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ESO Garching

Imaging & spectroscopy
of embedded dense massive clusters in our Galaxy

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with: F. Comeron (ESO)

AIP

M.J. McCaughrean (Exeter)

Scientific Requirements for Extremely Large Telescopes
Proceedings IAU Symposium No. 232, 2005
P. Whitelock, M. Dennefeld & B. Leibundgut, eds.

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ELT near-infrared and thermal-infrared studies of massive star formation: direct imaging and integral field spectroscopy of ultracompact HII regions

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Abstract. In this contribution, we show how a future ELT (>25 m diameter) helps to understand the formation and early dynamical evolution of massive stars embedded in dust-enshrouded very compact HII regions. We describe how to exploit the ELT's near- and mid-IR enhanced sensitivity and high angular resolution to peer through huge amounts of dust extinction, taking direct nearly diffraction-limited images and doing IFU spectroscopy. Together with ALMA, an ELT will be a powerful observing platform to reveal one of the most hidden secrets of stellar astrophysics: the origin of massive stars.

Abstract

We discuss the progress that can be expected from infrared imaging and IFU spectroscopic studies with the 42m E-ELT of the very obscured birthplaces of massive stars in Galactic molecular cloud clumps and ultracompact HII regions. The E-ELT in the K-band can penetrate as much as 200 mag of visual extinction. The combination of astrometric and radial velocity measurements is required to study dynamical processes associated with dense massive star cluster formation.

AIP

THE E-ELT DESIGN REFERENCE MISSION

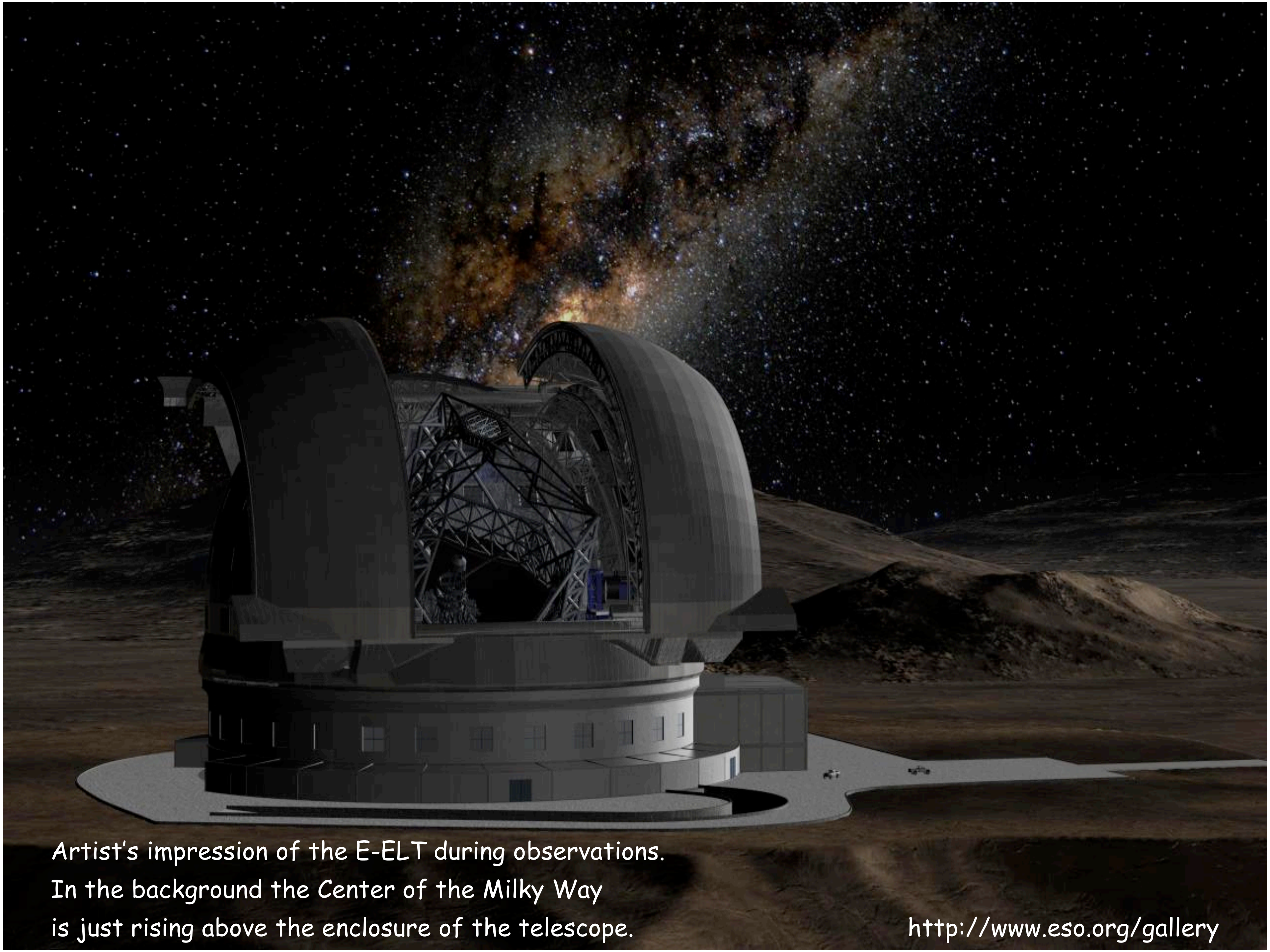
DRM SCIENCE CASES

The following is the list of 'prominent' science cases chosen by the SWG to be studied by the DRM:

- Planets & Stars
  - S3: From giant to terrestrial exoplanets: detection, characterization and evolution (demo case)
  - S9: Circumstellar disks
  - ➔ S5: Young stellar clusters and the Initial Mass Function
- Stars & Galaxies
  - G4: Imaging and spectroscopy of resolved stellar populations in galaxies (demo case)
  - G9: Black holes and AGN
- Galaxies & Cosmology
  - C10: The physics of high redshift galaxies (demo case)
  - C4: First light - the highest redshift galaxies
  - C7: Is the low-density intergalactic medium metal enriched?
  - C2: A dynamical measurement of the expansion history of the Universe

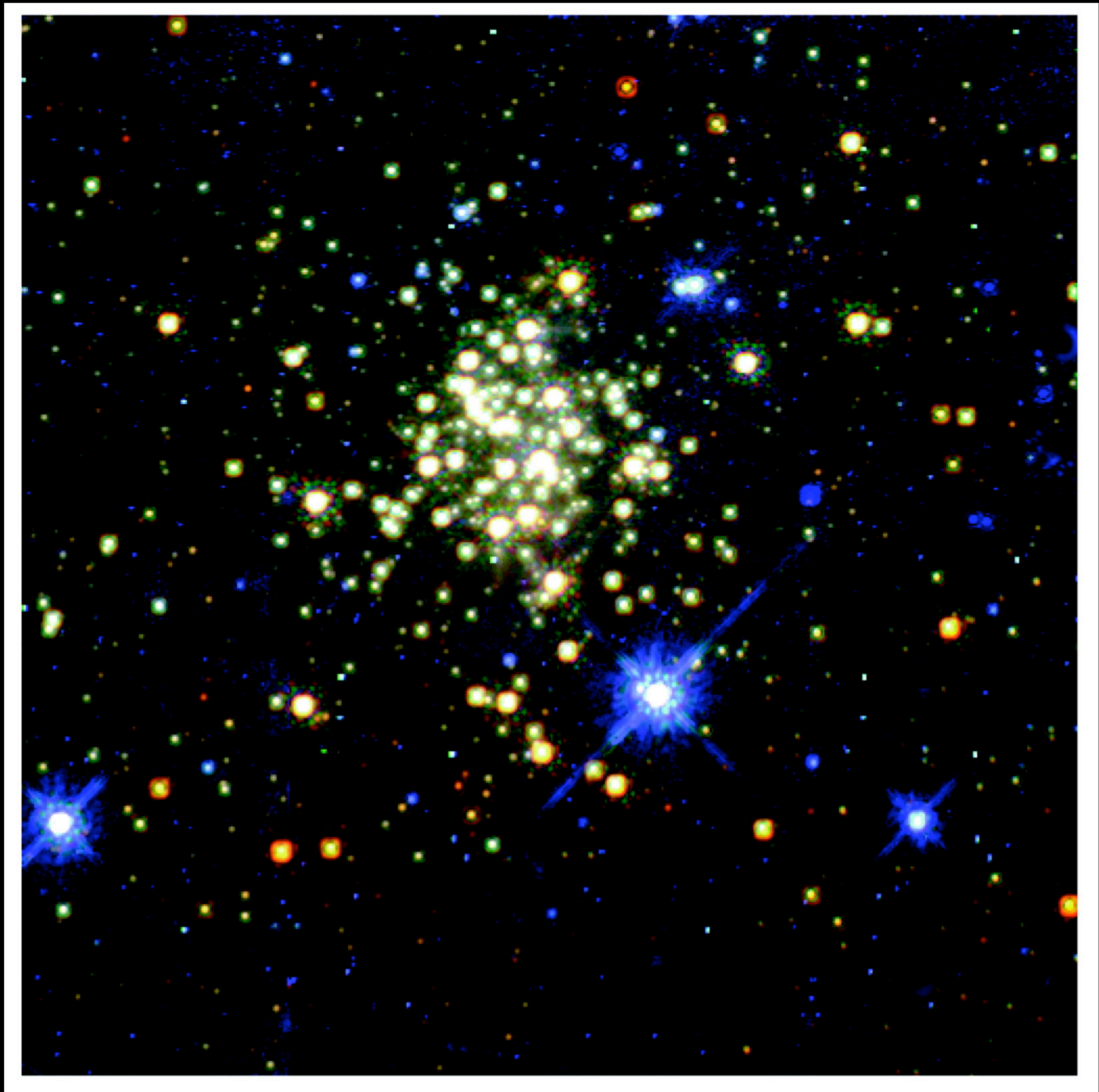
The letter/number combinations refer to the science case designations in the SWG's first report.

