High-mass star formation in the outer Milky Way

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Copenhaguen
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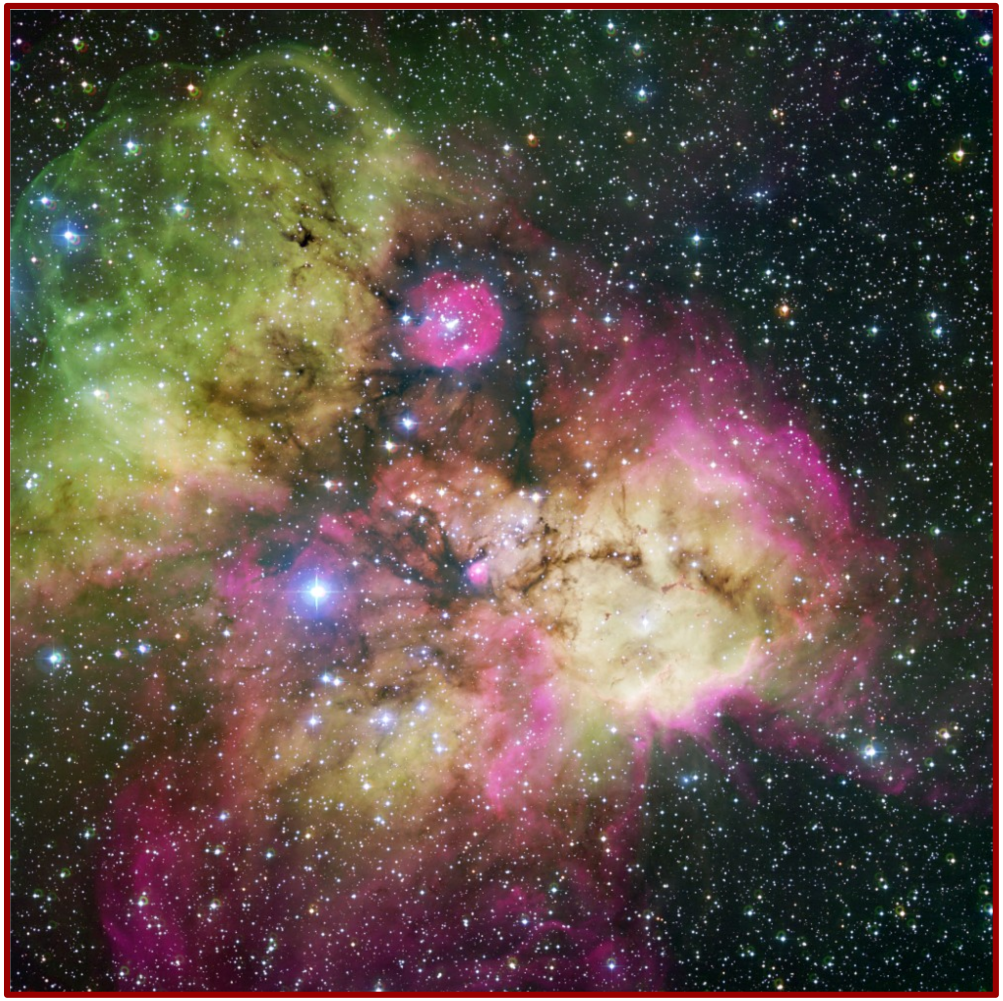
Young clusters with massive stars

- Laboratories for massive stars
- Prime sites for star formation
- Initial mass function
- H II regions and molecular clouds

The Anticentre region



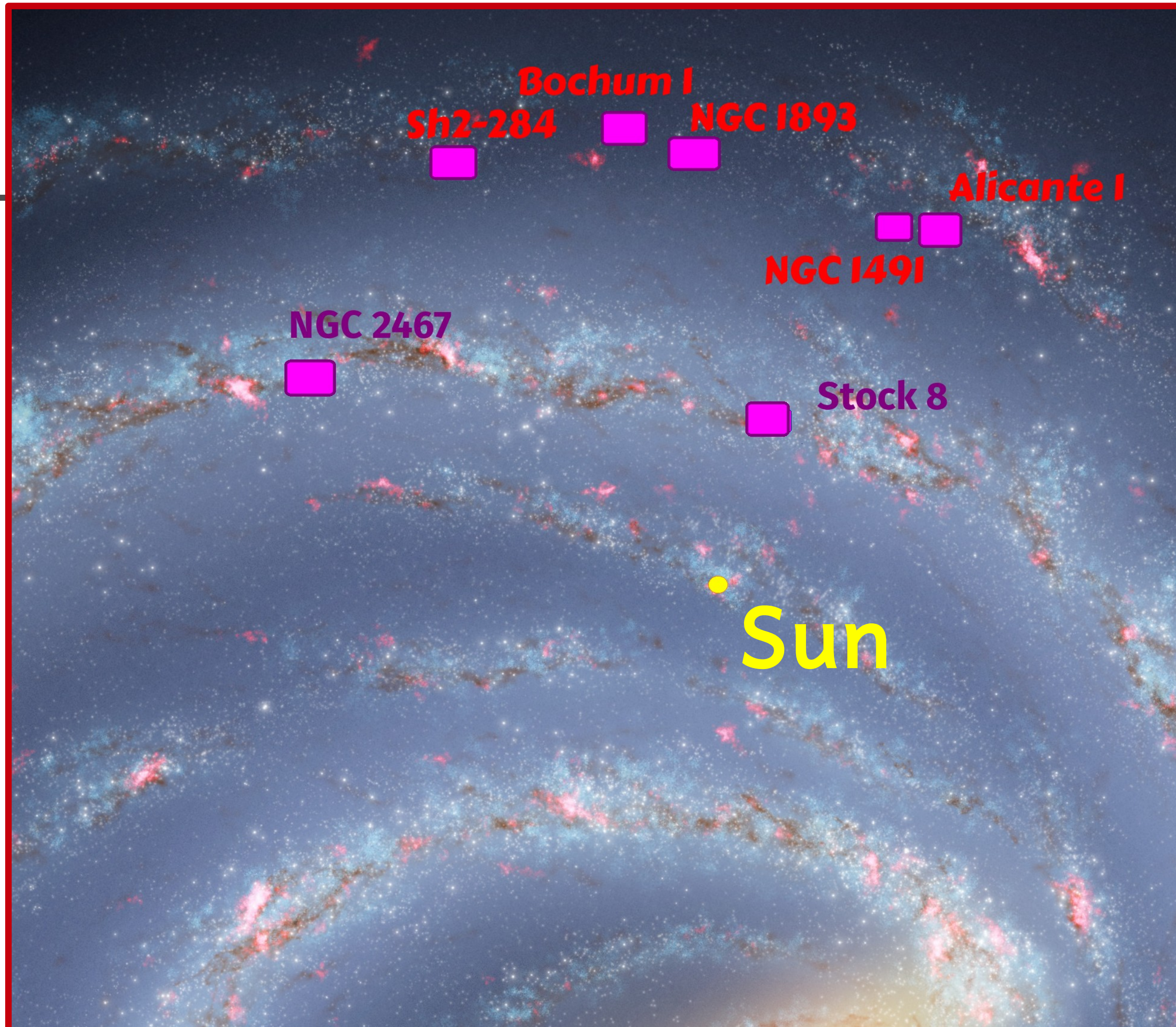
Young clusters with massive stars

- Low foreground extinction
- Negligible background contamination
- Star formation in a "quiet" environment

Tracing the Outer Arm
Negueruela & Marco 2003, A&A 406, 119

Solving high-mass eclipsing binaries
PhD of J. Lorenzo

- Don't use photometry alone to study OB stars
- Take advantage of wide field imaging



Don't use photometry to study OB stars!!

Massey et al. (1995, ApJ 454, 151)

Fitzgerald (1970, A&A 4, 234)

Table 1. *Adopted* $(B-V)_0$ *colours*

	V	IV-V	IV	III-IV	III	II-III	II	Ib	Iab	Ia
O5	−0.32									
O6	−0.32									
O7	−0.32									
O7.5	−0.31									
O8	−0.31				−0.31				−0.29	
O9	−0.31	−0.31	−0.31	−0.31	−0.31	−0.31	−0.31	−0.28	−0.28	−0.28
O9.5	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.27	−0.27	−0.27
B0	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.29	−0.24	−0.24	−0.24
B0.5	−0.28	−0.28	−0.28	−0.28	−0.28	−0.30	−0.28	−0.22	−0.22	−0.22
B1	−0.26	−0.26	−0.26	−0.26	−0.26	−0.28	−0.24	−0.19	−0.19	−0.19
B1.5	−0.25	−0.25	−0.25	−0.25	−0.25	−0.27	−0.22	−0.17	−0.18	−0.18
B2	−0.24	−0.24	−0.24	−0.24	−0.24	−0.22	−0.21	−0.16	−0.17	−0.17
B2.5	−0.22	−0.22	−0.22	−0.22	−0.22	−0.20	−0.19	−0.15	−0.15	−0.15
B3	−0.20	−0.20	−0.20	−0.20	−0.20	−0.18	−0.17	−0.13	−0.13	−0.13
B4	−0.18	−0.18	−0.18	−0.18	−0.18					−0.11

Don't use photometry to study OB stars!!

Turner (1980, ApJ 240, 137)

TABLE 2

ADOPTED SPECTRAL TYPE—M_V RELATION FOR OB STARS

Spectral Type	V	IV	III	II	Ib	Iab	Ia
O3	−5.4	...	...	...	−6.4	...	...
O4	−5.2	...	−6.4	...	...	...	−7.0
O5	−5.1	...	−6.3	...	...	...	−7.0
O6	−5.0	...	−5.9	...	−6.4	...	−7.0
O7	−4.8	...	−5.6	−5.9	−6.3	...	−7.0
O8	−4.4	...	−5.5	−5.9	−6.2	−6.6	−7.0
O9	−4.1	−5.0	−5.4	−5.9	−6.2	−6.5	−7.0
O9.5..................	−4.0	−4.7	−5.3	−5.8	−6.1	−6.5	−7.0
B0	−3.7	−4.5	−5.0	−5.6	−6.0	−6.5	−7.0
B0.5..................	−3.6	−4.3	−4.8	−5.3	−5.9	−6.5	−7.0
B1	−3.0	−3.8	−4.4	−5.0	−5.9	−6.4	−7.0
B2	−2.2	−3.1	−3.9	−4.7	−5.4	−6.3	−7.1

	V	IV-V	IV							Ia
O5	−0.32									
O6	−0.32									
O7	−0.32									
O7.5	−0.31									
O8	−0.31				−0.31				−0.29	
O9	−0.31	−0.31	−0.31	−0.31	−0.31	−0.31	−0.31	−0.28	−0.28	−0.28
O9.5	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.27	−0.27	−0.27
B0	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.29	−0.24	−0.24	−0.24
B0.5	−0.28	−0.28	−0.28	−0.28	−0.28	−0.30	−0.28	−0.22	−0.22	−0.22
B1	−0.26	−0.26	−0.26	−0.26	−0.26	−0.28	−0.24	−0.19	−0.19	−0.19
B1.5	−0.25	−0.25	−0.25	−0.25	−0.25	−0.27	−0.22	−0.17	−0.18	−0.18
B2	−0.24	−0.24	−0.24	−0.24	−0.24	−0.22	−0.21	−0.16	−0.17	−0.17
B2.5	−0.22	−0.22	−0.22	−0.22	−0.22	−0.20	−0.19	−0.15	−0.15	−0.15
B3	−0.20	−0.20	−0.20	−0.20	−0.20	−0.18	−0.17	−0.13	−0.13	−0.13
B4	−0.18	−0.18	−0.18	−0.18	−0.18					−0.11

Don't use photometry to study OB stars!!

Fitzgerald (1970, A&A 4, 234)

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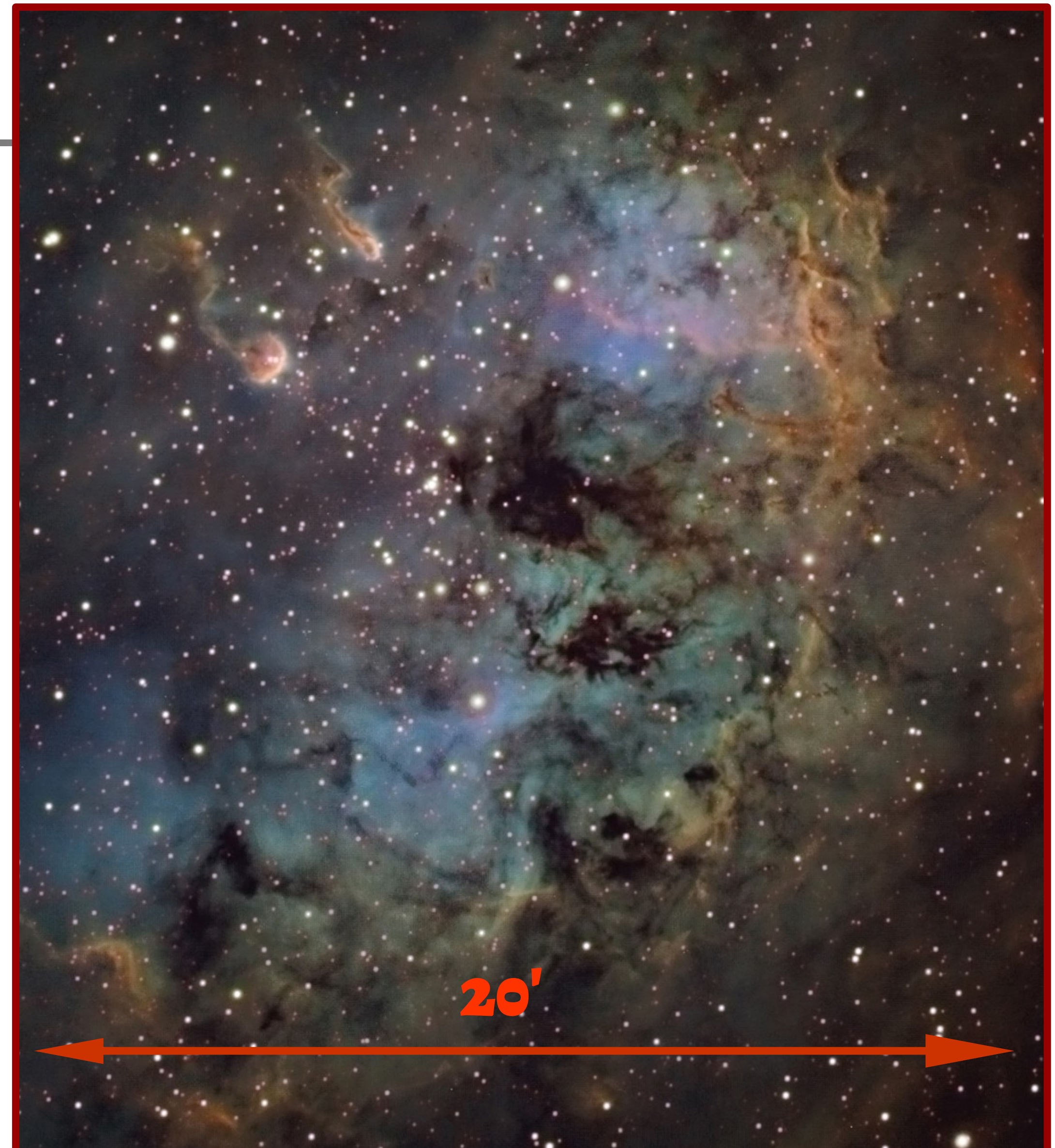
O9.5	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.27	−0.27	−0.27
B0	−0.30	−0.30	−0.30	−0.30	−0.30	−0.30	−0.29	−0.24	−0.24	−0.24
B0.5	−0.28	−0.28	−0.28	−0.28	−0.28	−0.30	−0.28	−0.22	−0.22	−0.22
B1	−0.26	−0.26	−0.26	−0.26	−0.26	−0.28	−0.24	−0.19	−0.19	−0.19
B1.5	−0.25	−0.25	−0.25	−0.25	−0.25	−0.27	−0.22	−0.17	−0.18	−0.18
B2	−0.24	−0.24	−0.24	−0.24	−0.24	−0.22	−0.21	−0.16	−0.17	−0.17
B2.5	−0.22	−0.22	−0.22	−0.22	−0.22	−0.20	−0.19	−0.15	−0.15	−0.15
B3	−0.20	−0.20	−0.20	−0.20	−0.20	−0.18	−0.17	−0.13	−0.13	−0.13
B4	−0.18	−0.18	−0.18	−0.18	−0.18					−0.11

