Astronomical imaging & image processing

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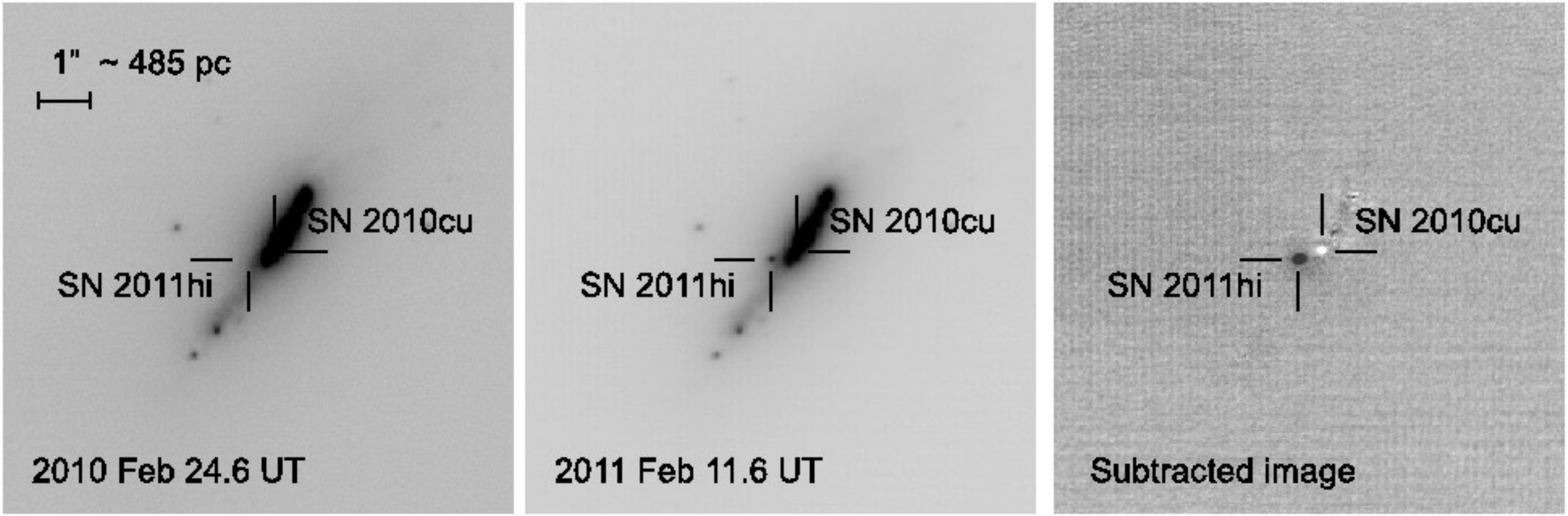
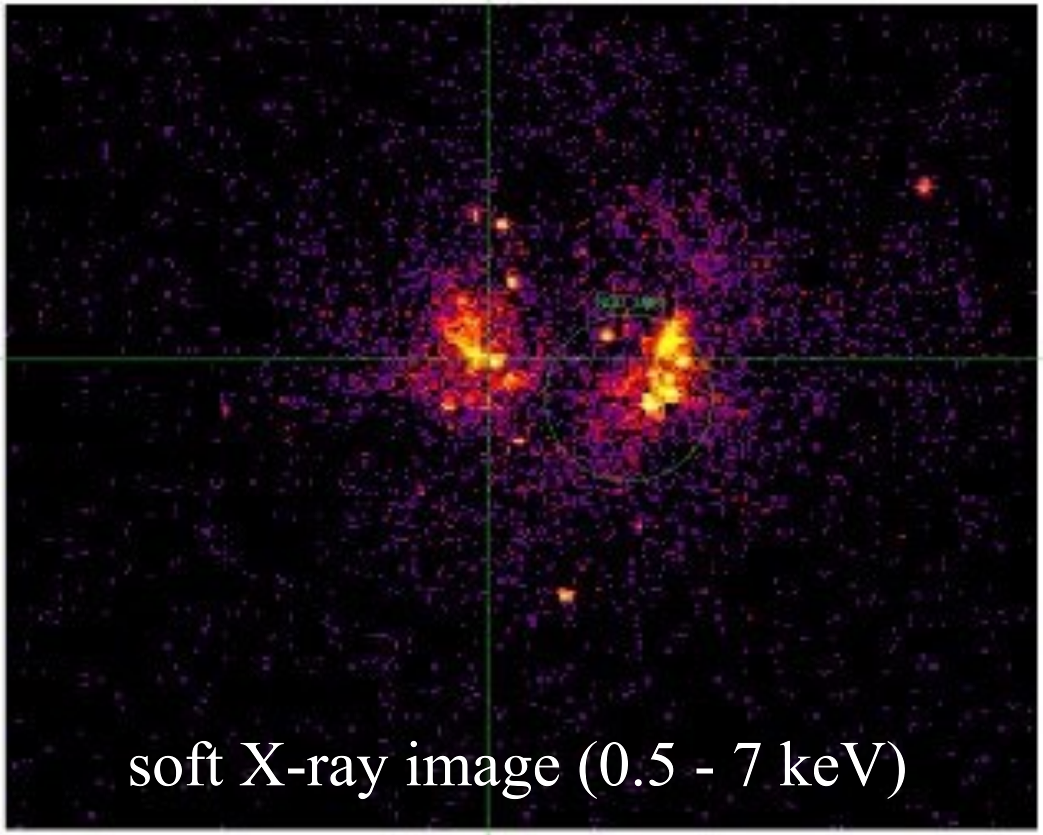
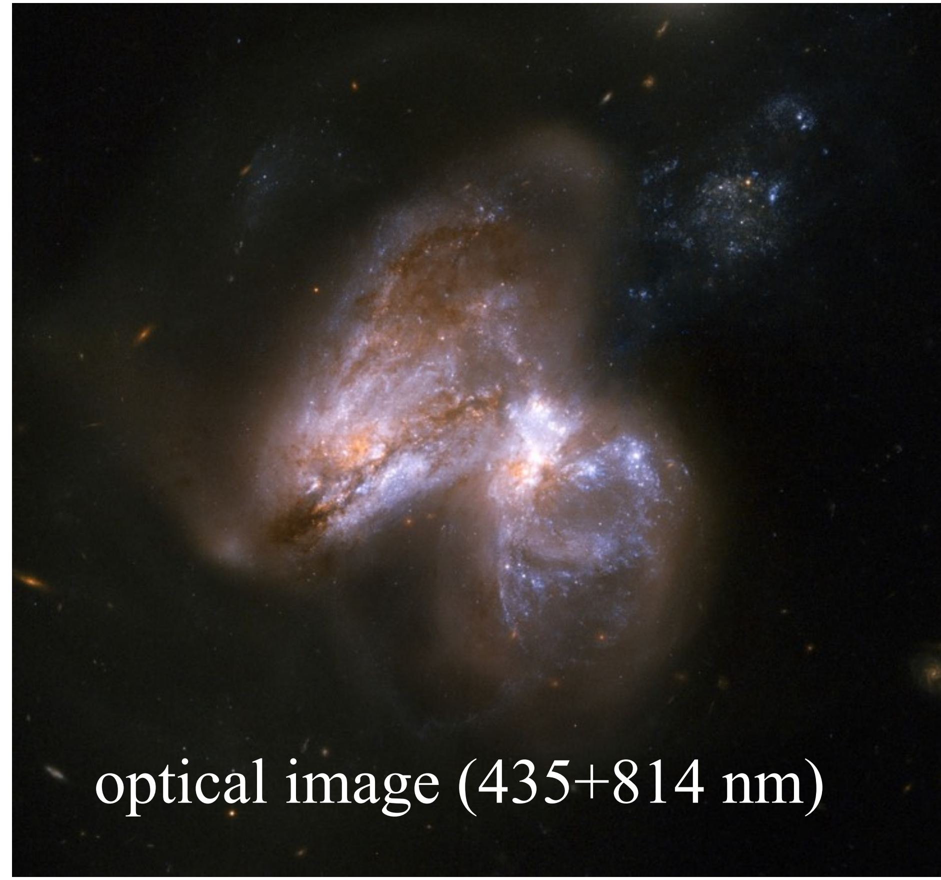
Department of Physics and Astronomy, University of Turku



Examples of astronomical imaging data

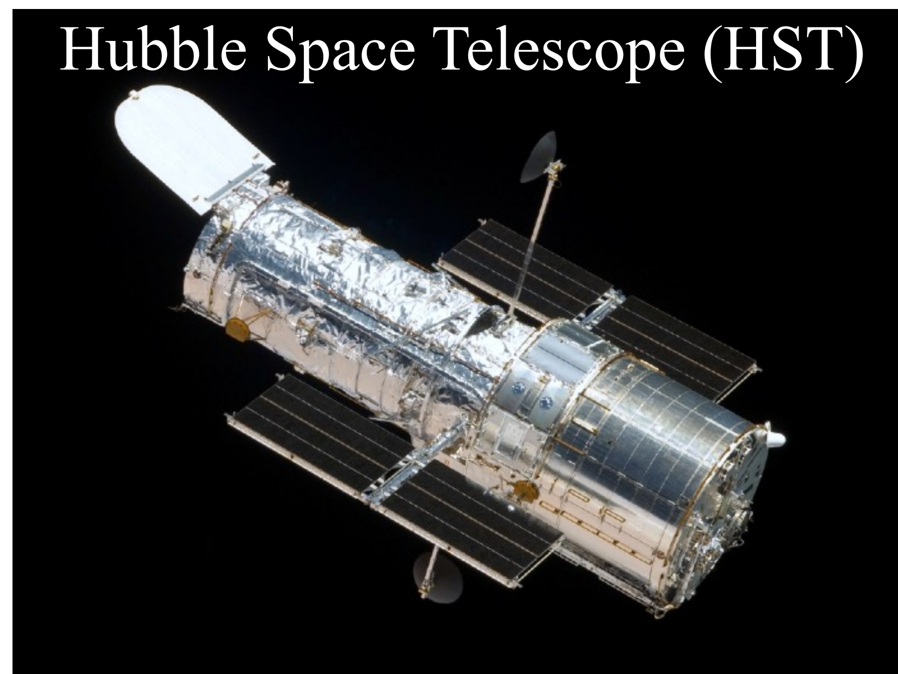


soft X-ray image (0.5 - 7 keV)



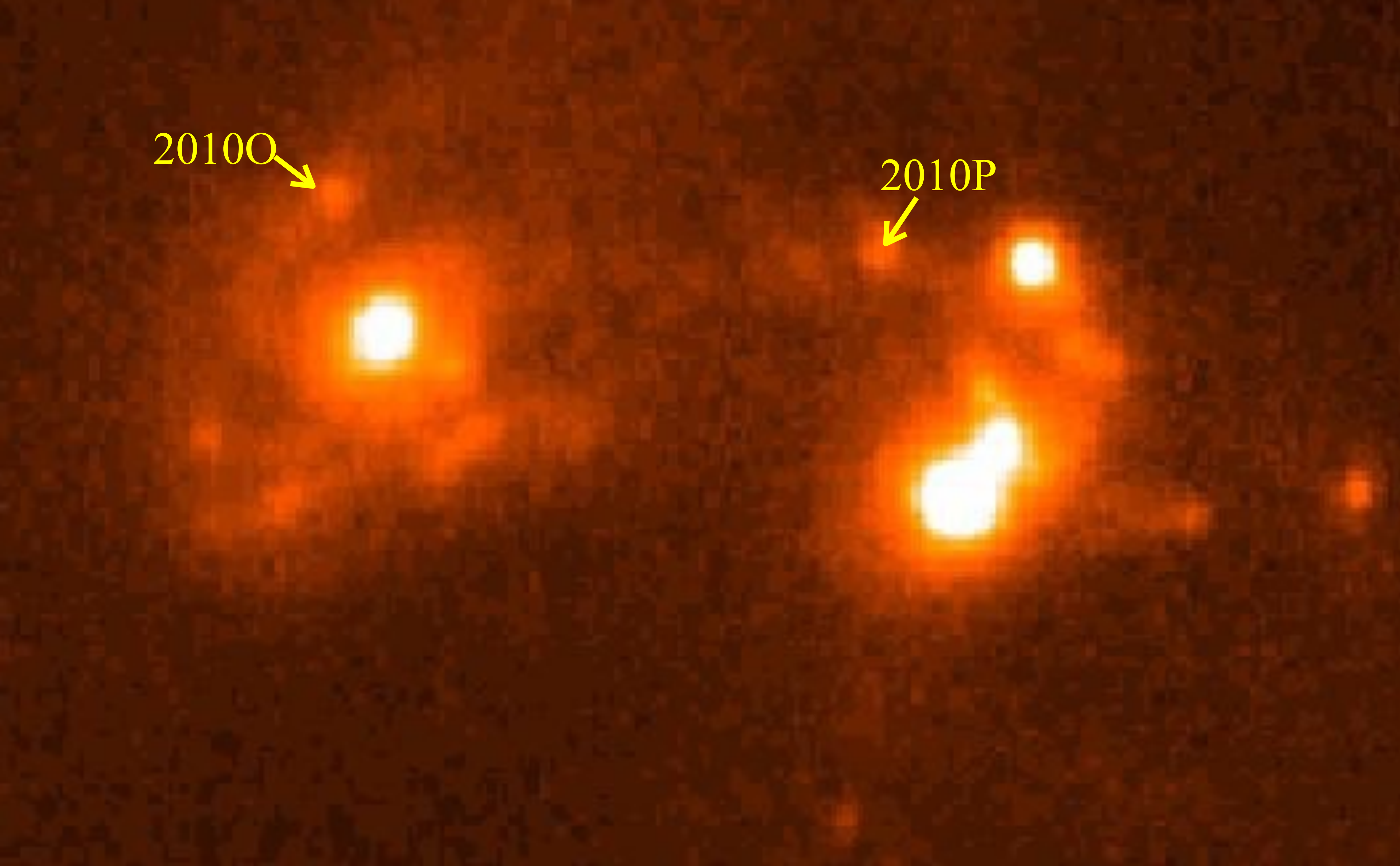
optical image (435+814 nm)