http://www.eso.org/sci/facilities/eelt/science/drm/cases.html



Artist's impression of the E-ELT during observations.
In the background the Center of the Milky Way
is just rising above the enclosure of the telescope.

http://www.eso.org/gallery



Arches cluster

HST infrared image
F205W (*red*),
F160W (*green*),
and F110W (*blue*)

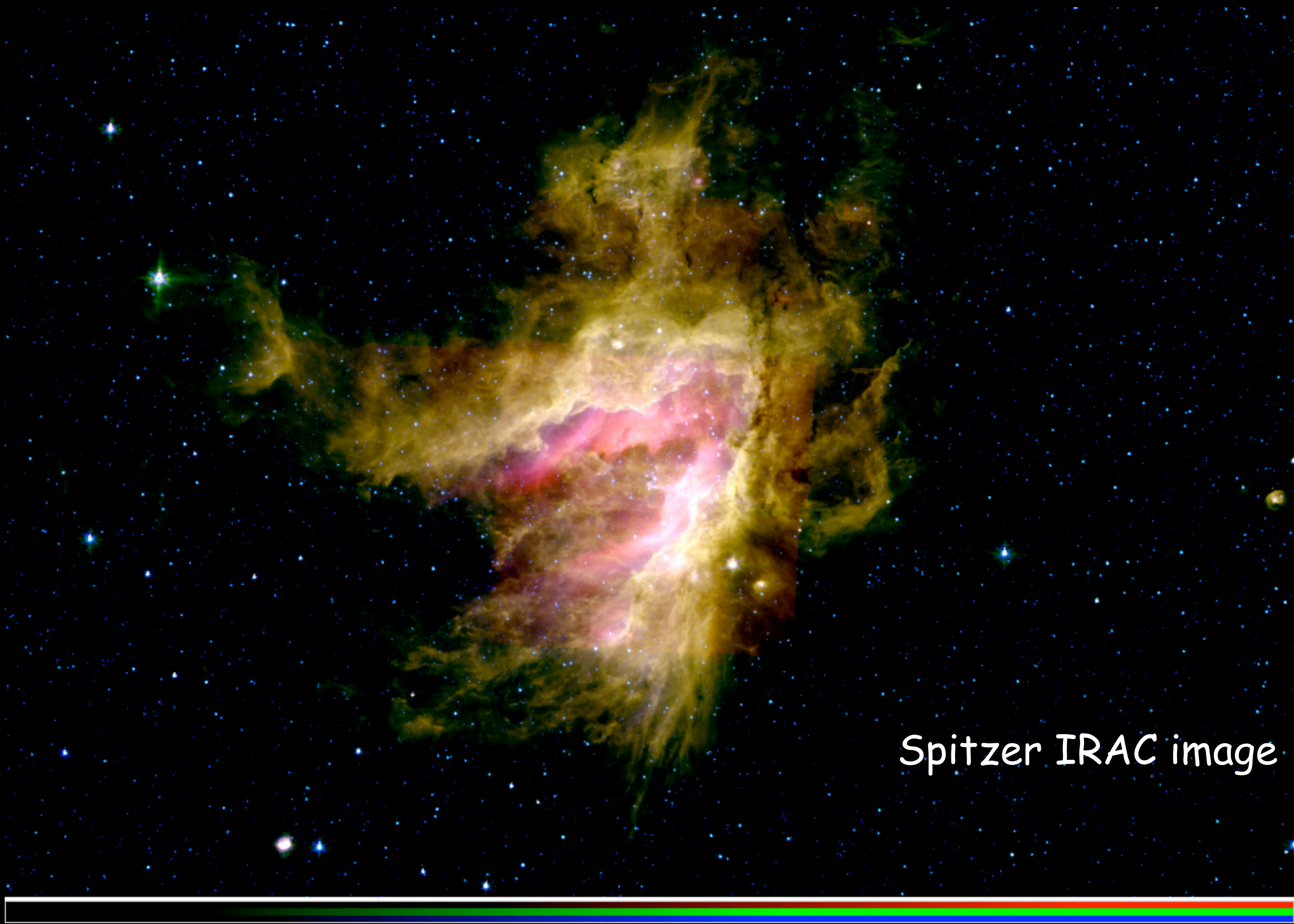
Figer et al. 1999

NGC 3603

VLT/ISAAC JHK

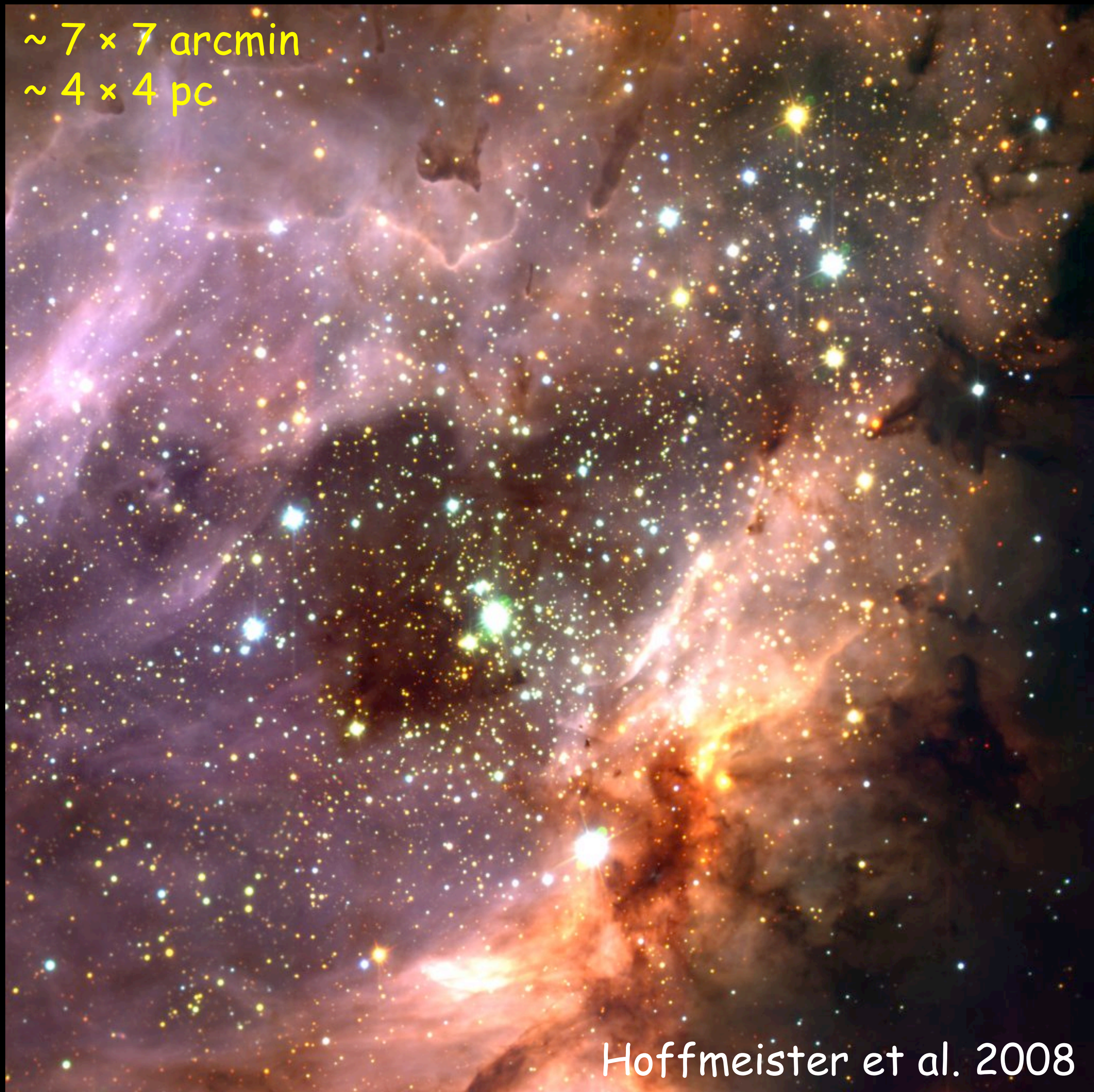
FOV 3.4´ x 3.4´

Brandl et al. 1999



Omega Nebula (M17), distance ~2 kpc,
expanding HII region, IRAC bands 234

M17 expanding young cluster, VLT/ISAAC JHK-image



completely embedded
S255-IR cluster
(JHK/VLT/ISAAC)
FOV: 2.5 × 2.5 arcmin

Correia & Zinnecker 2008

STAR FORMATION PARADIGM

massive stars form in the centers of dense clusters
see Orion-Trapezium, M17, NGC3603, Arches, etc.
and R136/30Dor in LMC

QUESTION

what did these clusters look like
when they were still deeply embedded
in their protocluster parent cloud?
Have protocluster clouds been found?

