(Some) basics of astronomical observations and data processing

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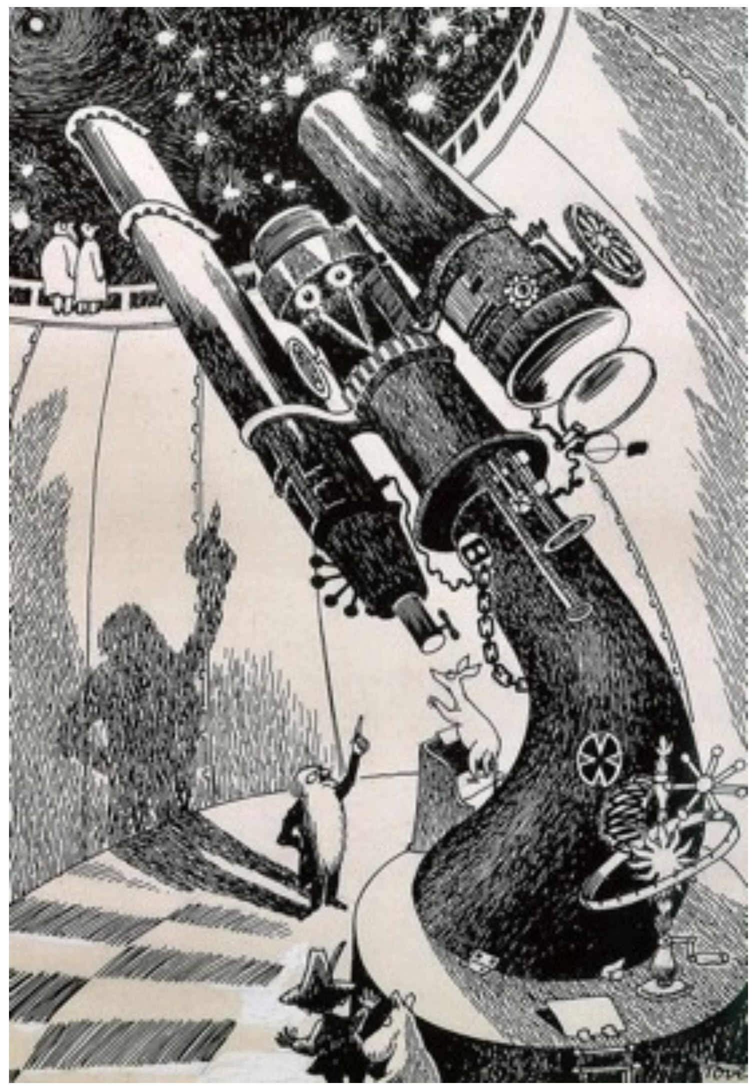
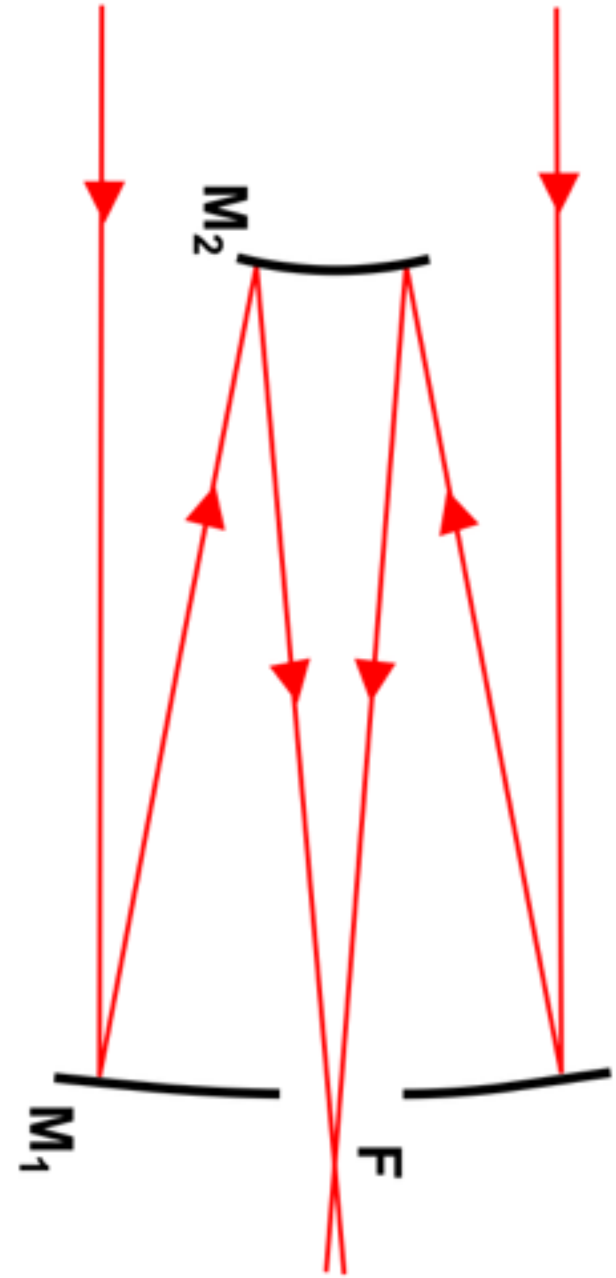


Tove Janson, 1946

Astronomical observations

Telescopes

Nordic Optical Telescope, La Palma, Canary Islands



Telescopes

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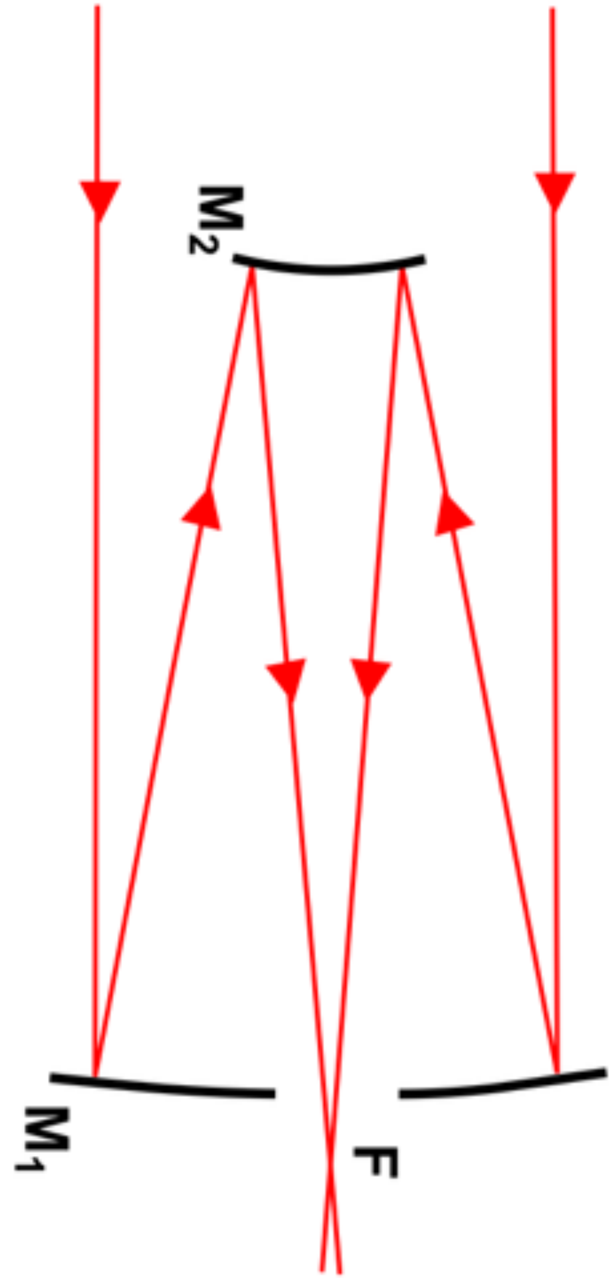
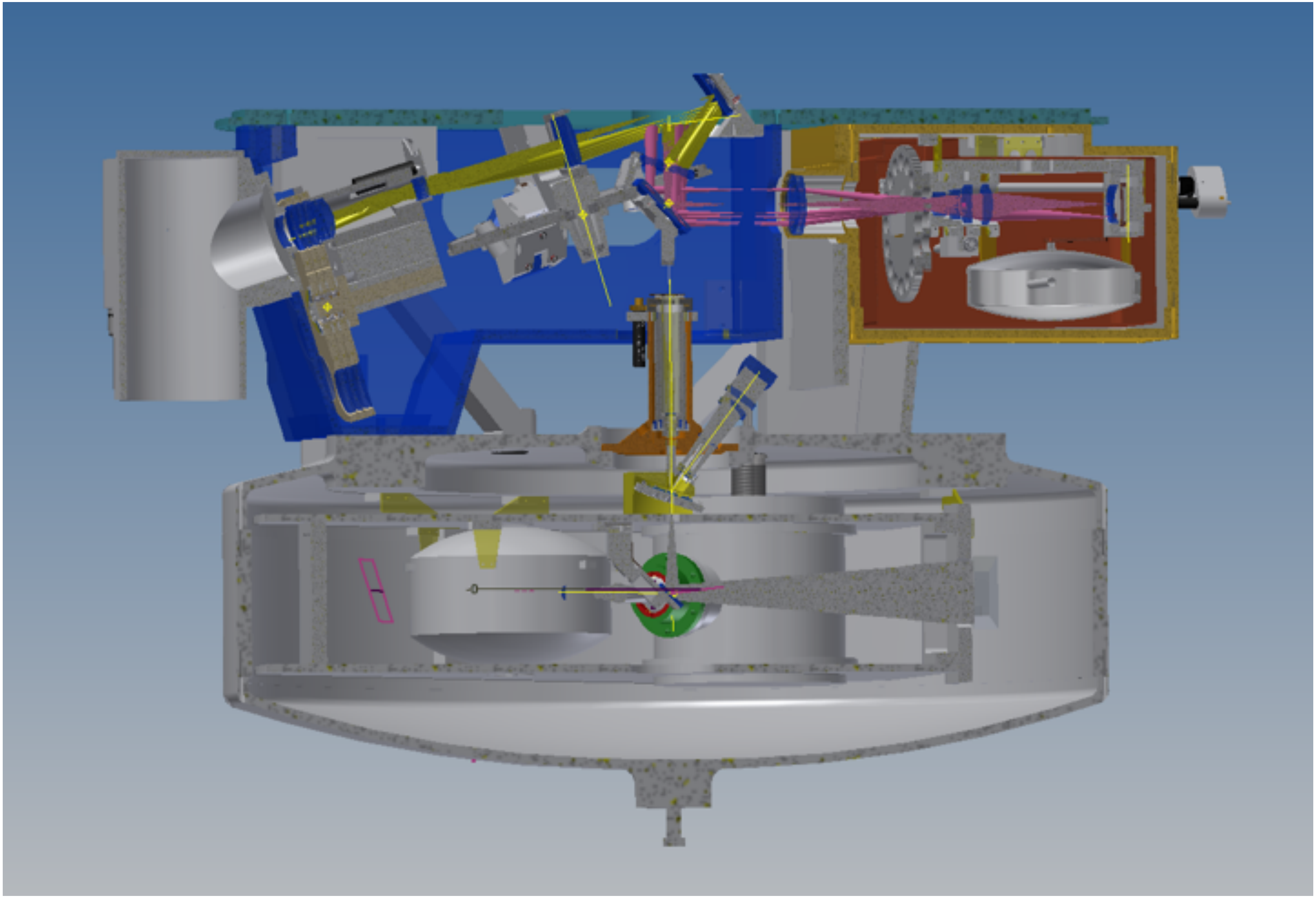


Astronomical instruments



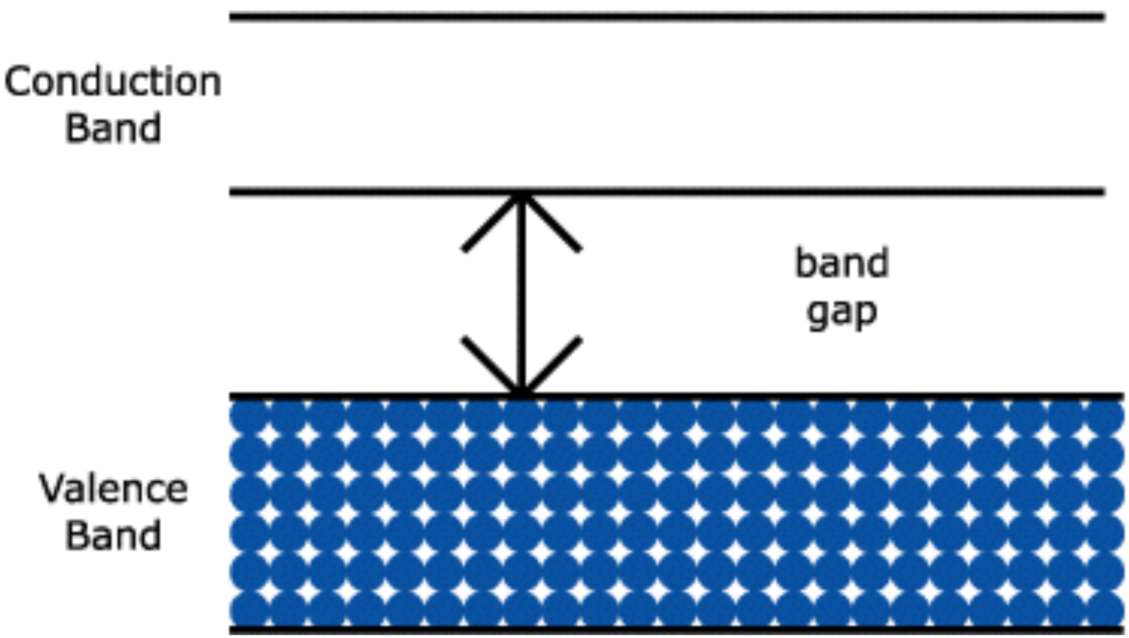
The Nordic Transient Explorer (NTE) being built by the Niels Bohr Institute

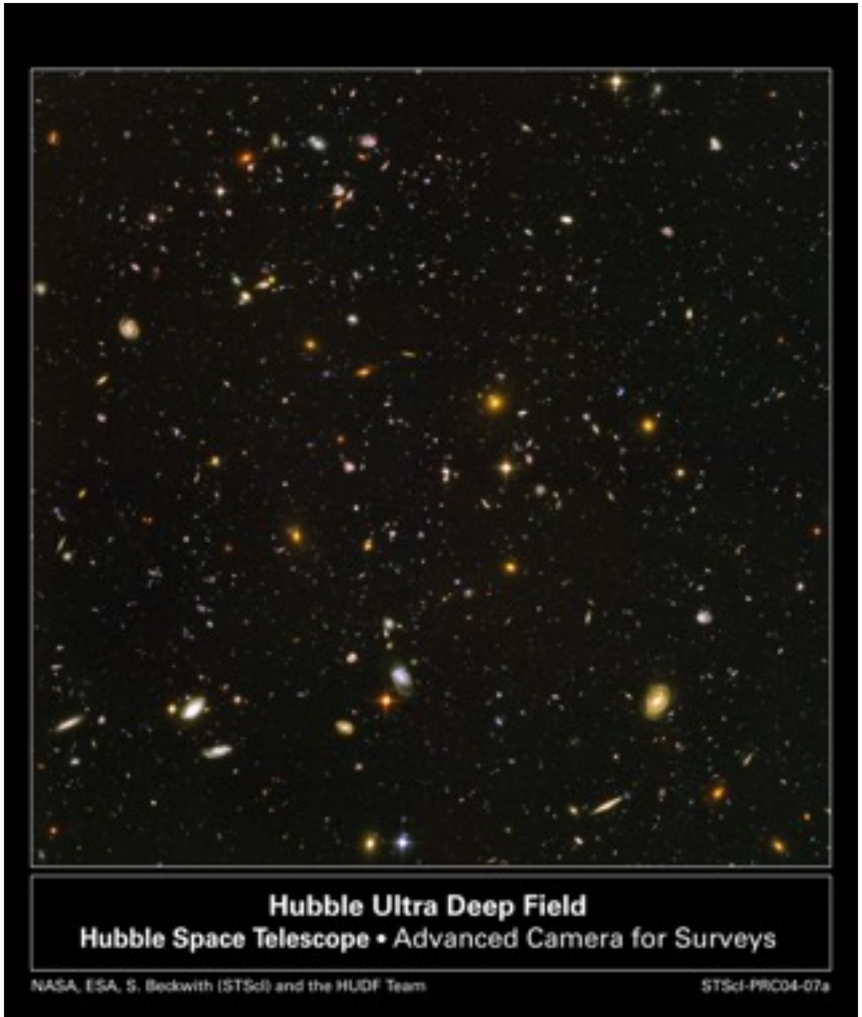
Observing modes

- Visitor mode (researcher travels to the observatory for the observations)
- Service mode (observations carried out by the observatory staff)
- Target of Opportunity (interrupting the scheduled observations)
- Remote observations (for educational use)


Basic principles of a charge-coupled device (CCD)

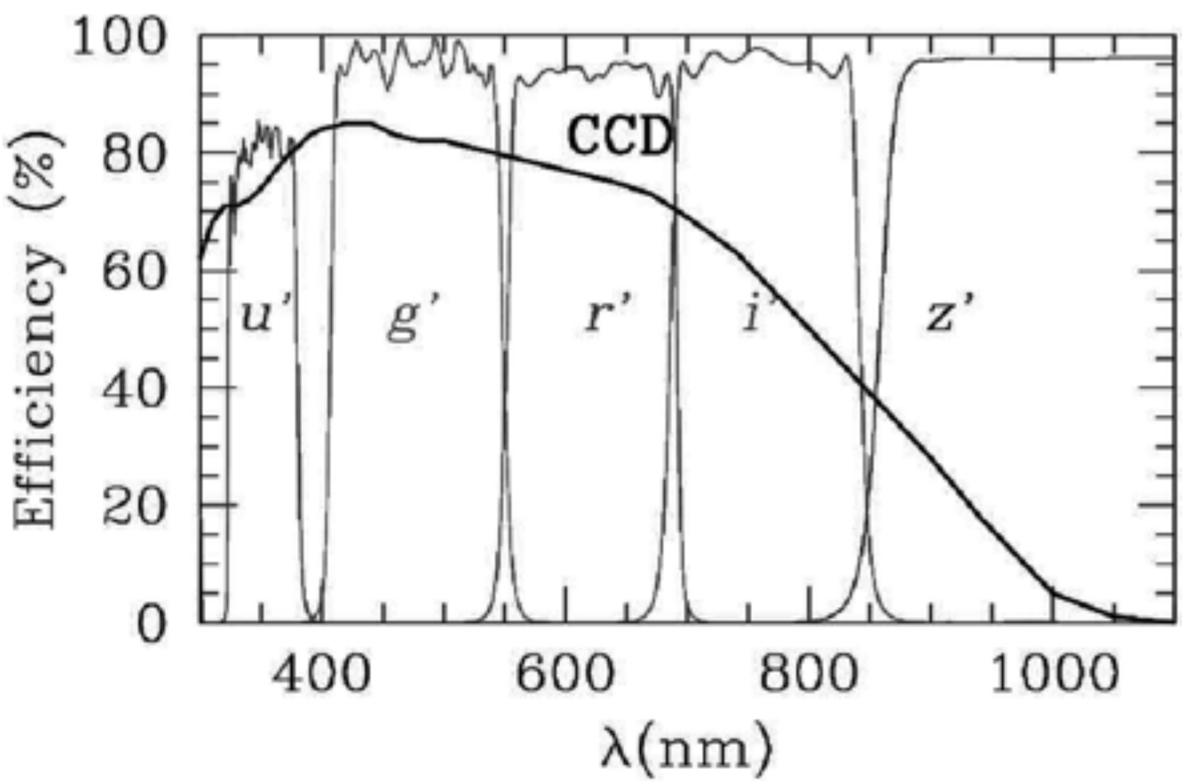
- Photoelectric effect – silicon exhibits an energy gap between the valence and conduction bands
- Incoming photons with a suitable energy interact with the Si atoms and excite valance electrons into the the conduction band
- An electric field applied for capturing the free electrons, this way a CCD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