NASA Chandra X-ray observatory

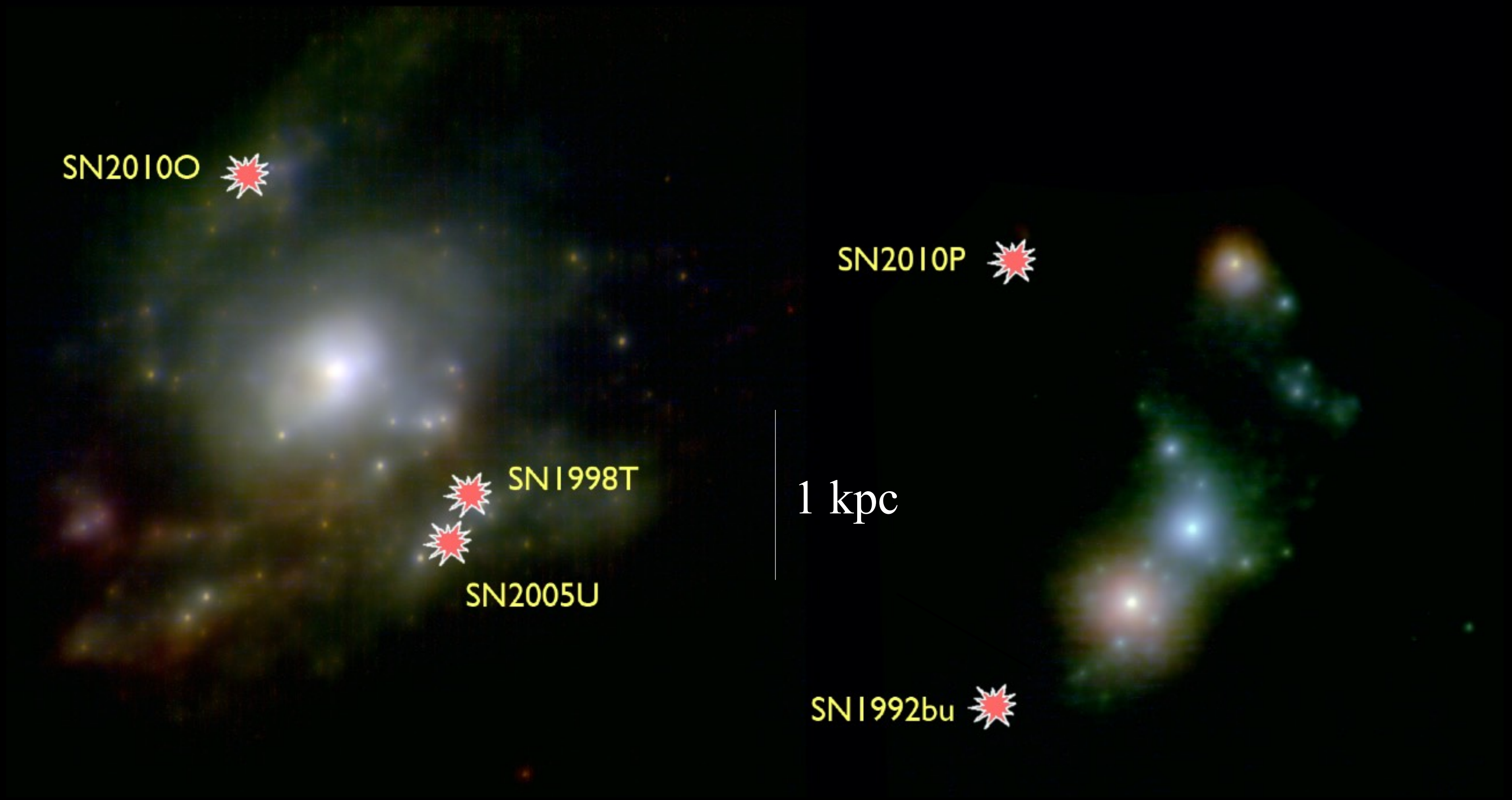


Hubble Space Telescope (HST)

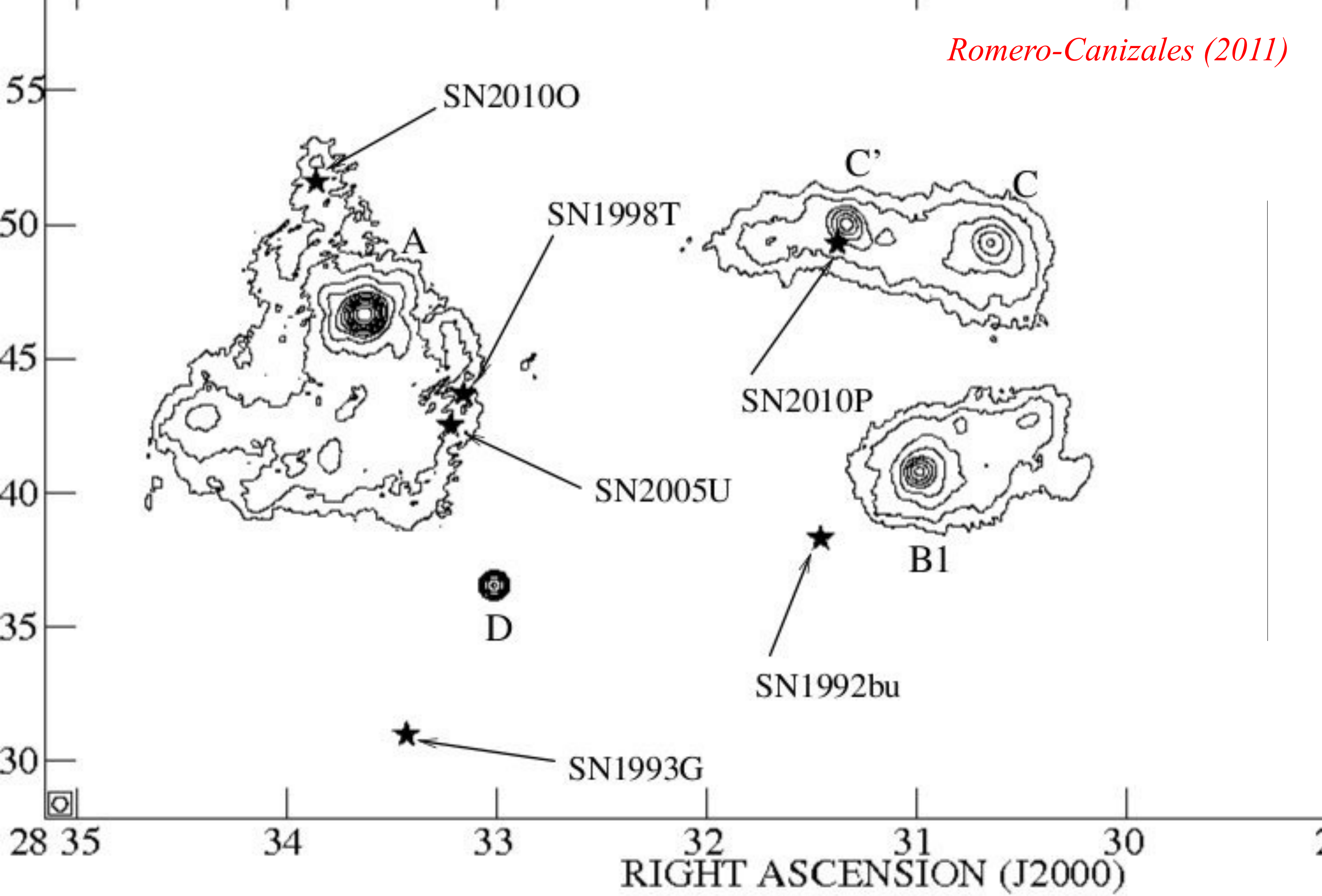
Hubble Space Telescope (HST) optical (435 + 814 nm) (PSF FWHM ~ 0.1”)



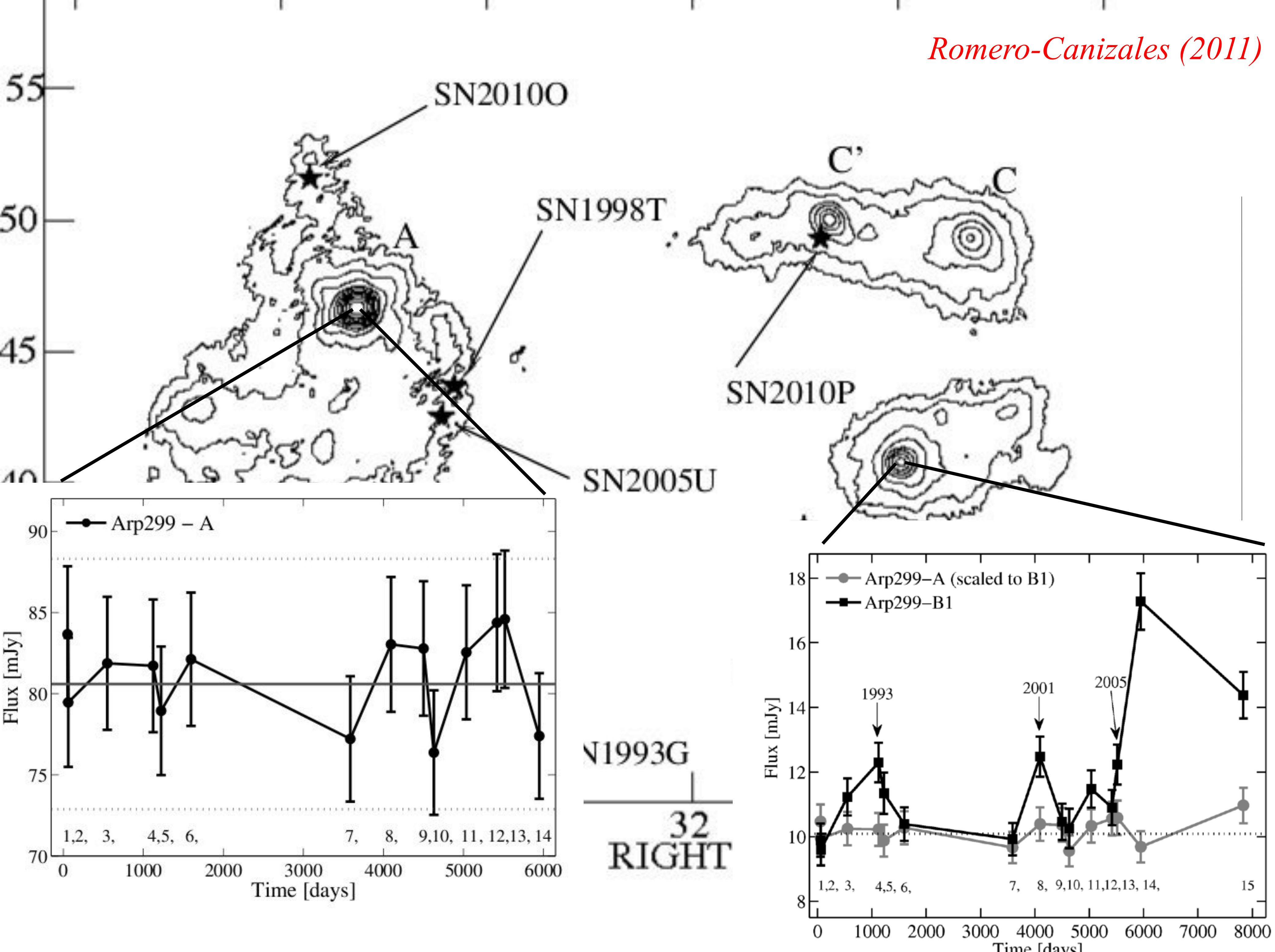
NOT/NOTCam near-infrared (2.2 μm) (PSF FWHM ~ 1”)



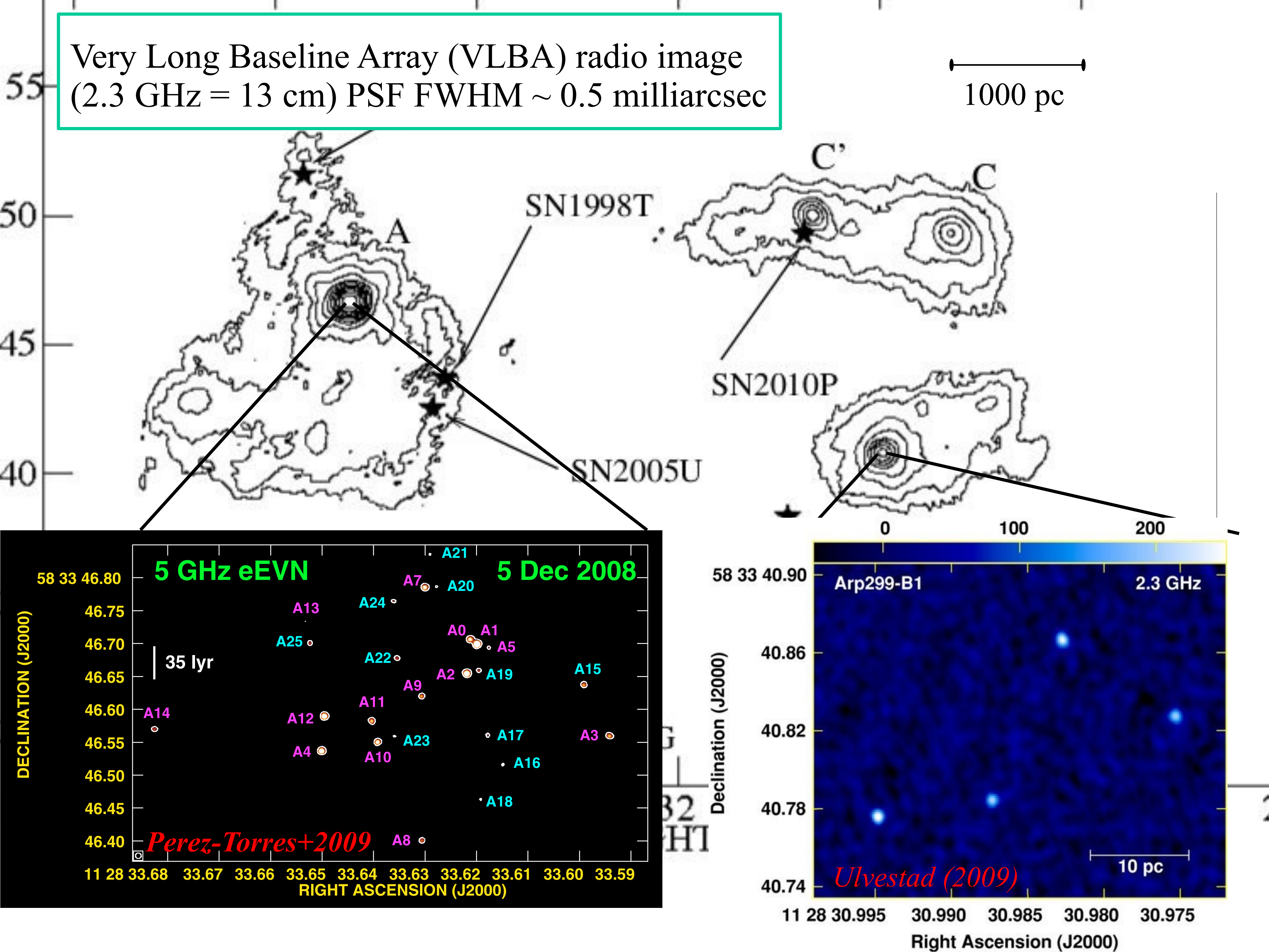
Gemini-N/Altair near-infrared (1.1-2.2 μm) (PSF FWHM ~ 0.1”)



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

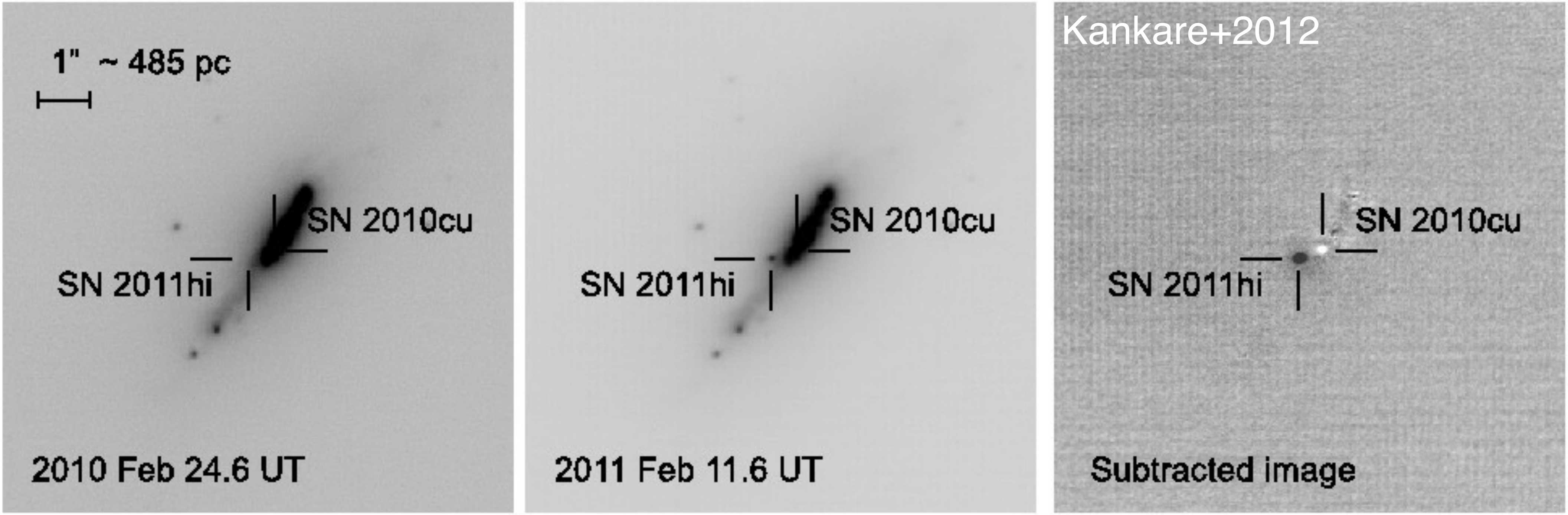


55
50
45
40
SN2010O
SN1998T
SN2005U
A
C'
C
SN2010P
N1993G
32
RIGHT
Arp299 – A
Flux [mJy]
Time [days]
1,2, 3, 4,5, 6, 7, 8, 9,10, 11, 12,13, 14
Arp299−A (scaled to B1)
Arp299−B1
1993
2001
2005
1,2, 3, 4,5, 6, 7, 8, 9,10, 11,12,13, 14, 15


