

Search for star-forming region in the extreme outer Galaxy with WISE data

Natsuko Izumi ¹

Naoto Kobayashi ¹, Chikako Yasui ¹, Alan T. Tokunaga
², Masao Saito ^{3,4}, Satoshi Hamano ¹

1. University of Tokyo

2. University of Hawaii

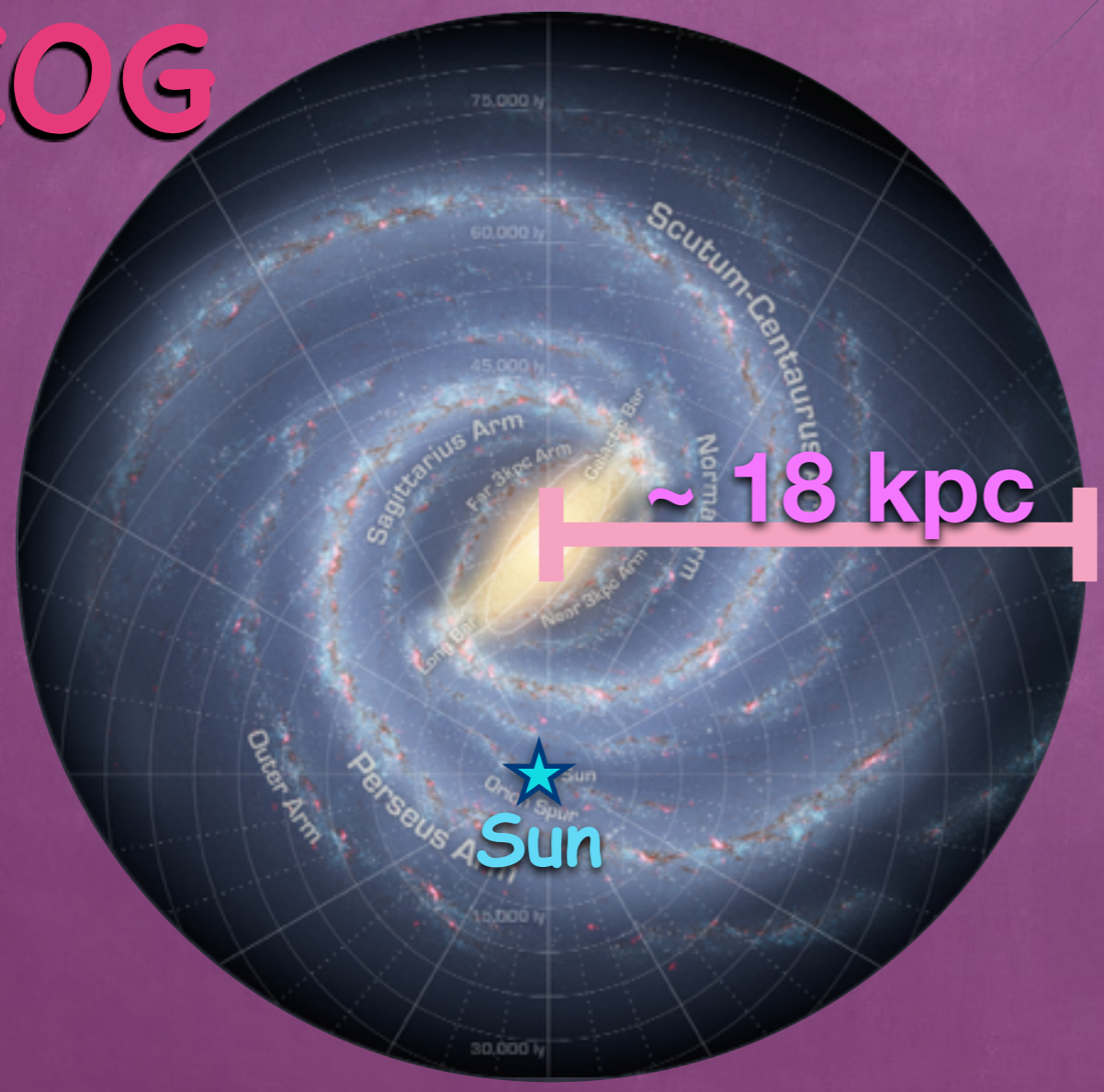
3. Nobeyama Radio Observation, NAOJ, Japan

4. (SOKENDAI)Graduate University for Advanced Studies, Japan

Introduction I: EOG

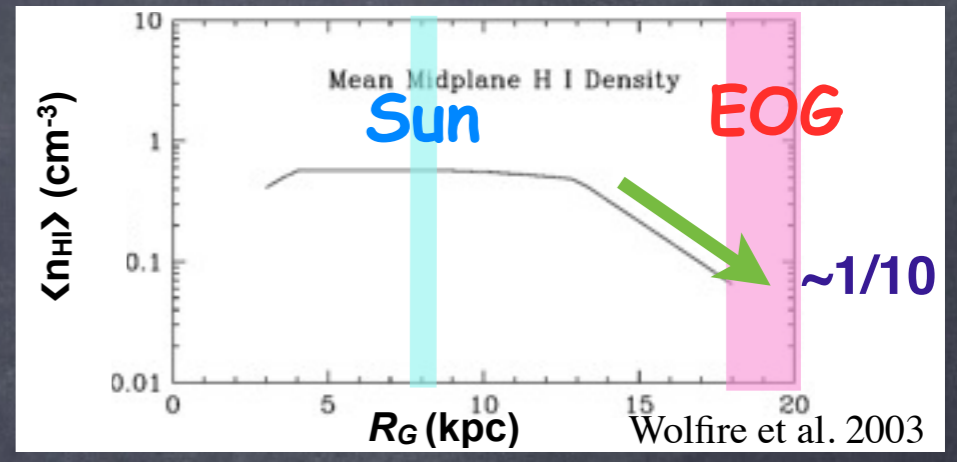
■ Extreme outer galaxy (EOG) : $R_G \cong \sim 18$ kpc

EOG

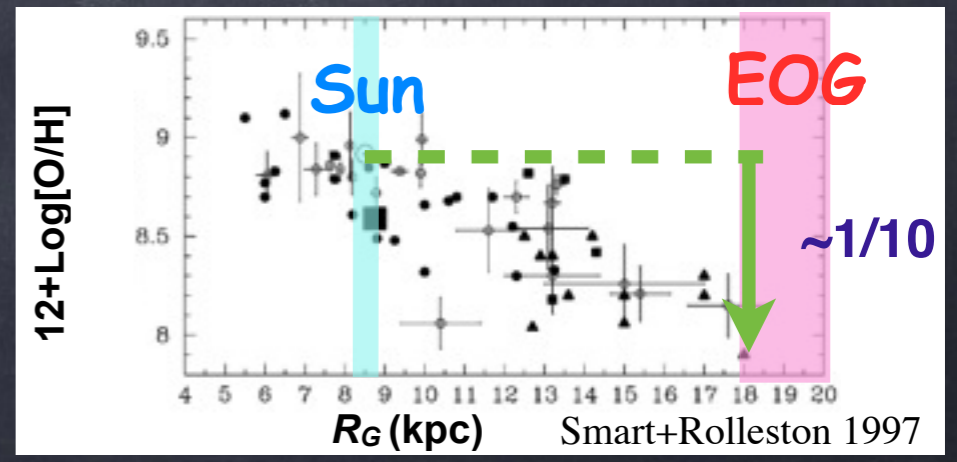


- Environment

1. Small or no perturbation from the spiral arm
2. Low gas density



3. Low metallicity



Introduction I : EOG

■ Why are we interested in the EOG ?

1. Unexplored region

→ Determine the size and shape of our Galaxy

2. **Excellent laboratory** for studying star-forming processes in **low-density** and **low-metallicity** environment

3. Similar characteristics with dwarf galaxy and **the early phase of the formation of our Galaxy**

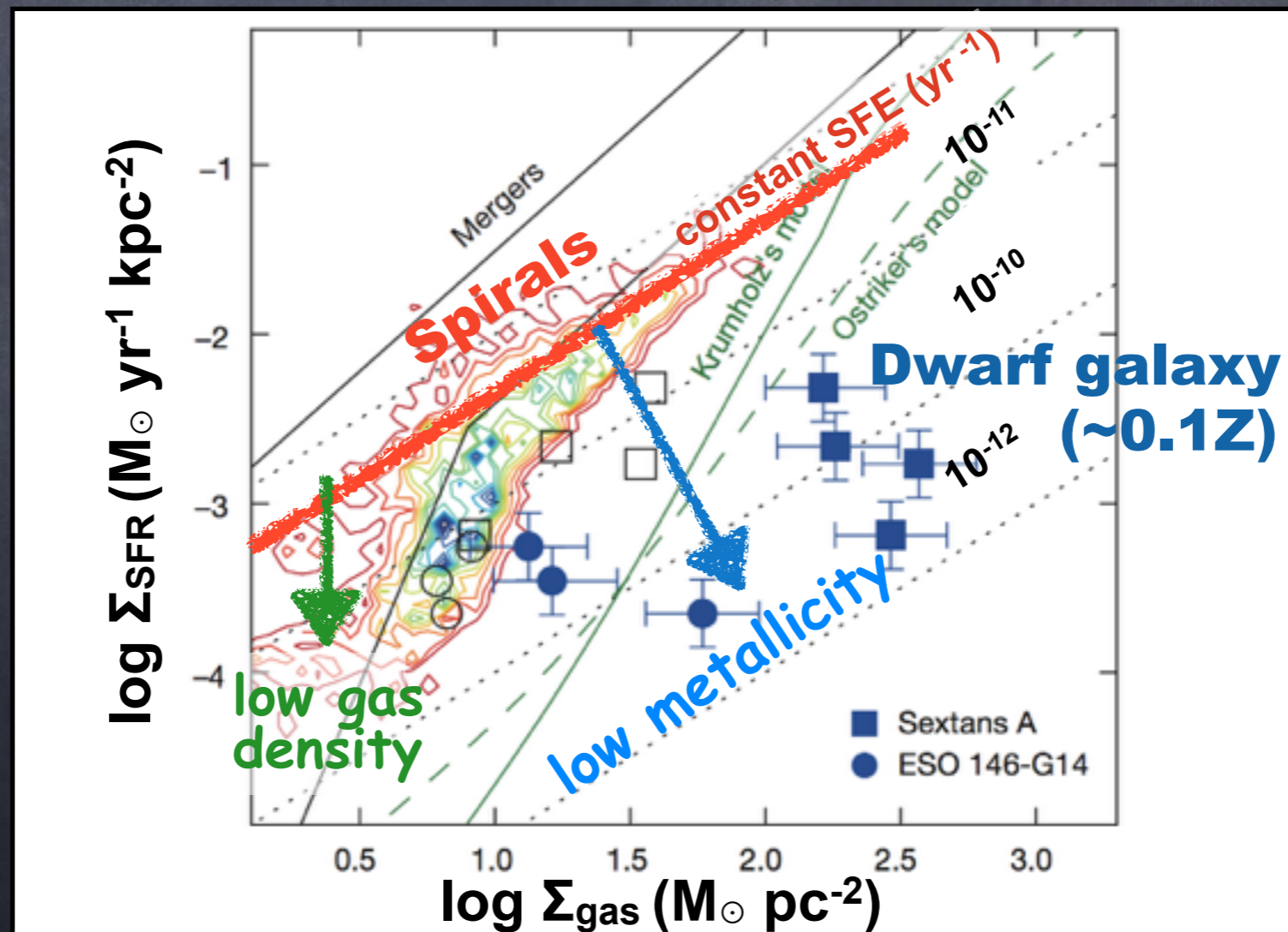
Ferguson et al. 1998, Kobayashi et al. 2008

We may be able to **directly observe “galaxy formation processes”** in **unprecedented detail** at much closer distance than High-z galaxies

Introduction II : Our Study

Our objective

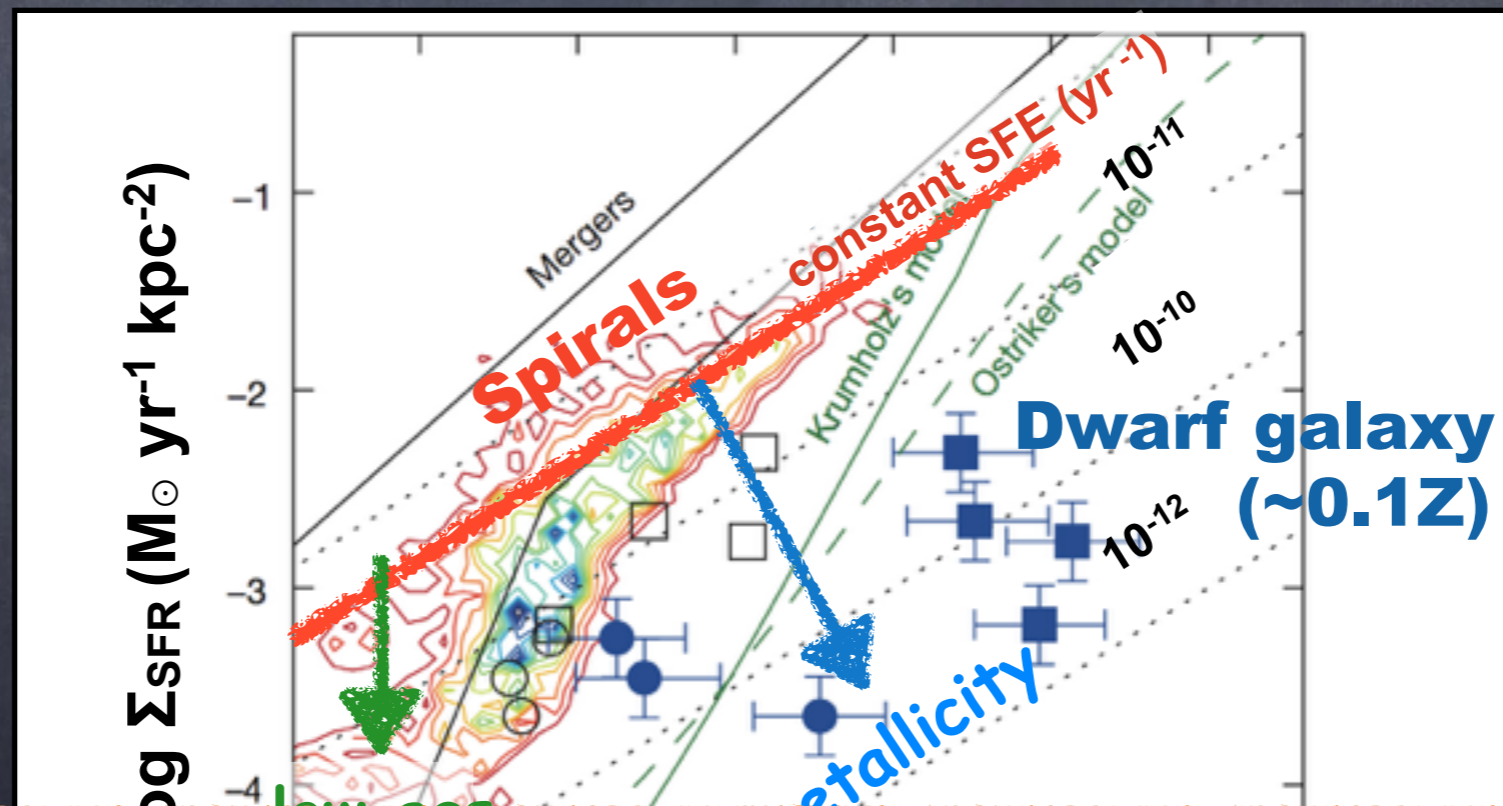
- Examine star-formation properties in the EOG
 - Star formation rate (SFR)
 - Star formation efficiency (SFE)
 - ▶ SFR/SFE appear to decrease significantly under low-density / low-metallicity environments



Introduction II : Our Study

■ Our objective

- Examine star-formation properties in the EOG
 - Star formation rate (SFR)
 - Star formation efficiency (SFE)
 - ▶ SFR/SFE appear to decrease significantly under low-density / low-metallicity environments



Should confirm if such trend is present in our Galaxy
in molecular cloud scale (pc scale)

Introduction II : Our Study

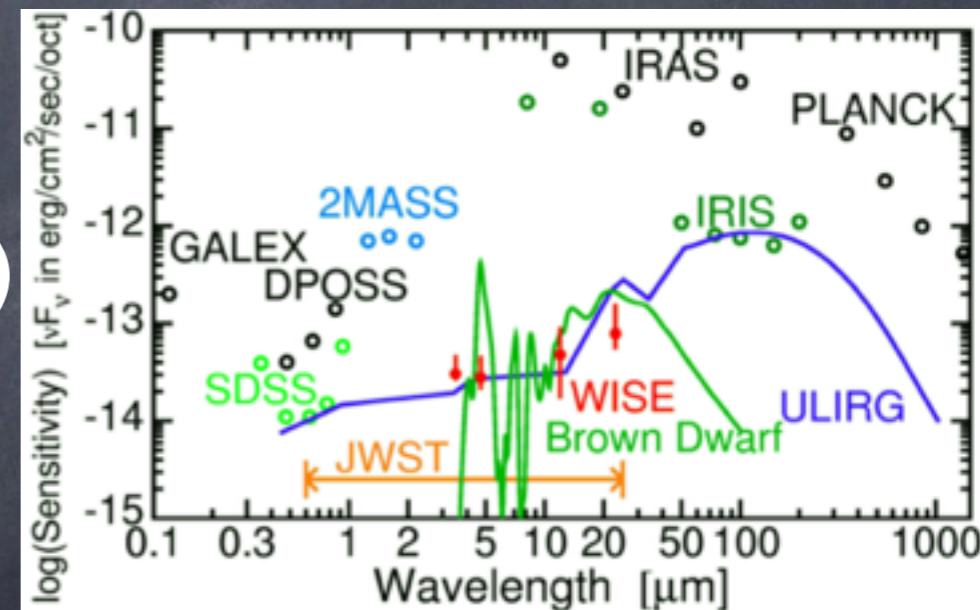
■ Search for young star-forming regions in the EOG (w/ embedded clusters)

- **Past studies**

- ▶ Mostly based on IRAS color e.g., Brand and Wouterloot 1995, Snell et al. 2002
- ▶ Only few star-forming regions are confirmed in the EOG
(Sensitivity-limited ?) Kobayashi & Tokunaga 2000 Brand & Wouterloot 2007

- **WISE**

- ▶ Great increase in sensitivity
(100 times more sensitive than *IRAS*)
- ▶ Very high potential in searching for distant star-forming regions



Fabinsky, 2006

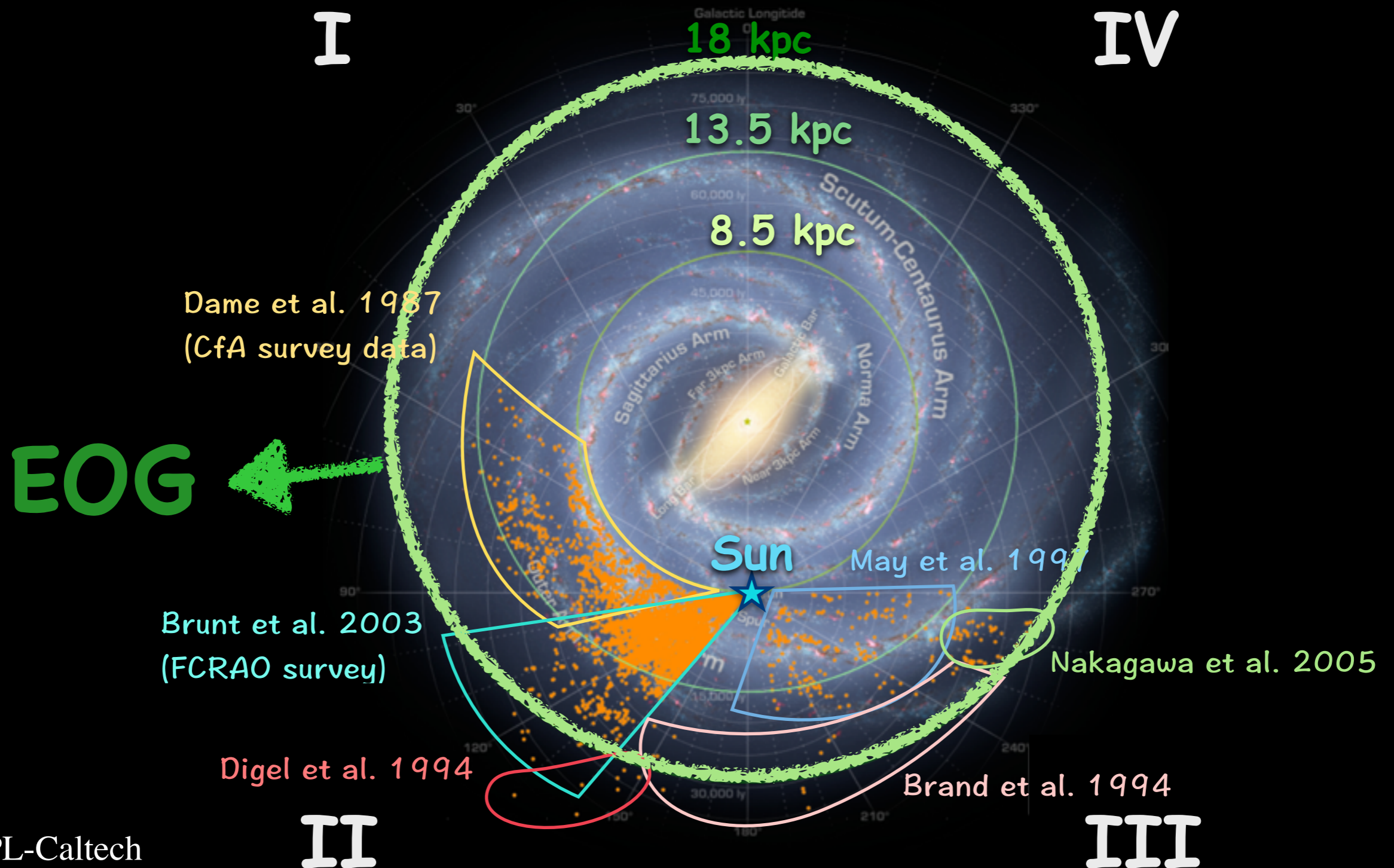
- **Our target : CO molecular clouds**

- ▶ There are many surveys of CO molecular clouds in recent years

Introduction II : Our Study

■ Search for young star-forming regions in the EOG (w/ embedded clusters)

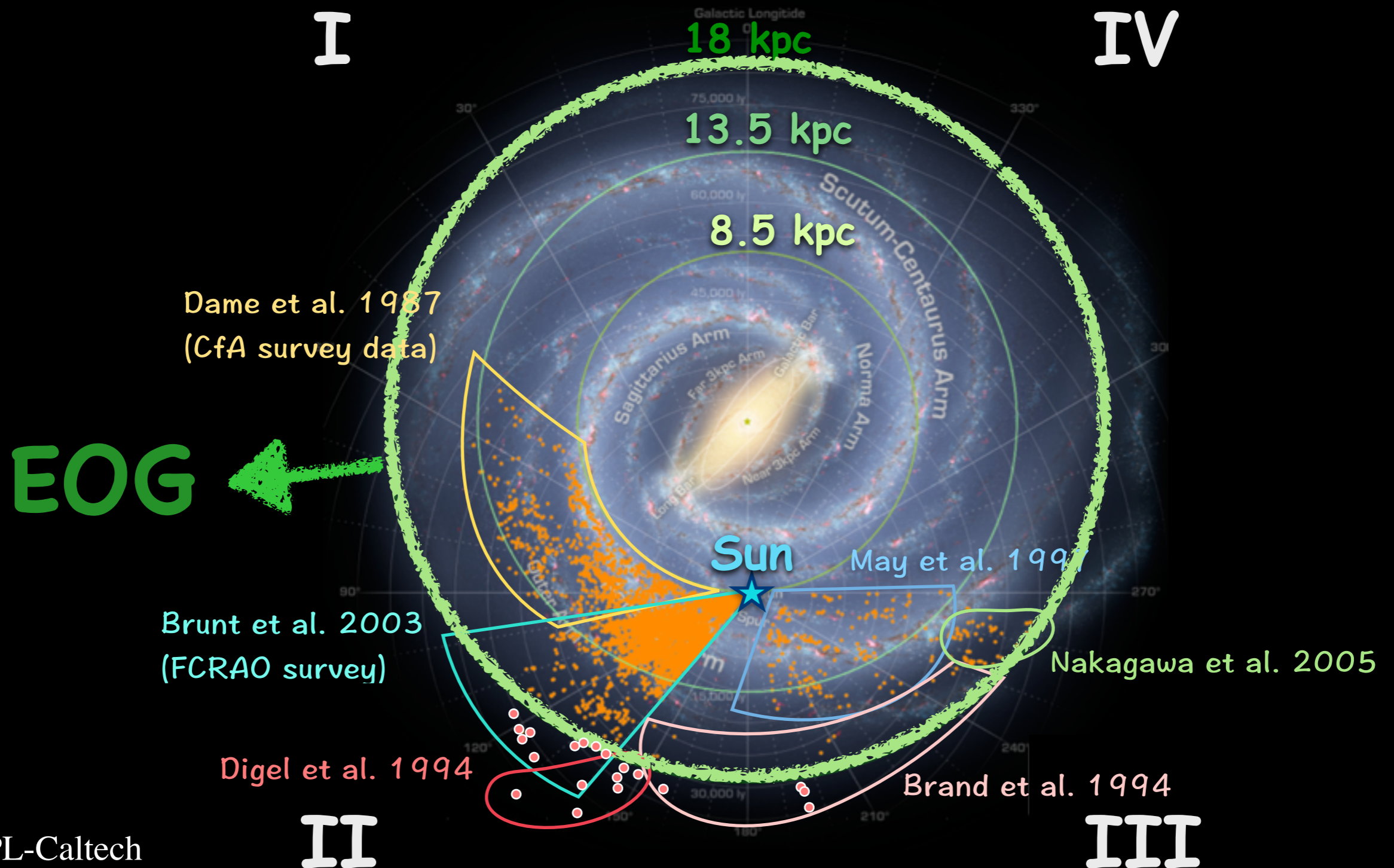
▶ CO survey (II and III quadrant)



