JWST and the ELTs Workshop
13 – 16 April 2010
ESO Garching

The early evolution of dense embedded star clusters

Imaging & spectroscopy of massive clusters in our Galaxy

Hans Zinnecker (Astrophysical Institute Potsdam, Germany)

with: A. Calamida (ESO) M.J. McCaughrean (ESA)

AIP

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

doi:10.1017/S1743921306000858

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

Hans Zinnecker

Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
email: hzinnecker@aip.de

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. JWST/MIRI may not have sufficient spatial resolution to tackle this problem.

THE E-ELT DESIGN REFERENCE MISSION

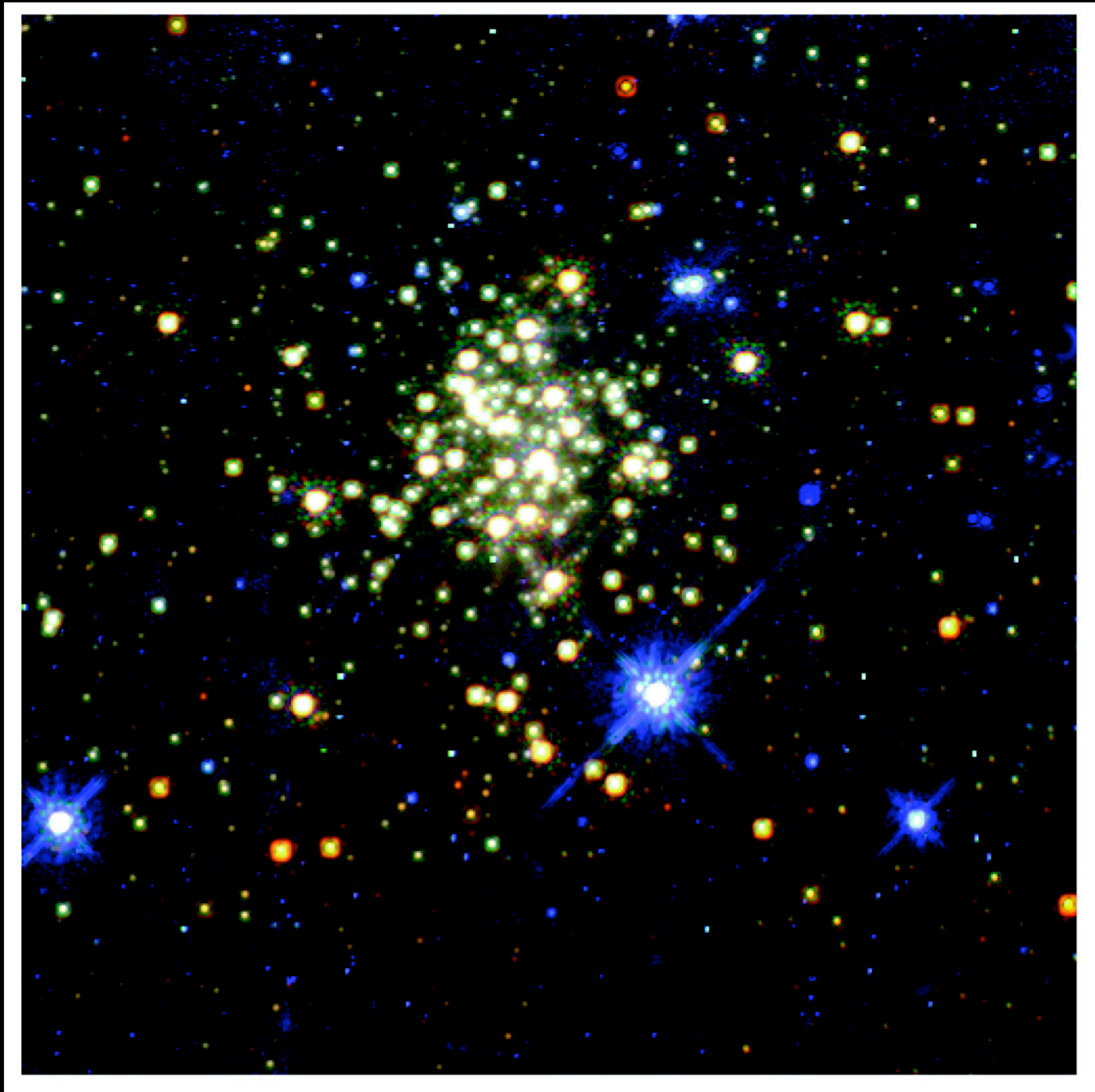
DRM SCIENCE CASES

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



Arches cluster

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

Figer et al. 1999

NGC 3603

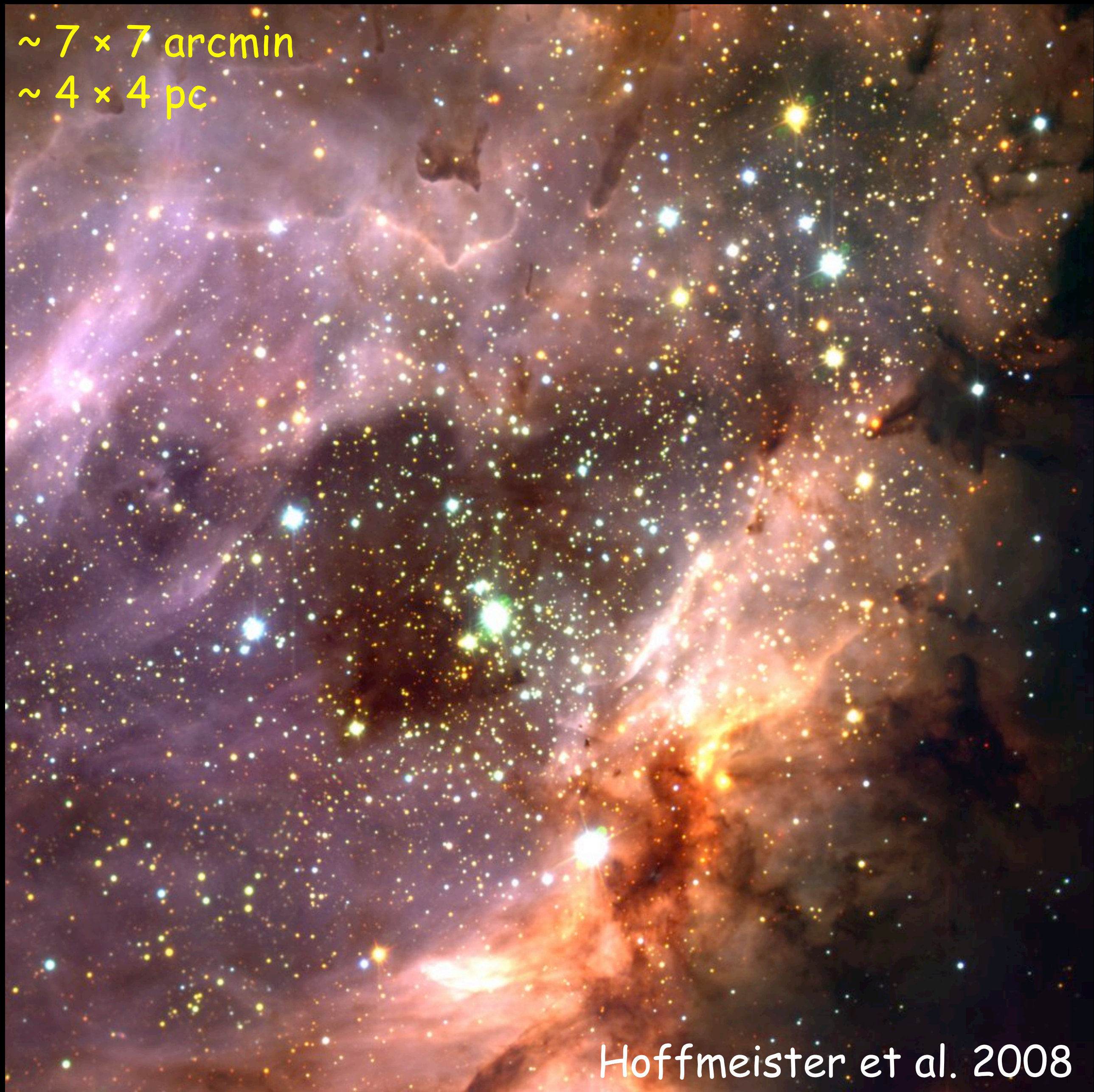
VLT/ISAAC JHK

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



Credit:
McCaughrean & Rayner

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

First task:

how to find massive protostellar clusters?