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

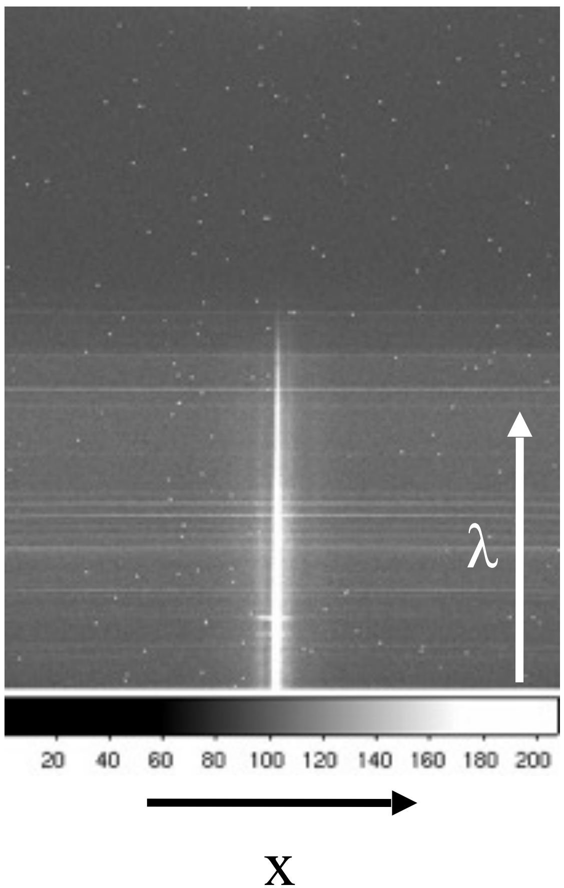


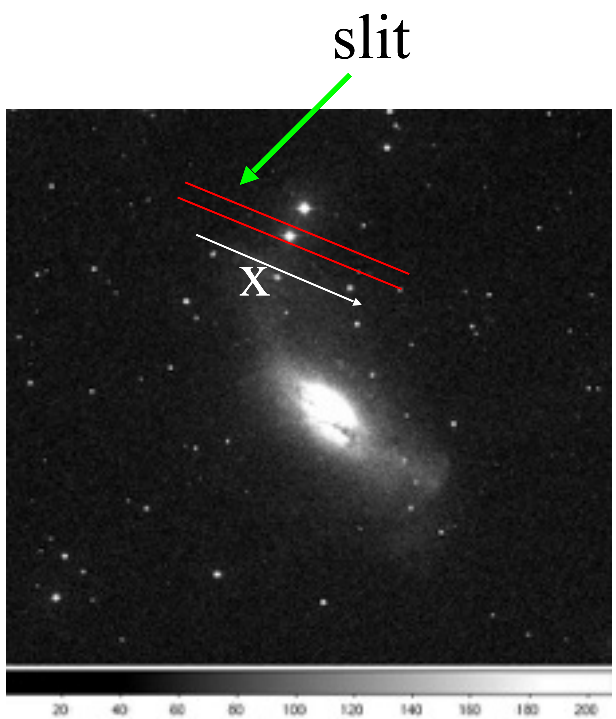
The Cosmic Bird

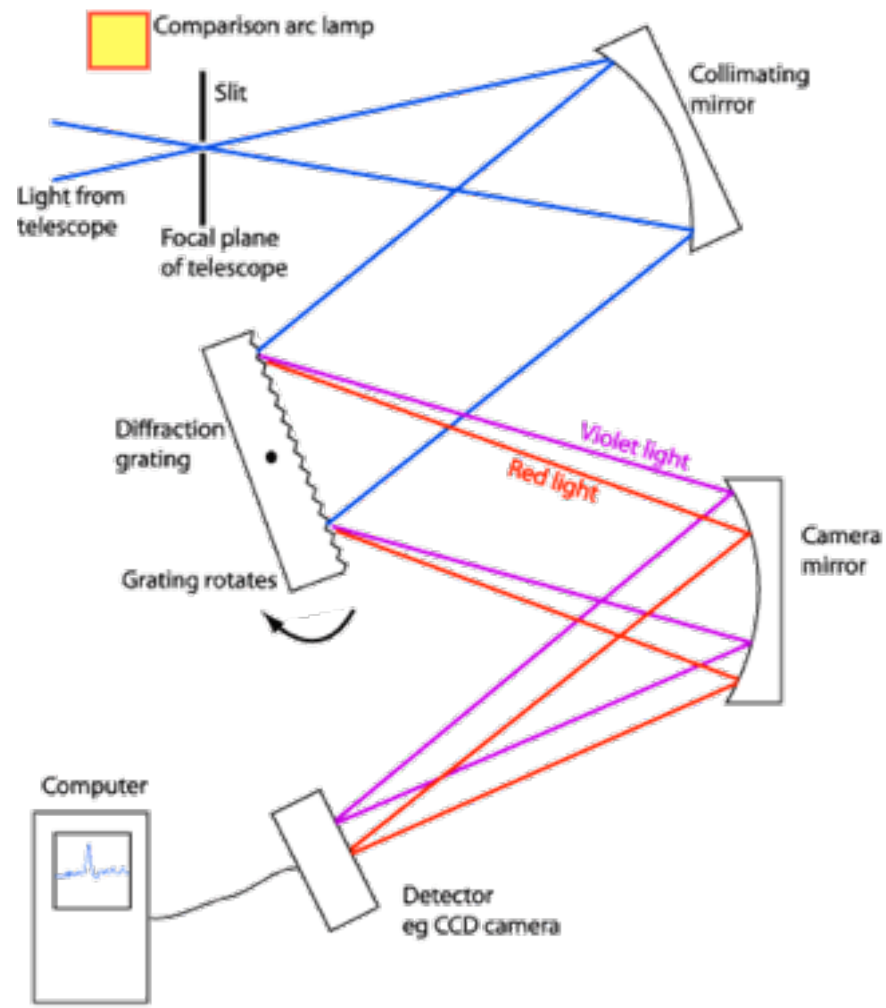
ESO Press Photo 54a/07 (21 December 2007)

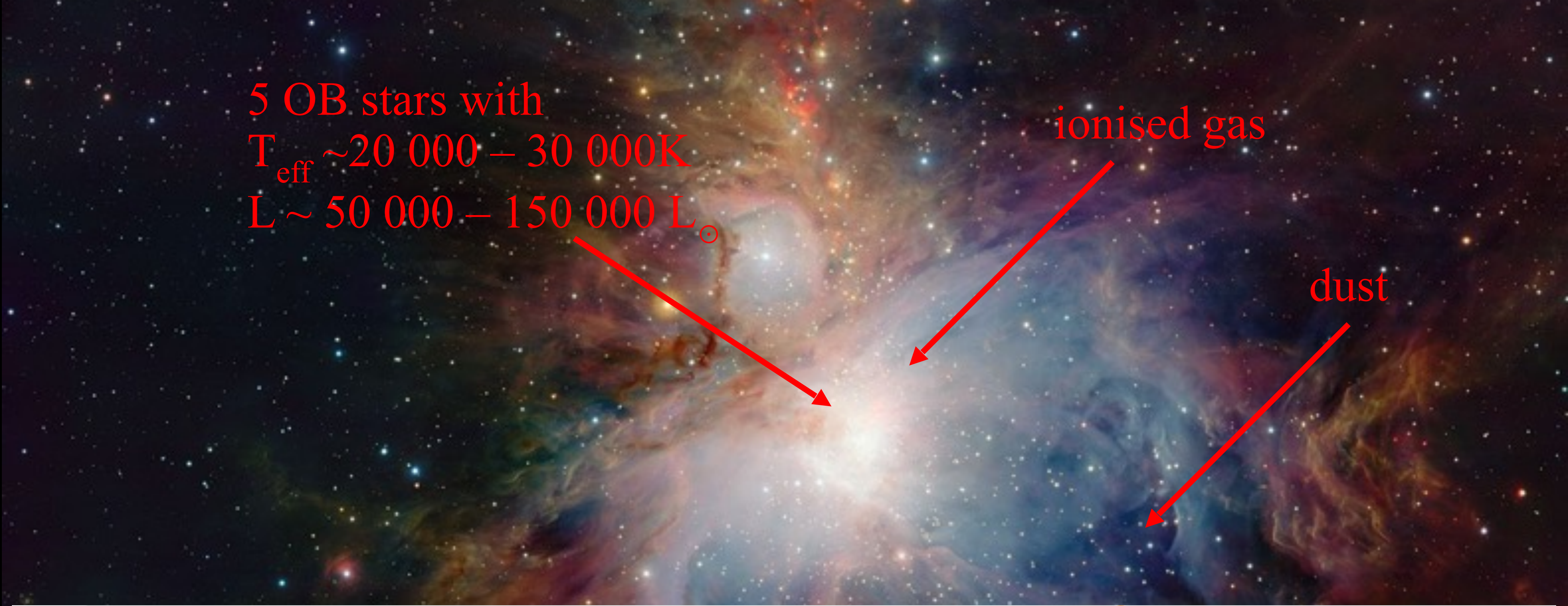
Spectroscopic observations

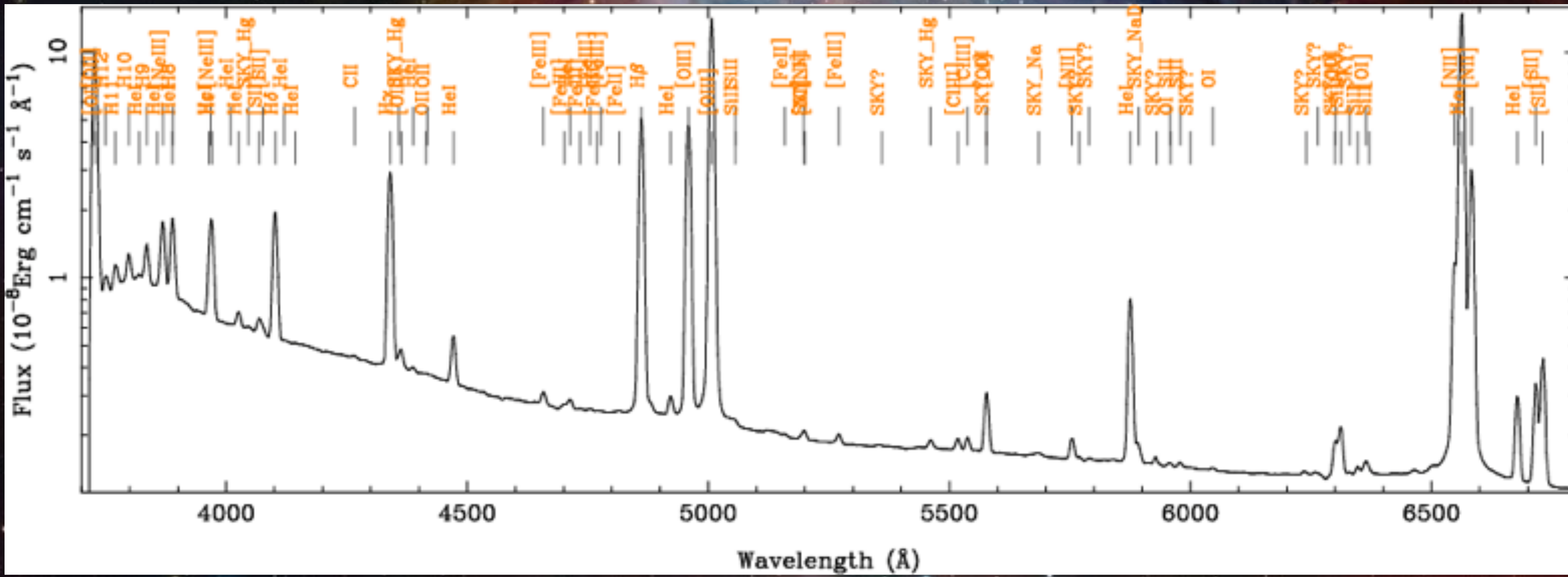
- Determine the flux density as a function of wavelength (spectral energy distribution, spectral lines, physical conditions, velocities etc.)
- Use a mask with a narrow aperture (slit) to cut the 2D image to 1D
- Use a diffraction grating (or a grism) to disperse the incident light beam into spectrum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








5 OB stars with
T_{eff} ~20 000 – 30 000K
L ~ 50 000 – 150 000 $L_\odot$
ionised gas
dust


Flux (10^{-8}Erg cm^{-1} s^{-1} Å^{-1})
10
1
4000
4500
5000
5500
6000
6500
Wavelength (Å)

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

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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
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TELESCOP= 'ESO-VLT-U4'         / ESO Telescope Name
INSTRUME= 'NAOS+CONICA'        / Instrument used
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DEC     =                 -69. / -69:16:11.1 DEC (J2000) pointing (deg)
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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)
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OBSERVER= 'UNKNOWN '           / Name of observer
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HIERARCH ESO OBS OBSERVER = 'UNKNOWN ' / Observer Name
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HIERARCH ESO TPL DID = 'ESO-VLT-DIC.TPL-1.9' / Data dictionary for TPL
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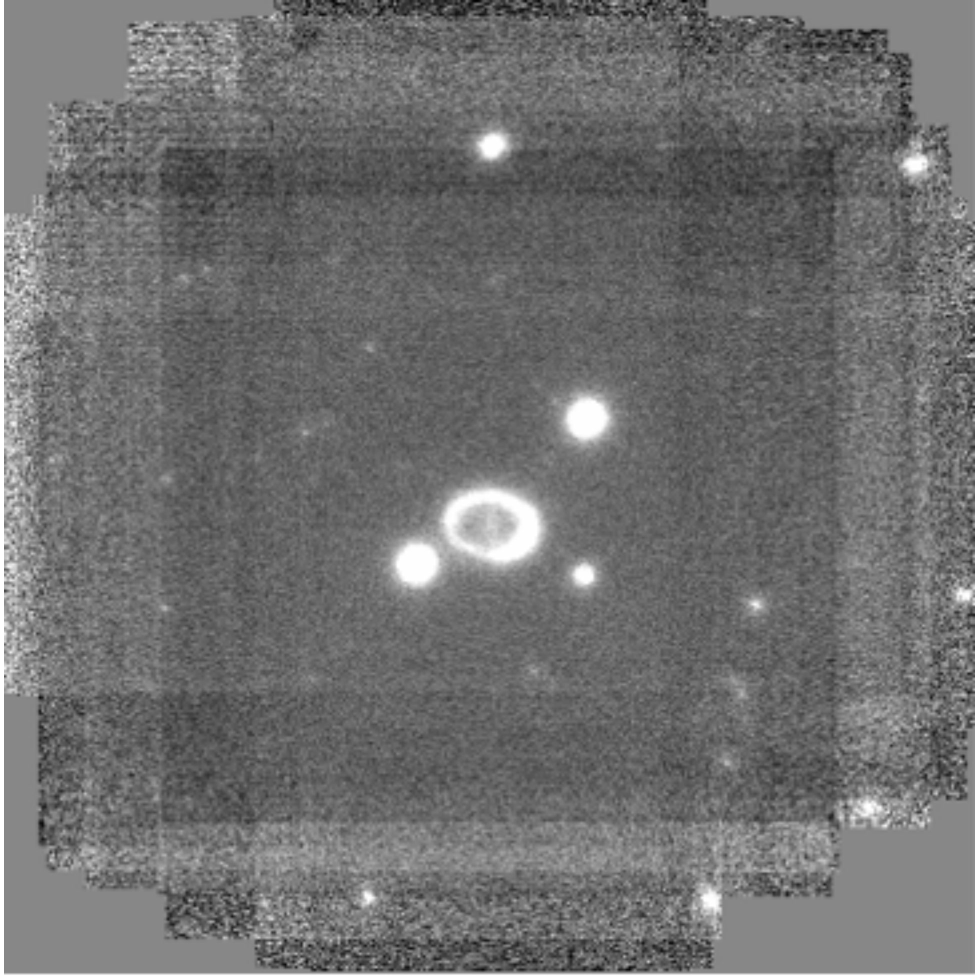


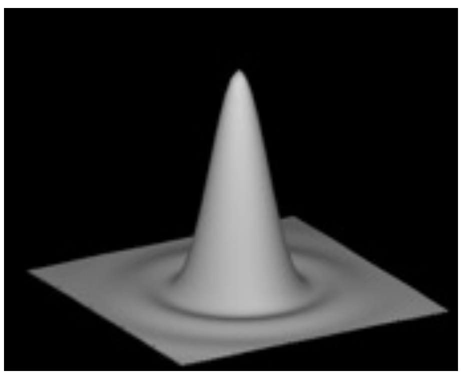
Flexible Image Transport System (FITS)

- 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

Point spread function (PSF)

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

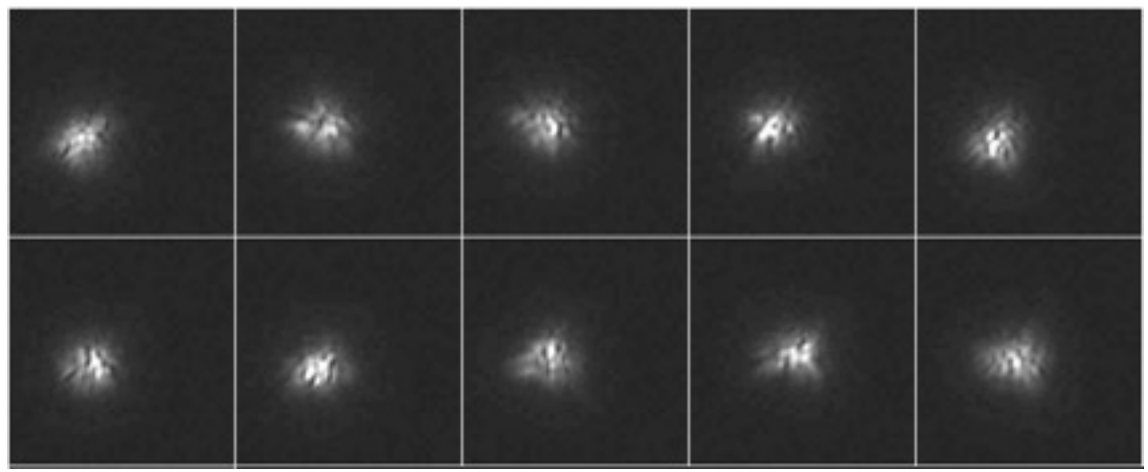
• Determines the spatial resolution of an observation
• Can be measured and modelled using stars (point-sources) present in the astronomical images
• Knowing the PSF allows precise astrometric and photometric measurements by PSF fitting techniques and detection of variability by image subtraction



Ideal (diffraction limited) PSF if no atmosphere

$\theta \sim 1.22 \times \lambda / D$

(where λ is wavelength, D the diameter of the telescope and θ is in radians)



Atmospheric turbulence broadens the PSF resulting in a Gaussian PSF (seeing)

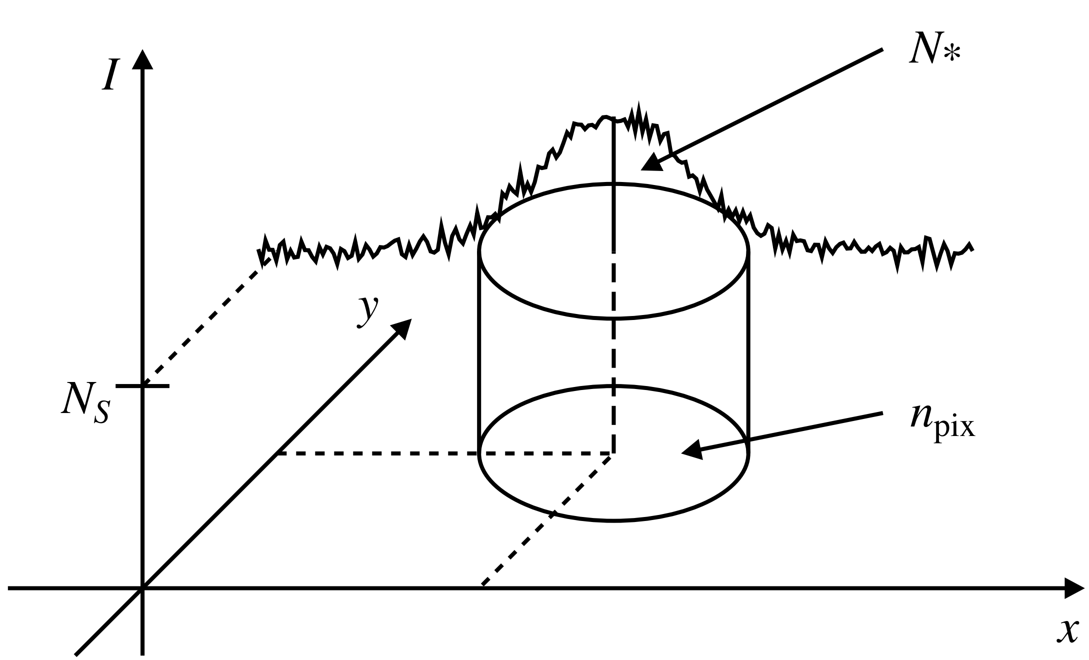
Signal-to-Noise Ratio

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

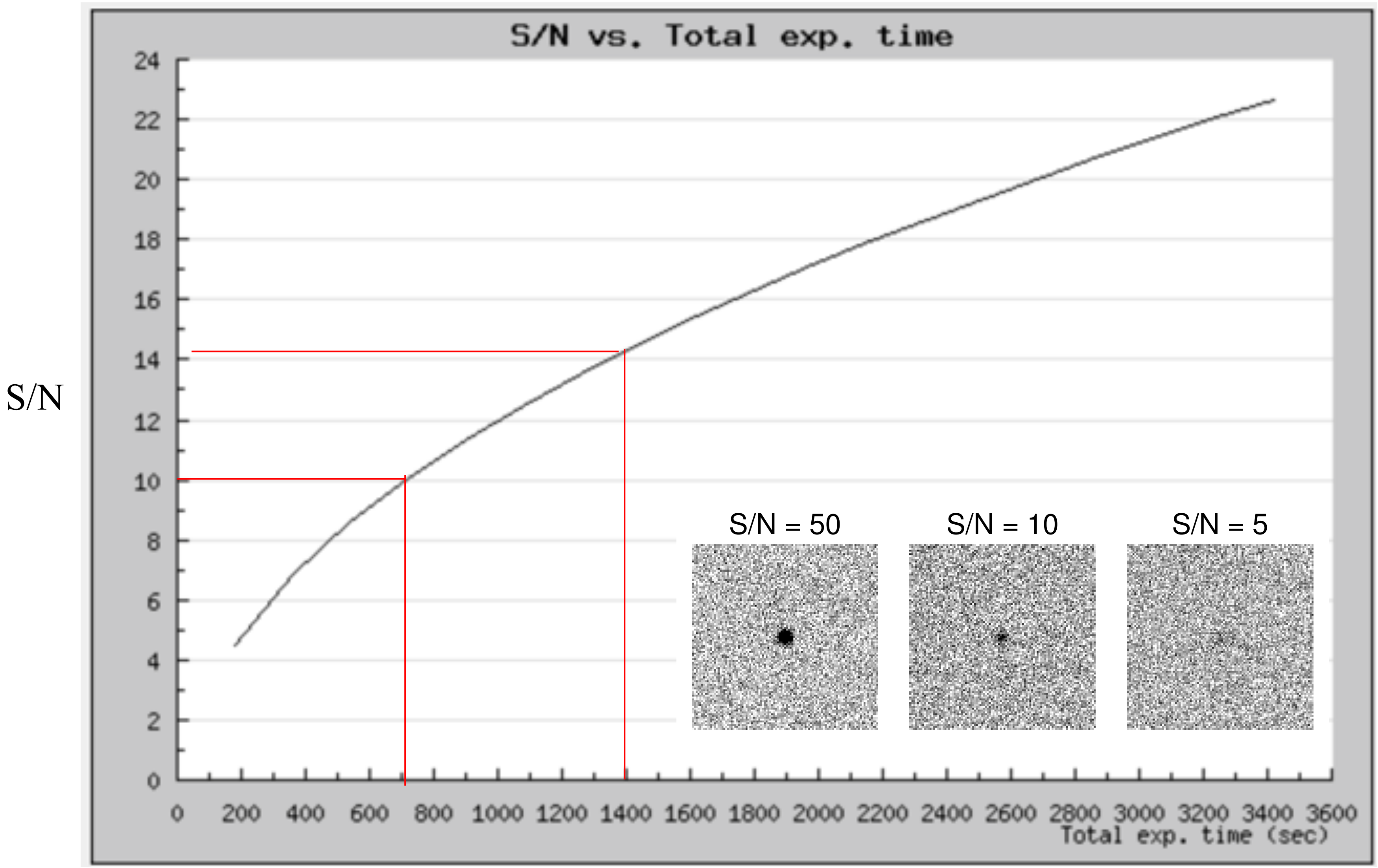
$$\frac{S}{N} = \frac{signal}{\sqrt{noise_1^2 + noise_2^2 + \ldots + noise_n^2}}$$