Very Long Baseline Array (VLBA) radio image
(2.3 GHz = 13 cm) PSF FWHM ~ 0.5 milliarcsec
1000 pc
A
C'
C
SN1998T
SN2010P
SN2005U
5 GHz eEVN
5 Dec 2008
35 lyr
A0
A1
A2
A3
A4
A5
A7
A8
A9
A10
A11
A12
A13
A14
A15
A16
A17
A18
A19
A20
A21
A22
A23
A24
A25
DECLINATION (J2000)
RIGHT ASCENSION (J2000)
Perez-Torres+2009
Arp299-B1
2.3 GHz
10 pc
Declination (J2000)
Right Ascension (J2000)
Ulvestad (2009)

Detecting time-variability: astronomical and medical imaging

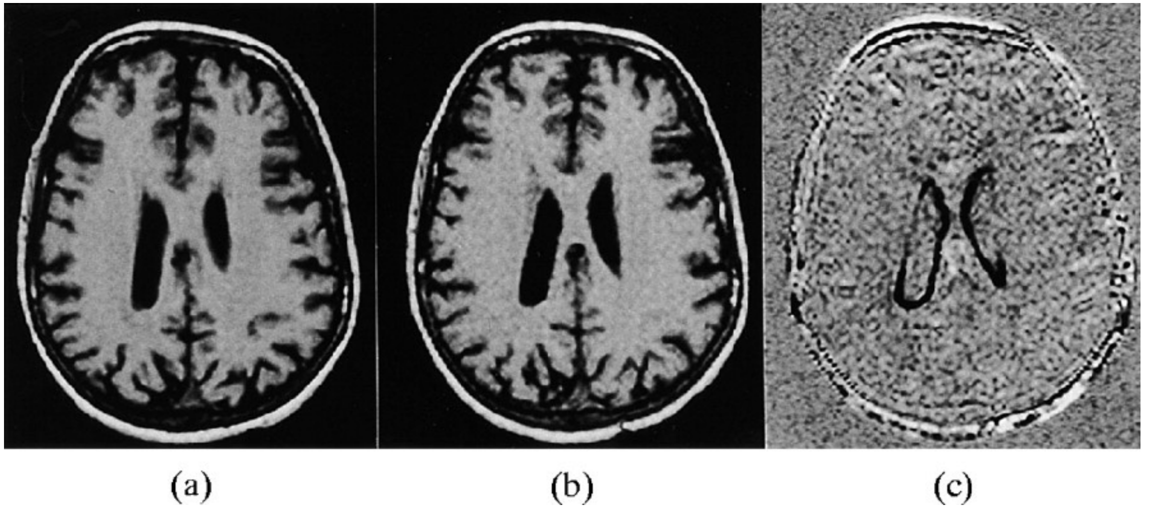
- Detection and study of stellar explosions (supernovae) by repeated imaging of galaxies
  - SN detection by precise image alignment, matching of the point spread functions (PSFs), intensity and background levels followed by image subtraction



Detecting time-variability: astronomical and medical imaging

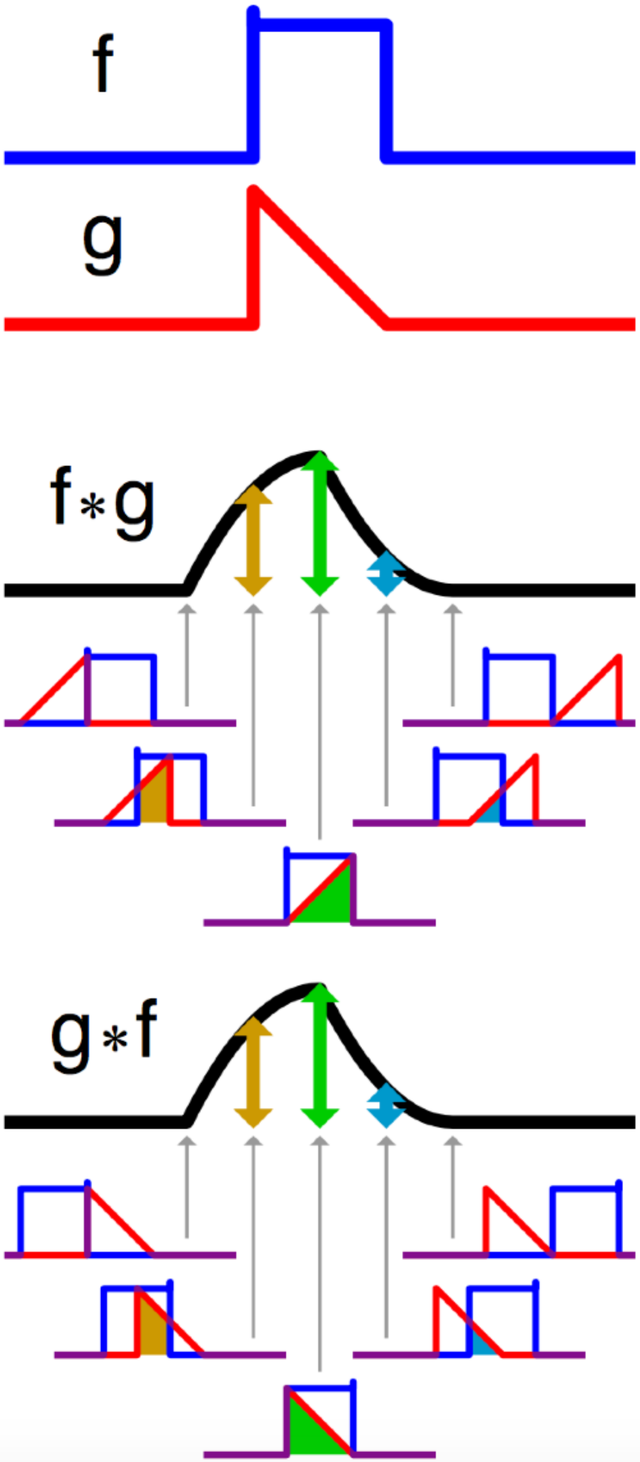
- Detection and study of stellar explosions (supernovae) by repeated imaging of galaxies
  - SN detection by precise image alignment, matching of the point spread functions (PSFs), intensity and background levels followed by image subtraction
- Monitoring of volumetric changes, e.g., loss of tissue in Alzheimer's
  - Register new and reference images using natural landmarks, normalise image intensities and apply image subtraction to reveal tiny volumetric changes

Reference new +6 months subtracted



Bradley et al. 2002, British J. of Radiology, 75, 506

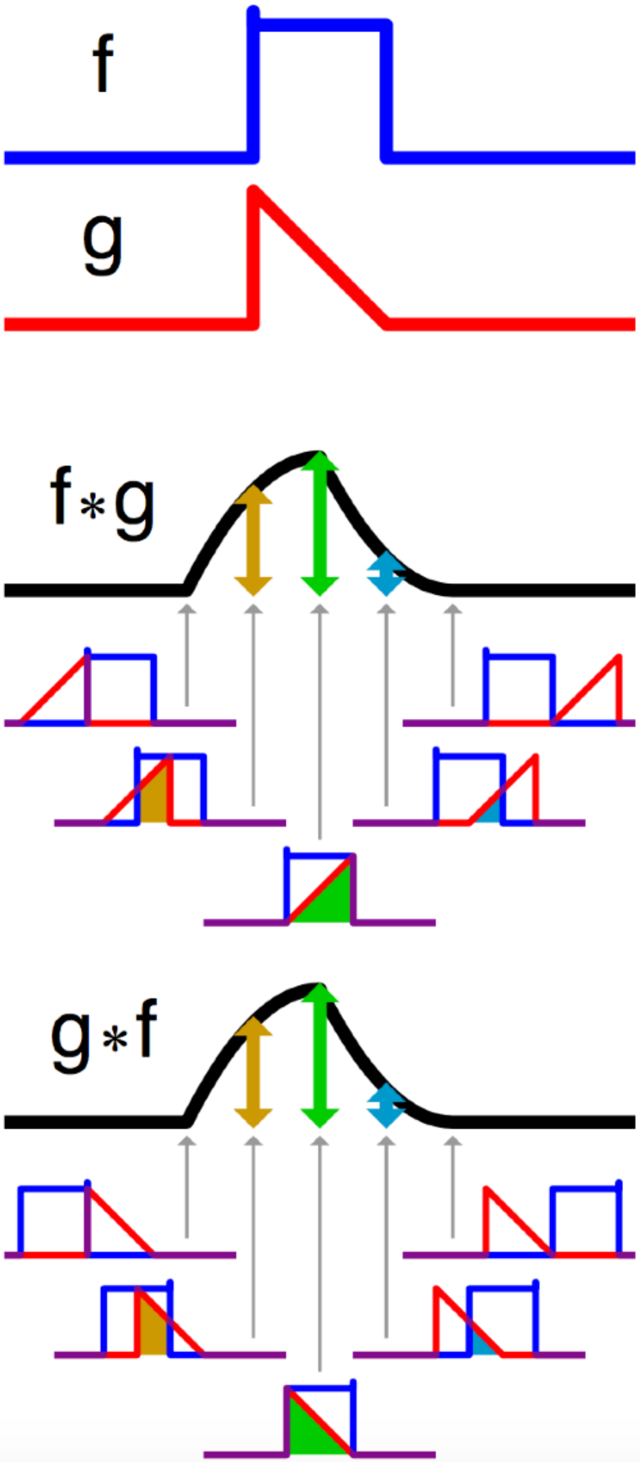
Convolution



$$(f * g)(x) = \int_{-\infty}^{\infty} f(\tau) g(x - \tau) \quad d\tau$$

$$(f * g)_j = \sum_{k=-m/2+1}^{m/2} f_k g_{j-k}$$

Convolution



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

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

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

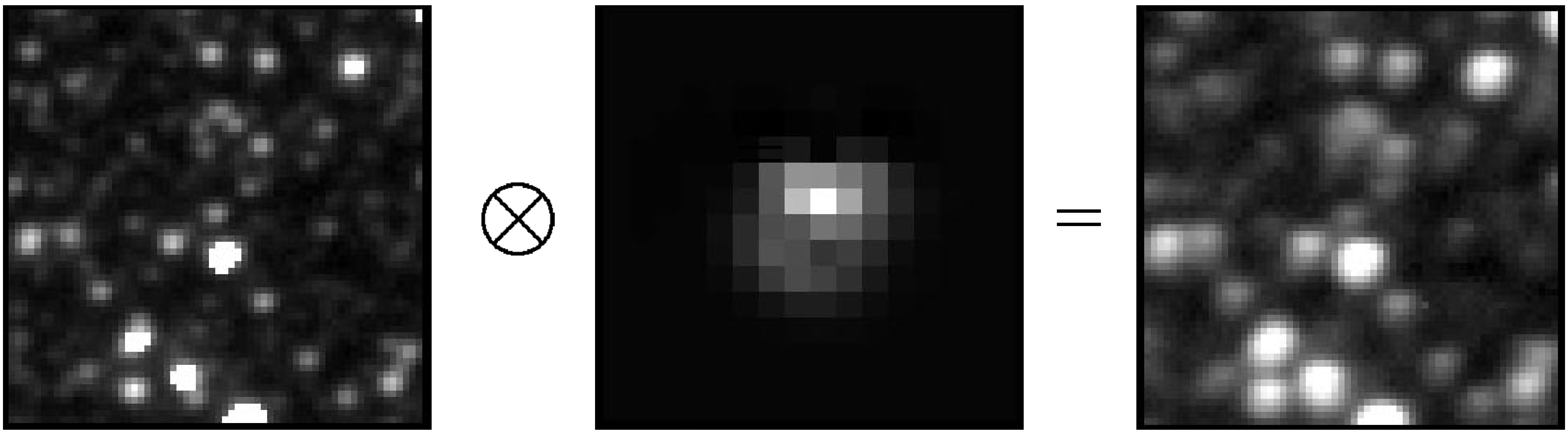
Convolution

- With convolution can reduce the noise and therefore increase the S/N while degrading spatial resolution

"real" signal **additive noise**

$$b(\vec{x}) = f(\vec{x}) * p(\vec{x}) + n(\vec{x})$$

observed signal **PSF**



$$ref(x,y) \otimes kernel(x,y,u,v) = im(x,y)$$

Aland & Lupton 1998: A method for optimal image subtraction, arXiv:astro-ph/9712287

Convolution

- With convolution can reduce the noise and therefore increase the S/N while degrading spatial resolution

"real" signal **additive noise**

$$b(\vec{x}) = f(\vec{x}) * p(\vec{x}) + n(\vec{x})$$

observed signal **PSF**

In the case of 1-D functions

$$(f * g)(x) = \int_{-\infty}^{\infty} f(\tau) g(x - \tau) \quad d\tau$$

In the case of discrete 1-D functions

$$(f * g)_j = \sum_{k=-m/2+1}^{m/2} f_k g_{j-k}$$

Deconvolution

We have observed data *I* (intensity distribution) corresponding to an observation of a "real image" O through an imaging system characterised by the PSF *P* and additive noise *N*.

$$I(x,y) = \int_{x_1=-\infty}^{+\infty}\int_{y_1=-\infty}^{+\infty} P(x-x_1,y-y_1)O(x_1,y_1)dx_1dy_1$$

$$+ \; N(x,\, y)$$

$$= (P * O)(x,\, y) + N(x,\, y),$$

The Convolution Theorem: Convolution in either domain is equivalent to multiplication in the other.