Second task:

can we perform good photometry/astrometry?

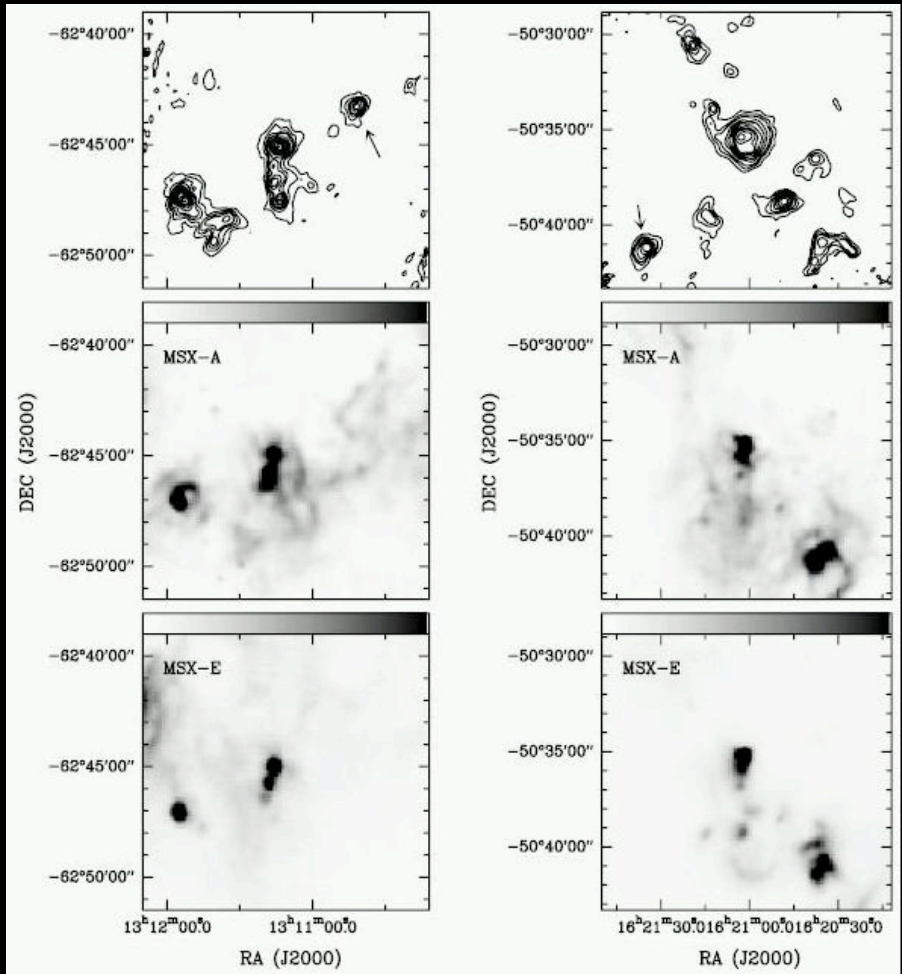
Star counts, infrared excess, proper motions

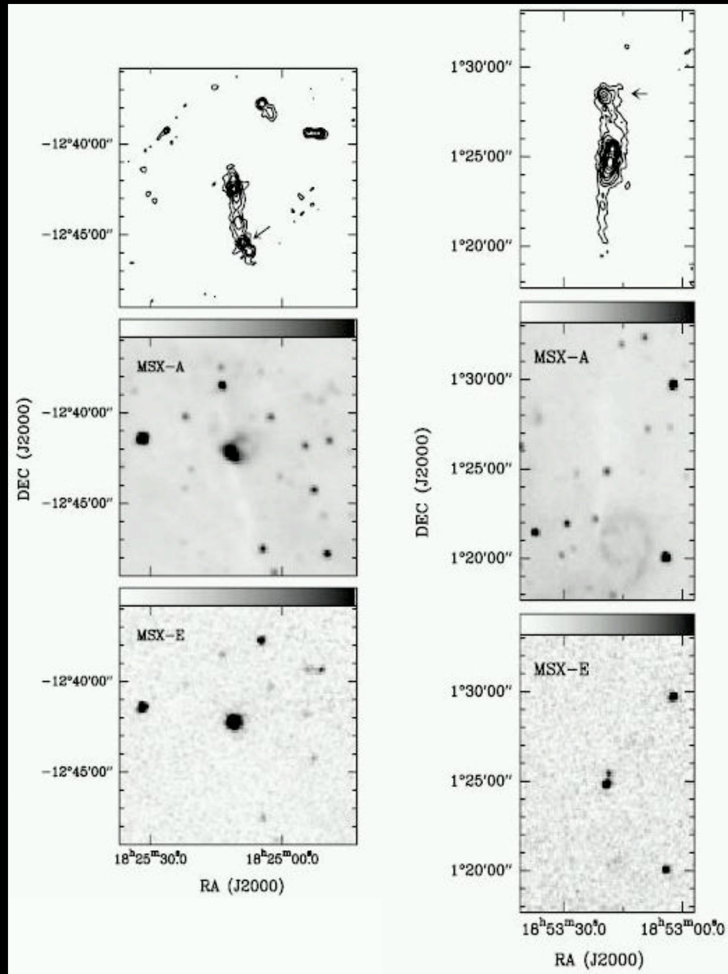
Third task:

can we do spectroscopy: accretion/outflows?

HII region gas dynamics (10 km/s)? best lines?

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)

need MICADO (close to diffraction limited astrometry)

need HARMONI (K-band spectroscopy, 10mas spaxels)

need METIS (L- and M-band imaging, IFU spectroscopy)

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.