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

- Determines the integration time required for your observation

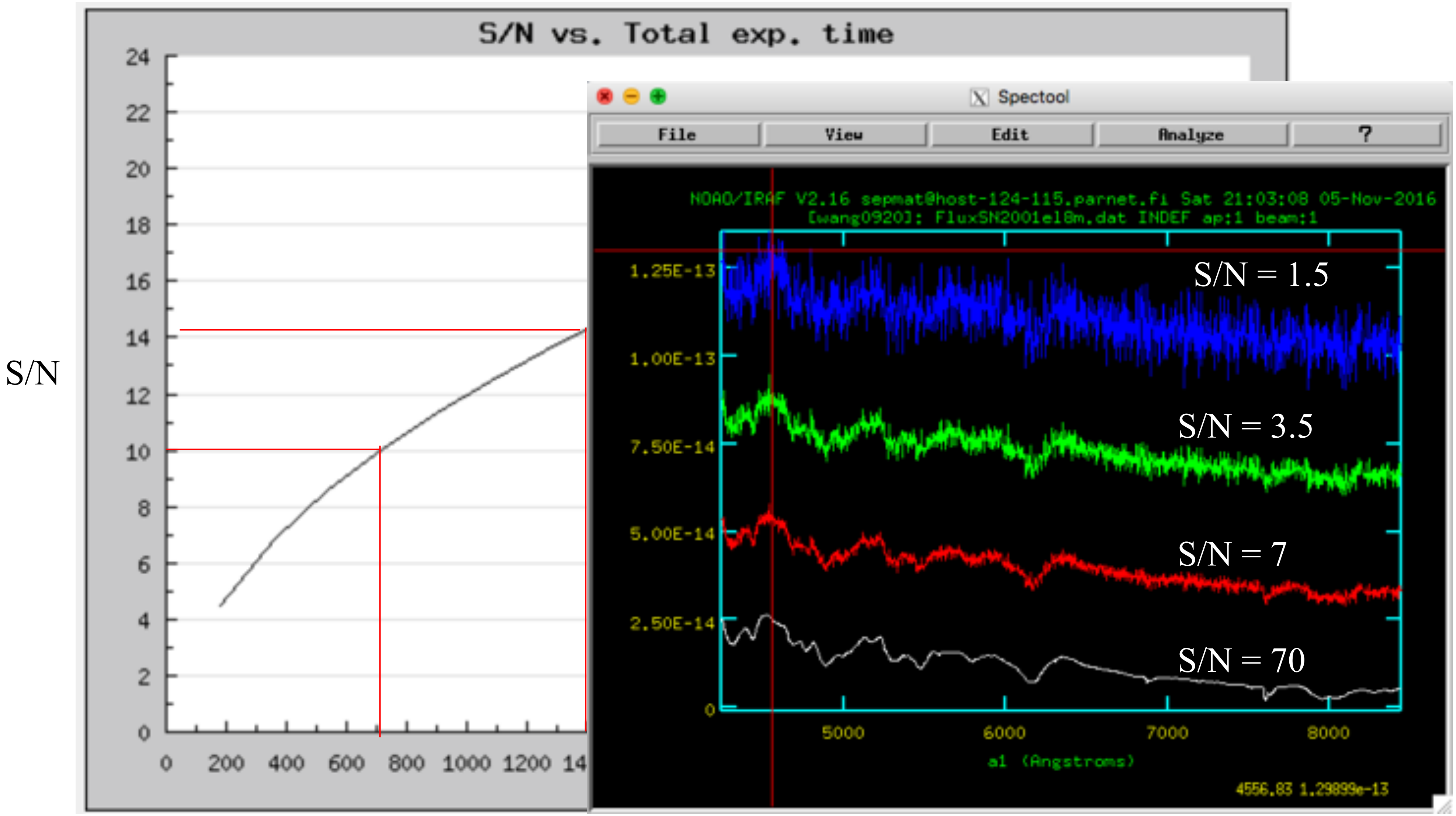


Signal-to-Noise vs. exp. time



Increasing exposure time by x2 only increases S/N by x sqrt(2)

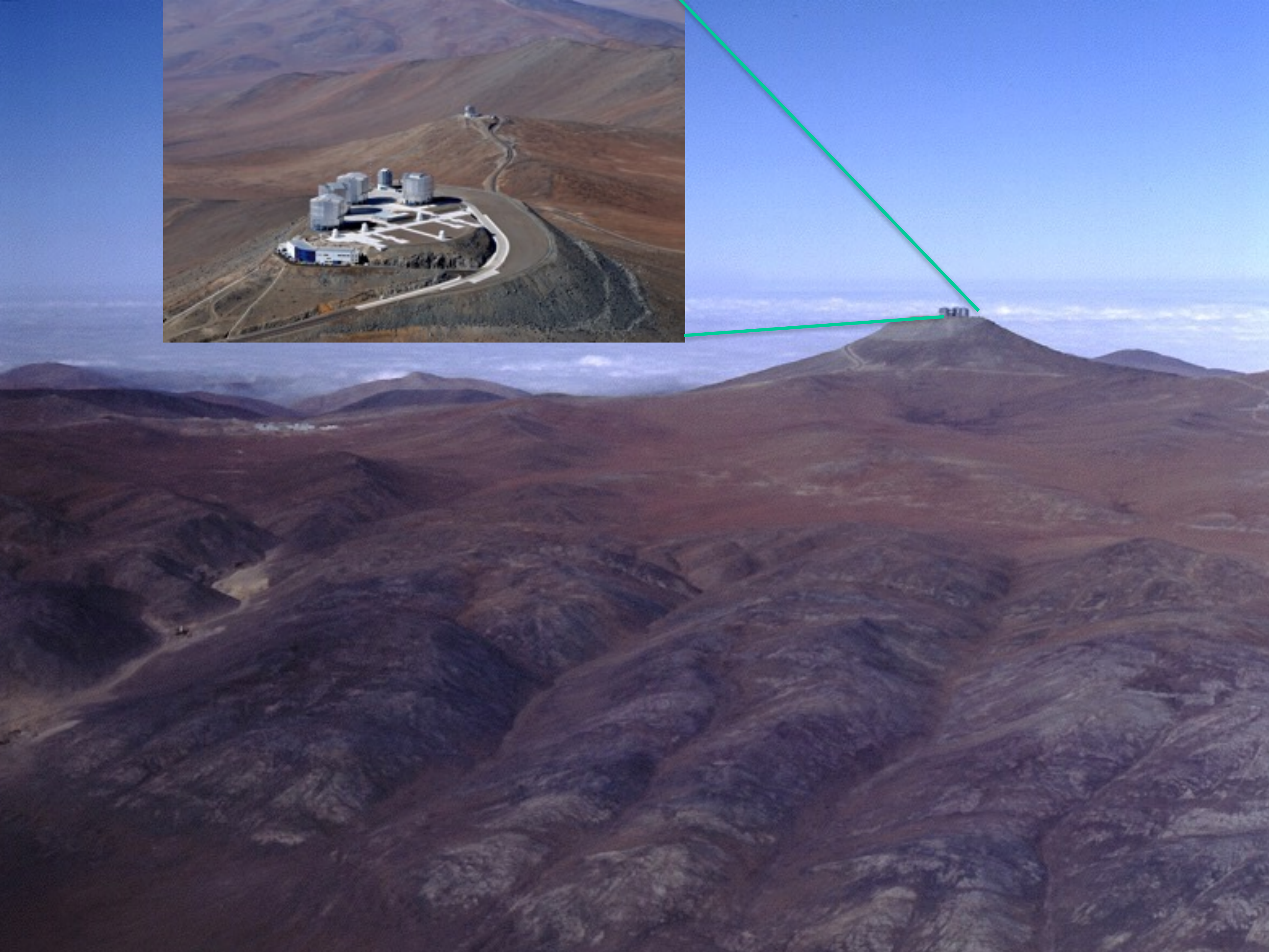
Signal-to-Noise vs. exp. time



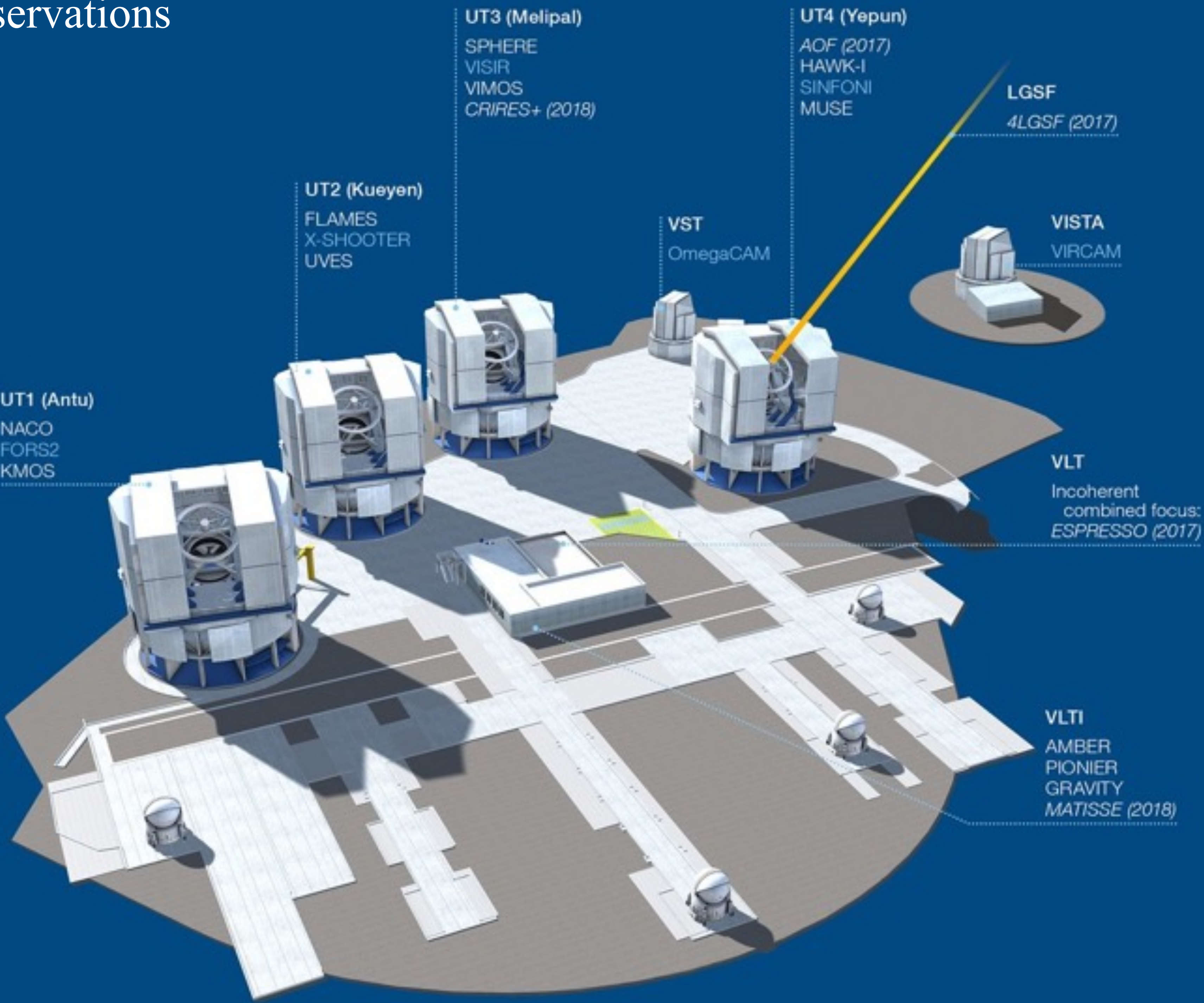
Increasing exposure time by x2 only increases S/N by x sqrt(2)

Astronomical observatories

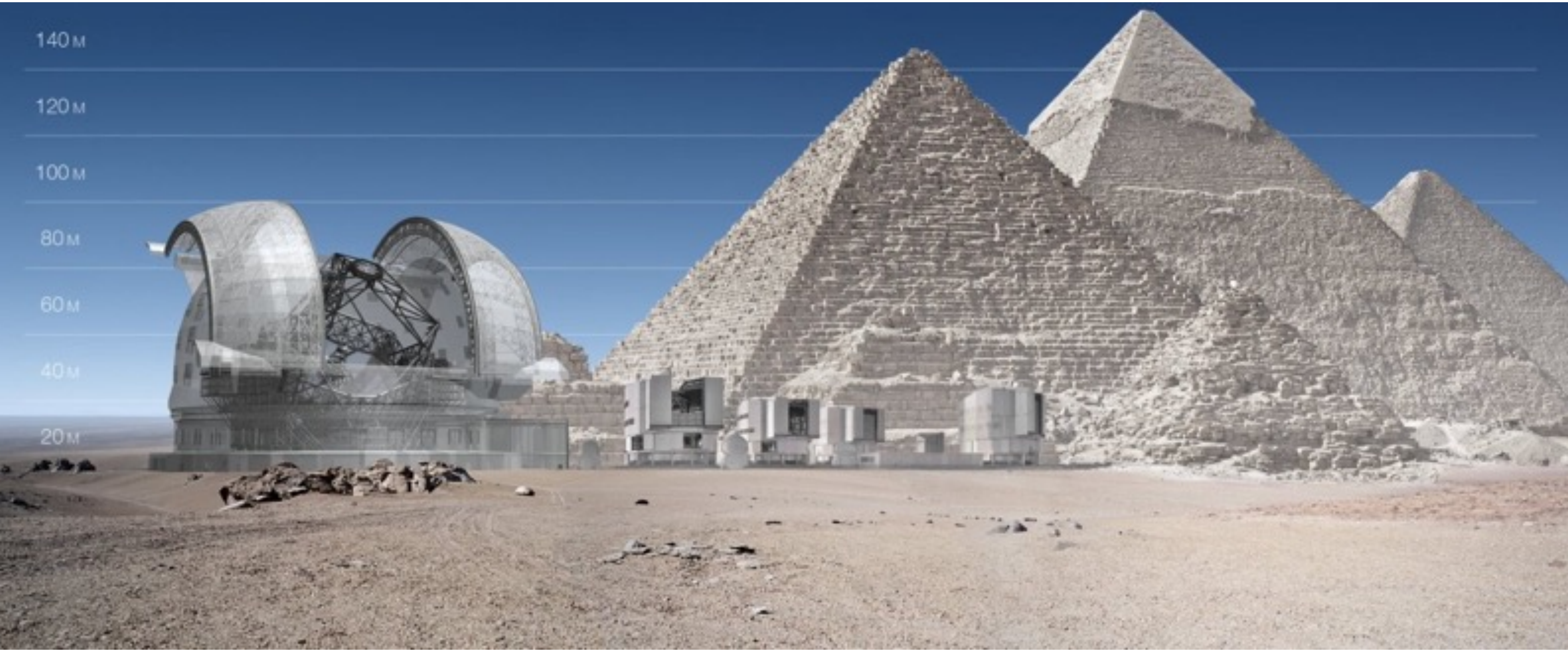
ESO'S OBSERVATION FACILITIES IN CHILE

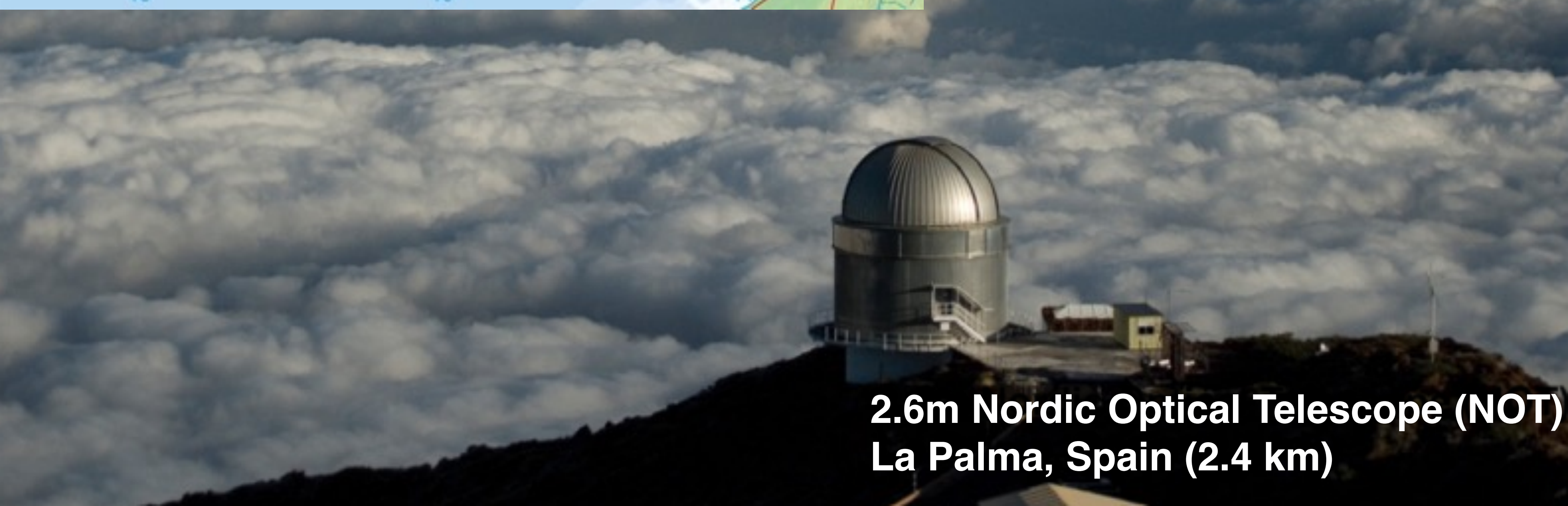


Very Large Telescope (VLT): 4 x 8.2 m telescopes for optical and infrared observations



Extremely Large Telescope (ELT): 39 m telescope for optical and infrared observations (first light 2024)