NGC 1893

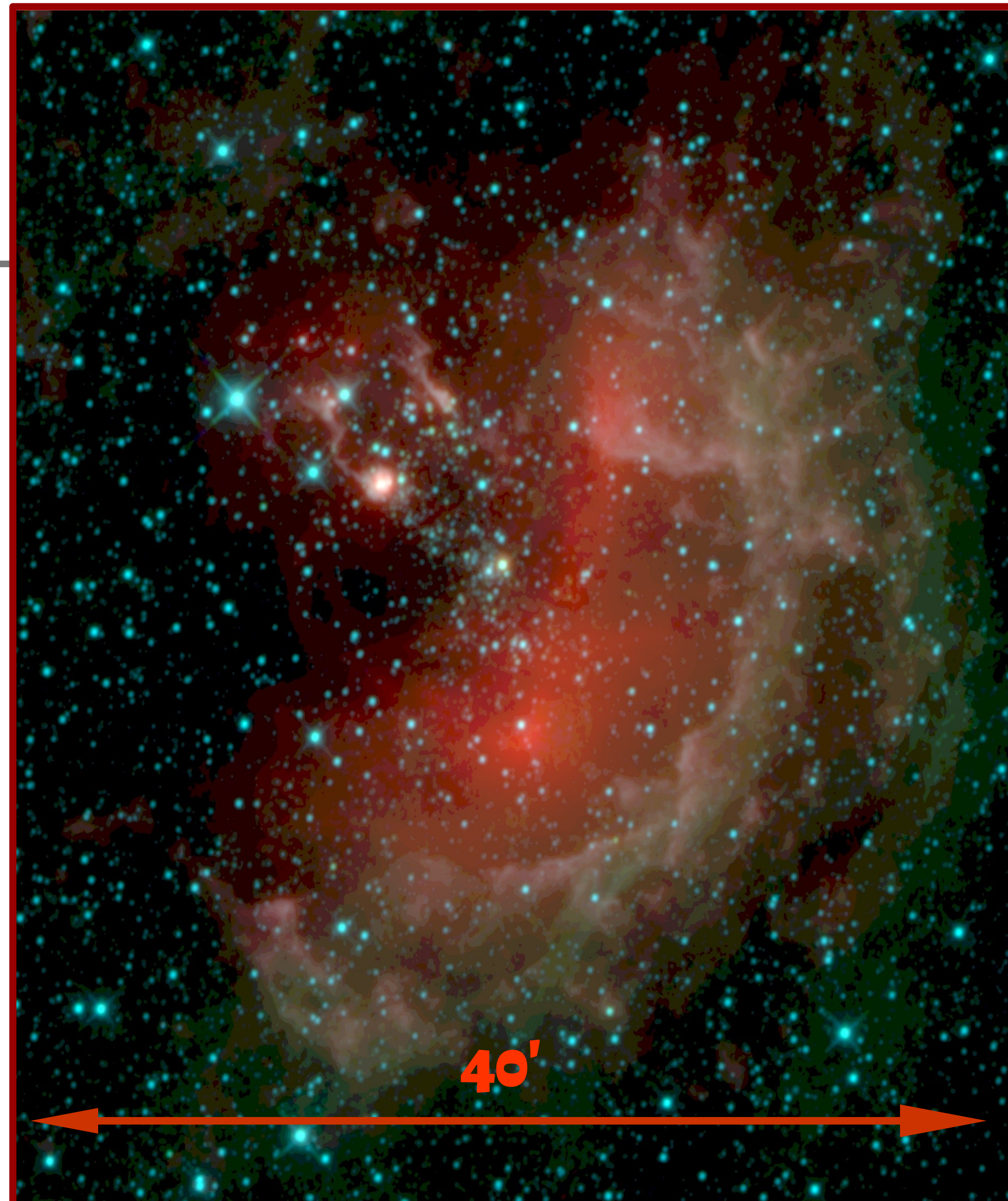


IC 410 + NGC 1893
$\ell = 175^{\circ}$
$d = 5$ kpc

See Negueruela et al. (2007, A&A 471, 485)

APOD image (© Jacob Bassoe)

NGC 1893



On-going star formation

Caramazza et al. 2012, A&A 539, A74
(*Chandra*)
Prisinzano et al. 2011, A&A 527, A77
(Spitzer)
Caramazza et al. 2008, A&A 488, 211
Maheswan et al. 2007, MNRAS 379, 1237

See Negueruela et al. (2007, A&A 471, 485)

WISE three-colour image

NGC 1893

Simis 129

Simis 130

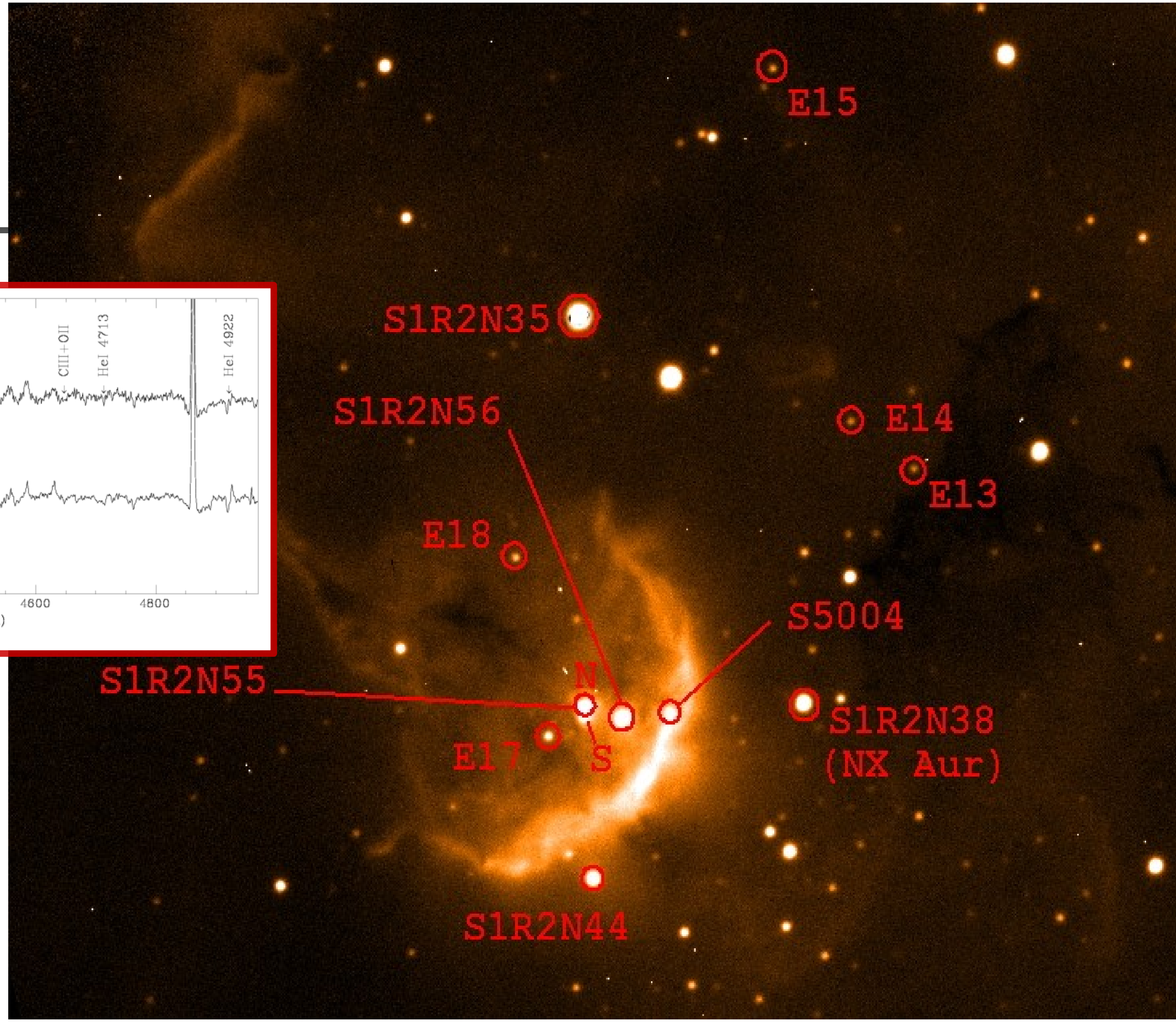
Lim et al. 2014, MNRAS 443, 454

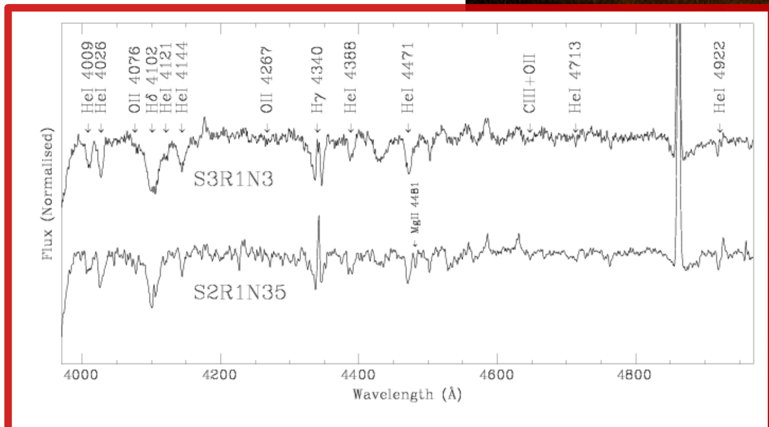
Distance ~3.5 kpc from low-mass star isochrone fit

Age 1.7 Myr with a spread of 5 Myr

See Negueruela et al. (2007, A&A 471, 485)

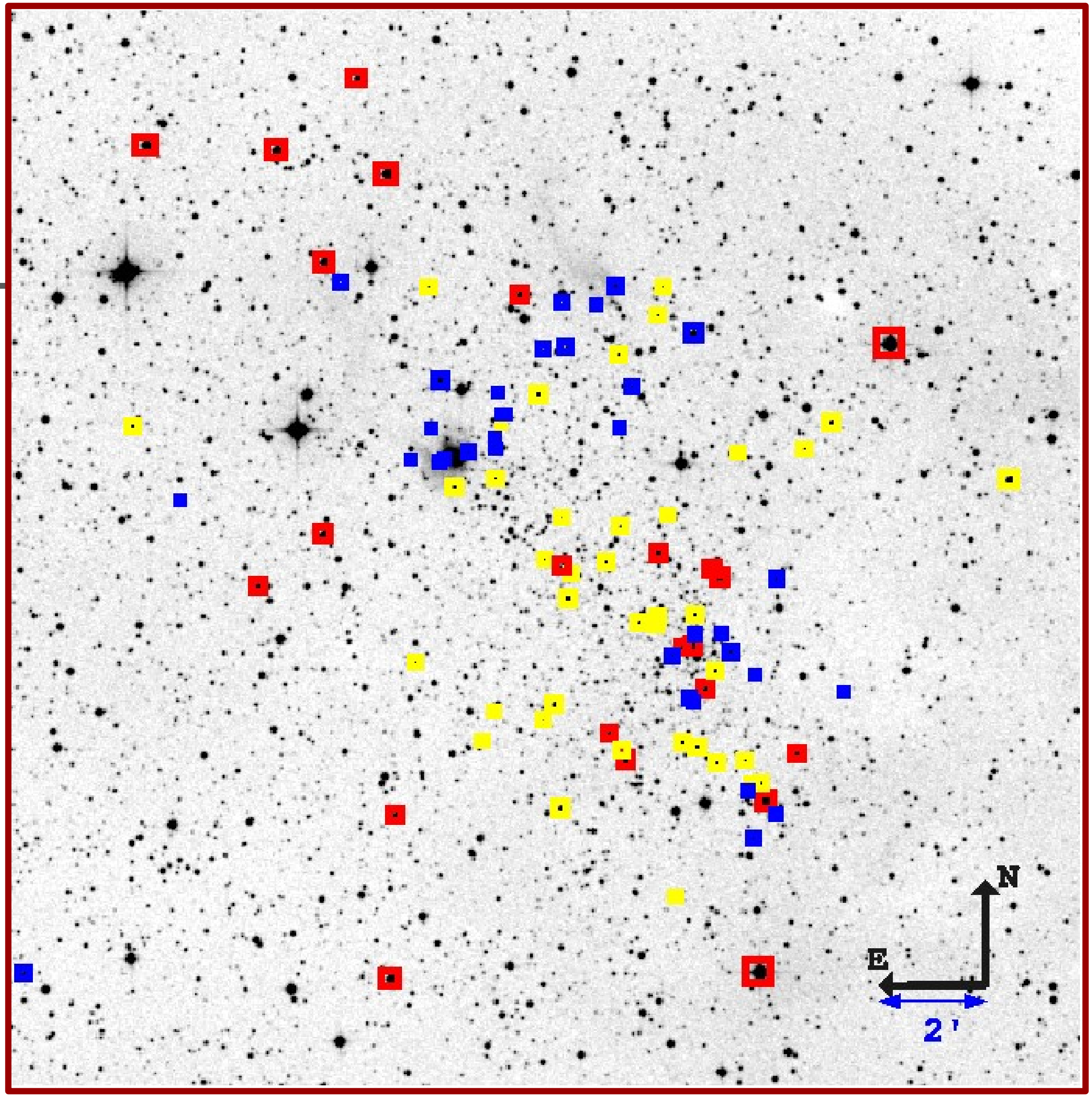
APOD image (© Jacob Bassoe)





Simis 130
Hα image
(NOT+ALFOSC)

Negueruela et al. 2007, A&A 471, 485



OB stars

B3-B8

PMS (Herbig Be, T Tauri, naked PMS)

Negueruela et al. 2007, A&A 471, 485

NGC 1893

HD 242908

O4.5 V

Sota et al. 2011 (ApJS 193, 24)

APOD image (© Jacob Bassoe)

Dolidze 25 (Sh2-284)

Sh2-284
Major star forming region in the outer Milky Way
COROT field

Puga et al. 2009 (A&A 503, 107)
Cusano et al. 2011 (MNRAS 410, 227)

$\ell = 212^{o}$
d = 3.5-5.5 kpc

Image by Kevin Jardine combining Spitzer/IRAC + Hα

Dolidze 25 (Sh2-284)

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Major star forming region in the outer Milky Way
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Puga et al. 2009 (A&A 503, 107)
Cusano et al. 2011 (MNRAS 410, 227)

$\ell = 212^{\circ}$
$d = 3.5\text{-}5.5$ kpc

Image by Kevin Jardine combining Spitzer/IRAC + Hα

Dolidze 25 (Sh2-284)

Dolidze 25

6 Myr from *UBV*
Turbide & Moffat 1993 (AJ 105, 1831)
$Z = 0.04$ from spectral analysis
Lennon et al. 1990 (A&A 240, 349)
3 Myr + older population
$d = 3.6$ kpc from photometry
Delgado et al. 2010 (A&A 509, A104)