Introduction II : Our Study

■ Search for young star-forming regions in the EOG (w/ embedded clusters)

▶ CO survey (II and III quadrant)



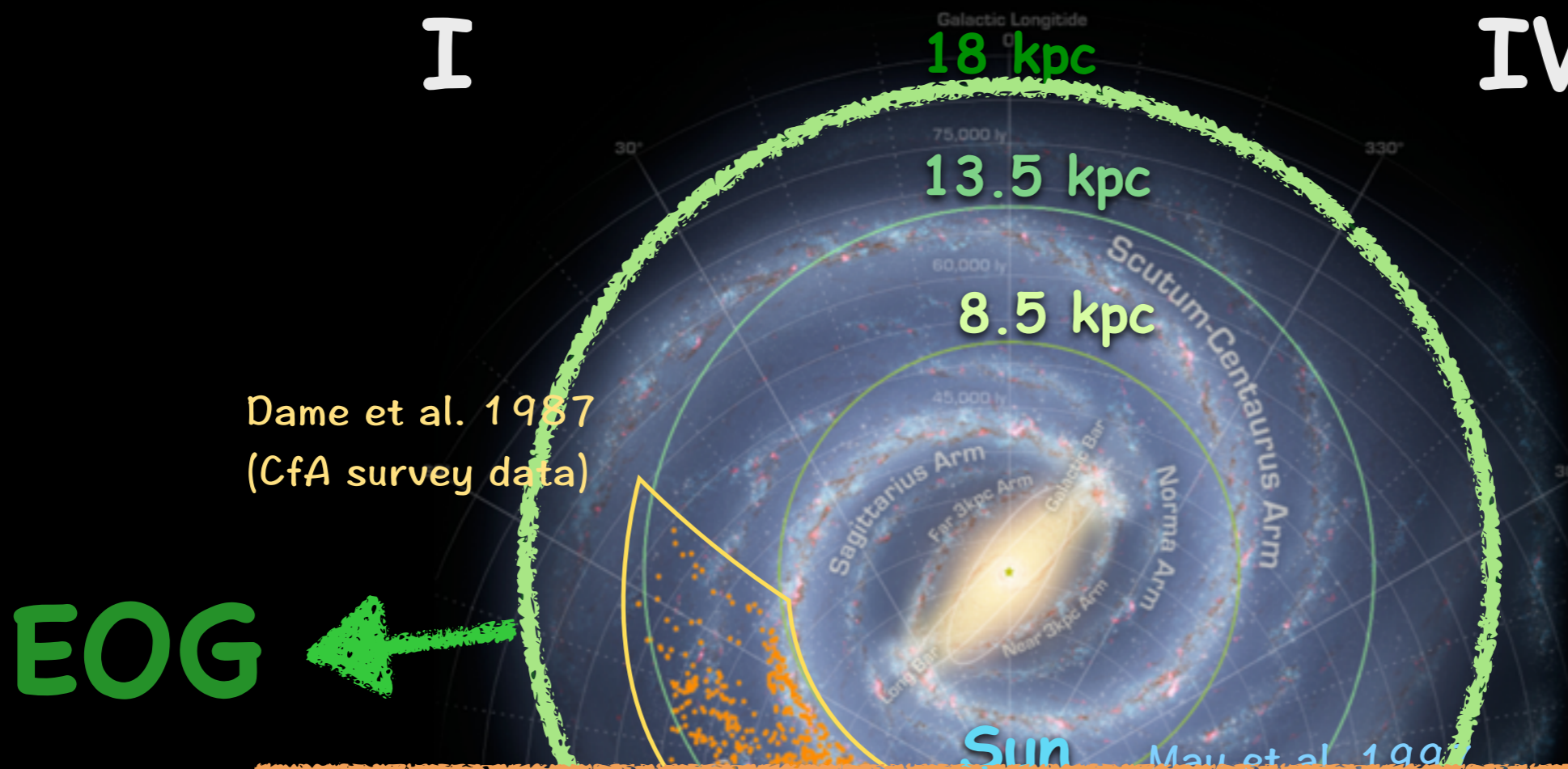
Introduction II : Our Study

■ Search for young star-forming regions in the EOG (w/ embedded clusters)

▶ CO survey (II and III quadrant)

I

IV



Dame et al. 1987
(CfA survey data)

EOG

New surveys with even higher sensitivity are ongoing

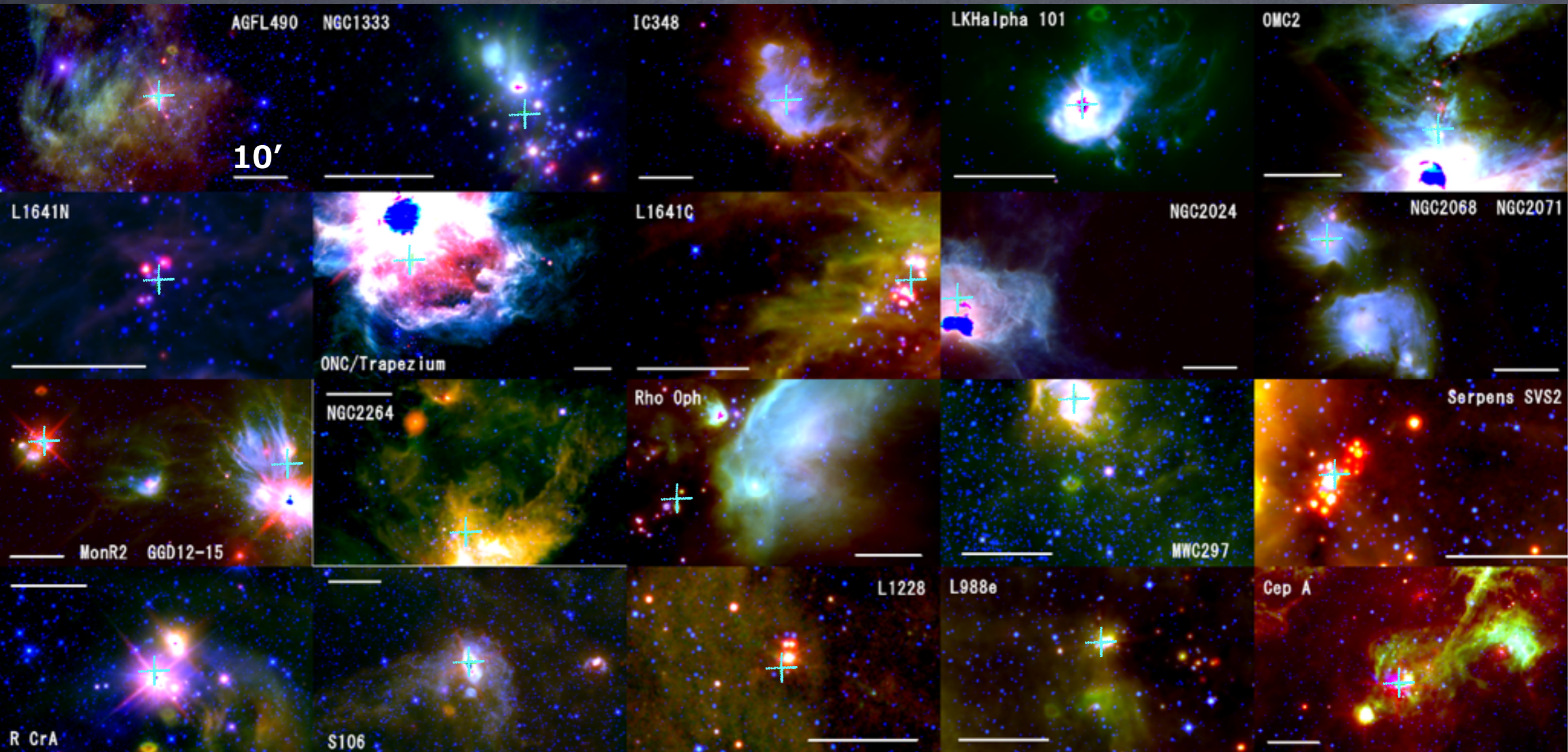
- Nobeyama 45m Galactic plane survey (Japan)
- Milky Way Imaging Scroll Painting Project (China)

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WISE View of Star-Forming Regions

1) Solar neighbourhood

- $D \leq 1$ kpc (clusters in Lada & Lada 2003)

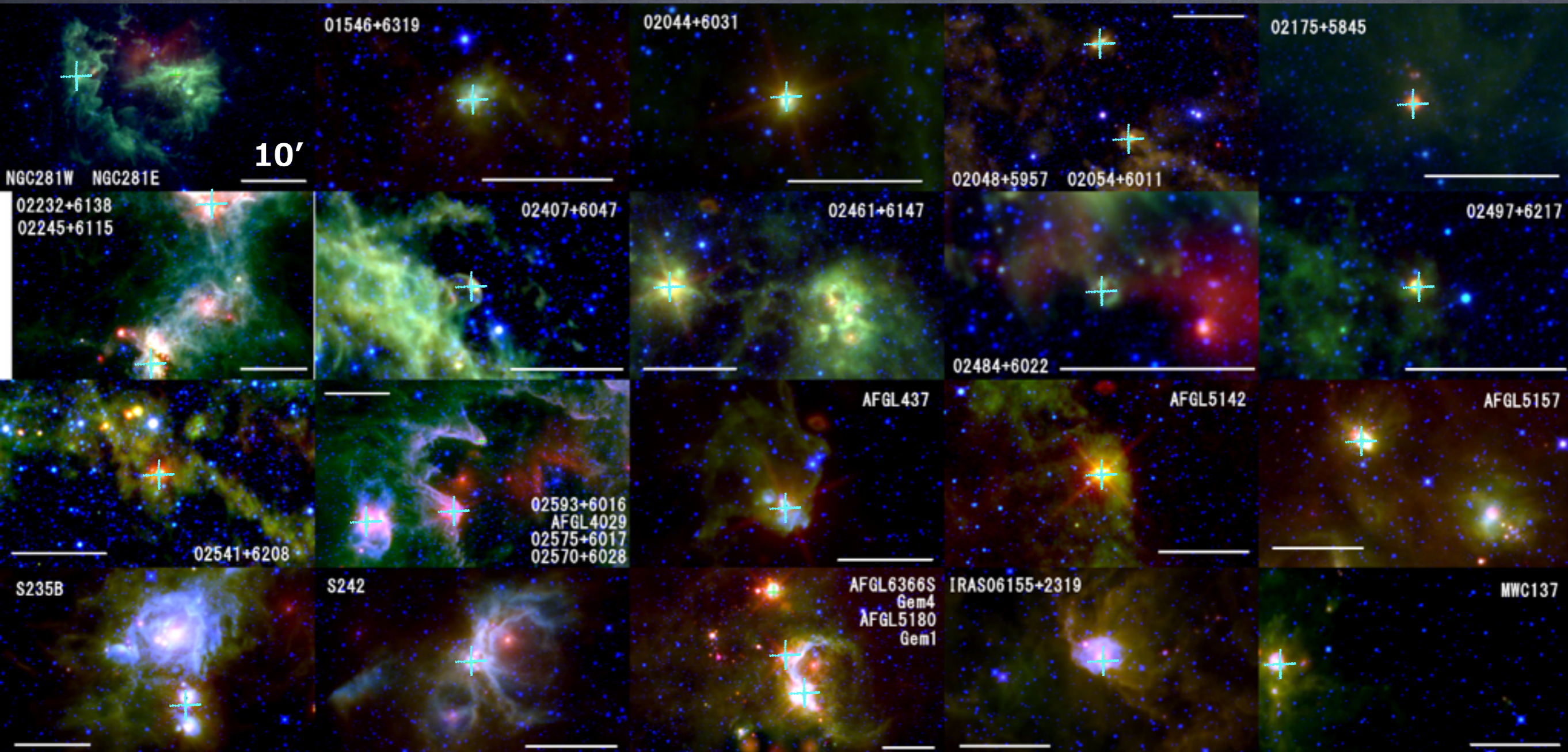


(3.4: blue, 12:green, 22:red)

WISE View of Star-Forming Regions

2) Near outer Galaxy

- $D = 1 \sim 3$ kpc (clusters in Lada & Lada 2003)

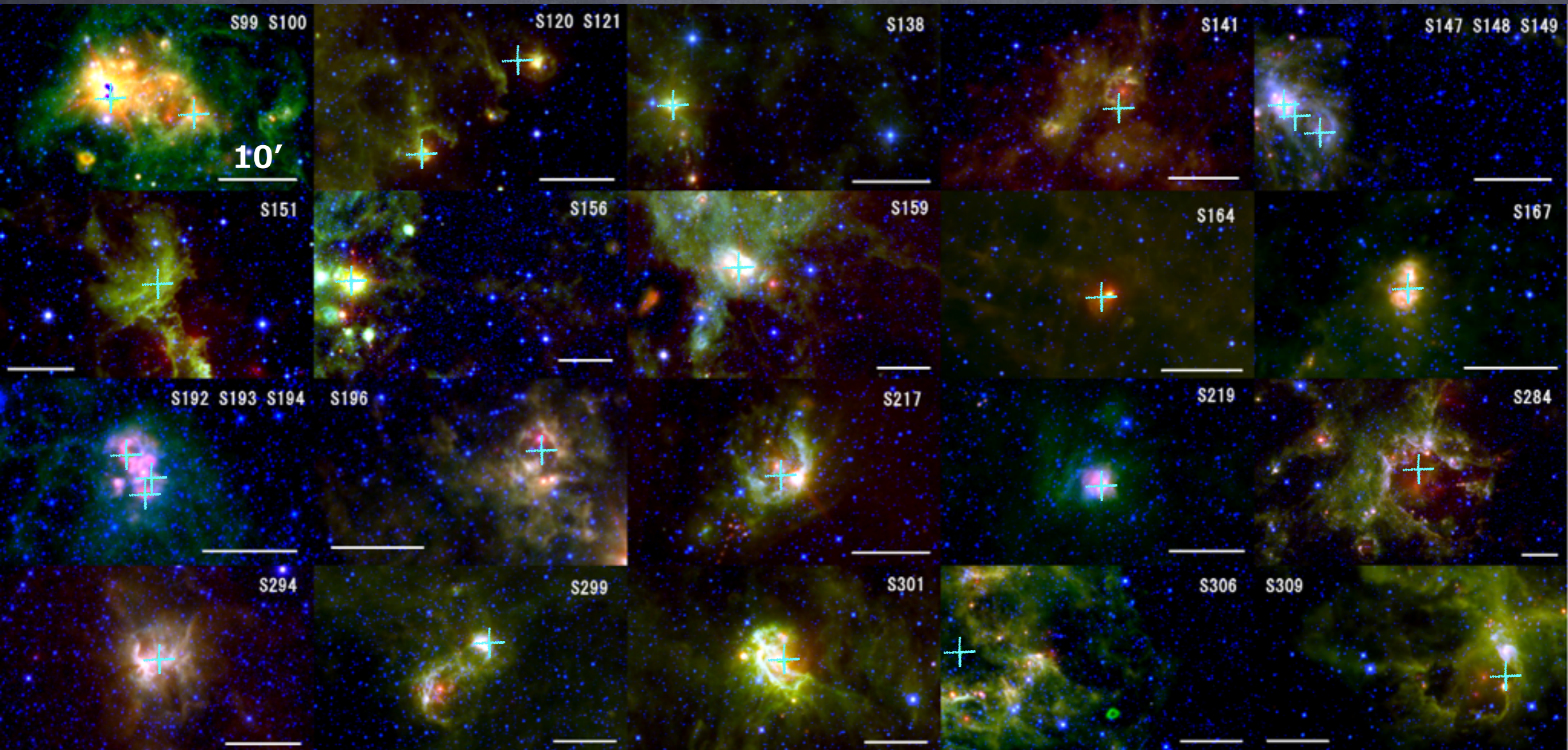


(3.4: blue, 12:green, 22:red)

WISE View of Star-Forming Regions

3) Outer Galaxy

- $D = 4 \sim 8$ kpc (HII regions in Fitch et al. 1984)

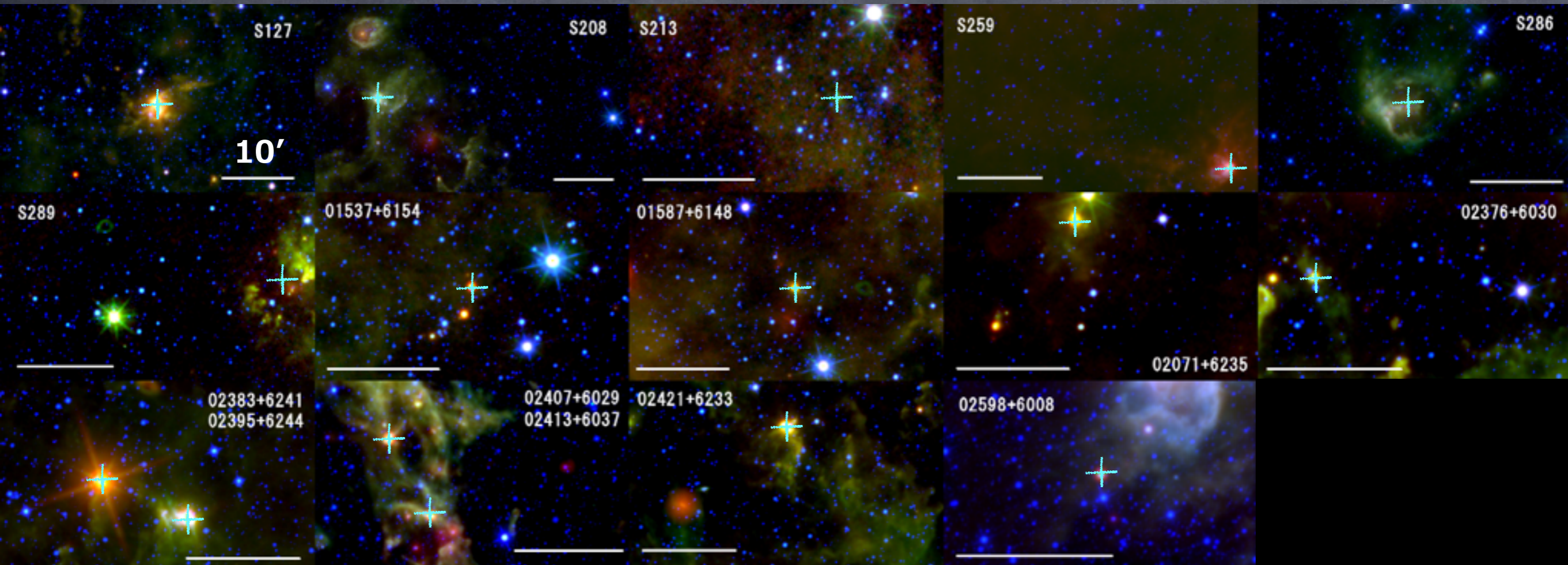


(3.4: blue, 12:green, 22:red)

WISE View of Star-Forming Regions

4) Far outer Galaxy

- $D = 7 \sim 10$ kpc (HII regions in Fitch et al. 1984 clusters in Snell et al. 2002)



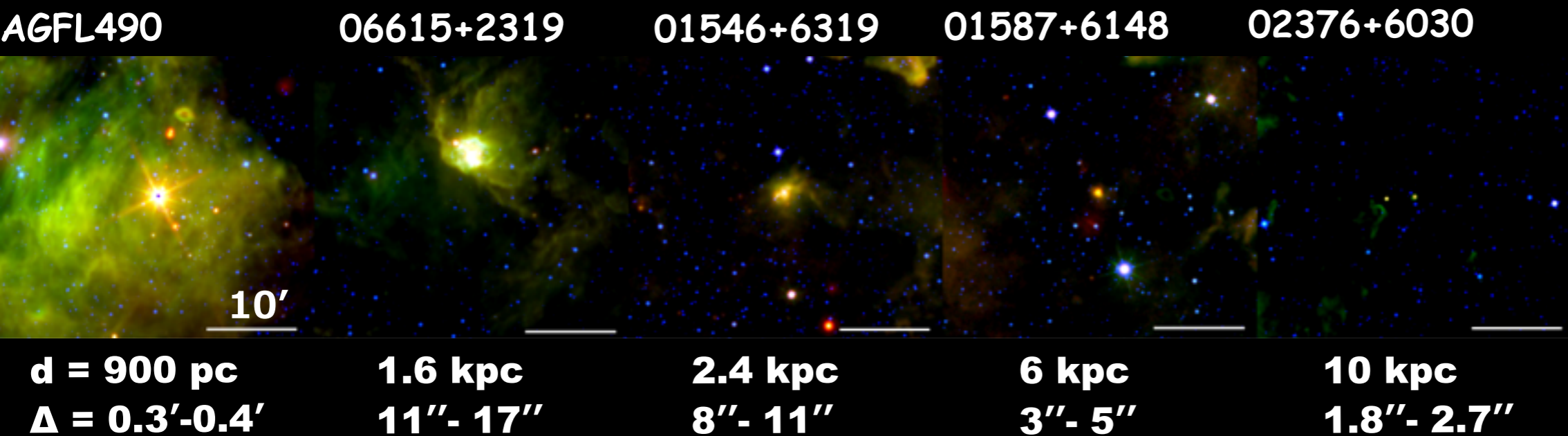
(3.4: blue, 12:green, 22:red)

WISE View of Star-Forming Regions

■ Representative cases

- Low-mass cluster ($M_{\text{cluster}} \sim 10^2 M_{\odot}$)
- Resolved or unresolved ?
 - Typical distance between cluster members :
 $\Delta = 2\text{-}3'$ at $d=150$ pc (case for Taurus)
 - WISE resolution : $6\text{-}12''$

Near  **Distance** **Far**

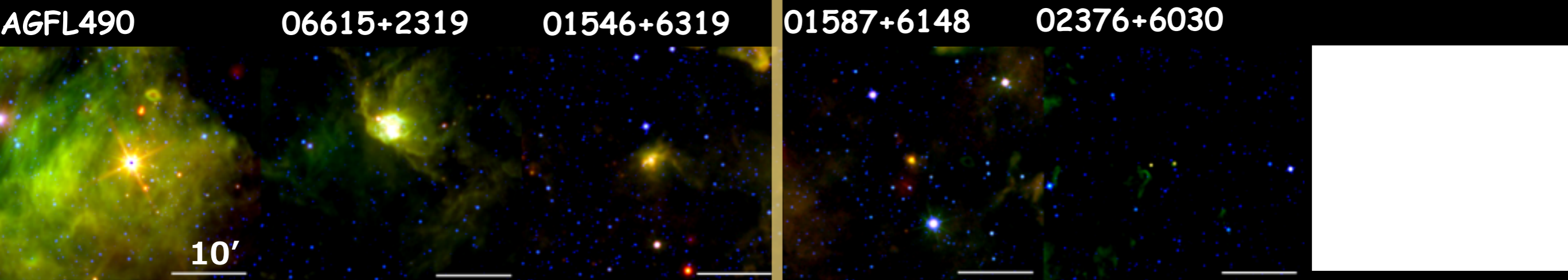


WISE View of Star-Forming Regions

■ Representative cases

- Low-mass cluster ($M_{\text{cluster}} \sim 10^2 M_{\odot}$)
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 $\Delta = 2\text{-}3'$ at $d=150$ pc (case for Taurus)
 - WISE resolution : $6\text{-}12''$

Near  **Distance**  **Far**



d = 900 pc $\Delta = 0.3'\text{-}0.4'$	1.6 kpc $11''\text{-}17''$	2.4 kpc $8''\text{-}11''$	6 kpc $3''\text{-}5''$	10 kpc $1.8''\text{-}2.7''$
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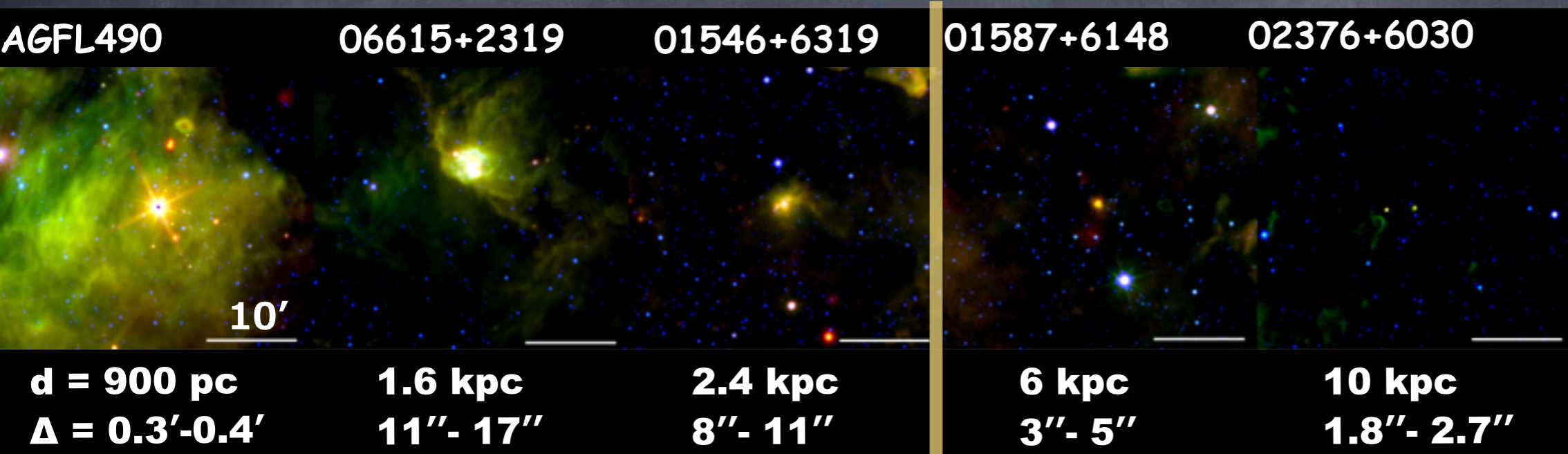
 **Resolved**  **Unresolved** 

WISE View of Star-Forming Regions

Representative cases

- Low-mass cluster ($M_{\text{cluster}} \sim 10^2 M_{\odot}$)
- Resolved or unresolved ?
 - Typical distance between cluster members : $\Delta = 2-3'$ at $d=150$ pc (case for Taurus)
 - WISE resolution : $6-12''$

Near **Distance** **Far**



Cluster in the EOG ?

