Subaru UM FY2025

Subaru/MOIRCS Wide-field Multi-object Spectroscopy of Very Low-mass Objects in the R CrA region

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Introduction

Very Low-mass Objects

Planetary mass-objects(PMO)	Brown Dwarfs (BD)
M<0.013M⊙	0.08M⊙

Objectives

- How abundant are the very low-mass objects (VLMOs)?
- How do they form?
- Do their formations depend on the local environment or not?

Characteristics of VLMOs

- Cool temperatures
- Relatively bright at younger ages

→ NIR Photometric/spectroscopic surveys of young BDs/PMOs in the various star-forming regions

Survey of Very low-mass objects

JHK Photometric Survey — Identify VLMO candidates

- Select YSO candidates from existence of NIR excess
- Estimate mass from derived luminosity with the age assumption of 1 Myr

Follow-up Spectroscopy — Confirm young VLMOs

- Identify YSOs from observed spectra
- Determine Teff from the water absorption bands
- Derive mass/ages of YSOs from the evolutionally tracks

We have been conducted photometric/spectroscopic surveys in various (massive-, intermediate-, low-mass) star-forming regions to reveal the formations of VLMOs.

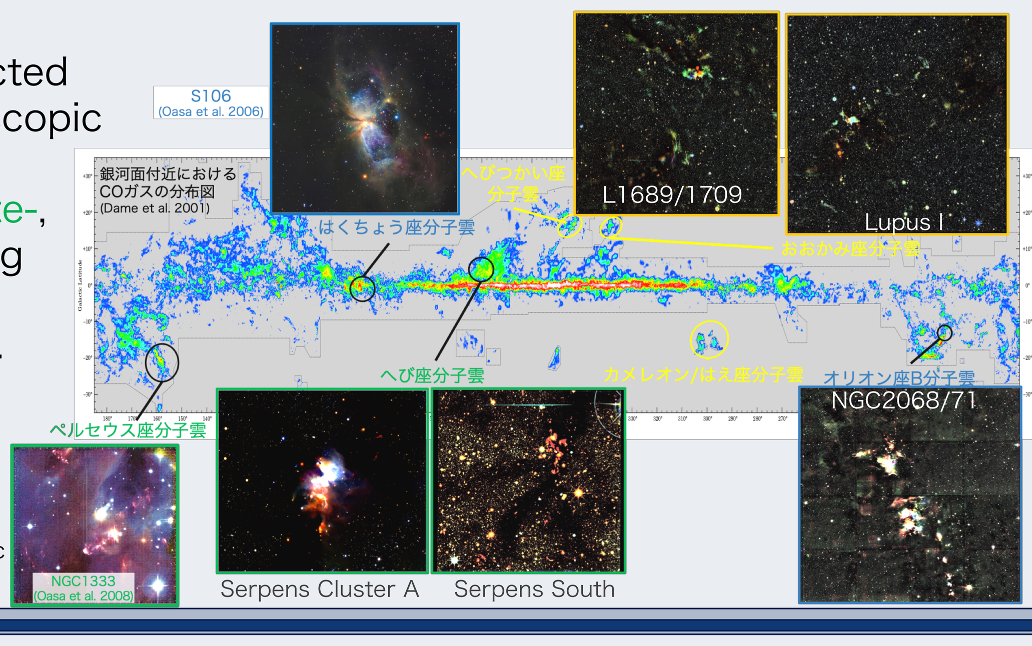

Fig.1: Regions that NIR photometric survey had been conducted

R Corona Australis region

Low to intermediate-mass star-forming region
Distance : ~150pc (Gali et al. 2020) R CrA: Herbig Be star (Gray et al. 2006)
Cloud mass : ~820M⊙ (Bresnahan et al. 2018)

- Dozens of YSOs were identified from X-ray to Radio observations (e.g. Nehauser & Forbrich 2008).
- YSOs including BDs that are not embedded in the cloud were identified from Gaia DR2 astrometry and NIR spectroscopy (Esplin & Luhman 2022).
- Deep NIR survey for embedded BDs/PMOs has not been performed.

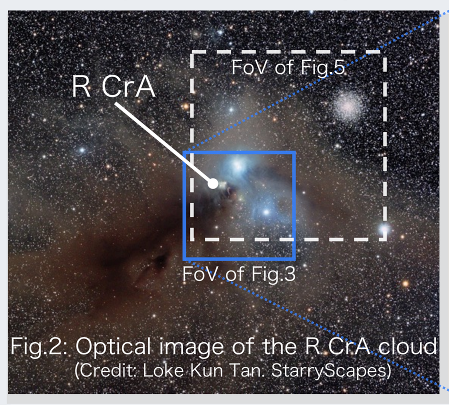

Fig.2: Optical image of the R.CrA cloud (Credit: Loke Kun Tan: StarryScapes)