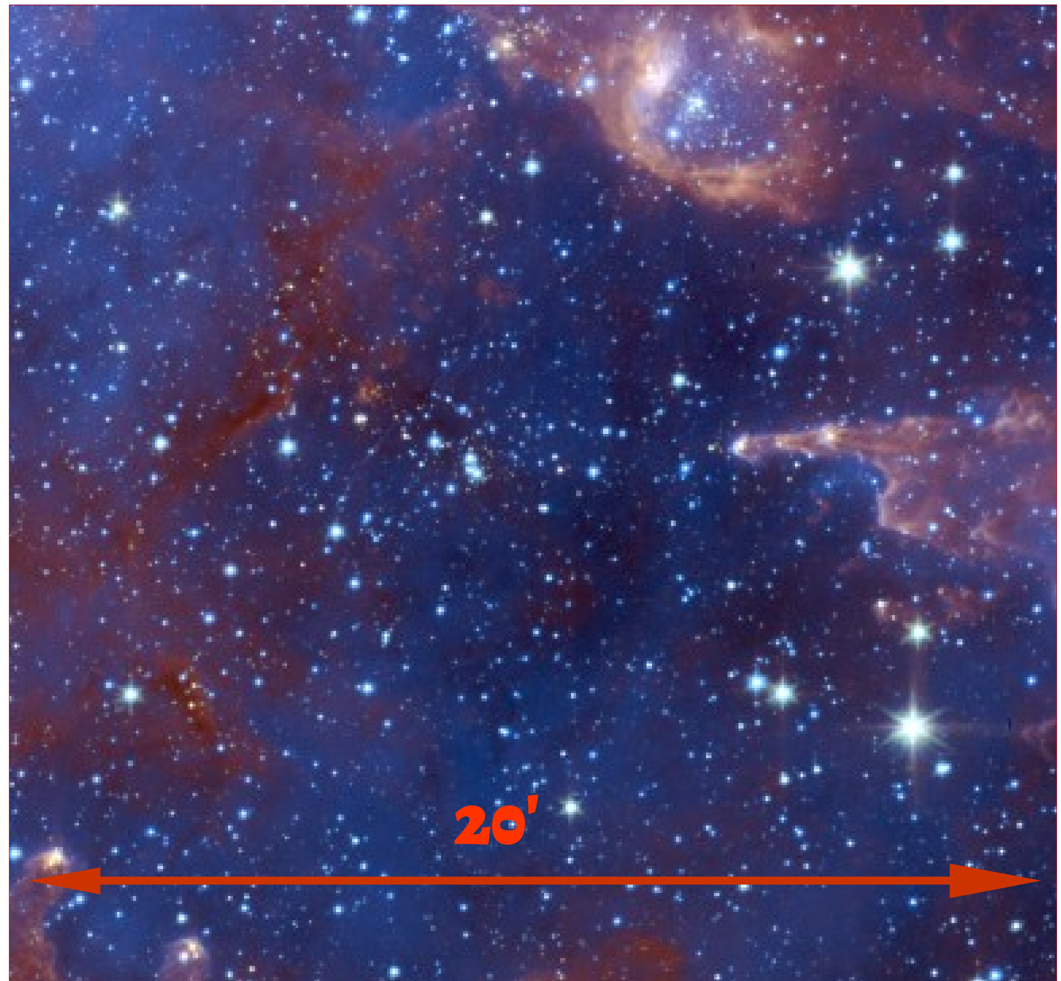


Image by Kevin Jardine combining Spitzer/IRAC + Hα

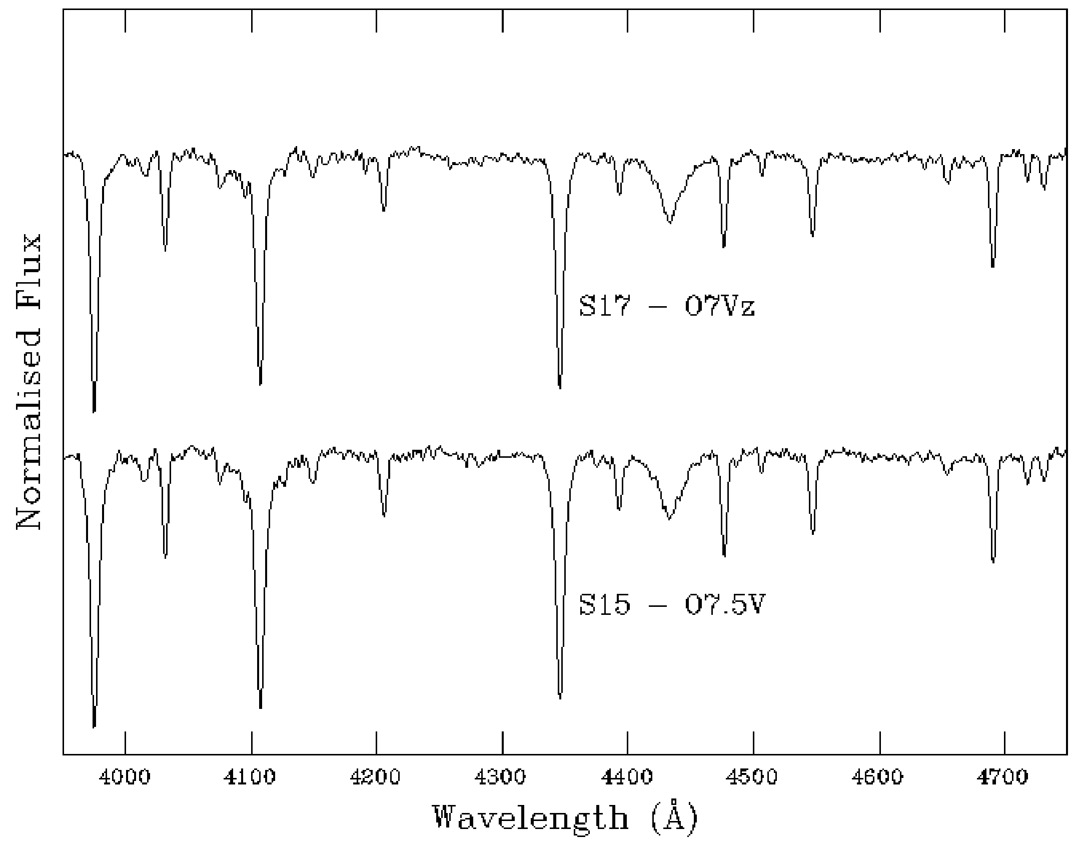
Dolidze 25 (Sh2-284)

NOT + FIES

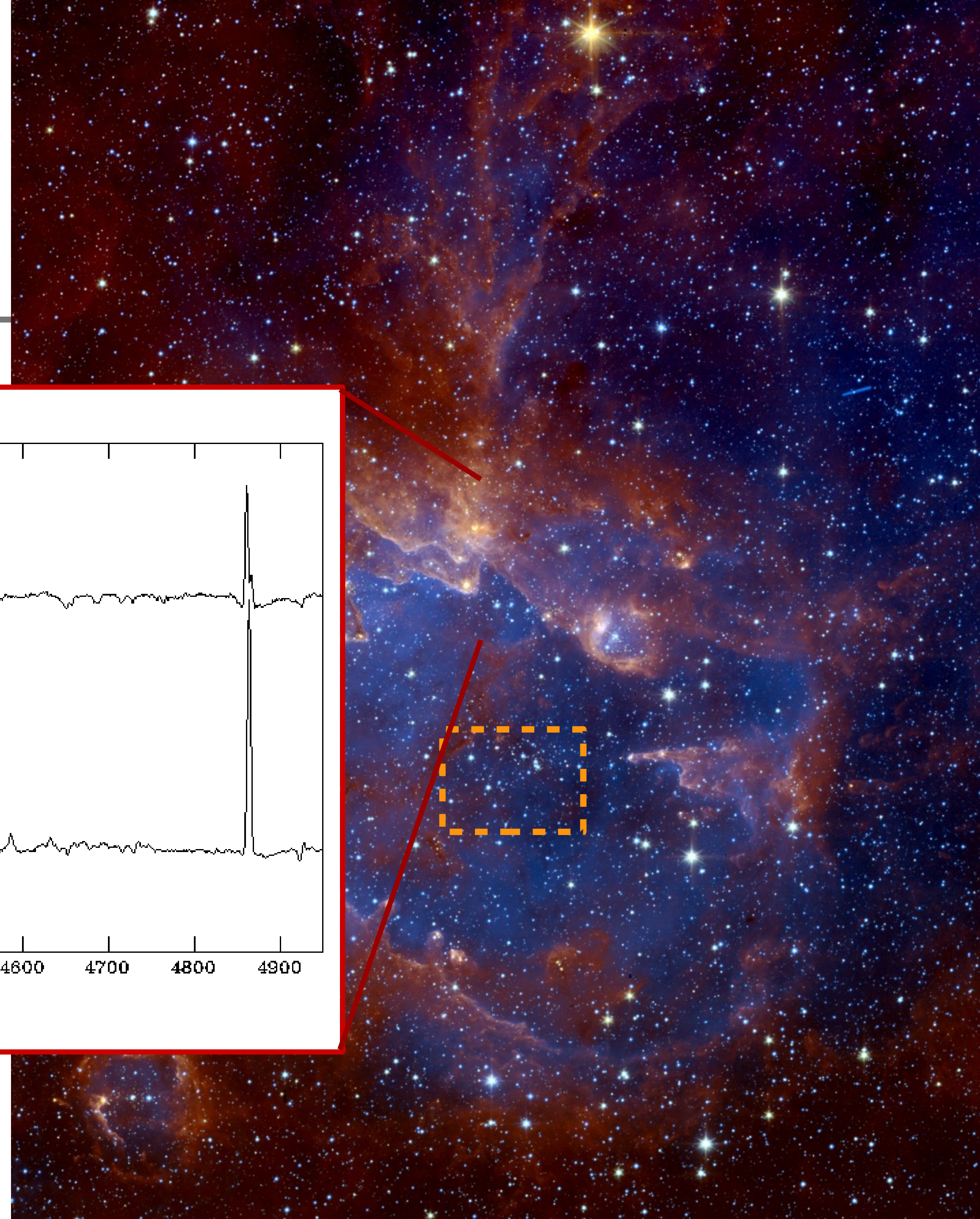
échelle spectra $R = 25\,000$

FASTWIND analysis of three O9.7 or B0V stars by Sergio Simón-Díaz

Abundances of O and Si are moderately subsolar ($\lesssim$0.3 dex) .



Dolidze 25 (Sh2-284)



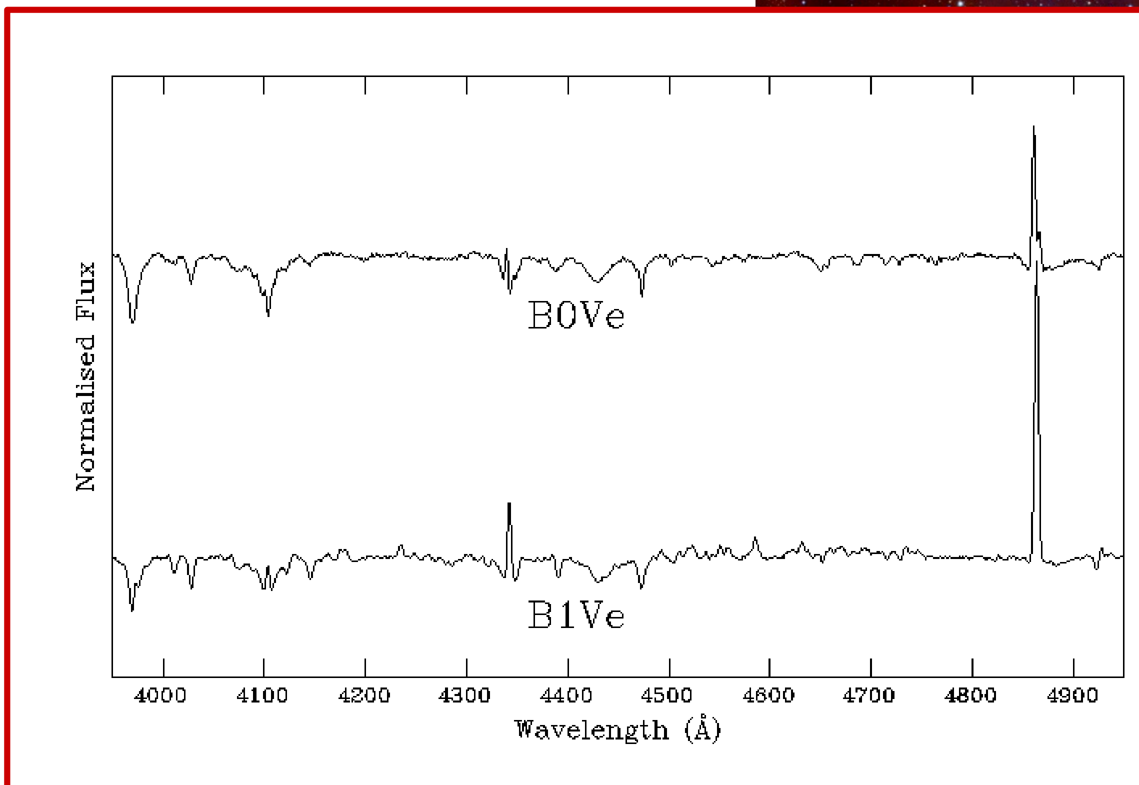


Image by Kevin Jardine combining Spitzer/IRAC + Hα

Dolidze 25 (Sh2-284)

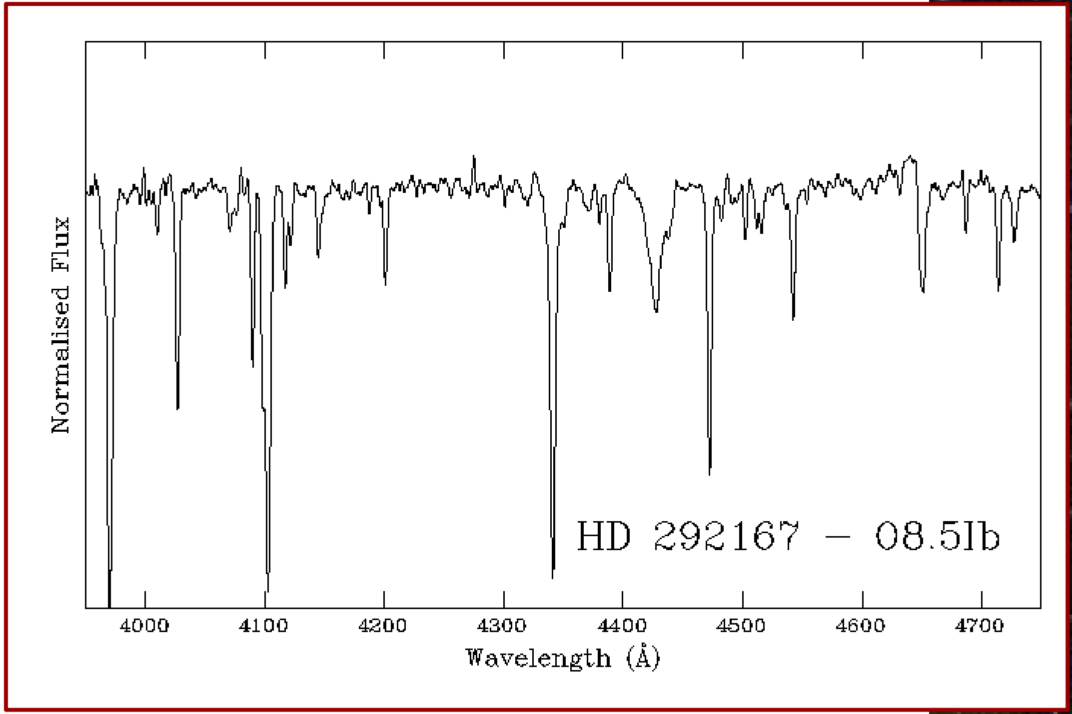
Image by Jim Wood & Eric Chasak

Dolidze 25 (Sh2-284)

HD 292167

Image by Jim Wood & Eric Chasak

Dolidze 25 (Sh2-284)



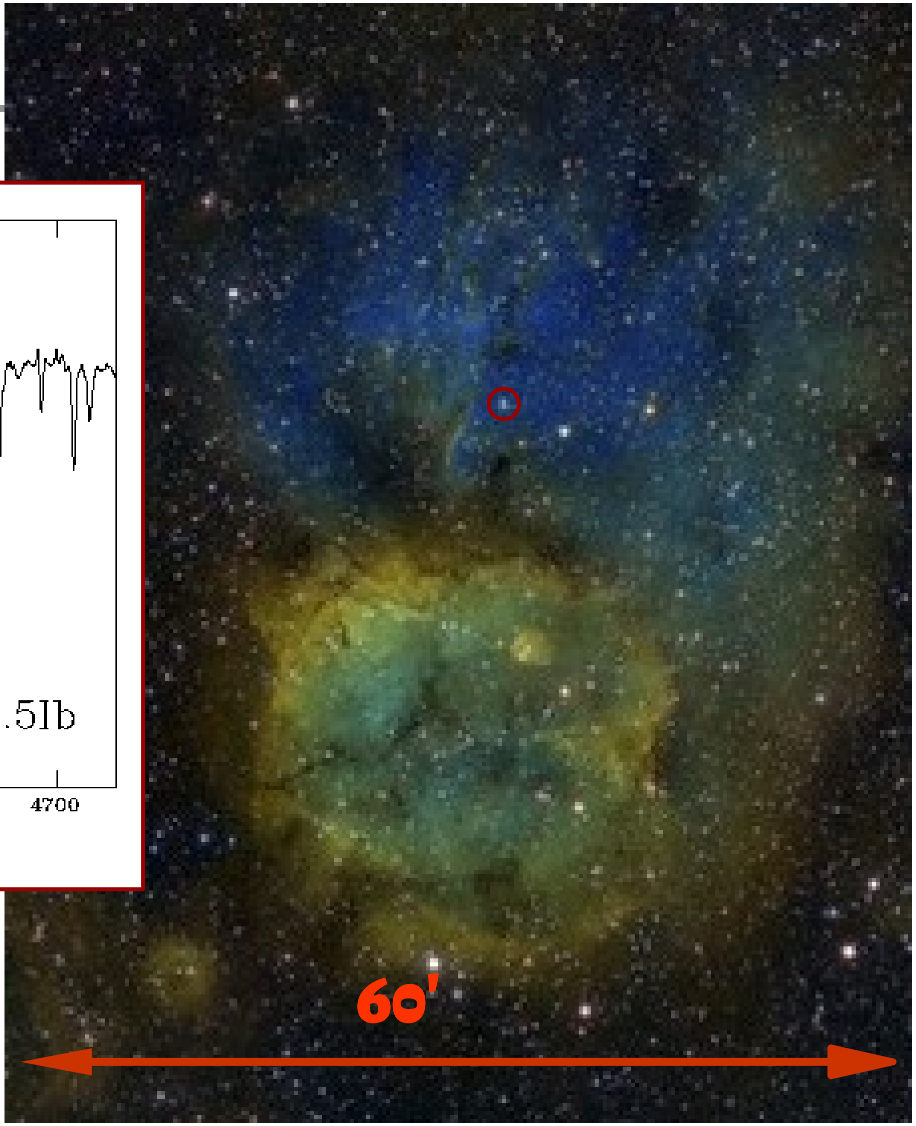


Image by Jim Wood & Eric Chasak

Stock 8

Smaller cluster in the Perseus Arm
Sh2-234 = IC 417

Jose et al. 2008 (MNRAS 384, 1675)