ANSWER

a new class of infrared dark clouds
found in absorption in mid-infrared
(MSX, Spitzer)

obs example

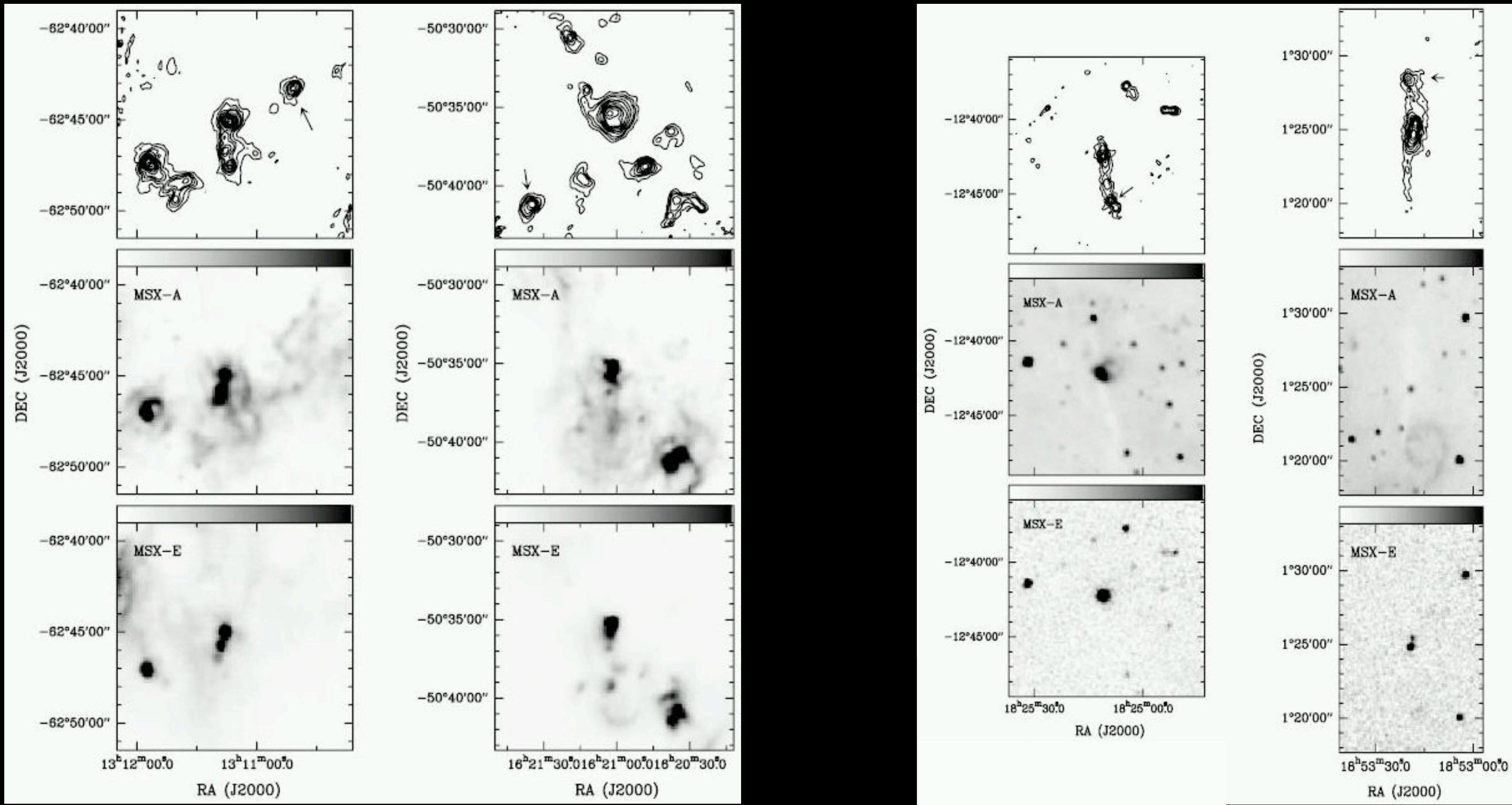
mass, size, column density, extinction

Implications

likely much more compact configuration
before protocluster cloud is dispersed

Typical gas densities $2 \cdot 10^5$ cm^{-3}, sizes ~0.5 pc

$\Rightarrow N_{H2} = 3 \cdot 10^{23}$ cm^{-2} $\Rightarrow A_V = 200$ mag



1.3mm dust continuum observations (contours, top row)
of 4 dense molecular proto-cluster regions

MSX mid infrared images of the same regions

Garay et al. 2004

observational requirements

need to penetrate 100-200 mag of visual extinction

=> K-band: $A_K = 0.11\ A_V$ (extinction law see later)

need to resolve crowded fields (compact clusters)

=> diffraction limit in K-band is 10 mas for D = 42 m

need to study stellar/gas dynamics in protoclusters

=> astrometric precision 1 mas/yr = 20 km/s at 4 kpc

corresponding RV-res $R = 10^4$ => IR-IFU (AO)

3 competing models
of massive star formation

1) monolithic collapse (as in low-mass stars)

2) "competitive accretion" in a protocluster

3) stellar collisions in very dense clusters

see Zinnecker & Yorke (2007, Ann. Rev. A&A 45, 481)

measurement goals

a) stellar number density of massive stars
to investigate if collisions are likely

b) stellar radial velocities and proper motion
to discover binary systems and runaway stars

gas dynamics (expanding HII region: 10 km/s)
in combination with ALMA submm observations

typical velocity dispersion 20 km/s > c(HII)
for a star cluster of $M = 10^4 M_{\odot}$ and $r = 0.1$ pc

c) massive rotating circumstellar disks and
massive protostellar infall (accretion rate)

d) mass segregation: high mass stars in center
is this the case from the very beginning?

e) cloud fragmentation & core size distribution
to test the different MSF model predictions

Fig. 2
Color-composite image constructed from the F110W (*blue*), F160W (*green*), and F222M (*red*) mosaics of the W3 IRS 5 region, encompassing the whole region surveyed in the NICMOS measurements. The box shows the region displayed in Fig. 3.

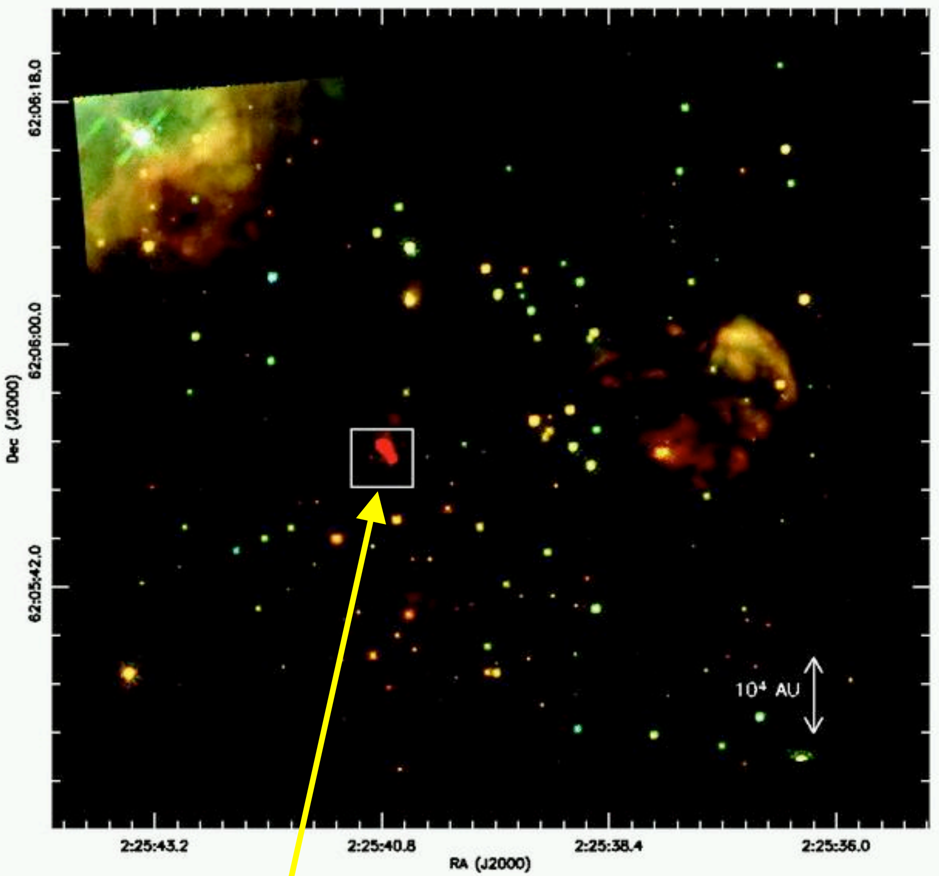
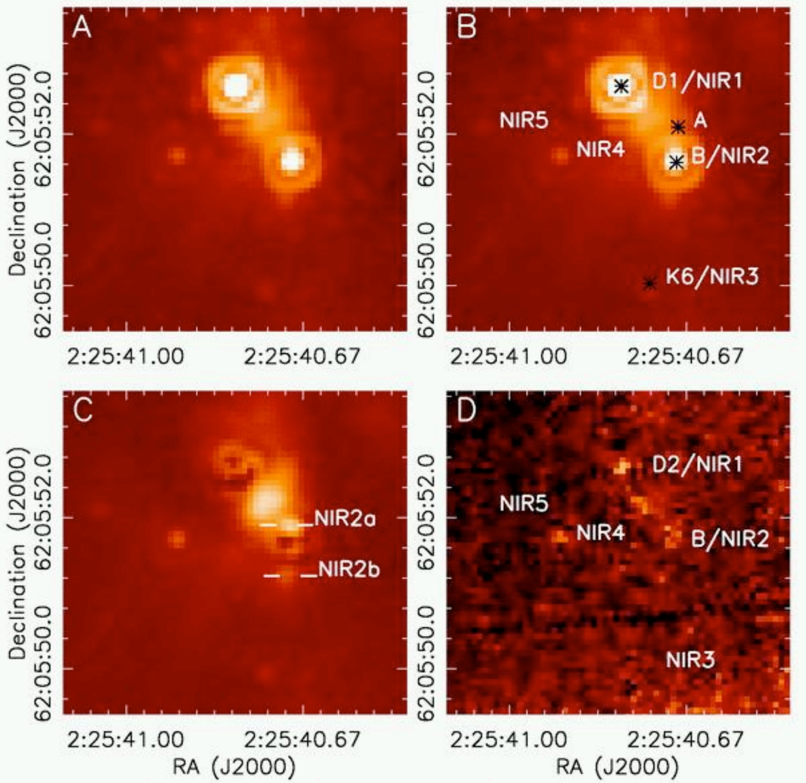