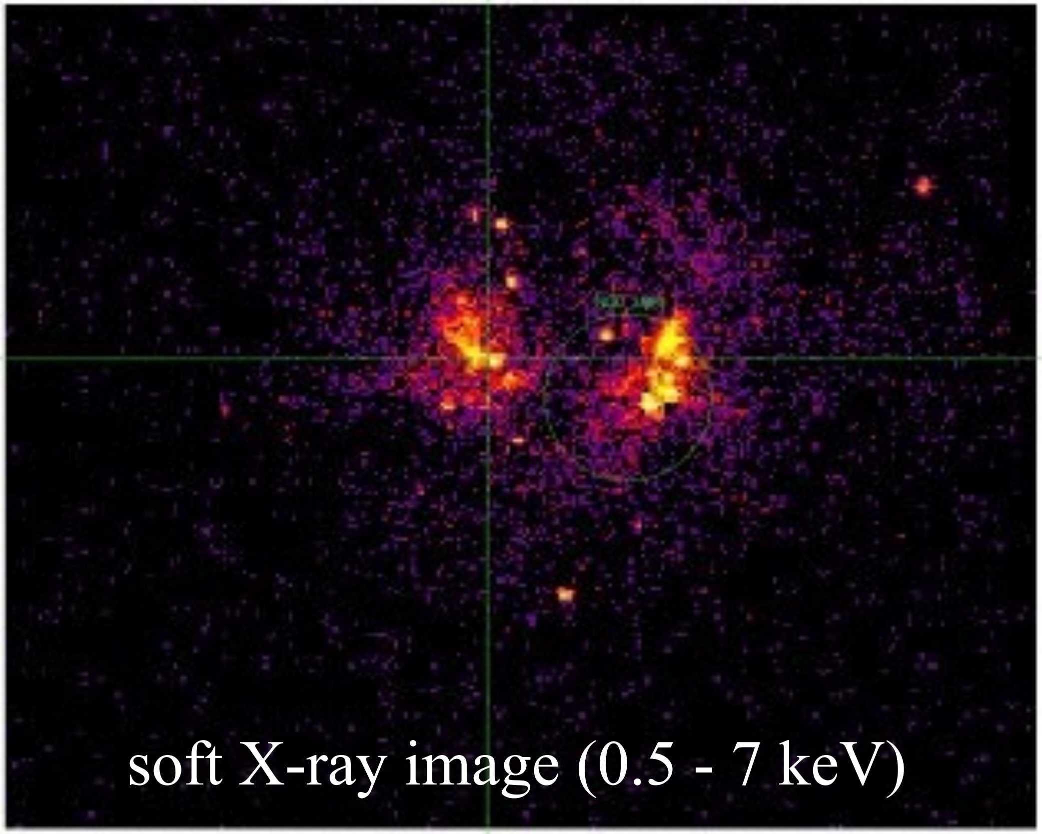


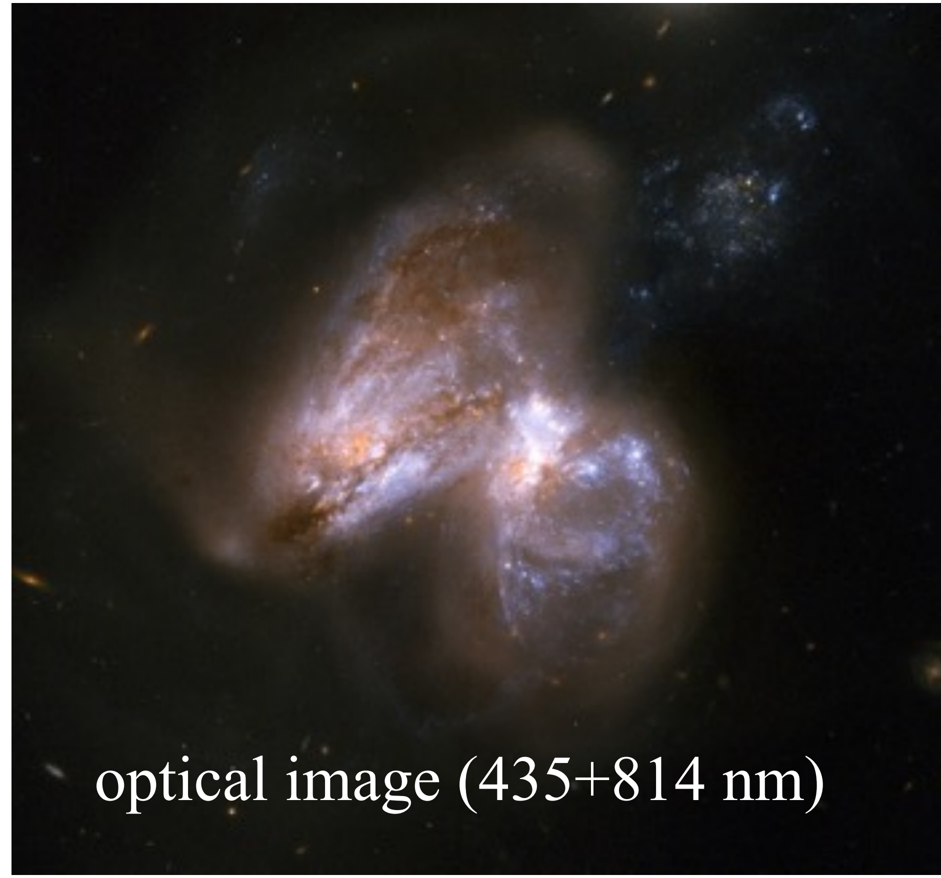
2.6m Nordic Optical Telescope (NOT)
La Palma, Spain (2.4 km)

Atacama Large Millimeter Array (ALMA):
66 x 12 meter antennas for interferometric radio observations
(350μm - 10 mm)

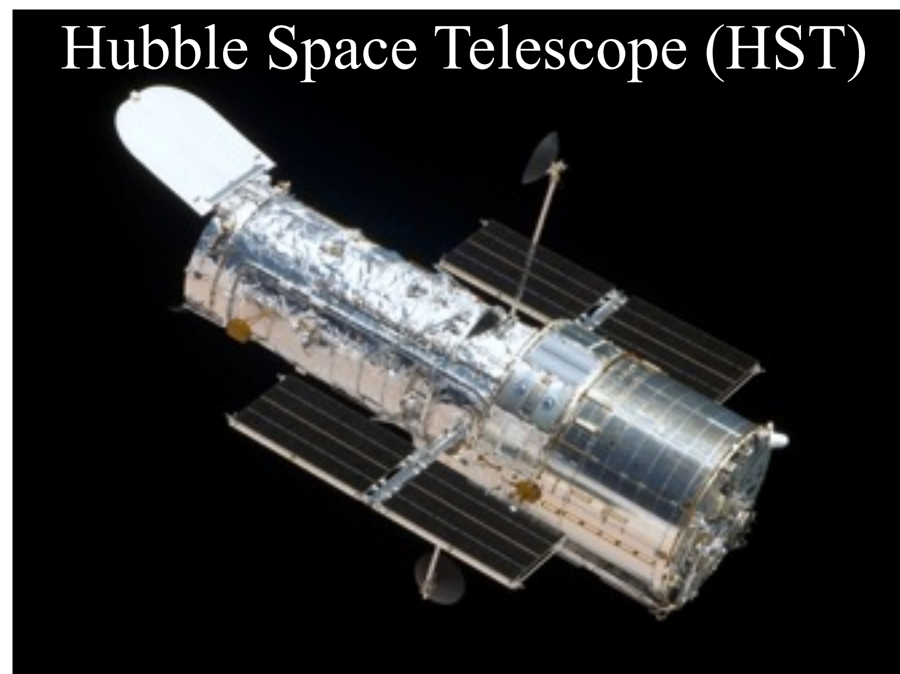
Global Very Long Baseline Interferometry (VLBI) Array: interferometric radio observations (cm wavelenghts)

Examples of astronomical imaging data

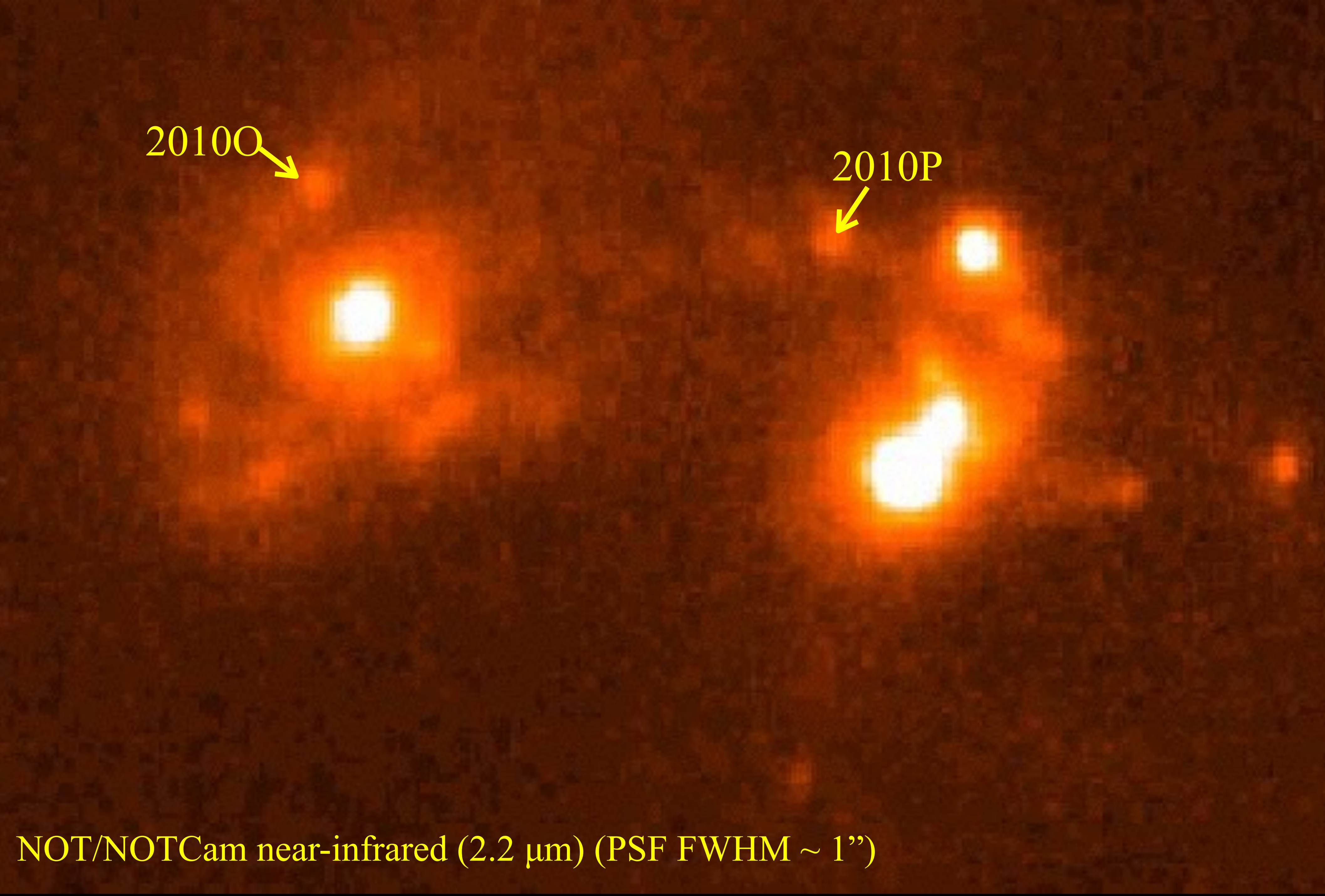

soft X-ray image (0.5 - 7 keV)

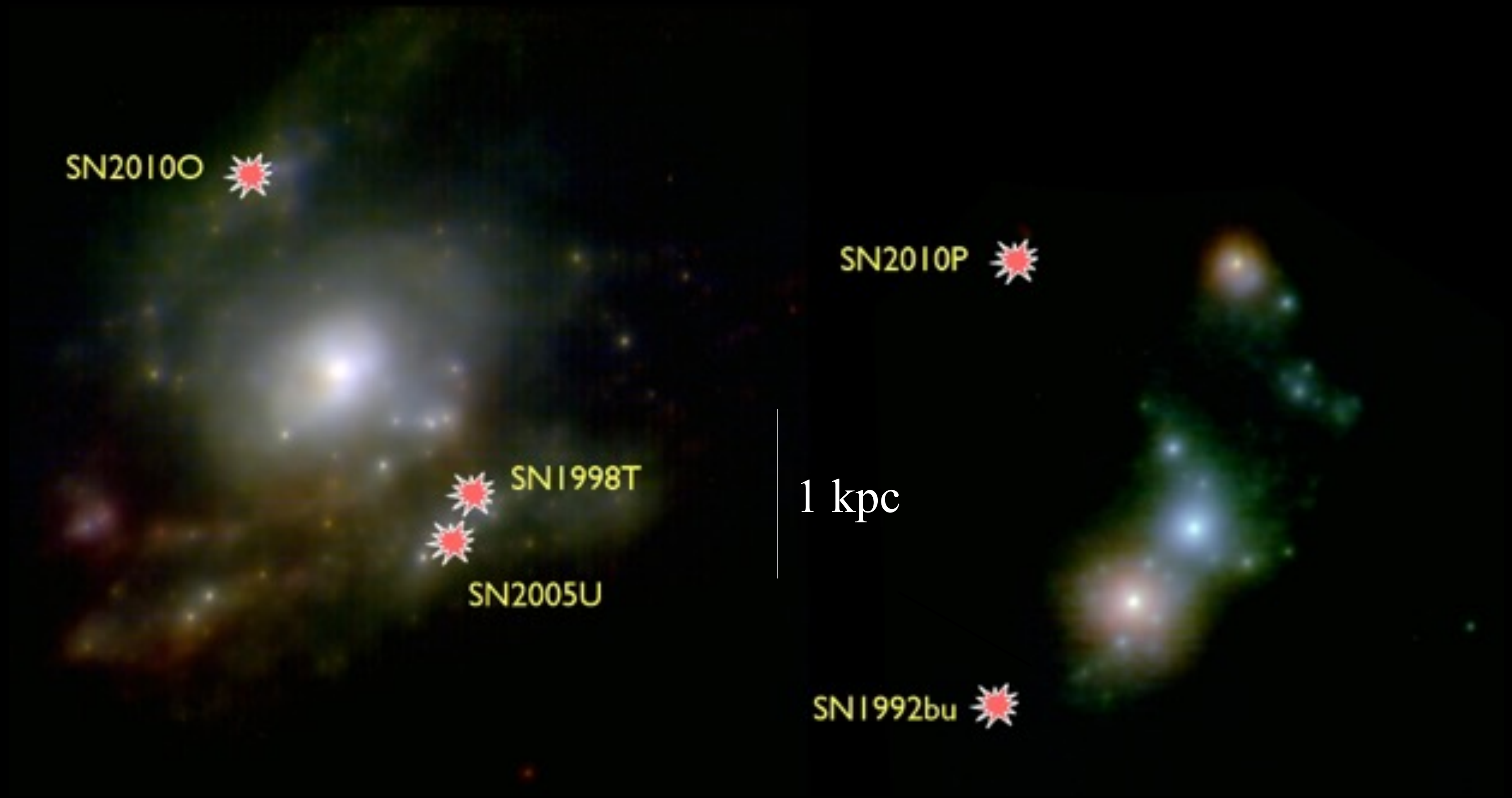

optical image (435+814 nm)


NASA Chandra X-ray observatory

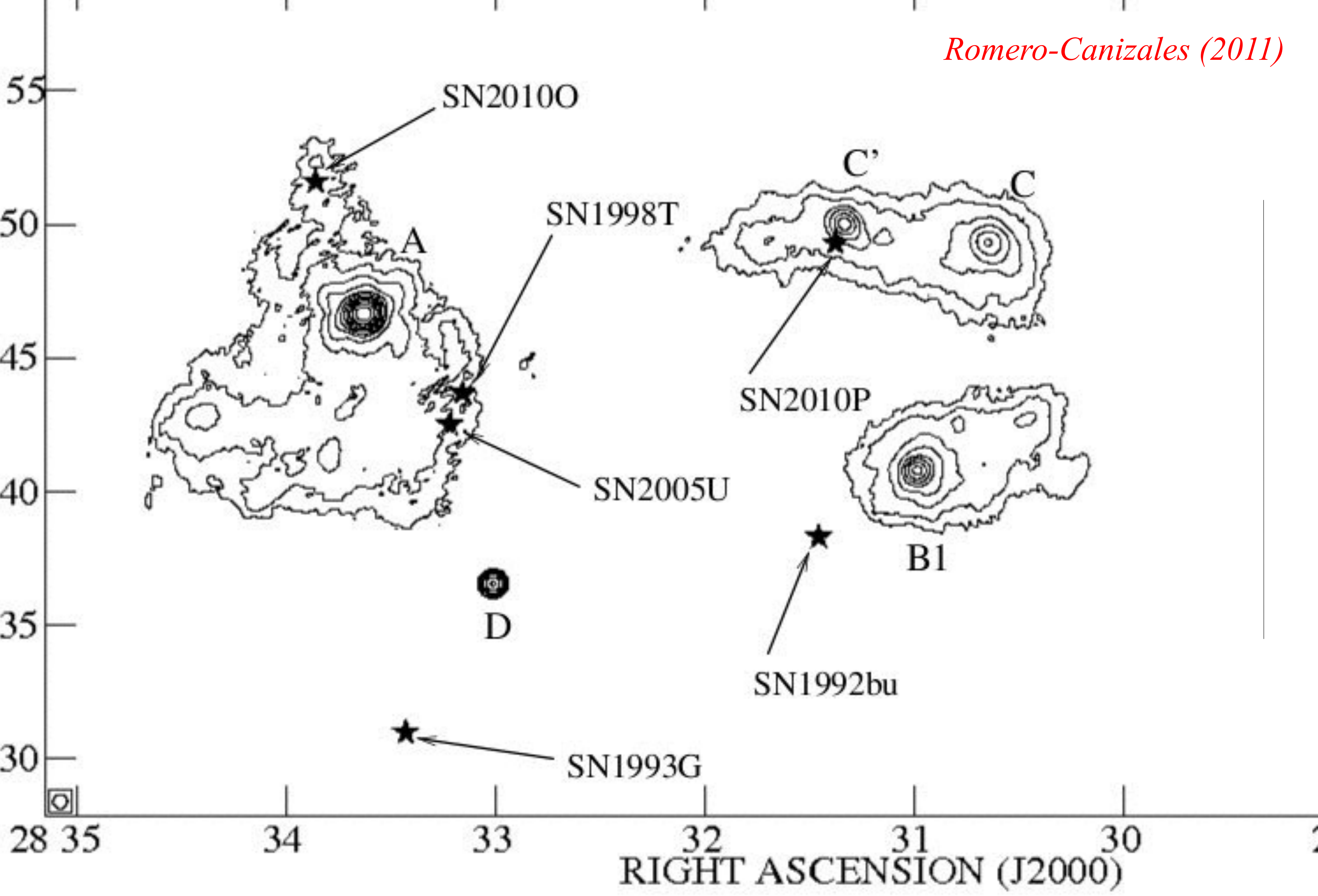

Hubble Space Telescope (HST)


Hubble Space Telescope (HST) optical (435 + 814 nm) (PSF FWHM ~ 0.1”)


2010O
2010P
NOT/NOTCam near-infrared (2.2 μm) (PSF FWHM ~ 1")