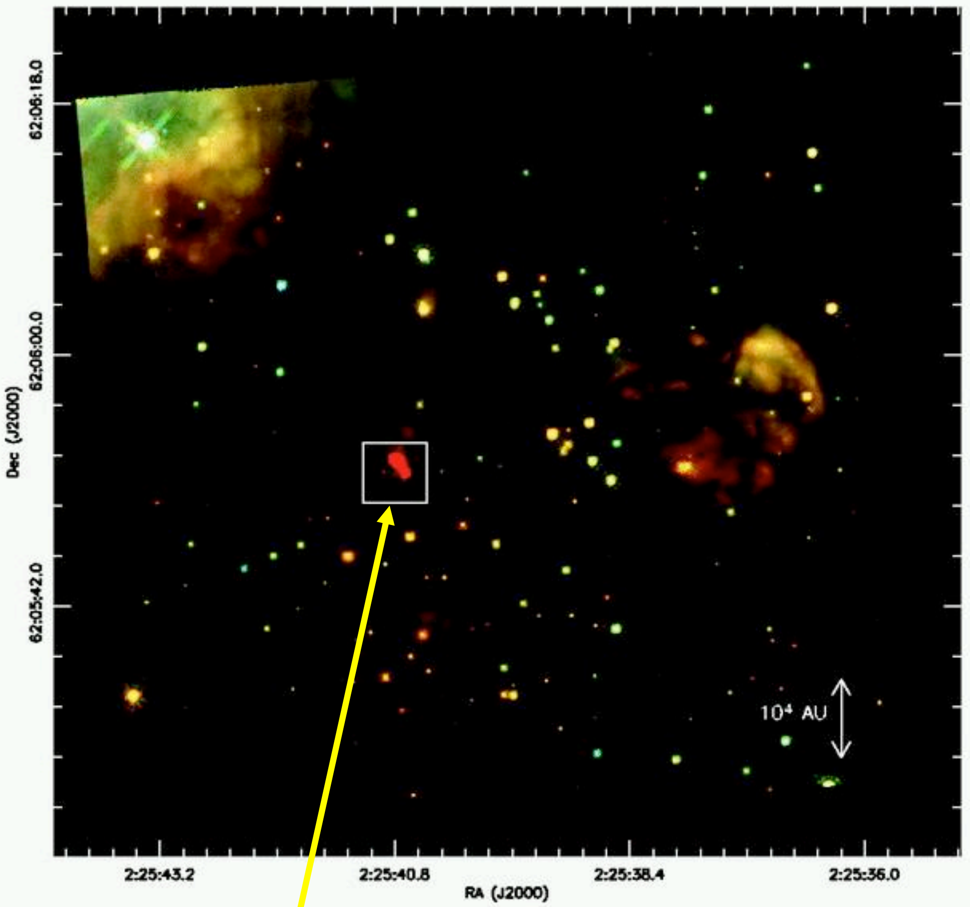
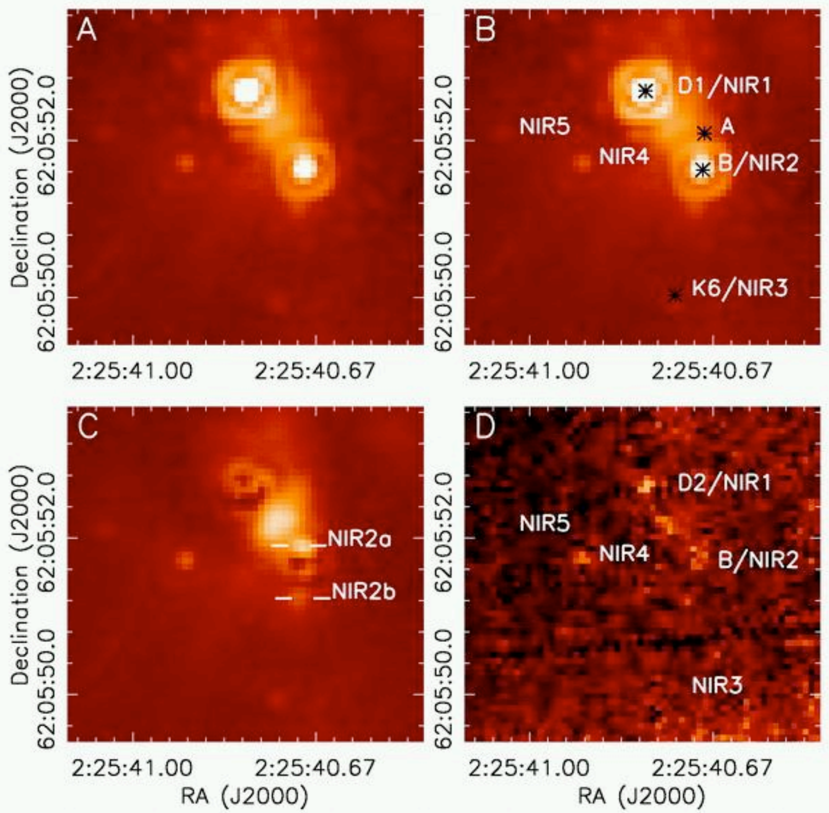


Fig. 3
F222M (2.22 μm) and F160W (1.60 μm) images of W3 IRS 5 and the neighboring red sources and nebulosities. In panel A we show the F222M image using a cube root scaling. In panel B we show the same image, but with the main NIR sources marked. The asterisks mark the positions of the associated radio 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, ~$10^4 \times 10^4$ AU
(cf. IFU scales of HARMONI/METIS)

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 = 5 in t = 1 hour integration time

(for point sources, diffraction limited)

K ~ 28 mag (see ELT exposure time calculator)

L ~ 20 mag (about 5 mag deeper than 8m VLT)

M ~17 mag (Paranal sky backround 1.2 mag/arcsec2)

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

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

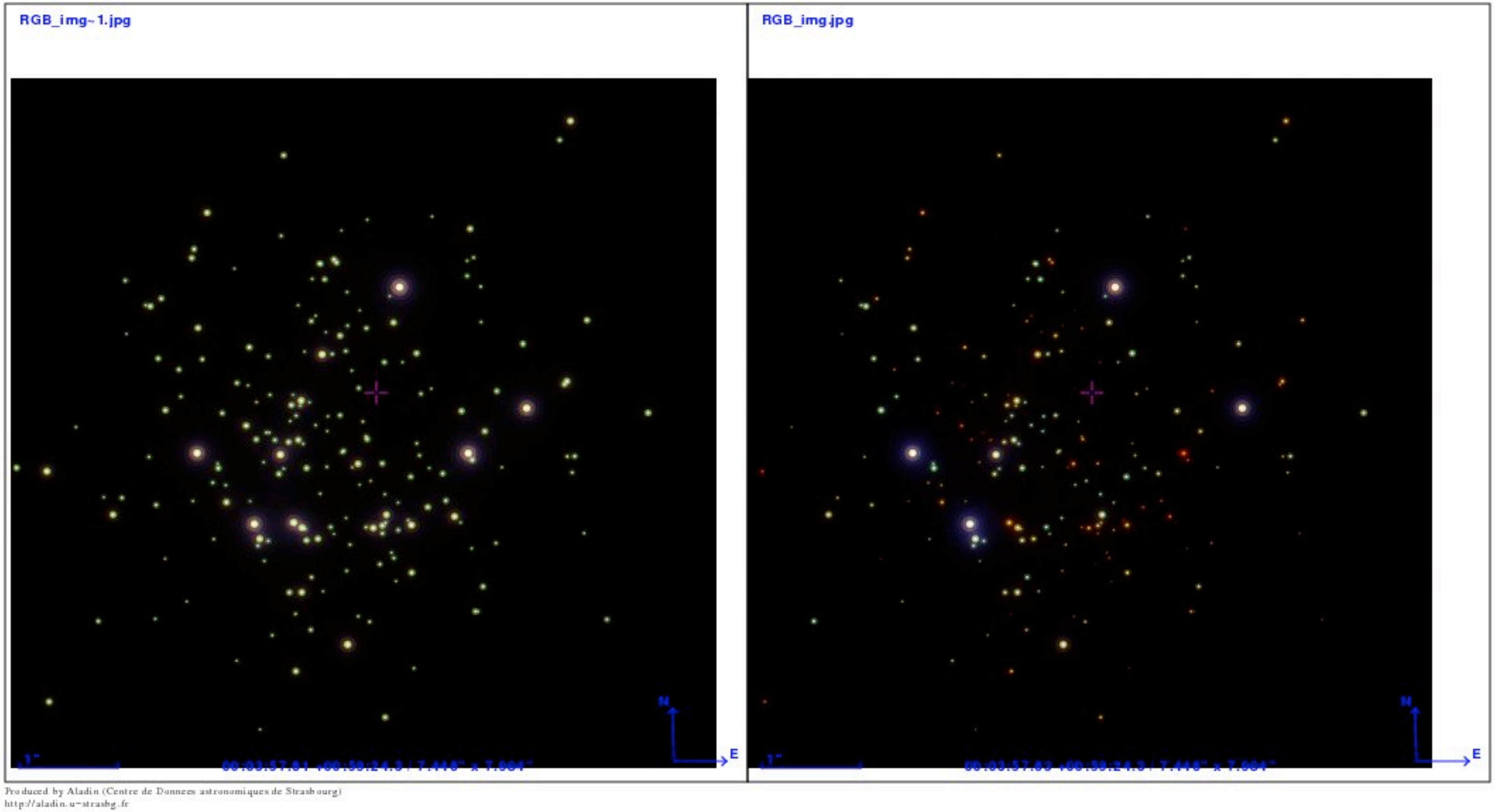
$A_H = 36$ mag $A_M = 4$ mag

$A_K = 22$ 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)

