[2\pi i(ux+vy)]\, dx\, dy$$

Linearity

$$\mathrm{FT}\{f(x,y) + g(x,y)\} = F(u,v) + G(u,v)$$

Convolution

$$\mathrm{FT}\{f(x,y) \star g(x,y)\} = F(u,v) \cdot G(u,v)$$

Shift

$$\mathrm{FT}\{f(x - x_i, y - y_i)\} = F(u,v)\ \exp[2\pi i(ux_i + vy_i)]$$

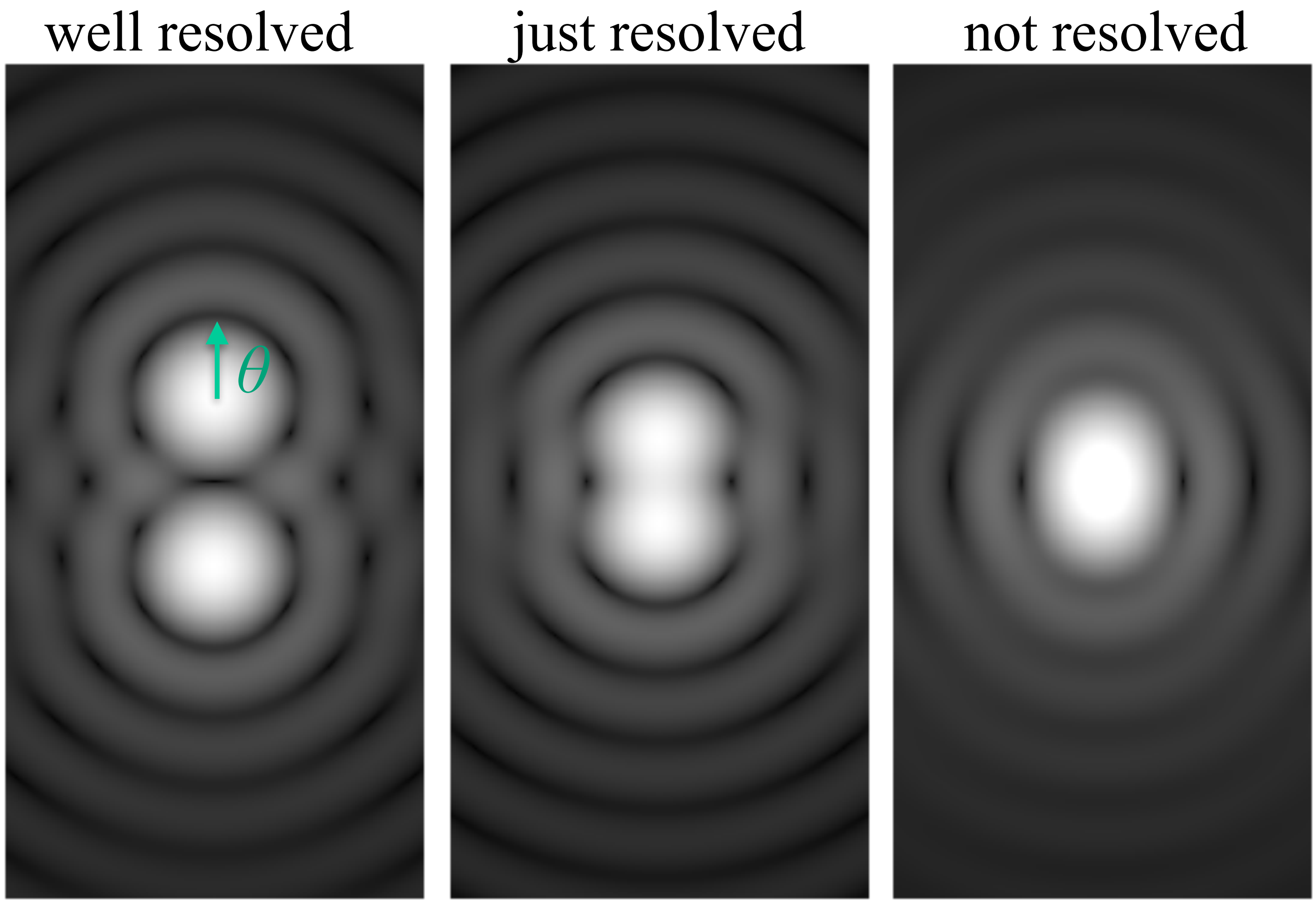
Similarity

$$\mathrm{FT}\{f(ax, by)\} = \frac{1}{|ab|} F\left(\frac{u}{a}, \frac{v}{b}\right)$$

For a telescope aperture the diffraction pattern can be obtained from a 2-dimensional **Fourier transform** of the **pupil function** that describes the aperture shape and wave-front aberrations. Can show for the angular size θ of the first minimum of the **diffraction pattern**

$$\sin\theta \sim \theta = 1.22\ \lambda\, /\, D \text{ [rad]}$$

where λ is the wavelength of the observation and D the telescope's diameter



For a telescope aperture the diffraction pattern can be obtained from a 2-dimensional **Fourier transform** of the **pupil function** that describes the aperture shape and wave-front aberrations. Can show for the angular size θ of the first minimum of the **diffraction pattern**

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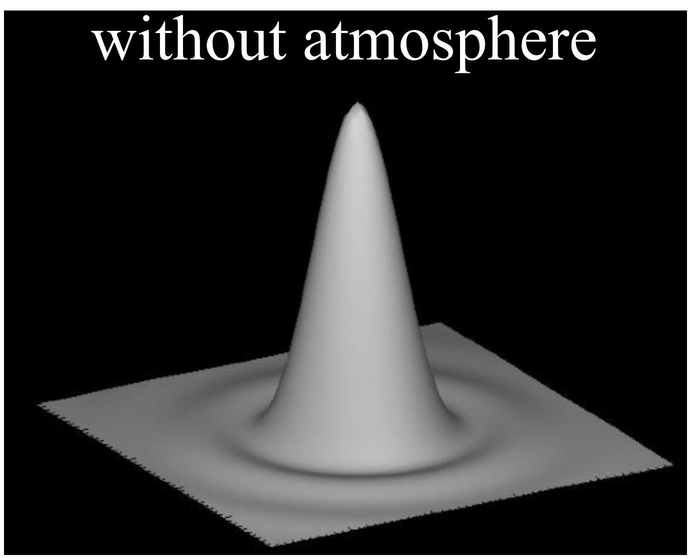
Point spread function (PSF)

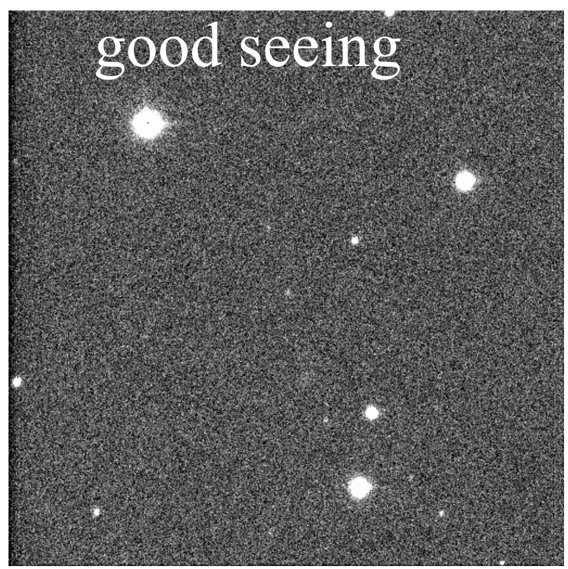
$$I_{observed} = I_{real} \otimes PSF$$

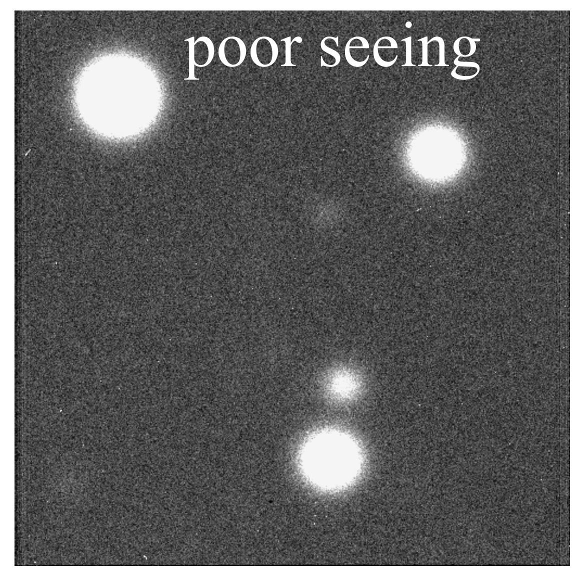
- Determines the spatial resolution of an observation
- Can be measured and modelled using stars (point-sources) present in the astronomical images
- Knowing the PSF allows precise astrometric and photometric measurements by PSF fitting techniques and detection of variability by image subtraction

Atmospheric turbulence broadens the PSF resulting in a Gaussian PSF

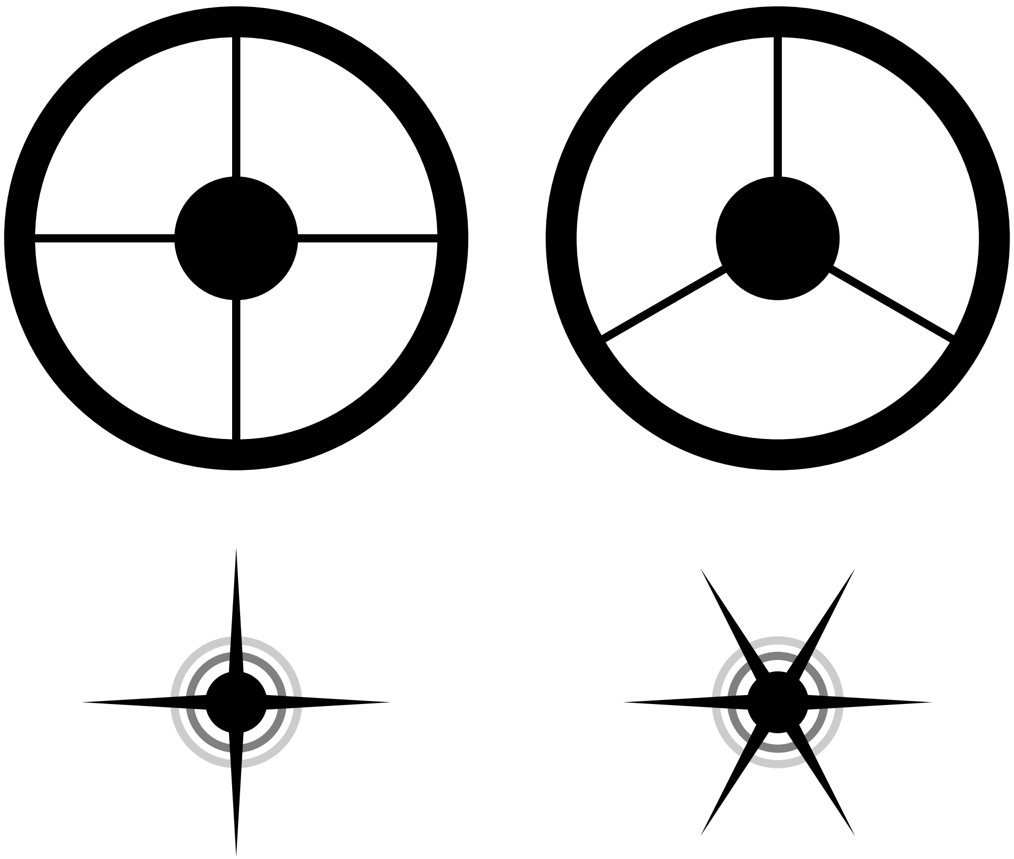
$$I(r) = I(0)\exp(-r^2/2\sigma^2)$$

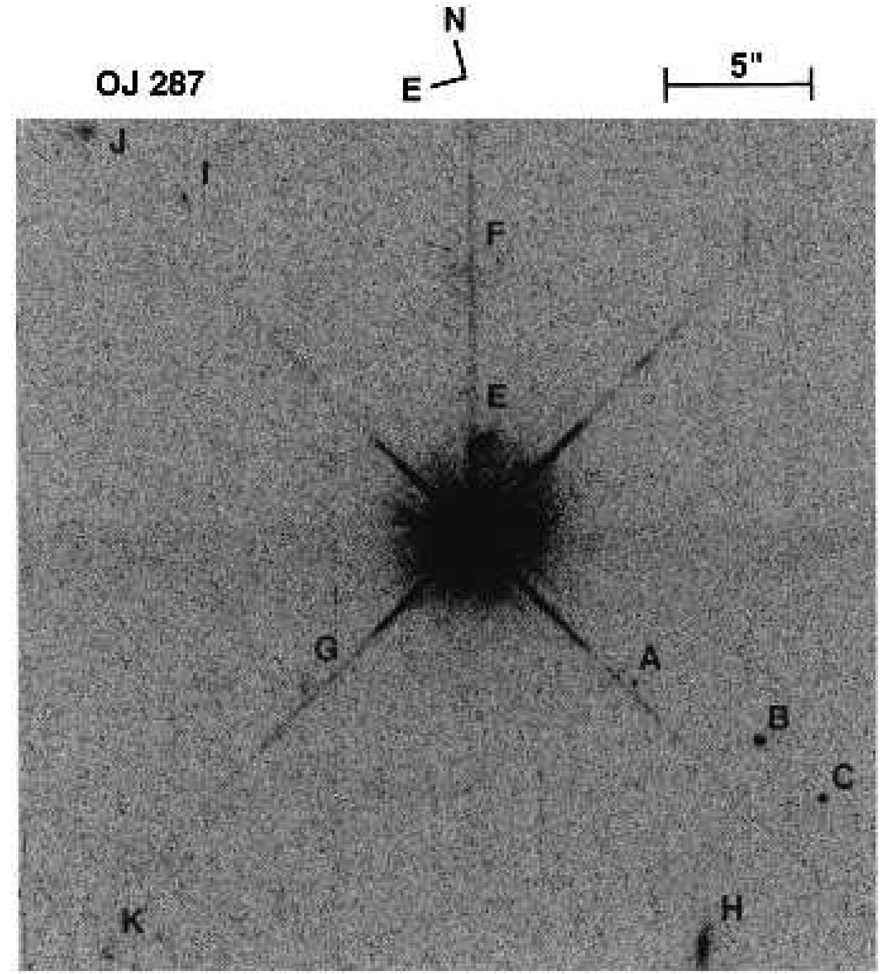






Point spread function (PSF)