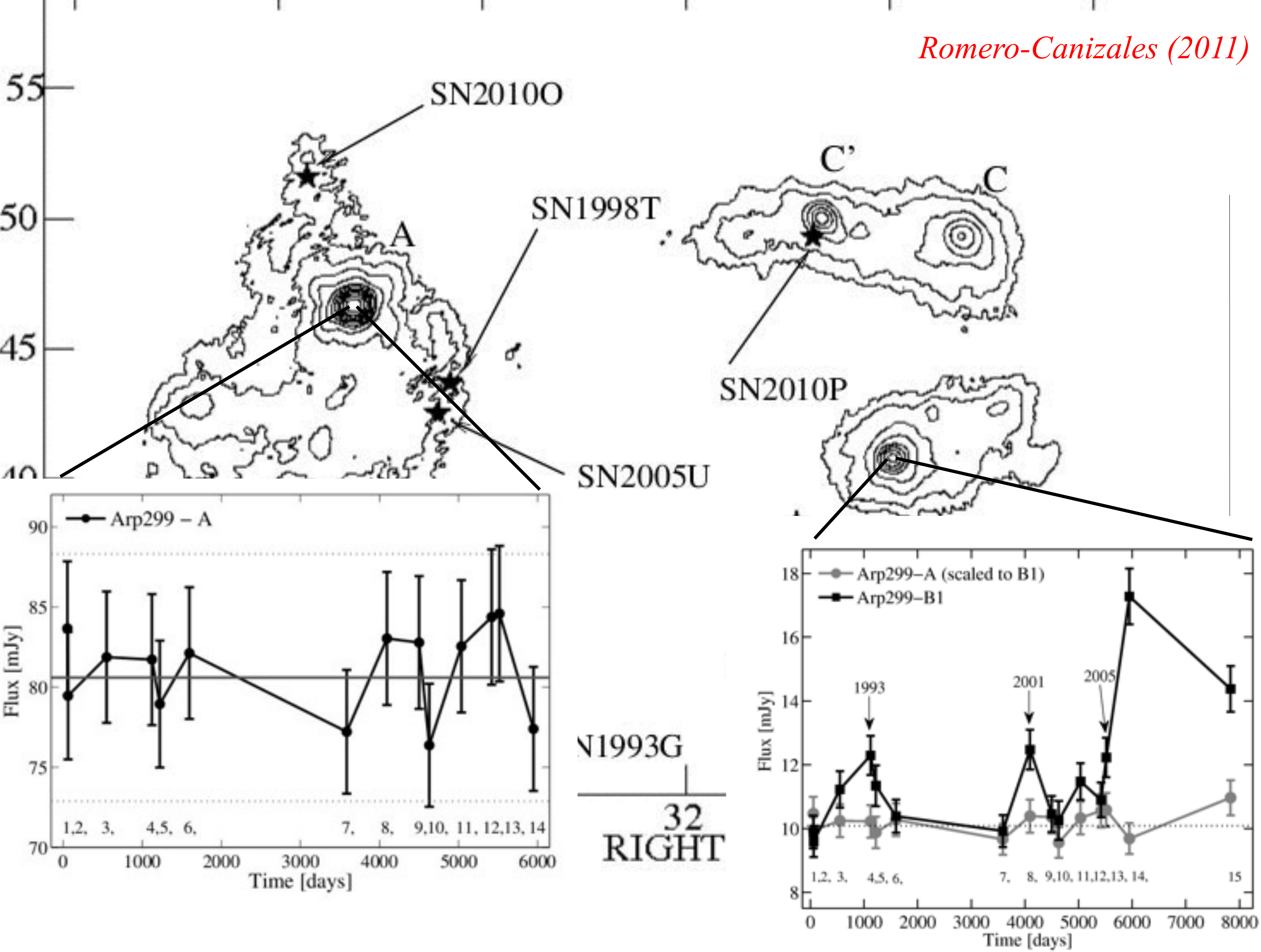


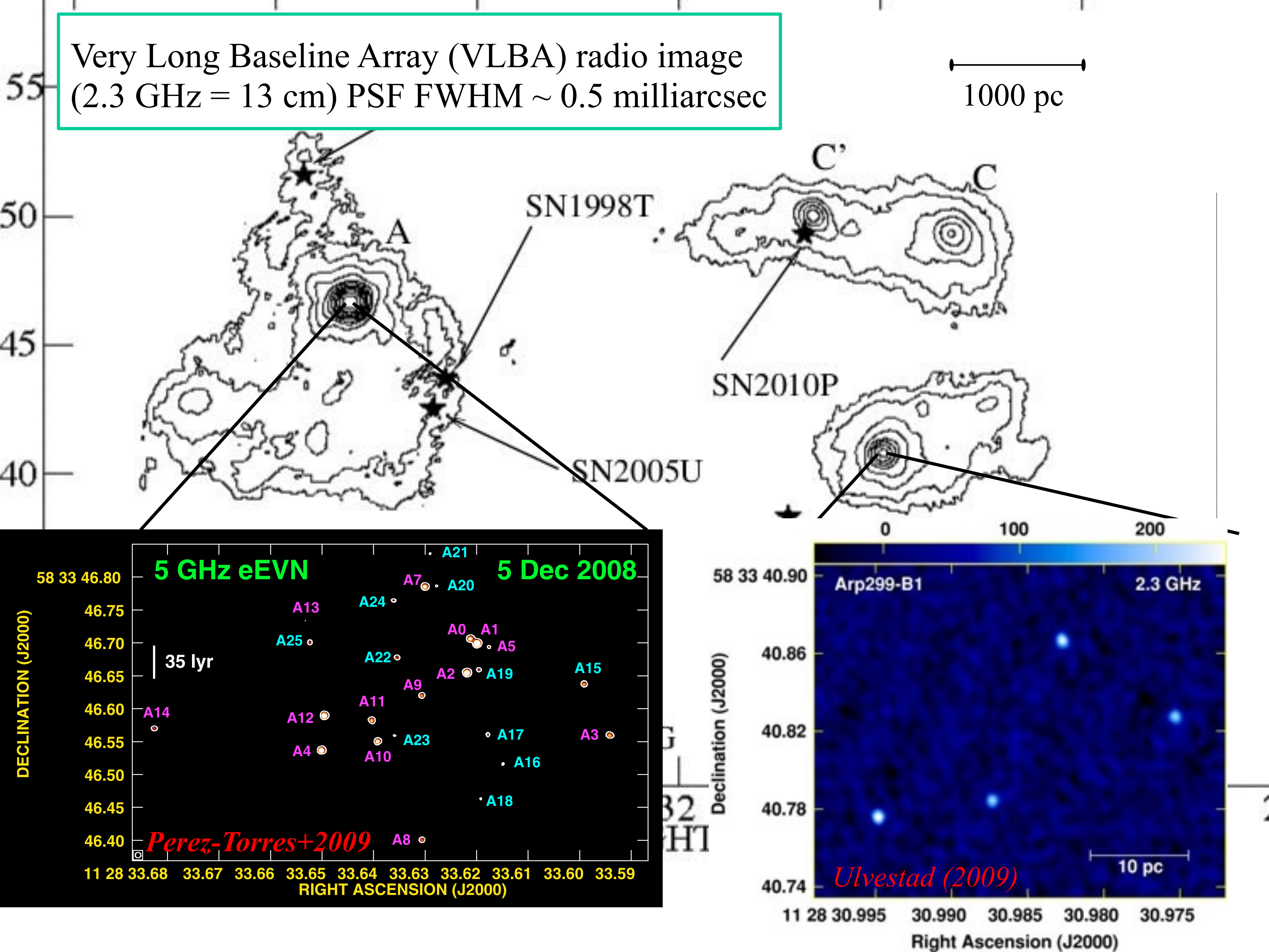
Gemini-N/Altair near-infrared (1.1-2.2 μm) (PSF FWHM ~ 0.1”)



Very Large Array (VLA) radio image (8.46 GHz = 3.5 cm) (PSF FWHM ~ 0.5")

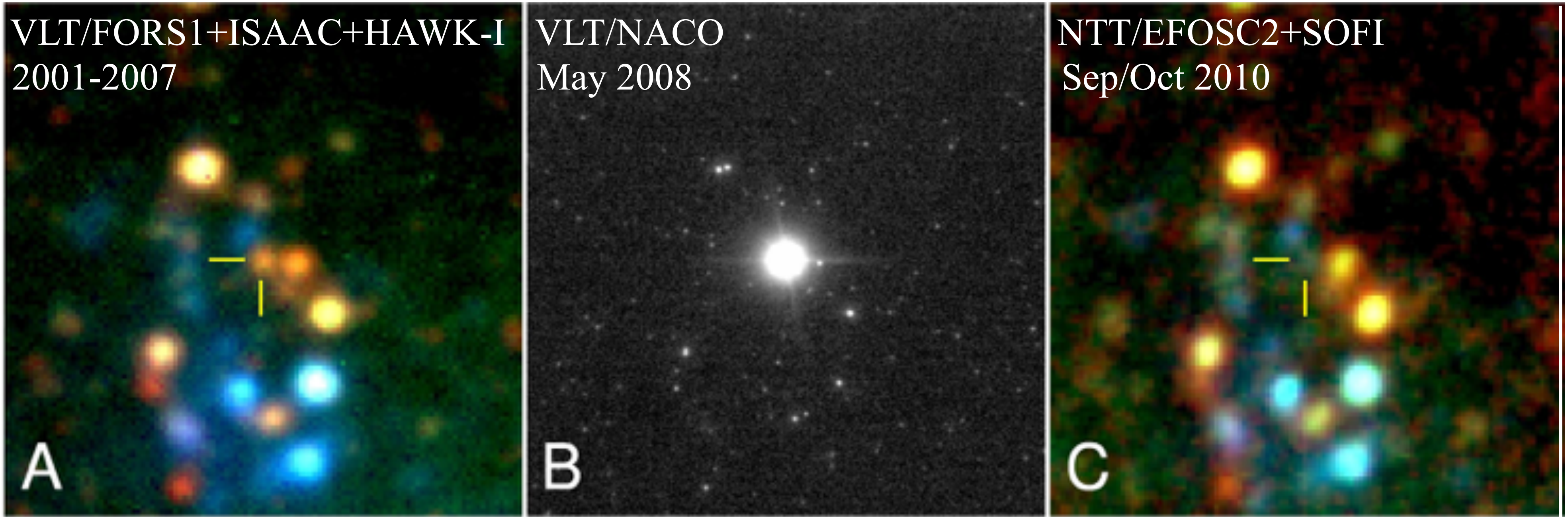
Romero-Canizales (2011)





Very Long Baseline Array (VLBA) radio image
(2.3 GHz = 13 cm) PSF FWHM ~ 0.5 milliarcsec
1000 pc
55
50
45
40
A
SN1998T
C'
C
SN2010P
SN2005U
5 GHz eEVN
5 Dec 2008
35 lyr
DECLINATION (J2000)
58 33 46.80
46.75
46.70
46.65
46.60
46.55
46.50
46.45
46.40
A21
A7
A20
A13
A24
A25
A0
A1
A5
A22
A2
A19
A15
A9
A11
A14
A12
A17
A3
A23
A4
A10
A16
A18
A8
Perez-Torres+2009
11 28 33.68
33.67
33.66
33.65
33.64
33.63
33.62
33.61
33.60
33.59
RIGHT ASCENSION (J2000)
0
100
200
58 33 40.90
Arp299-B1
2.3 GHz
40.86
40.82
40.78
40.74
Declination (J2000)
10 pc
Ulvestad (2009)
11 28 30.995
30.990
30.985
30.980
30.975
Right Ascension (J2000)

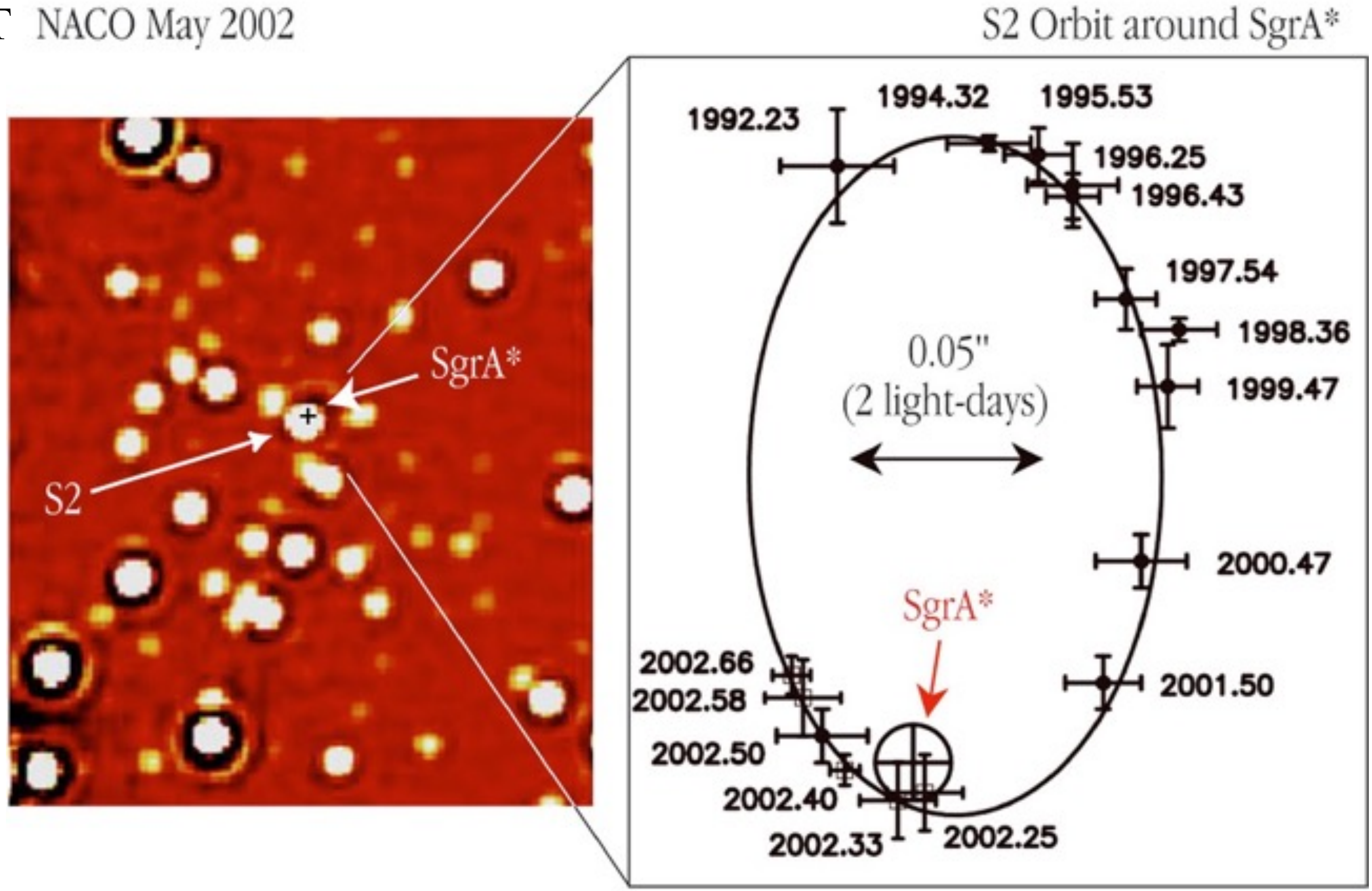
Supernova progenitor detections by relative astrometry



Mattila et al. (2008)
Maund et al. (2014)

The motion of a star around the central black hole in the Milky Way

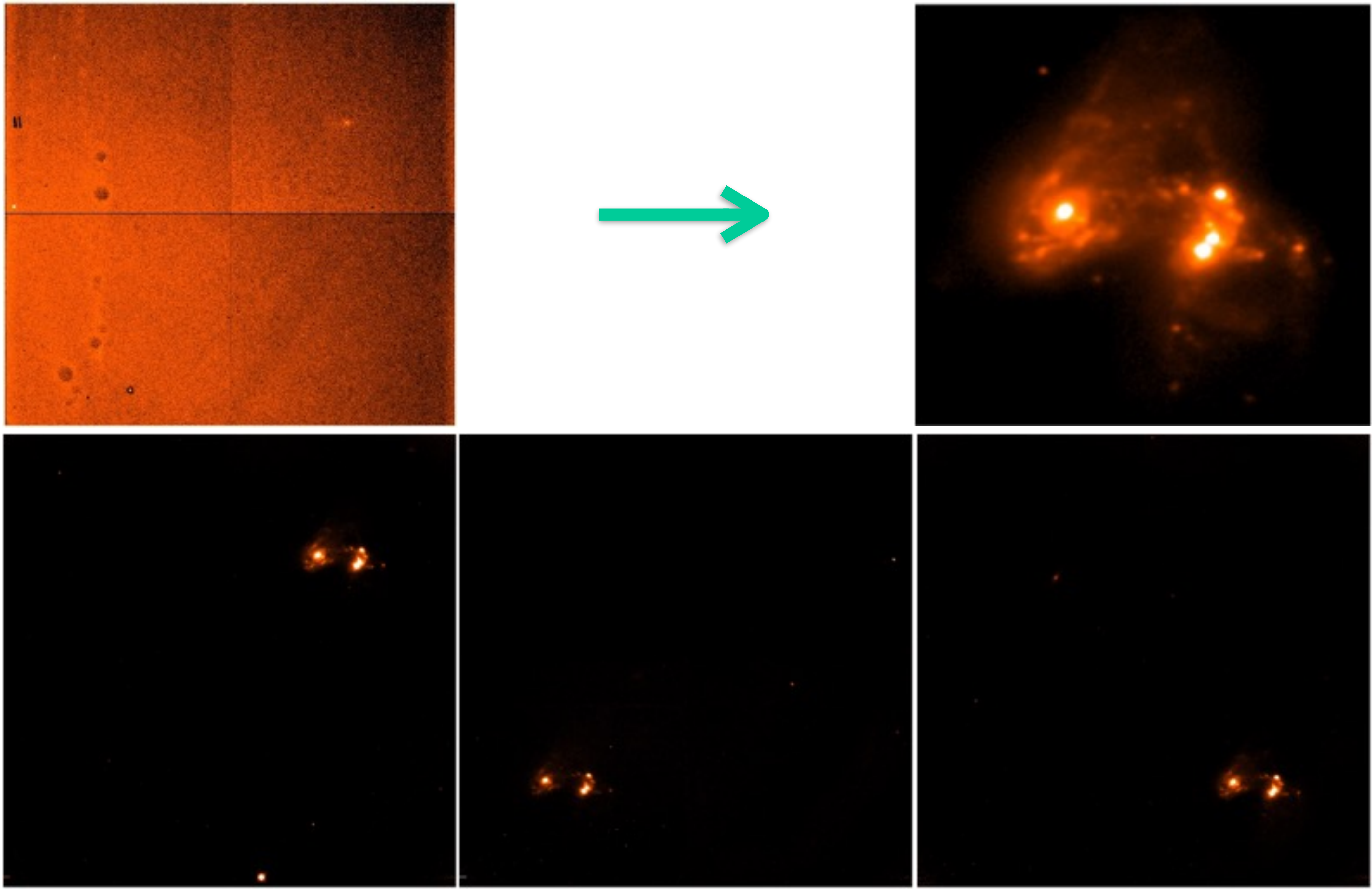
VLT



ESO Science Release 226

Calibration of astronomical observations

Data reduction: removal of instrumental signatures

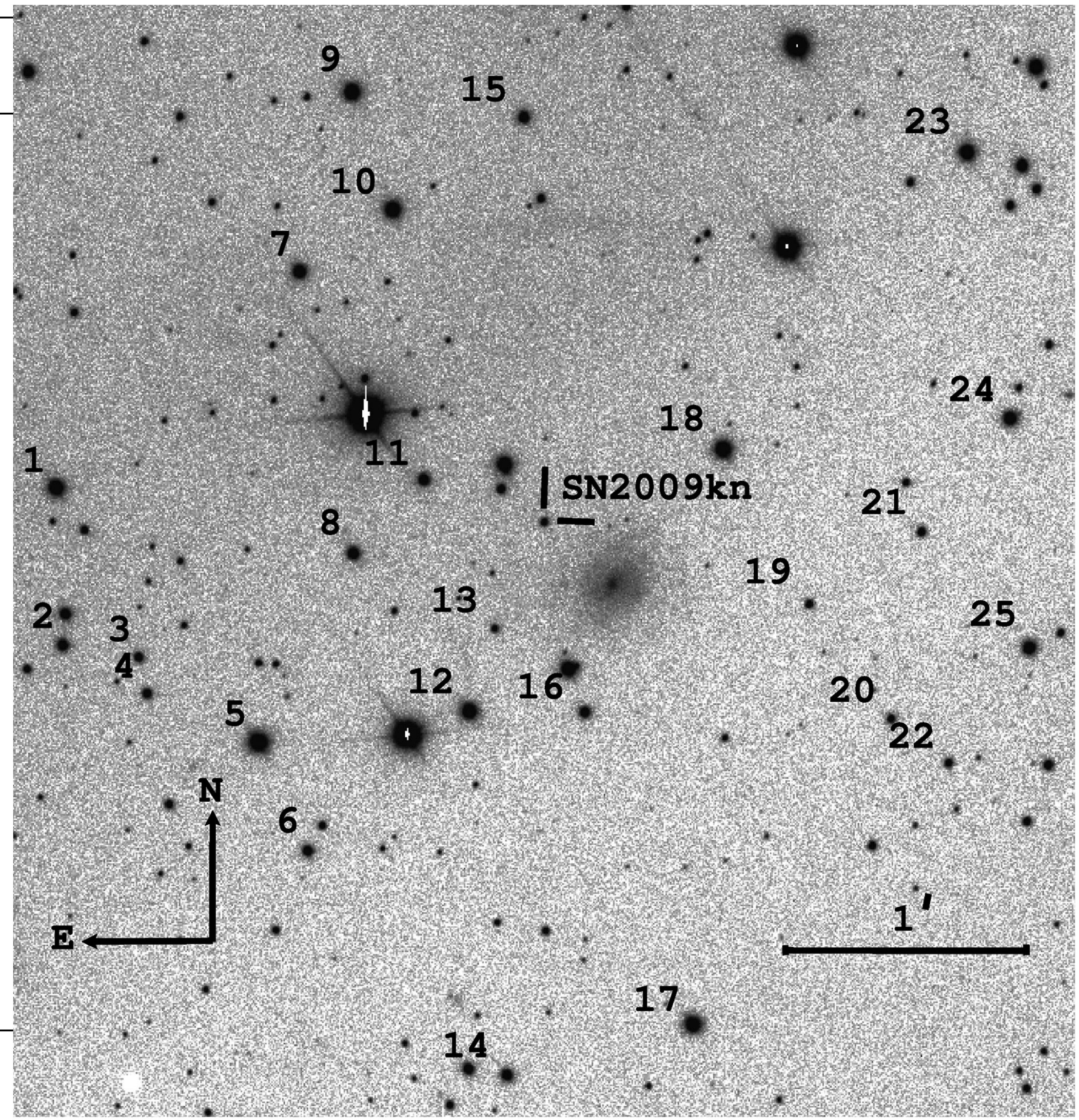


Photometric calibration of imaging observations

- 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)