$\ell = 173^{\circ}$
$d = 2$ kpc

Image by Adam Block/Mount Lemmon SkyCenter/University of Arizona

Stock 8

Smaller cluster in the Perseus Arm

Jose et al. 2008 (MNRAS 384, 1675)

$\ell = 173^{\circ}$
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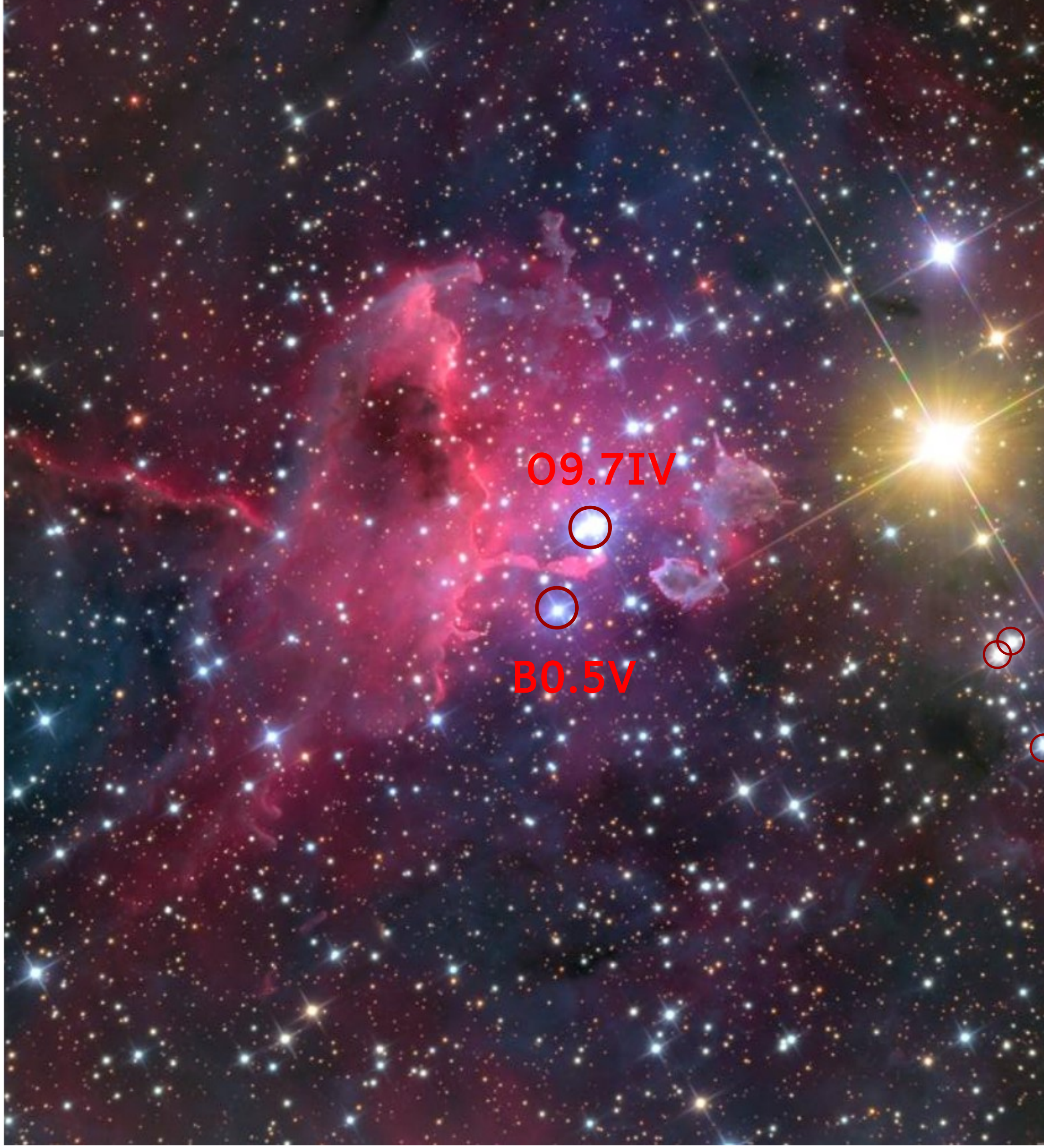

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Stock 8

Smaller cluster in the Perseus Arm

Marco et al., in prep.

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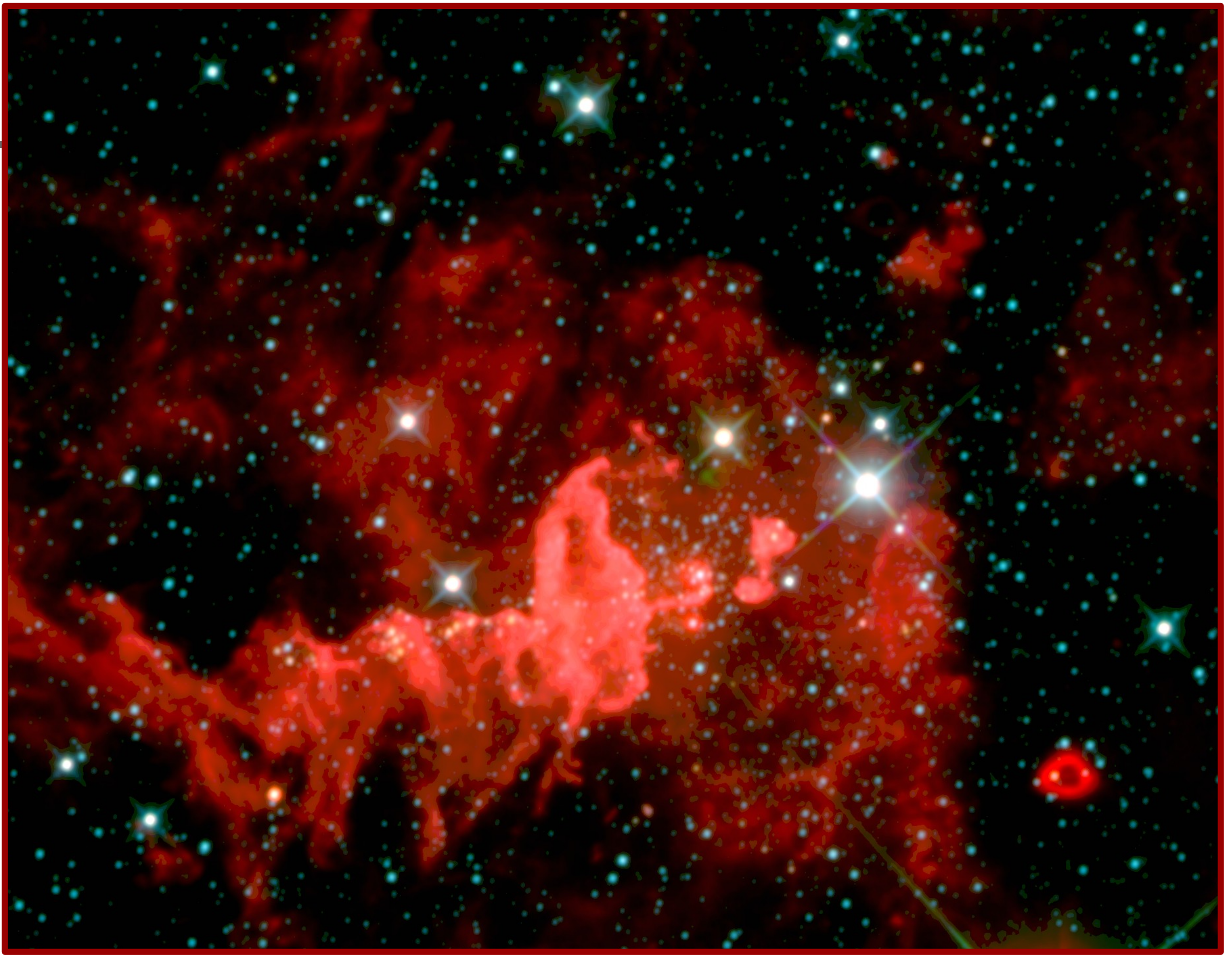

WISE threecolour image (W1, W2, W3)

Stock 8

Smaller cluster in the Perseus Arm

Marco et al., in prep.

$\ell = 173^{\circ}$
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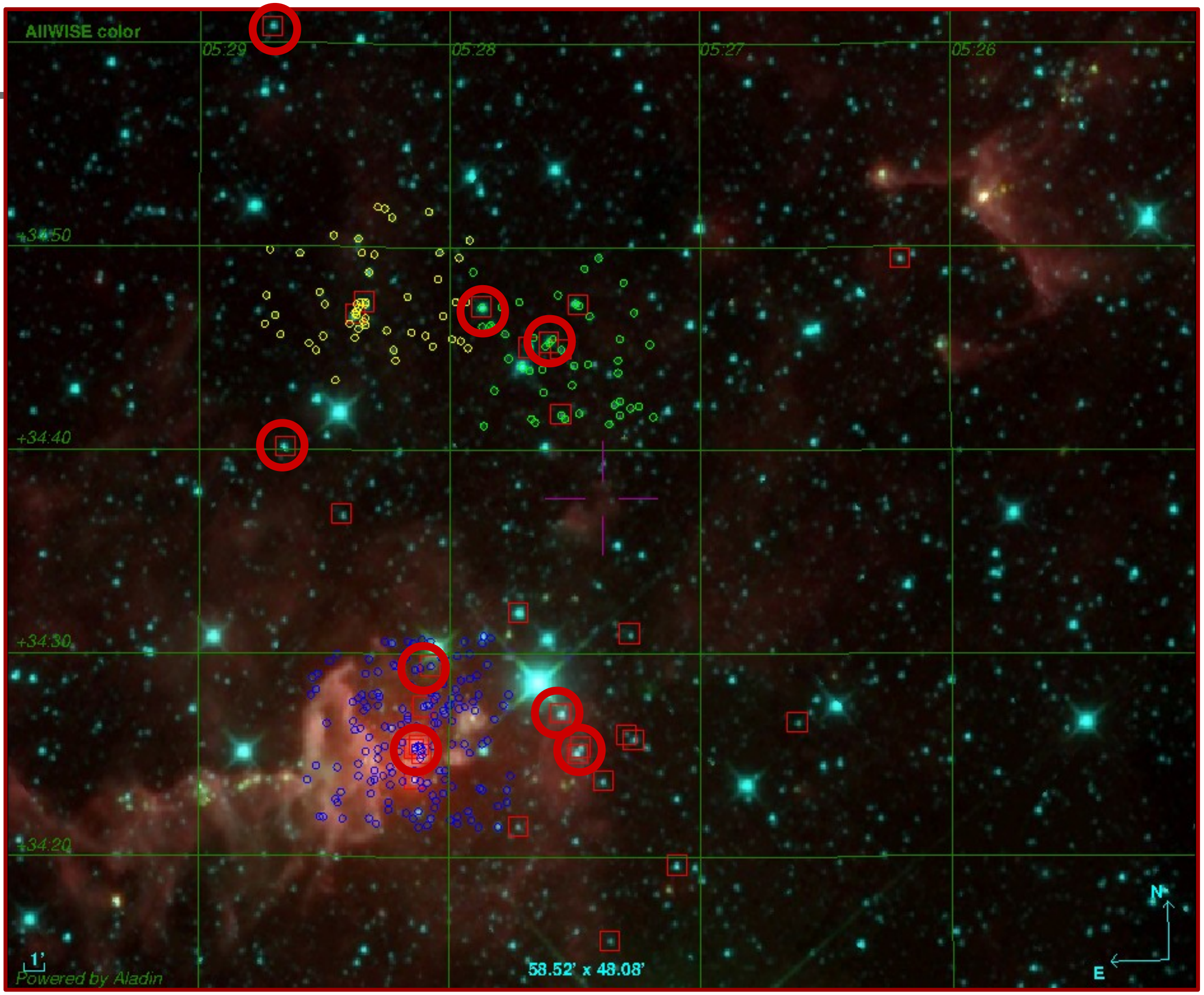


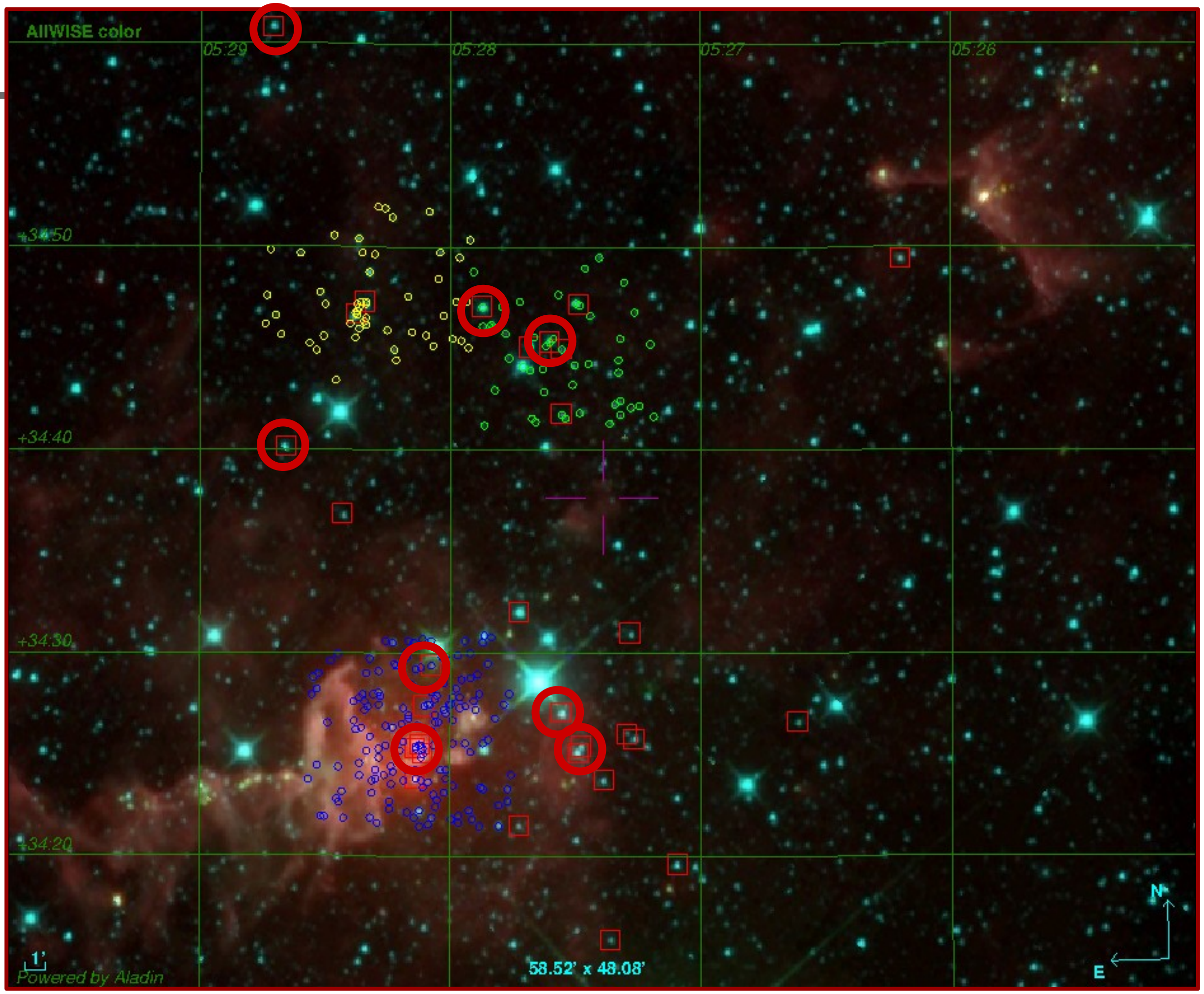
WISE three-colour image (W1, W2, W3)

Stock 8

Extended association with >30 OB stars

Marco et al., in prep.