Signal-to-Noise Ratio

- Most important measure of the level of 'goodness' of your observation

$$\frac{S}{N} = \frac{signal}{\sqrt{noise_1^2 + noise_2^2 + \ldots + noise_n^2}}$$

where $noise_1$, $noise_2$, ... are different sources of noise

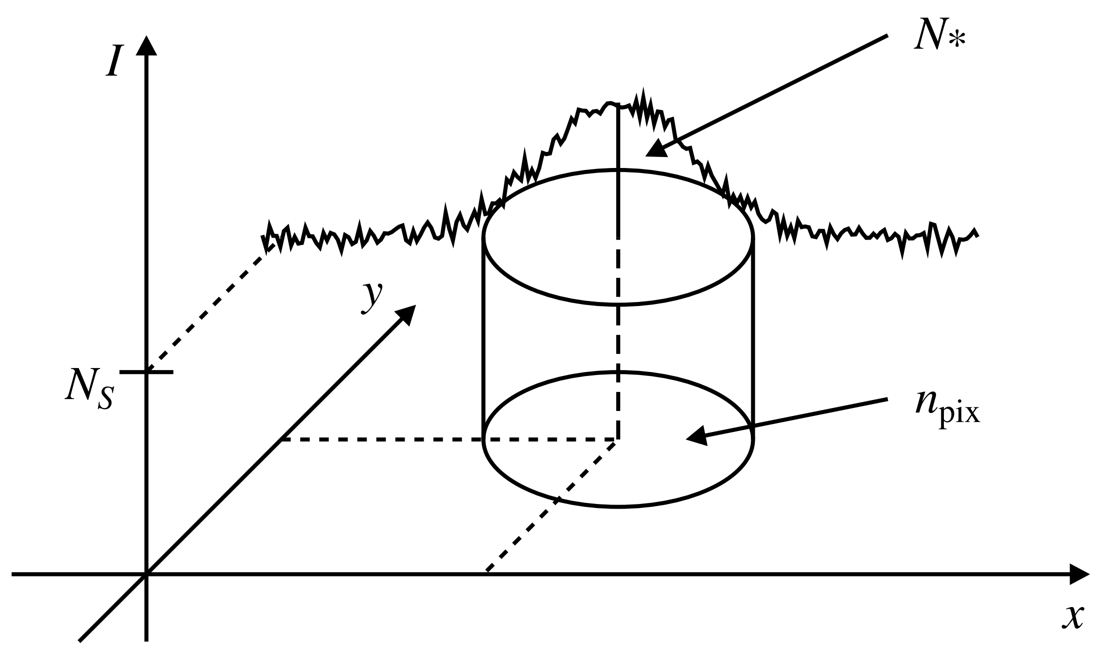
Signal-to-Noise Ratio

- Most important measure of the level of 'goodness' of your observation

$$\frac{S}{N} = \frac{N^*}{\sqrt{N^* + n_{\rm pix}(N_{\rm sky} + N_D + N_R^2)}}$$

where $N*$ is the number of photons N_{sky} N_D N_R different sources of noise

- Determines the minimum integration time required for your observation



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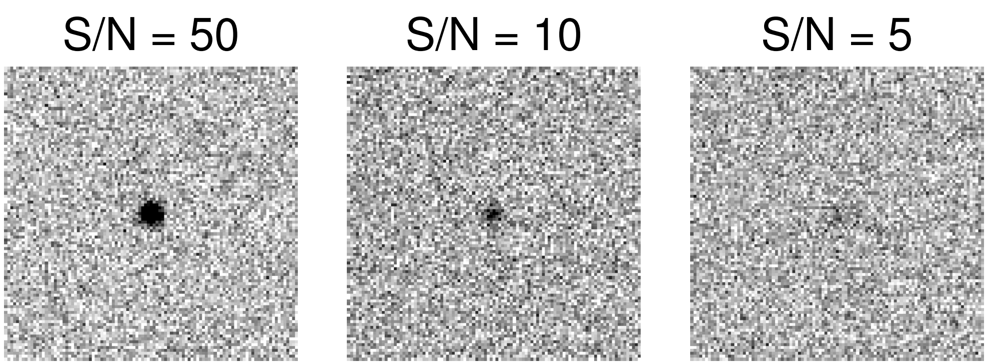
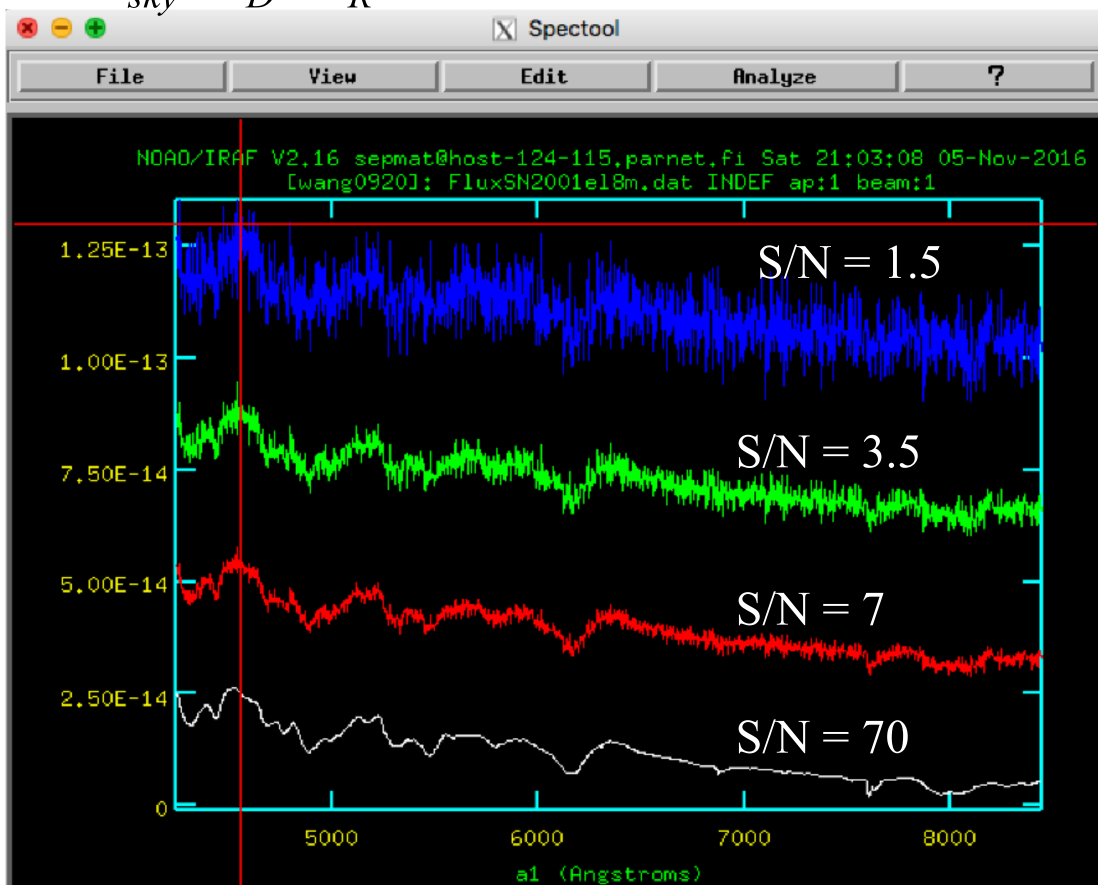
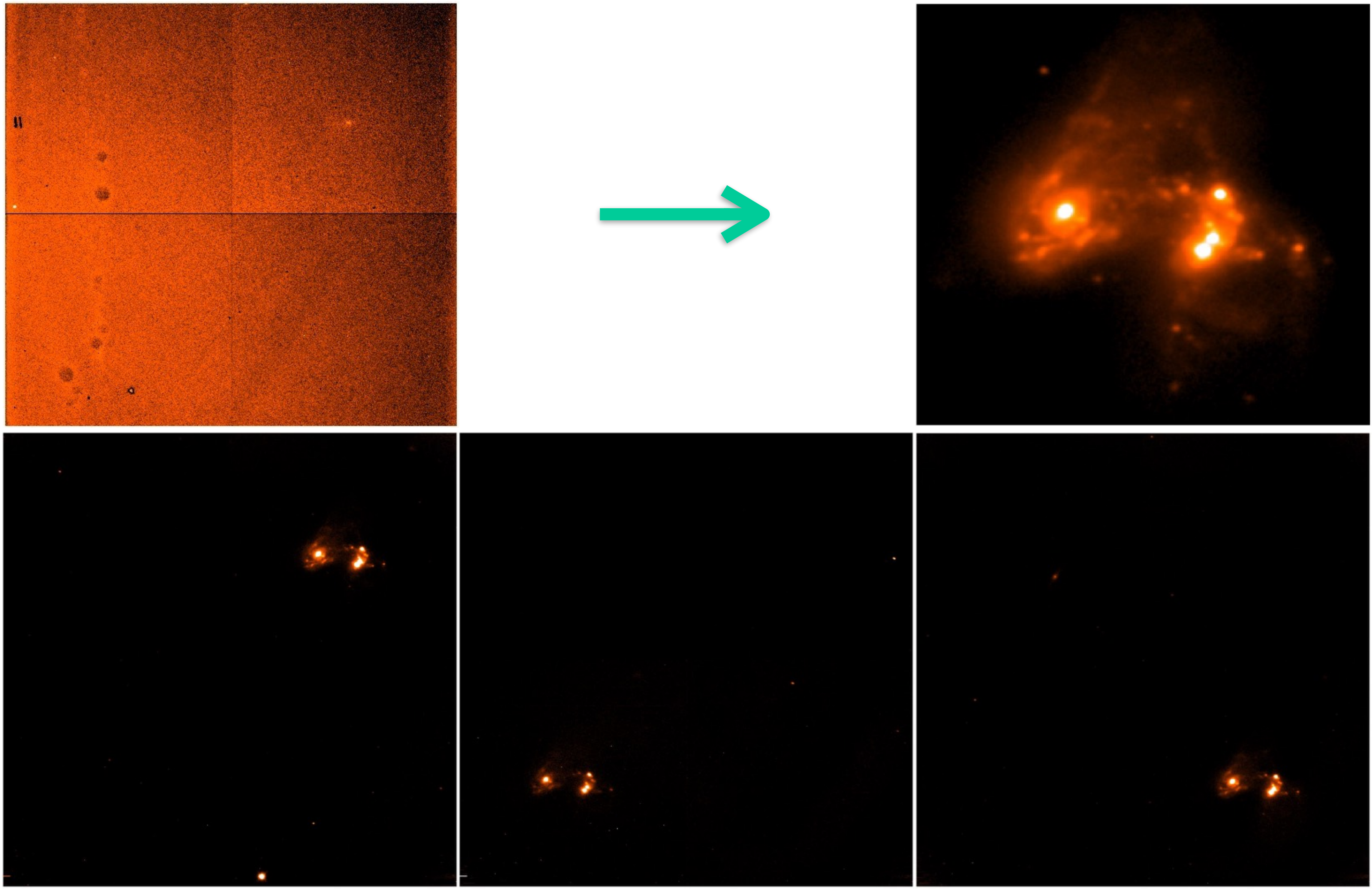
where N_* is the number of photons N_{sky} N_D N_R different sources of noise





Data reduction: removal of instrumental signatures

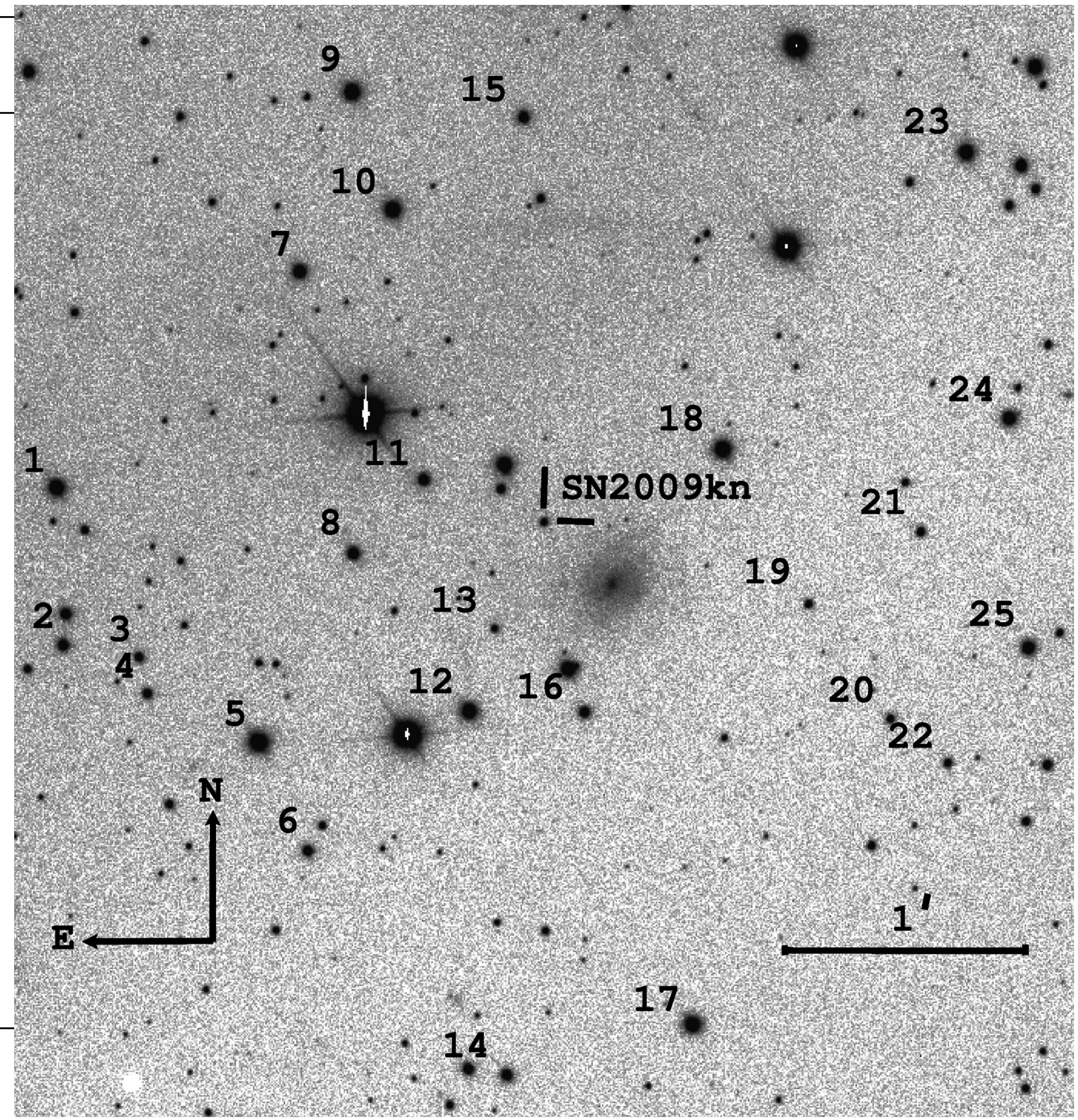


Photometric calibration of imaging observations

- Need to calibrate observations from each night (different atmospheric conditions)
- Can use field stars for precise relative calibration between different nights

Table 1. Magnitudes of the SN 2009kn field stars (for the identifications, see Fig. 1). The 1σ statistical errors are given in brackets.