Photometric calibration of imaging observations

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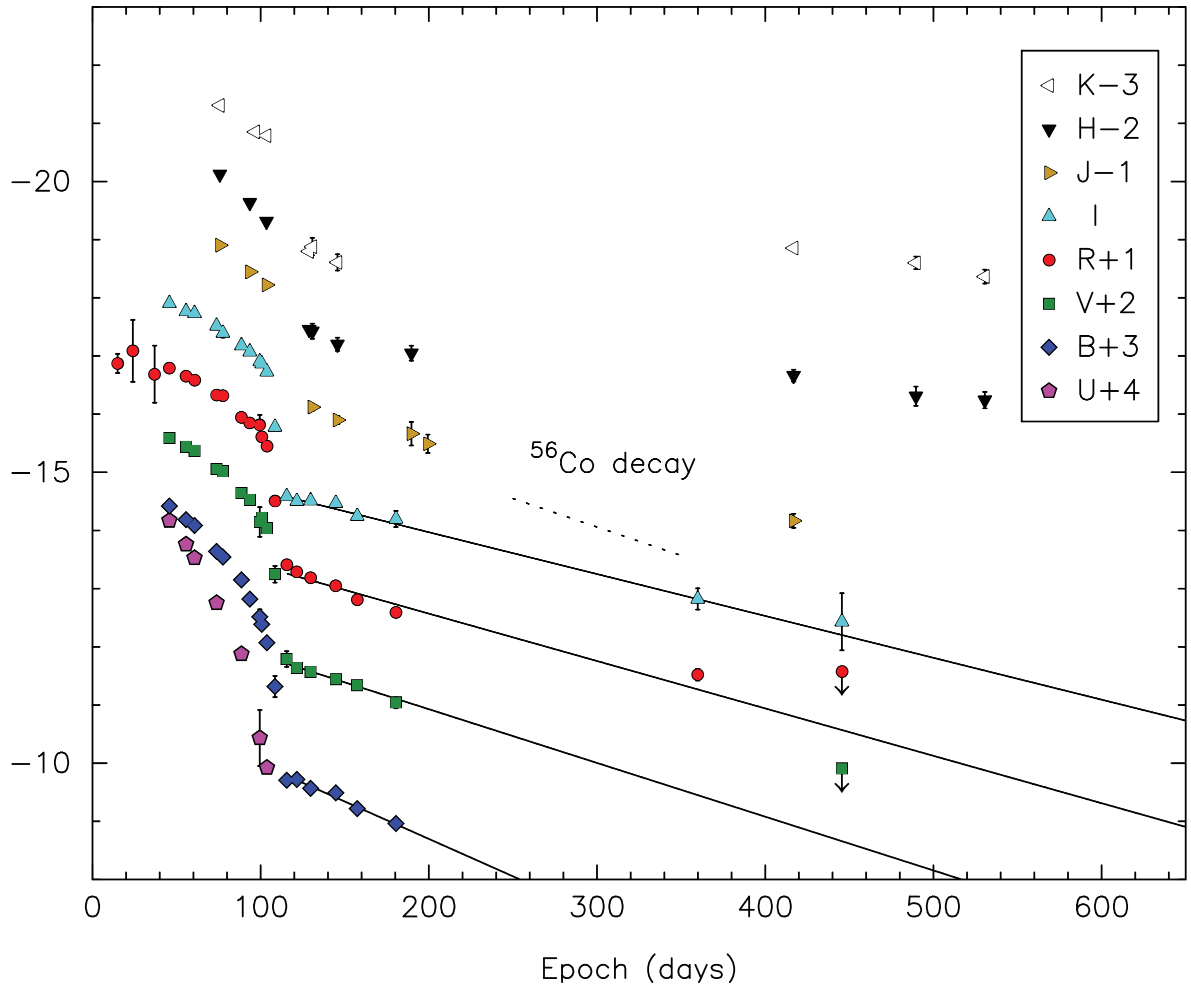
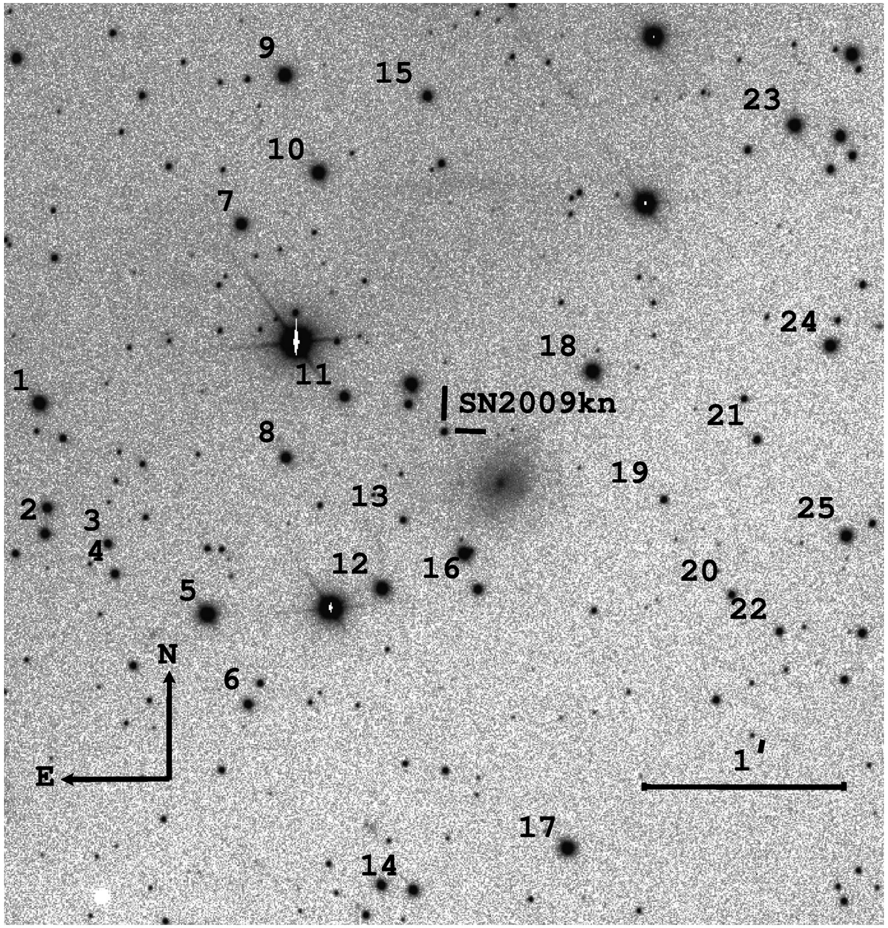
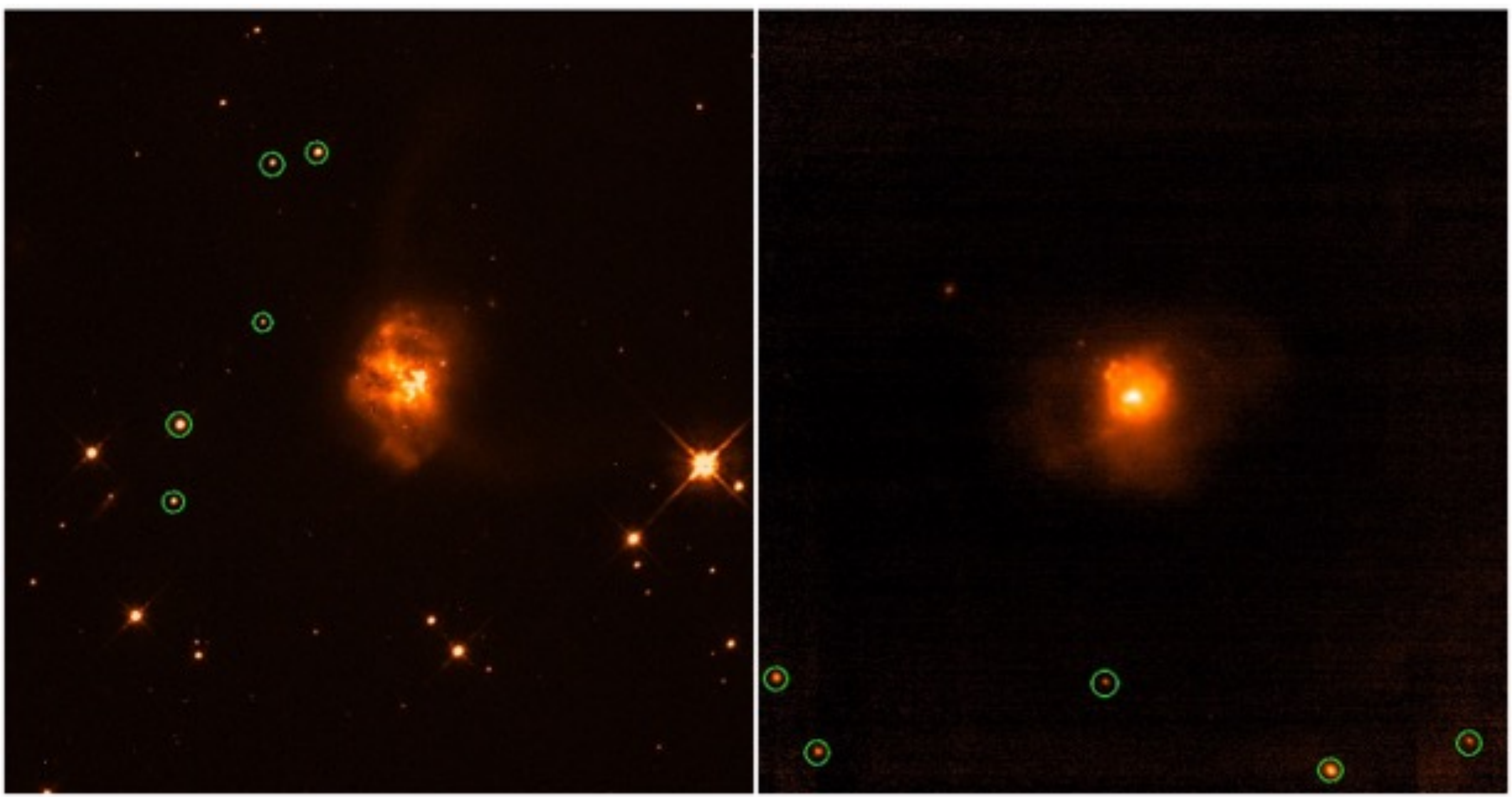




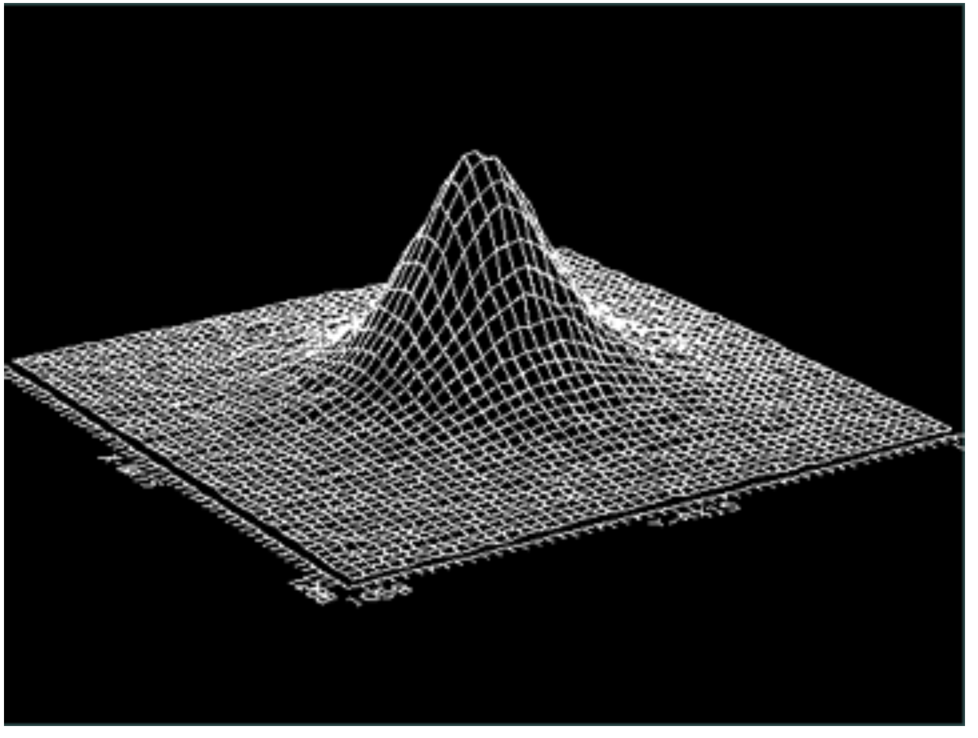
Astrometric calibration of imaging observations

- *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)



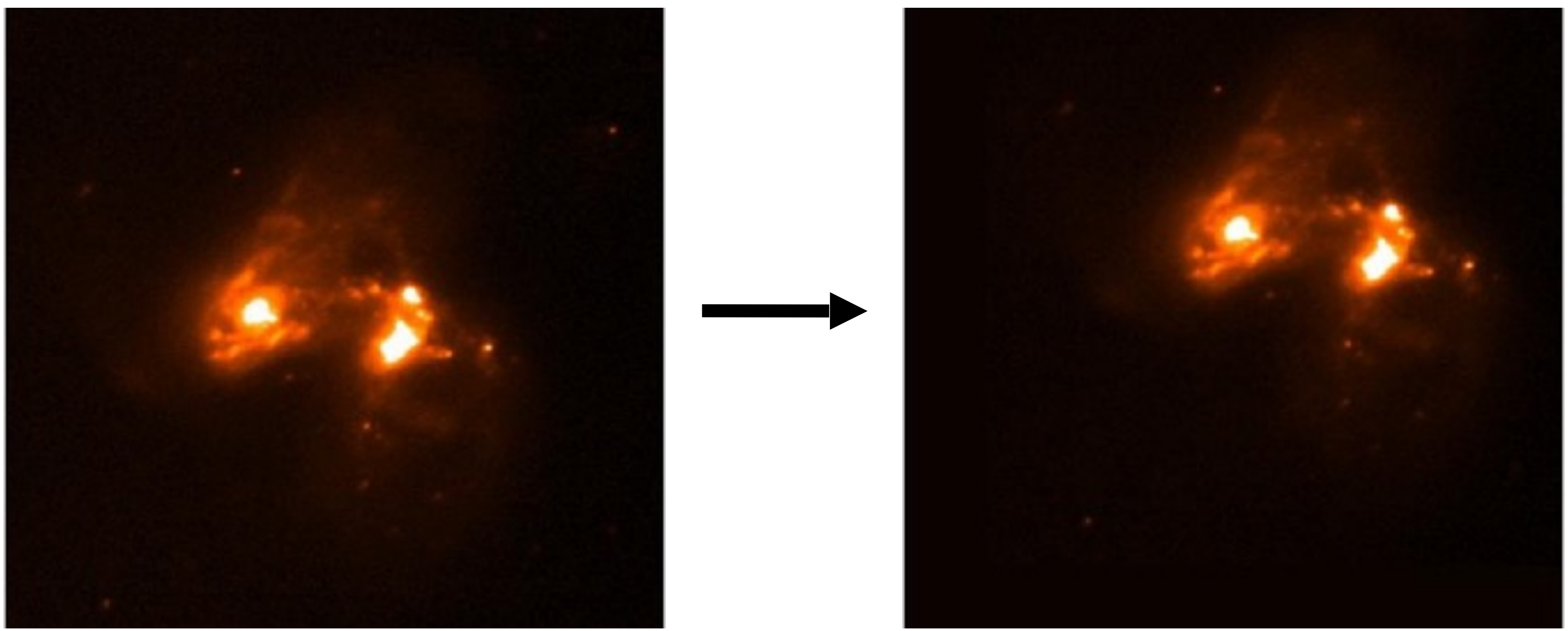
Geometric transformations: shift

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

$$x_B = a + x_A$$

$$y_B = b + y_A$$

Number of free parameters: 2

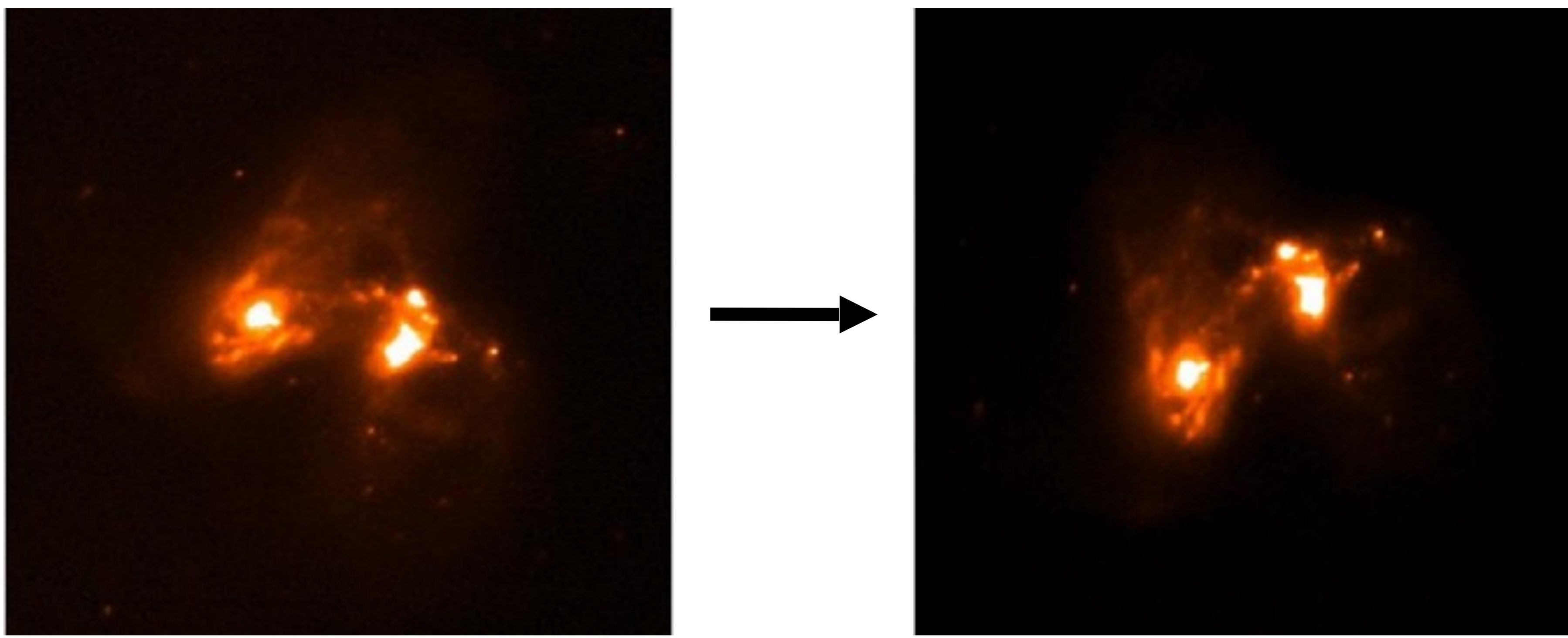


Geometric transformations: rotation

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

$$x_B = x_A \cos(\Theta) - y_A \sin(\Theta)$$
$$y_B = x_A \sin(\Theta) + y_A \cos(\Theta)$$

Number of free parameters: 1 (2 if different for x and y)



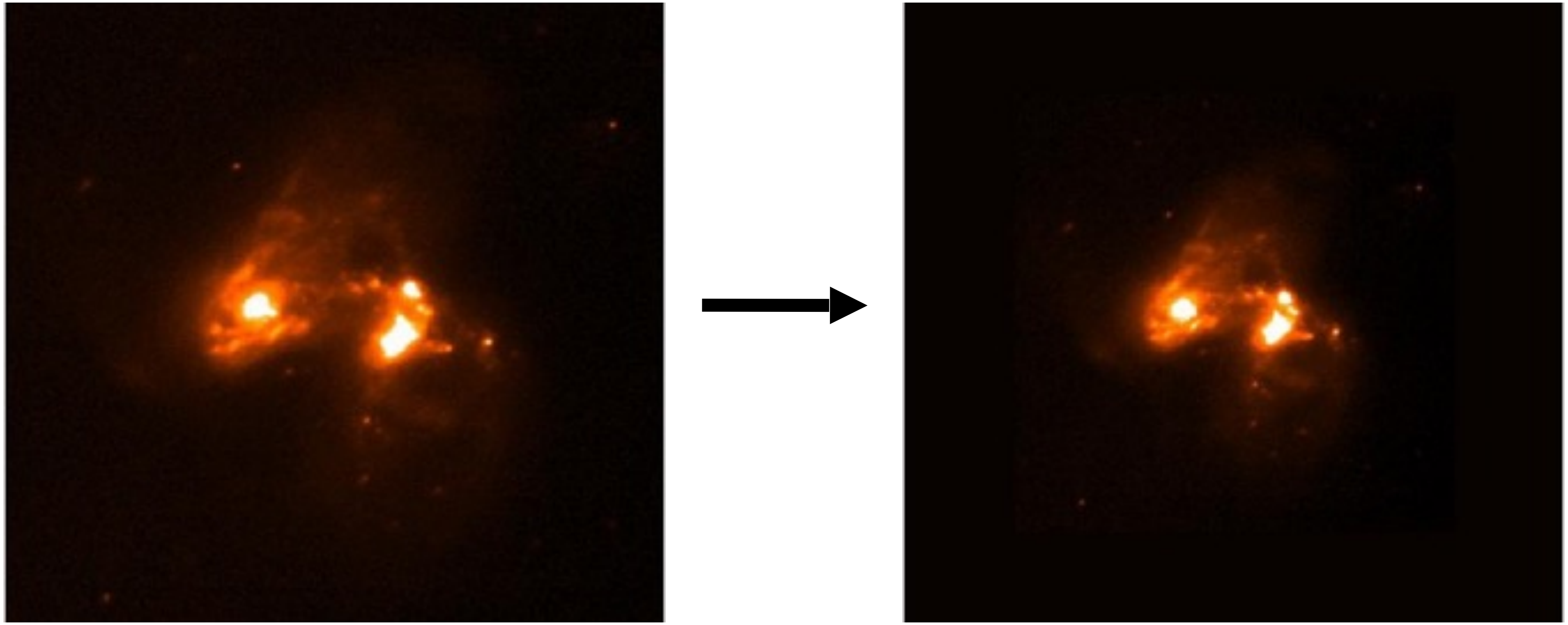
Geometric transformations: scale

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

$$x_B = S_x x_A$$

$$y_B = S_y y_A$$

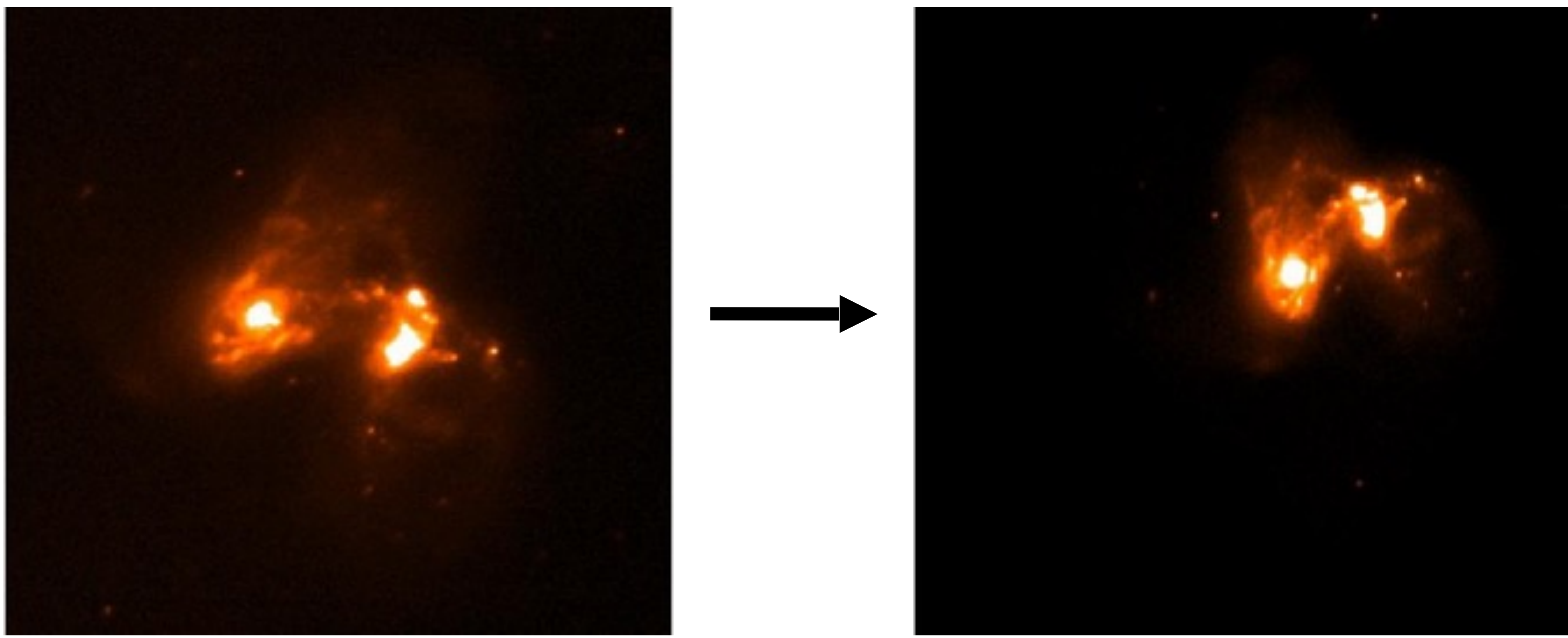
Number of free parameters: 1 (2 if different for x and y)