$\ell = 173^{\circ}$
$d = 2$ kpc



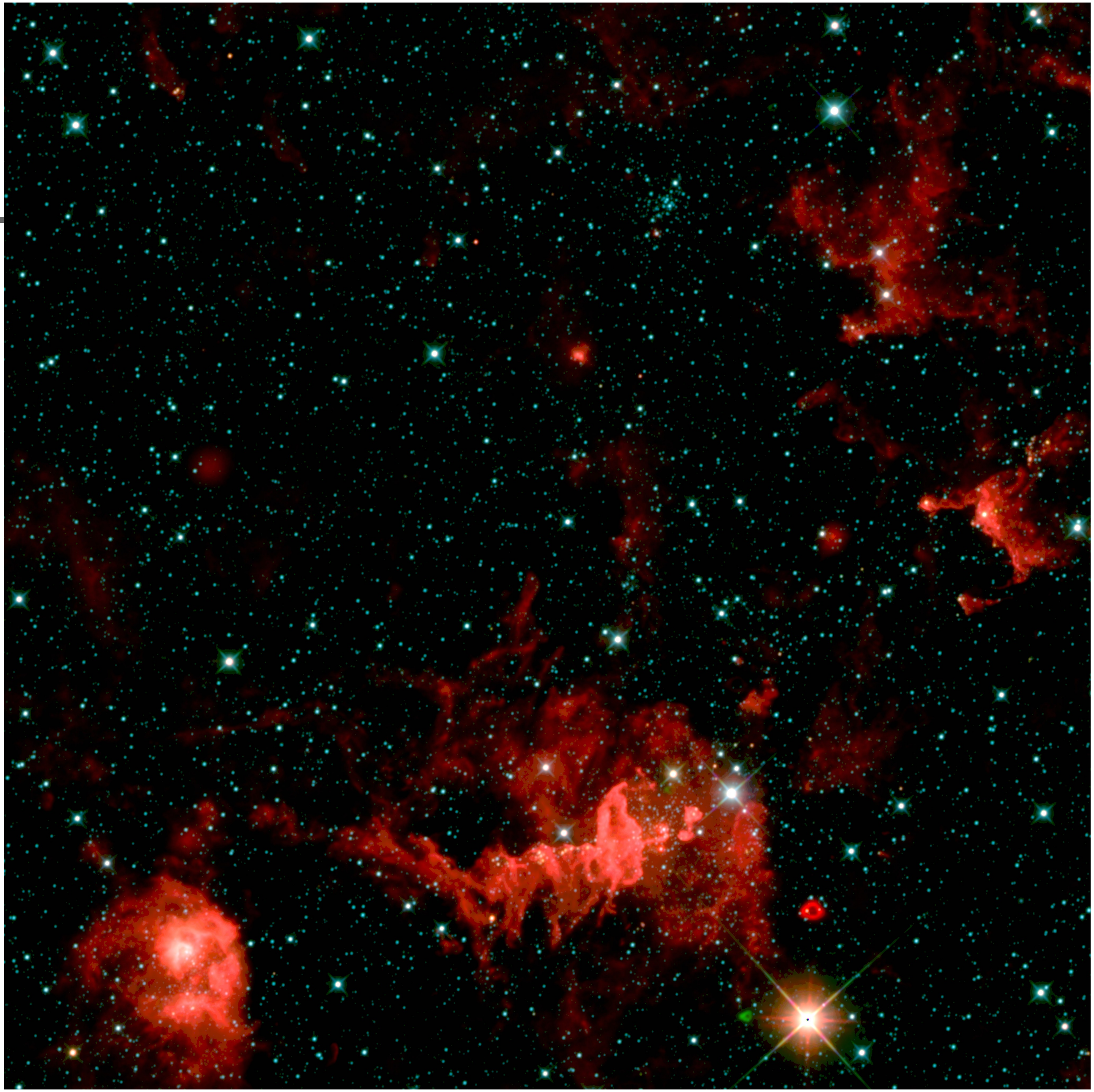
WISE three-colour image (W1, W2, W3)

Stock 8

Part of an even bigger structure?

$\ell = 173^{\circ}$
$d = 2$ kpc

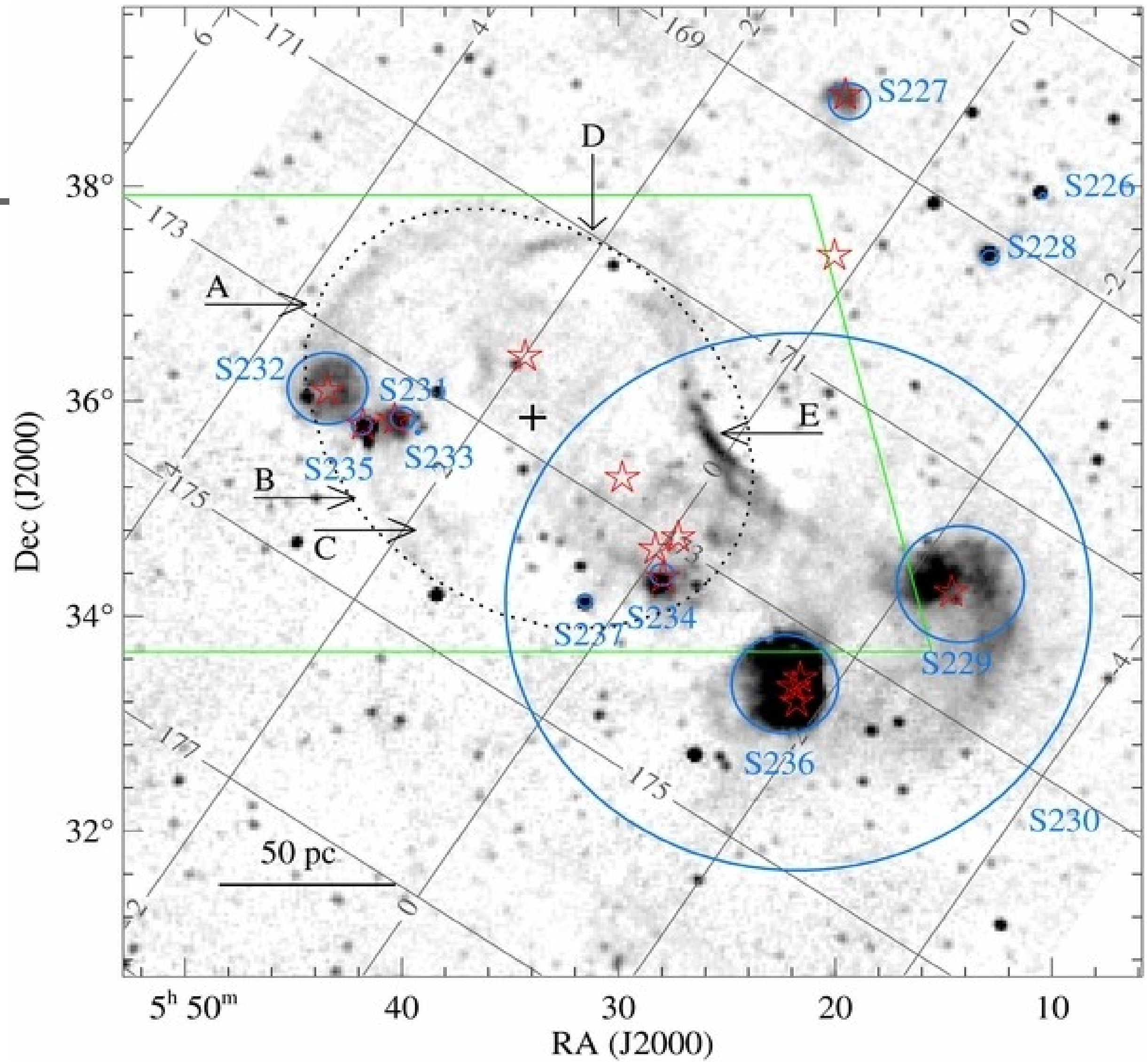
WISE three-colour image (W1, W2, W3)



Stock 8

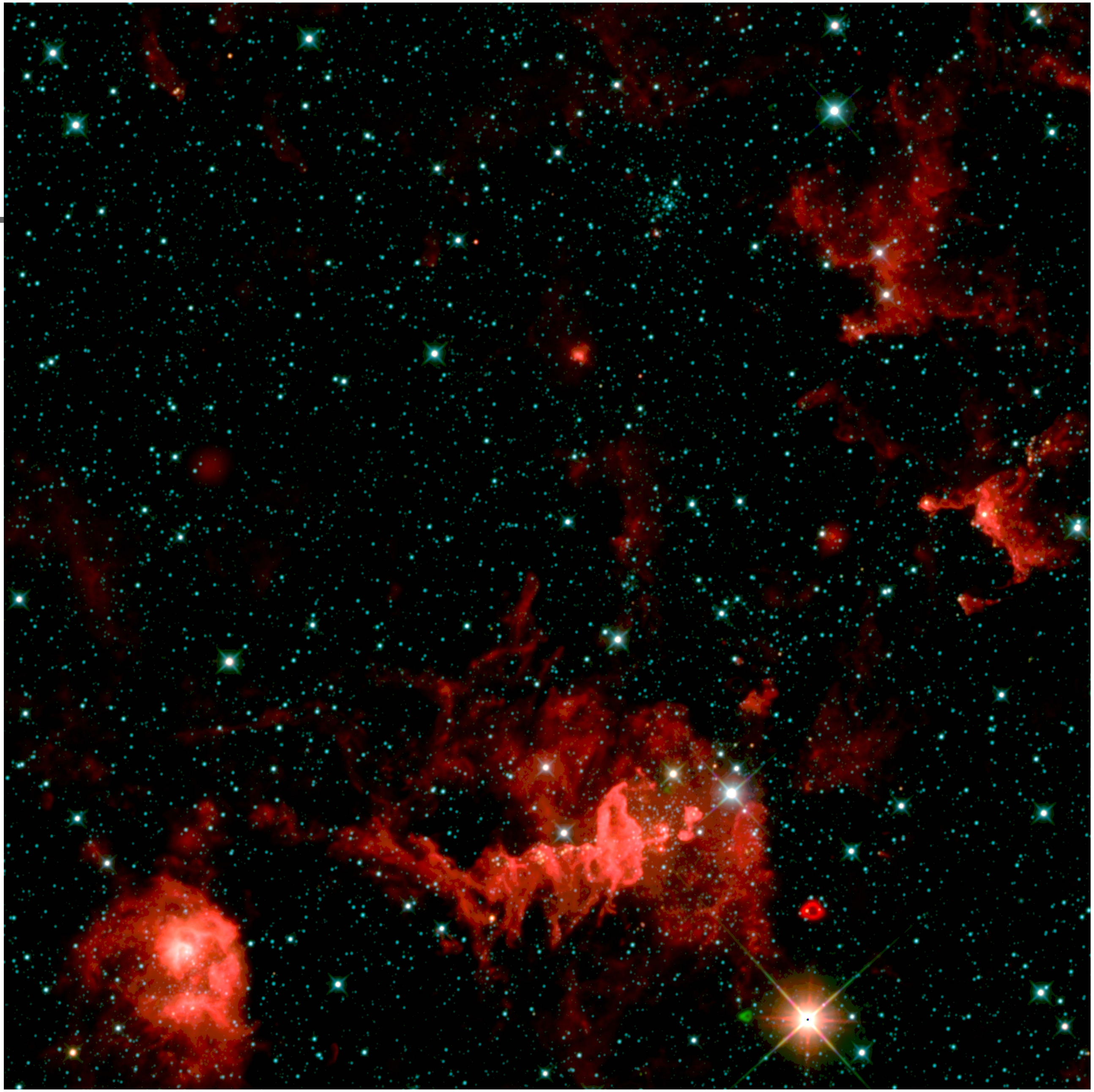
Effelsberg 11 cm radio continuum

H I observations with Arecibo telescope show a coherent structure with similar v_{LSR} velocities



An Old Supernova Remnant within an H II Complex at ℓ~173°: FVW 172.8+1.5
Kang et al. 2012, AJ 143, 75

Stock 8



Part of an even bigger structure?

$\ell = 173^{\circ}$
$d = 2$ kpc

WISE three-colour image (W1, W2, W3)

NGC 1491

H II region Sh2-206

Radio study
Deharveng et al. 1976, A&A 48, 63

$\ell = 151^\circ$
$d \sim 3.5$ kpc

Image by Peter Jackson and Rena Smith/Adam Block/NOAO/AURA/NSF

NGC 1491

H II region Sh2-206

$\ell = 151^{\circ}$
$d \sim 3.5$ kpc

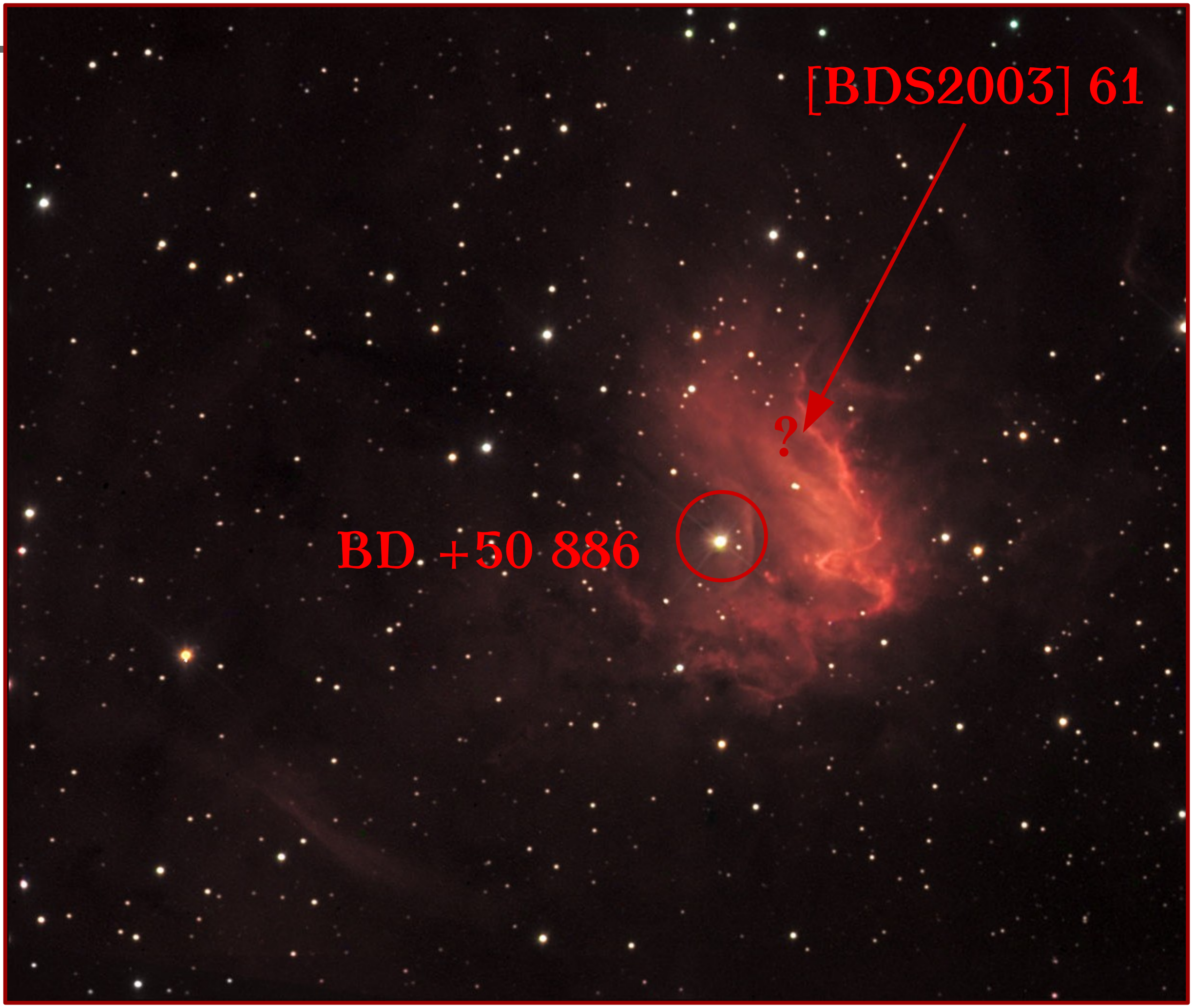
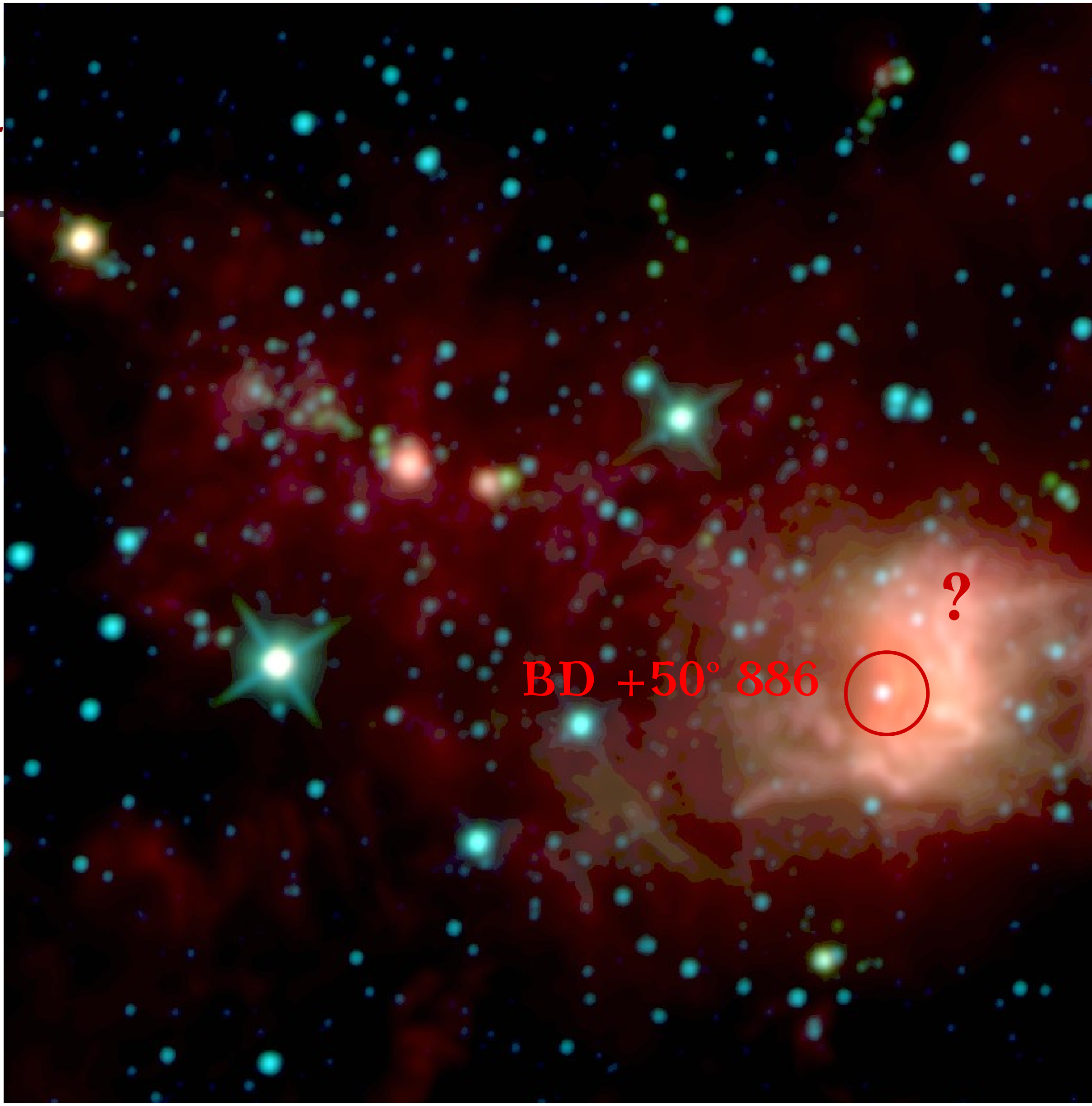