Star #	m_U (mag)	m_B (mag)	m_V (mag)	m_R (mag)
1	14.722(0.005)	14.852(0.011)	14.313(0.026)	13.958(0.025)
2	16.063(0.012)	16.213(0.014)	15.652(0.027)	15.186(0.026)
3	17.224(0.021)	17.198(0.016)	16.510(0.022)	16.015(0.024)
4	17.388(0.024)	17.196(0.015)	16.455(0.023)	15.899(0.026)
5	14.388(0.006)	14.225(0.007)	13.546(0.045)	13.318(0.058)
6	16.615(0.016)	16.655(0.012)	15.960(0.017)	15.492(0.026)
7	15.489(0.008)	15.525(0.006)	14.867(0.008)	14.544(0.012)
8	16.586(0.014)	16.168(0.008)	15.380(0.013)	14.947(0.008)
9	15.010(0.007)	14.876(0.011)	14.185(0.011)	13.742(0.036)
10	14.669(0.006)	14.762(0.008)	14.223(0.010)	13.888(0.023)
11	16.181(0.012)	16.136(0.007)	15.525(0.009)	15.204(0.007)
12	15.107(0.006)	15.046(0.005)	14.345(0.018)	13.970(0.013)
13	17.828(0.038)	17.981(0.020)	17.442(0.017)	17.110(0.012)
14	15.806(0.012)	15.959(0.015)	15.506(0.009)	15.188(0.035)
15	16.208(0.013)	16.237(0.011)	15.685(0.010)	15.385(0.025)
16	16.554(0.016)	16.522(0.008)	15.891(0.015)	15.533(0.009)
17	14.933(0.009)	14.866(0.012)	14.175(0.010)	13.832(0.052)
18	14.814(0.007)	14.683(0.006)	14.080(0.008)	13.701(0.029)
19	18.566(0.069)	18.046(0.021)	17.196(0.013)	16.756(0.018)
20	17.727(0.037)	17.625(0.015)	16.891(0.012)	16.539(0.014)
21	17.487(0.028)	17.463(0.015)	16.850(0.014)	16.534(0.020)
22	17.822(0.037)	17.628(0.016)	16.898(0.011)	16.584(0.017)
23	16.545(0.018)	15.644(0.010)	14.660(0.026)	14.070(0.056)
24	16.149(0.015)	15.747(0.006)	15.013(0.012)	14.593(0.030)
25	16.069(0.015)	15.739(0.007)	15.024(0.007)	14.702(0.023)



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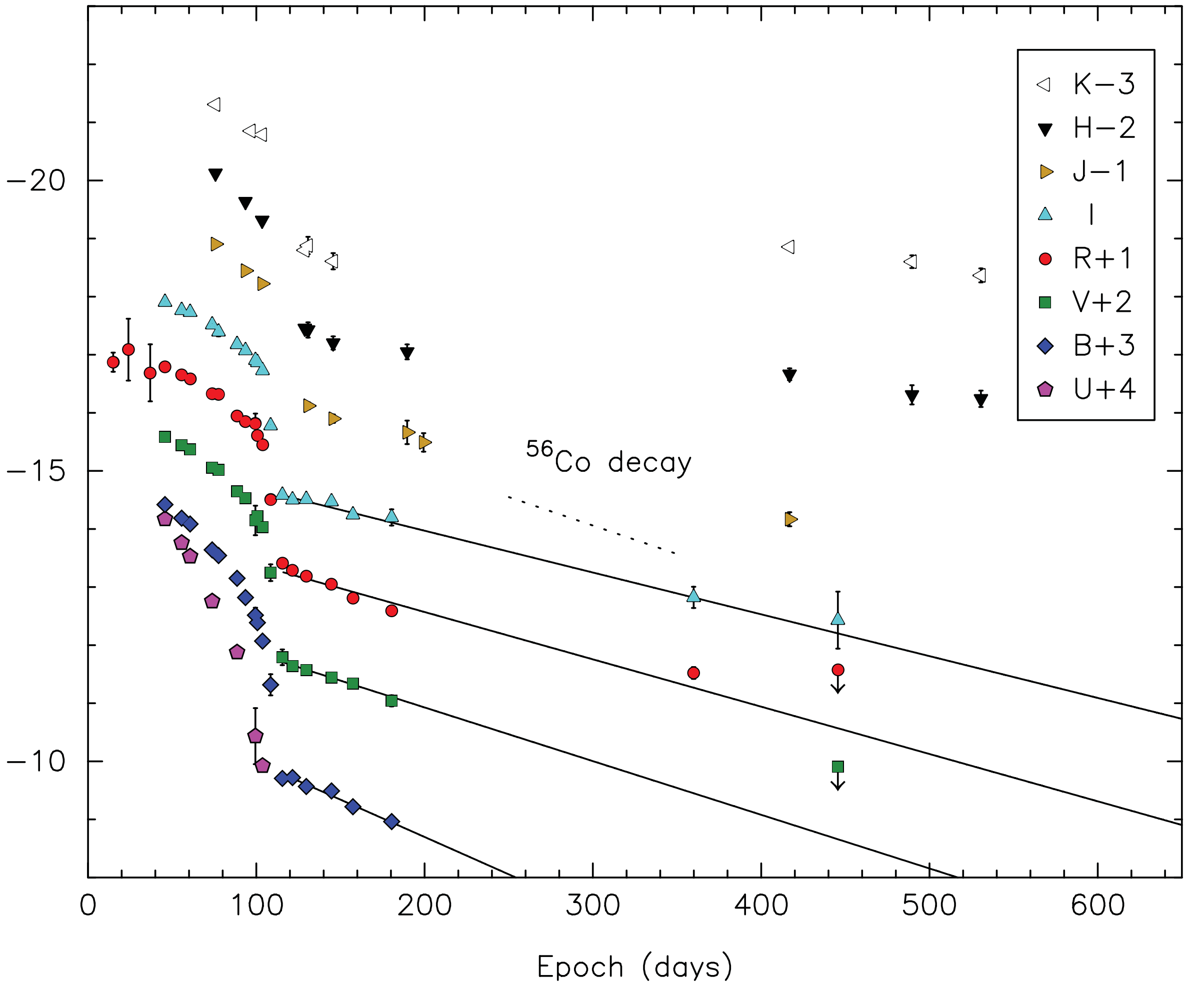
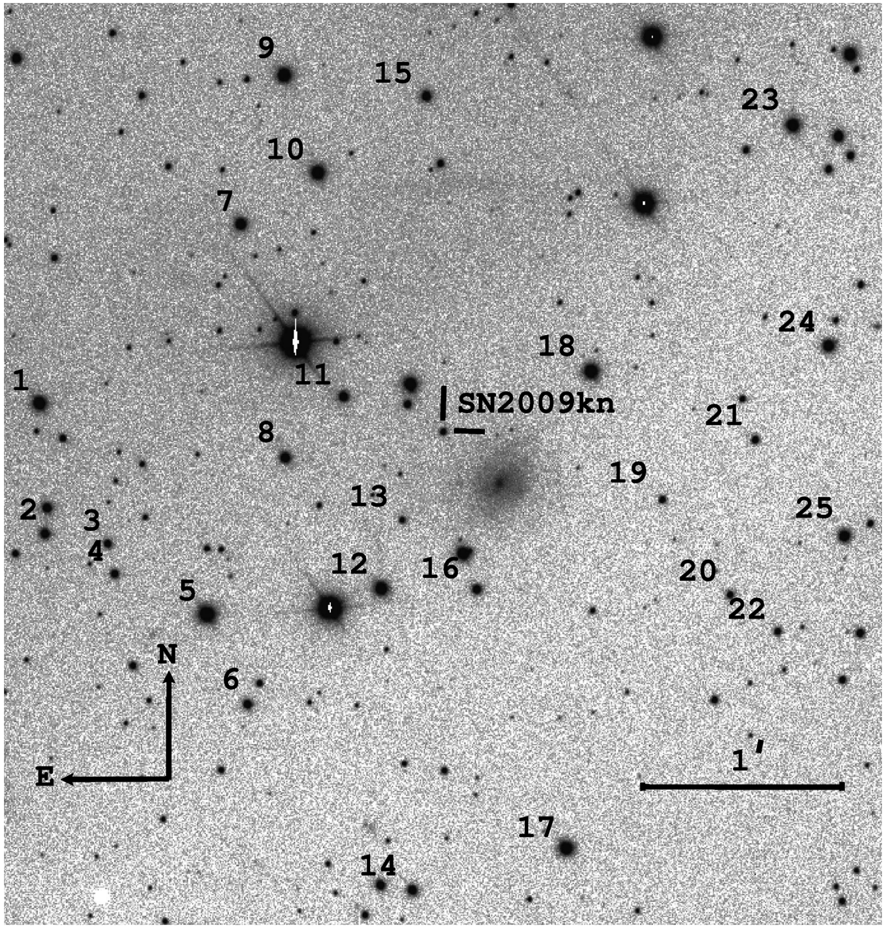
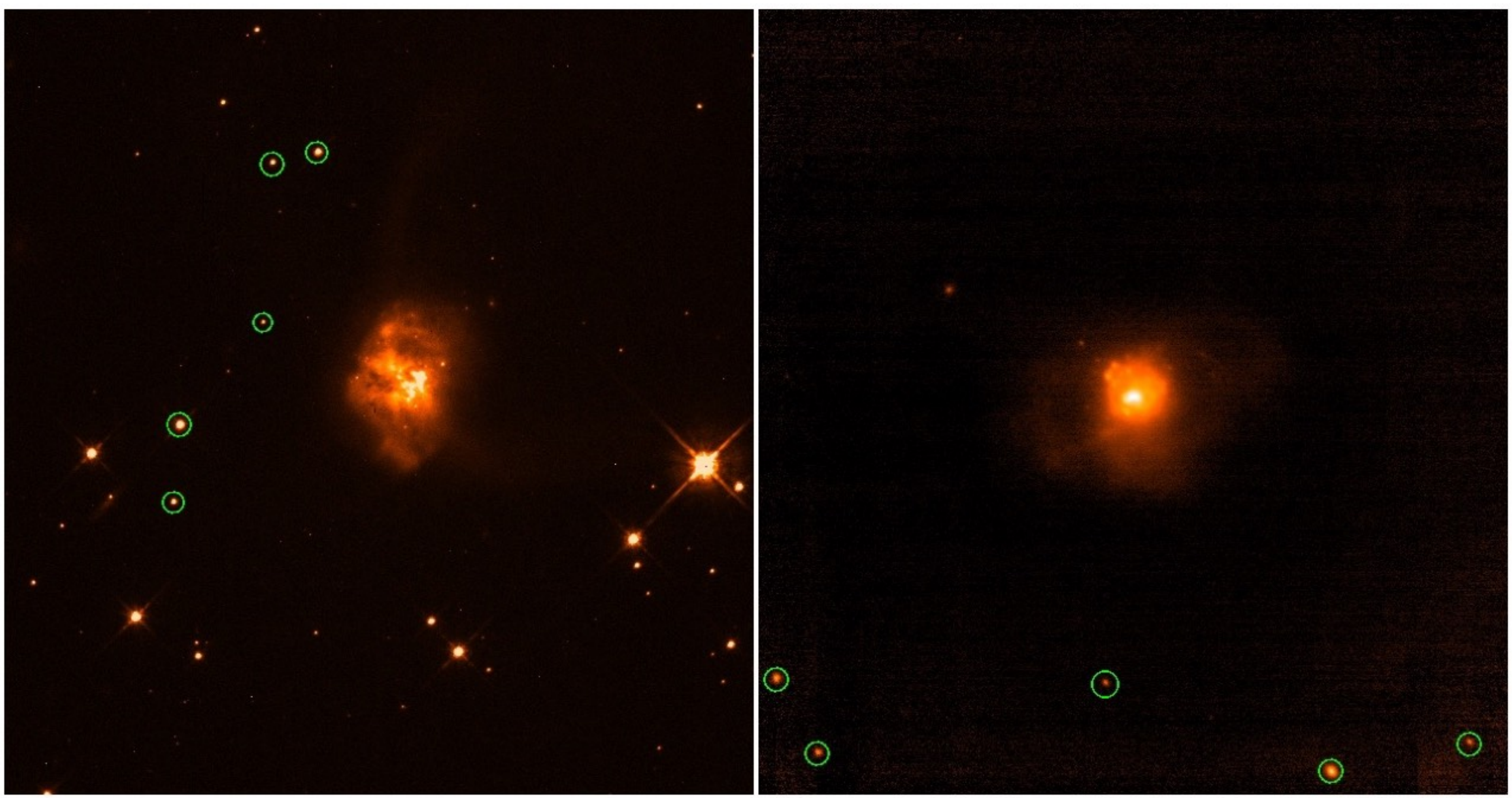




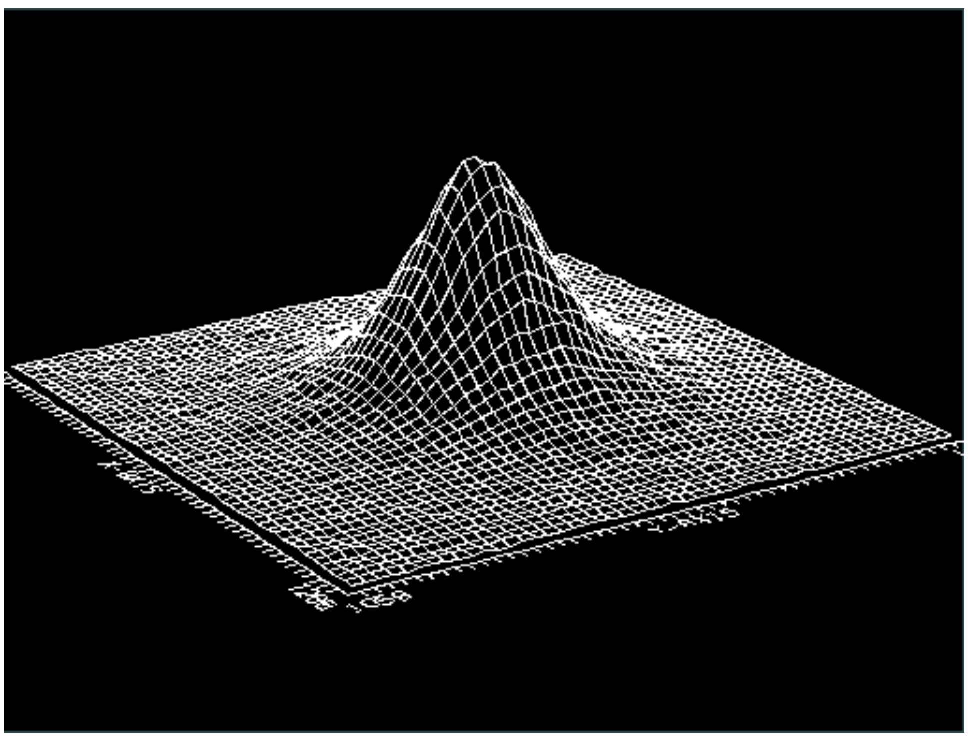
Astrometric calibration of imaging observations

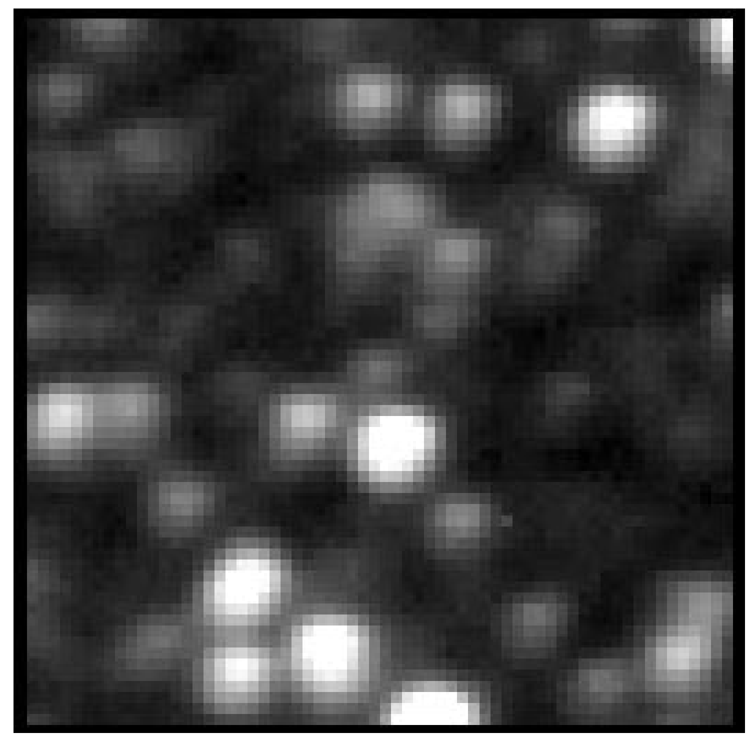
- *Absolute astrometry* in a real coordinate system
  - E.g., reporting the coordinates of a newly discovered supernova
- *Relative (or differential) astrometry* wrt other objects in the observed field
  - Object position in image coordinates (x,y)
- *Alignment* of images
- Can usually identify a number of point sources (stars) common in both images
- Apply geometric transformation for x and y shifts, pixel scale, rotation



Determining positions of objects in the images

- For absolute/relative astrometry need to measure accurate (x,y) coordinates for the objects in the images
- *Centroiding* most commonly used: calculate the intensity weighted mean in (x,y)
- *Gaussian fitting* with fixed FWHM separately in x and y
- *PSF fitting* (needed in crowded fields)