In Fourier space:

$$\hat{I}(u,\, v) = \hat{O}(u,\, v)\hat{P}(u,\, v) + \hat{N}(u,\, v).$$

Starck, Pantin & Murtagh 2002: Deconvolution in Astronomy
https://iopscience.iop.org/article/10.1086/342606/pdf

Deconvolution

In Fourier space:

$$\hat{I}(u, v) = \hat{O}(u, v)\hat{P}(u, v) + \hat{N}(u, v).$$

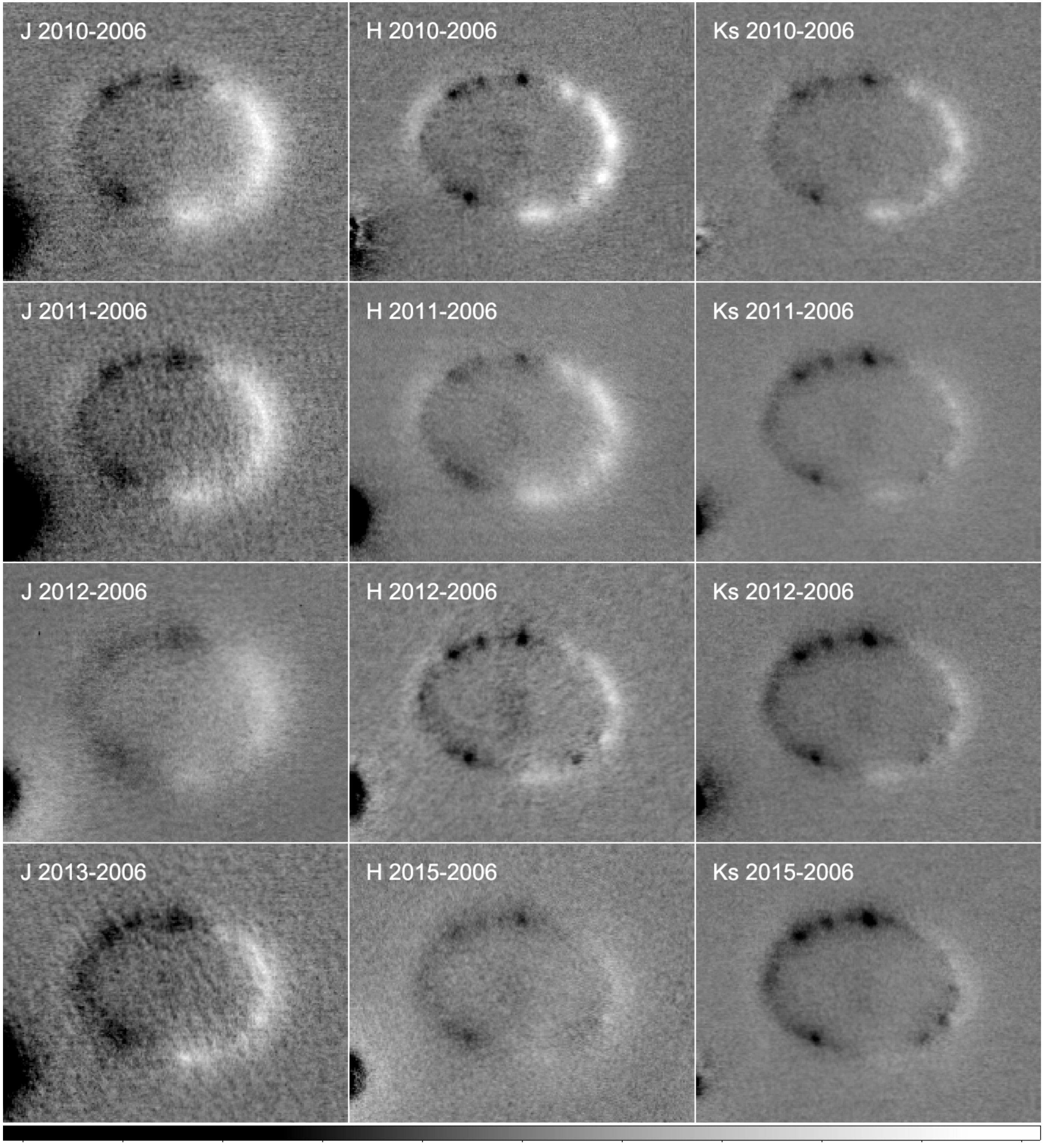
$$\frac{\hat{I}(u, v)}{\hat{P}(u, v)} = \hat{O}(u, v) + \frac{\hat{N}(u, v)}{\hat{P}(u, v)} .$$

This method, sometimes called the *Fourier-quotient method*, is very fast. We need to do only a Fourier transform and an inverse Fourier transform. However, in the presence of noise, this method cannot be used.

Starck, Pantin & Murtagh 2002: Deconvolution in Astronomy
https://iopscience.iop.org/article/10.1086/342606/pdf

Difference imaging in astronomy

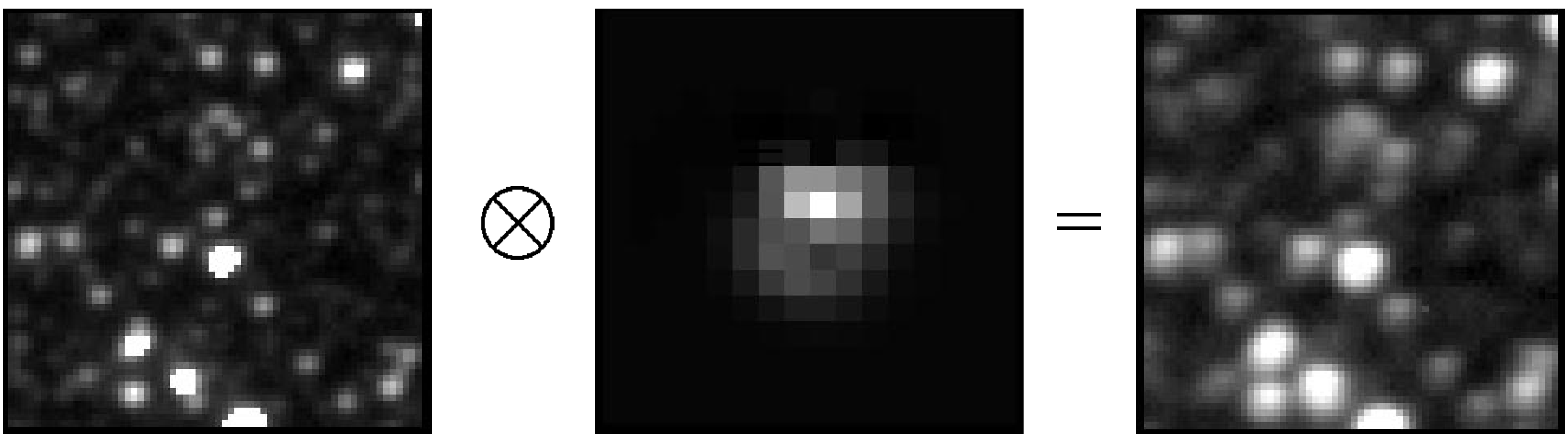

Sep, 1994
Mar, 1995
Feb, 1996
Jul, 1997
Feb, 1998
Apr, 1999
Nov, 2000
Dec, 2001
Jan, 2003
Nov, 2003
Sep, 2005
Apr, 2006
Dec, 2006
May, 2007
Feb, 2008
Apr, 2009
Dec, 2009
Jan, 2011
Feb, 2013
Jun, 2014


J 2010-2006
H 2010-2006
Ks 2010-2006
J 2011-2006
H 2011-2006
Ks 2011-2006
J 2012-2006
H 2012-2006
Ks 2012-2006
J 2013-2006
H 2015-2006
Ks 2015-2006
-25
-20
-15
-10
-5
0
5
10
15
20
25

Ahola (2018)

Optimal Image Subtraction

$$ref(x,y) \otimes kernel(x,y,u,v) = im(x,y) + bg(x,y)$$

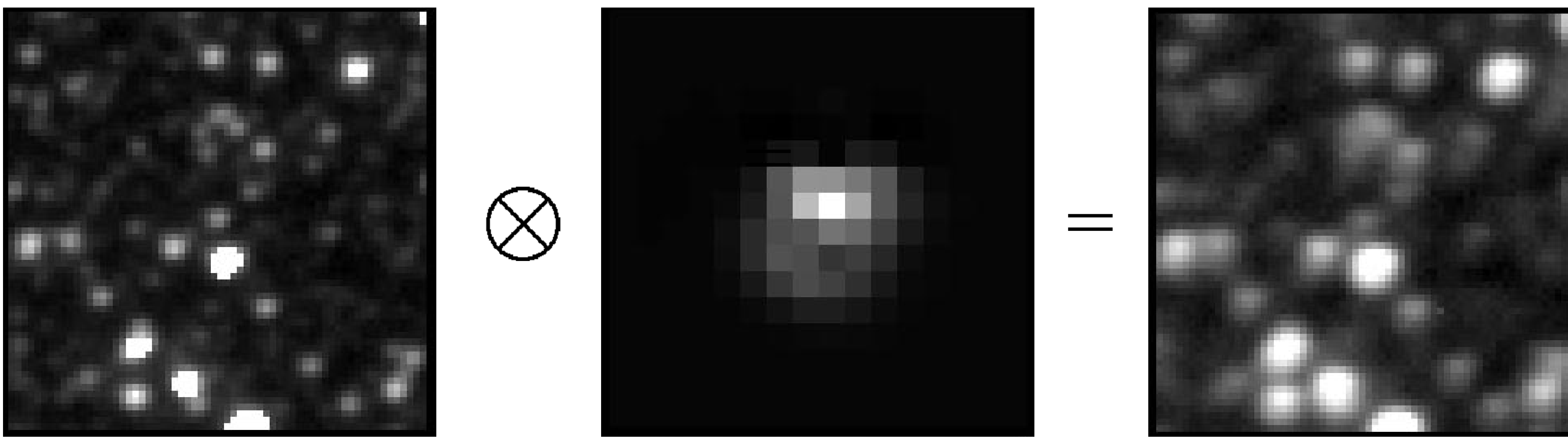


Aland & Lupton 1998: A method for optimal image subtraction, arXiv:astro-ph/9712287

Optimal Image Subtraction

$$ref(x,y) \otimes kernel(x,y,u,v) = im(x,y) + bg(x,y)$$

$$kernel(x,y,u,v) = \sum_{n} \sum_{d_n^x} \sum_{d_n^y} \sum_{\delta^x} \sum_{\delta^y} [a_n \underbrace{x^{\delta^x} y^{\delta^y}}_{3} \underbrace{e^{-(u^2+v^2)/2\sigma_n^2}}_{1} \underbrace{u^{d_n^x} v^{d_n^y}}_{2}]$$



Aland & Lupton 1998: A method for optimal image subtraction, arXiv:astro-ph/9712287

Optimal Image Subtraction

$$ref(x, y) \otimes kernel(x, y, u, v) = im(x, y) + bg(x, y)$$

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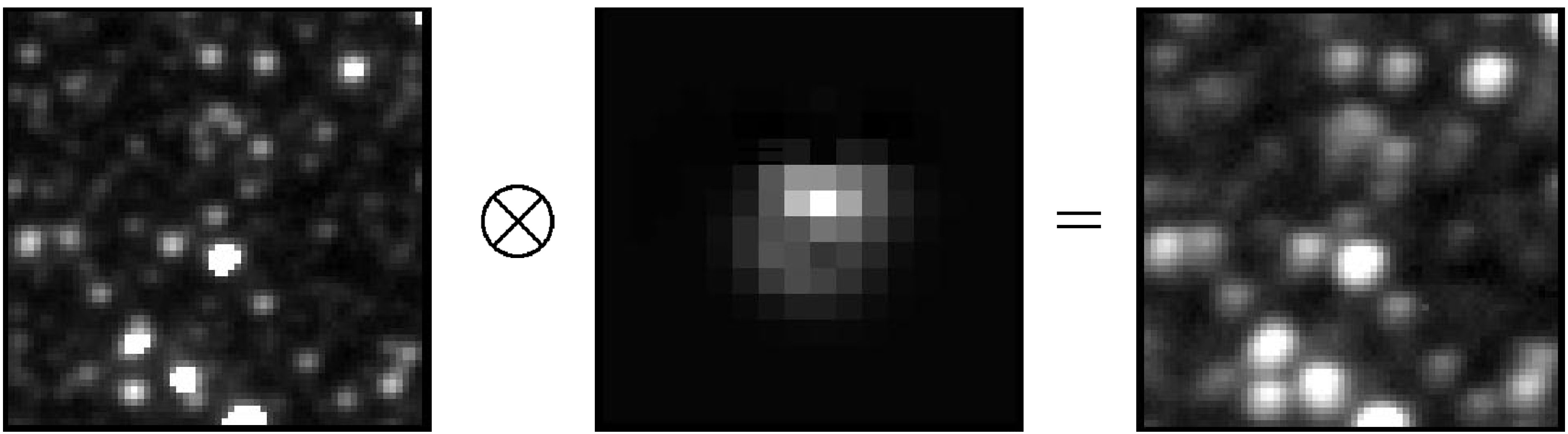
The convolution kernel consists of a set of Gaussian functions (1) which are modified by polynomials (2) and a model for the spatial variations of the kernel (3) where $0 < \mathrm{d}_n^y + \mathrm{d}_n^x \leq \mathrm{D}_n$, and $0 < \delta^y + \delta^x \leq \mathrm{D}^k$.



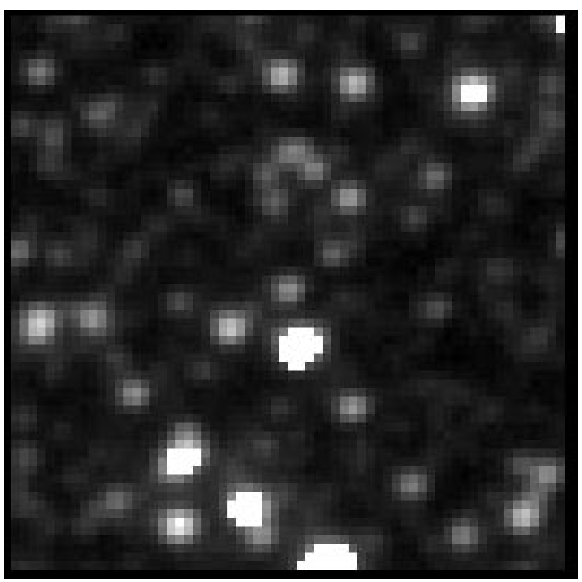
Aland & Lupton 1998: A method for optimal image subtraction, arXiv:astro-ph/9712287

Optimal Image Subtraction

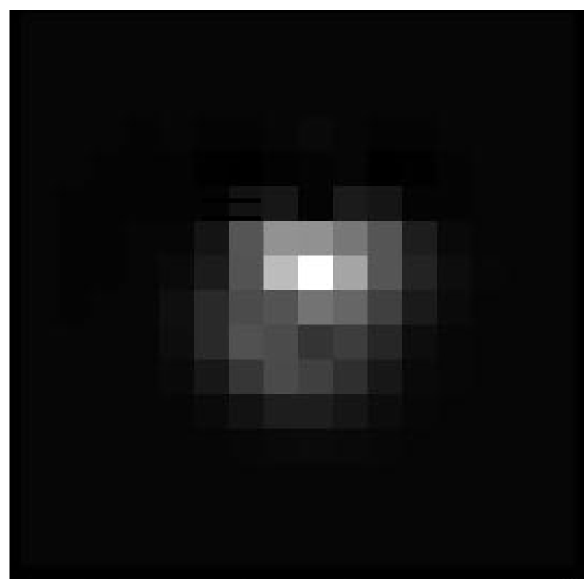
$$ref(x,y) \otimes kernel(x,y,u,v) = im(x,y) + bg(x,y)$$

$$kernel(x,y,u,v) = \sum_{n} \sum_{d_n^x} \sum_{d_n^y} \sum_{\delta^x} \sum_{\delta^y} \left[a_n \underbrace{x^{\delta^x} y^{\delta^y}}_{3} \underbrace{e^{-(u^2+v^2)/2\sigma_n^2}}_{1} \underbrace{u^{d_n^x} v^{d_n^y}}_{2}\right]$$

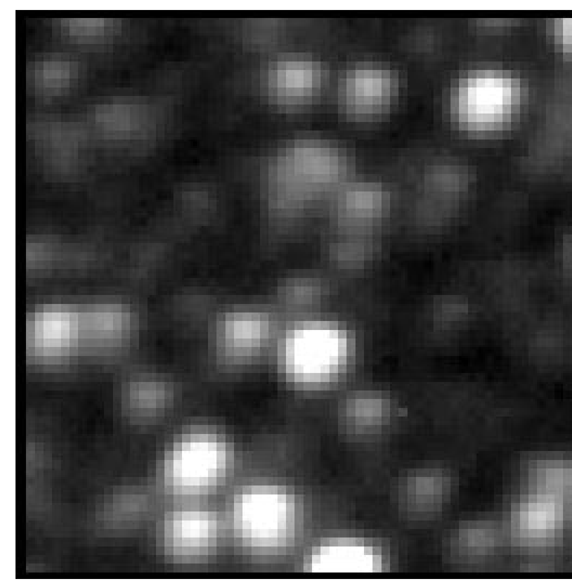
$$bg(x,y) = \sum_{i} \sum_{j} a_i x^i y^j$$