Resolved **Unresolved**

How star forming regions look like in the EOG?

WISE View of Star-Forming Region in the EOG

■ Star-forming regions in the EOG

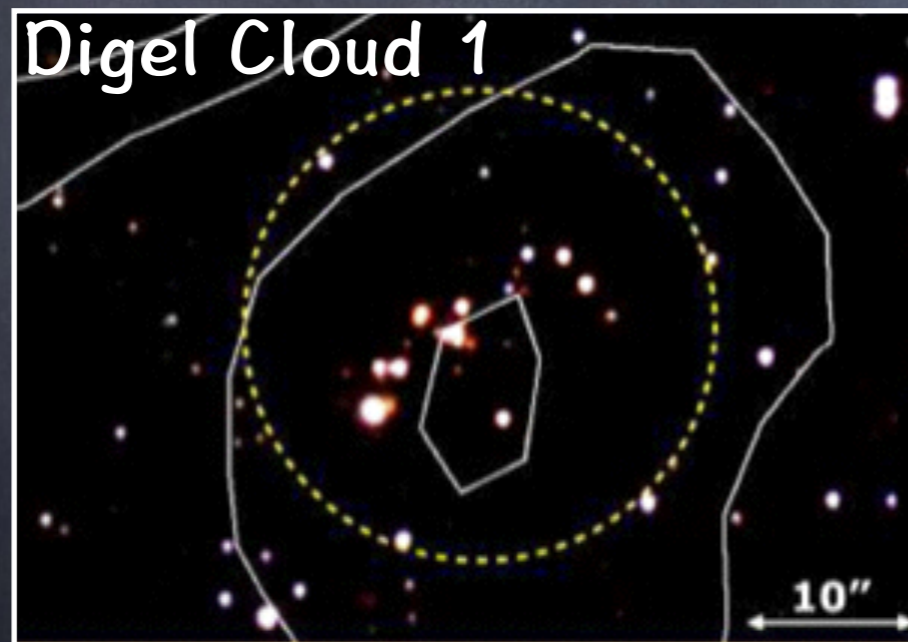
- Only three are known

- Digel Cloud 1 : $R_G = 22$ kpc ($D = 16$ kpc)
- Digel Cloud 2 : $R_G = 19$ kpc ($D = 12$ kpc)
- WB89-789 : $R_G = 20$ kpc ($D = 12$ kpc)

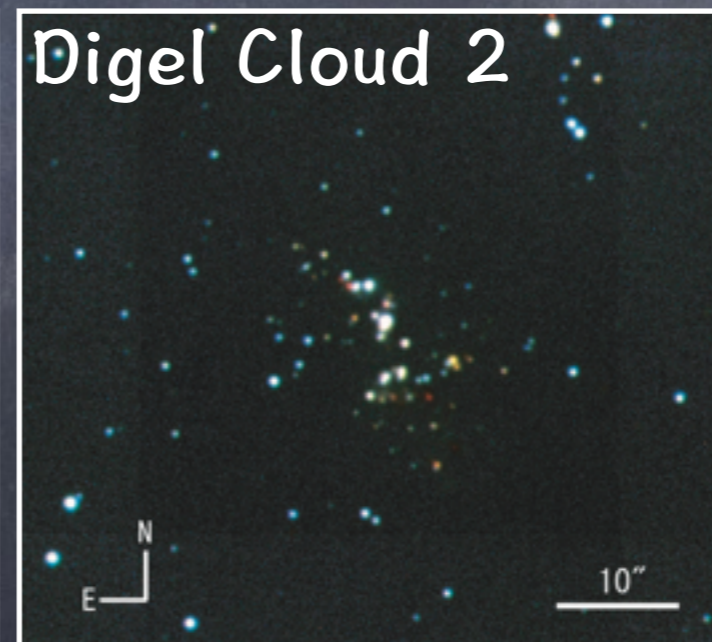
Izumi et al. 2014

Yasui et al. 2006, 2008,
Kobayashi et al. 2008

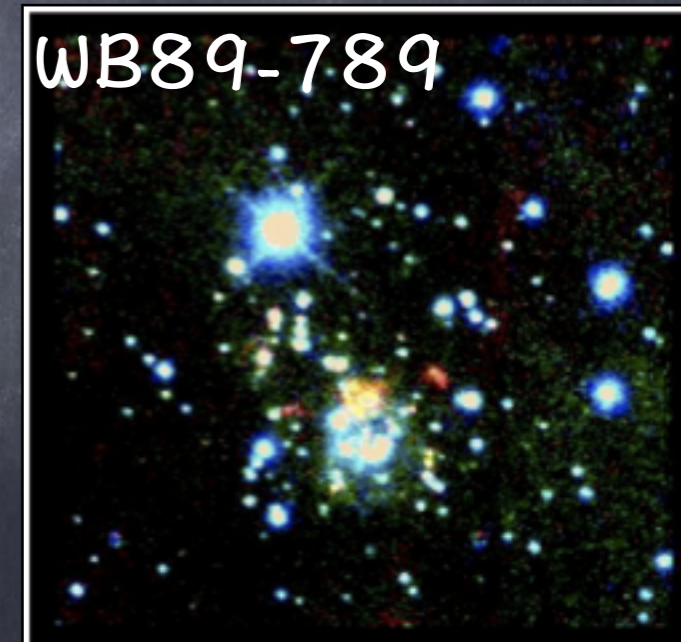
Brand & Wouterloot 2007



Izumi et al. 2014



Yasui et al. 2008



Brand & Wouterloot 2007

WISE View of Star-Forming Region in the EOG

■ Star-forming regions in the EOG

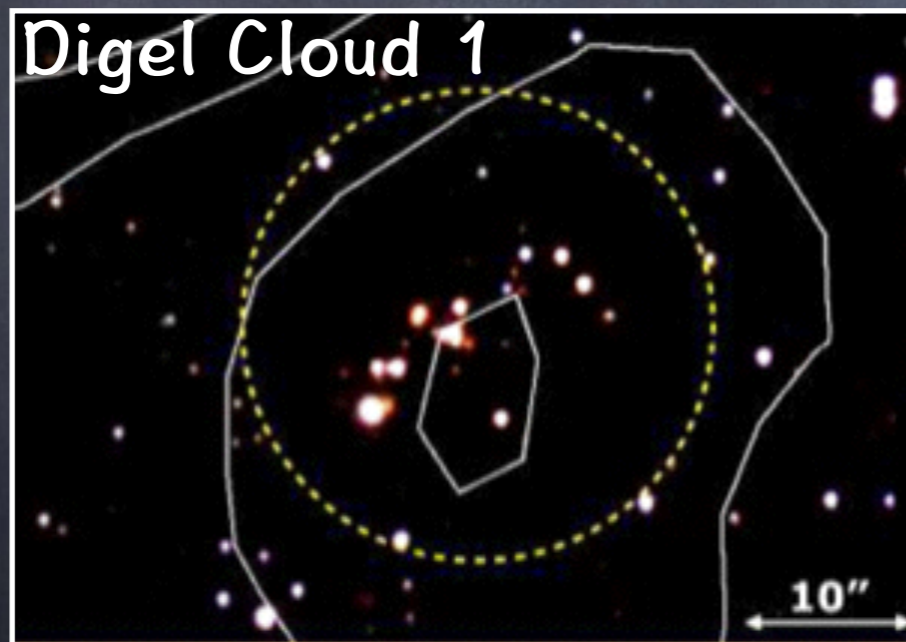
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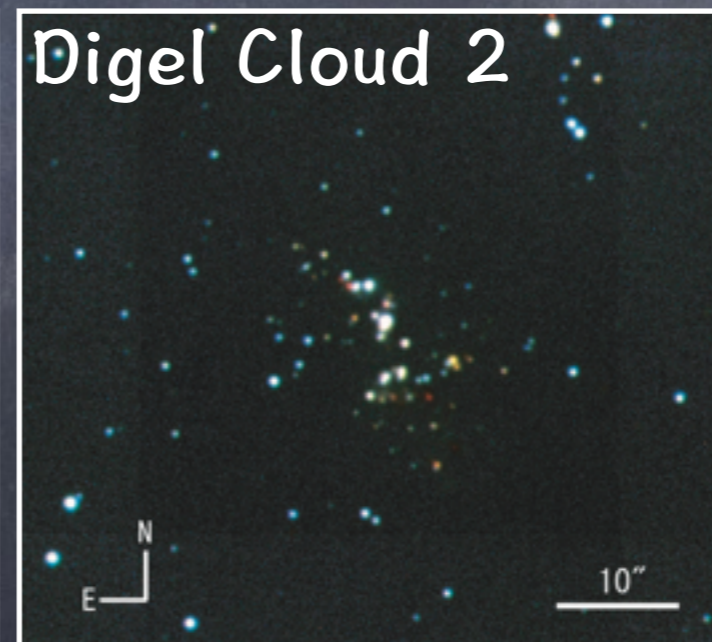
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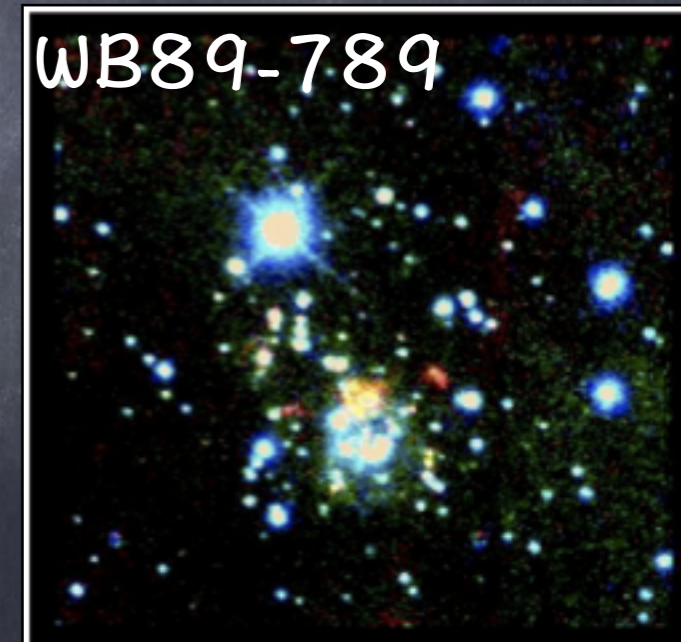
Brand & Wouterloot 2007



Izumi et al. 2014



Yasui et al. 2008



Brand & Wouterloot 2007

WISE View of Star-Forming Region in the EOG

■ Star-forming regions in the EOG

- Digel Cloud 1, 2

Izumi et al. 2014, Yasui et al. 2006, 2008

EOG

Dame et al. 1987
(CfA survey data)

Brunt et al. 2003
(FCRAO survey)

Digel et al. 1994
(Digel Clouds)

Digel Cloud 1

Sun

May et al. 1997

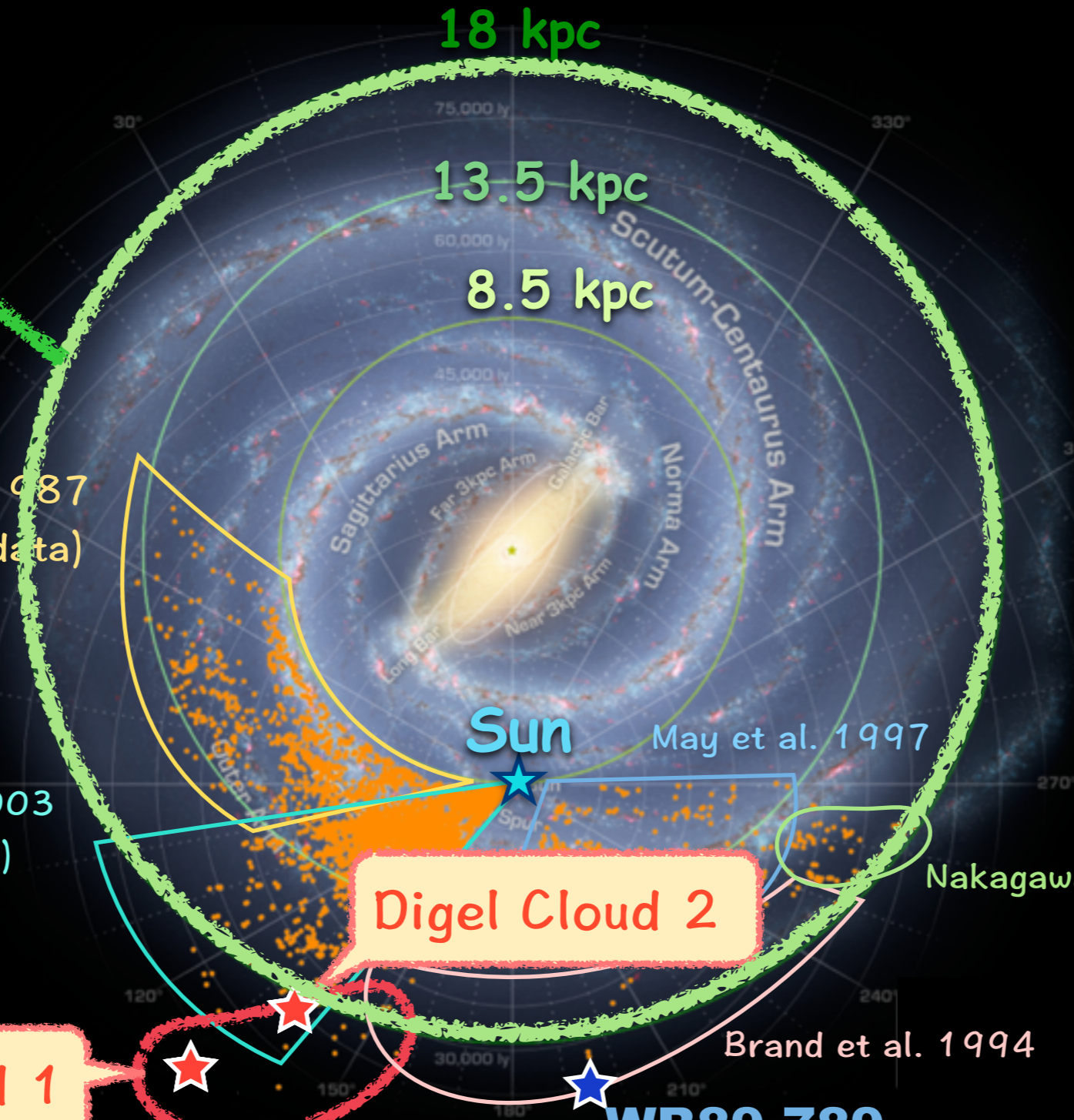
Digel Cloud 2

Nakagawa et al. 2005

Brand et al. 1994

WB89-789

NASA/JPL-Caltech



WISE View of Star-Forming Region in the EOG

■ Star-forming regions in the EOG

- Digel Cloud 1, 2

Izumi et al. 2014, Yasui et al. 2006, 2008

EOG

Dame et al. 1987
(CfA survey data)

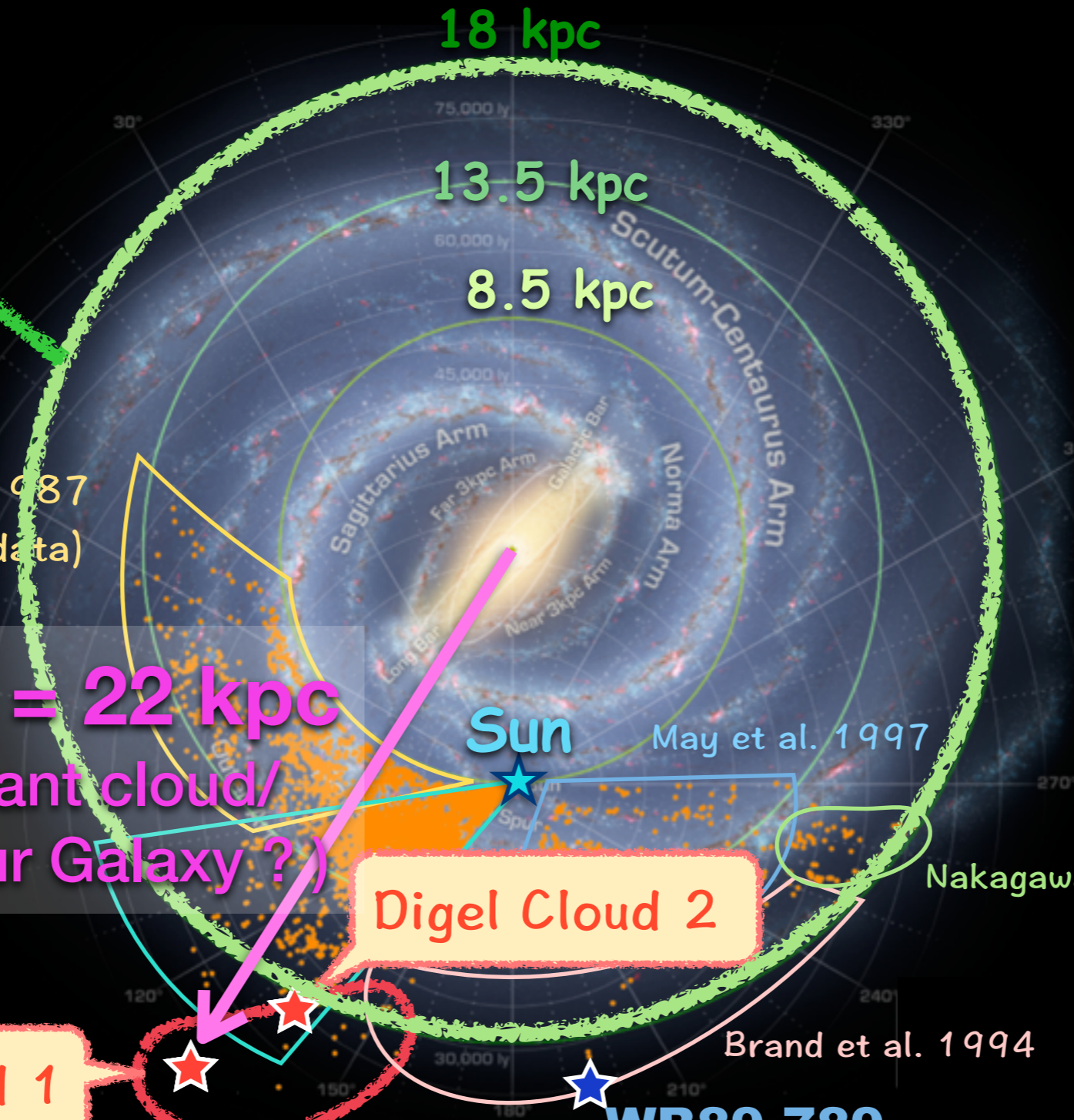
$R_G = 22 \text{ kpc}$
(most distant cloud/
cluster in our Galaxy?)

Digel et al. 1994
(Digel Clouds)

Digel Cloud 1

Digel Cloud 2

WB89-789



May et al. 1997

Nakagawa et al. 2005

Brand et al. 1994

WISE View of Star-Forming Region in the EOG

■ Star-forming regions in the EOG

- Digel Cloud 1, 2

Izumi et al. 2014, Yasui et al. 2006, 2008

Our observations

- High resolution ^{12}CO mapping
 - ▶ Nobeyama 45 m radio telescope
 - ↑ Beam size : 17"
- Deep NIR (J, H, Ks) imaging
 - ▶ Subaru 8.2 m telescope
 - ↑ Limiting mag : 22.0(J), 21.5(H), 20.5(Ks) mag, 5σ

EOG

Dame et al.
(CfA survey)

$R_G = 22 \text{ kpc}$
(most distant cloud/
cluster in our Galaxy ?)

Digel et al. 1994
(Digel Clouds)

Digel Cloud 1

Digel Cloud 2

WB89-789

Sun

May et al. 1997

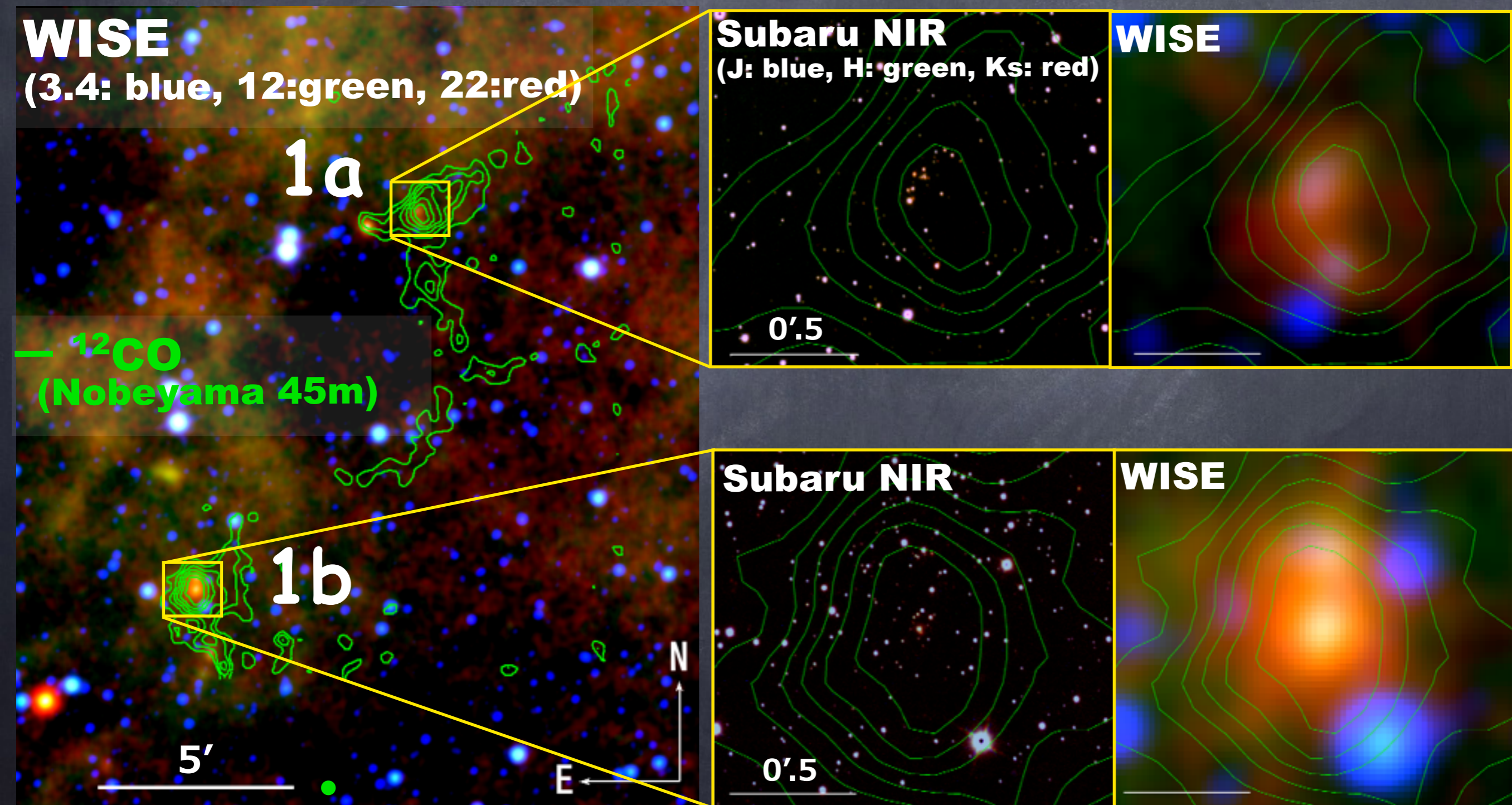
Nakagawa et al. 2005

Brand et al. 1994

WISE View of Star-Forming Region in the EOG

Digel Cloud 1

- Embedded clusters are detected in the two CO peaks (Cloud 1a Cloud 1b)

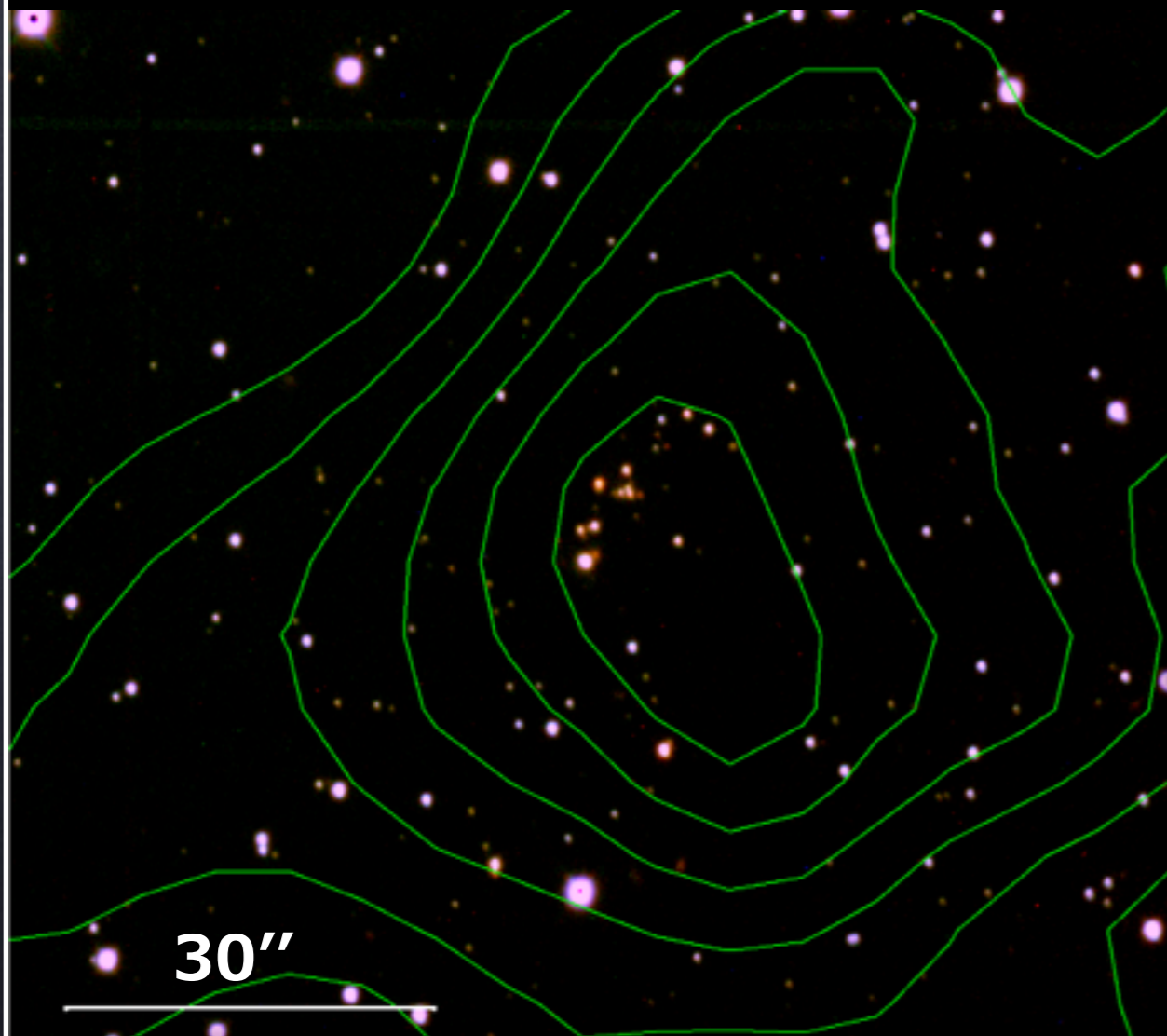


WISE View of Star-Forming Region in the EOG

- Cloud 1a ($N_{\text{cluster}} = 18$, $M_{\text{cluster}} \sim 27 M_{\odot}$)