Fig. 3
F222M (2.22 μm) and F160W (1.60 μm) images of W3 IRS 5 and the neighboring red sources and nebulosities. In panel A we show the F222M image using a cube root scaling. In panel B we show the same image, but with the main NIR sources marked. The asterisks mark the positions of the associated radio sources D2, B, A, and K6. In panel C we show the image with the NIR 1 and NIR 2 sources subtracted. An extended nebulosity between the two sources is clearly evident. Two additional point sources partially hidden by the PSF of NIR 2 are marked. The ringlike pattern is a residual from the PSF subtraction. In panel D we show the F160W image toward this region, with the five IR sources marked.



W3 IRS 5 with NICMOS
a proto-Trapezium system

FOV: 4 × 4 arcsec, ~10^4 × 10^4 AU

Megeath, Wilson & Corbin 2005

Diffraction limit (~ λ/D) of a D=42m telescope:

at 2 micron	~10mas
at 3 micron	~15mas
at 5 micron	~25mas

astrometric precision at 2 microns: 1 mas/yr (20 km/s at 4 kpc)

sensitivity limit of a D=42m telescope

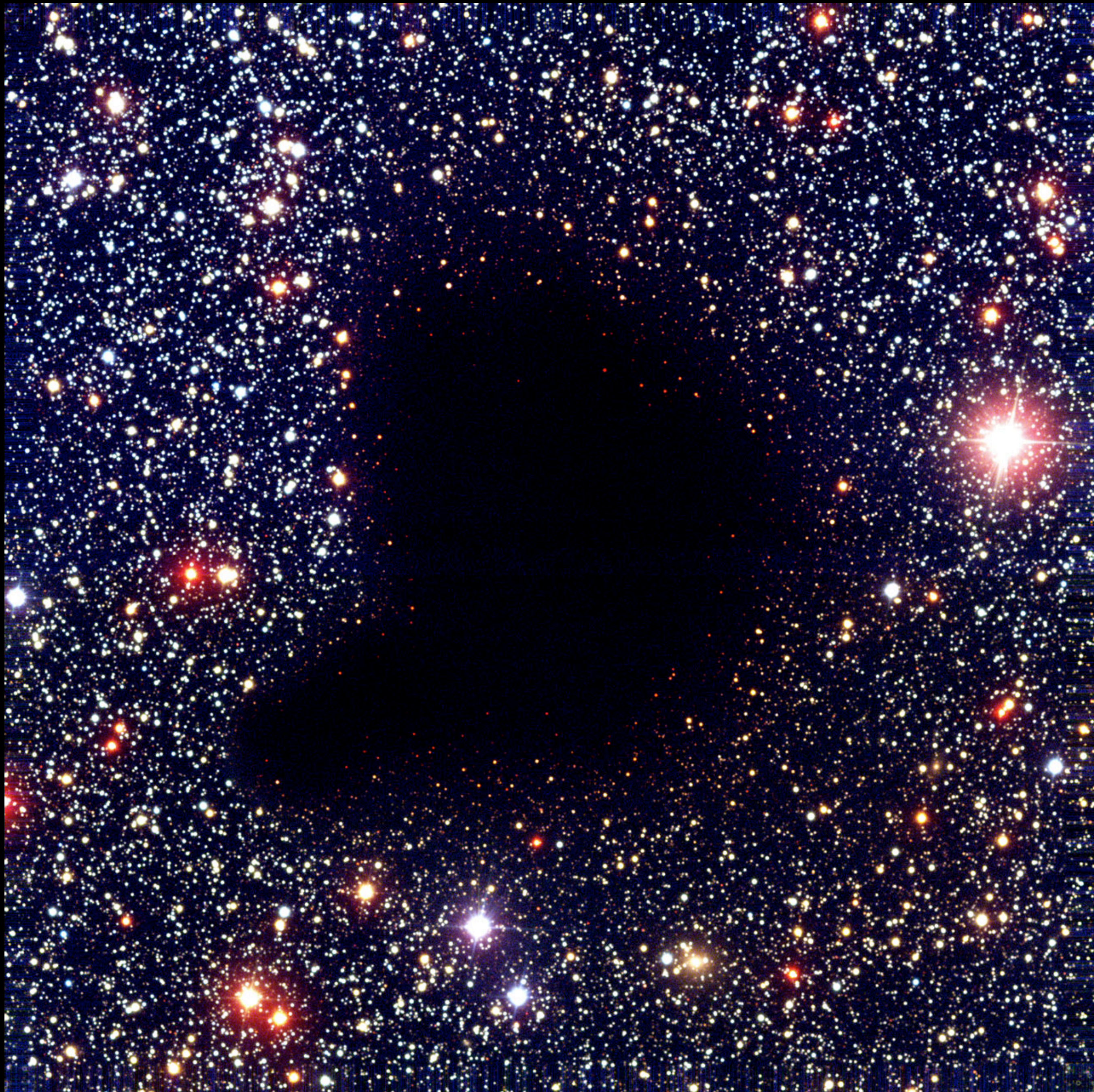
for S/N = 10 in t = 1 hour integration time

(for point sources, diffraction limited)

K =	28 mag	(see ELT exposure time calculator)
L =	22 mag	(about 7 mag deeper than 8m VLT)
M ~	20 mag	(Paranal sky backround 1.2 mag/arcsec2)

B. Brandl (priv. commun.)

PS. note that for a given S/N, integration time ~ D^{-4} in the background noise limited case



B 68 dark cloud

credit: J. Alves, ESO

Looking Through the Dark Cloud B68 (NTT + SOFI)

ESO PR Photo 29a/99 (2 July 1999)

Interstellar Extinction in the Infrared

(Rieke and Lebofsky 1985, D. Lutz 1999)

$A_J = 0.28 A_V$ $A_L = 0.06\ A_V$

$A_H = 0.18 A_V$ $A_M = 0.02 A_V$

$A_K = 0.11\ A_V$

for A_V = 200 mag ($N_{H2} = 10^{23.5}$ cm^{-2})

ie. a dense protocluster cloud clump

A_J = 56 mag A_L = 12 mag

A_H = 36 mag A_M = 4 mag

A_K = 22 mag

HERE IS THE KEY MESSAGE TO TAKE HOME:

a 42m ELT can penetrate A_K = 22 mag (A_V = 200 mag) of extinction in the K-band to detect nearby (4-8 kpc) deeply embedded luminous massive stars (M_K = -7 mag)

in addition, there are the hydrogen recomb.
lines Br_g, Pf_g, Br_a, Hu (14-6)
whose ratios have well-defined values
(e.g. $Br_g/Br_a = 1/3$; $Br_g/H_\alpha = 1/100$)
in optically thin ionised gas (Menzel Case B)
to infer the extinction to individual objects

DRM proposal: The origin of massive stars
(a particular science case for the E-ELT)

- embedded dense stellar population
- embedded stellar (and gas) dynamics

the centers of massive proto-clusters
- K-, L-, M-band imaging
- K-, L-, M-band 3D IFU Spectroscopy