$\otimes$

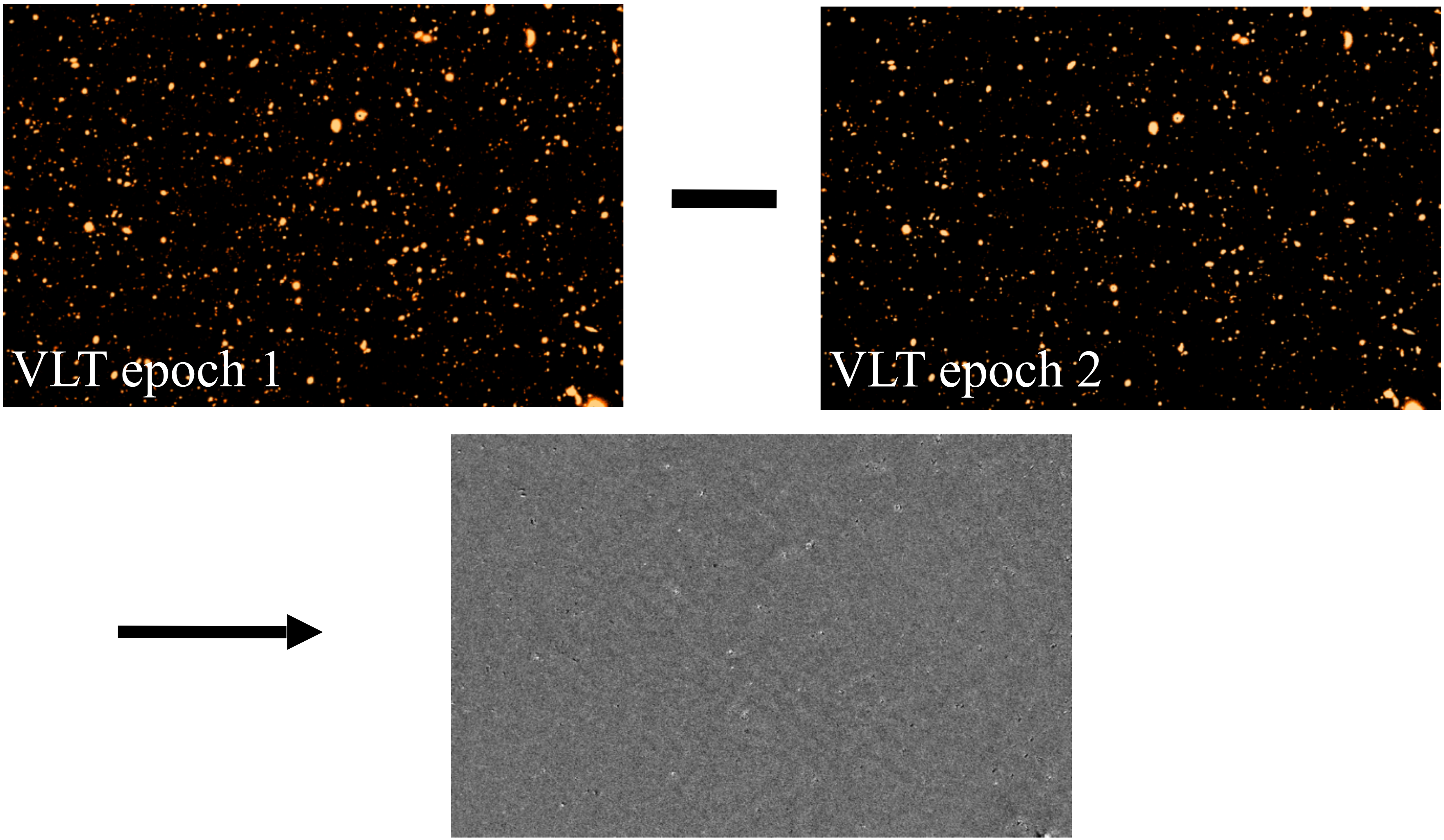


$=$

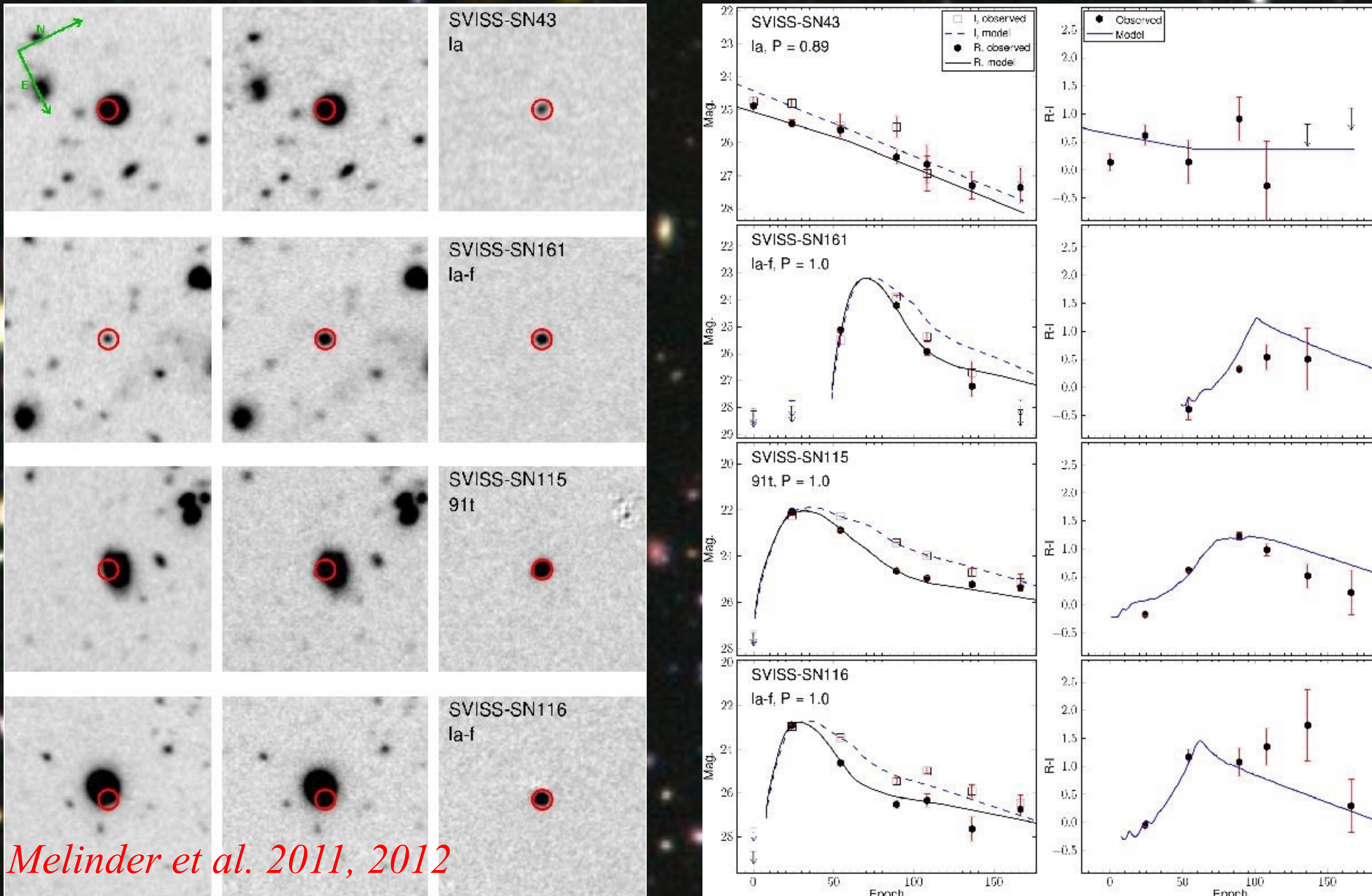


Aland & Lupton 1998: A method for optimal image subtraction, arXiv:astro-ph/9712287

Discovery of new astrophysical transients by precise alignment, PSF matching and subtraction of images




VLT/VIMOS
B 10 hours
V 5 hours
R 15 hours
I 30 hours
Melinder et al. 2011, 2012


N
E
SVISS-SN43
Ia
SVISS-SN161
Ia-f
SVISS-SN115
91t
SVISS-SN116
Ia-f
Melinder et al. 2011, 2012
SVISS-SN43
Ia, P = 0.89
I, observed
I, model
R, observed
R, model
Observed
Model
SVISS-SN161
Ia-f, P = 1.0
SVISS-SN115
91t, P = 1.0
SVISS-SN116
Ia-f, P = 1.0
Mag.
R-I
Epoch

Examples of deconvolution

Application of the Richardson-Lucy algorithm in astronomy

THE ASTRONOMICAL JOURNAL VOLUME 79, NUMBER 6 JUNE 1974

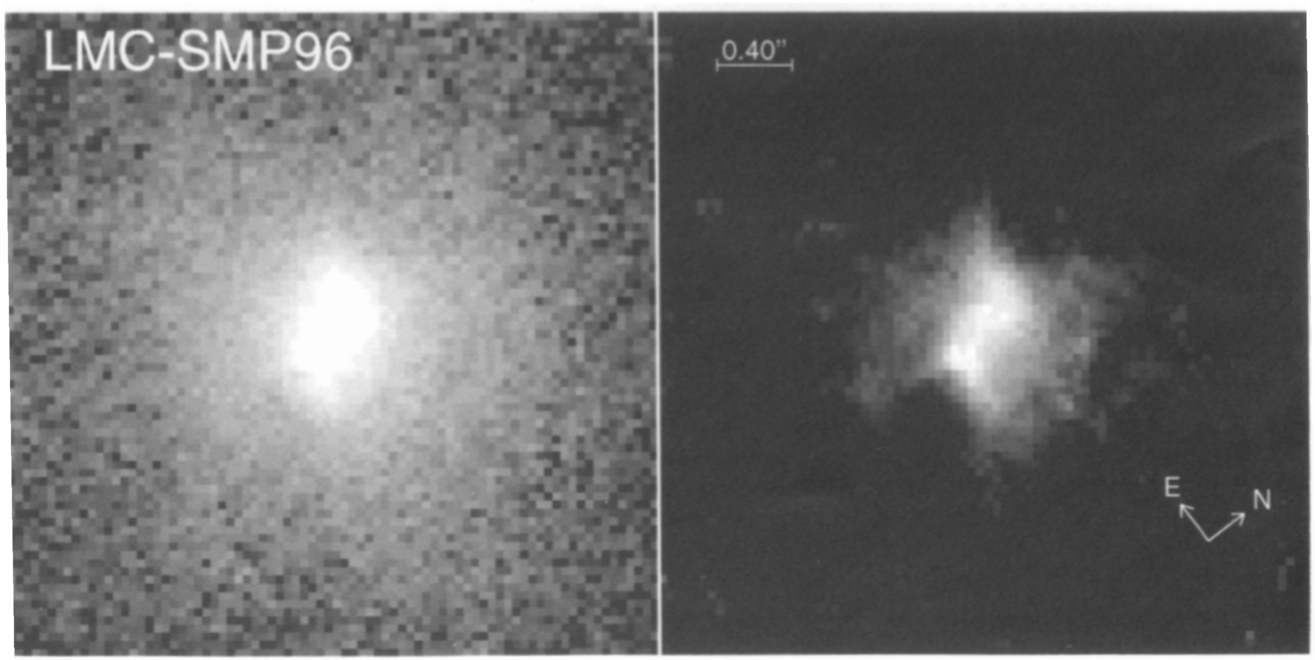
An iterative technique for the rectification of observed distributions

L. B. Lucy*

Departments of Physics and Astronomy, The University of Pittsburgh, Pittsburgh, Pennsylvania 15213

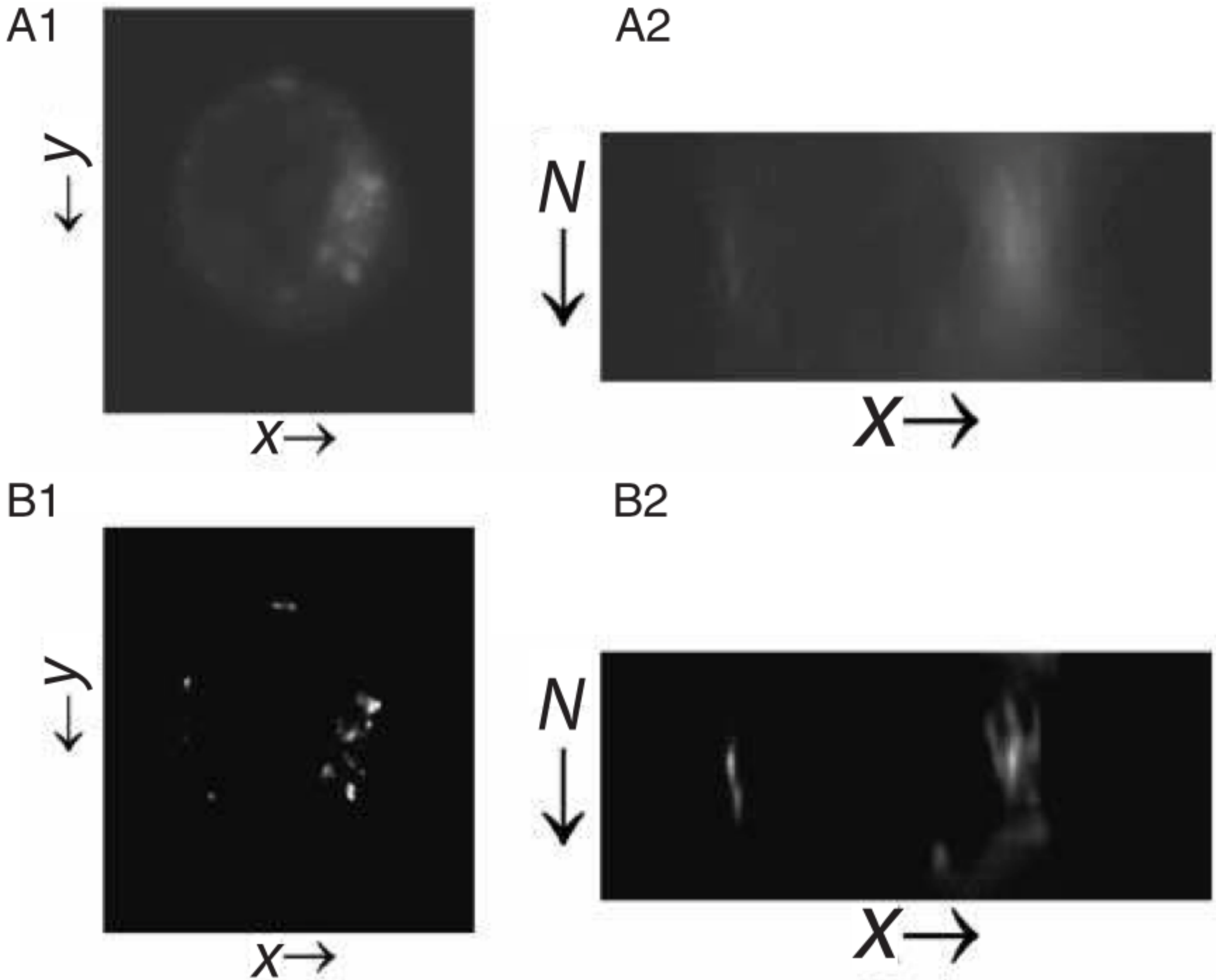
(Received 15 January 1974; revised 26 March 1974)

An iterative technique is described for generating estimates to the solutions of rectification and deconvolution problems in statistical astronomy. The technique, which derives from Bayes' theorem on conditional probabilities, conserves the constraints on frequency distributions (i.e., normalization and non-negativeness) and, at each iteration, increases the likelihood of the observed sample. The behavior of the technique is explored by applying it to problems whose solutions are known in the limit of infinite sample size, and excellent results are obtained after a few iterations. The astronomical use of the technique is illustrated by applying it to the problem of rectifying distributions of $v \sin i$ for aspect effect; calculations are also reported illustrating the technique's possible use for correcting radio–astronomical observations for beam-smoothing. Application to the problem of obtaining unbiased, smoothed histograms is also suggested.