FoV: 6" × 6 ", ~ 0.2pc at ~ 7 kpc



Uniform extinction (Av = 50 mag)

Clumpy extinction (clumps scale 0.25")

Simulations: DRM case S5_2

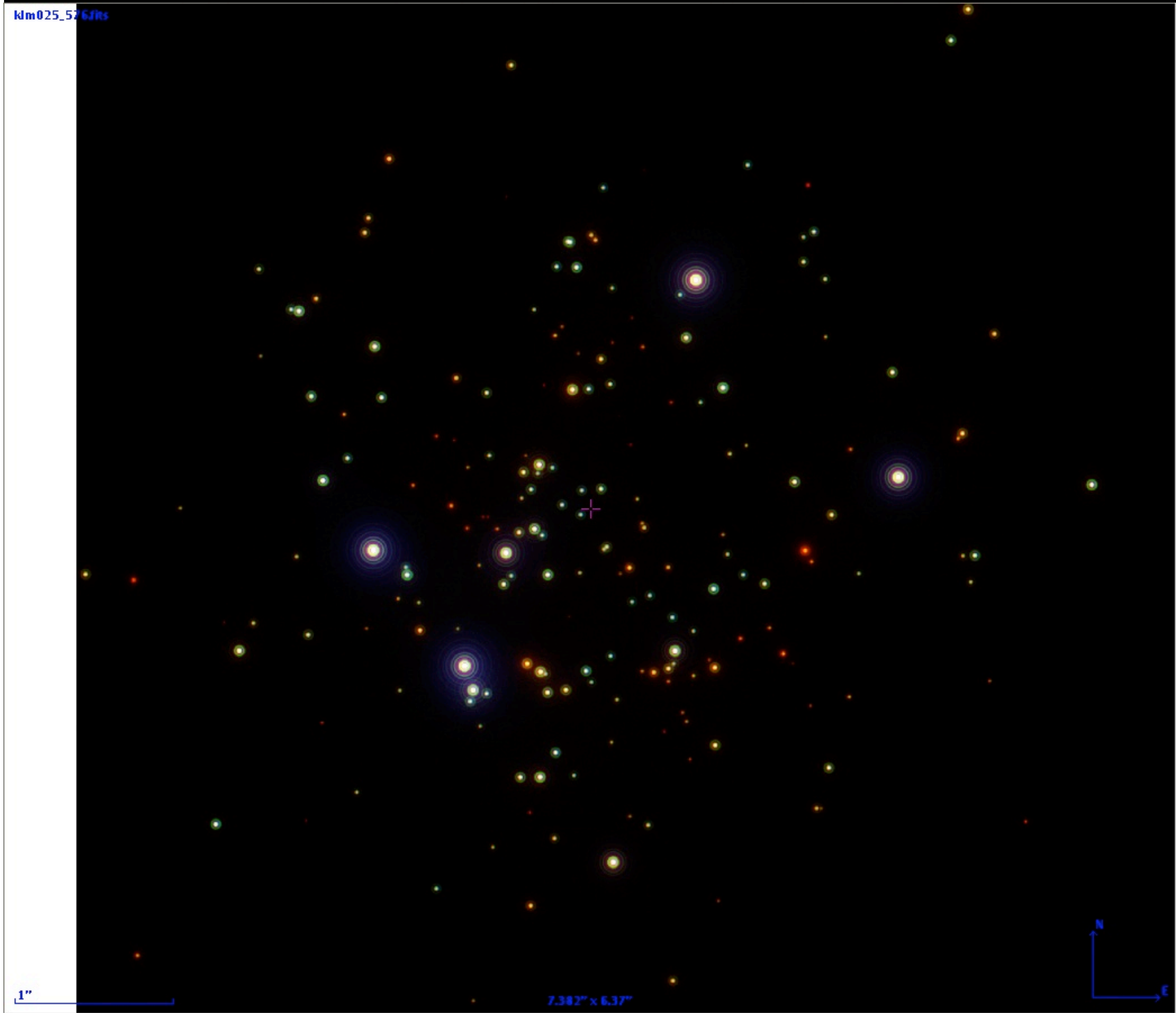
- Salpeter mass function from 8 to 130 M⊙ (200 Main Sequence stars)
- Geneva isochrone with log(t)= 5.9 yrs & Z=0.02

From the DRM technical database:

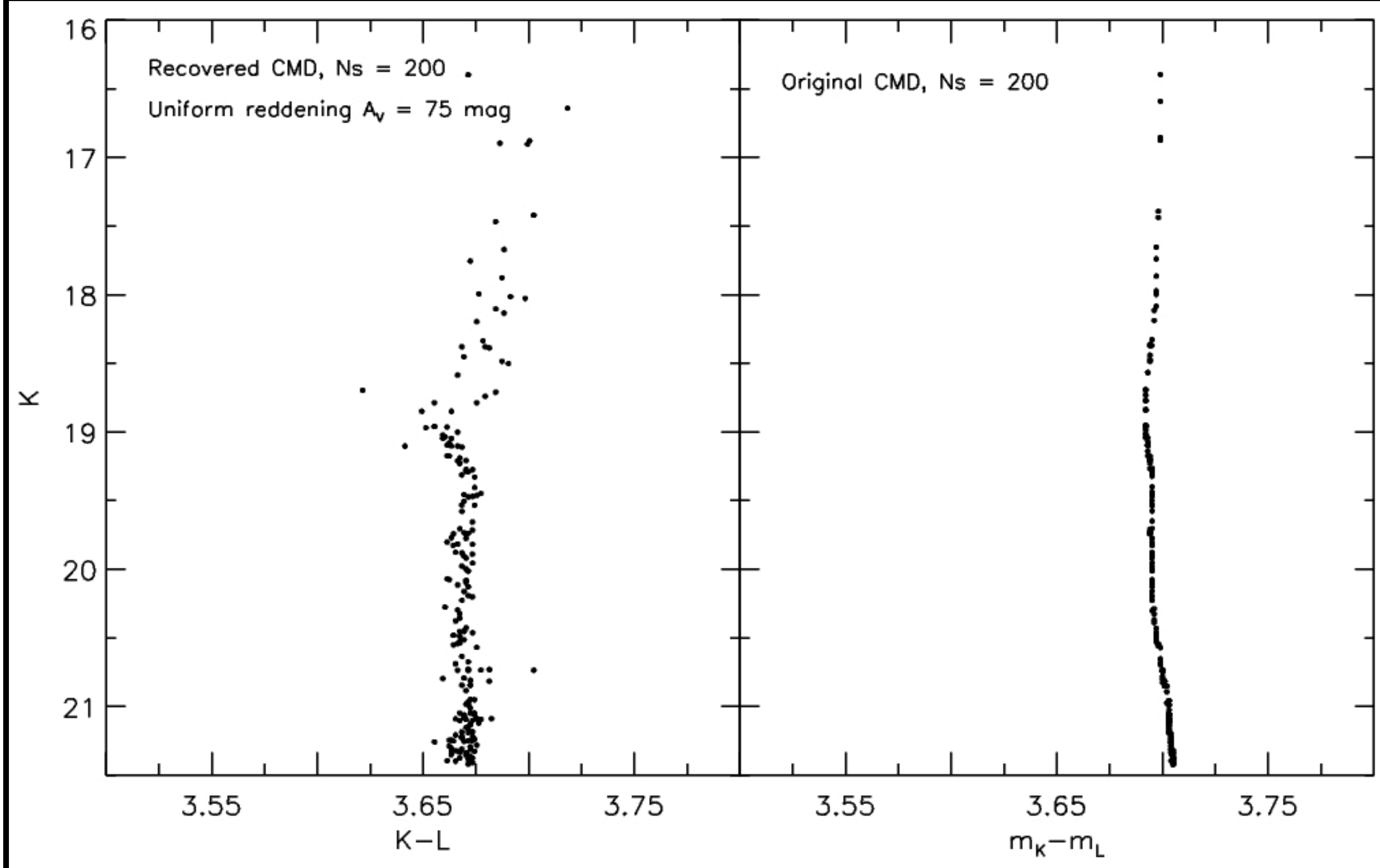
- K, L, M-band Laser Tomography Adaptive Optic (LTAO) PSFs
- Pixel scales 3.5 mas (K), 5.6 mas (L), 7.7 mas (M)
- Sky brightness (mag/arcsec^2): 13 mag (K), 5.3 mag (L) and 1.3 mag (M)
- Distance modulus = 14 mag + [pop. depth ~ 0.1 mag] **+ reddening:** 1) Uniform reddening of A_V = 75 mag (A_K=0.11 A_V, A_L=0.06A_V, A_M=0.02A_M) 2) Extinction distribution: gaussian with a peak of A_V = 100 mag, FW = 3″ 3) Clumpy extinction: clumps with scale of 0.25″ and peaks of 50 A_V on top of a uniform extinction of 50 A_V