Image by Peter Jackson and Rena Smith/Adam Block/NOAO/AURA/NSF

NGC 1491

H II region Sh2-206

$\ell = 151°$
$d \sim 3.5$ kpc



WISE three-colour image (W1, W2, W3)

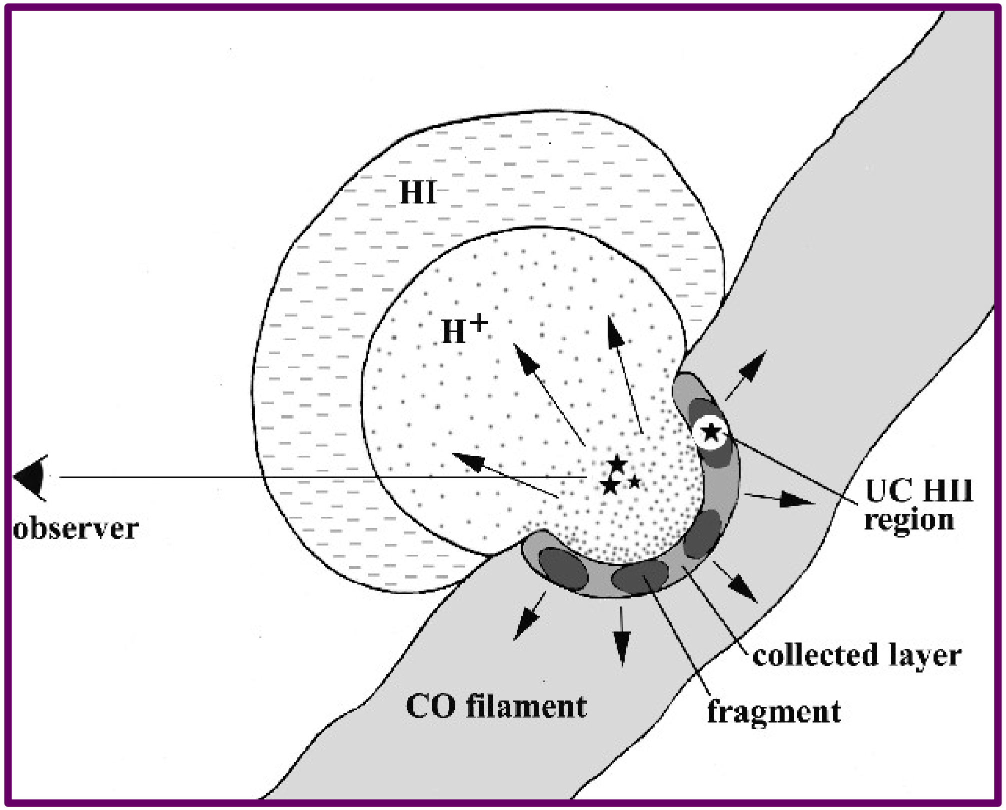
NGC 1491

Similar case Sh2-212

O-type supergiant + some B-types
Triggered formation on the rim
Deharveng et al. 2008, A&A 482, 585

$\ell = 155^{\circ}$
$d \sim 6$ kpc

WISE three-colour image
(W1, W2, W3)



NGC 2467

Not considered a real "cluster"

Sh2-321

$\ell = 243^{\circ}$
$d \sim 6$ kpc

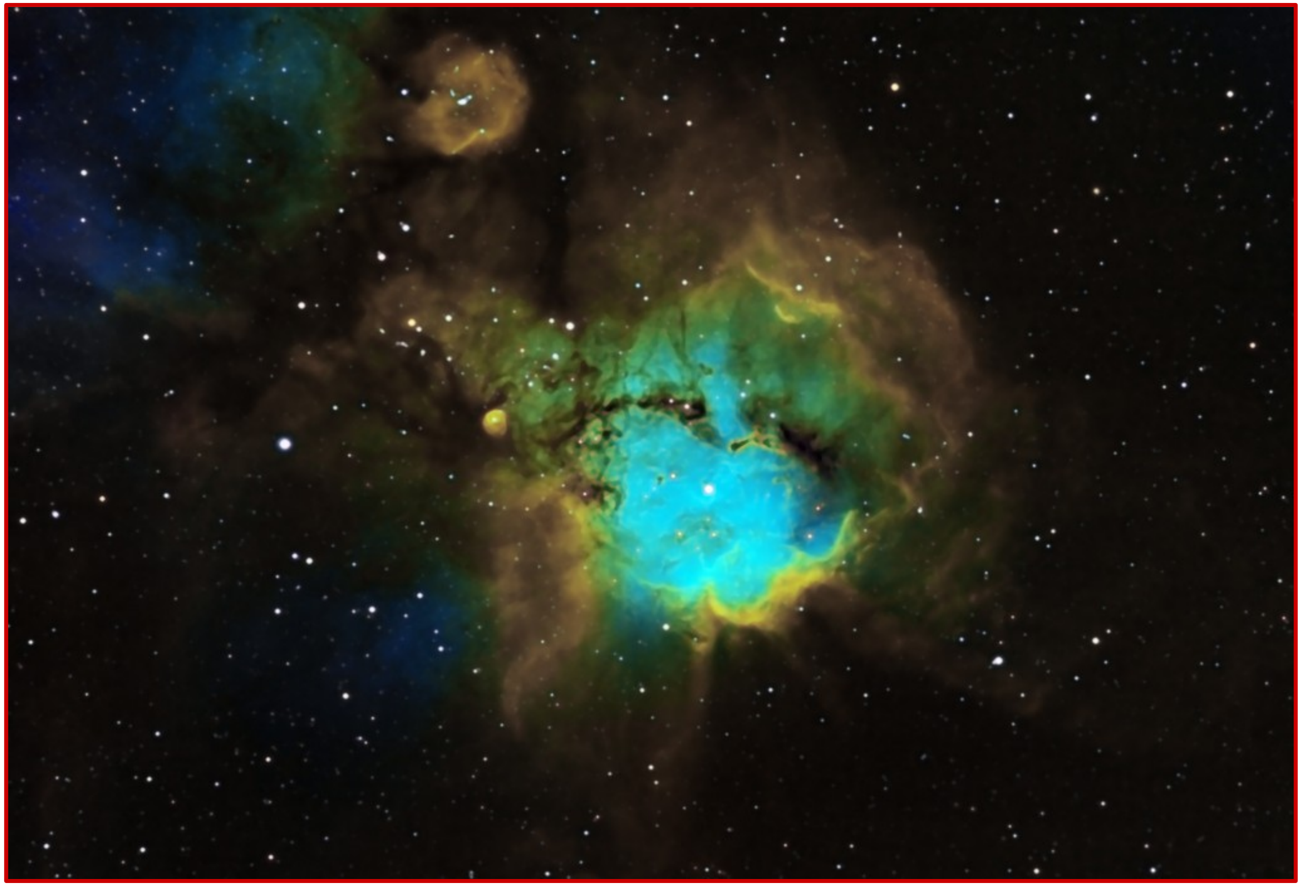


Image by Dale Libenberg (Hα, [O III], [Si II])

NGC 2467

Not considered a real "cluster"

$\ell = 243^{o}$
$d \sim 6$ kpc

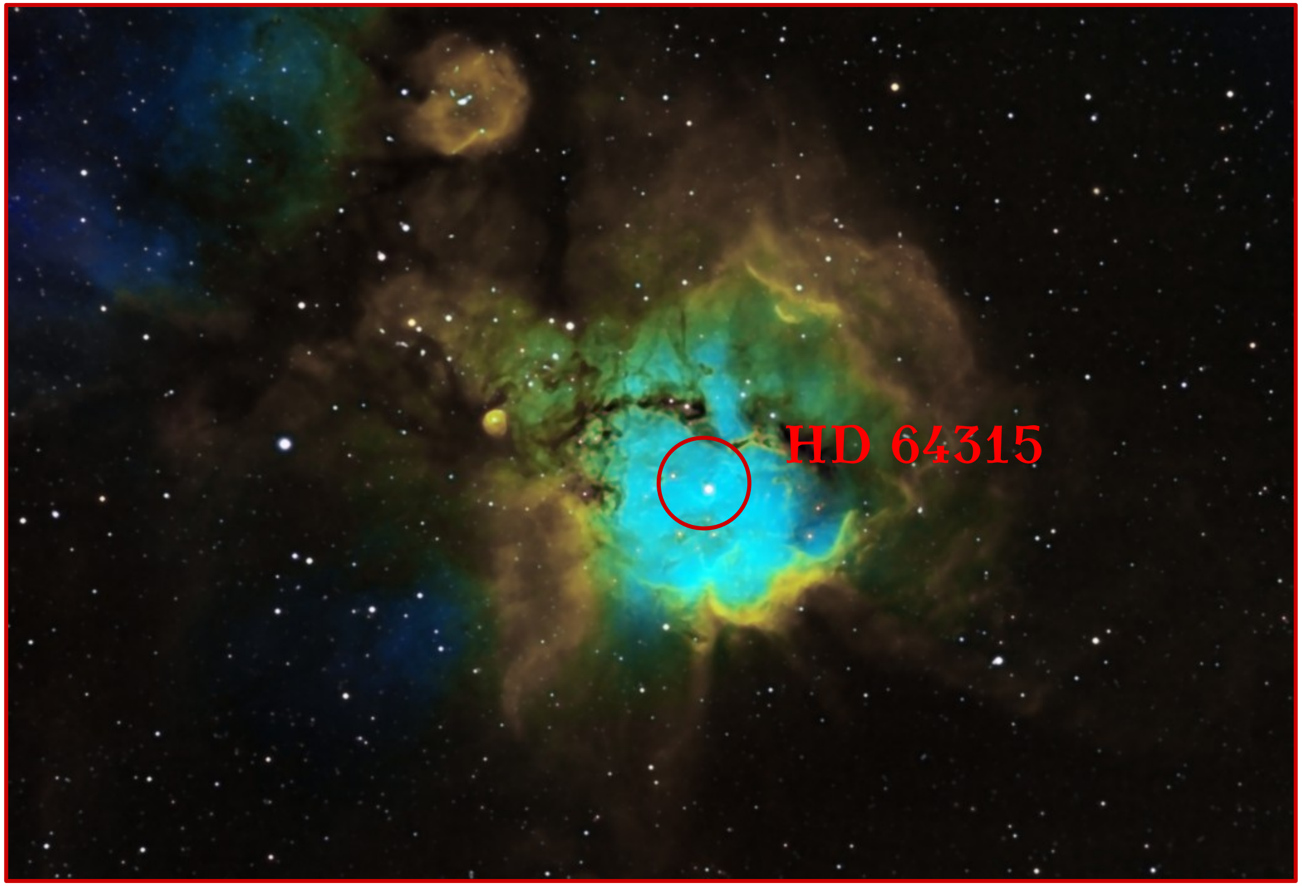


Image by Dale Libenberg ($H\alpha$, [O III], [Si II])

NGC 2467

Not considered a real "cluster"

$\ell = 243^{o}$
$d \sim 6$ kpc

HST image
NASA, ESA and Orsola De Marco (Macquarie University)

(*VRR*)

NGC 2467

Not considered a real "cluster"

$\ell = 243^{\circ}$
$d \sim 6$ kpc

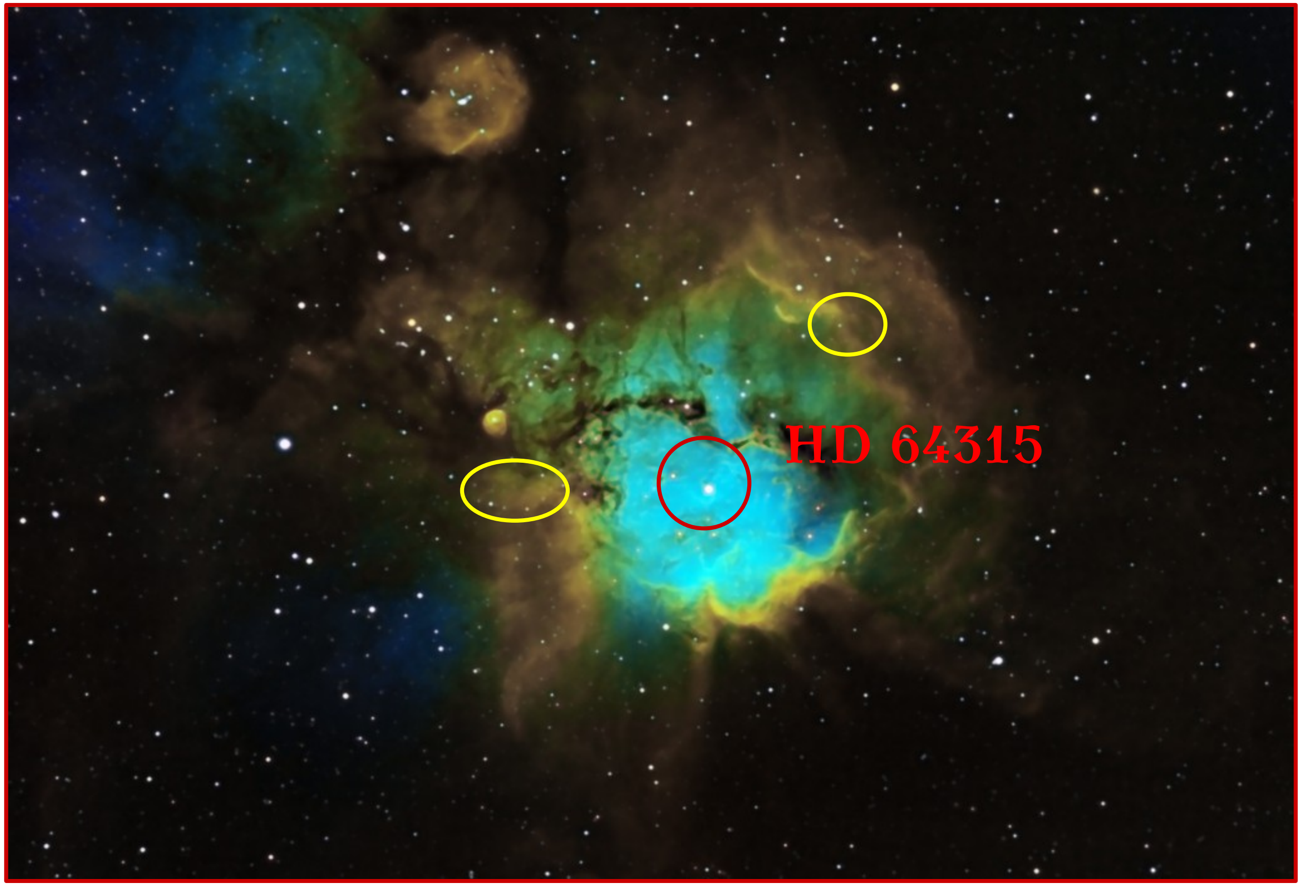


Image by Dale Libenberg (Hα, [O III], [Si II])