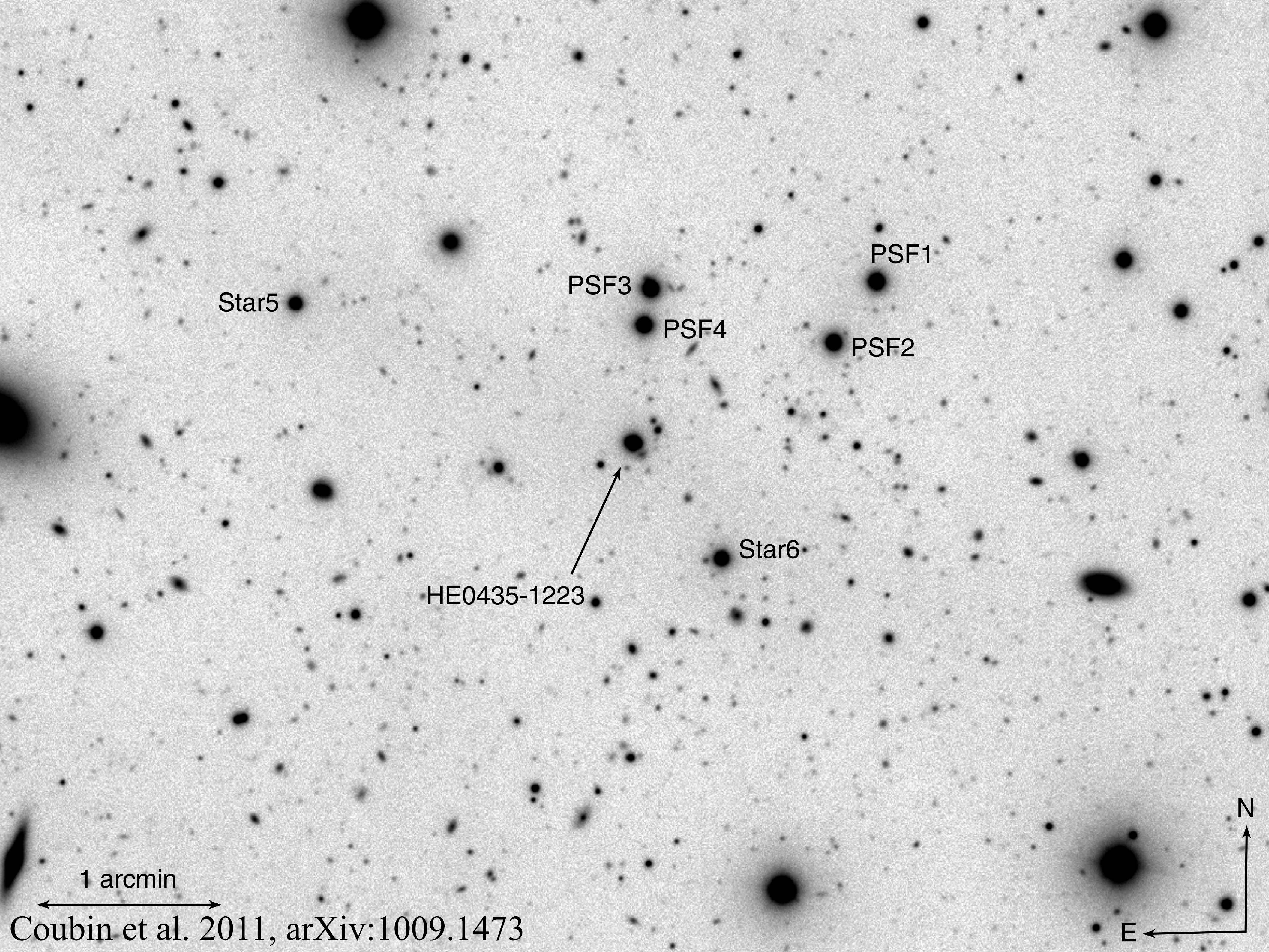


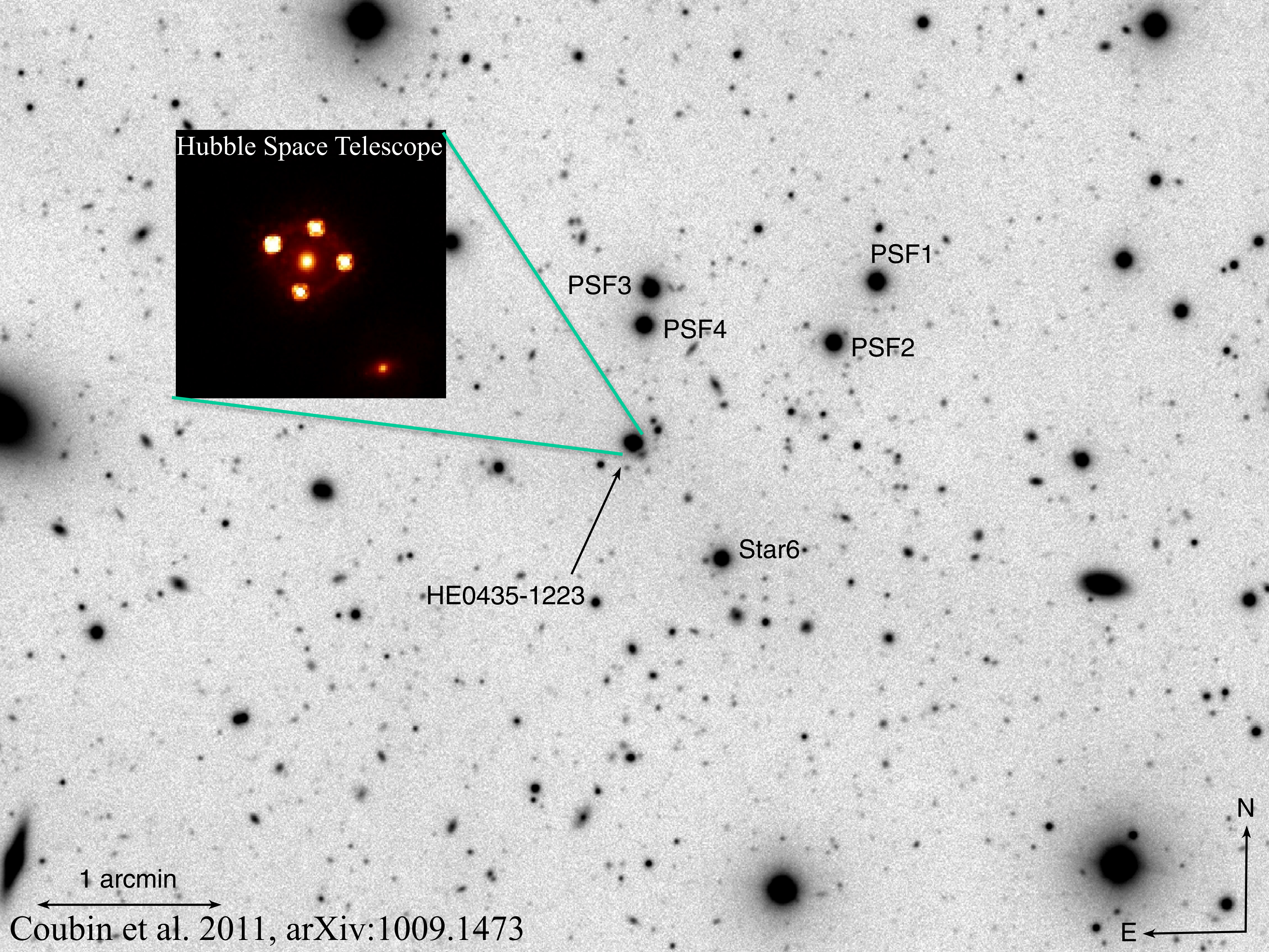
Dopita et al. 1996: Hubble Space Telescope observations of planetary nebulaea

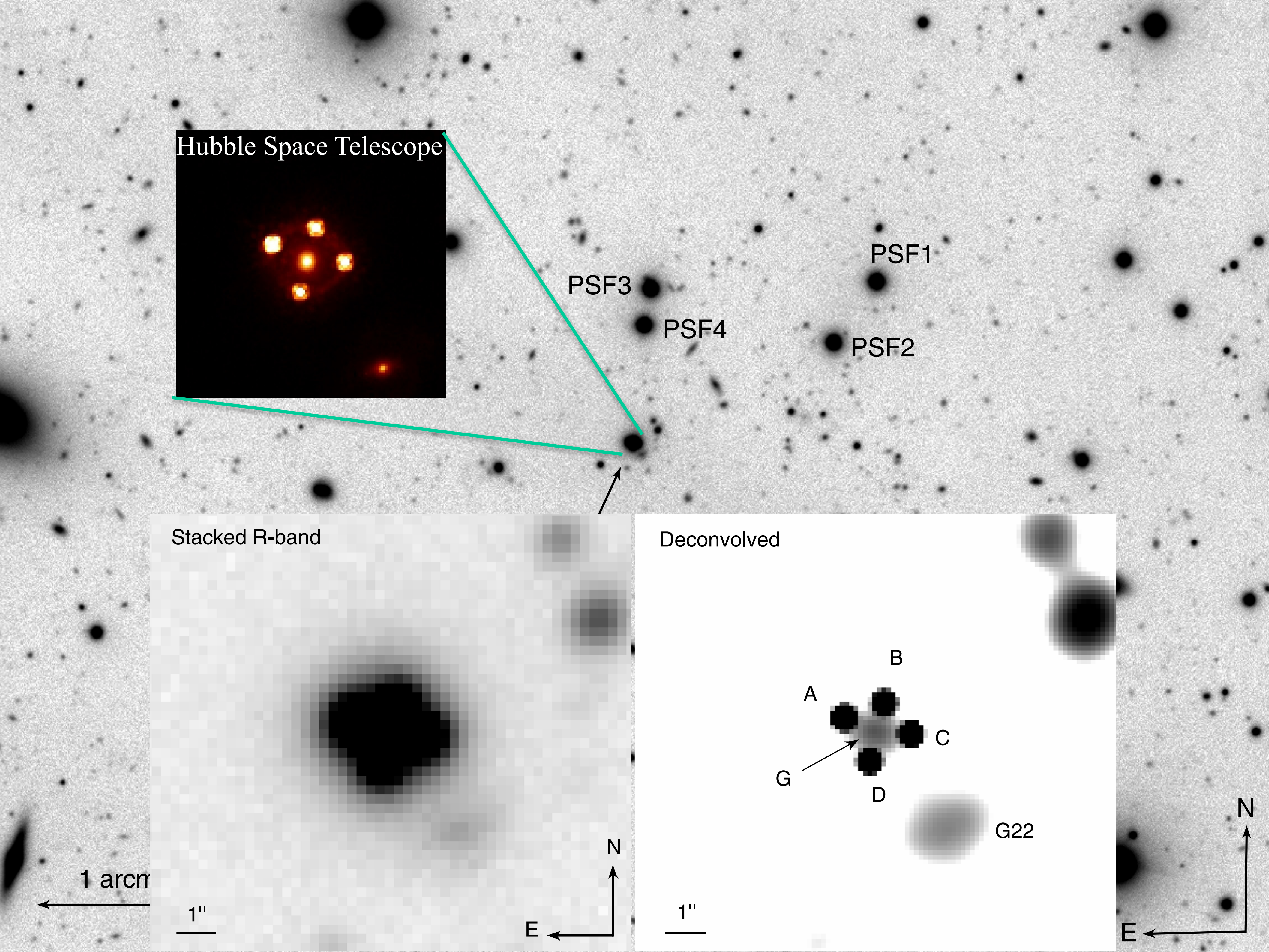
Application of the Richardson-Lucy algorithm to medical images



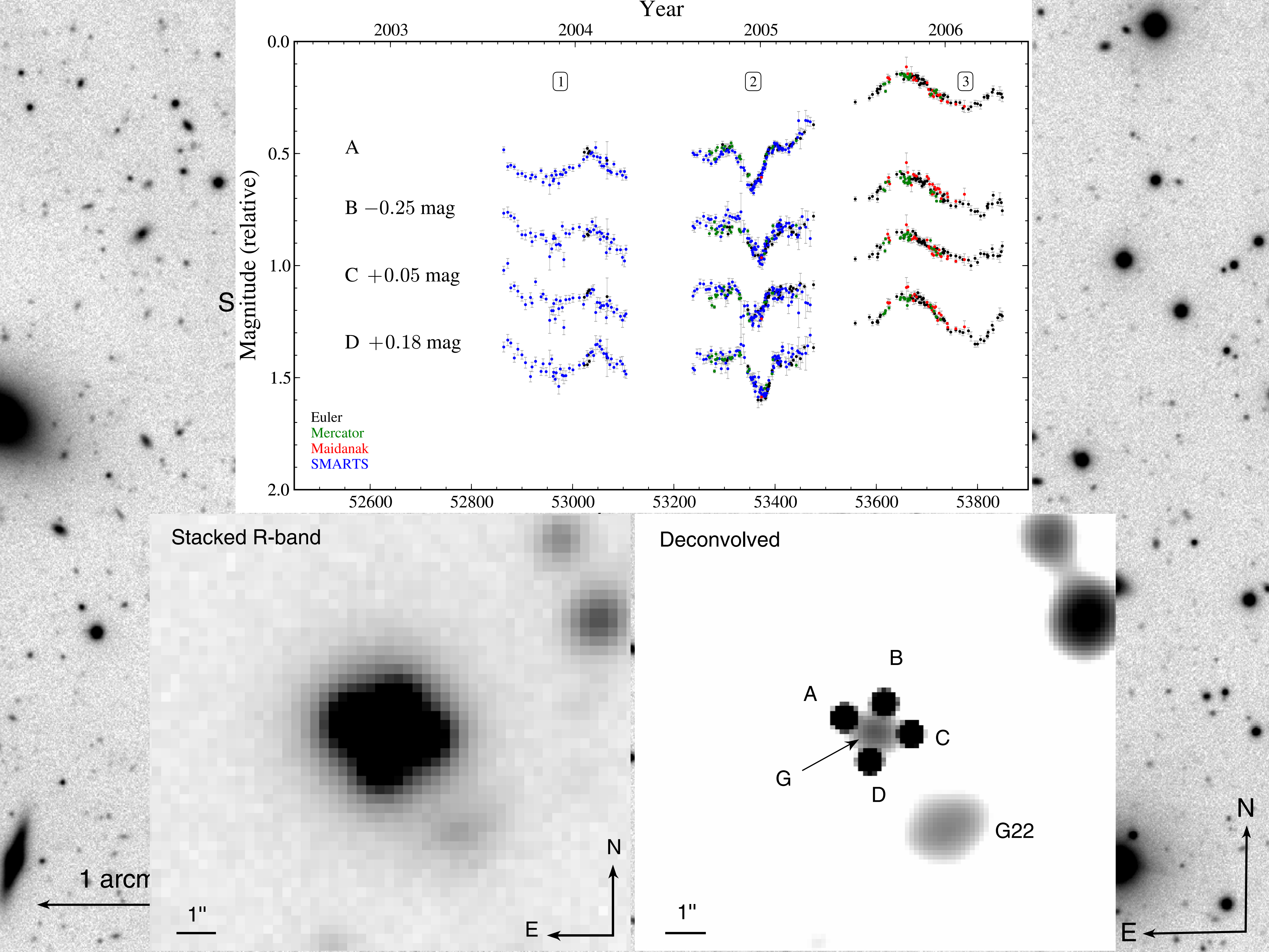
Lai et al. 2003, Journal of Microscopy


PSF1
PSF3
Star5
PSF4
PSF2
Star6
HE0435-1223
1 arcmin
Coubin et al. 2011, arXiv:1009.1473
N
E


Hubble Space Telescope
PSF1
PSF3
PSF4
PSF2
Star6
HE0435-1223
1 arcmin
N
E
Coubin et al. 2011, arXiv:1009.1473



Hubble Space Telescope
PSF1
PSF3
PSF4
PSF2
Stacked R-band
Deconvolved
B
A
C
G
D
G22
N
E
1"
1 arcm


Year
2003
2004
2005
2006
0.0
0.5
1.0
1.5
2.0
Magnitude (relative)
S
1
2
3
A
B −0.25 mag
C +0.05 mag
D +0.18 mag
Euler
Mercator
Maidanak
SMARTS
52600
52800
53000
53200
53400
53600
53800
Stacked R-band
Deconvolved
A
B
C
D
G
G22
N
E
1"
1 arcm