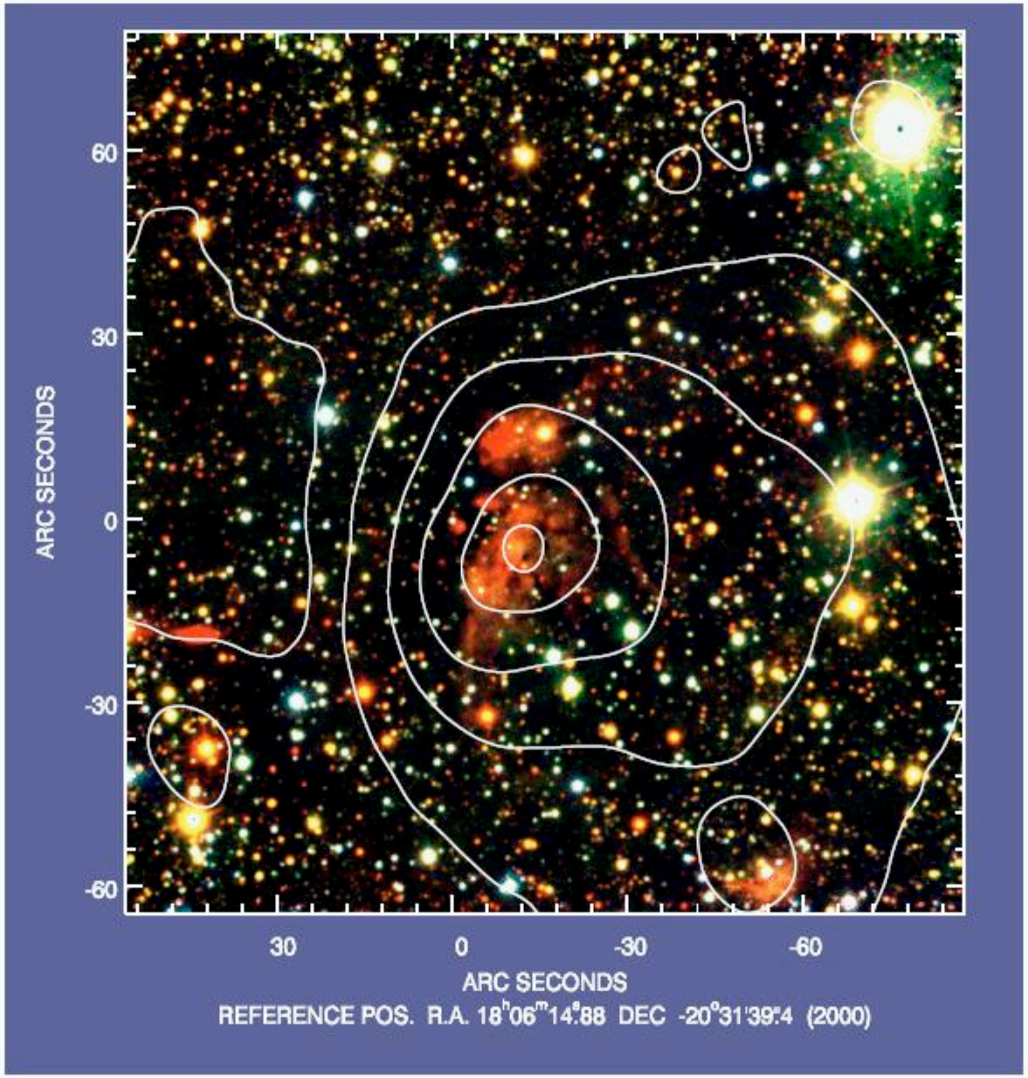


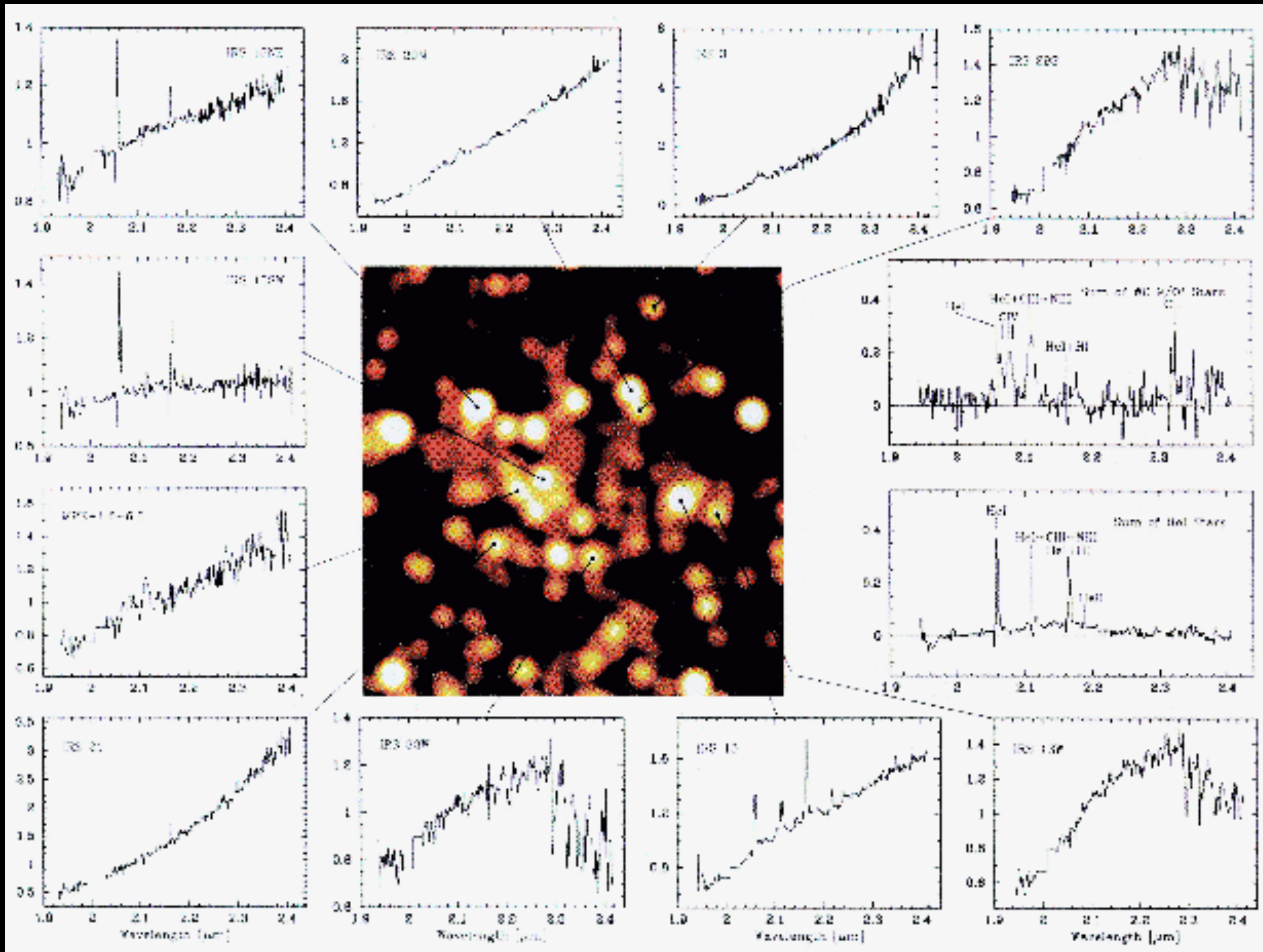
Fig. 1. Colour-coded image of the entire G9.62+0.19 region taken in the three broad-band NIR filters J (blue), H (green), and K_s (red). The large-scale contour lines denote the emission levels derived from the 8.28 μm image of the related *MSX* source. The left-most large contour line indicates the position of the close-by Infrared Dark Cloud.