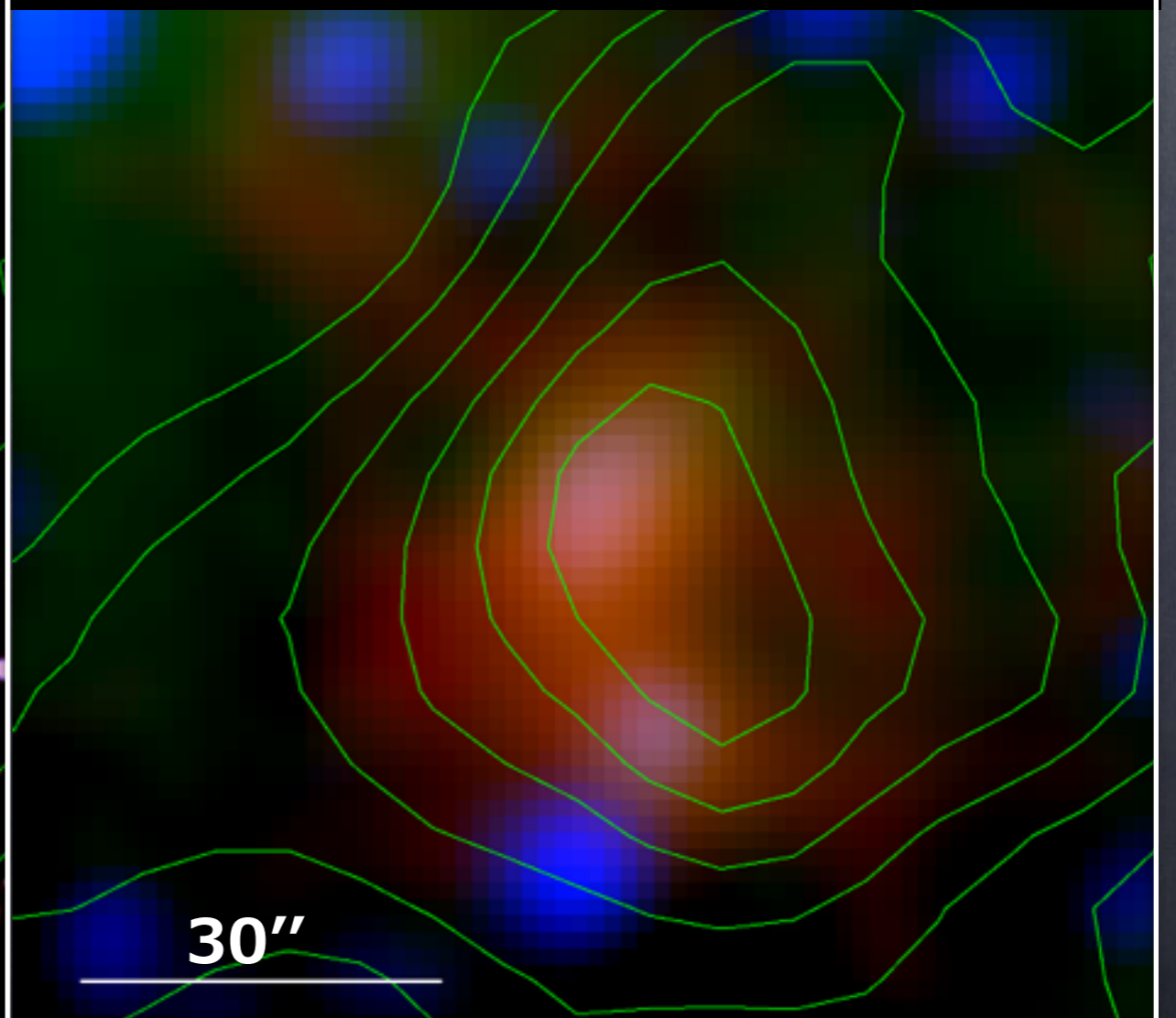
Subaru NIR

(J: blue, H: green, Ks: red)



WISE

(3.4: blue, 12:green, 22:red)

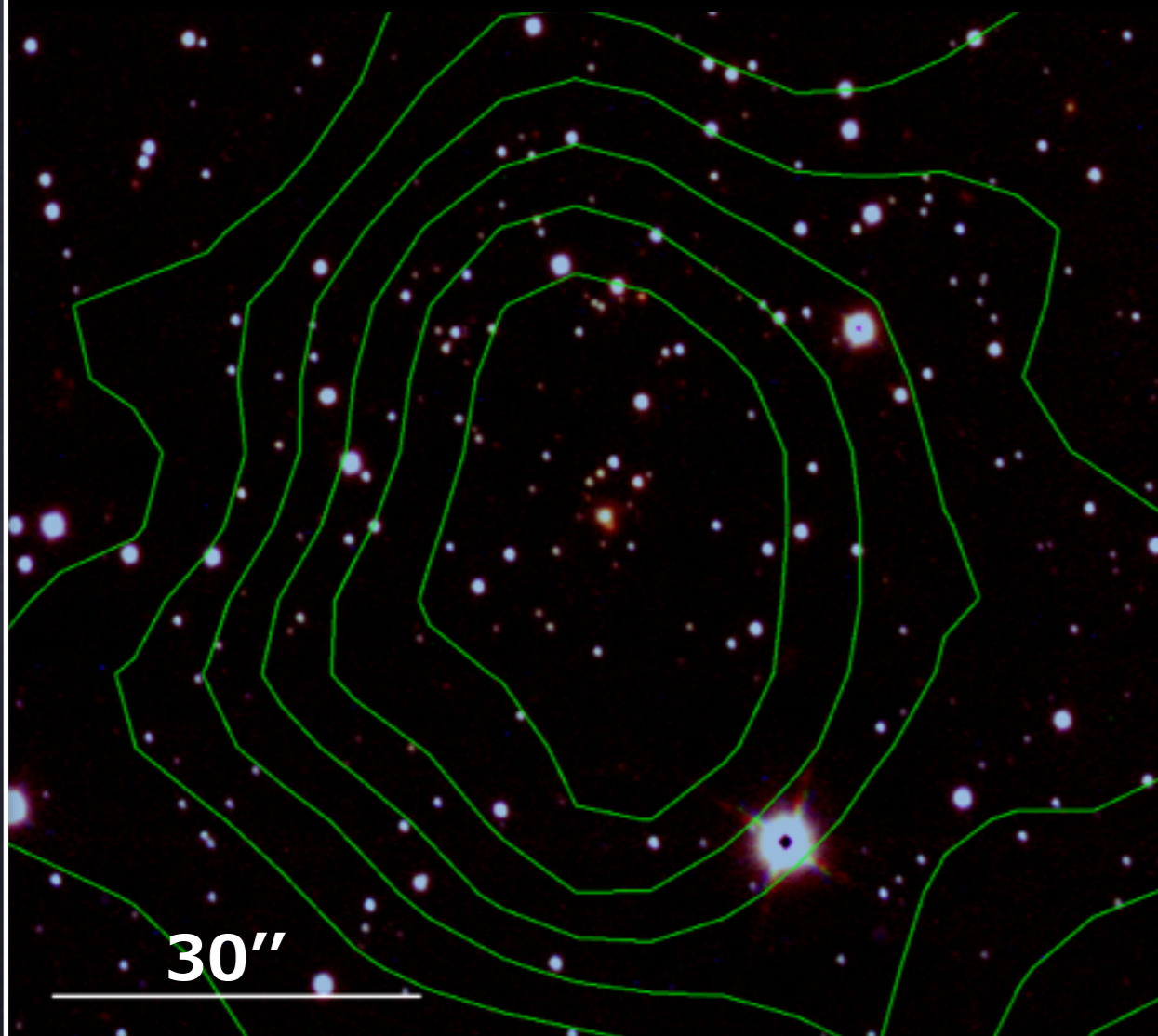


- Cluster is detected as a few point-like red sources

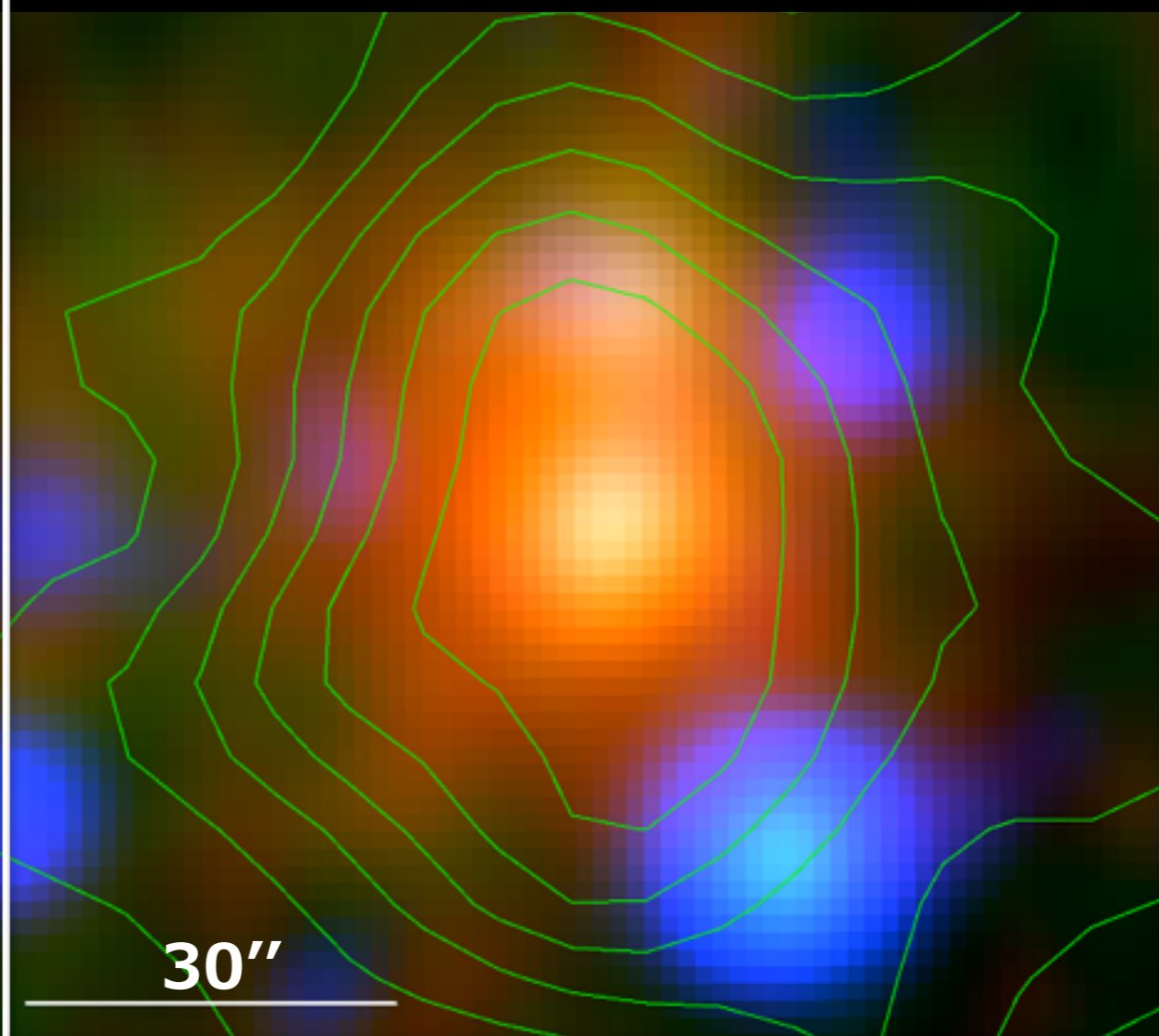
WISE View of Star-Forming Region in the EOG

- Cloud 1b ($N_{\text{cluster}} = 48$, $M_{\text{cluster}} \sim 28 M_{\odot}$)

Subaru NIR
(J: blue, H: green, Ks: red)



WISE
(3.4: blue, 12:green, 22:red)

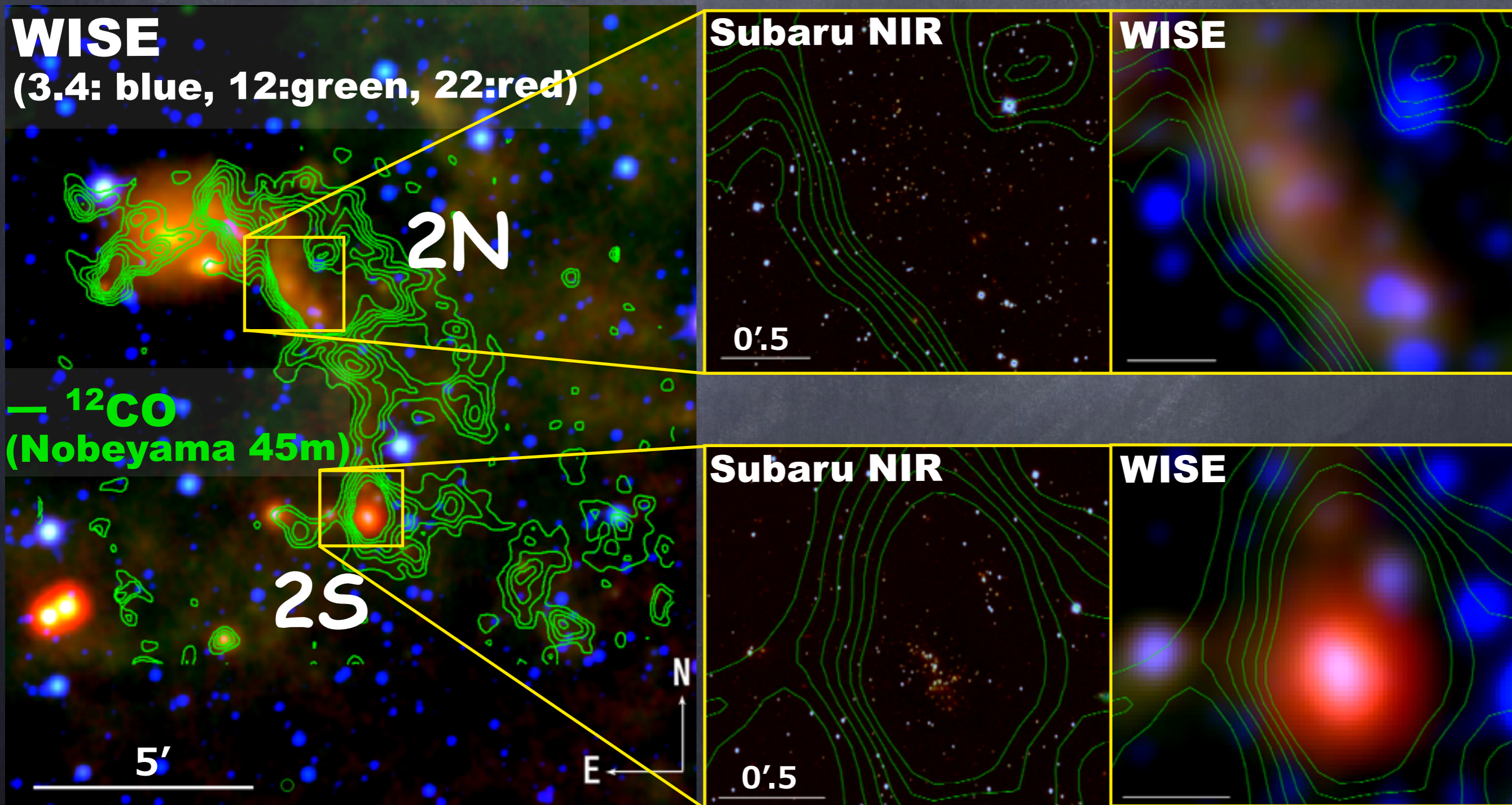


- Cluster is detected as a few point-like red sources

WISE View of Star-Forming Region in the EOG

Digel Cloud 2

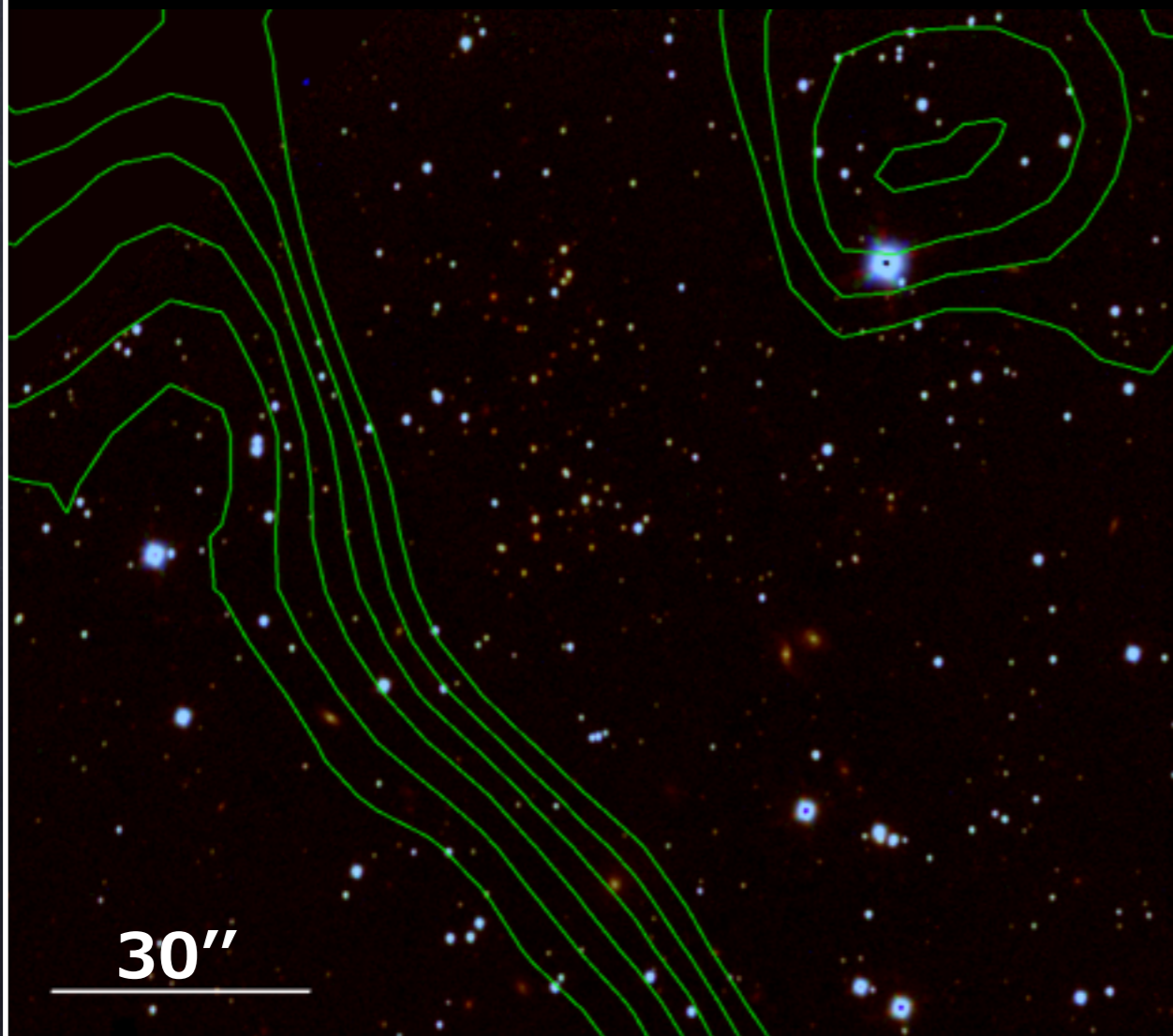
- Embedded clusters are detected in the two CO peaks (Cloud 2N Cloud 2S)



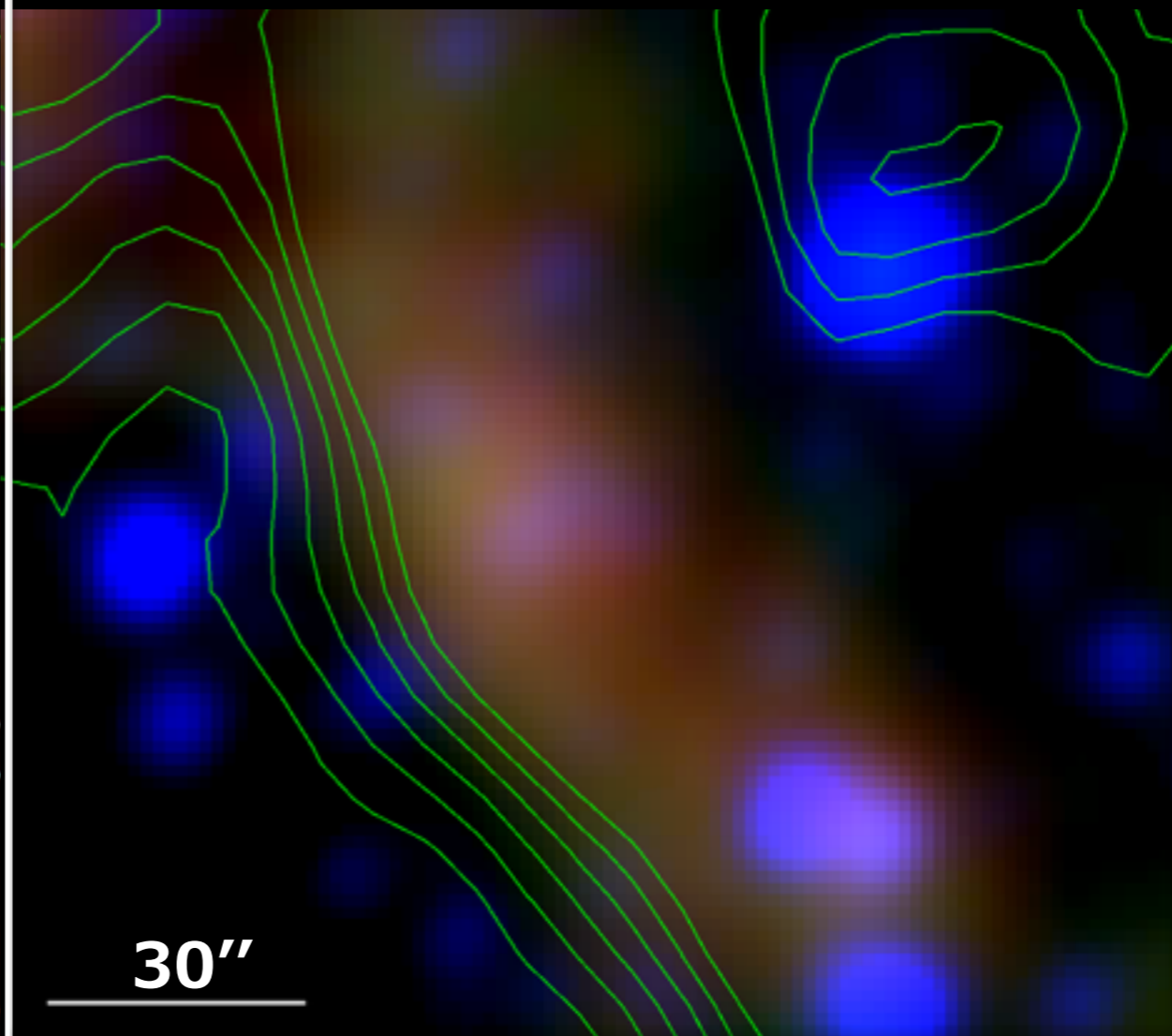
WISE View of Star-Forming Region in the EOG

- Cloud 2N ($N_{\text{cluster}} = 72$, $M_{\text{cluster}} \sim 43 M_{\odot}$)

Subaru NIR
(J: blue, H: green, Ks: red)



WISE
(3.4: blue, 12:green, 22:red)