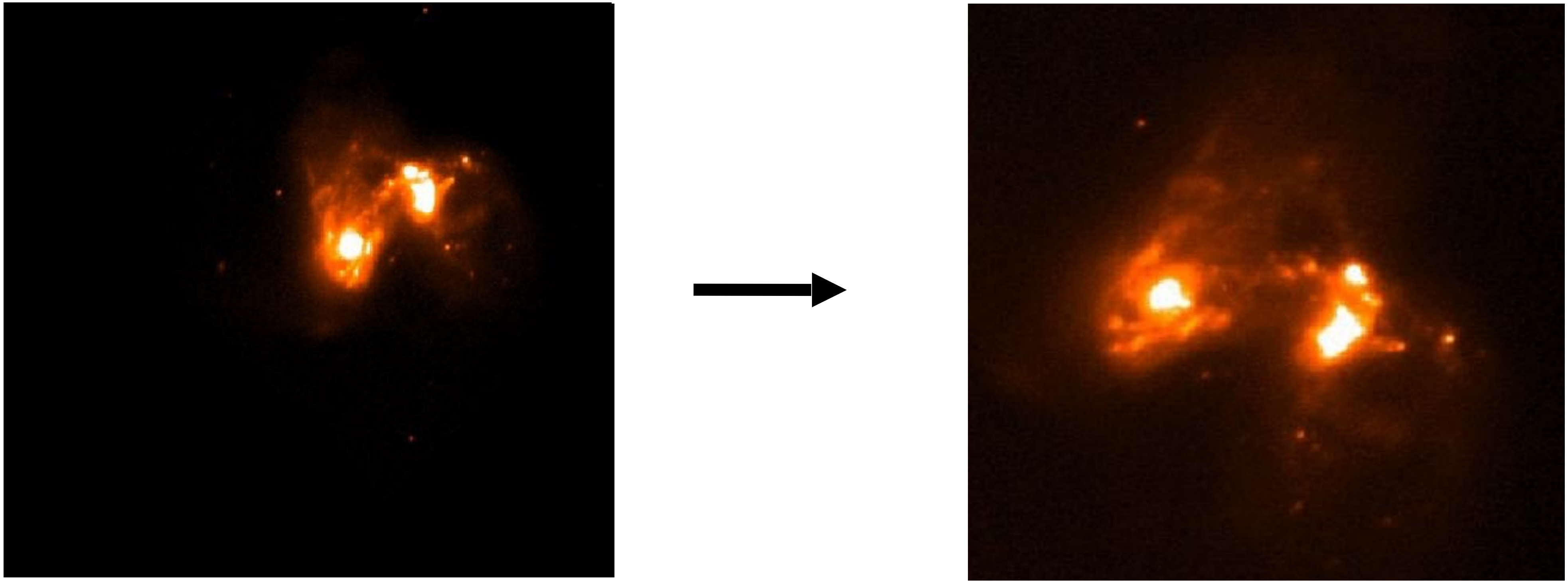




Geometric transformations: general

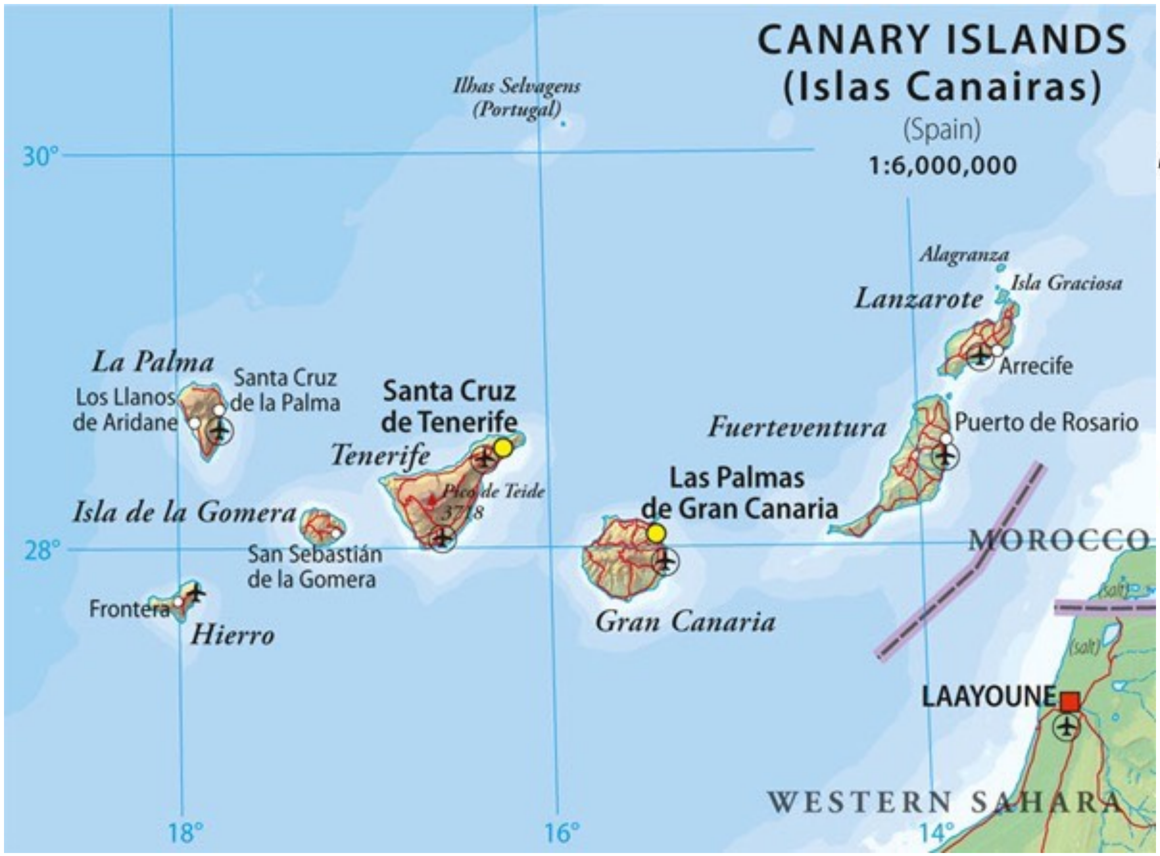
Derive a geometric transformation to align image A (x_A, y_A) to image B (x_B, y_B)

Number of free parameters: 4 (if rotation and scale the same for x and y)
6 (if different rotation and scale for x and y)
≥10 (if including also a distortion term)



Astronomical observatories and future facilities

Roque de los Muchachos Observatory on La Palma, Canary Islands
17.88°W, 28.76°N, 2382m above sea level



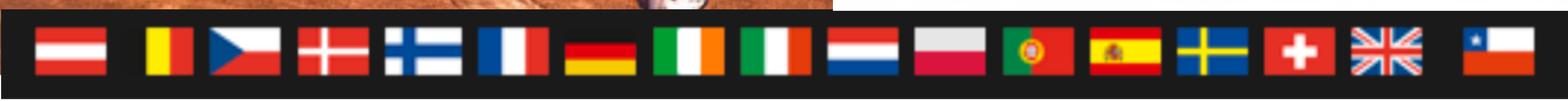

Observatorio del Roque de
los Muchachos, La Palma
17.88ºW, 28.76ºN, 2382m

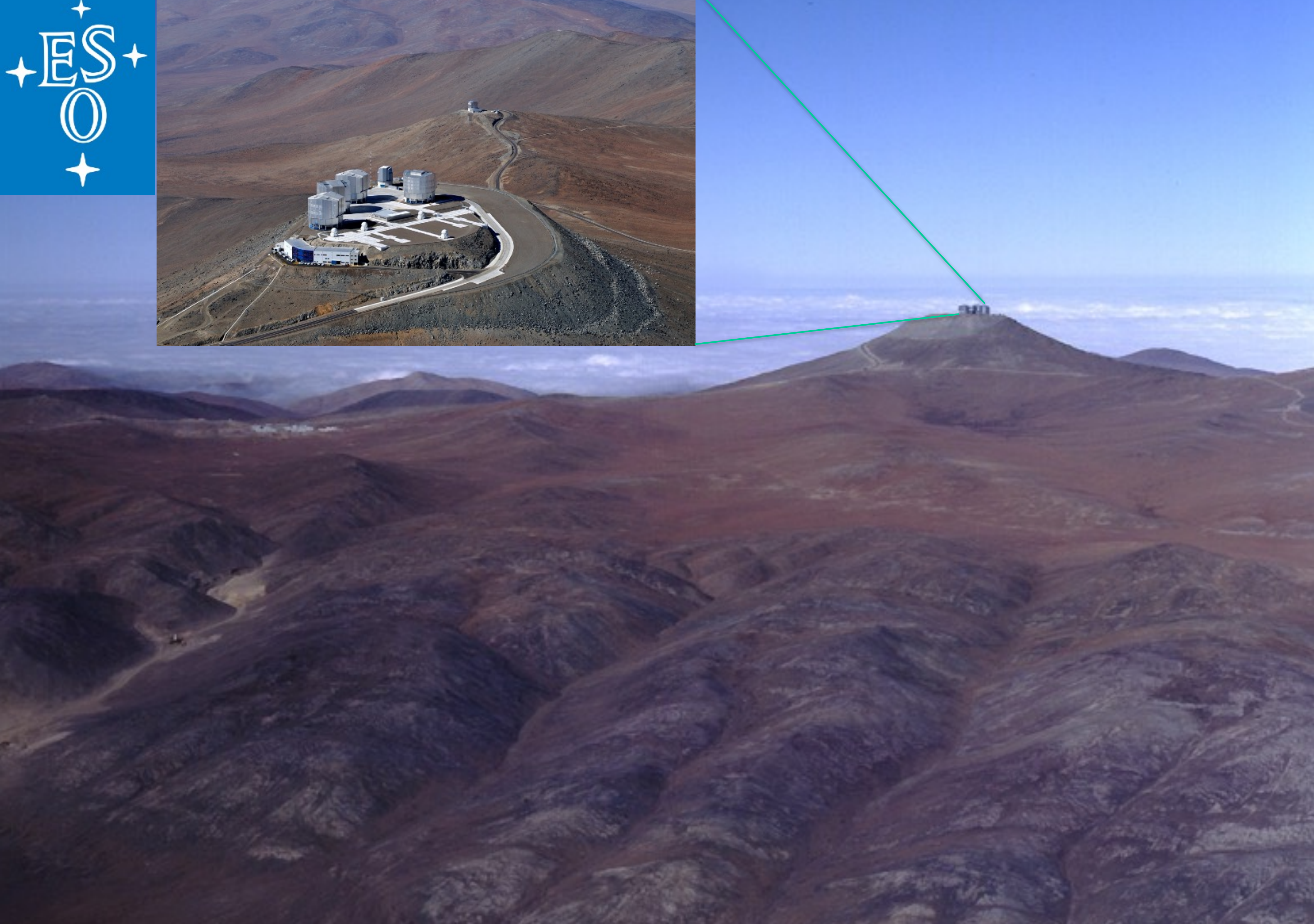
Nordic Optical Telescope (NOT)

- Nordic Optical Telescope (NOT) operational since 1990, optics manufactured at Tuorla Observatory (nowadays Opteon Oy)
- The ownership transferred to Univ. of Turku and Aarhus University in 2020
- Operations based on long-term collaboration between Finland, Denmark, Norway, Iceland and Stockholm University

European Southern Observatory (ESO)

- European intergovernmental research organisation, establ. in 1962
- 16 member countries incl. Finland + Chile as the host country
- Headquarters in Germany, world-class observatories in Chile
- Over 750 staff from over 30 countries, more than 22 000 users
- Science data archive, data reduction pipelines, technology and instrumentation development, top level research