Exposure times:

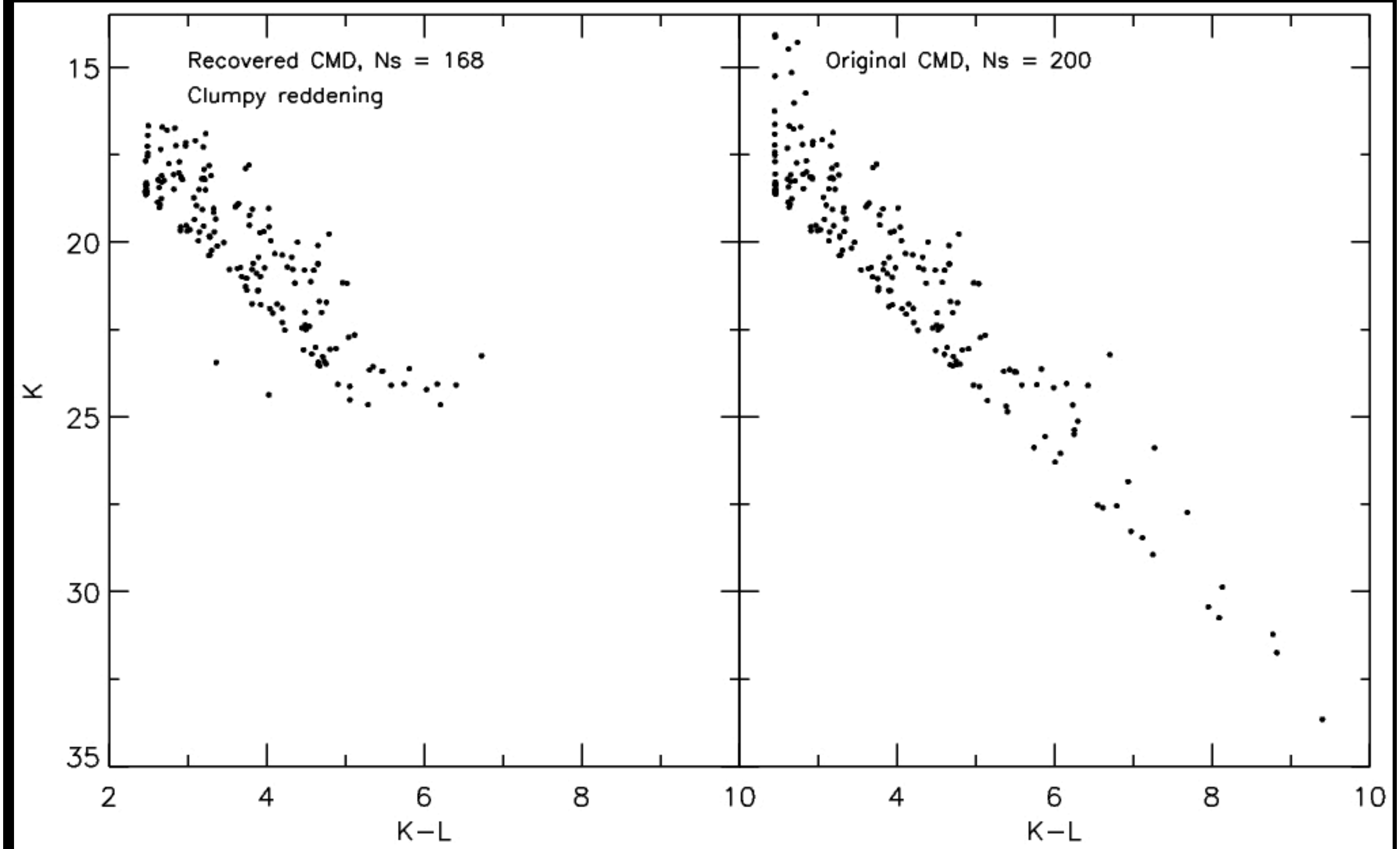
Ttot (K-band) = 400s, Ttot(L-band) = 400s, Ttot(M-band) = 63s



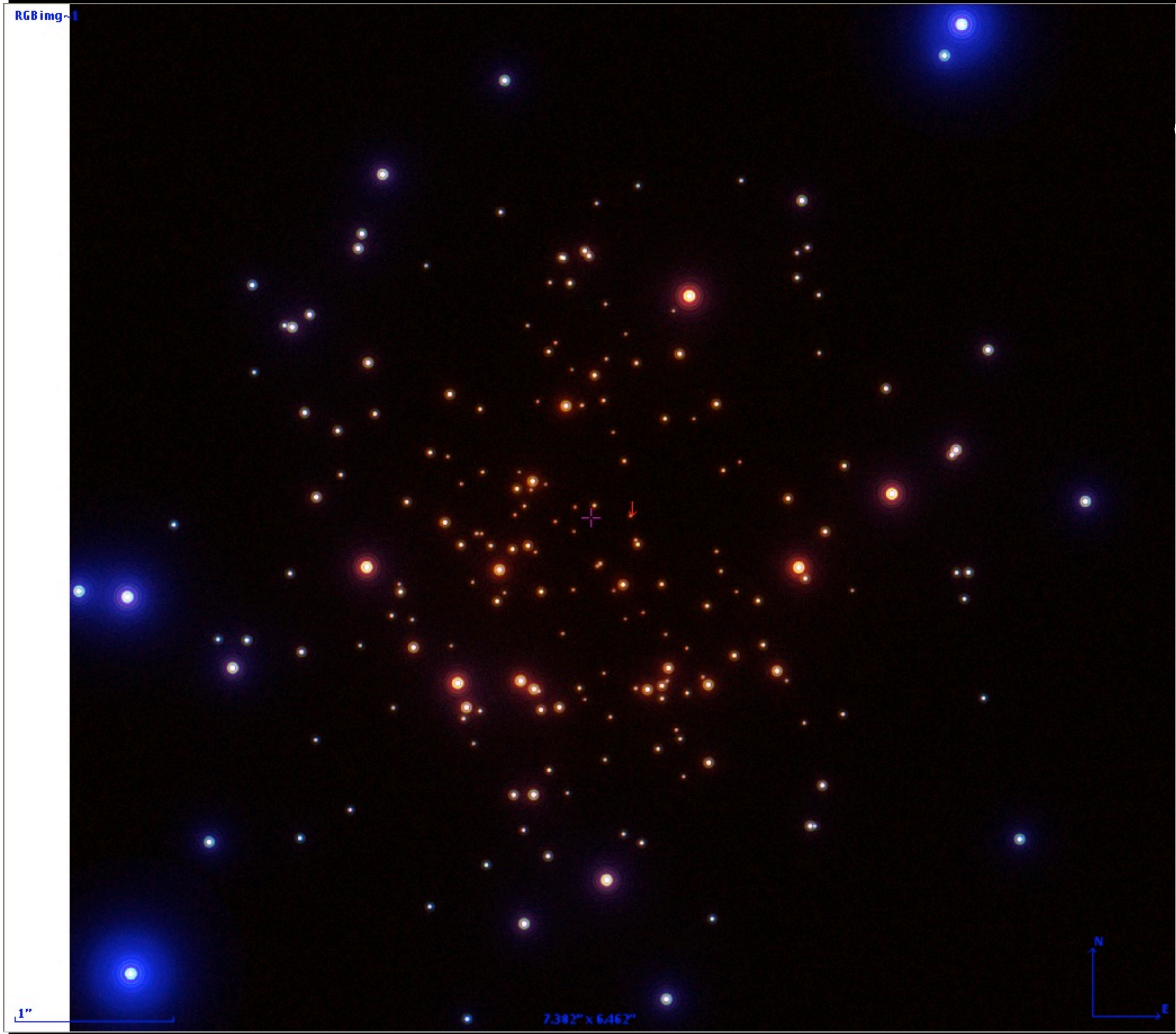
Faintest star:
K ~ 38 mag
L ~ 27 mag
M ~ mag