NGC 2467

Not considered a real "cluster"

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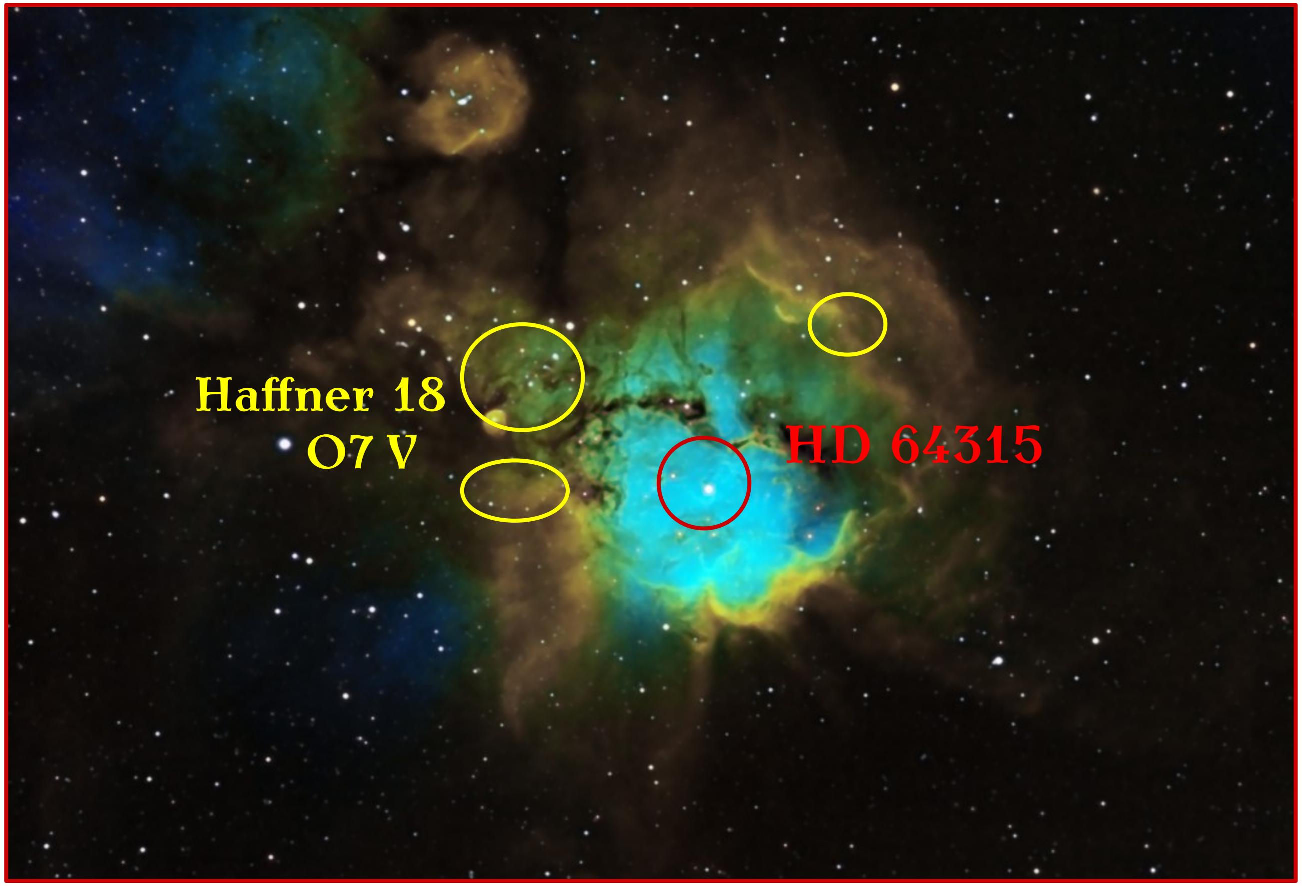
Image by Dale Libenberg
(Hα, [O III], [Si II])



NGC 2467

Haffner 18

Two clusters, one at 11 kpc!!

Vazquez et al. 2010, A&A 511, A38

d ~ 6 kpc

Munari et al. 1998, MNRAS 297, 867

FitzGerald & Moffat 1976, A&A 50, 44

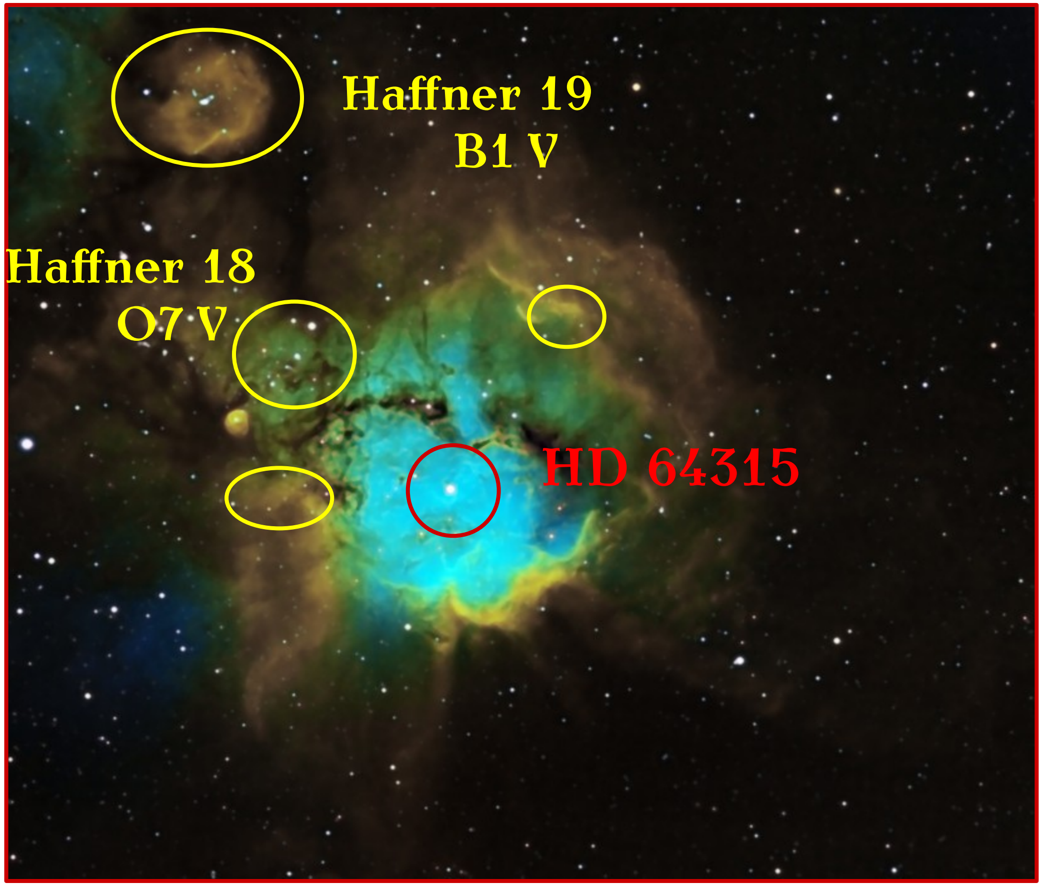


Image by Dale Libenberg
(Hα, [O III], [Si II])

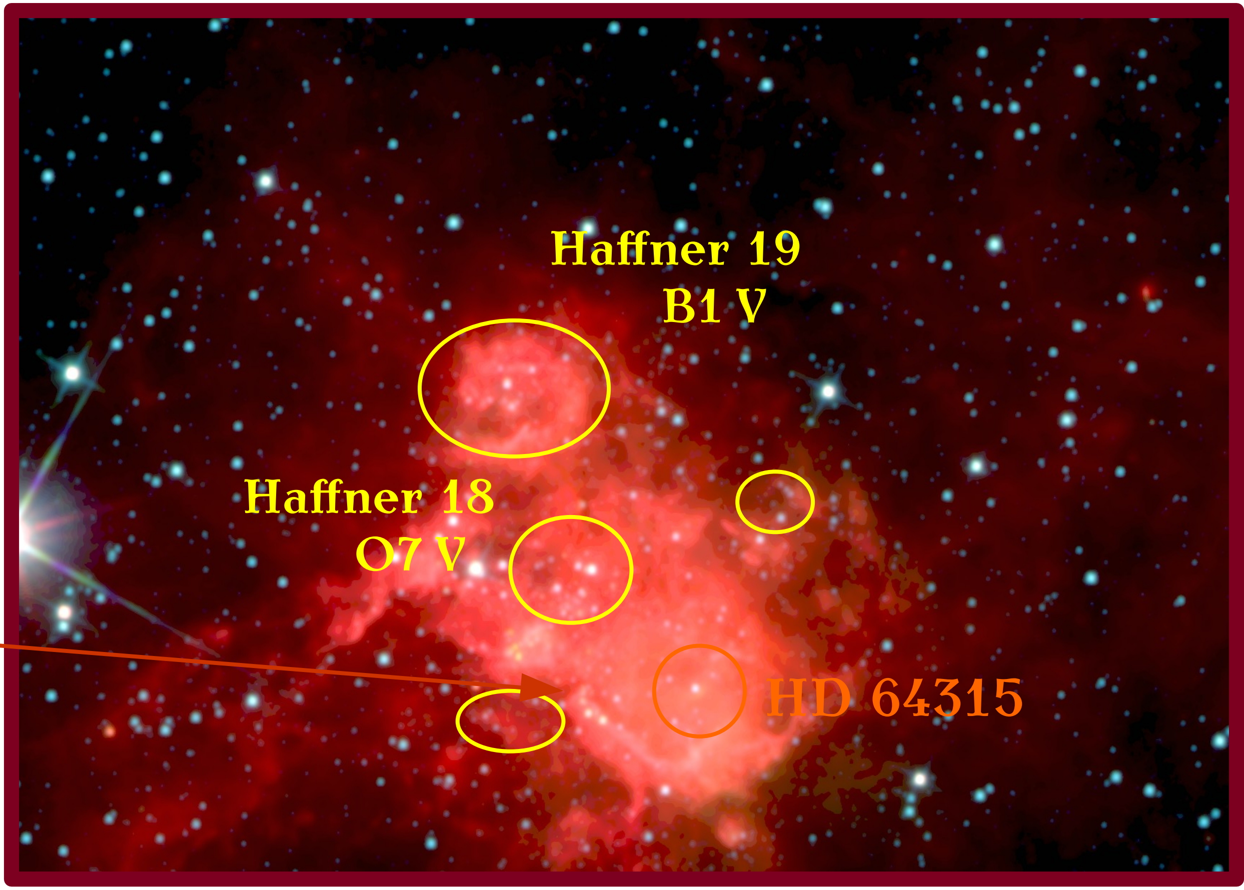
NGC 2467

Spitzer analysis

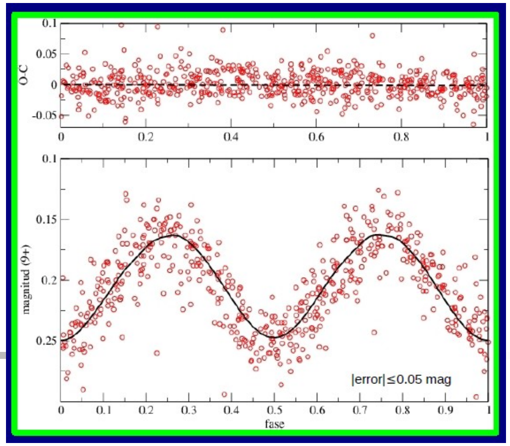
Single star forming region

Sneider et al. 2009, ApJ 700, 506

embedded cluster



HD 64315



- Classified as O6 Vnn, but SB2 (**Solivella & Niemela 1986, RmxAA 12, 188**)
- Now given as O5.5 Vz+O7 V (**Sota et al. 2014, ApJS 211, 10**)
- Resolved by interferometry into 2 (**Mason et al 2009, AJ 137, 3358**; **Aldoretta et al. 2014, AJ, in press**) or 3 (**Tokovinin et al. 2010, AJ 139, 743**) visual components
- Comprehensive spectroscopic campaign with FEROS (R = 48 000) during 2006+
- There are at least 2 SB2 systems in HD 64315, an EB with P_{orb}=1.0 d and another system with P_{orb}=2.7 d (**Lorenzo et al. 2010, ASPC 435, 409**; **Lorenzo et al., in prep.**)
- Is such a system an excellent ejector (cf. **Pflamm-Altenburg & Kroupa, 2006, MNRAS 373, 259**) or does it form in isolation?

Alicante 1

Small cluster at ~4 kpc

(Negueruela & Marco 2008, A&A 492, 441)

$\ell = 146^{\circ}$
$d \approx 4$ kpc

- Four OB stars
- Only a handful of B3-8 stars

False colour image from NOT/ALFOSC images

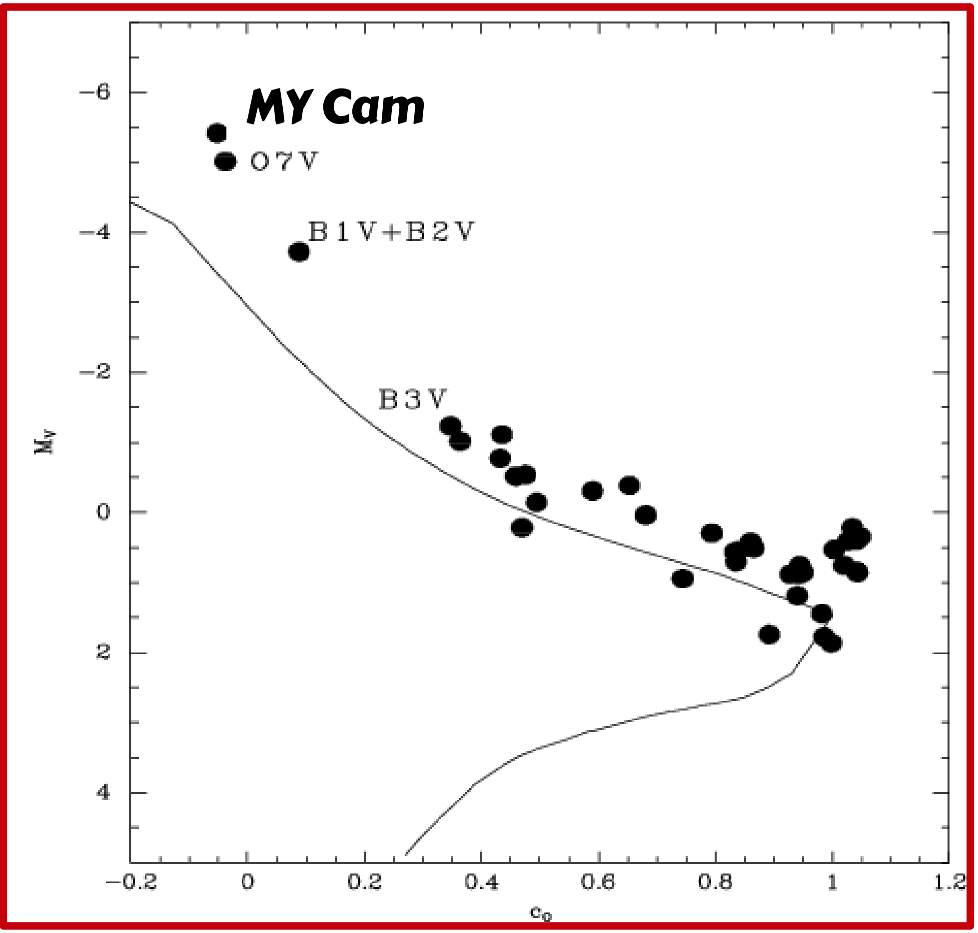
Alicante 1

Small cluster at ~4 kpc

(Negueruela & Marco 2008, A&A 492, 441)