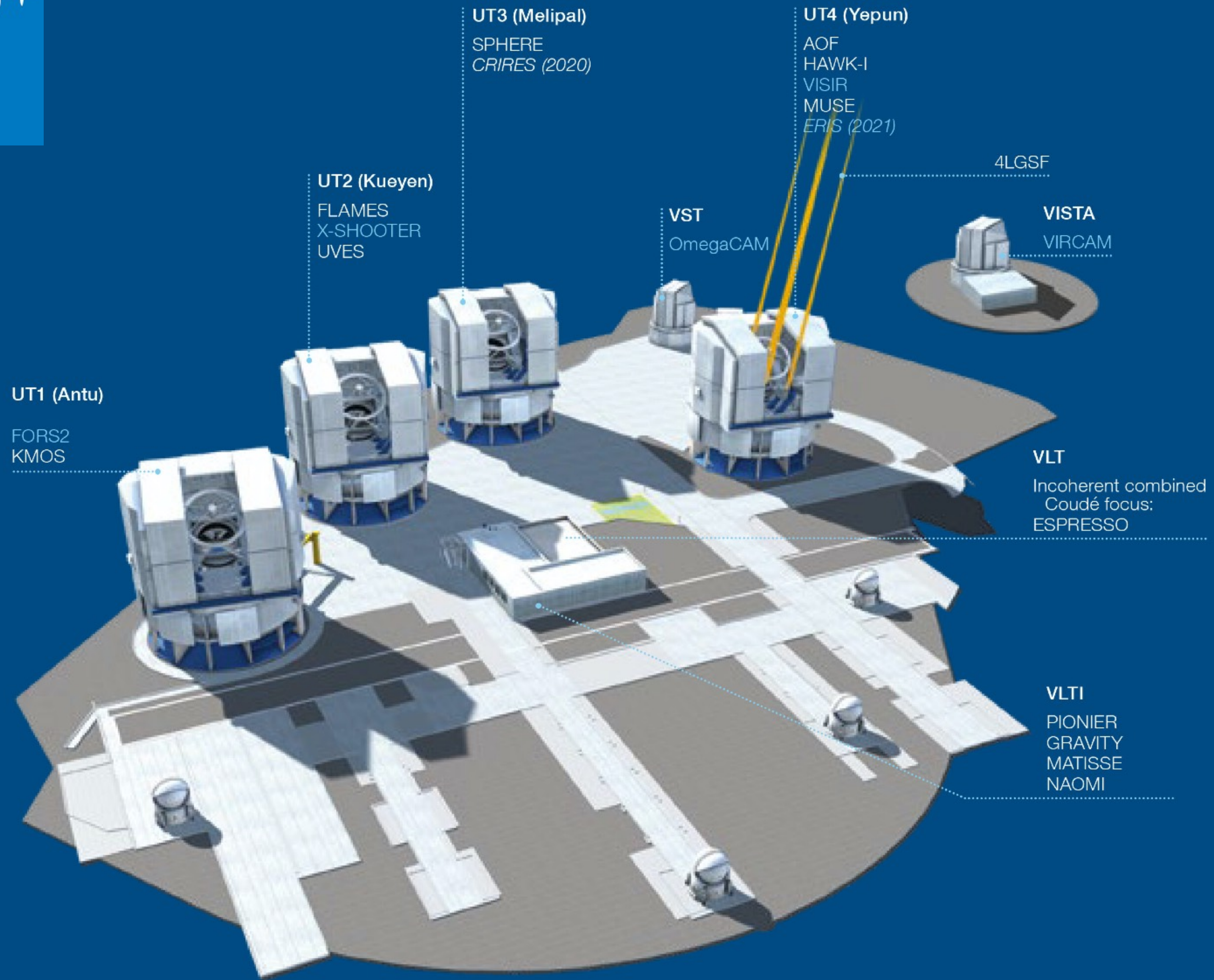




Paranal Observatory located on Cerro Paraxial at 2635m

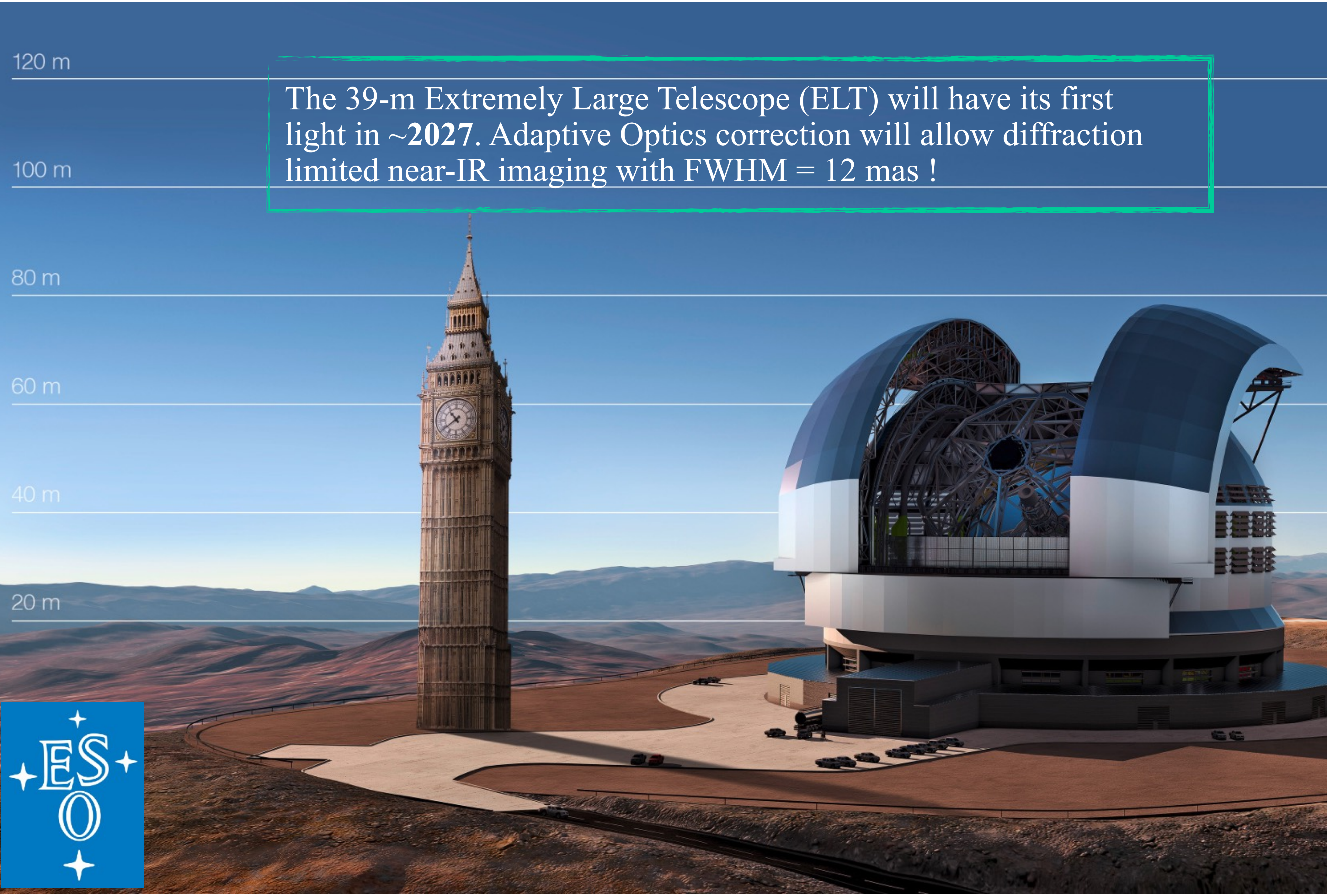
Very Large Telescope (VLT): 4 x 8.2-m unit telescopes

European Southern Observatory (ESO) Very Large Telescope (VLT)

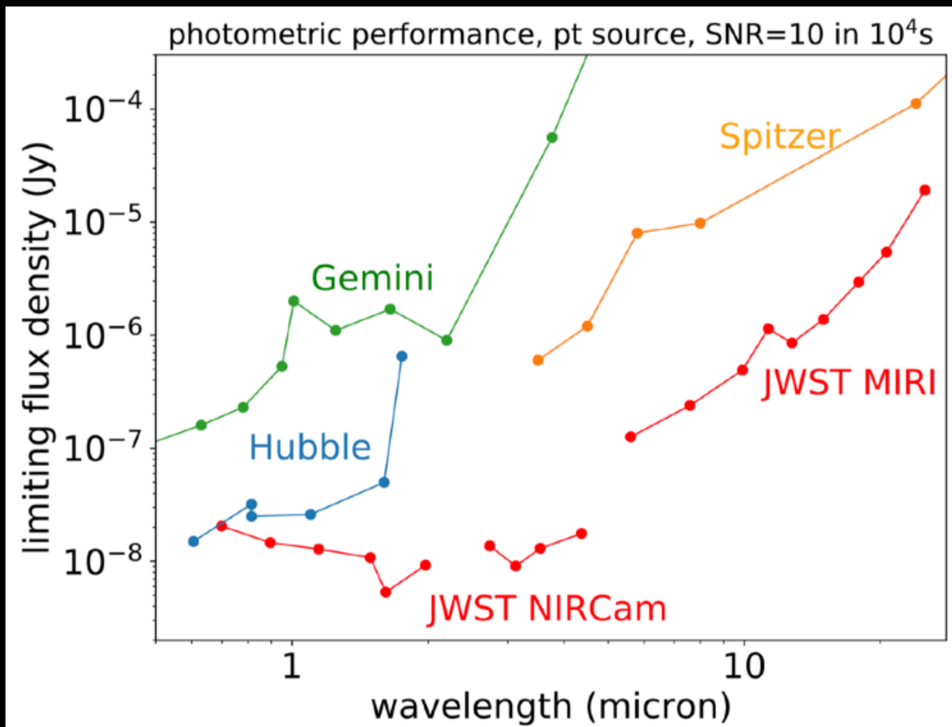


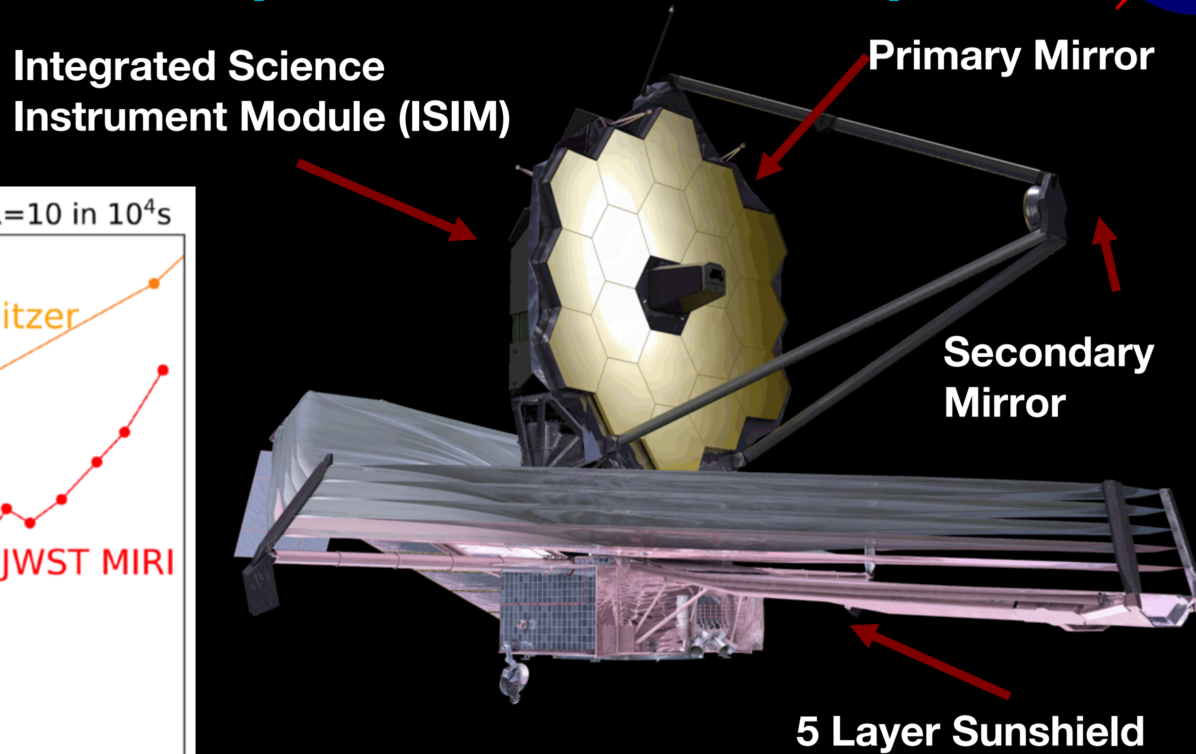

SONY

The 39-m Extremely Large Telescope (ELT) will have its first light in ~**2027**. Adaptive Optics correction will allow diffraction limited near-IR imaging with FWHM = 12 mas !



James Webb Space Telescope



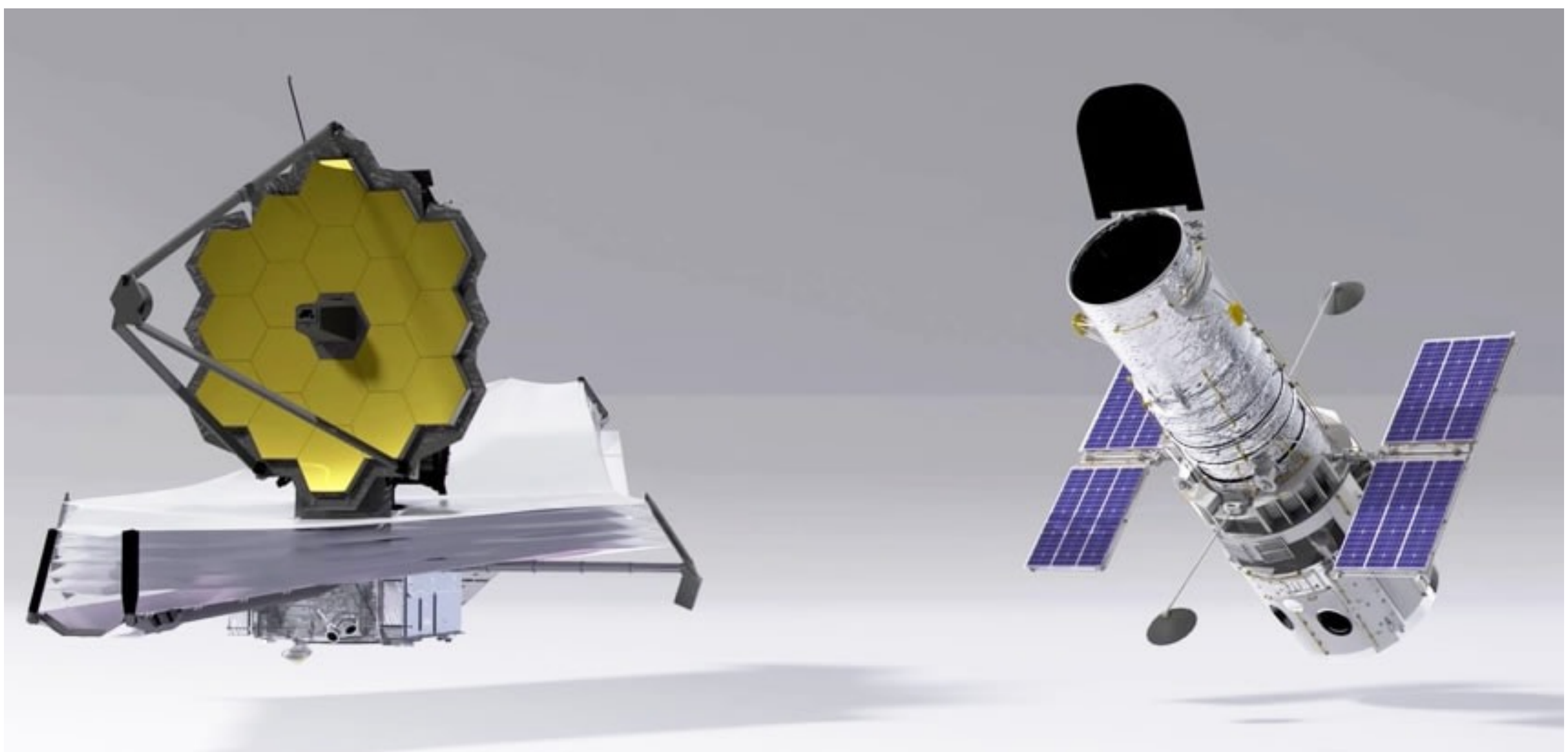


- The primary mirror will be 6.5 metres in diameter and is made of 18 mirror segments of gold-coated beryllium
- JWST's wavelength range covered by the scientific instruments will be from about 0.6 µm to 28 µm, compared to Hubble's 0.1 µm - 2.5 µm

credit: Jonathan P. Gardner, NASA's Goddard Space Flight Center

Capabilities of the JWST (in a nutshell)

- 6.5m primary mirror vs. 2.4m for HST - collecting area of $25m^2$ vs. $4.5m^2$
- Diffraction limited spatial resolution at 2µm similar to HST's at ~700nm
- Imaging and spectroscopy covering 600nm - 28µm (HST: ~100 nm - 2µm)
- NIRCam/JWST: $8x2048^2$ pix (0.6-2.3µm) + $2x2048^2$ pix (2.4-5µm) (WFC3/HST: 1024^2 pix)
- JWST operates at L2, uses solar shield to block the light from the Sun, Earth and Moon



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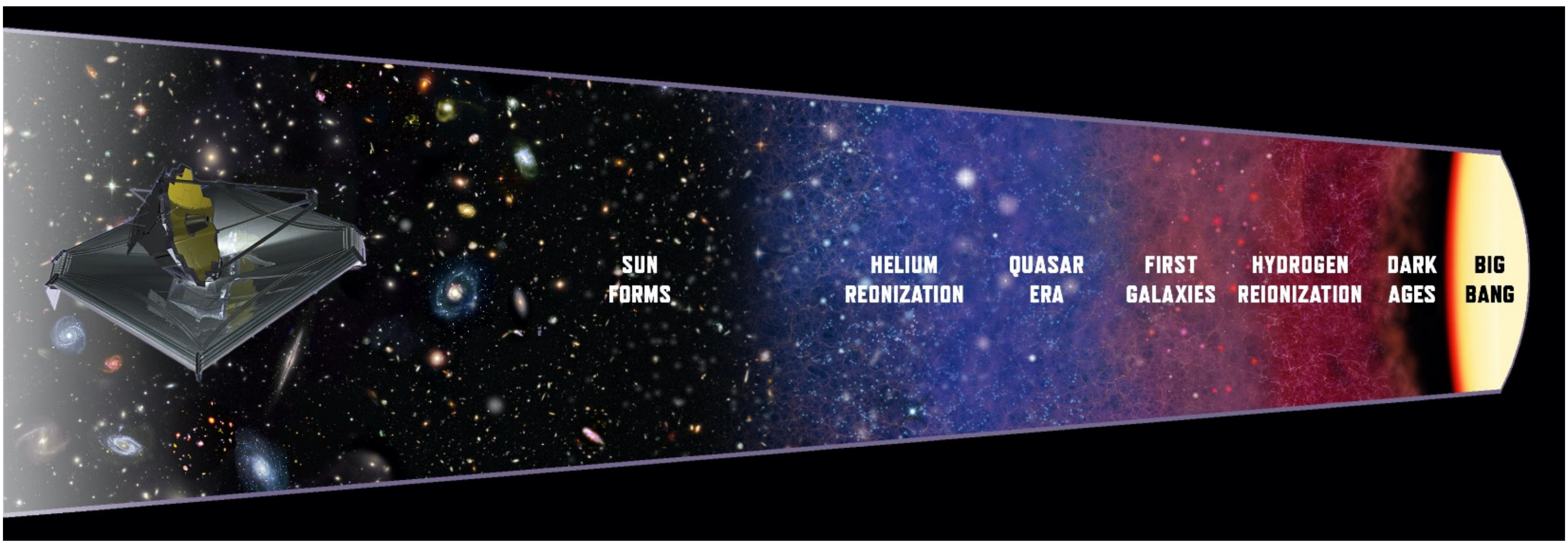
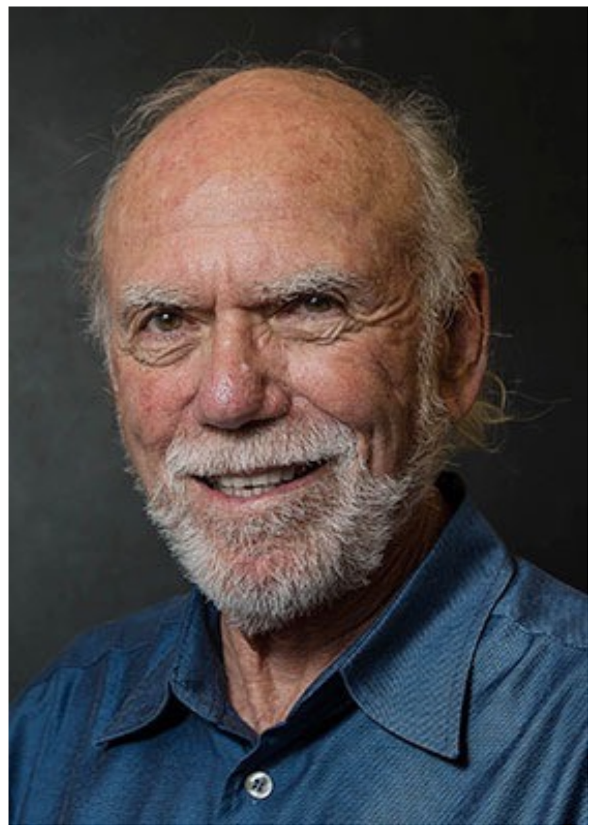


The Nobel prize in Physics 2017 was awarded “for decisive contributions to the LIGO detector and the observation of gravitational waves.”