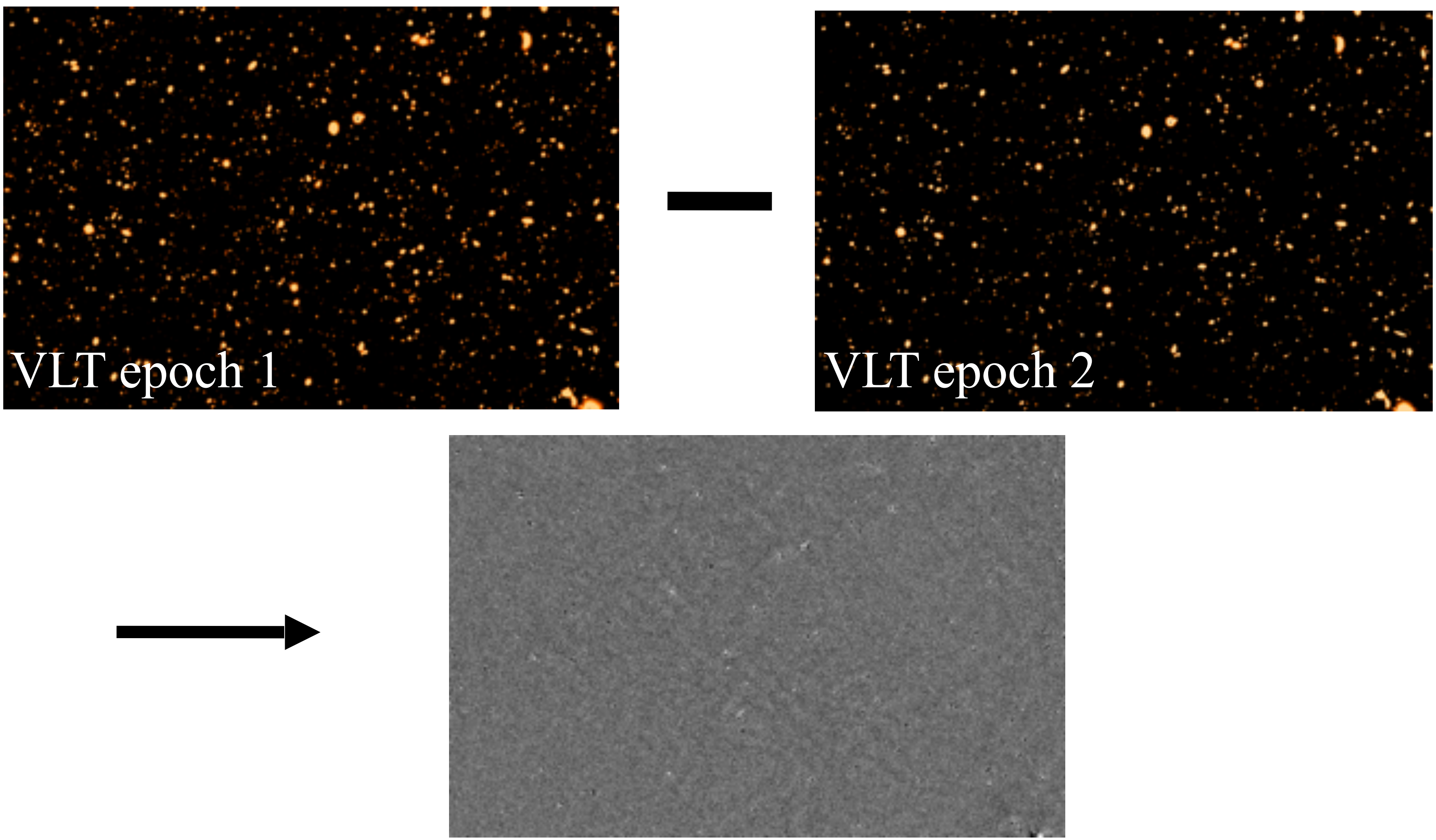
Geometric transformations: general

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)



Discovery of supernovae by precise alignment, PSF matching and subtraction of images



Advanced astronomical instrumentation

Adaptive Optics imaging

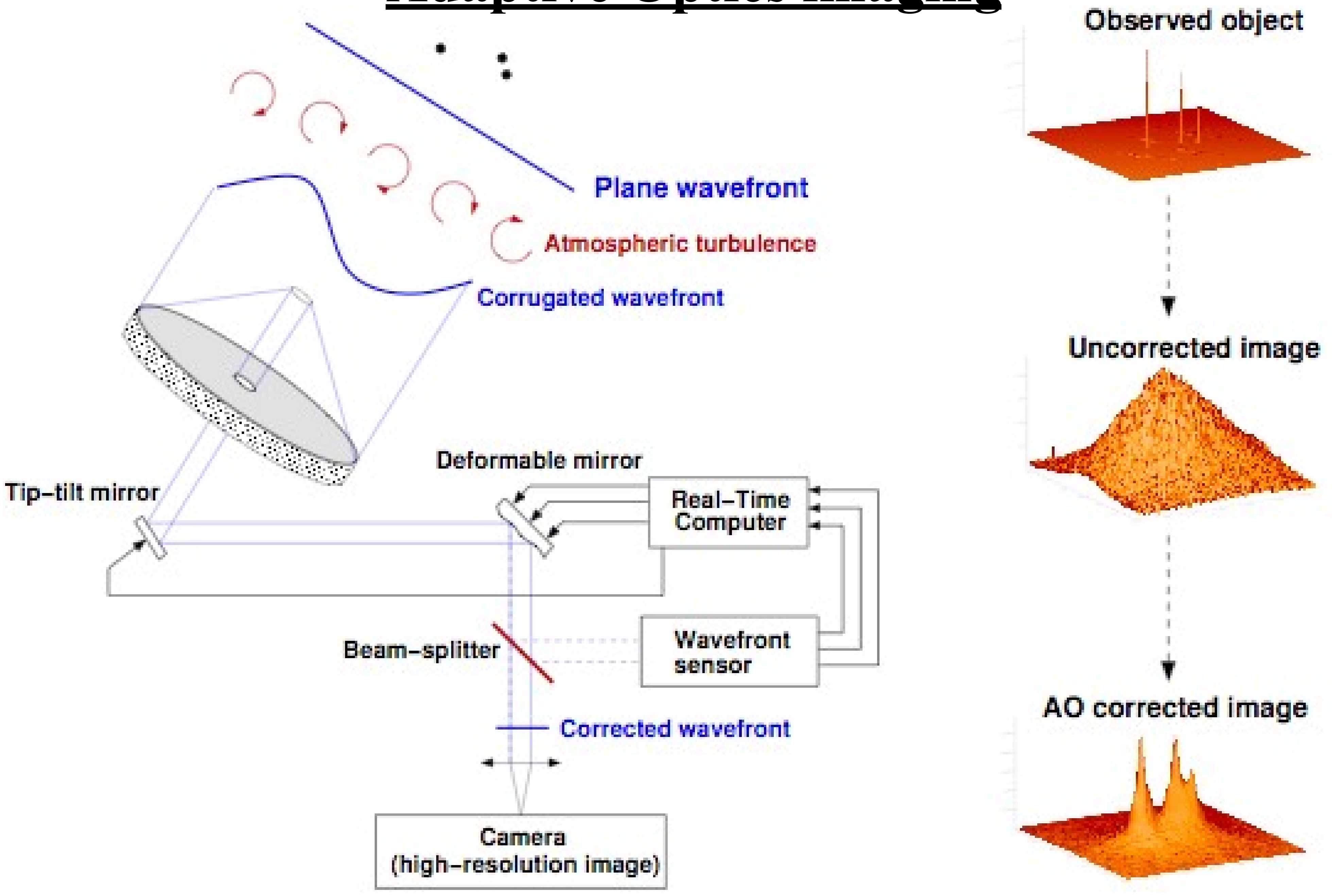
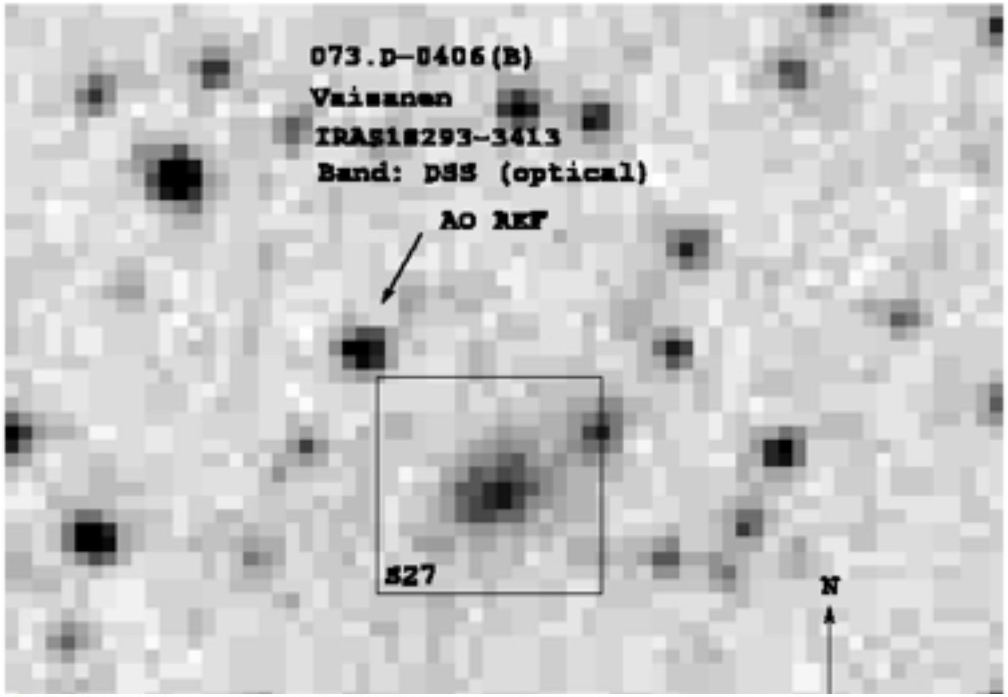
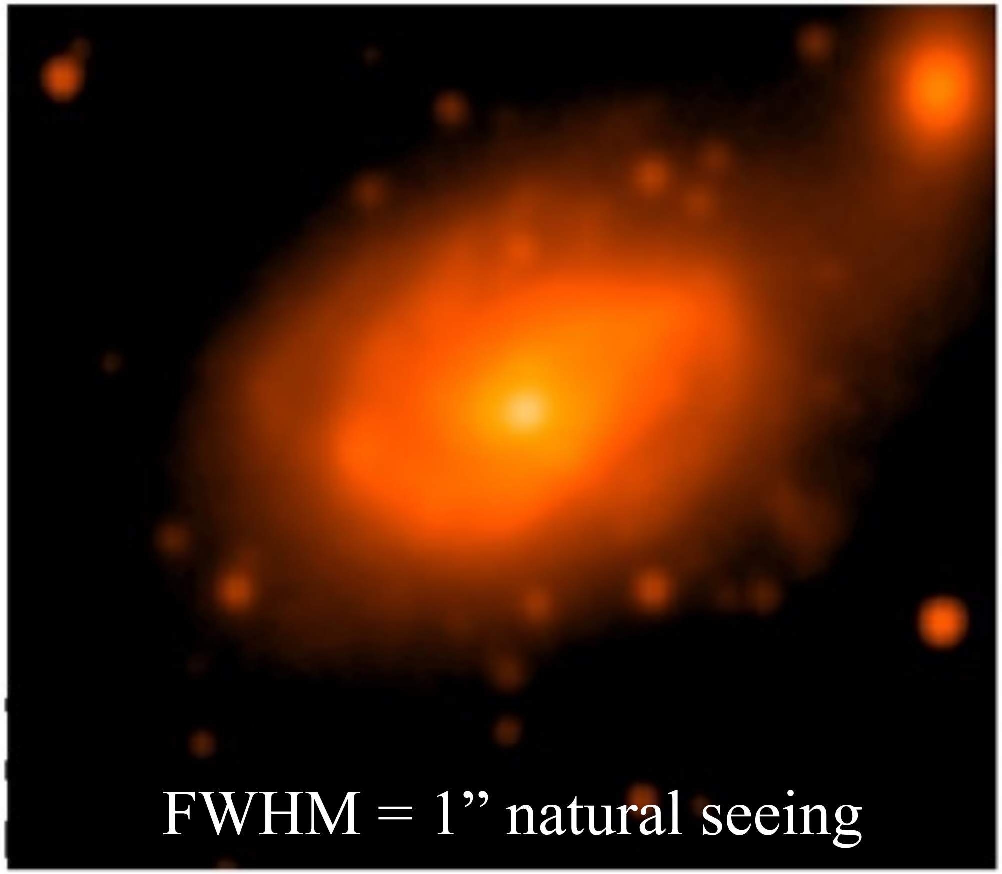


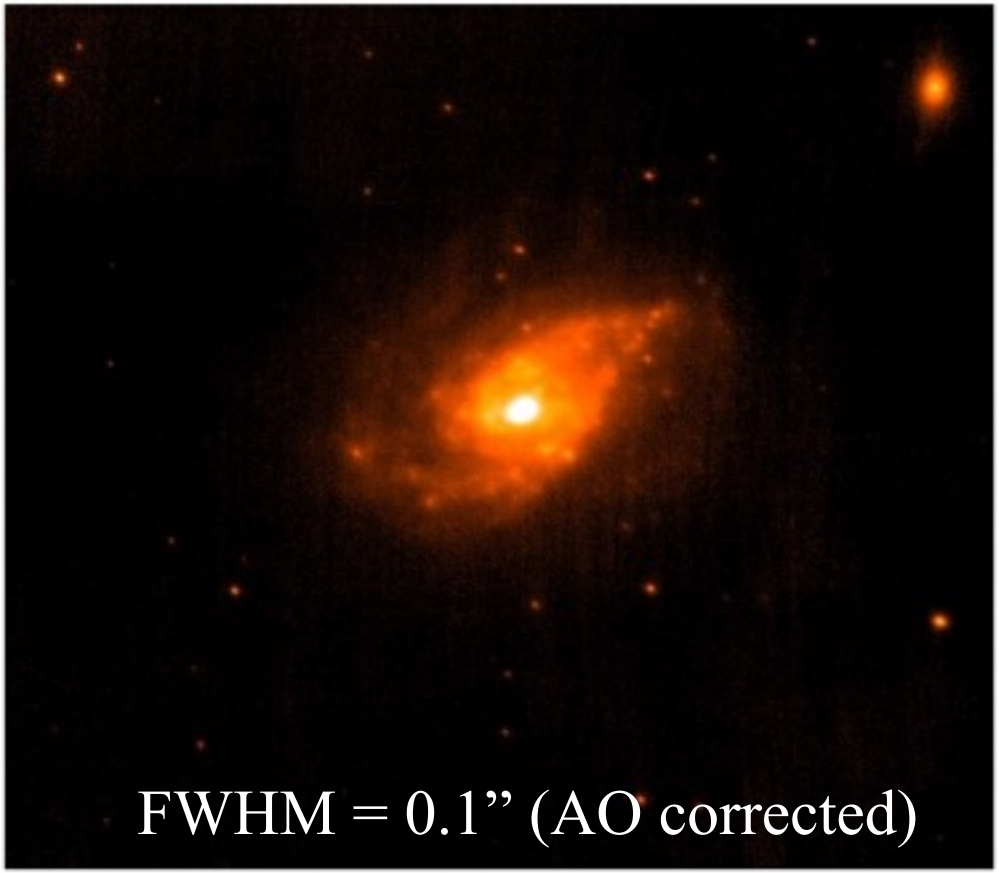
Figure 3-1: Principle of Adaptive Optics