$\ell = 146°$

$d \approx 4$ kpc



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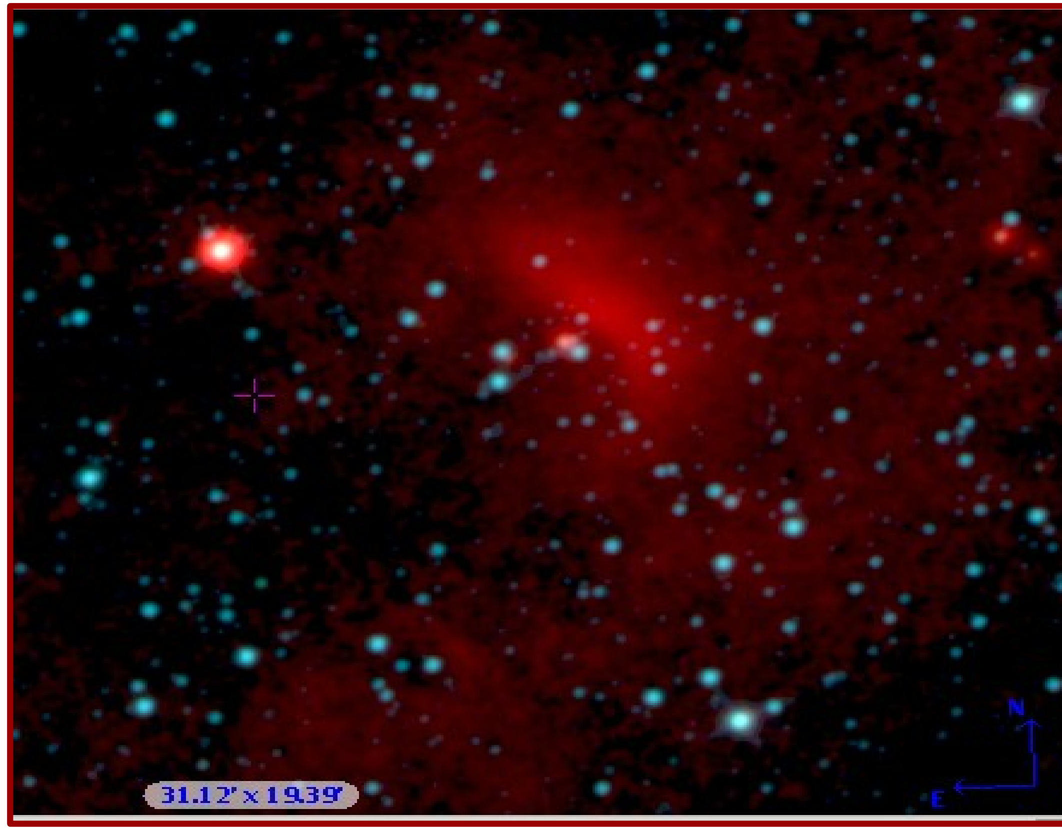

WISE three-colour image (W1, W2, W4)

$\ell = 146^{\circ}$
$d \approx 4$ kpc

- Four OB stars
- Only a handful of B3-8 stars

Alicante 1

Small cluster at ~4 kpc

(Negueruela & Marco 2008, A&A 492, 441)

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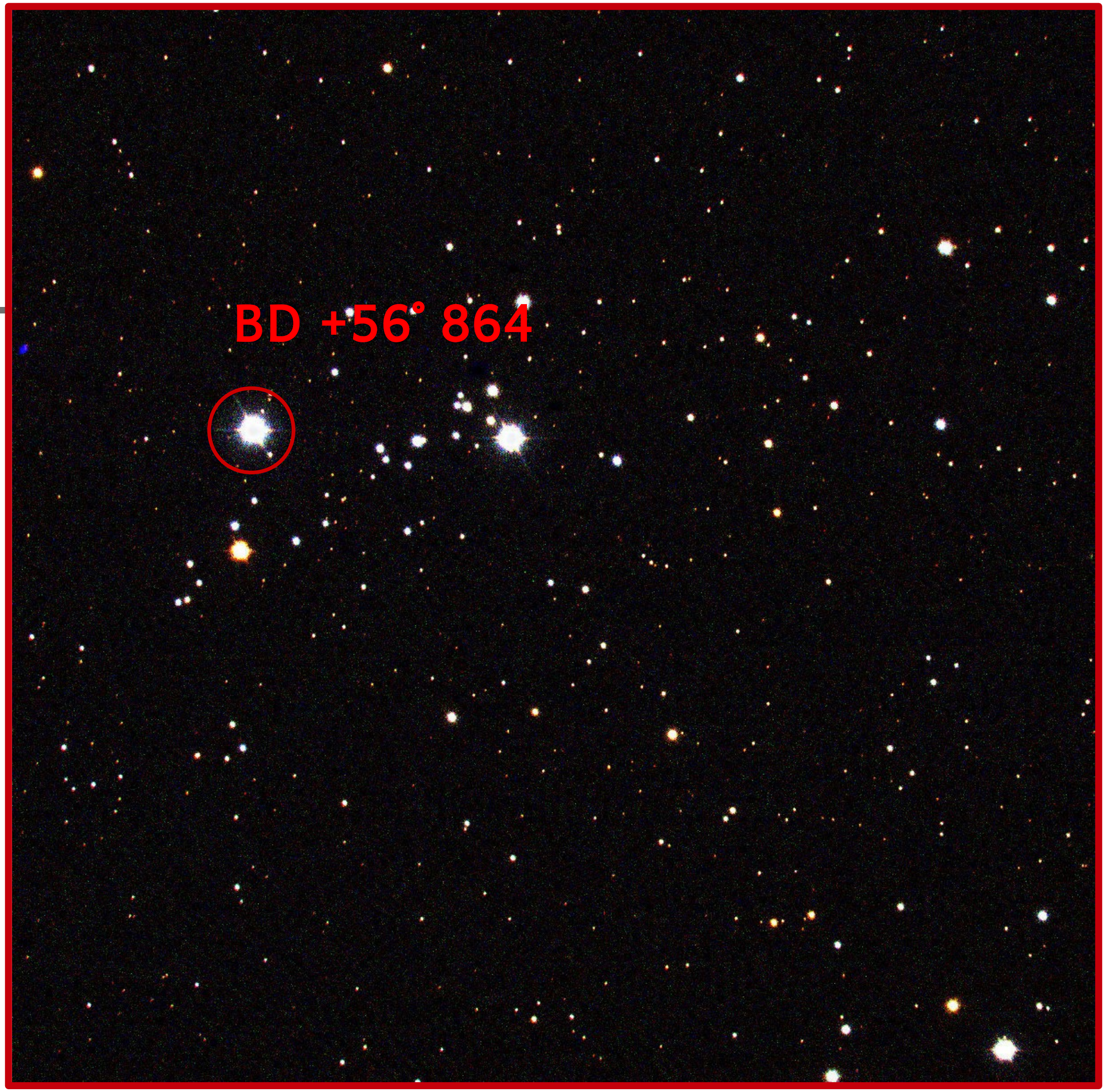
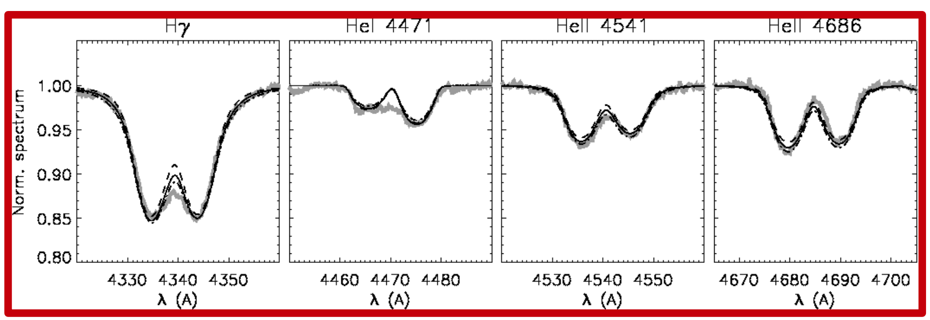
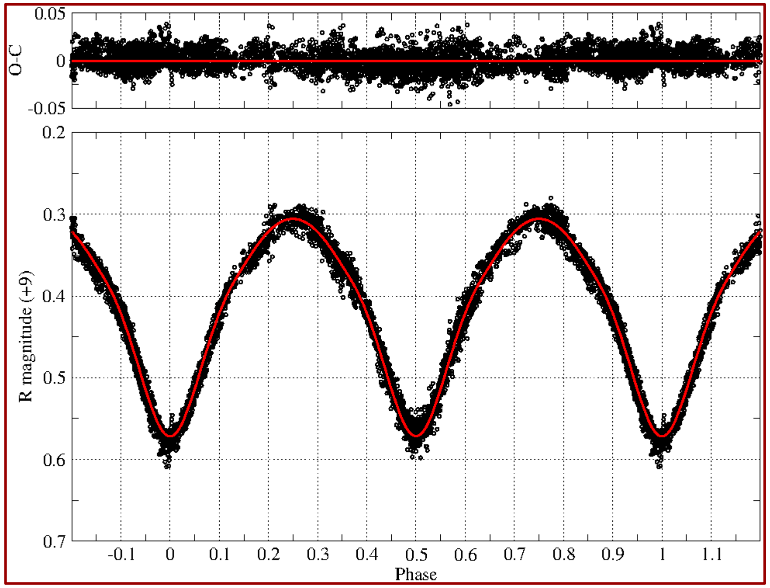


False colour image from NOT/ALFOSC images

BD +56°864 = MY Cam

- Classified as O6 Vnn
- Eclipsing binary
- Observed with the 2.2 m at Calar Alto + FOCES plus photometry with small telescopes.





BD +56°864 = MY Cam

Lorenzo et al. 2014, A&A, in press

- Orbital period 1.2 d
- Masses 32 $M_\odot$ and 38 $M_\odot$, compact stars
  - ZAMS
  - homogeneous evolution
- Parameters permit merger on the ZAMS (Wellstein et al. 2001; A&A 369, 939)
- Prime example of merger to form very massive star (cf. Banerjee et al. 2012; MNRAS 426, 1461)

Bochum 1

Dispersed group of early-type stars

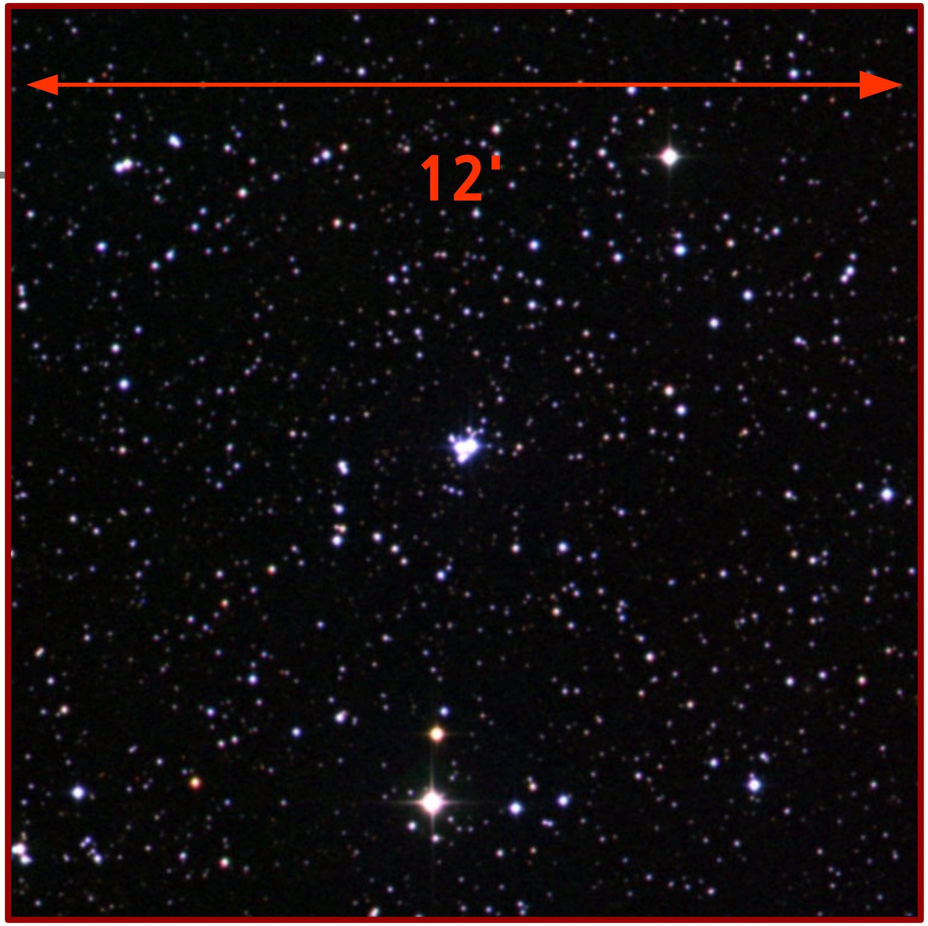
(Moffat & Vogt 1975, A&AS 20, 85)

No obvious cluster sequence

(Fitzsimmons 1993, A&AS 99, 15)

$\ell = 192^{o}$

$d \sim 4$ kpc



False colour image from DSS2 images

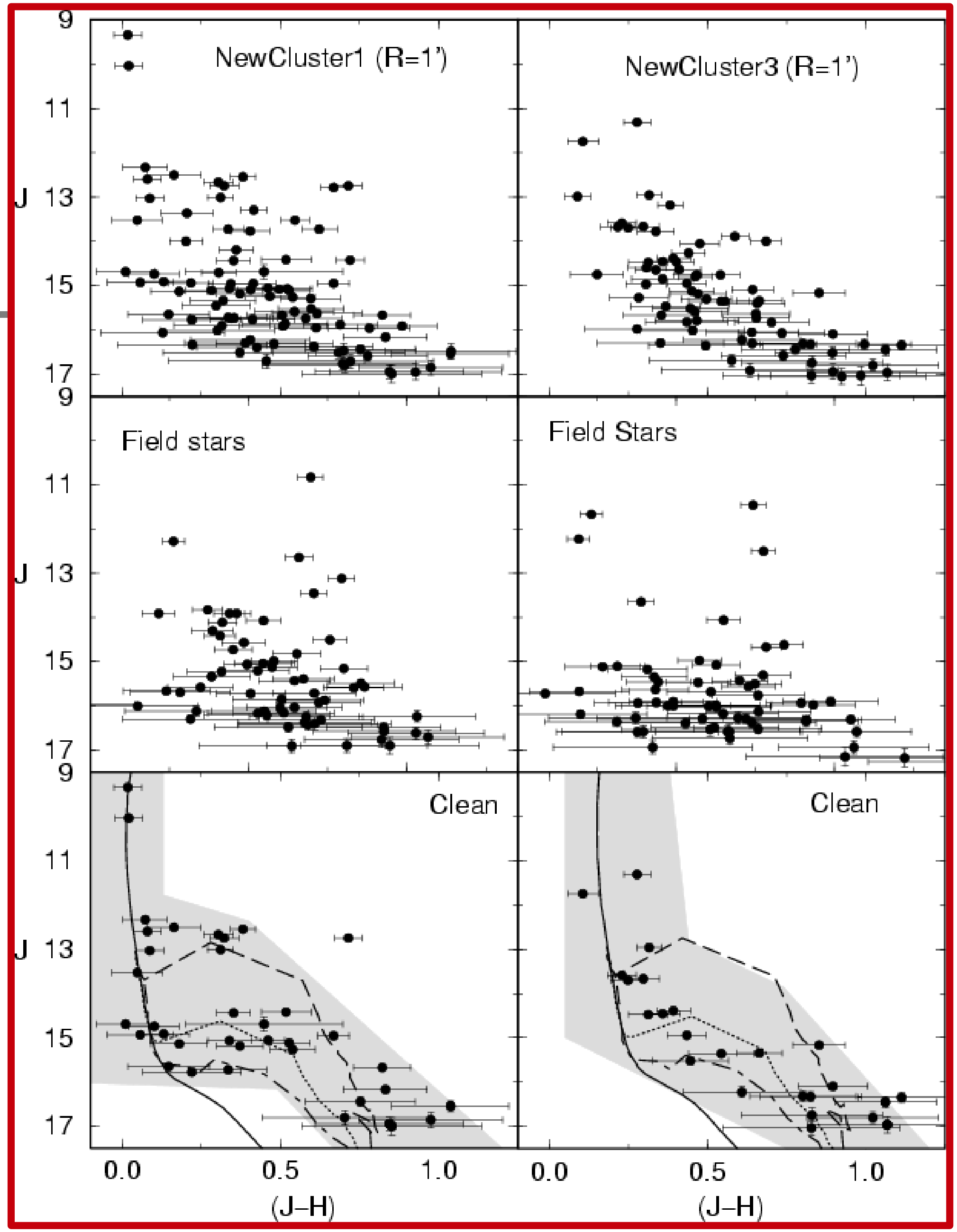
Bochum 1

Borderline between a young star cluster and a small stellar association

(Bica et al. 2008, A&A 489, 1129)

Two small (minimal) clusters

Age ~ 9 Myr
d ~ 4 kpc (DM =13.1)



Summary

- High-mass star formation in the outer Milky Way is characterised by dispersed clusters and small groups of stars.
- Evidence for sequential (triggered?) star formation is widespread.
- There is a very high incidence of the earliest spectral types, sometimes found in very small clusters: observational bias? (cf. **Weidner et al. 2010, MNRAS 401, 275**; **Popescu & Hanson 2014, ApJ 780, 27**)
- Excellent ground to test our knowledge, but spectroscopy always necessary.

High-mass star formation in the outer Milky Way

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