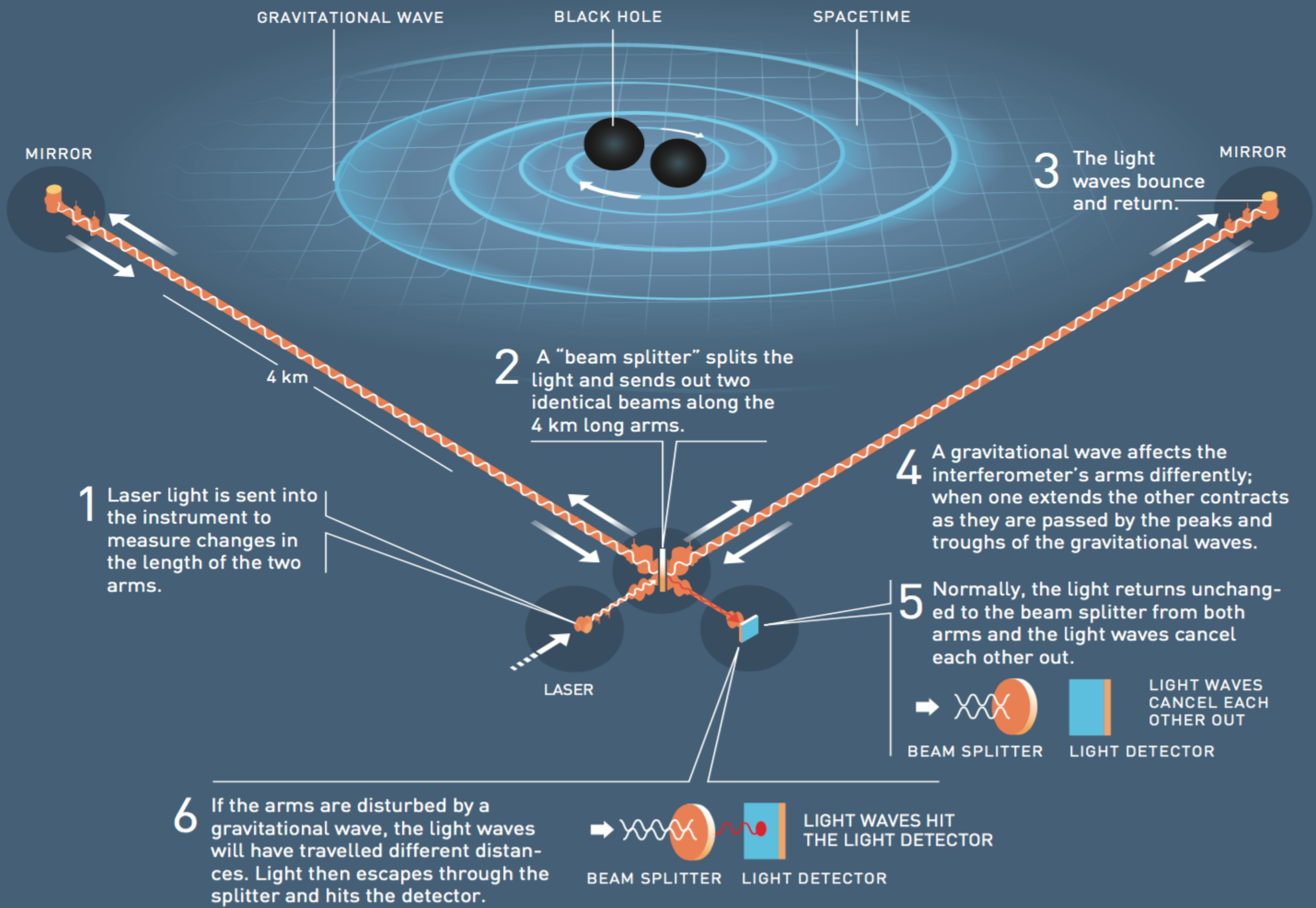
Rainer Weiss (MIT)



Barry Barish (Caltech)

Kip Thorne (Caltech)

LIGO – A GIGANTIC INTERFEROMETER



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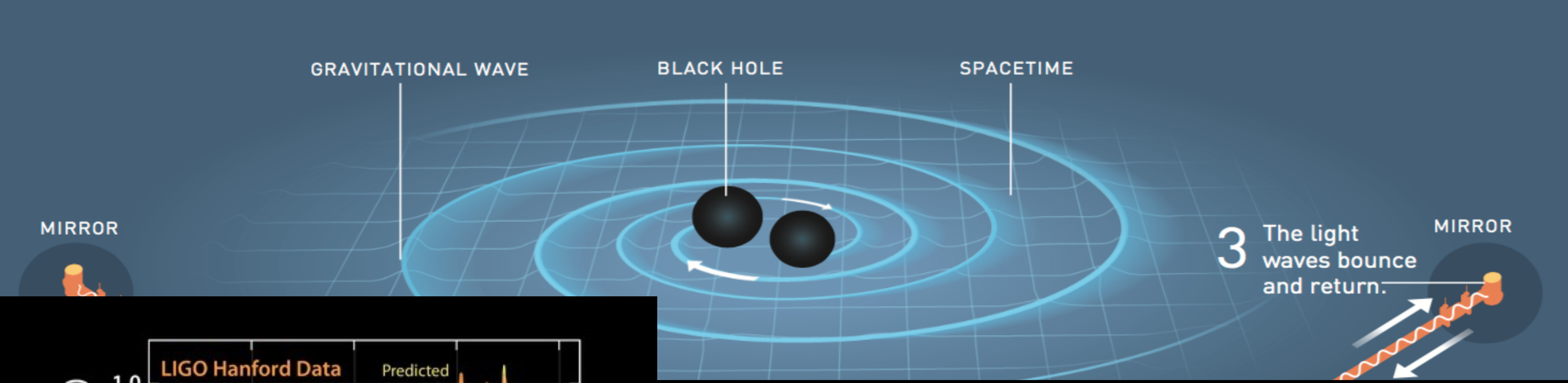

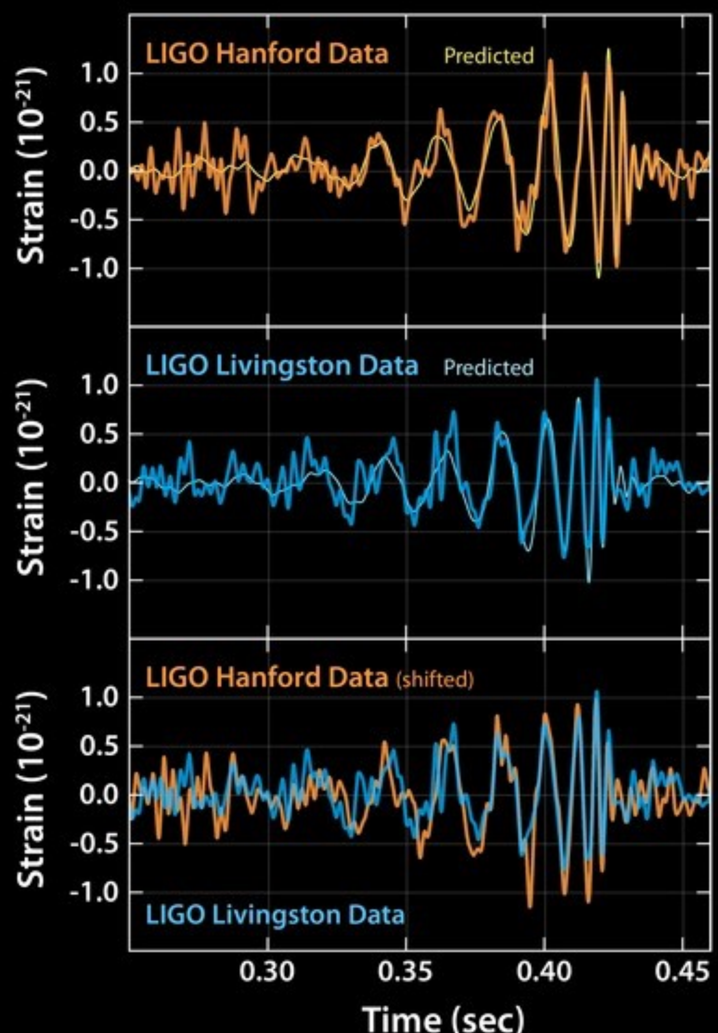

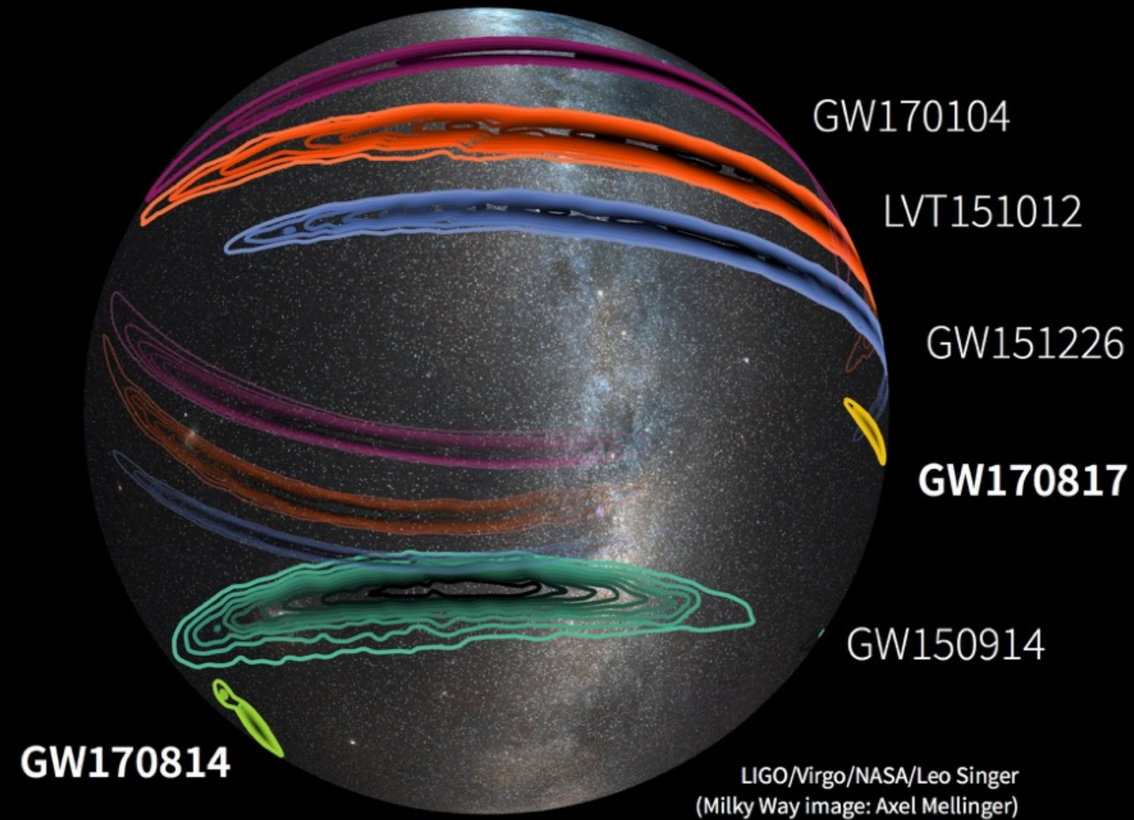

Systematic search for electromagnetic counterparts

- Large and complex sky localisation areas need to be searched over quickly for rapidly evolving transients for the identification of viable candidates for spectroscopic observations
- Gravitational-wave Optical Transient Observer (GOTO) being built on La Palma and Siding Springs Observatory in Australia: robotic, rapid-response system with ~80 deg^2 field of view

GOTO on La Palma, Canary Islands

GOTO is led by University of Warwick and Monash University with Univ. of Turku a member of the consortium