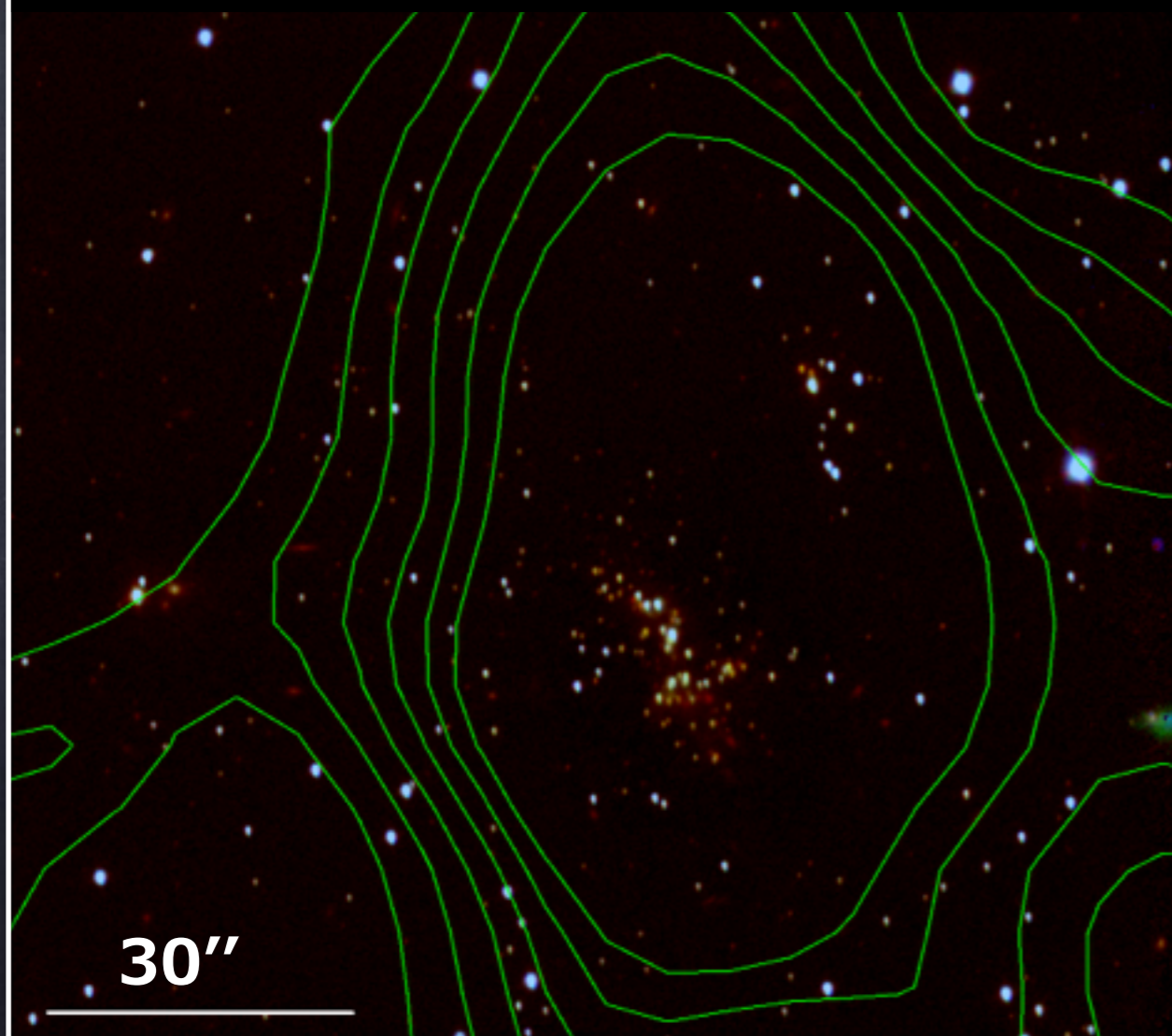


- Cluster is detected as an extended sources

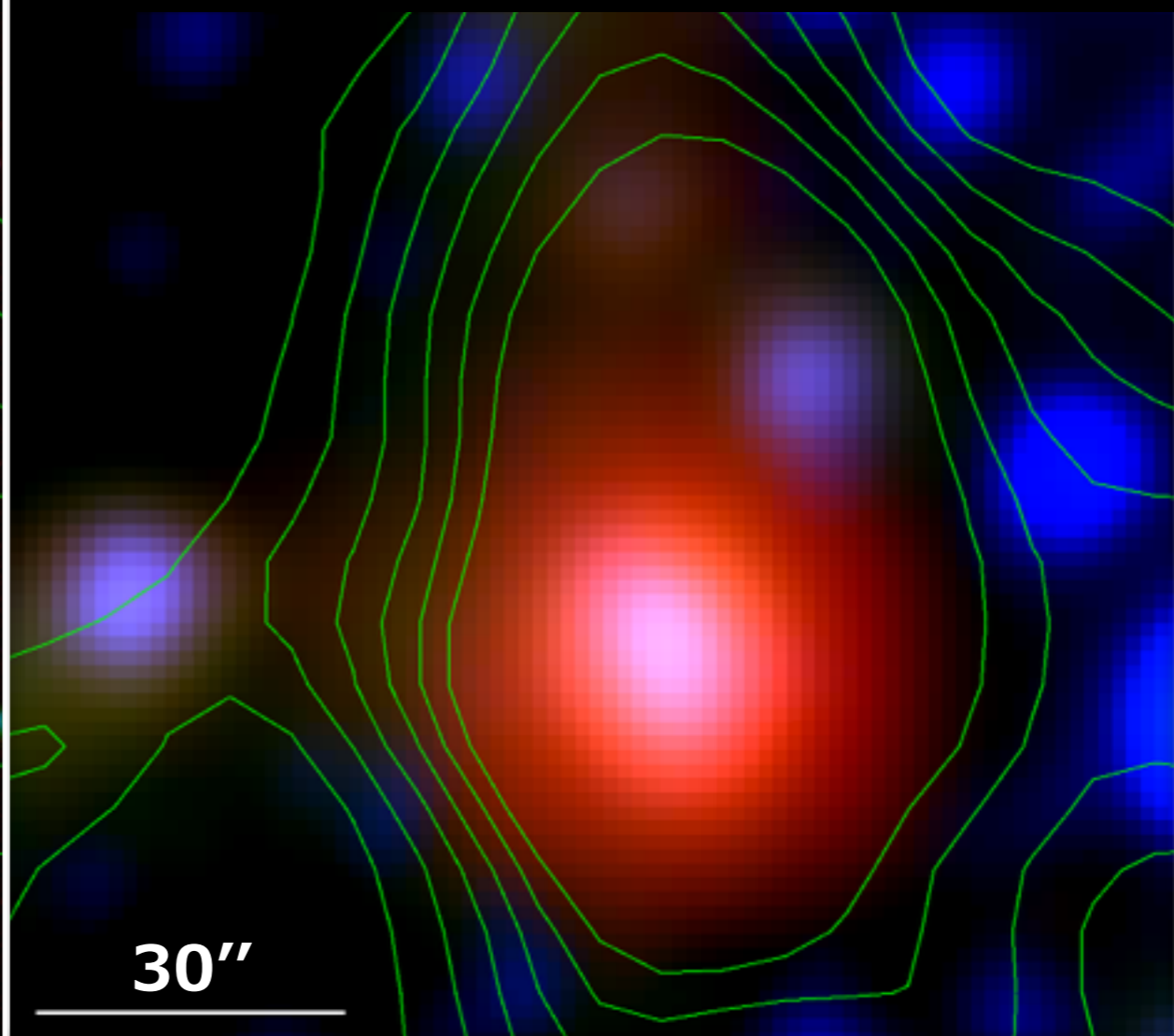
WISE View of Star-Forming Region in the EOG

- Cloud 2S ($N_{\text{cluster}} = 66$, $M_{\text{cluster}} \sim 40 M_{\odot}$)

Subaru NIR
(J: blue, H: green, Ks: red)



WISE
(3.4: blue, 12:green, 22:red)



- Cluster is detected as a few point-like red sources

WISE View of Star-Forming Region in the EOG

■ Case for Digel Cloud 1, 2

- Star-forming regions are **clearly detected with WISE in all four bands**
 - WISE can detect star-forming regions **even at**
 $R_G = 22$ kpc
- However, **cluster members are unresolved**
 - We must rely **only on integrated flux** to pick up star-forming regions with WISE data.

Search for star-forming region in the EOG with WISE data

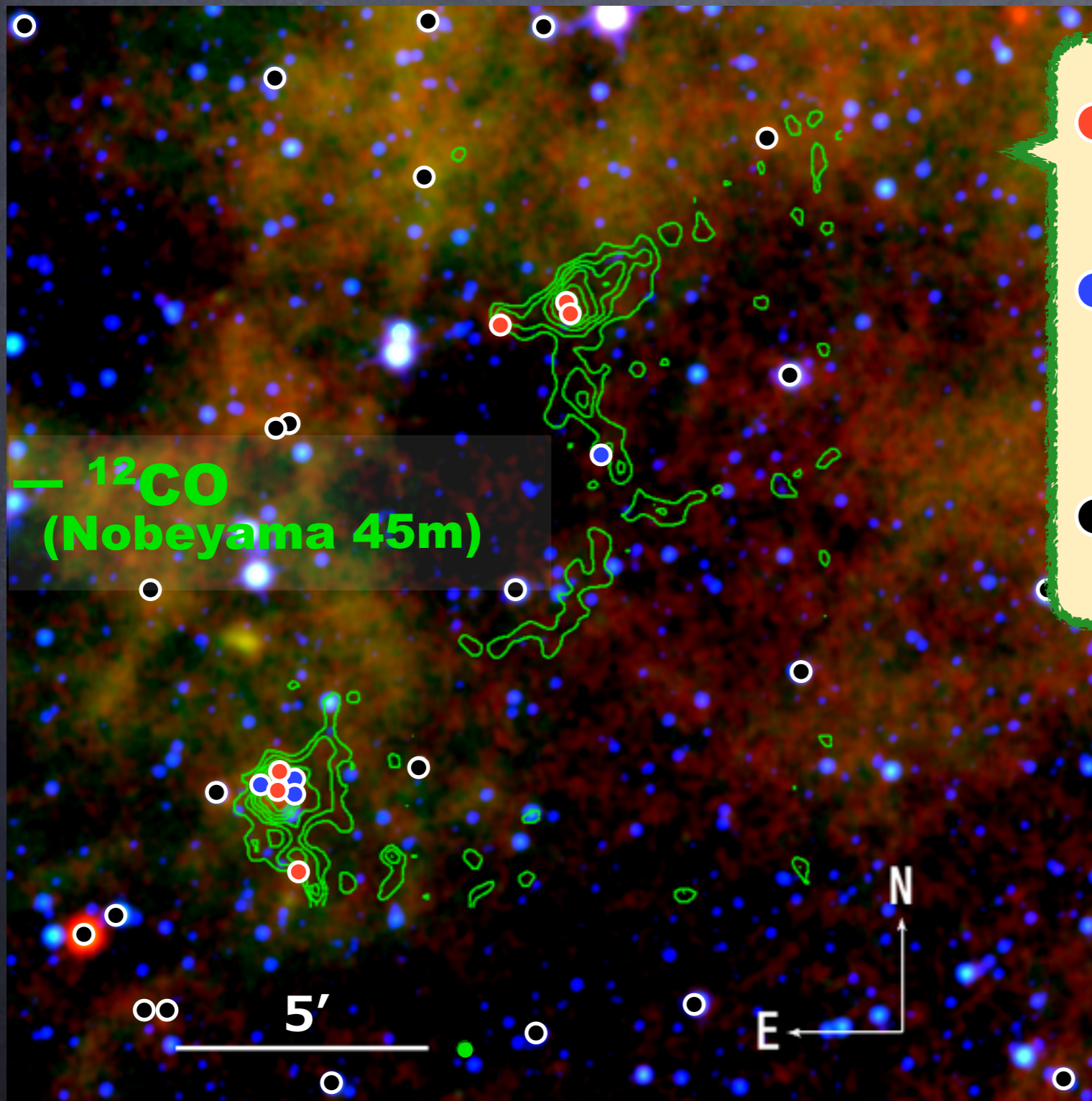
■ How can we find distant star-forming regions with WISE ?

- Construct detection criteria of distant star-forming regions using WISE colors of **confirmed star-forming regions with NIR imaging**

Search for star-forming region in the EOG with WISE data

■ AllWISE sources in the Cloud 1 field ($1^\circ \times 1^\circ$)

- SN > 5 (w1, w2, w3), SN > 3 (w4)



● Confirmed star-forming regions

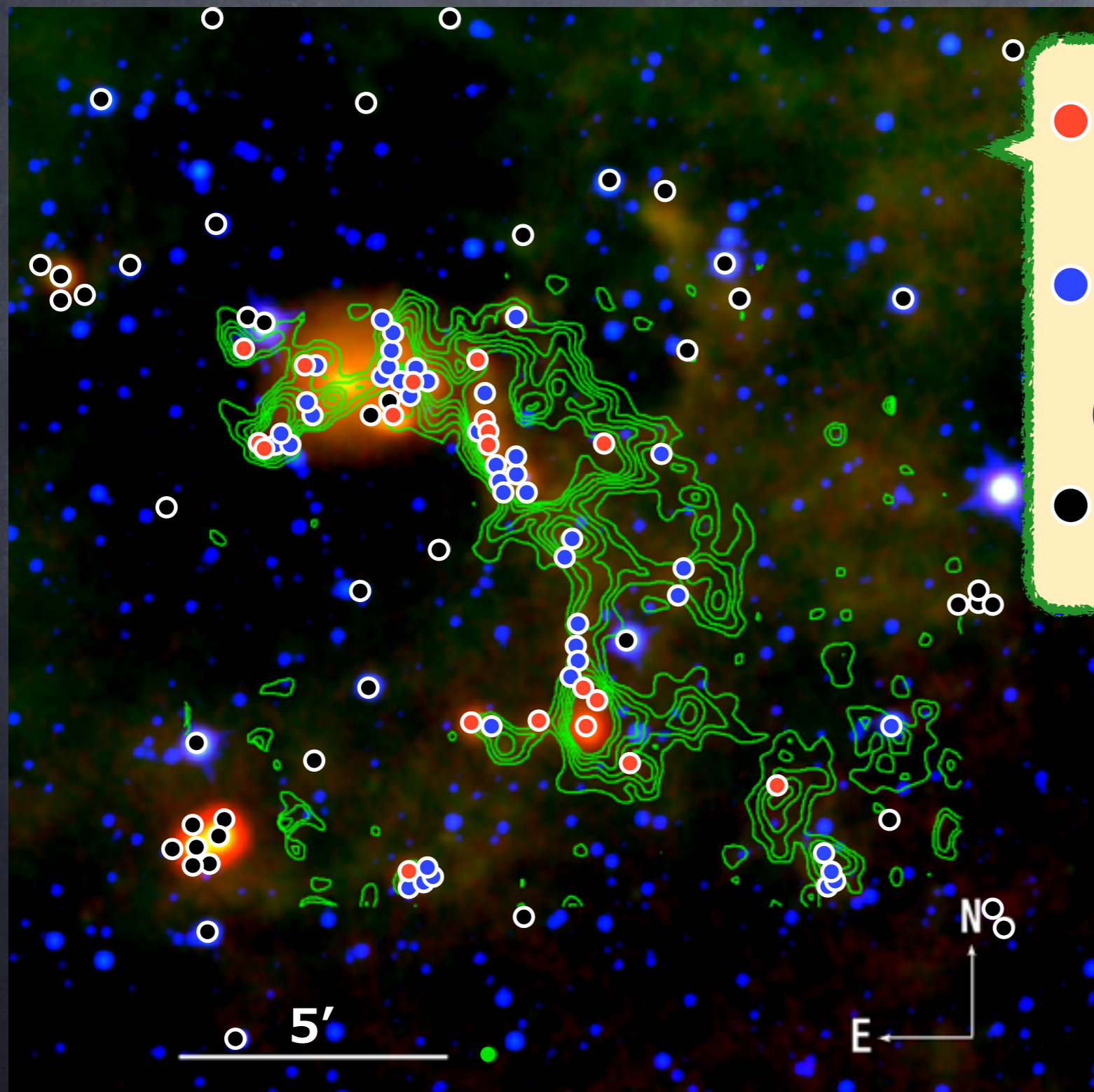
● Sources within molecular clouds (within 3σ contour)

● Field stars

Search for star-forming region in the EOG with WISE data

■ AllWISE sources in the Cloud 2 field ($1^\circ \times 1^\circ$)

- $SN > 5$ (w1, w2, w3), $SN > 3$ (w4)



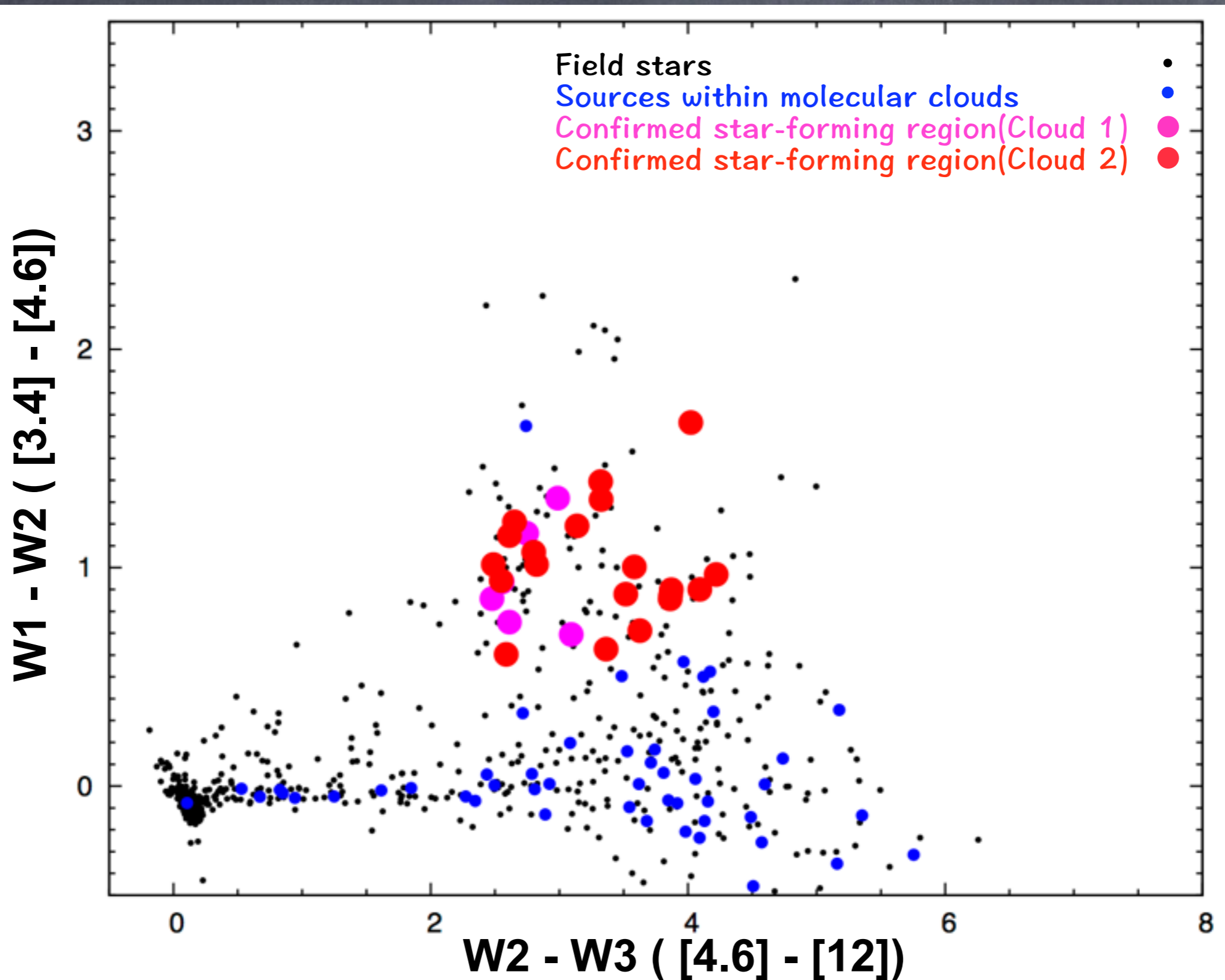
● **Confirmed star-forming regions**

● **Sources within molecular clouds**
(within 3σ contour)

● **Field stars**

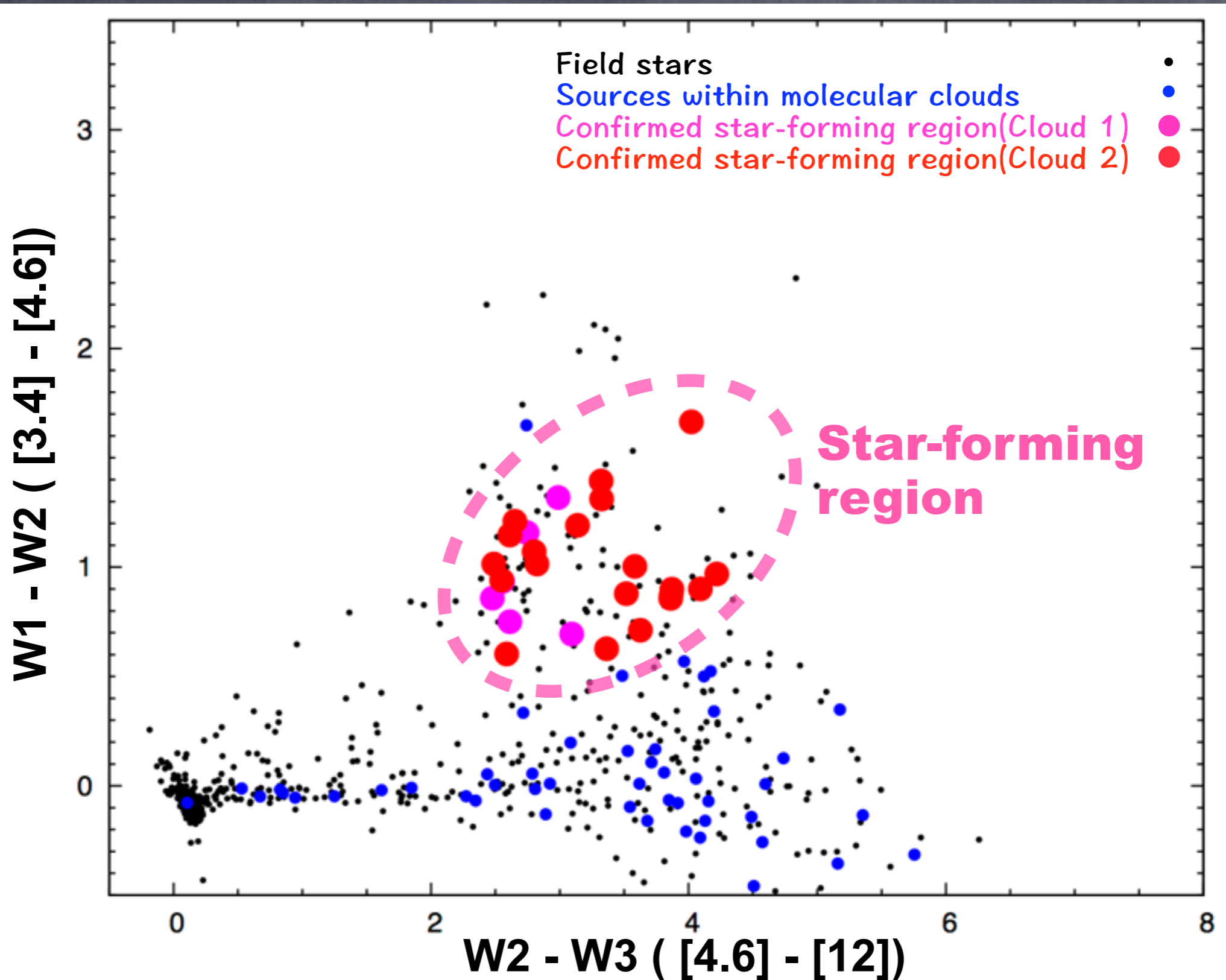
Search for star-forming region in the EOG with WISE data

■ Color - color diagram (w1-w2 vs w2-w3)



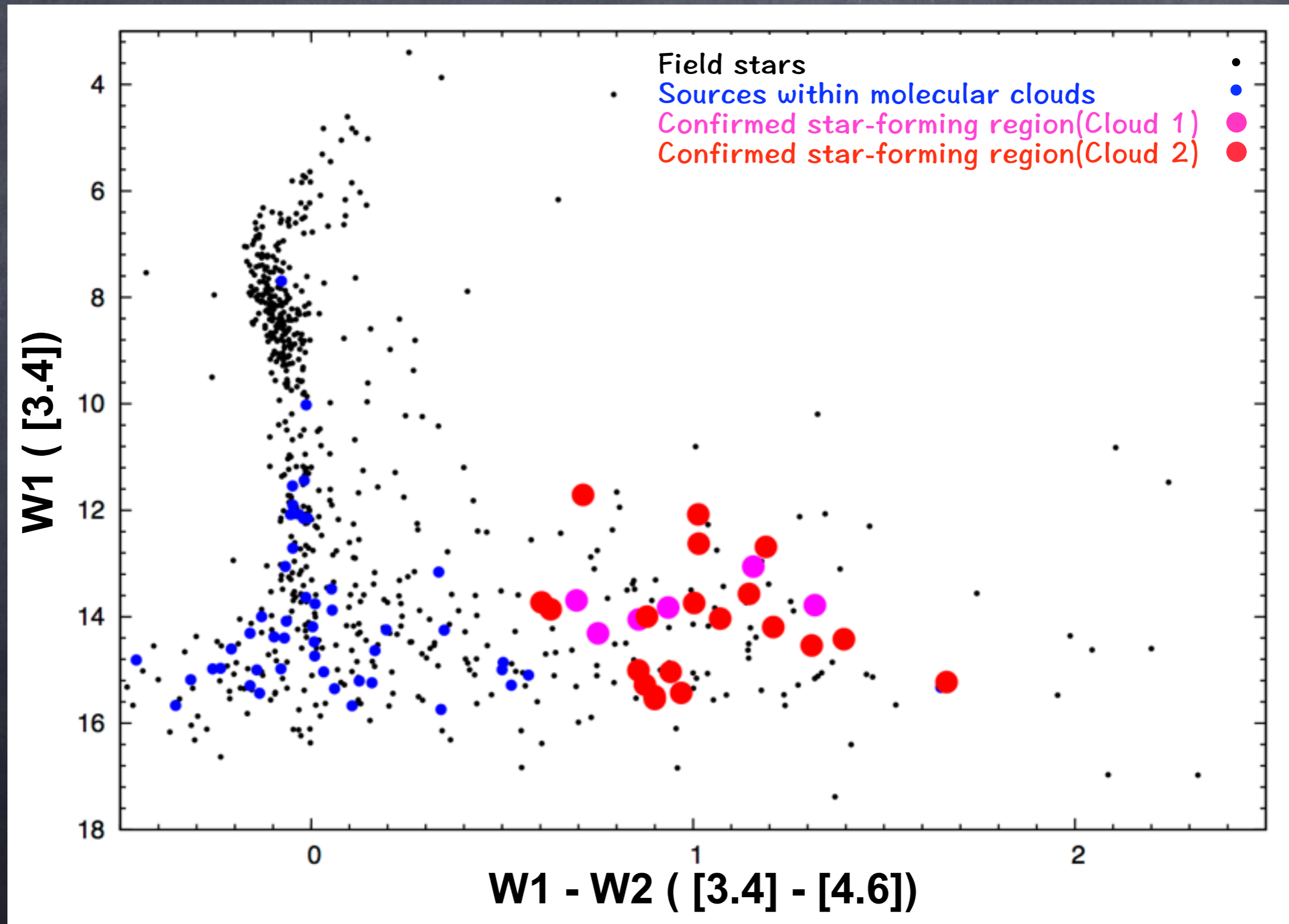
Search for star-forming region in the EOG with WISE data