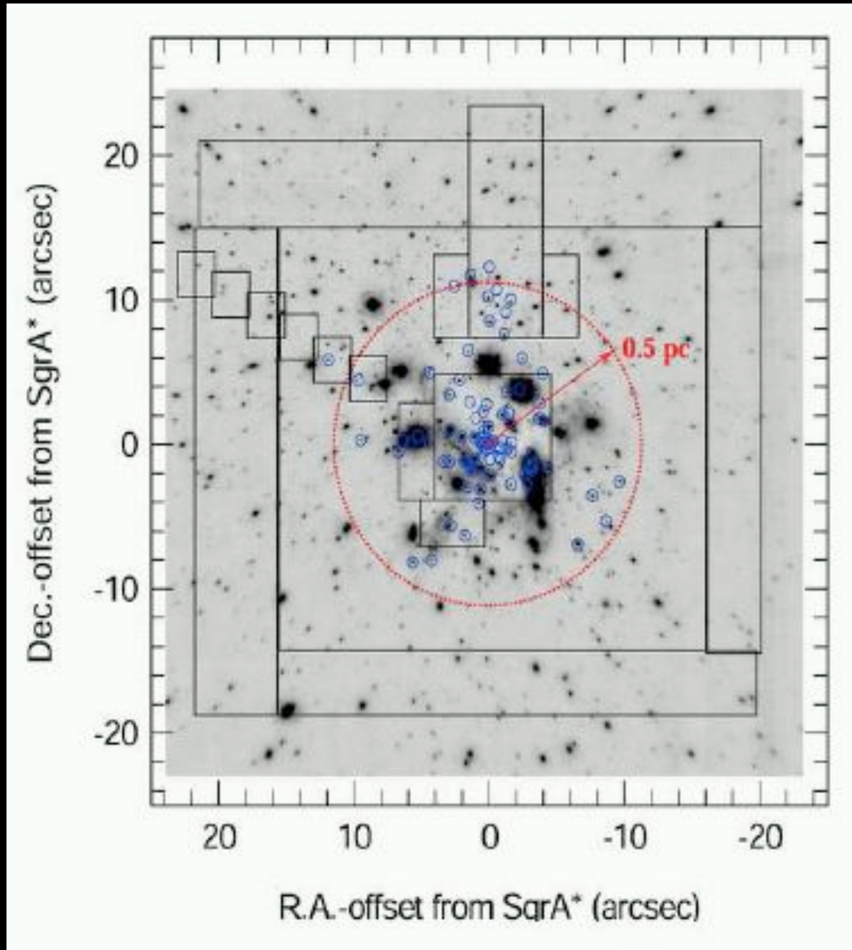
Linz et al. 2005

Credit:
McCaughrean & Rayner

Weitzel et al. 1996 / Eckart et al. 1995

Galactic Center massive star 3D spectroscopy

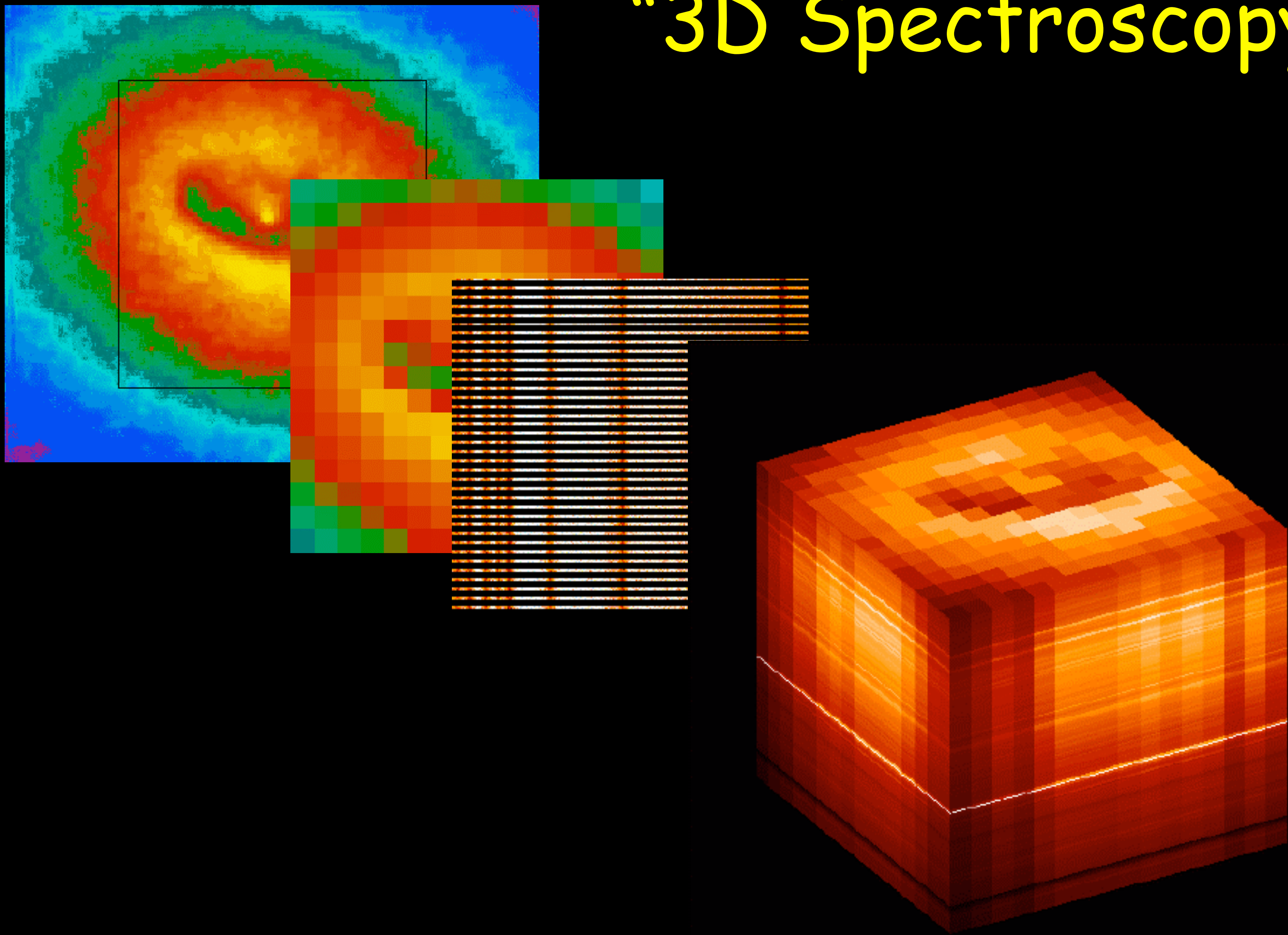




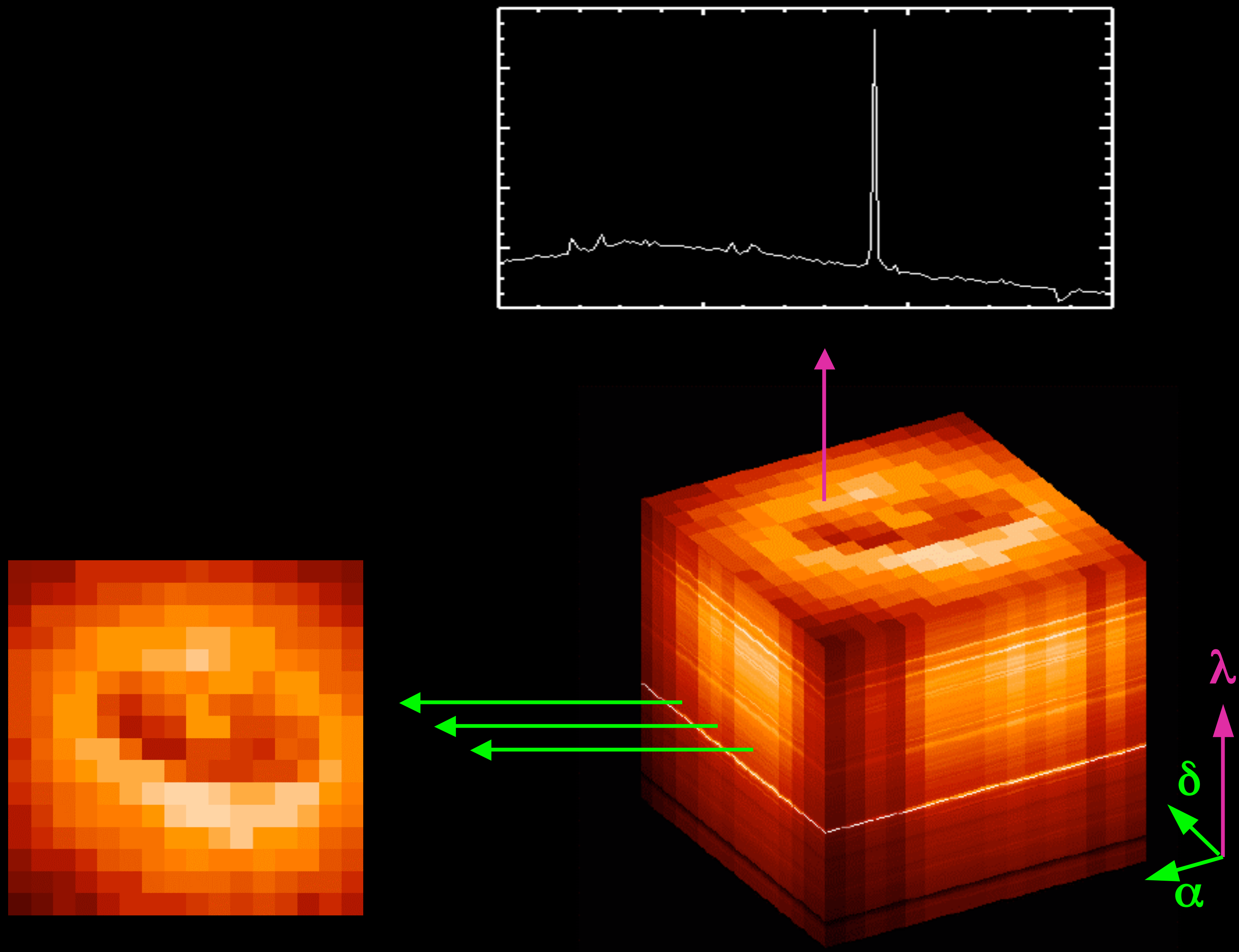
Outline of the various 2003-2005 SPIFFI/SINFONI H+K- and K-band cubes, superposed on a ~100 mas resolution, L-band NACO image (logarithmic scale). Small circles denote the 90 quality 1 and 2 early-type stars (OB I-V, Ofpe/WN9, W-R stars. A dotted circle denotes a 0.5 pc (20 arcsec) radius zone centered on Sgr A*, within which essentially all OB stars we have found appear to lie (from Paumard et al. 2006).

target	RA	DEC	time (hrs)	DM	FOV	note
BN/KL	06 00	-05 00	12	8.5	10´´	Orion-IRc2 protostar
SgrA*	17 59	-29 00	24	14	40´´	Galactic Center OB cluster
W51-IRS2	19 24	+14 30	8	14	10´´	dense embedded cluster
G10.6-0.4	18 10	-19 56	8	14	10´´	dense embedded HII region
BN/KL	06 00	-05 00	12	8.5	10´´	Orion-IRc2 protostar
SgrA*	17 59	-29 00	24	14	40´´	Galactic Center OB cluster
W51-IRS2	19 24	+14 30	8	14	10´´	dense embedded cluster
G10.6-0.4	18 10	-19 56	8	14	10´´	dense embedded HII region

“3D Spectroscopy”