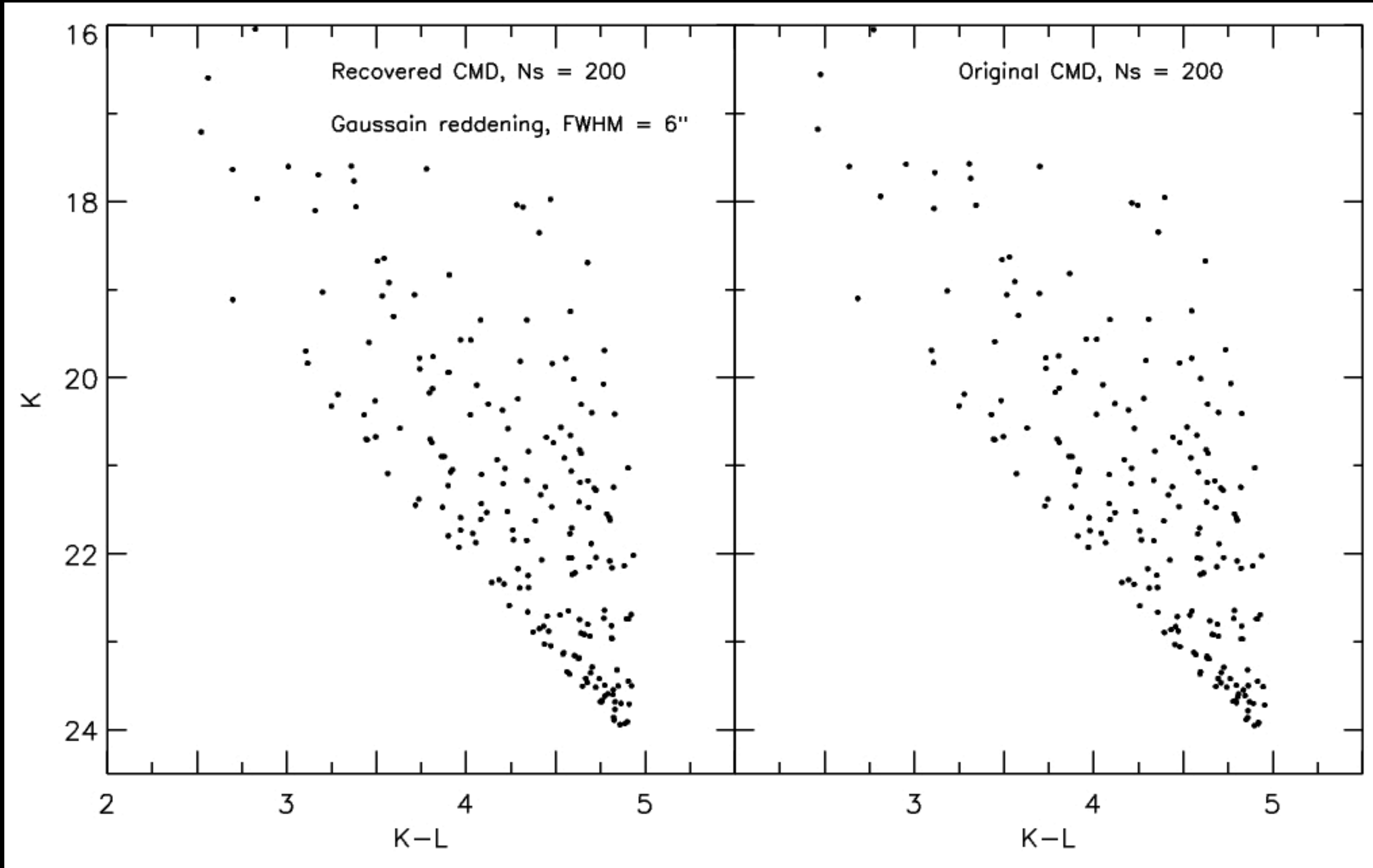
Recovered CMD, Ns = 200
Uniform reddening A_V = 75 mag
Original CMD, Ns = 200
K
16
17
18
19
20
21
3.55
3.65
3.75
K−L
$m_K - m_L$


Recovered CMD, Ns = 168
Clumpy reddening
Original CMD, Ns = 200
K
K−L
K−L
15
20
25
30
35
2
4
6
8
10
4
6
8
10