Color - color diagram (w1-w2 vs w2-w3)



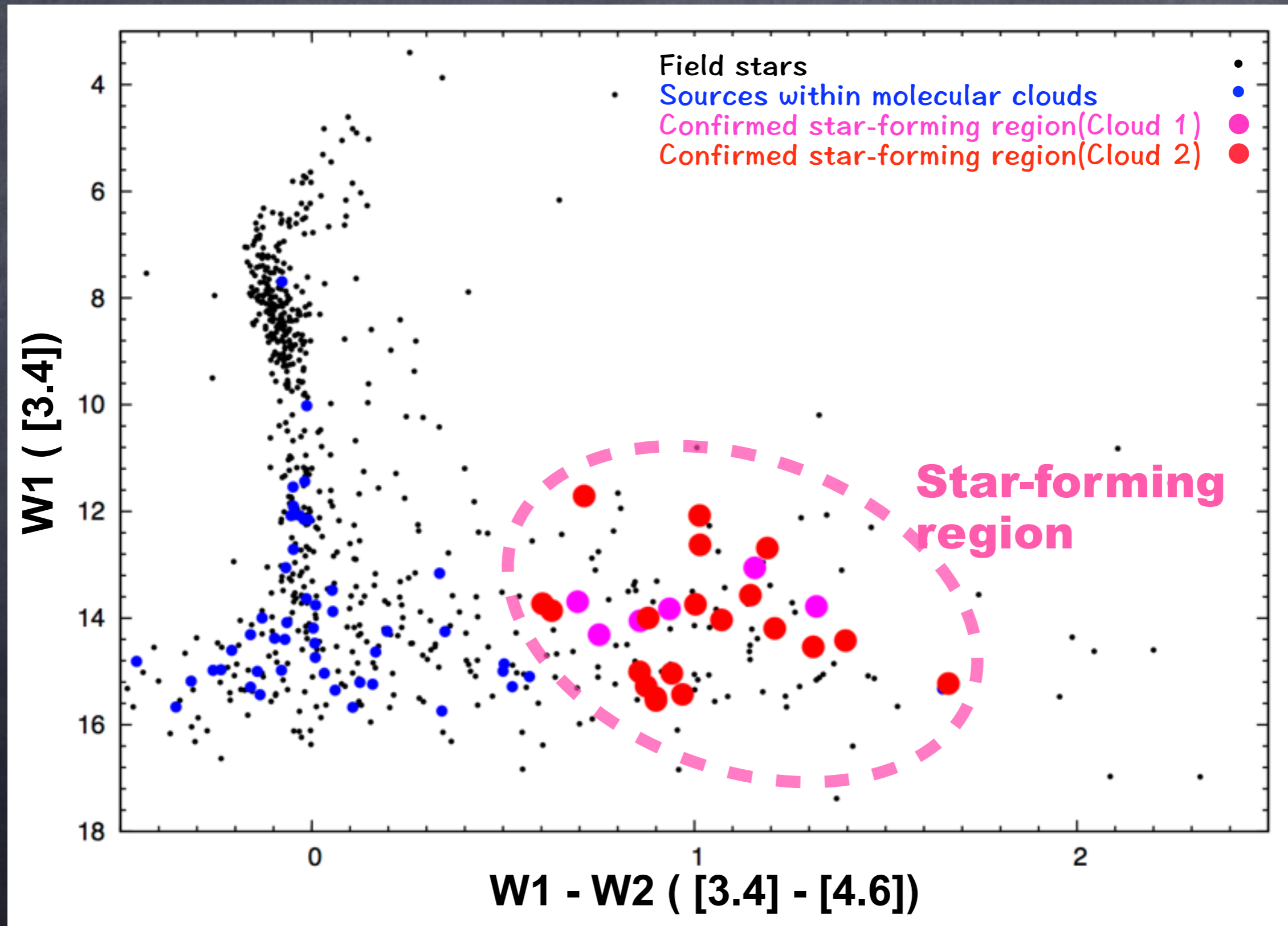
Search for star-forming region in the EOG with WISE data

Color - magnitude diagram (w1 vs w1-w2)



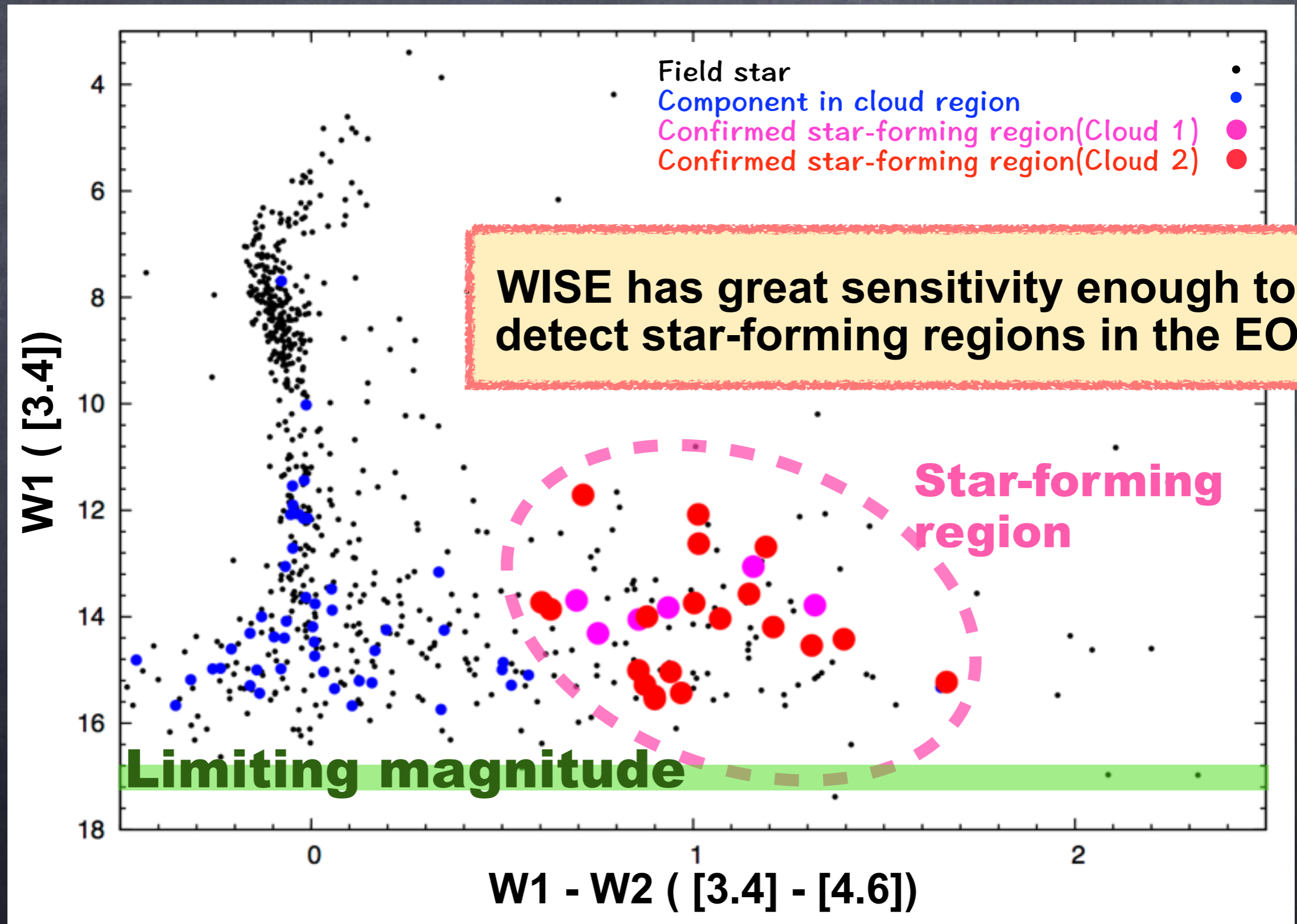
Search for star-forming region in the EOG with WISE data

Color - magnitude diagram (w1 vs w1-w2)



Search for star-forming region in the EOG with WISE data

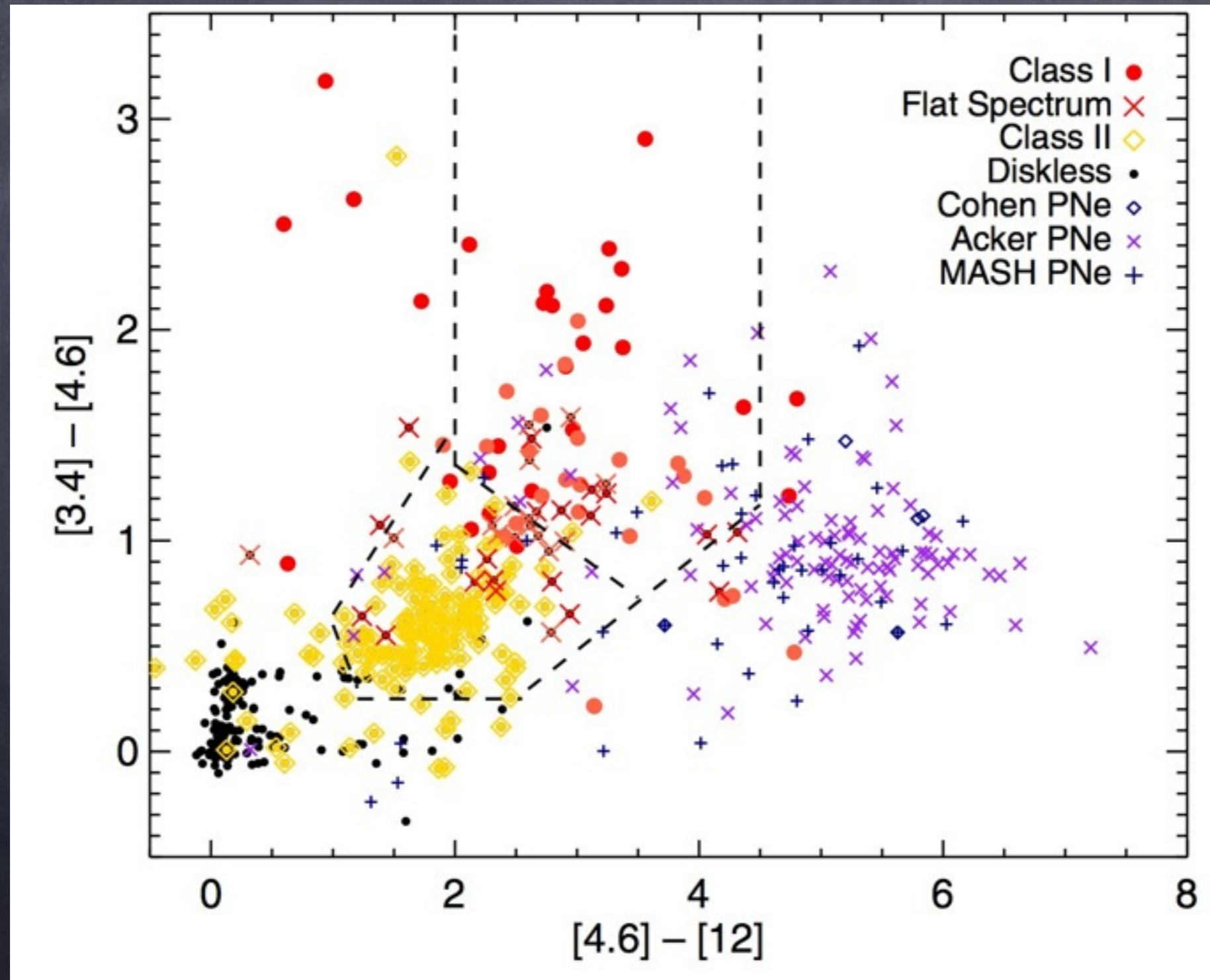
Color - magnitude diagram (w1 vs w1-w2)



Search for star-forming region in the EOG with WISE data

■ Comparison with Koenig's diagram

- Color-color diagram for individual YSOs

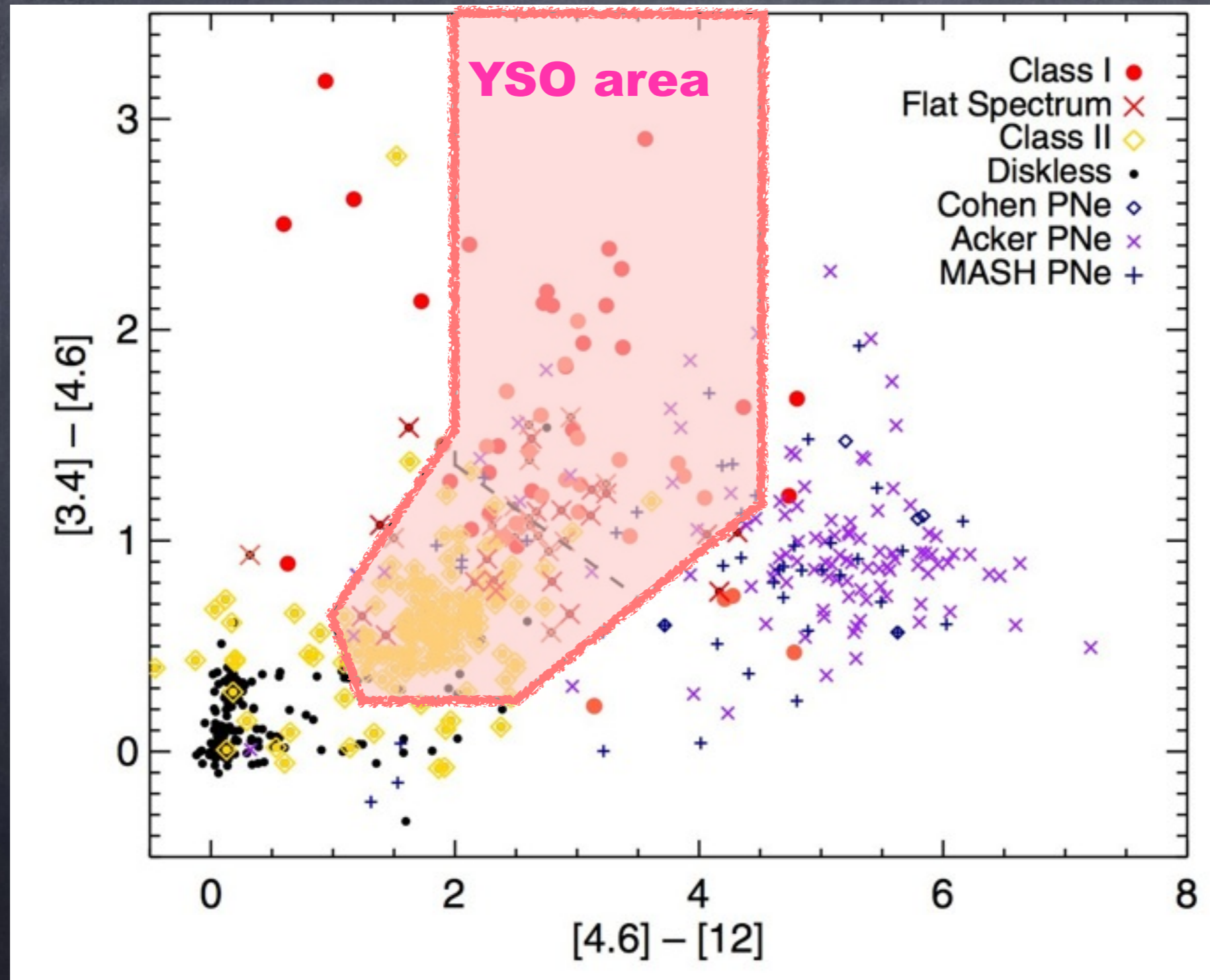


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ Comparison with Koenig's diagram

- Color-color diagram for individual YSOs

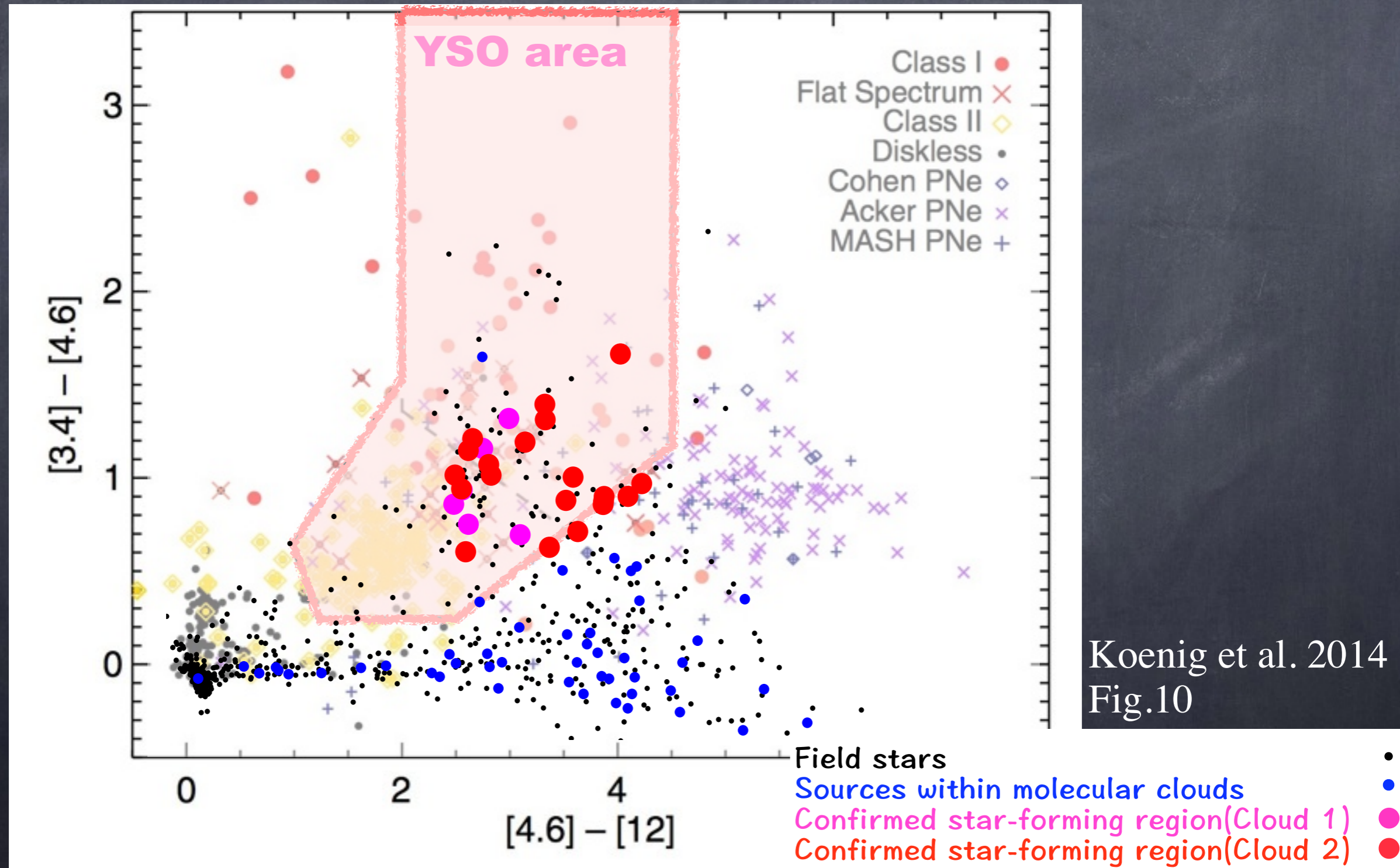


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ Comparison with Koenig's diagram

- Color-color diagram for individual YSOs

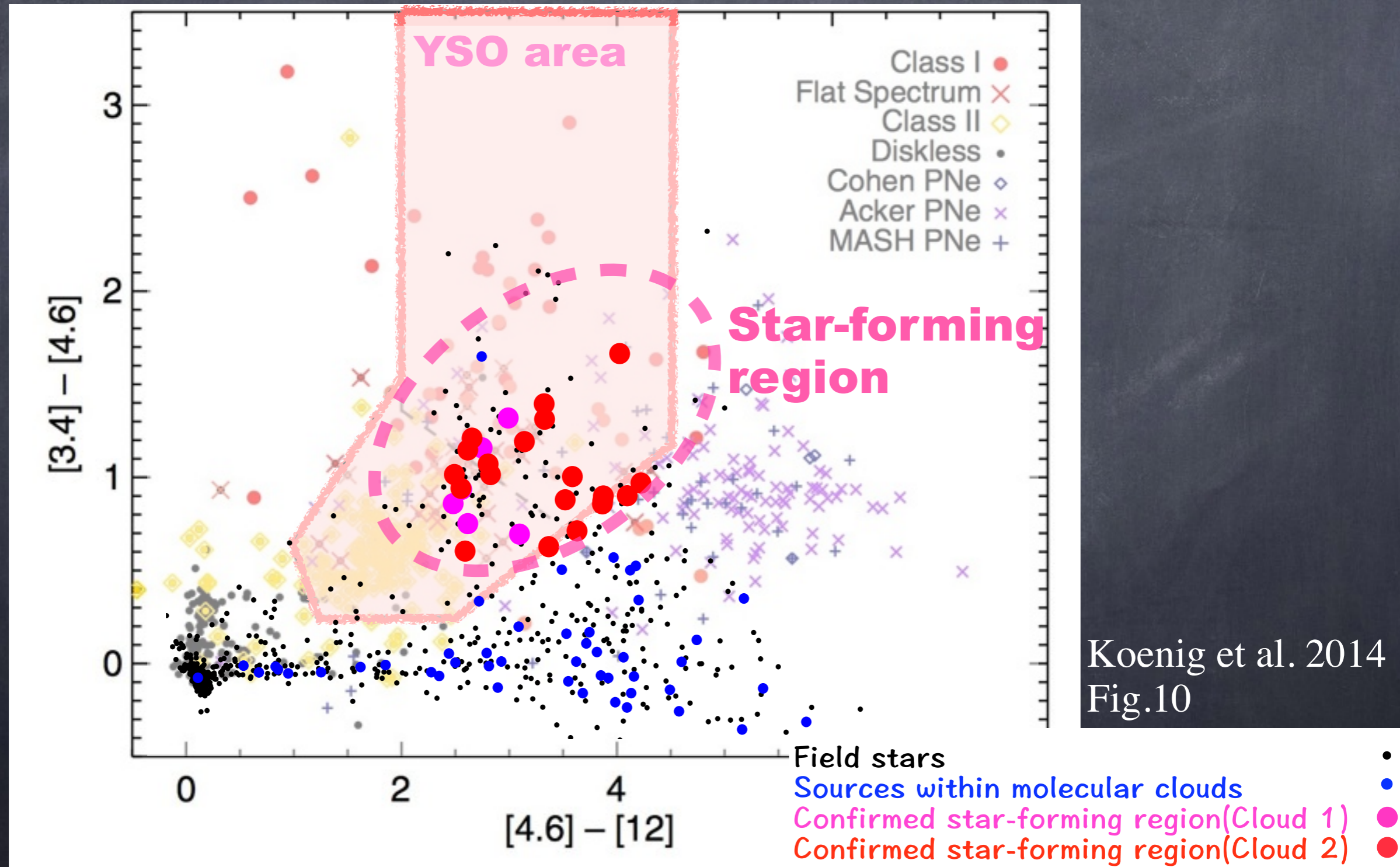


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ Comparison with Koenig's diagram

- Color-color diagram for individual YSOs



Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ WISE Properties of the star-forming region in the EOG

- Star-forming regions appear to have the **same color as individual YSOs.**
 - But we checked **only for two molecular clouds.**



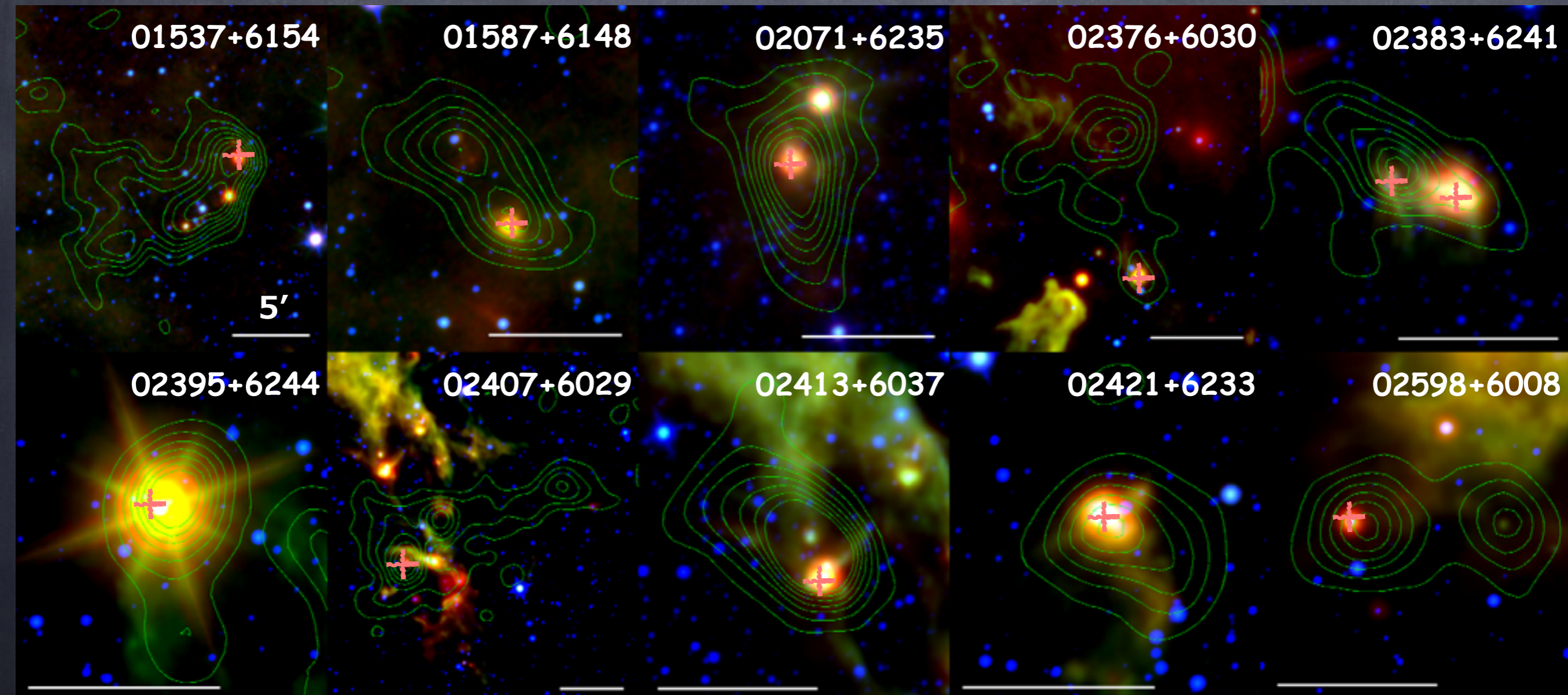
- Next, we are going to confirm this results with star-forming regions in the **FOG ($D = 7 \sim 10$ kpc, $R_G = 13.5 \sim 18$ kpc)**
 - There are 11 embedded clusters confirmed by NIR imaging in the FOG