Adaptive optics (AO) imaging

Davies R. 2012: Adaptive Optics for Astronomy
https://arxiv.org/pdf/1201.5741.pdf

Adaptive Optics imaging

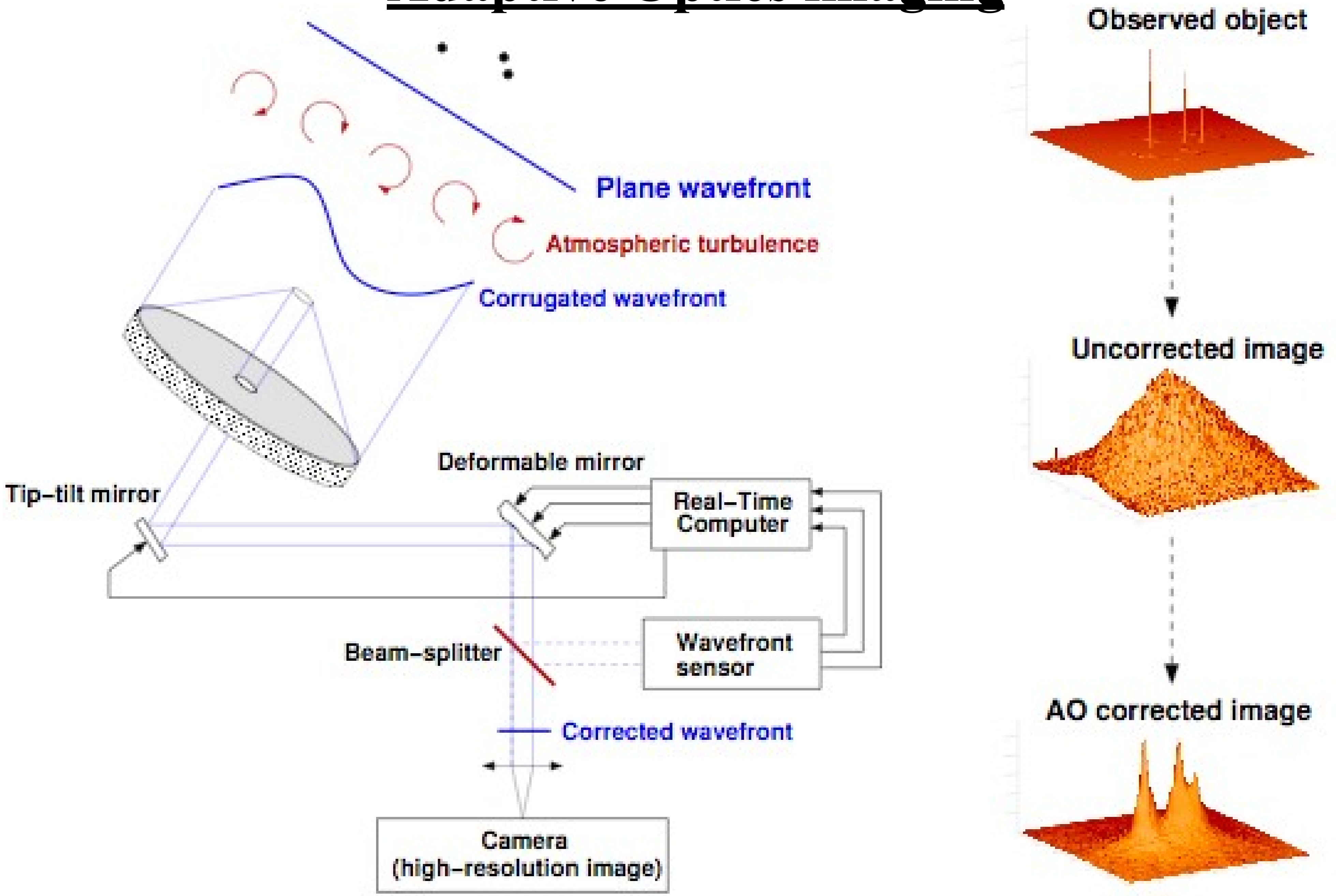
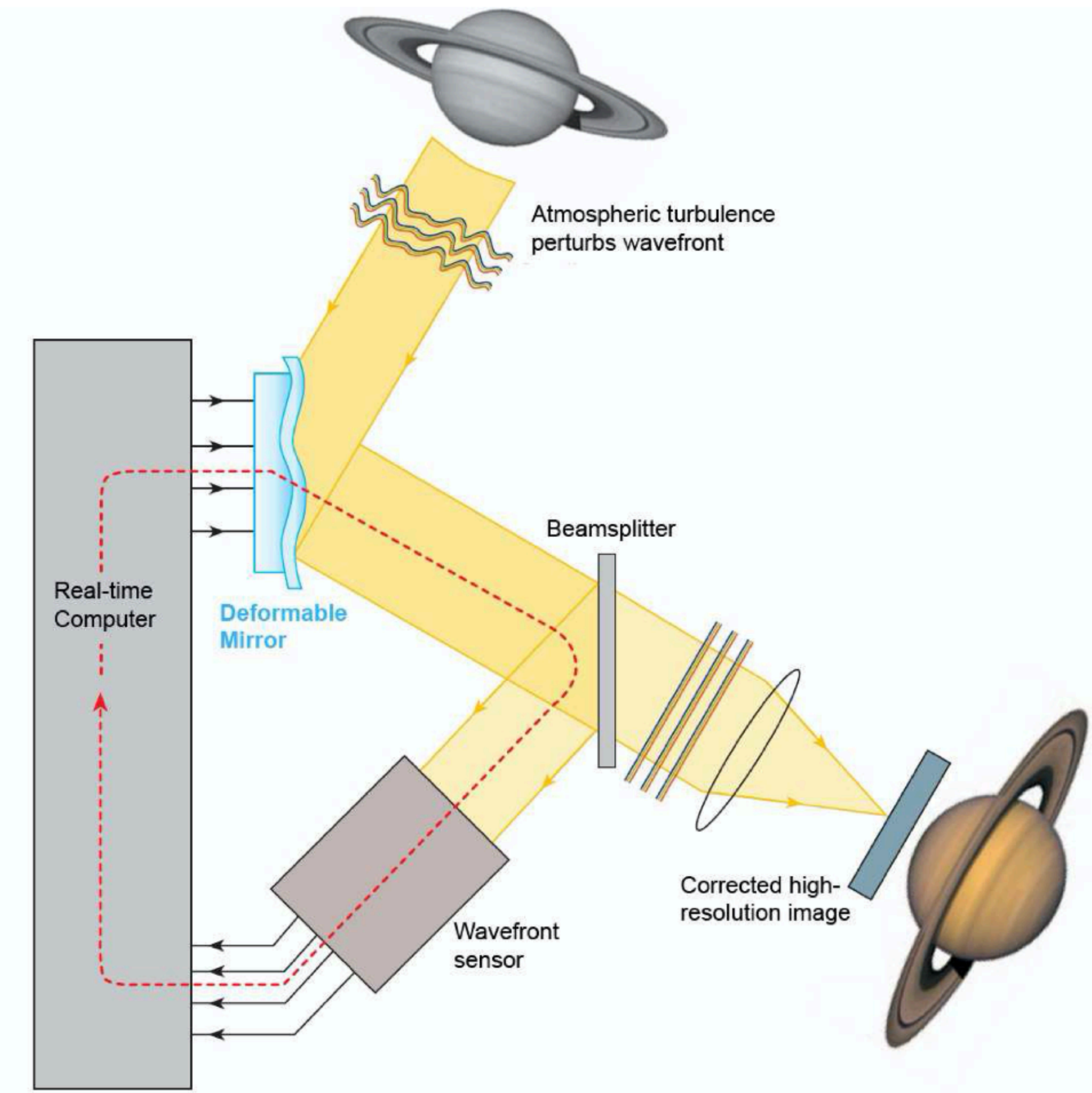
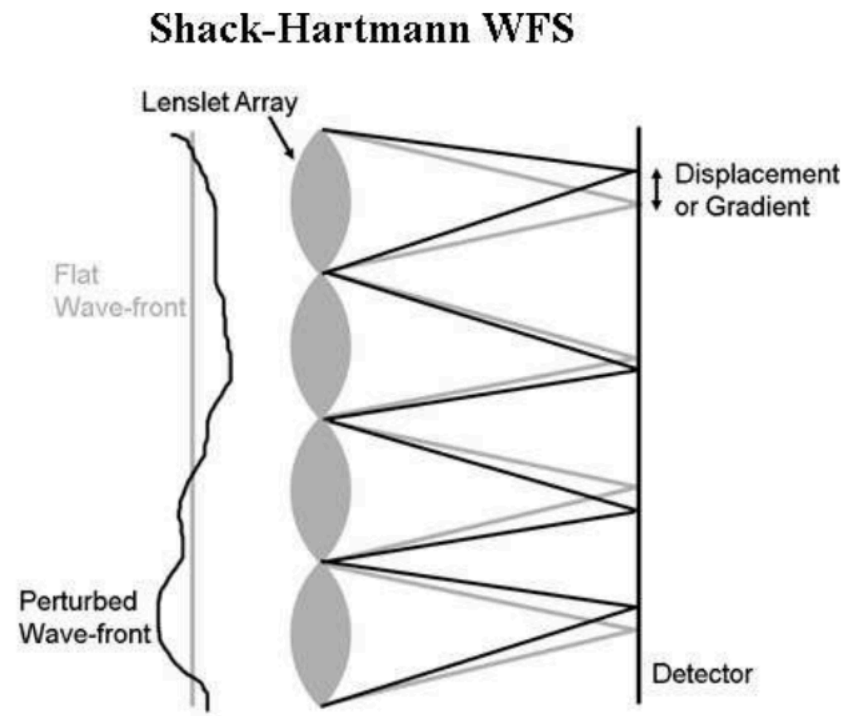