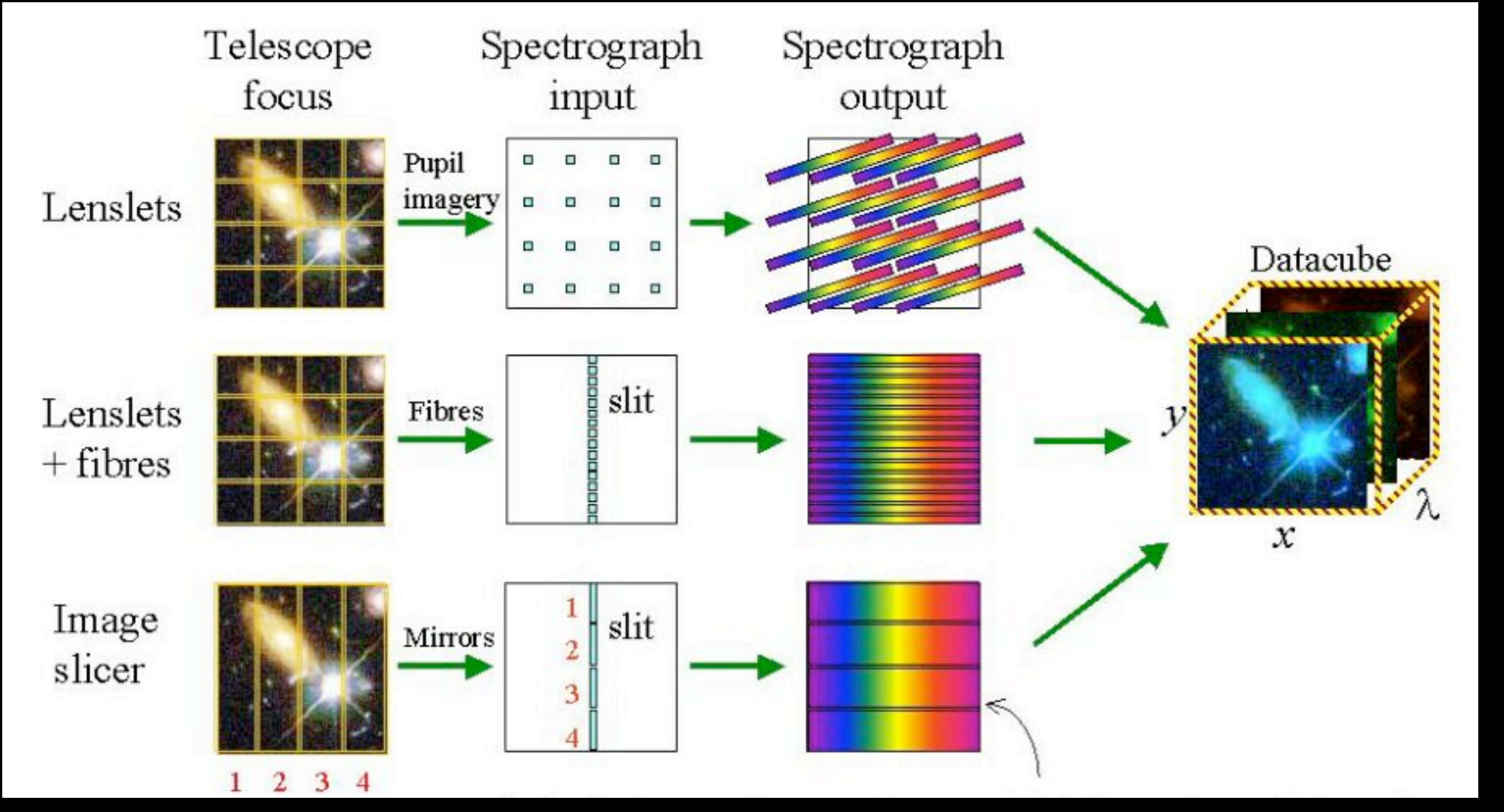


courtesy: M.M. Roth (AIP)

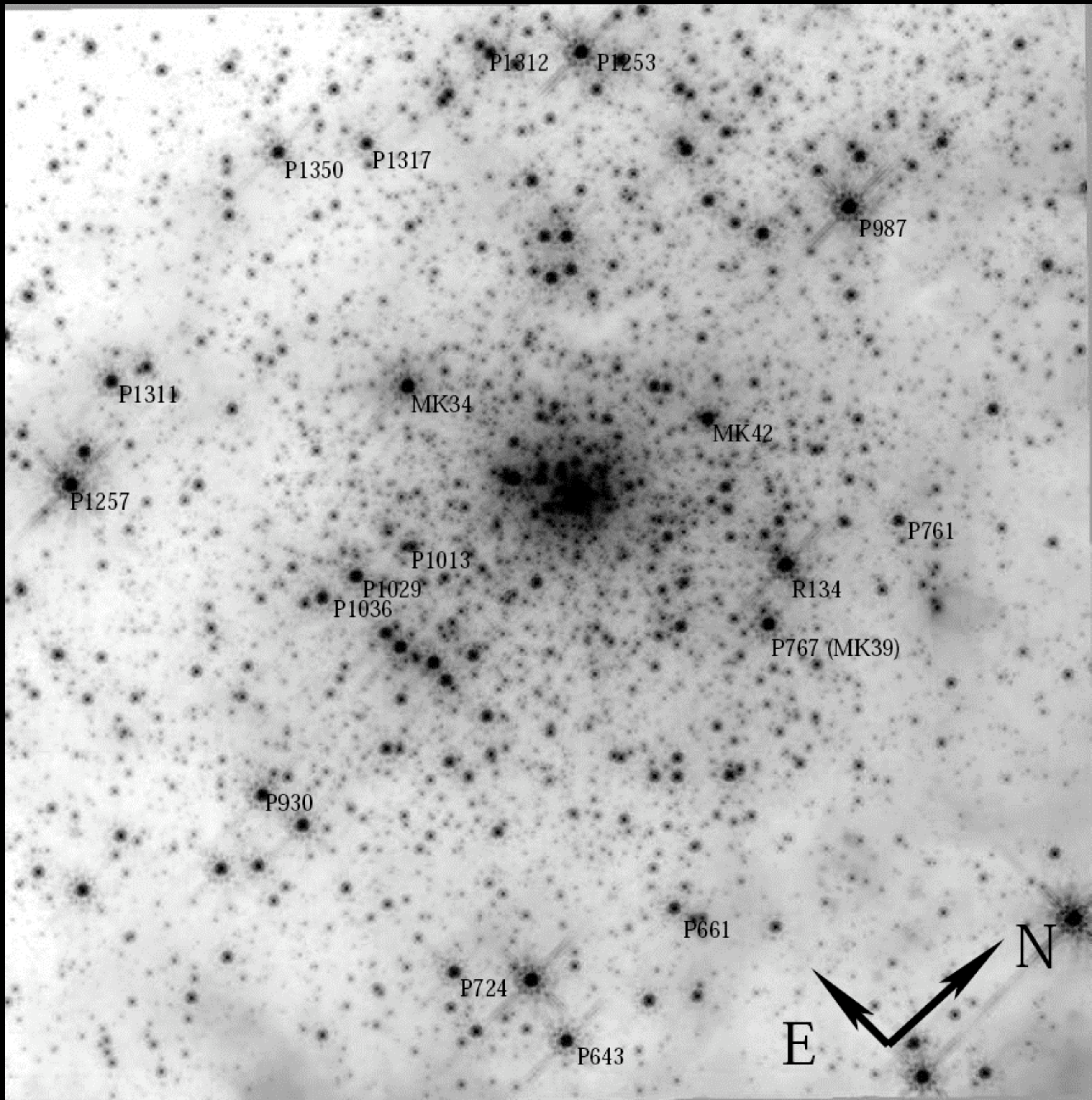


courtesy: M.M. Roth (AIP)

Principle of Operation



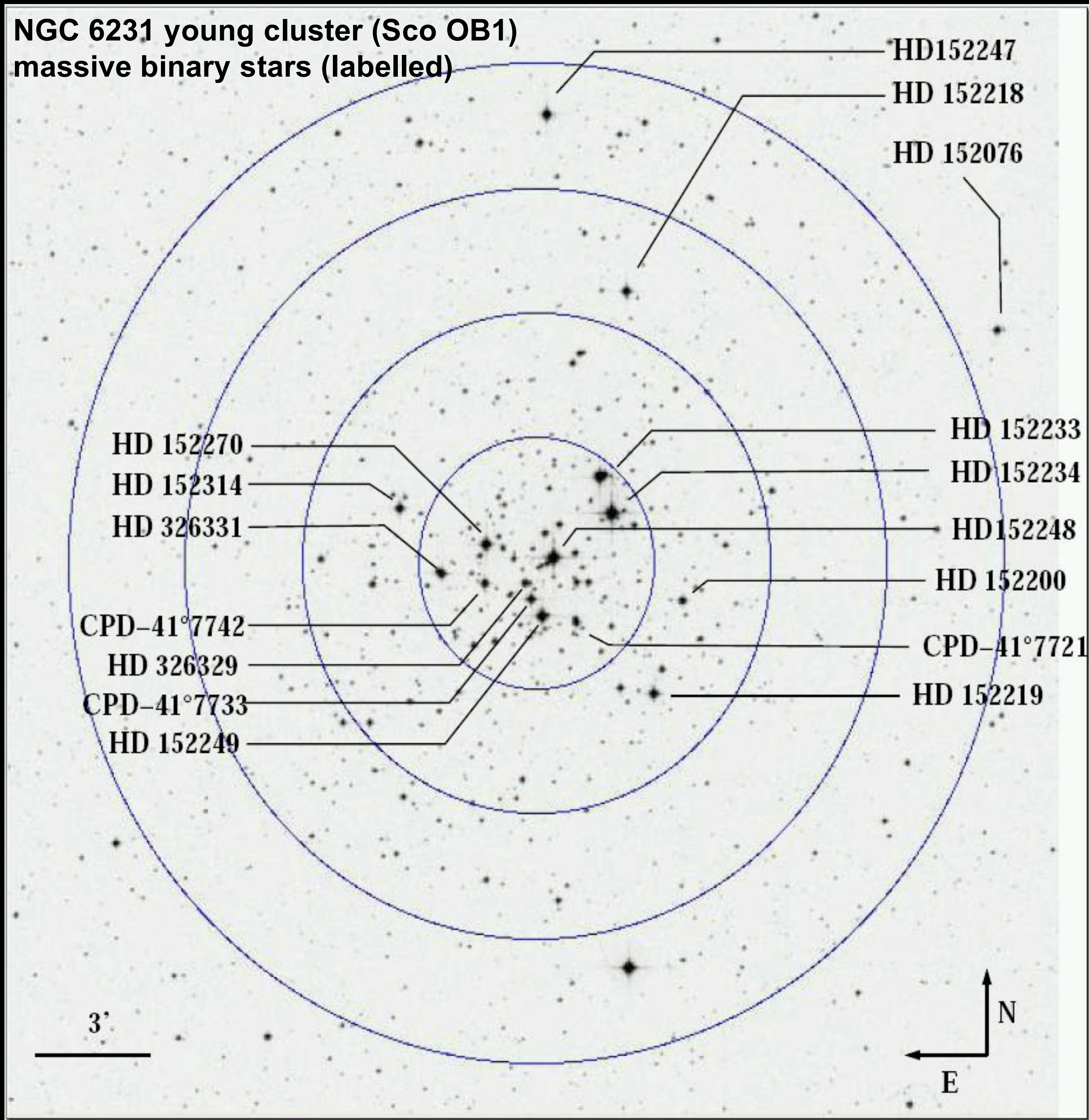
(courtesy J. Allington-Smith)