Snell et al. 2002

Search for star-forming region in the EOG with WISE data

■ Embedded cluster in the FOG

- WISE color images (3.4: blue, 12:green, 22:red)

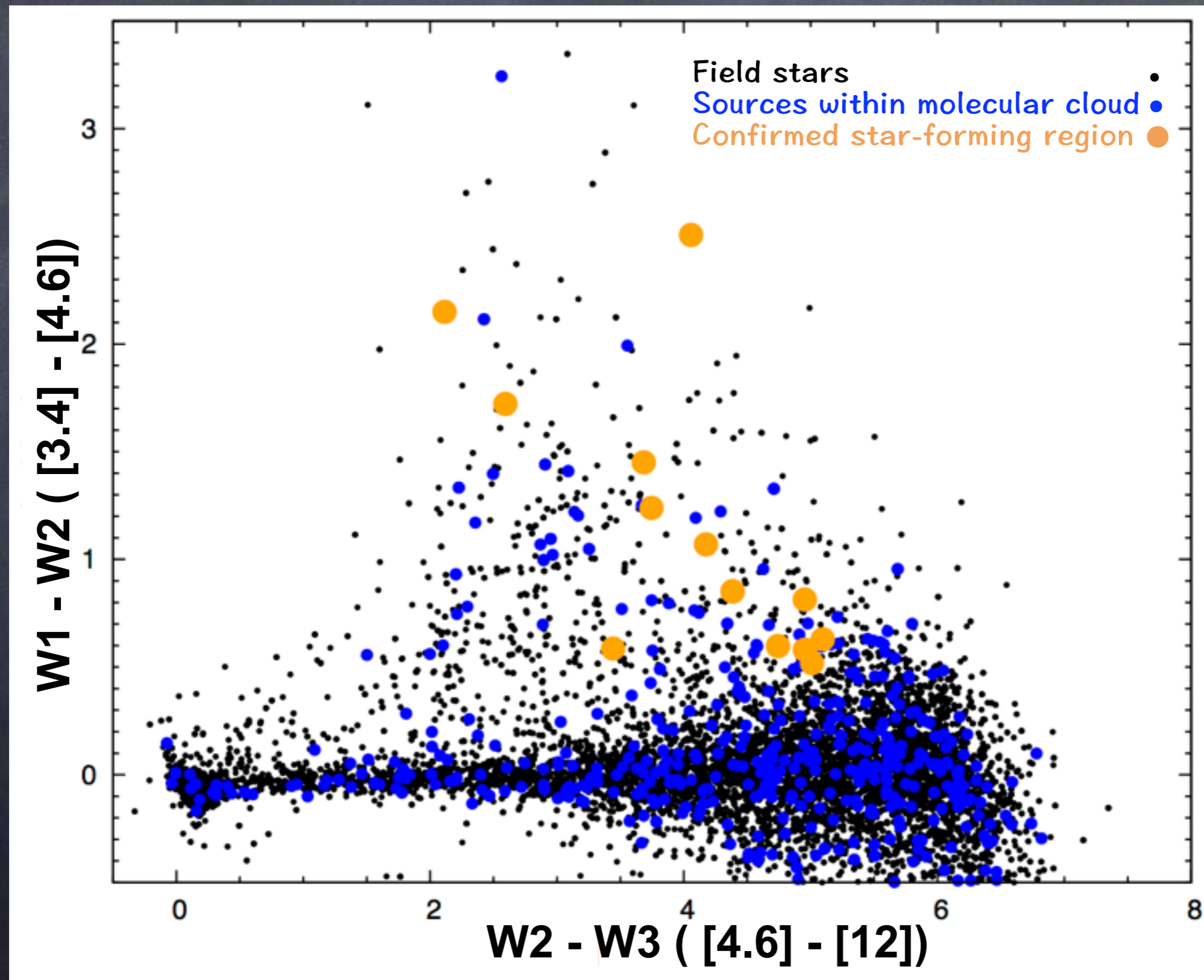


+ NIR Confirmed star-forming region

— ^{12}CO (FCRAO survey data : beam size ~ 45")

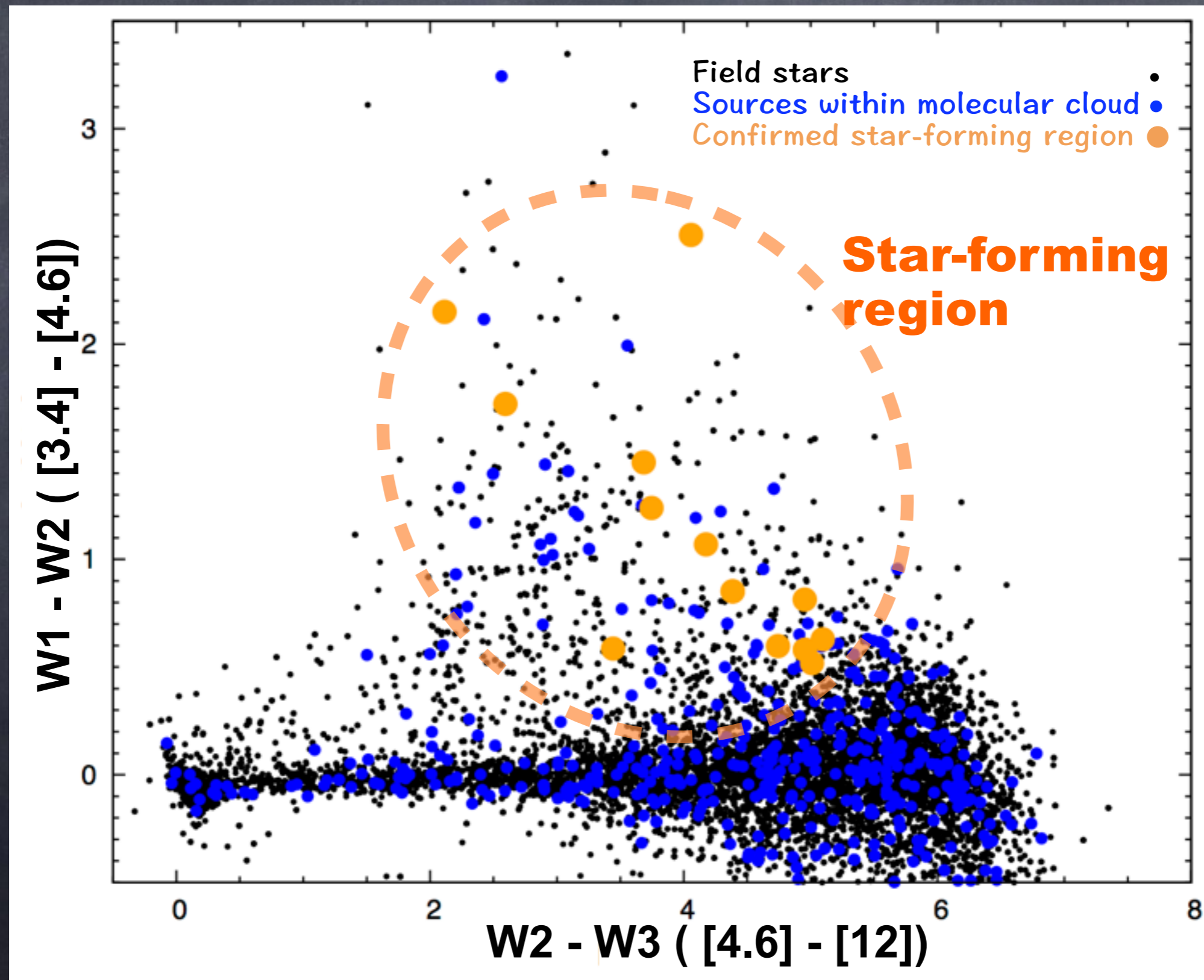
Search for star-forming region in the EOG with WISE data

■ Color-color diagram of the clusters in the FOG



Search for star-forming region in the EOG with WISE data

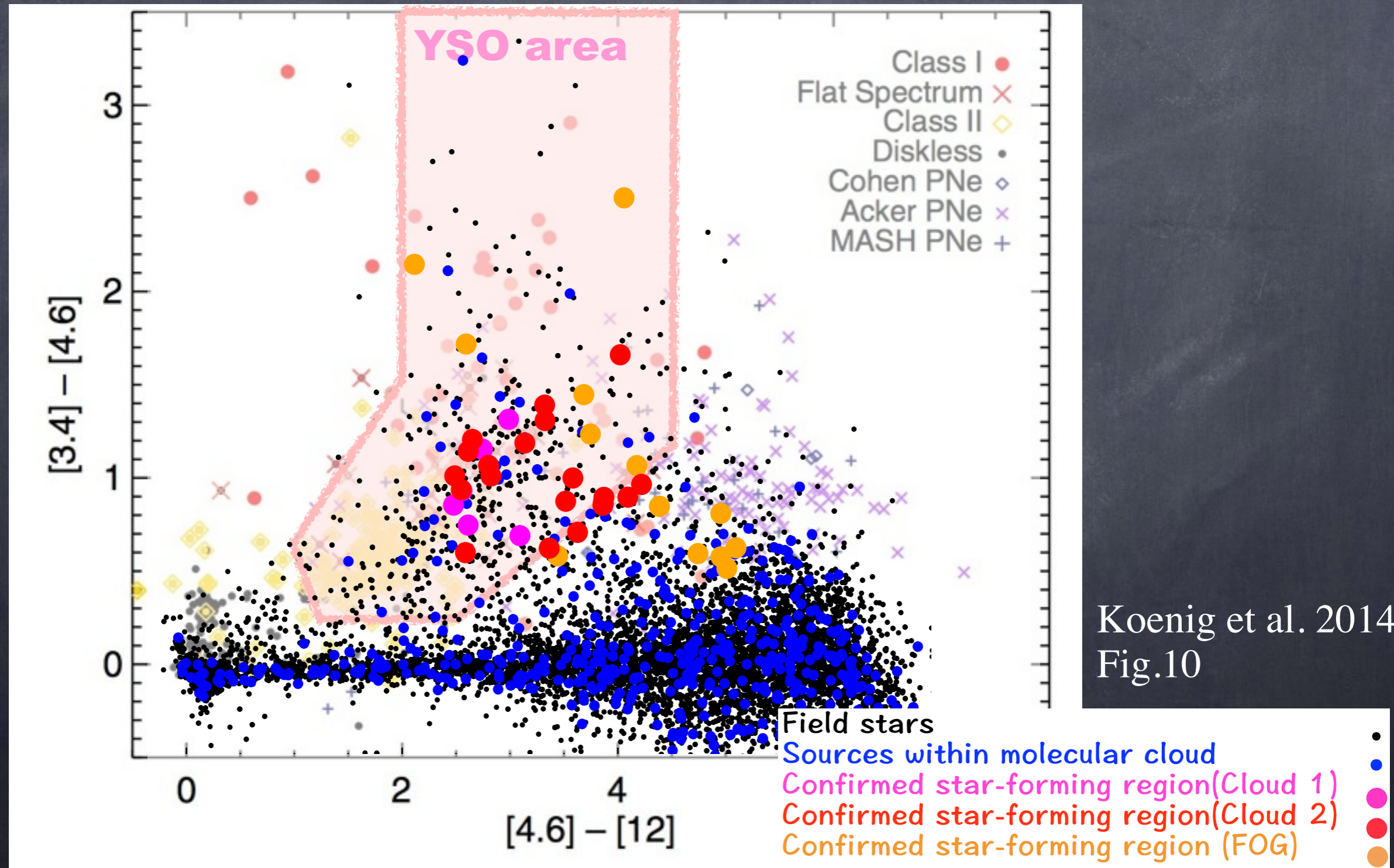
Color-color diagram of the clusters in the FOG