Figure 3-1: Principle of Adaptive Optics

VLT/NACO User manual

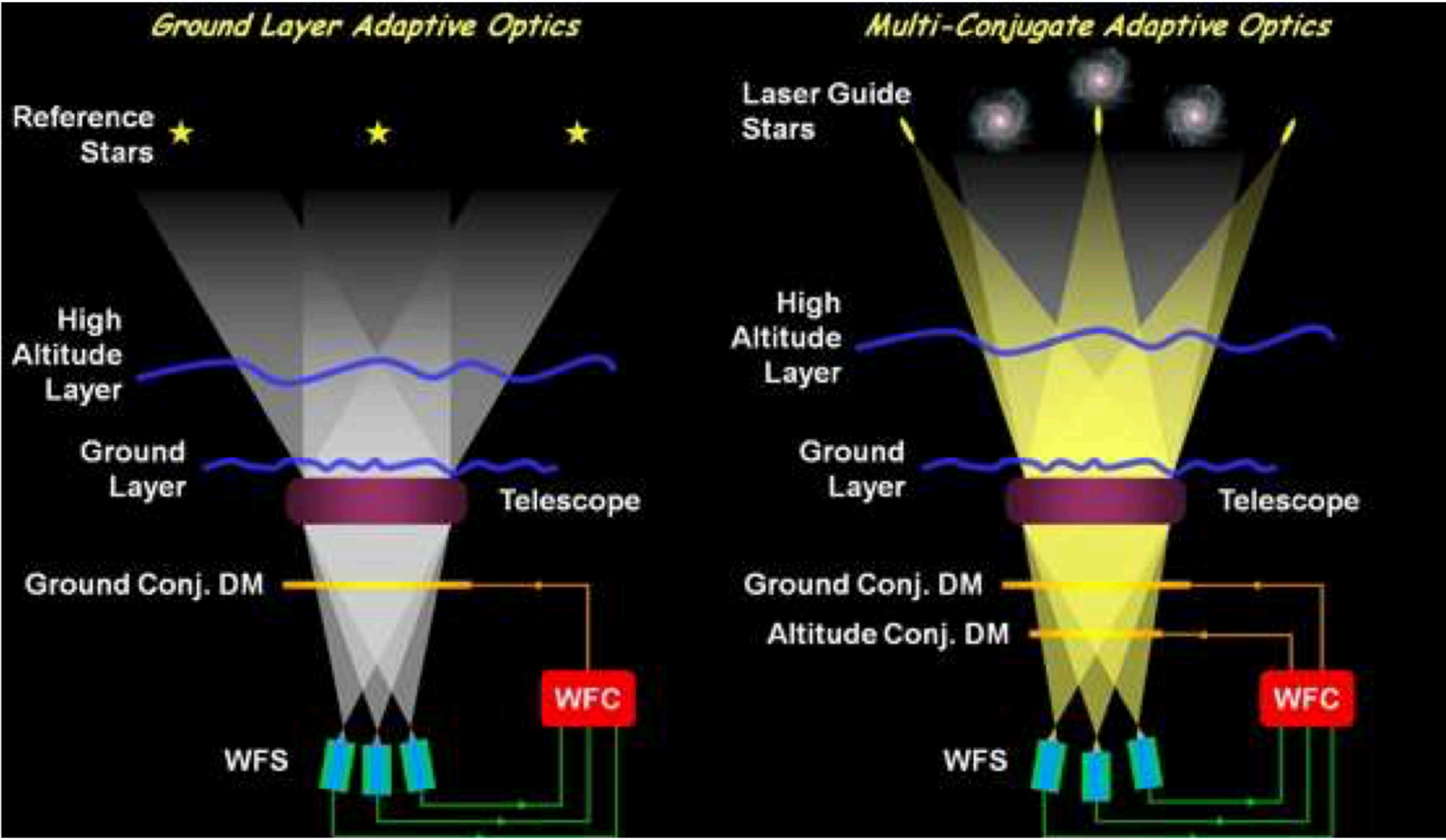
The principles of Adaptive Optics



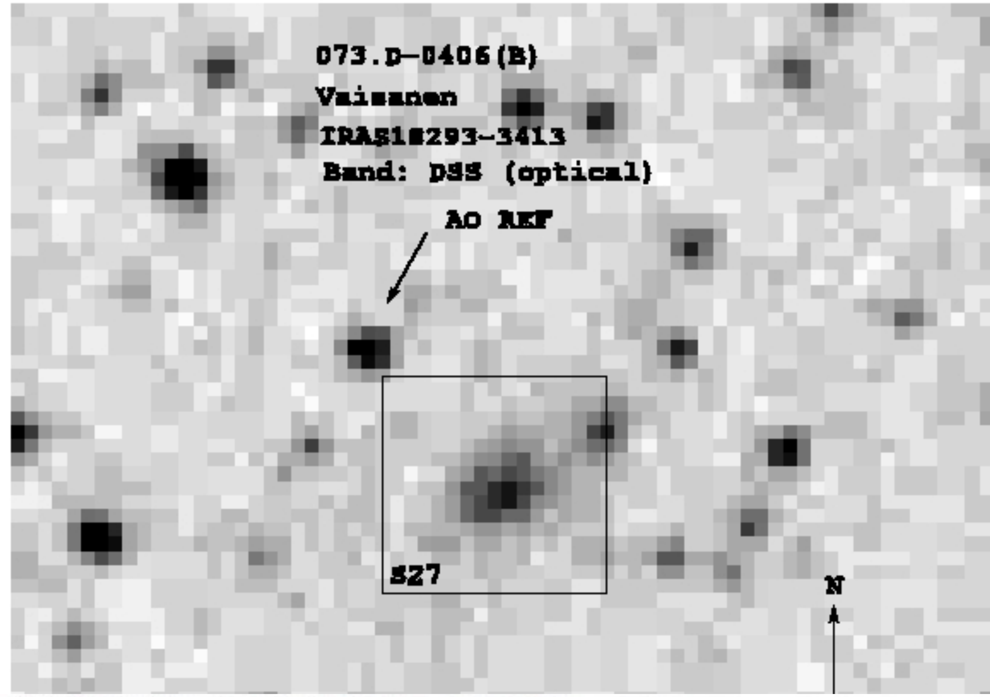


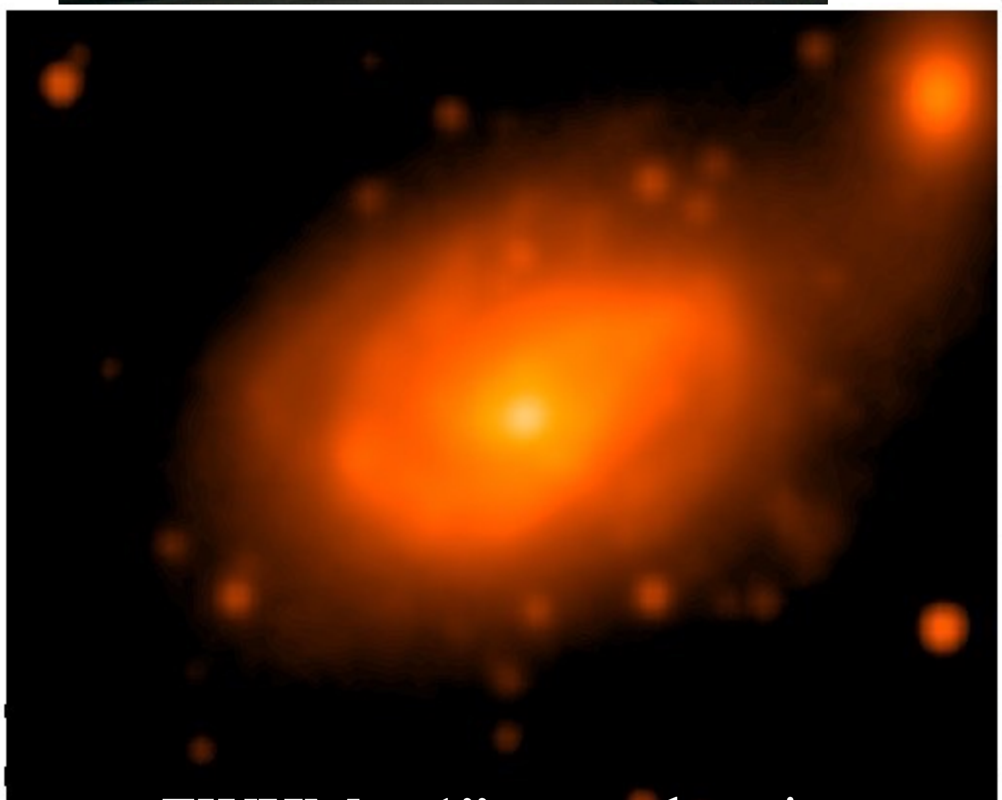
Davies et al. 2012

The principles of Adaptive Optics



Davies et al. 2012

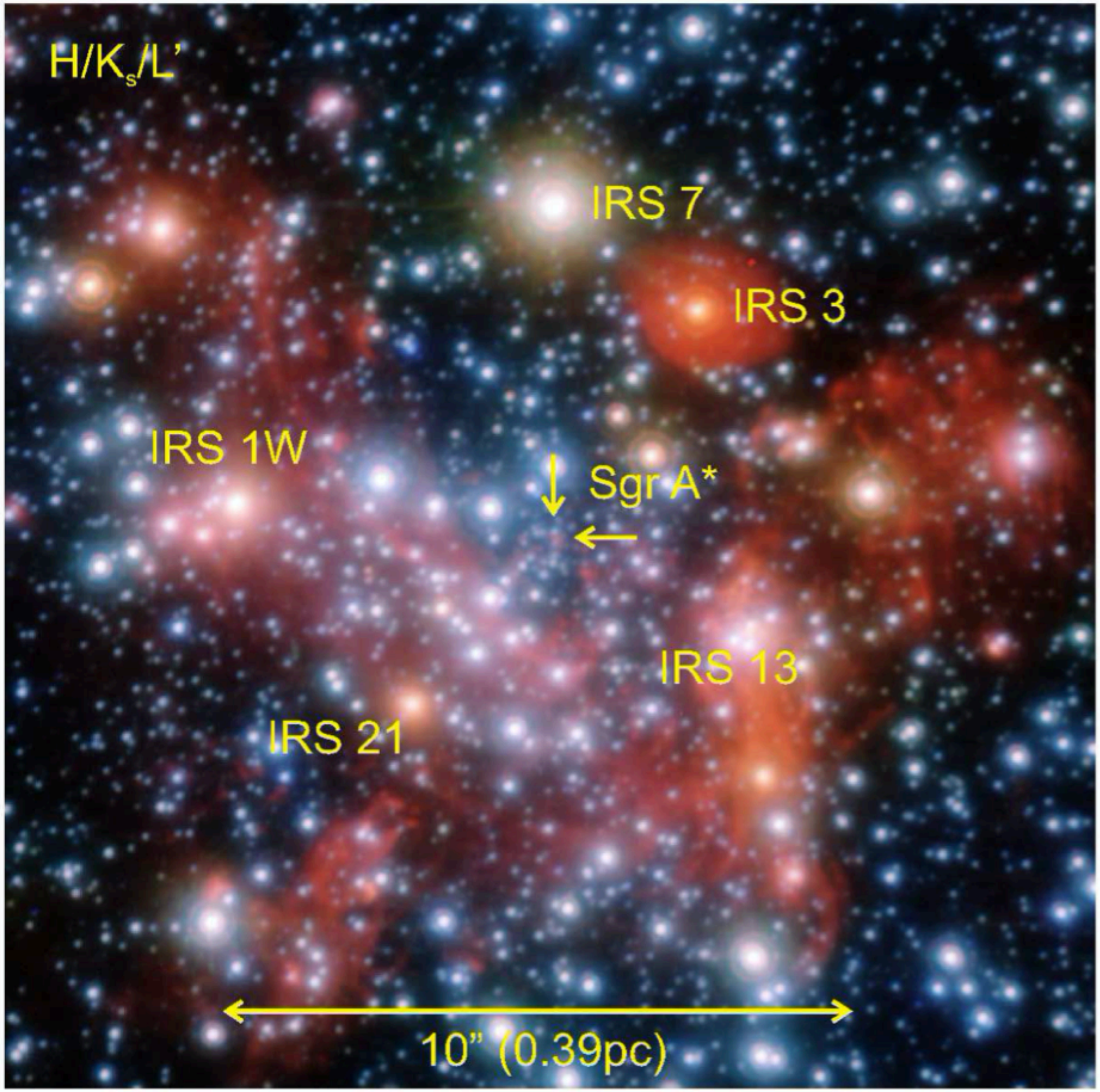


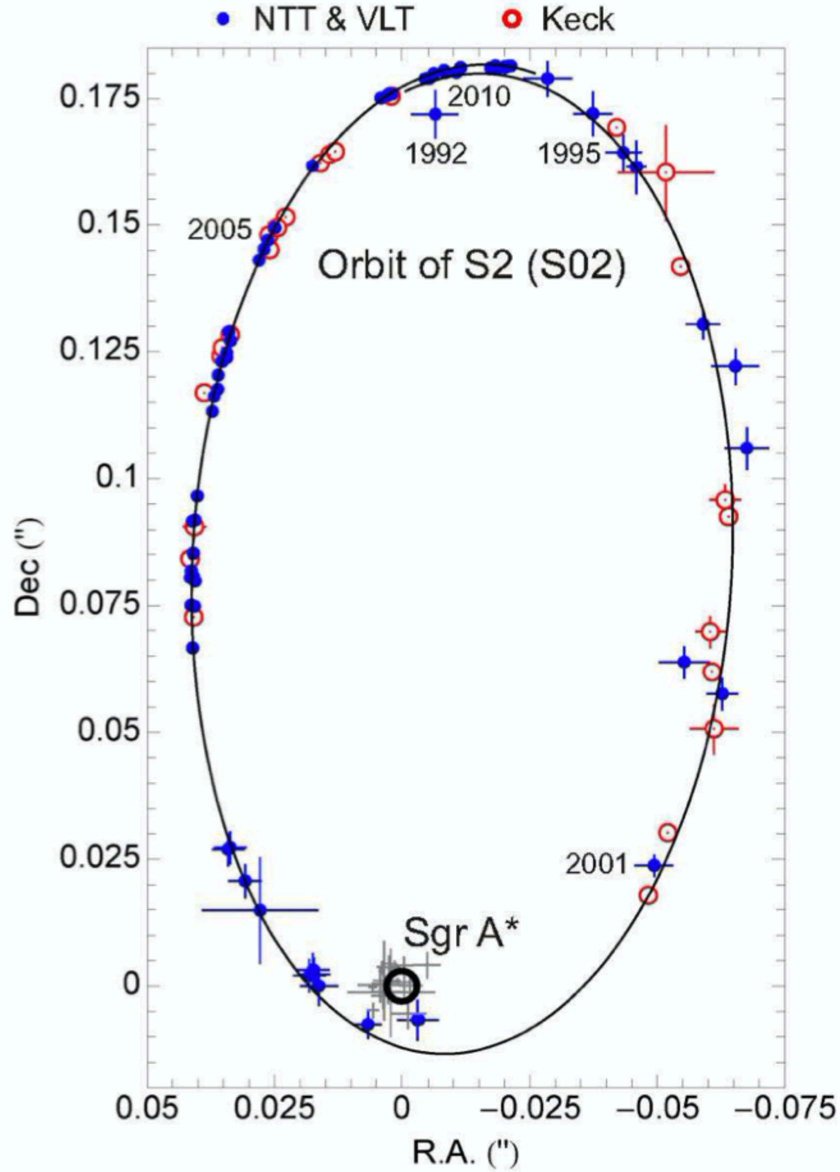


FWHM = 1” natural seeing

FWHM = 0.1” (AO corrected)

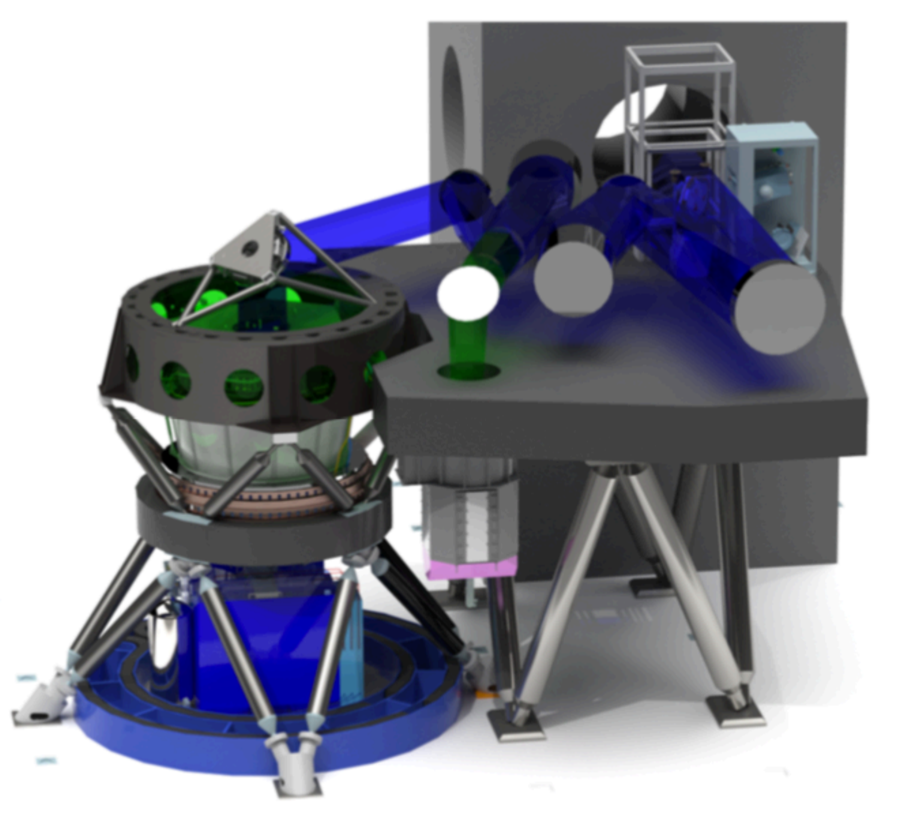
The motion of a star around the central black hole in the Milky Way

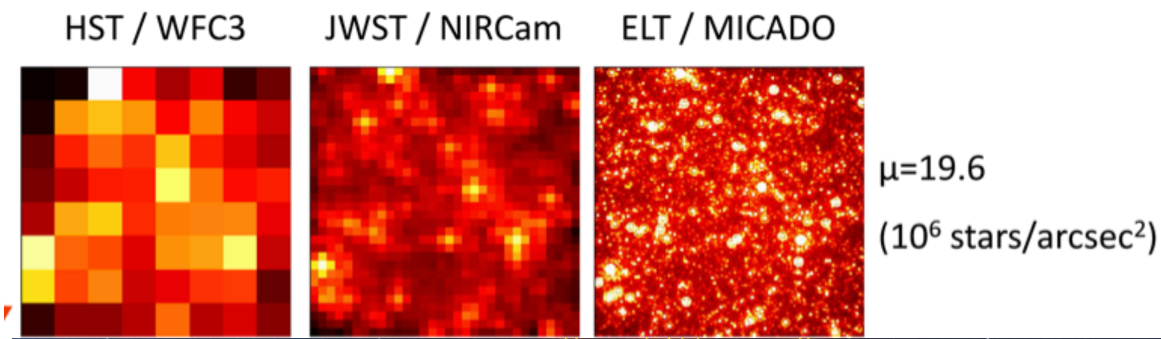


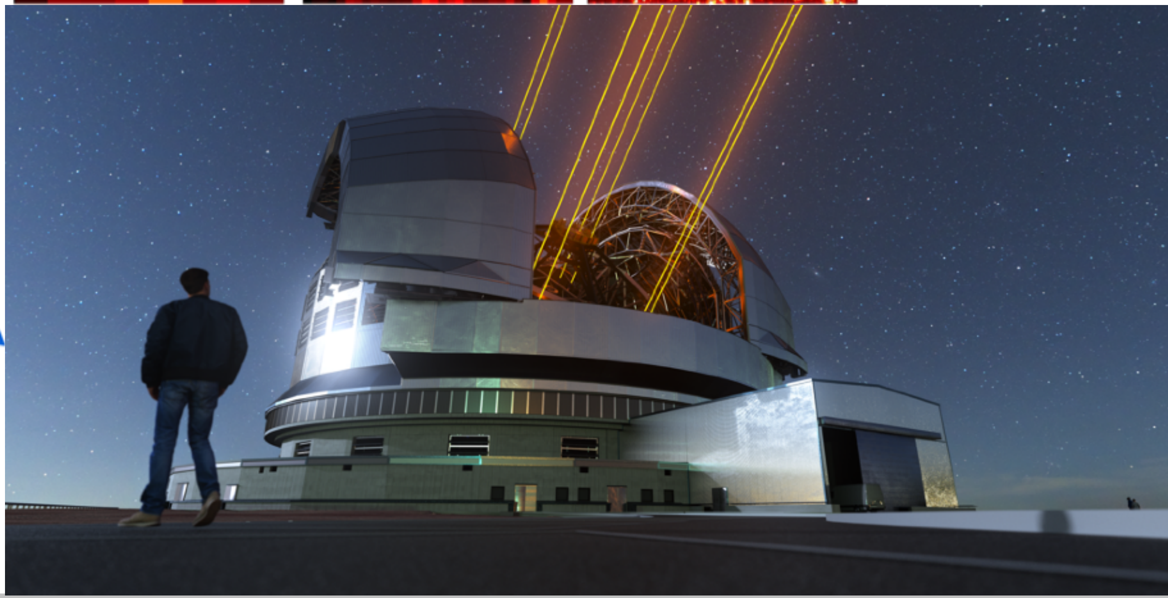


Multi-AO Imaging Camera for Deep Observations (MICADO) will enable ELT to perform diffraction limited: observations $\theta \sim 1.22 \times \lambda / D$

- 4 mas pixel scale providing 50” x 50” field of view with fully sampled diffraction limited PSF of the 39-m diameter ELT (FWHM = 12 mas at 2 μm)







Davies et al. 2018