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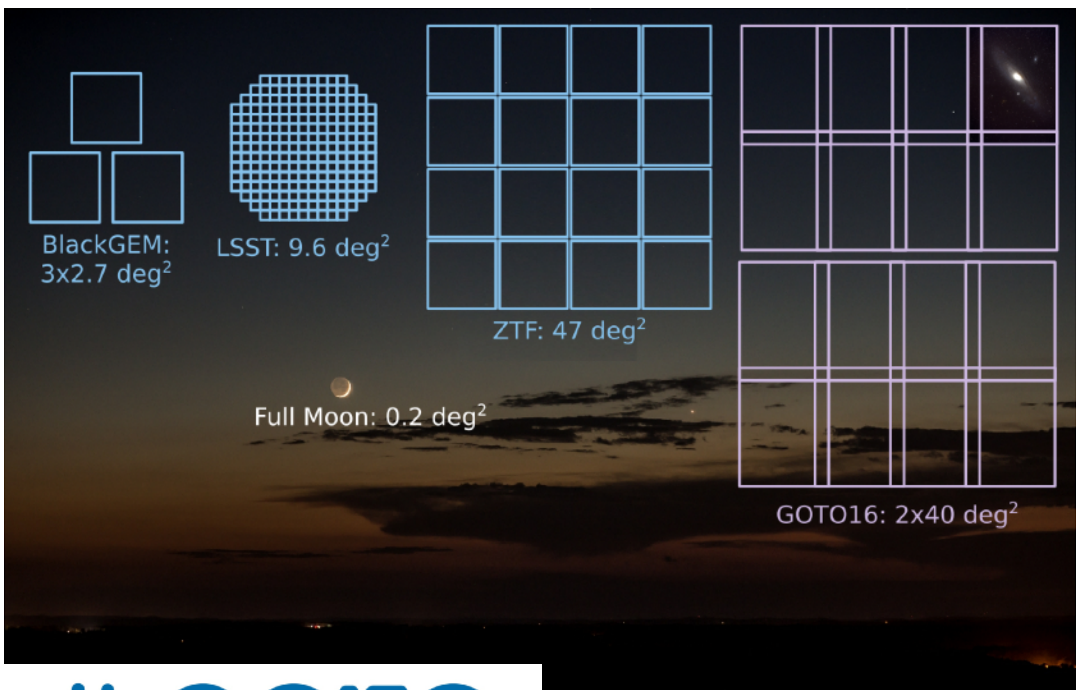
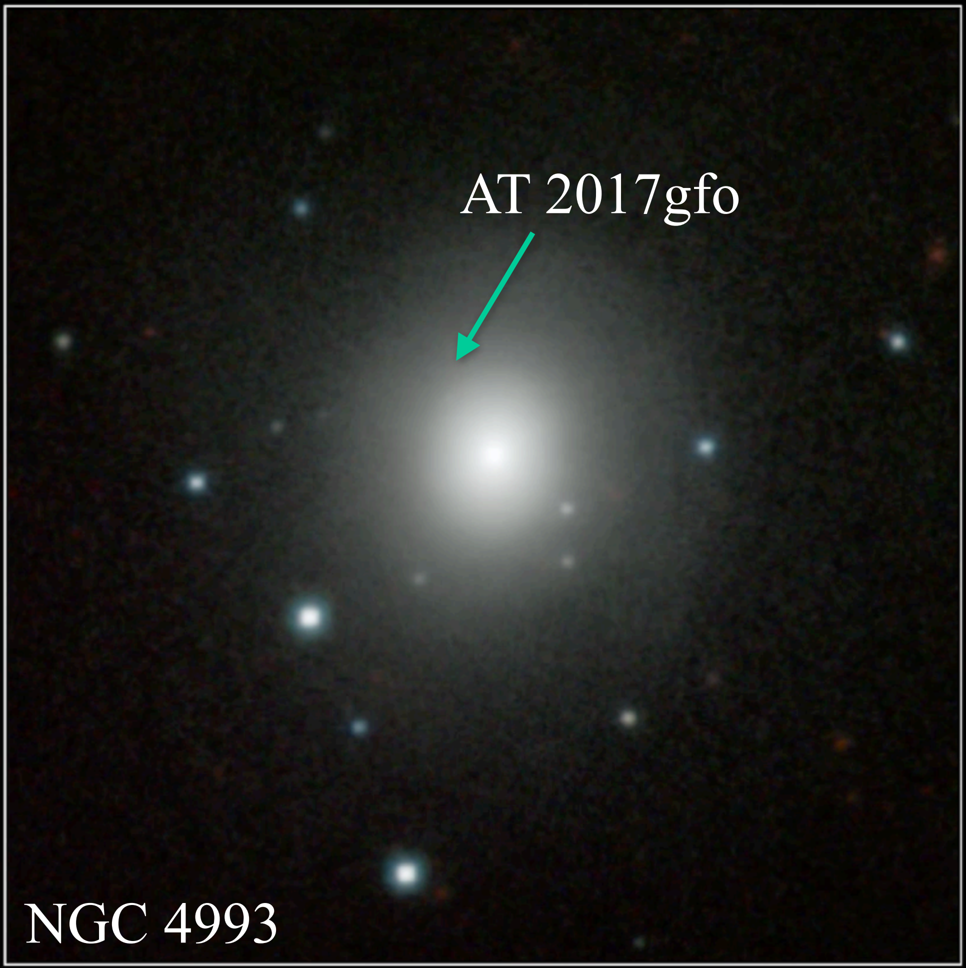
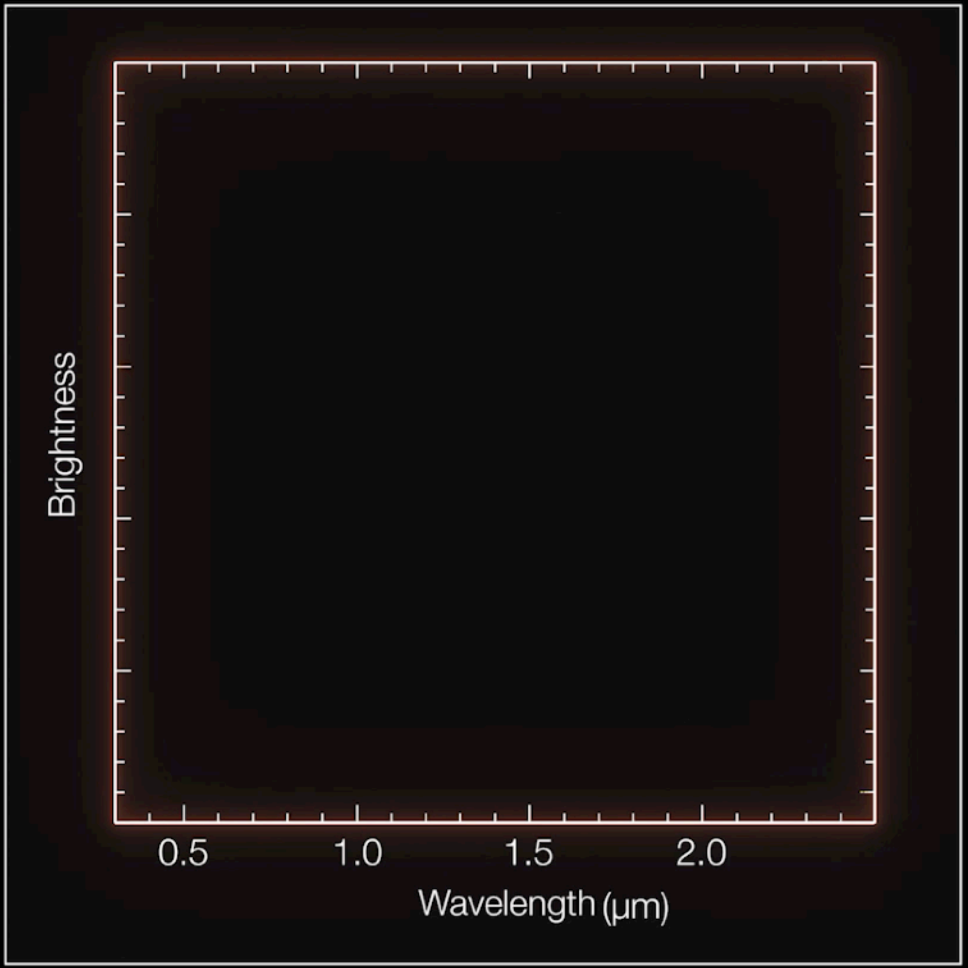


GOTO is led by University of Warwick and Monash University with Univ. of Turku a member of the consortium

GOTO
GRAVITATIONAL-WAVE OPTICAL TRANSIENT OBSERVER

Photometric and spectroscopic follow-up of the kilonova counterpart of GW170817



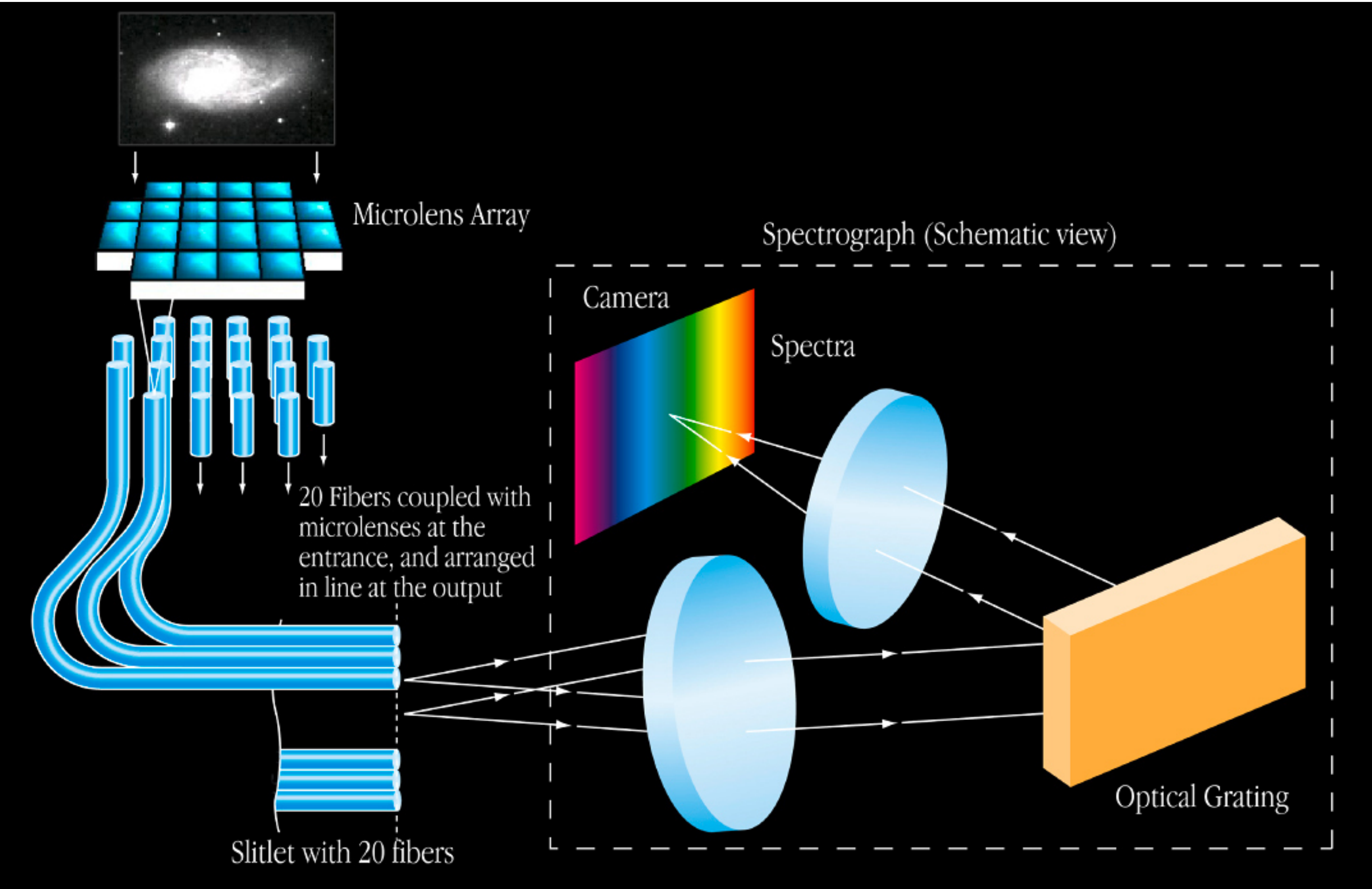


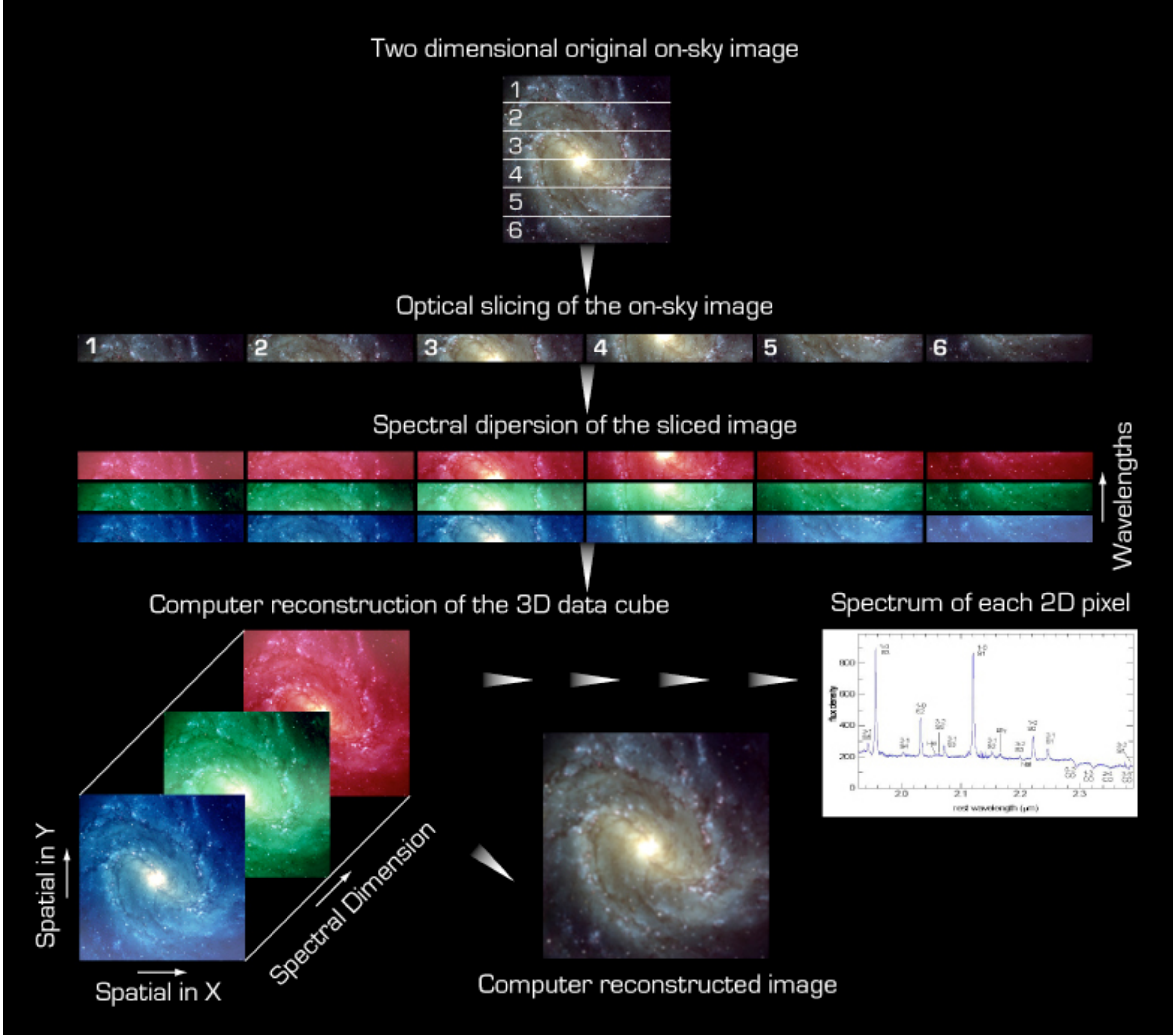
Time: -1225 days

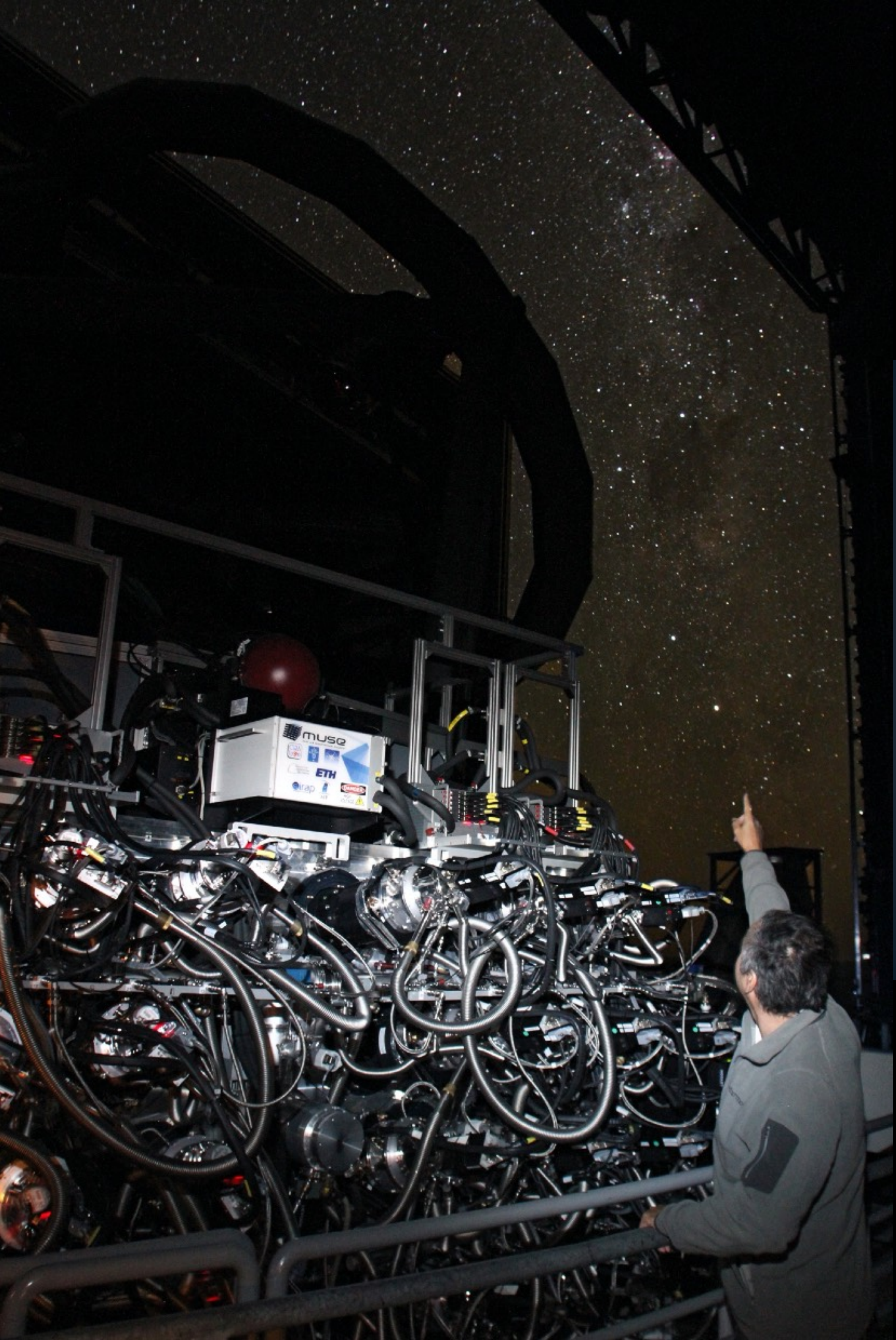
Abbott+2017; Andreoni+2017; Arcavi+2017; Chornock+2017; Coulter+2017; Cowperhwaite+2017; Drout+2017; Evans+2017; Kasliwal+2017; Lipunv+2017; Nichol+2017; Pian+2017; Smartt+2017; Tanvir+2017; Troja+2017; Utsumi+2017; Valenti+2018