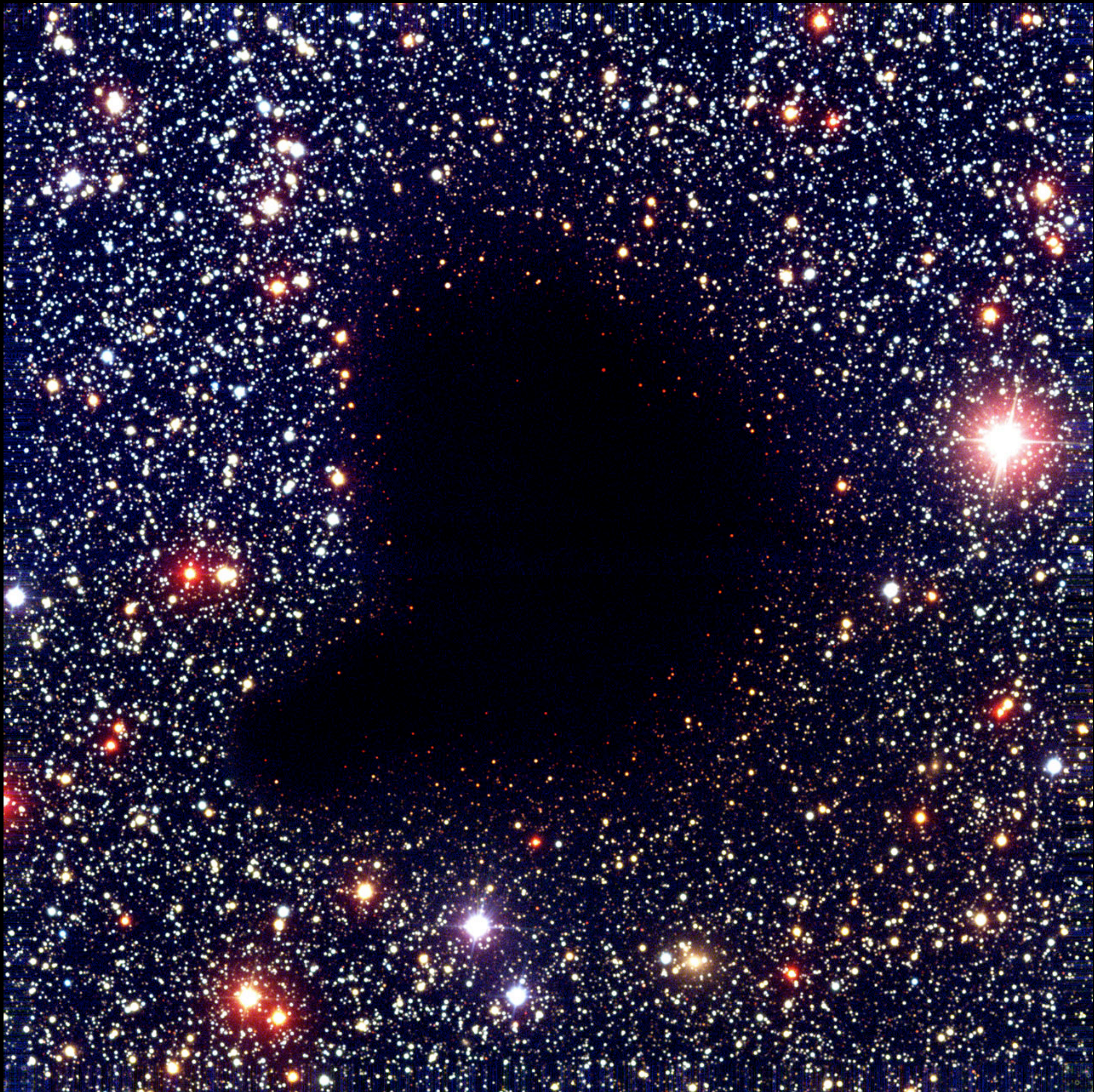
FoV: 6″ × 6 “, ~ 0.2pc at ~ 7 kpc



Gaussian
extinction profile
Peak Av=100 mag
FWHM= 6″



Recovered CMD, Ns = 200
Gaussain reddening, FWHM = 6"
Original CMD, Ns = 200
K
K−L
K−L
16
18
20
22
24
2
3
4
5
3
4
5



B 68 dark cloud

credit: J. Alves, ESO

Looking Through the Dark Cloud B68 (NTT + SOFI)

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

in addition, there are the hydrogen recomb.

lines Br_g, Pf_g, Br_a, Hu (14-6)

whose ratios have well-defined values

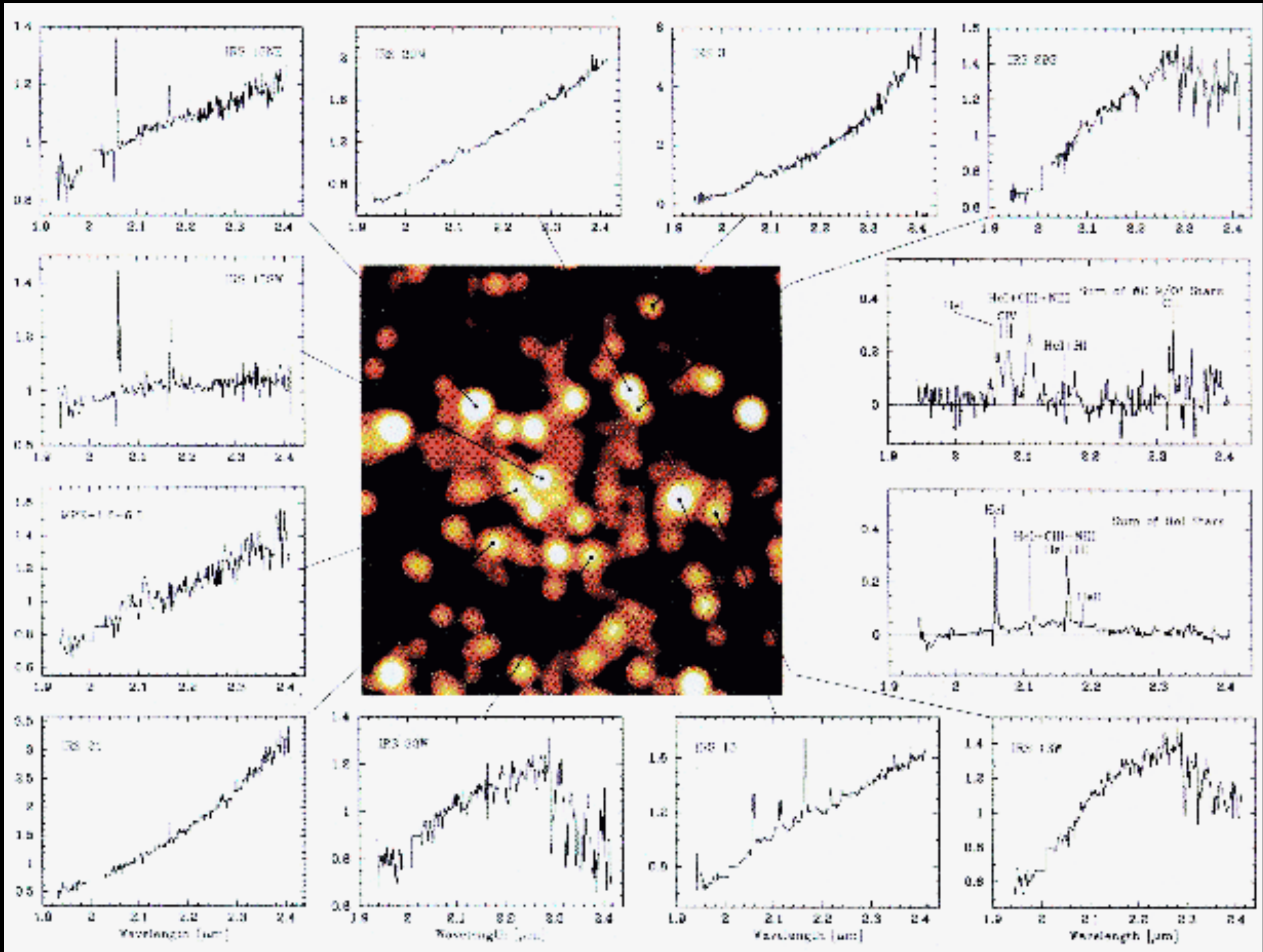
(e.g. Br_g/Br_a = 1/3; Br_g/H_α = 1/100)

in optically thin ionised gas (Menzel Case B)