Search for star-forming region in the EOG with WISE data

■ Comparison with Koenig's diagram

- Color-color diagram for individual YSOs

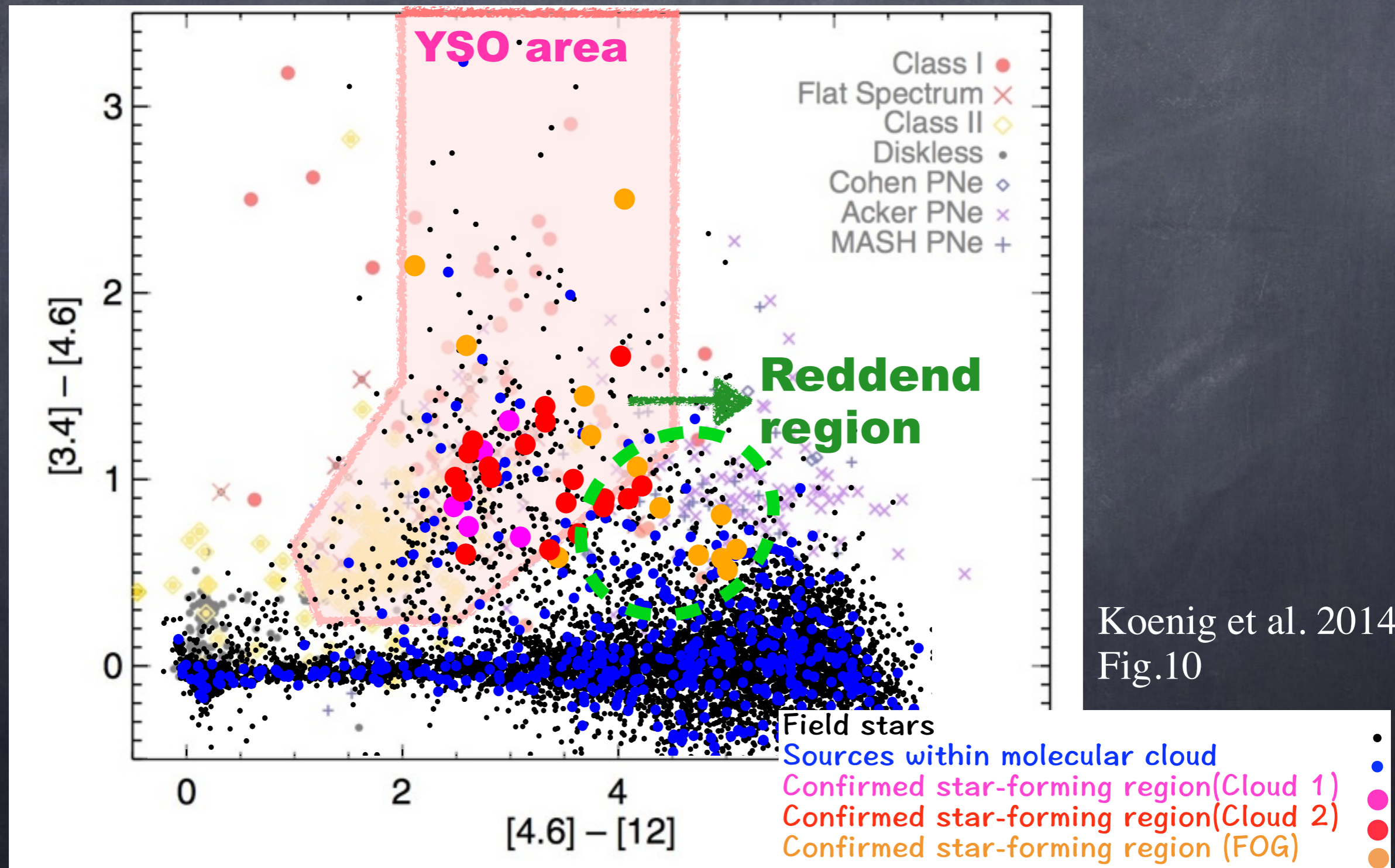


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

Location of Star-forming region

- Color-color diagram

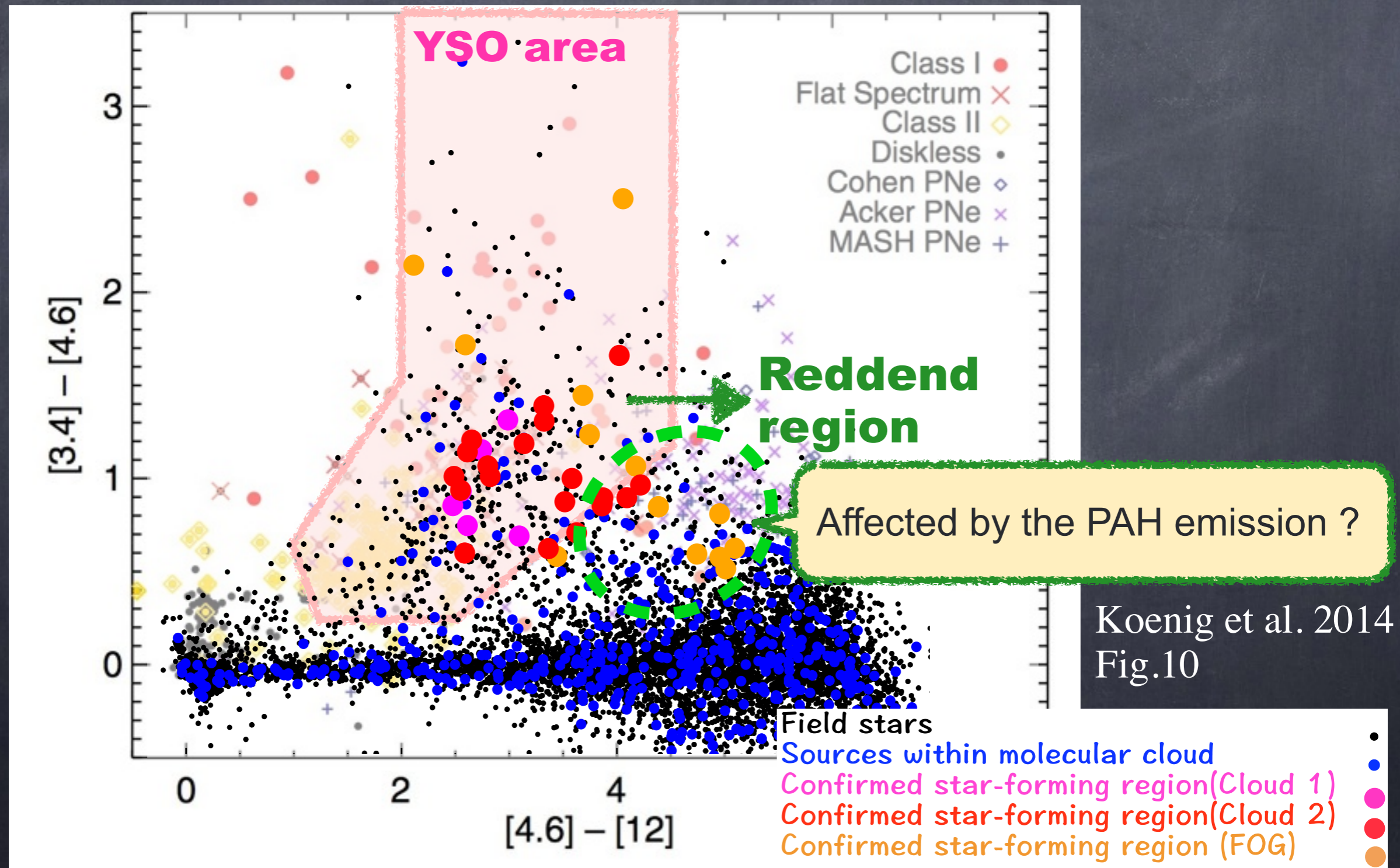


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

Location of Star-forming region

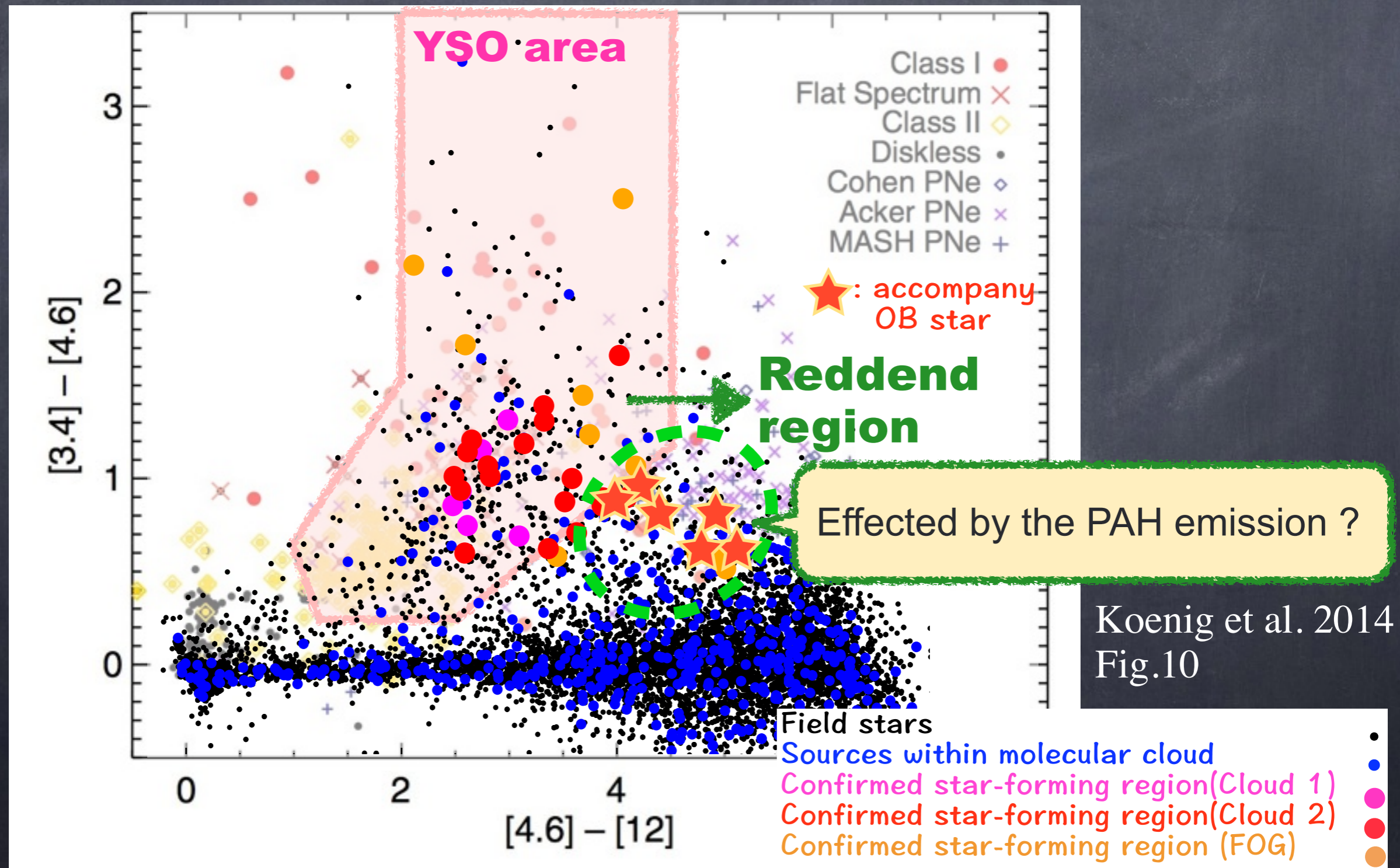
- Color-color diagram



Search for star-forming region in the EOG with WISE data

Location of Star-forming region

- Color-color diagram

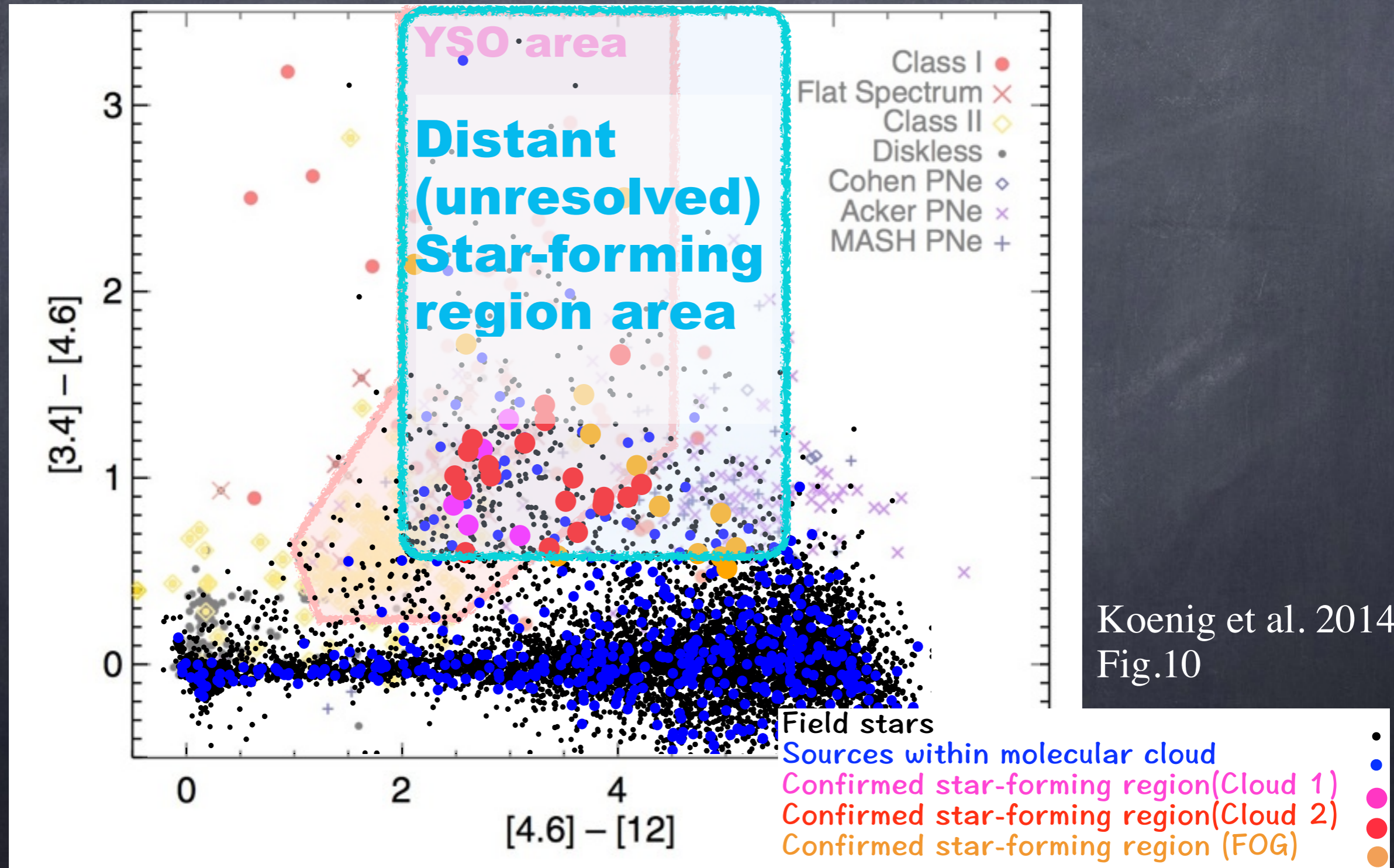


Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ Star-forming region area

- Color-color diagram



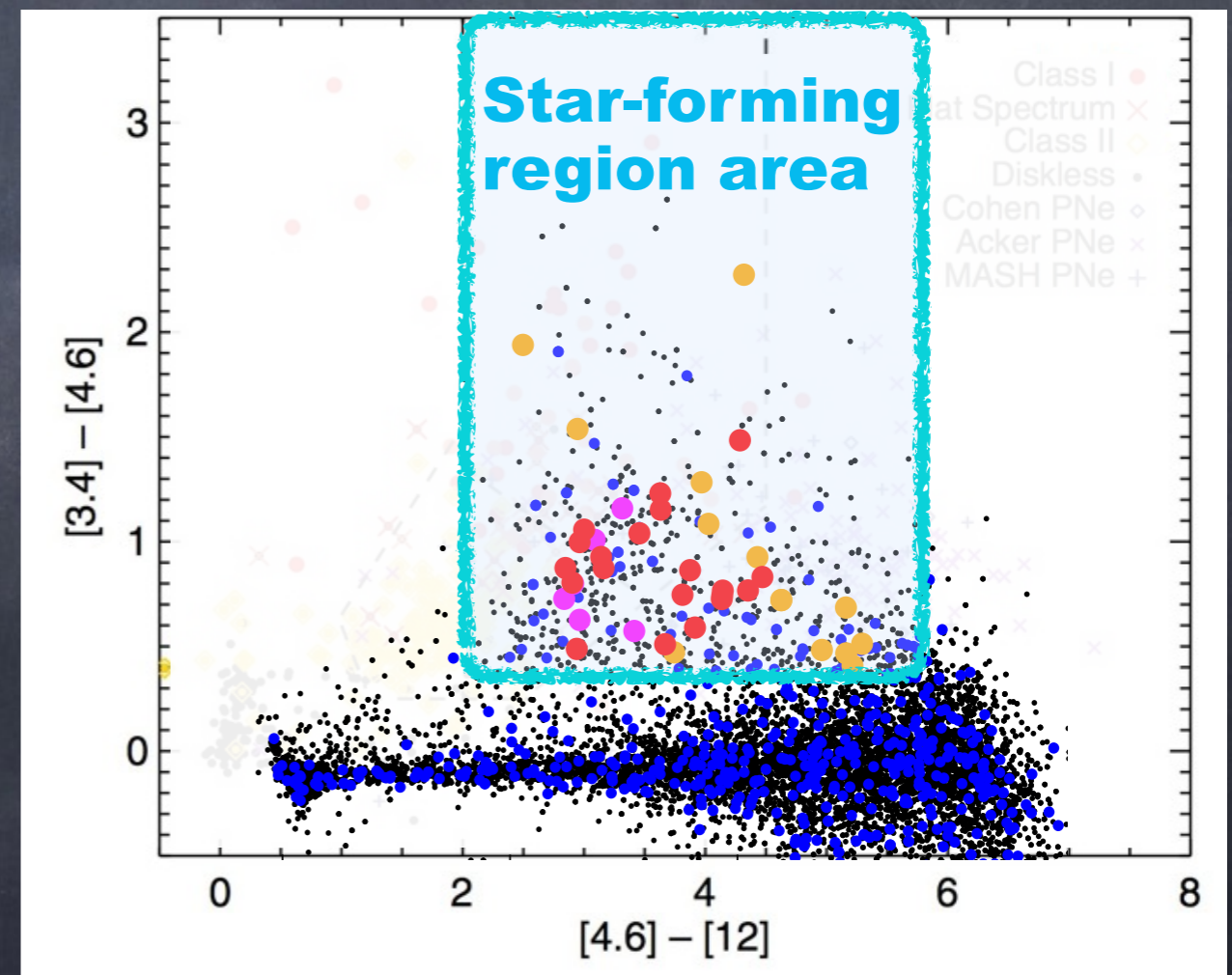
Koenig et al. 2014
Fig.10

Search for star-forming region in the EOG with WISE data

■ Detection criteria of distant (unresolved) star-forming region

1. Located within CO molecular clouds on the sky
2. Located at Star-forming region area in the color-color diagram

- $w1 - w2 \cong \sim 0.5$
- $w2 - w3 \cong \sim 2.0$
- $w2 - w3 \cong \sim 6.0$

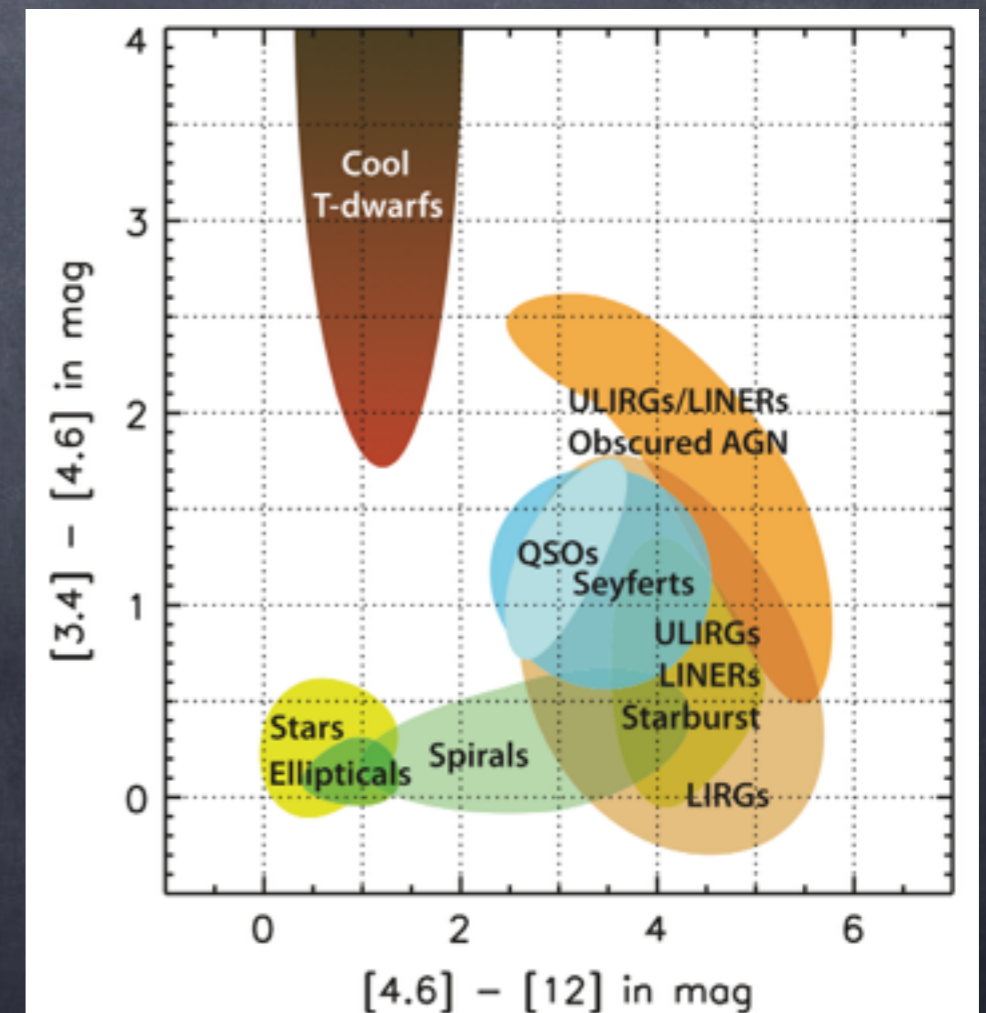
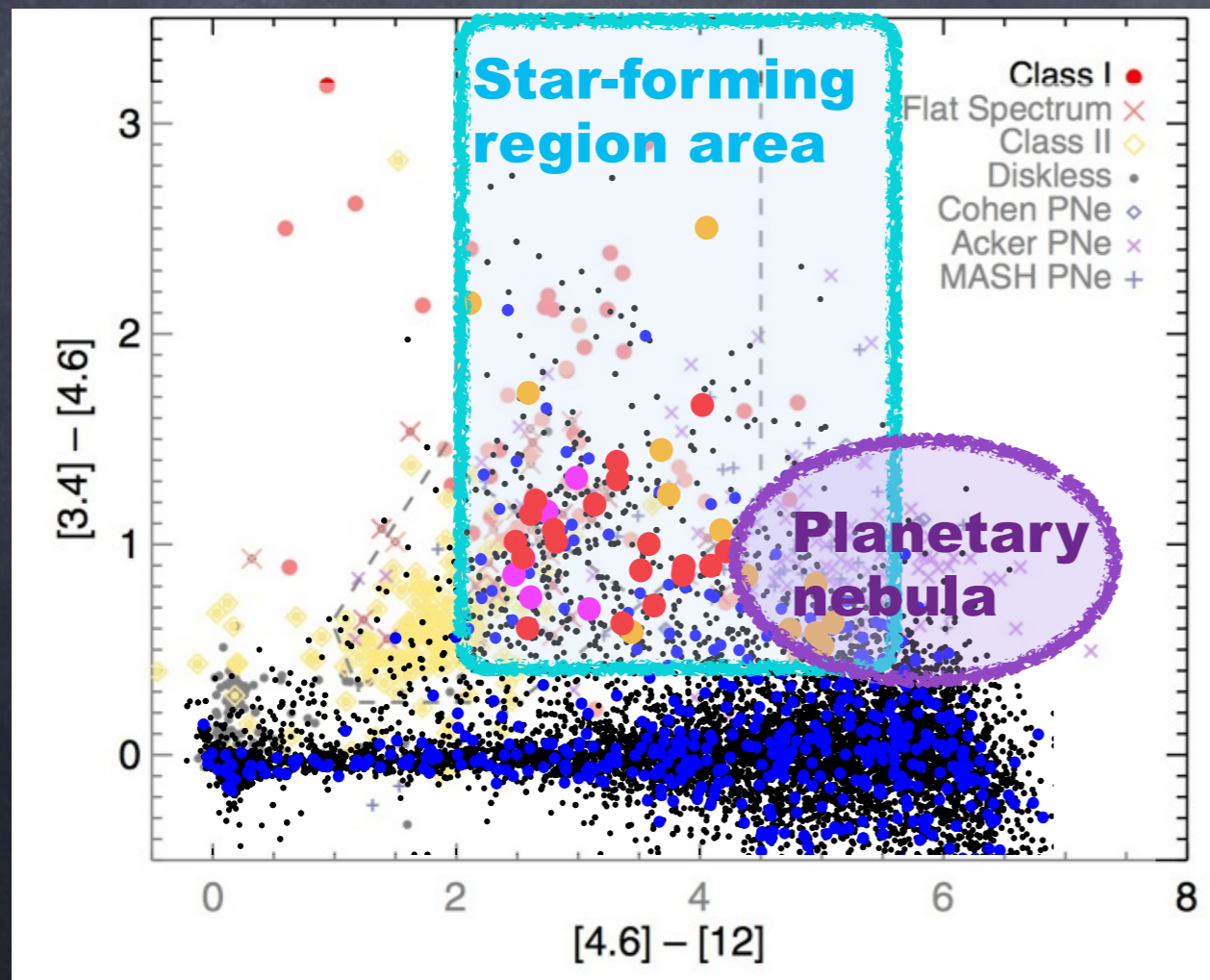


Search for star-forming region in the EOG with WISE data

■ Detection criteria of distant (unresolved) star-forming region

- Contamination Problems

- Ex) Planetary nebula, Background AGNs ...



Search for star-forming region in the EOG with WISE data

■ Detection criteria of distant (unresolved) star-forming region

- Contamination Problems

- Ex) Planetary nebula, Background AGNs ...
- The probability would be quite low in view of the small area of the distant molecular clouds.

→ Utilize **high-resolution CO data** to define the cloud region more clearly

Search for star-forming region in the EOG with WISE data

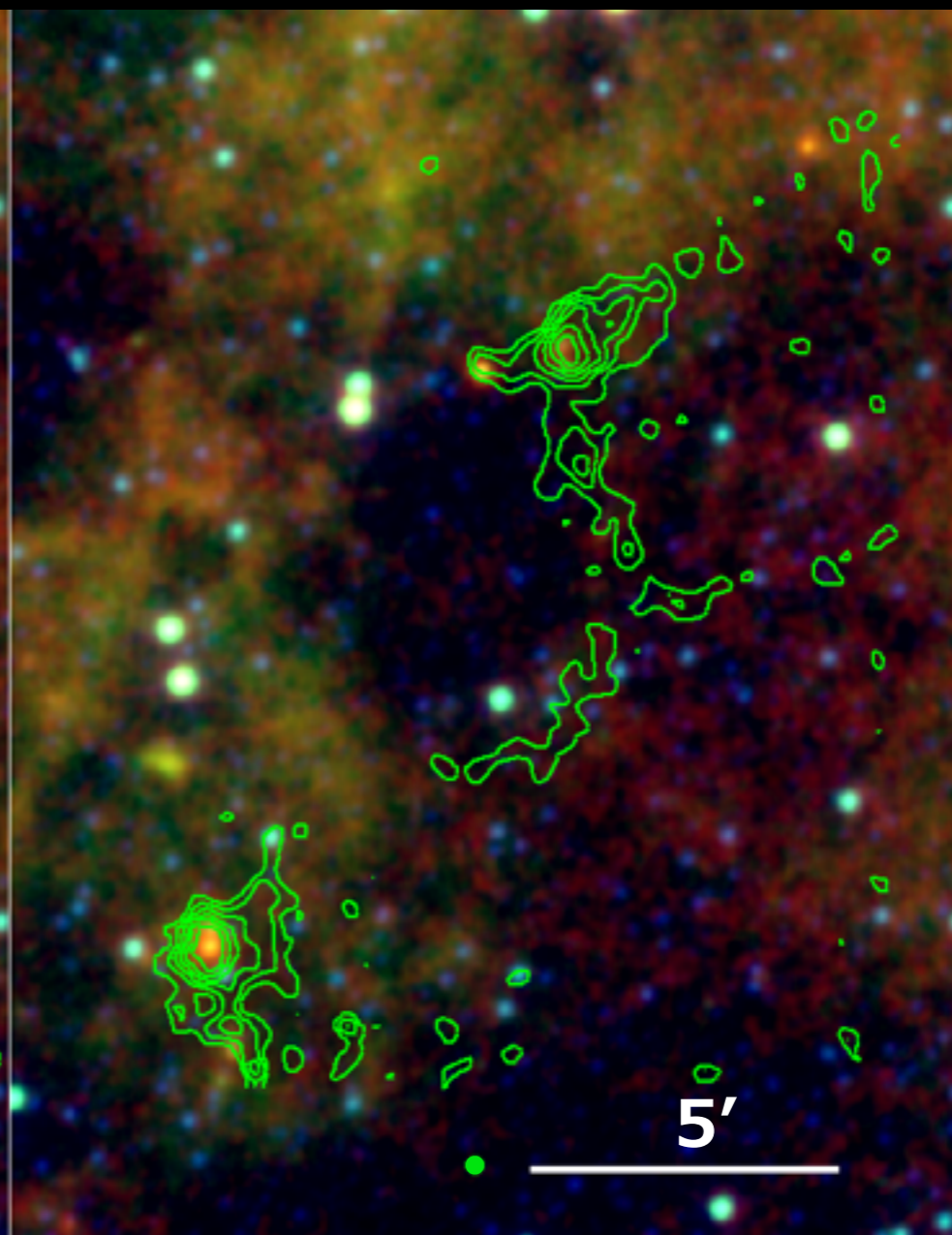
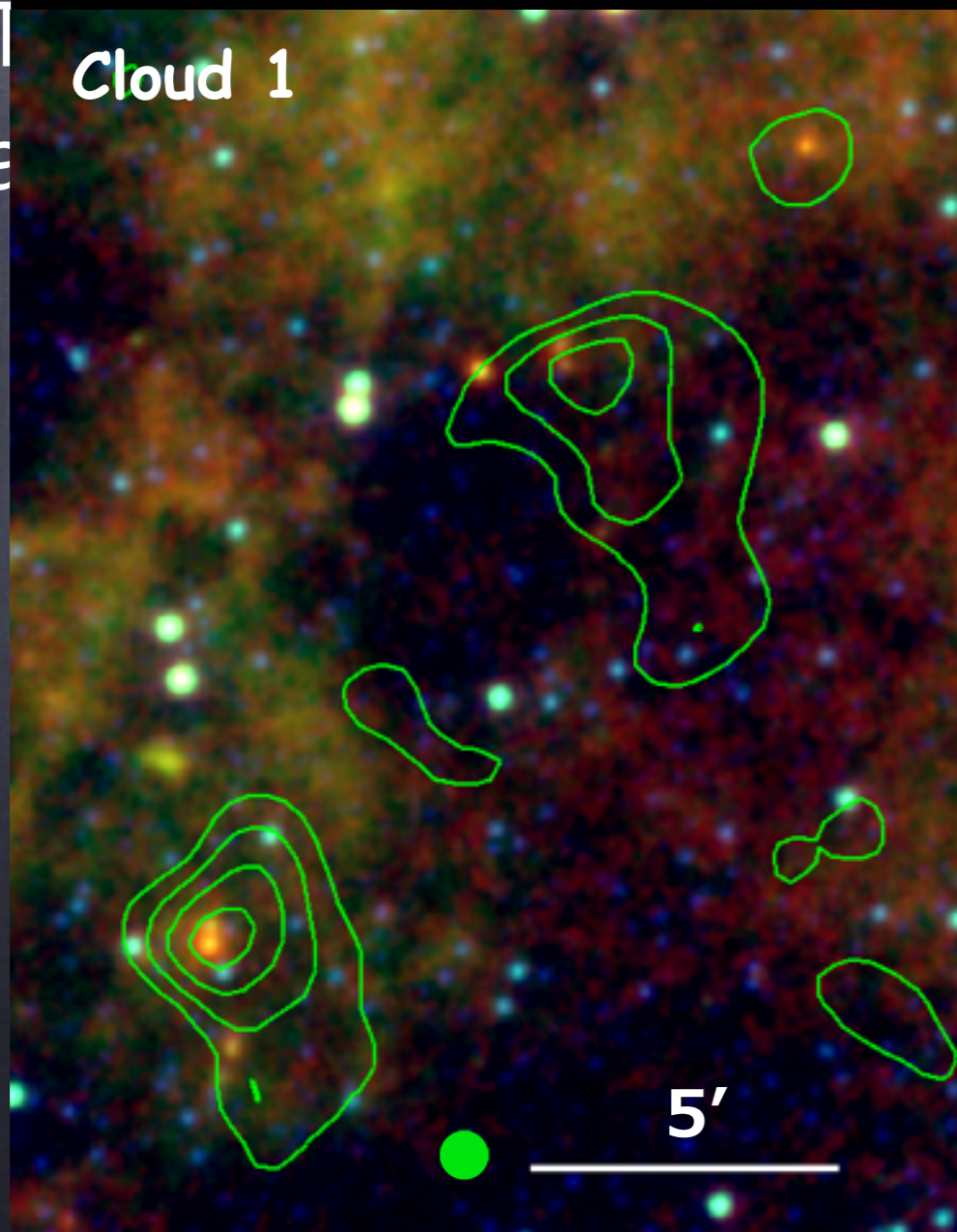
■ Detection criteria of distant (unresolved) star-forming region

- Contamination Problems

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FCRAO 14m
(resolution ~ 45'')

Nobeyama 45m
(resolution ~ 17'')



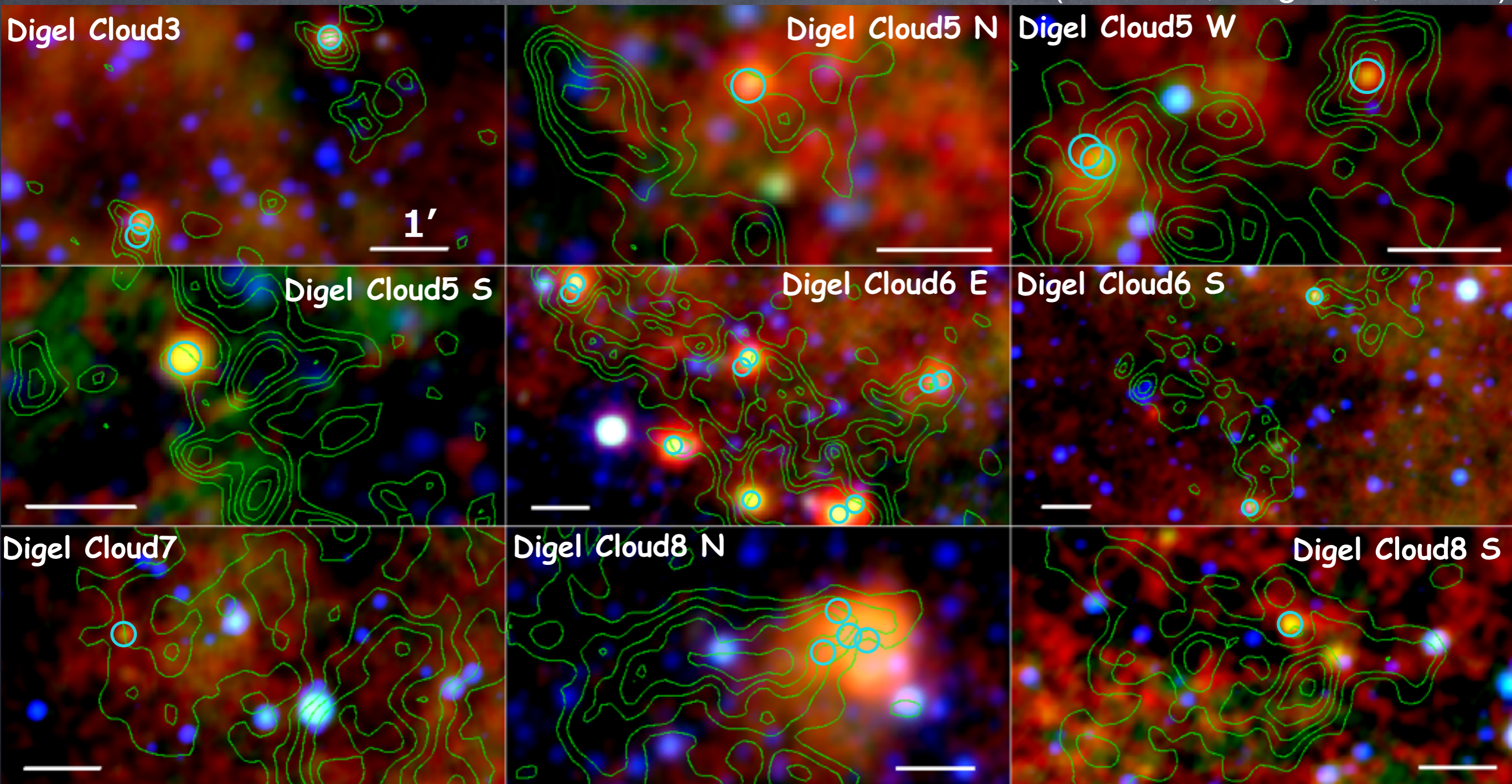
small

e the

Search for star-forming region in the EOG with WISE data

■ New candidates in the EOG

(3.4: blue, 12:green, 22:red)



○ New candidate

— ^{12}CO (Nobeyama 45m data : beam size ~ 17")

We found 17 new candidates for star-forming region

Summary and Future Works

■ Summary

- WISE has great sensitivity to detect distant star-forming regions even in the EOG ($R_G \geq 18$ kpc)

All star-forming regions could be detected up to the edge of the Galaxy

- We defined tentative detection criteria using WISE color-color diagram, which may be able to effectively pick up distant star-forming regions.

■ Future works

- Search for star-forming regions in all molecular clouds in the EOG from the recent CO surveys.
- Study star-formation properties (SFR, SFE) in the EOG with WISE data