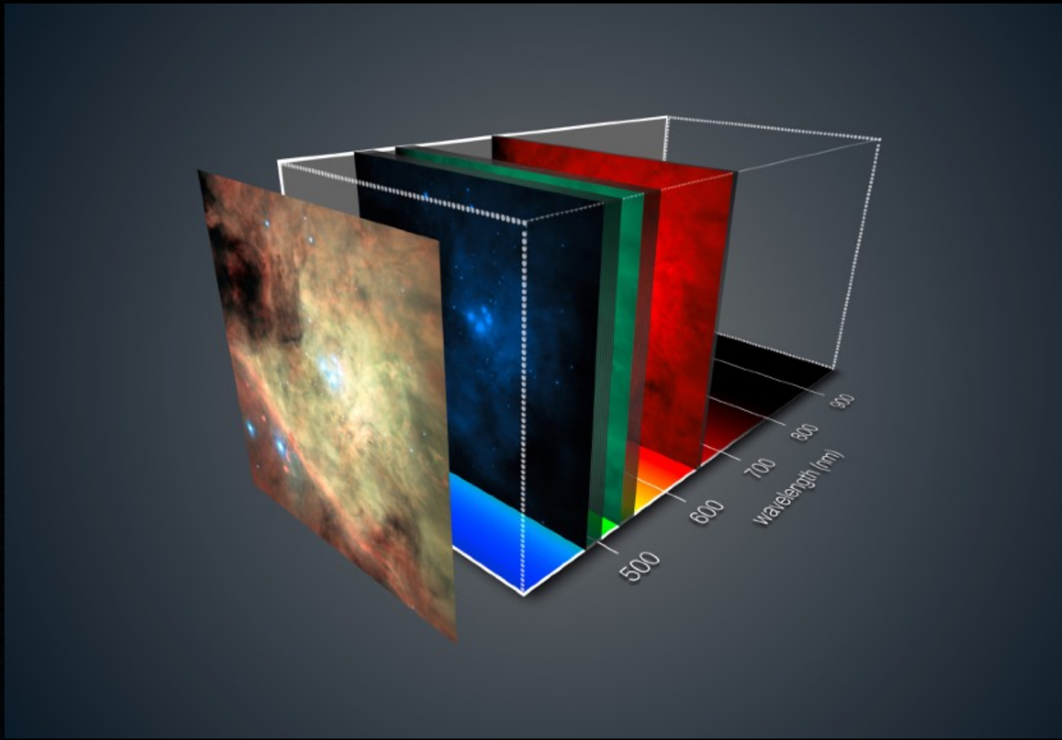
Advanced astronomical instrumentation

Integral-field spectroscopy

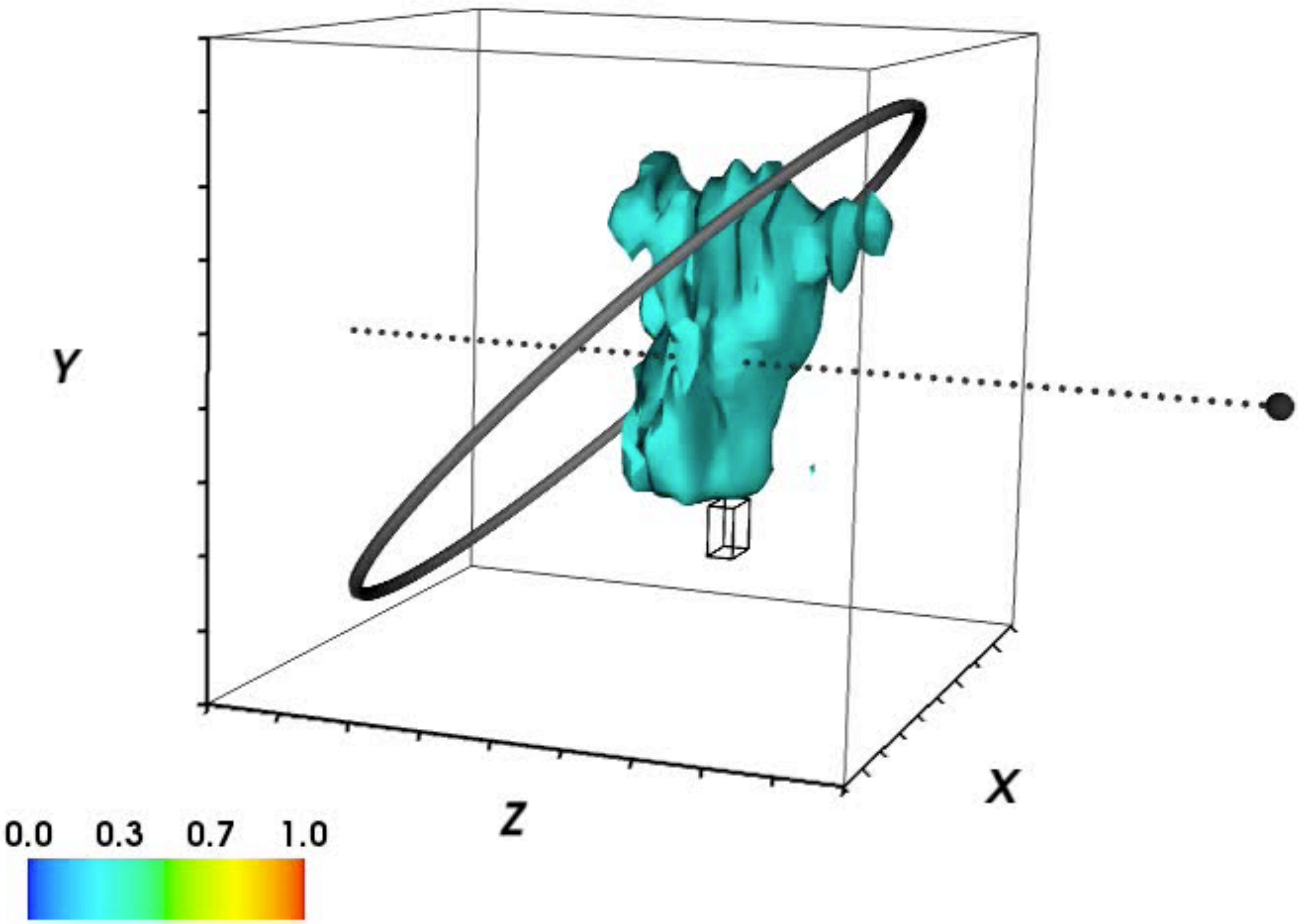



Two dimensional original on-sky image
1
2
3
4
5
6
Optical slicing of the on-sky image
1
2
3
4
5
6
Spectral dipersion of the sliced image
Wavelengths
Computer reconstruction of the 3D data cube
Spectrum of each 2D pixel
800
600
400
200
0
2.0
2.1
2.2
2.3
Spatial in Y
Spatial in X
Spectral Dimension
Computer reconstructed image





MUSE on the VLT


Y
Z
X
0.0
0.3
0.7
1.0

Big data !

LSST

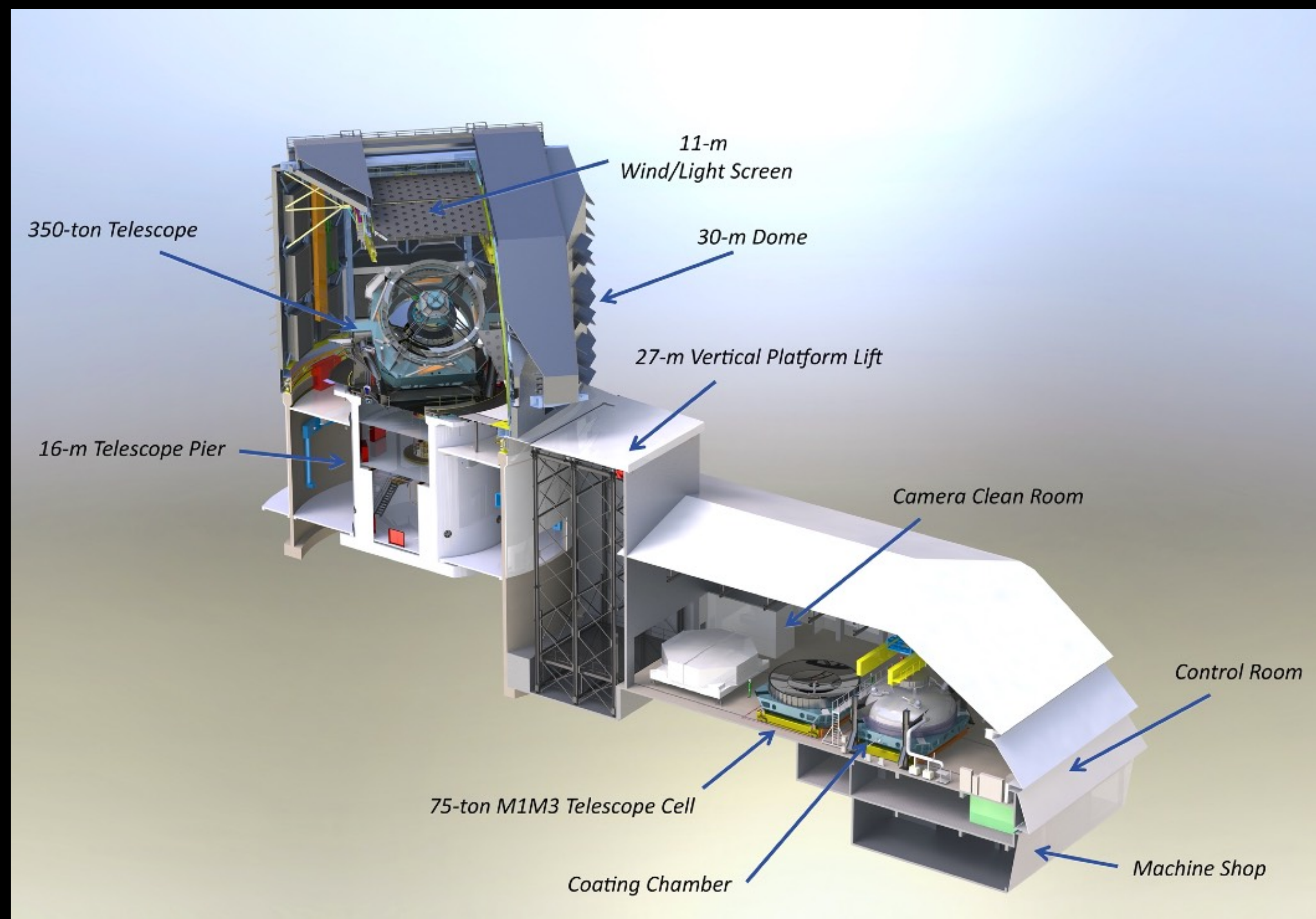
Legacy Survey of Space and Time

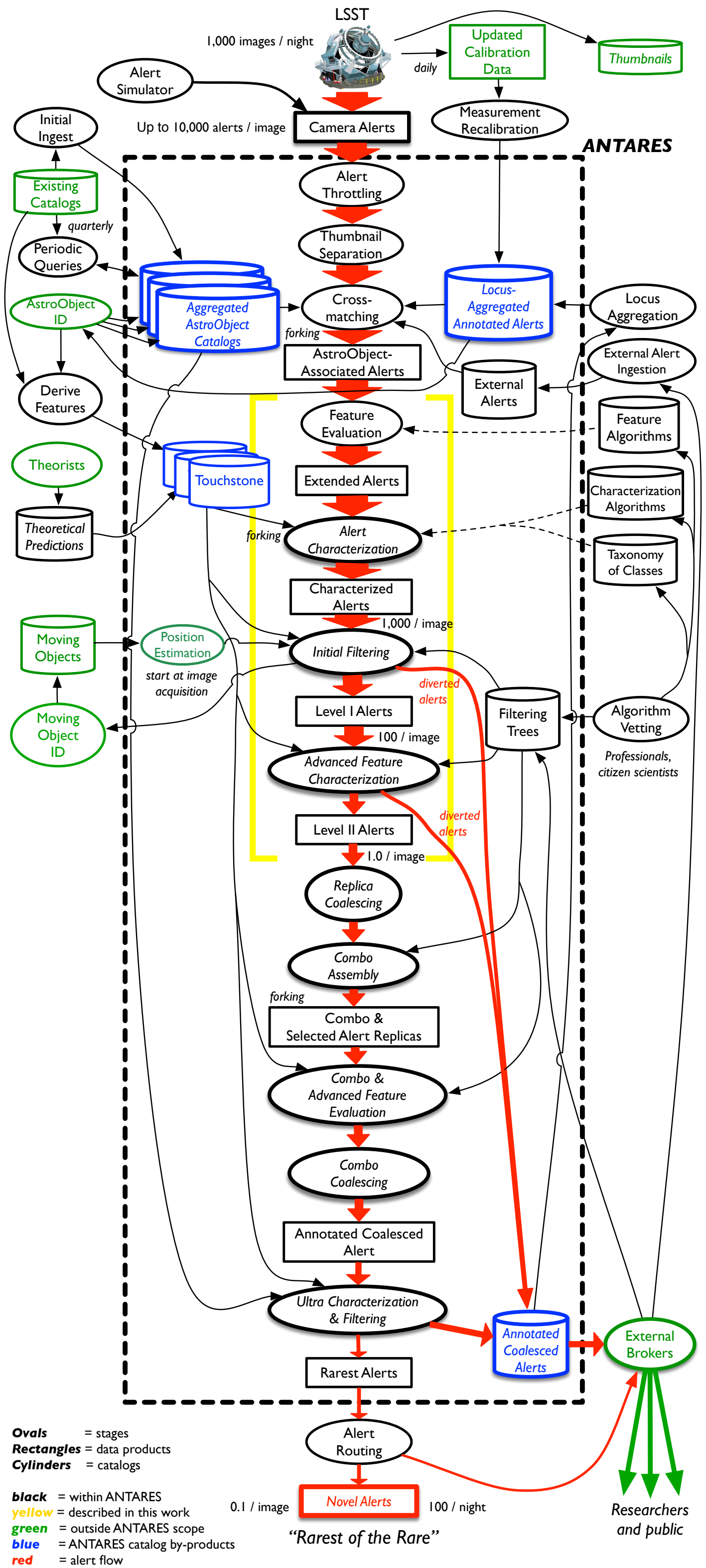
- Vera C. Rubin Observatory with 8.4 m primary mirror
- 3.2 Gpixel camera (3.5 deg FOV; full moon ~0.5 deg)
- 1000 images per night - 9600 deg^2 (41 250 deg^2 in the whole celestial sphere)
- ~450 calibration exposures
- ~20 TB of raw data per 24 hr
- 10^7 “alerts” per night
- Final data: 0.5 Exabytes
- Final database: 15 PB

Petabyte = 1000 TB

Exabyte = 1000 PB

- operational in end of 2023 !





1000 images (~20 terabytes of raw data) / night

~10^7 alerts per night

~10^6 alerts per night

~10^3 alerts per night

~10^2 alerts per night

SKA
SQUARE KILOMETRE ARRAY

Already, the first phase of the SKA will produce ~260 TB of raw data per second (~1 Exabytes per hour) !!