VLT/NACO User manual



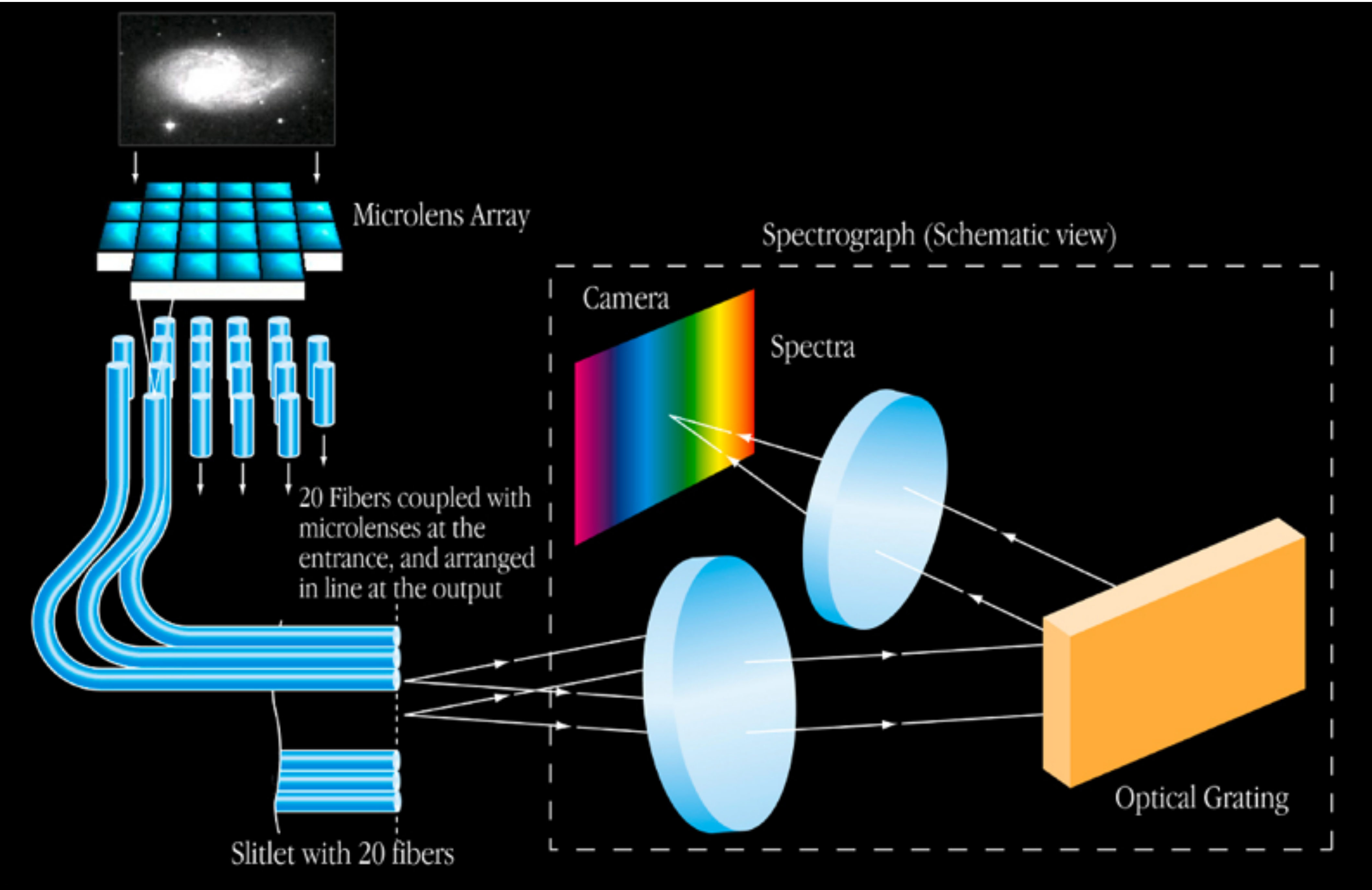


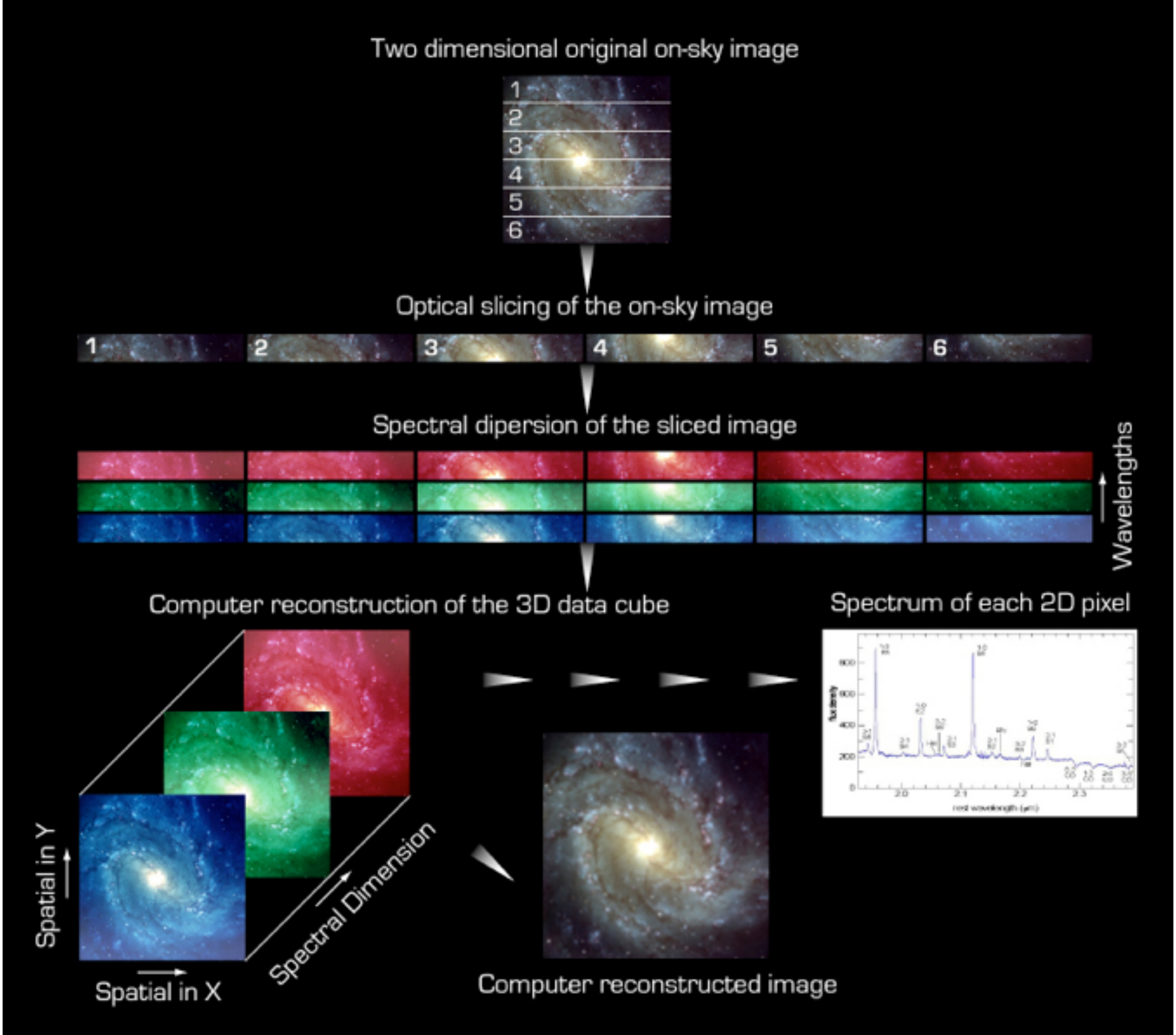
FWHM = 1” natural seeing

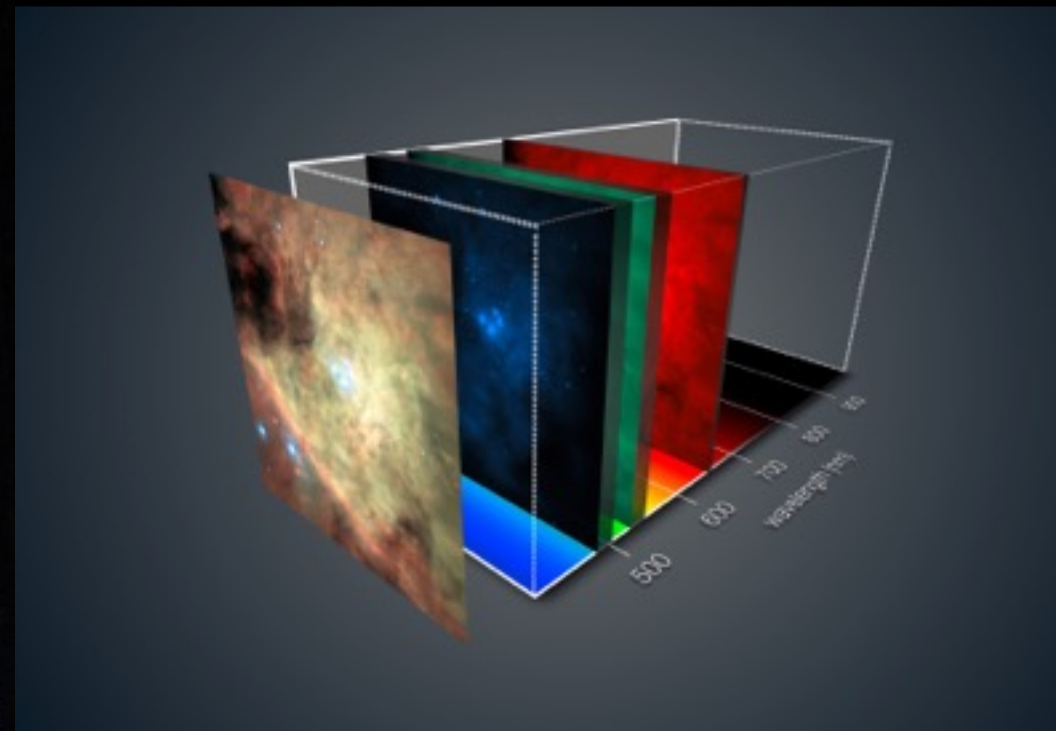


FWHM = 0.1” (AO corrected)

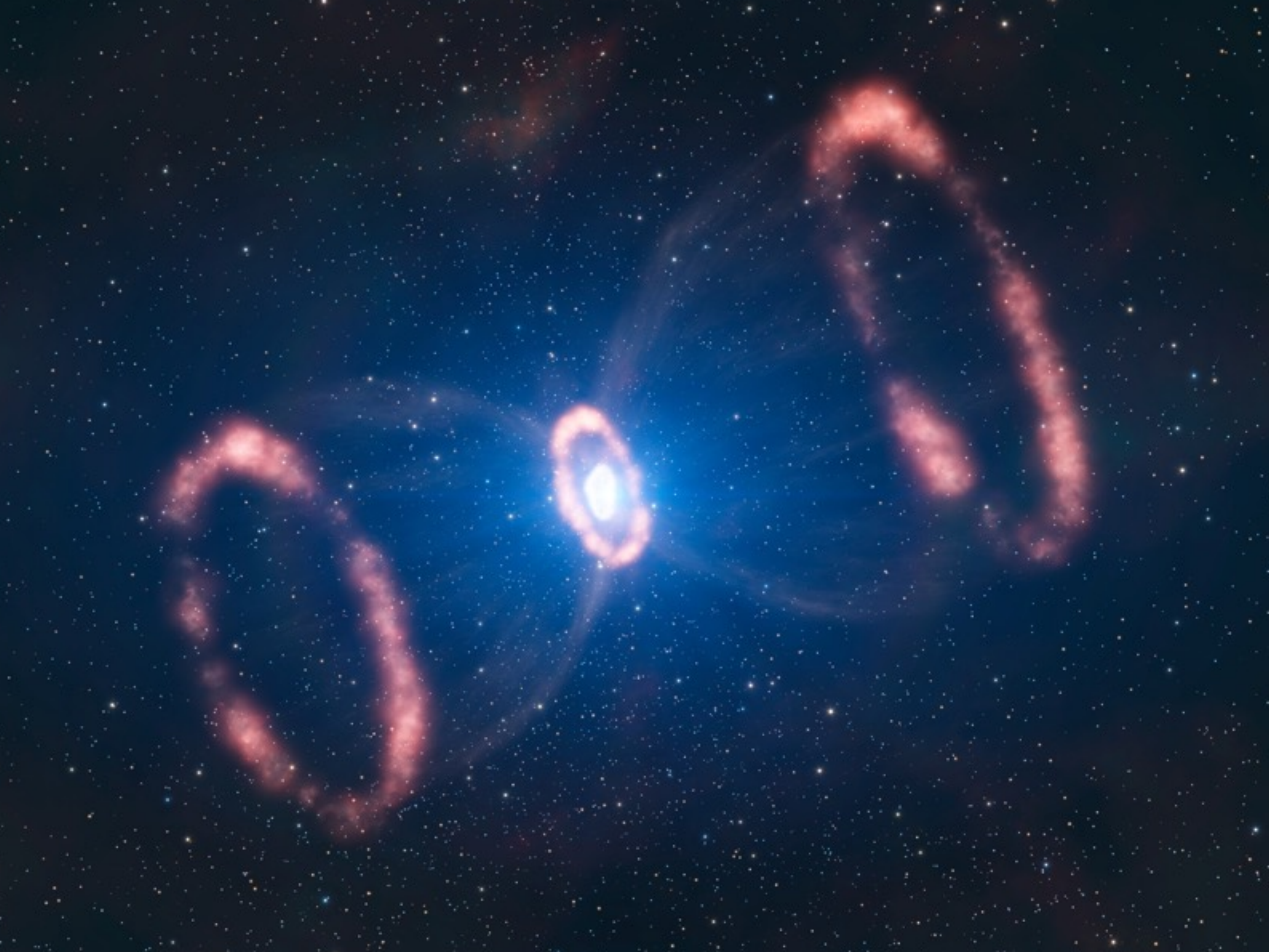
Integral-field spectroscopy

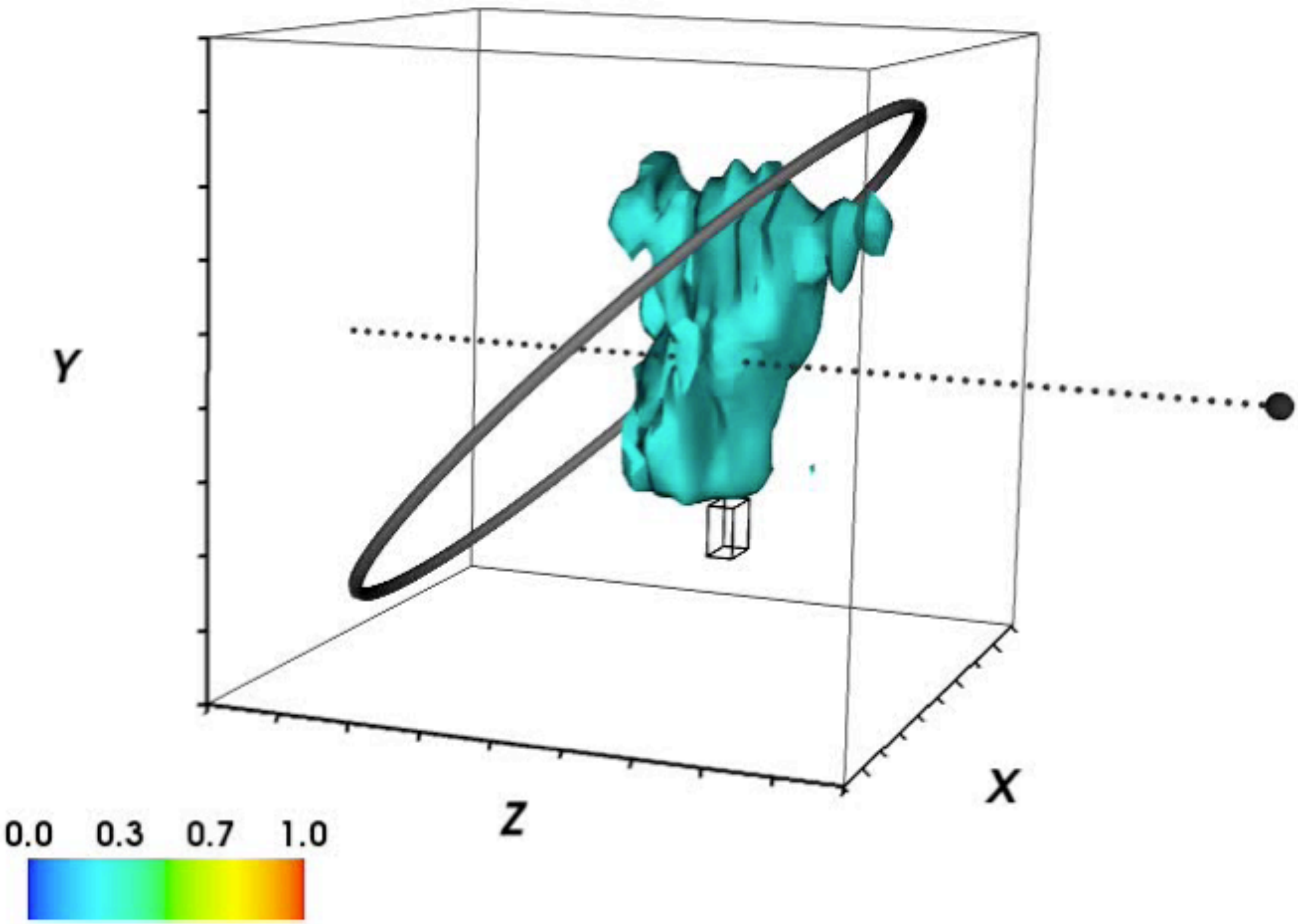



Two dimensional original on-sky image
1
2
3
4
5
6
Optical slicing of the on-sky image
Spectral dipersion of the sliced image
Wavelengths
Computer reconstruction of the 3D data cube
Spectrum of each 2D pixel
rest wavelength (μm)
Spatial in Y
Spatial in X
Spectral Dimension
Computer reconstructed image



MUSE on the VLT



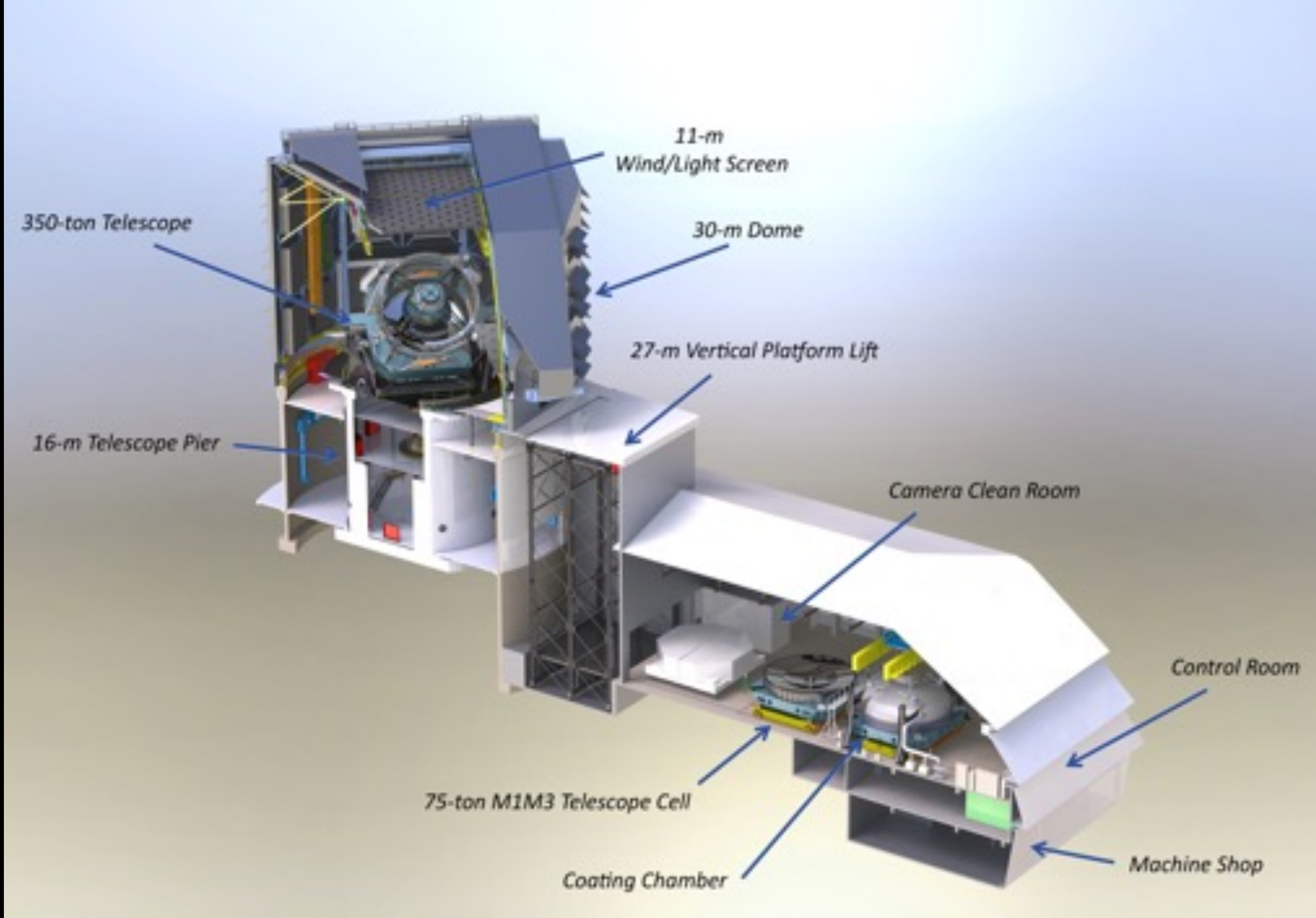

Y
Z
X
0.0
0.3
0.7
1.0

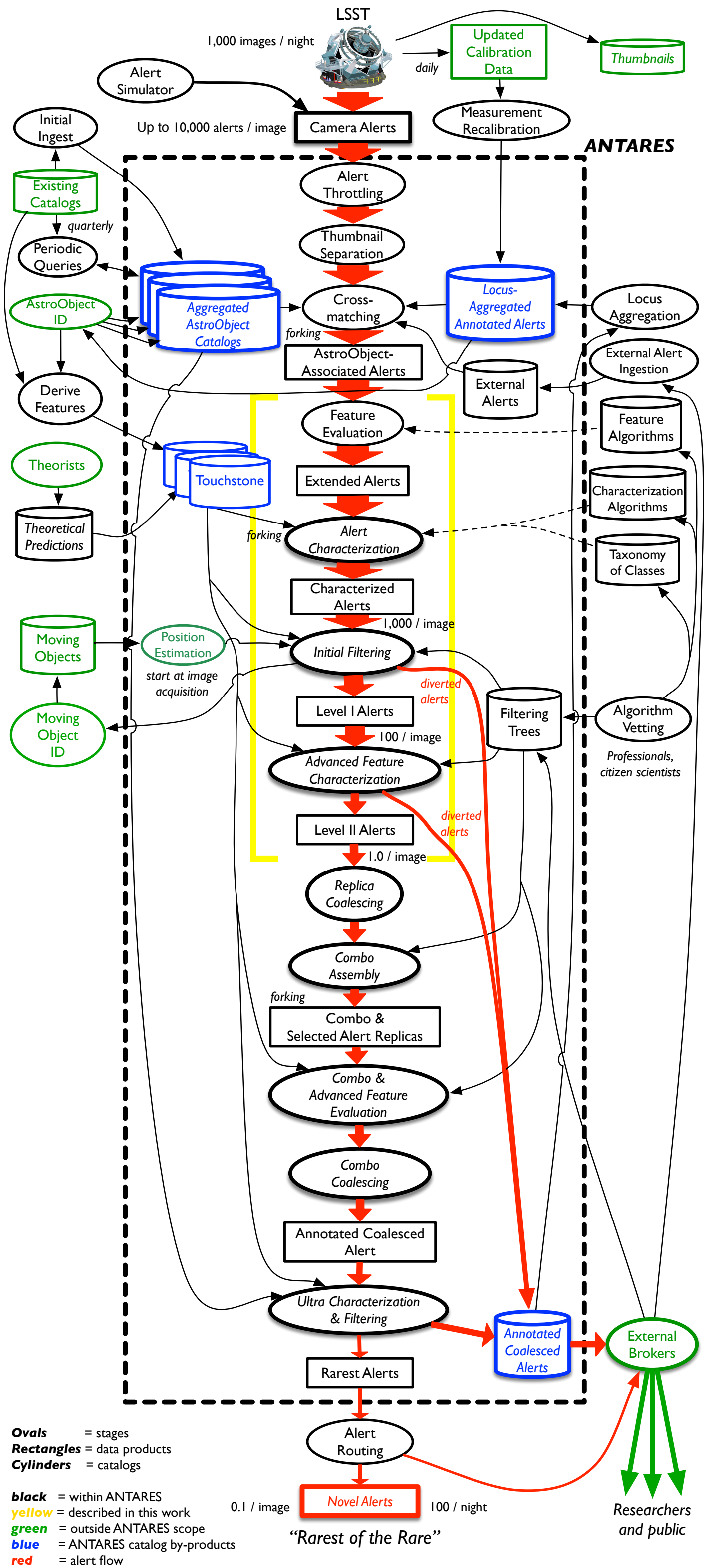
Big data

Large Synoptic Survey Telescope
Opening a Window of Discovery on the Dynamic Universe

- 8.4 m primary mirror
- 3.2 Gpixel camera (3.5 deg FOV)
- 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





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

$\sim 10^7$ alerts per night

$\sim 10^6$ alerts per night

$\sim 10^3$ alerts per night

$\sim 10^2$ 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) !!