NGC 2070 in the LMC
HST/NICMOS F160W
FOV 1 x 1 arcmin

compact core: R136
4 × 4 arcsec = 1 × 1 pc
SINFONI IFU target

M. Andersen PhD 2005


NGC 6231 young cluster (Sco OB1)
massive binary stars (labelled)
HD152247
HD 152218
HD 152076
HD 152270
HD 152314
HD 326331
CPD−41°7742
HD 326329
CPD−41°7733
HD 152249
HD 152233
HD 152234
HD152248
HD 152200
CPD−41°7721
HD 152219
3’
N
E

Cluster/ID	Multiplicity	Sp. Types	P (days)	M2/M1
NGC 6231				
CPD-41°7742	ESB2	O9V+O9.5V	2.44	0.56
HD 152219	ESB2	O9III+B1-2V/III	4.24	0.39
HD 152248	ESB2	O7III(f)+O7.5III(f)	4.82	0.99
HD 152218	SB2	O9IV+O9.7V	5.6	0.76
CPD-41°7733	SB2	O8.5V+B3	5.68	0.38
WR 79	SB2	WC7+O6V	8.89	0.37
HD 152234	SB2	O9.7I + O8V	126.6	0.83
HD 152247	SB2	O9III+O9.7V	~500	0.64
HD 152233	SB2	O6III(f)+ O8V:	~800	0.6
HD 152314	SB2	O8.5V+B1-3V	~3100	0.53
HD152076	single	O9.5III		
HD152200	single ?	O9.7V		
HD152249	single	O9Ib((f))		
HD326329	single	O9.5V		
HD326331	single	O8III((f))		
CPD-41 7721	single	O9V		
IC 2944				
HD101205	ESB2	O7V+OB:	~2	0.55
HD101190	SB1	O6.5V	~8	
HD101131	SB2	O6V+O8.5V	9.6	0.61
HD100099	SB2	O9V+O9.5V	~20d	0.91
HD101436	SB2	O7.5V+B0V	>20d	0.52
HD101413	SB2	O9III+B	Long P	0.45
HD101191	SB1	O8V	Long P	
HD101298	single	O8V		
HD101223	single	O7.5V		
CPD-62 2198	single	O9.5III		
HD101333	single	O9.5V		

H. Sana et al. 2008

DIFFRACTION-LIMITED KLM-IMAGING

Example: massive O-star (M_K = -7, M_L = -7),
obscured by A_V = 200 mag (A_K = 22, A_L = 12)
at a distance of 4 kpc (DM = 13 mag), has
m_K ~ 28 mag and m_L = 18 mag, doable with E-ELT!

INTEGRAL FIELD SPECTROSCOPY

Definition „spaxel"
FOV: 2 × 2 arcsec, 4k x 4k IR detectors (K, LM)
pixel scale: 5 mas (K), 10 mas (LM)
spectral resolution R = 10^4 (for RV variability)
IR stellar spectroscopy in crowded cluster centers
e.g. Br_g (2.17 μm), Br_a (4.05 μm); CO 2.3 μm, 4.6 μm

This E-ELT science case will require
the following focal plane instruments
(many expensive 2kx2k infrared arrays)

MICADO:	adaptive optics K-band imaging
HARMONI:	super-SINFONI-IFU (K-band)
EAGLE:	imaging and multi-IFU (K-band)
METIS:	diffr.-limited L-, M-band imaging and IFU spectroscopy

PS.: Why not use JWST? (6.5m diameter)
==> not enough angular resolution
for the expected crowded fields

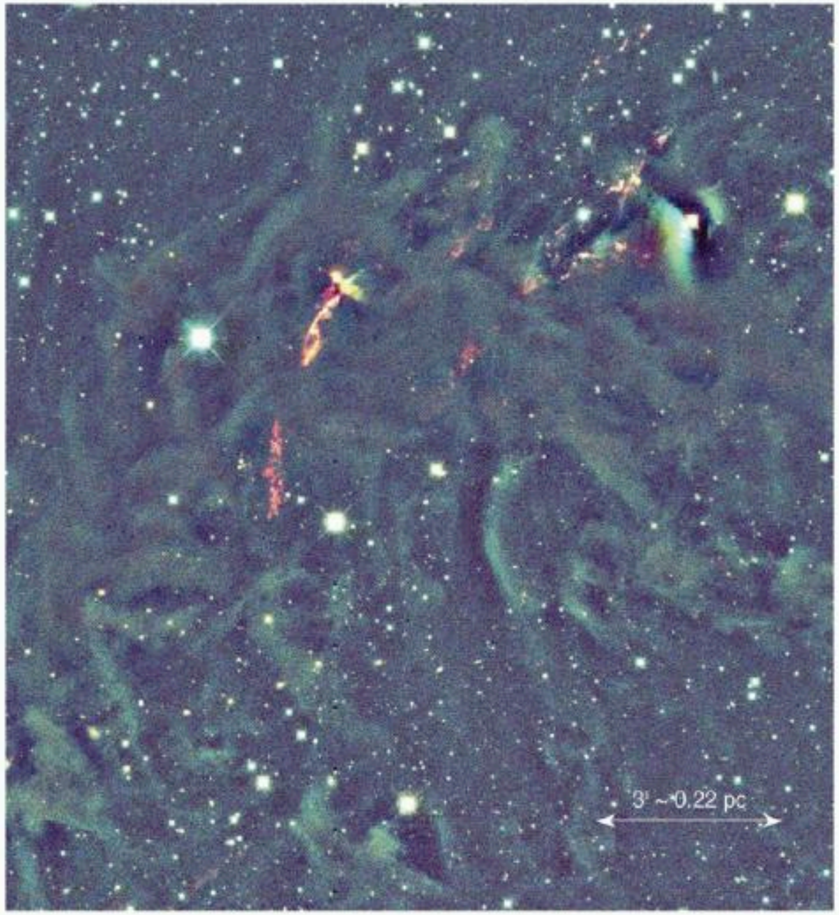


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown here as a muted glow with green edges. Dark features around extended bright objects (such as the reflection nebula) are the result of self-sky subtraction.

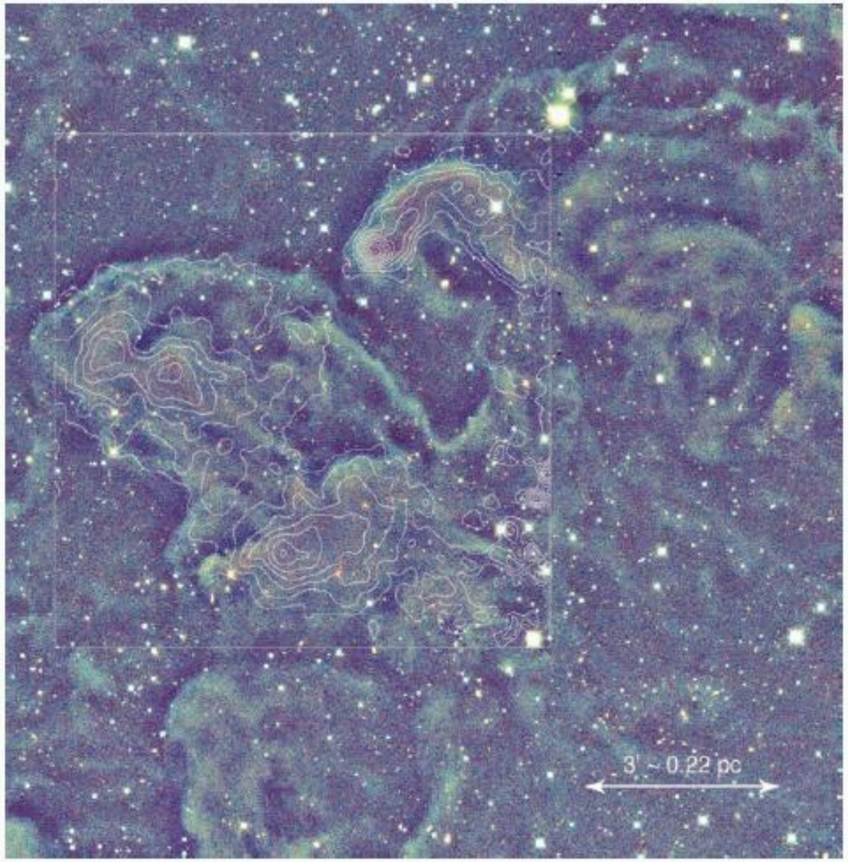


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color of cloudshine is a tracer of density. Redder regions have high dust continuum flux, and the edges of cloudshine match the edges of the dust emission. Dark edges around bright features (particularly noticeable along the northern edges) are the result of self-sky subtraction.

"cloud shine" JHK images (background noise)

Foster & Goodman 2006

Conclusion

The study of massive star formation in deeply embedded clusters
is all about

RESOLUTION, RESOLUTION ! !

Focal plane, Focal plane ! !

the E-ELT will likely provide a break-through
considerable synergy with ALMA