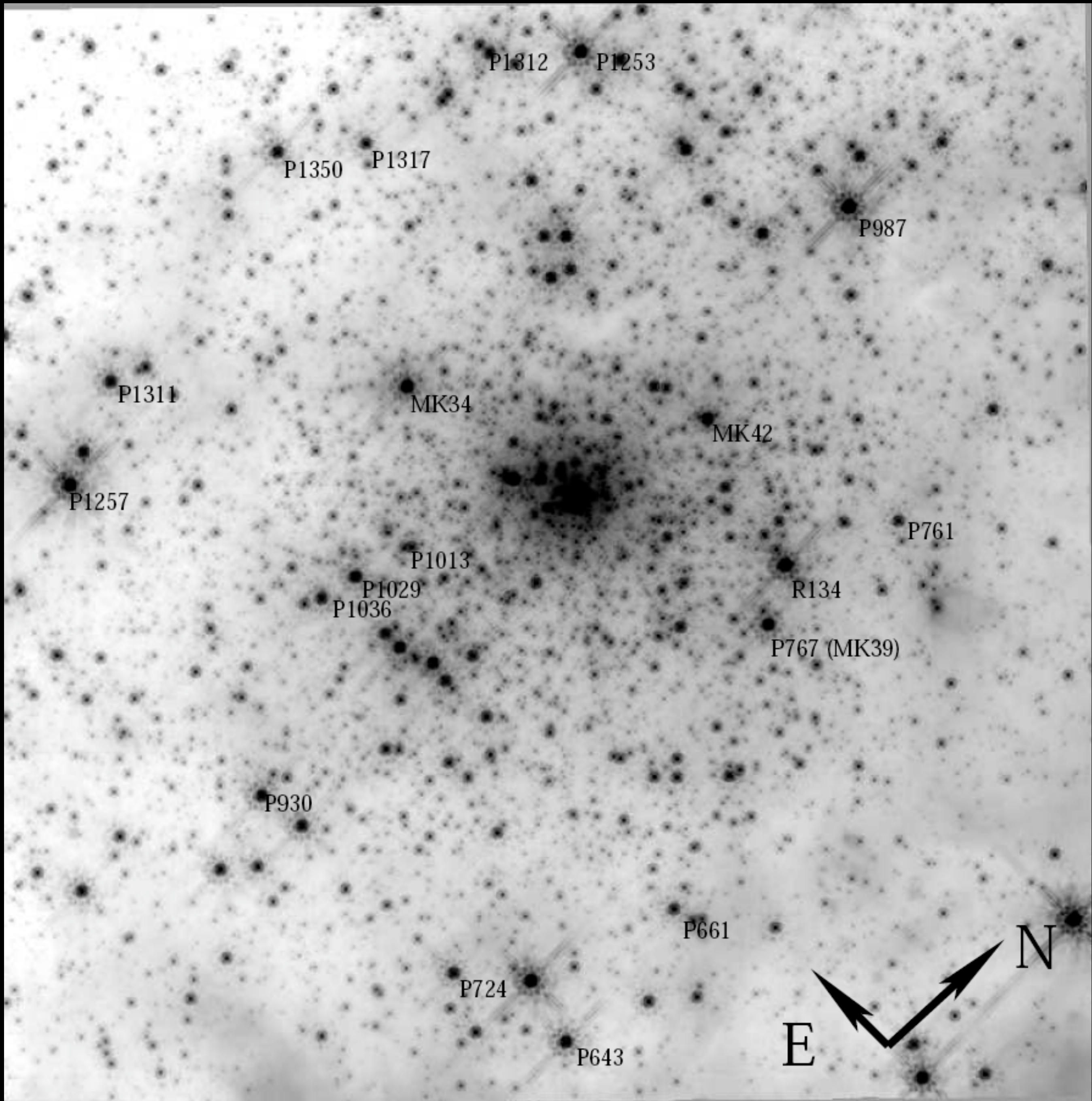
to infer the extinction to individual objects

Weitzel et al. 1996 / Eckart et al. 1995

Galactic Center massive star 3D spectroscopy



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



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

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

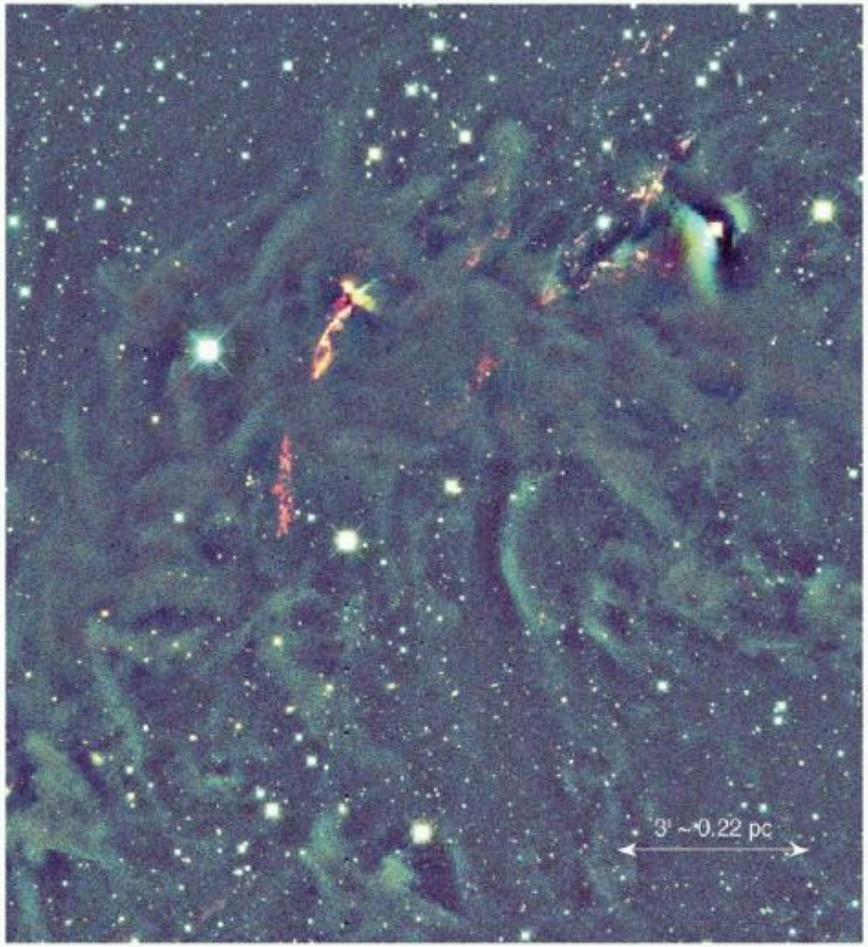


FIG. 1.—L1448 in false color. Component images have been weighted according to their flux in units of MJy sr^{-1}. J is blue, H is green, and K_s is red. Outflows from young stars glow red, while a small fan-shaped reflection nebula in the upper right is blue-green. Cloudshine, in contrast, is shown 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.

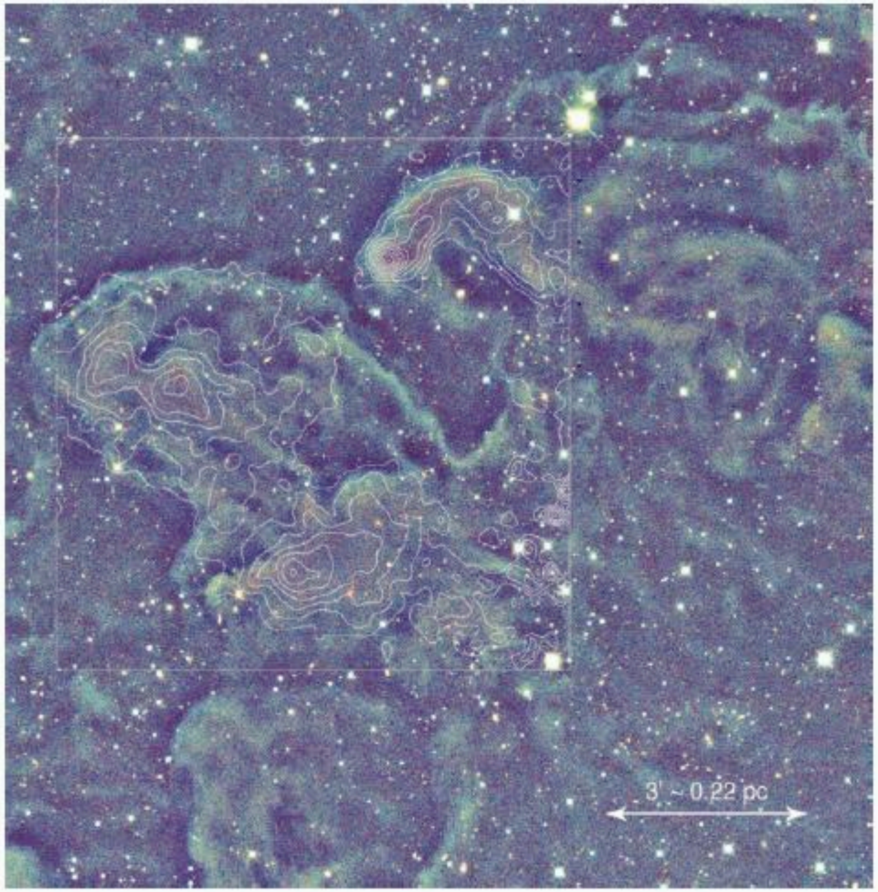


FIG. 2.—L1451 in false color. Again, each component image has been scaled to the same flux scale in units of MJy sr^{-1}; and J is blue, H is green, and K_s is red. A smaller map of 1.2 mm dust emission contours from COMPLETE (M. Tafalla 2006, in preparation) has been overlaid, showing that the color 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