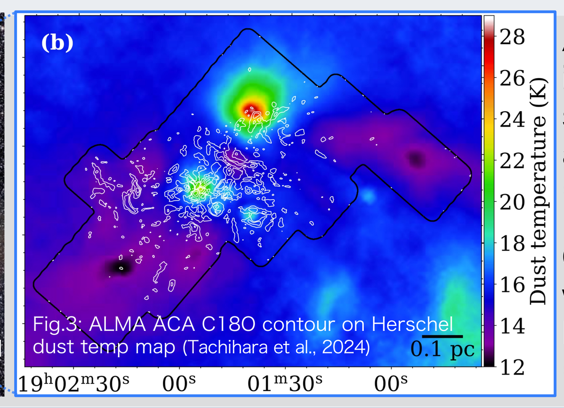

Fig.3: ALMA ACA C18O contour on Herschel dust temp map (Tachihara et al. 2024)

ALMA ACA observations identified ~100 filamentary structures with widths of a few thousand AU (Tachihara et al. 2024).

Cloud dust column density were estimated from Herschel observations (Bresnahan et al., 2018)

○Purposes

- Identify VLMO candidates from NIR photometric survey
- Derive the mass/age of VLMOs from follow-up spectroscopy

→ reveal the environmental dependencies of their formations

Photometric Survey

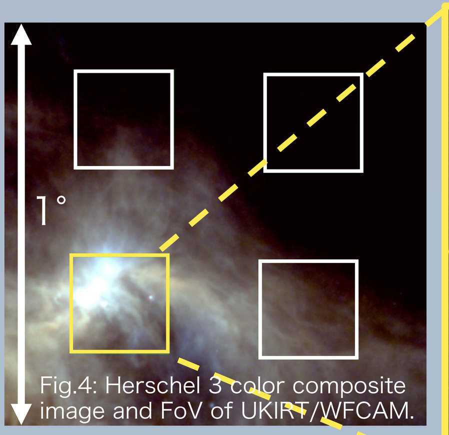

Fig.4: Herschel 3 color composite image and FoV of UKIRT/WFCAM.

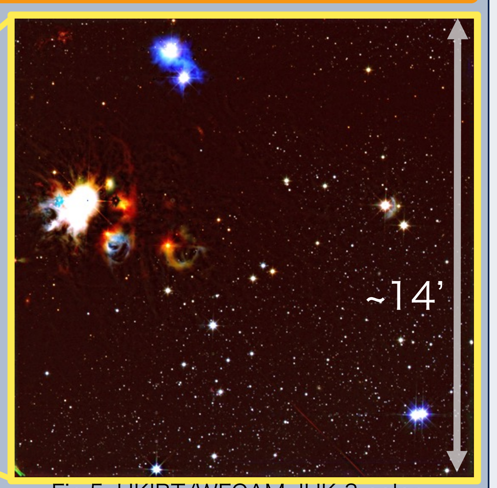

Fig.5: UKIRT/WFCAM JHK 3 color composite image of the R CrA region

Observations

Telescope/Instrument	UKIRT/WFCAM
Observed bands	J, H, K (expt. 800s)
Date of Obs.	2010/08/08
Field of View	13.7'×13.7'× 4 fields
Lim. mag.(S/N=10)	J ~21, H ~20, K ~19mag

1. YSO candidate selection

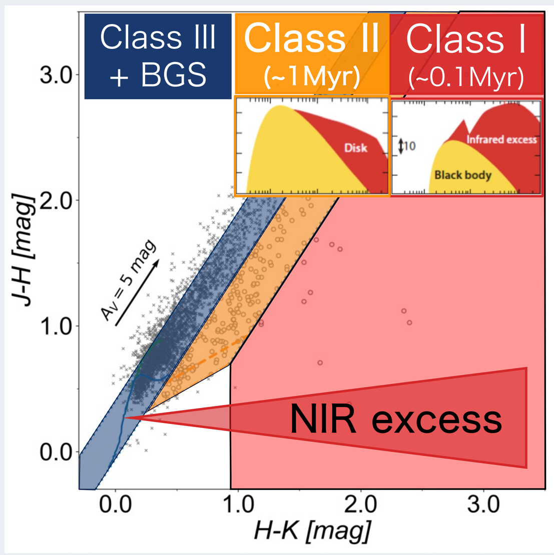

Fig.6 [J-H]/[H-K] color-color diagram

Select YSO candidates with NIR excess from observed colors.

Class III +BGS	Class II	Class I
2335	207	15

Estimate masses of Class II candidates from evolutionally tracks (Baraffe et al., 2015) with an age assumptions of 1 Myr.

PMO cand.	BD cand.	TTS cand.
196	5	6

2. Spatial distributions of YSO candidates

- Class I candidates
  → Cloud core region $N_{H2} \geqq 10\times10^{21}/cm^2$
- TTS/BD candidates
  → Southern part of the cloud $N_{H2} \geqq 2.5\times10^{21}/cm^2$
- PMO candidates
  → All over the observed region

Differ with the YSO mass ?

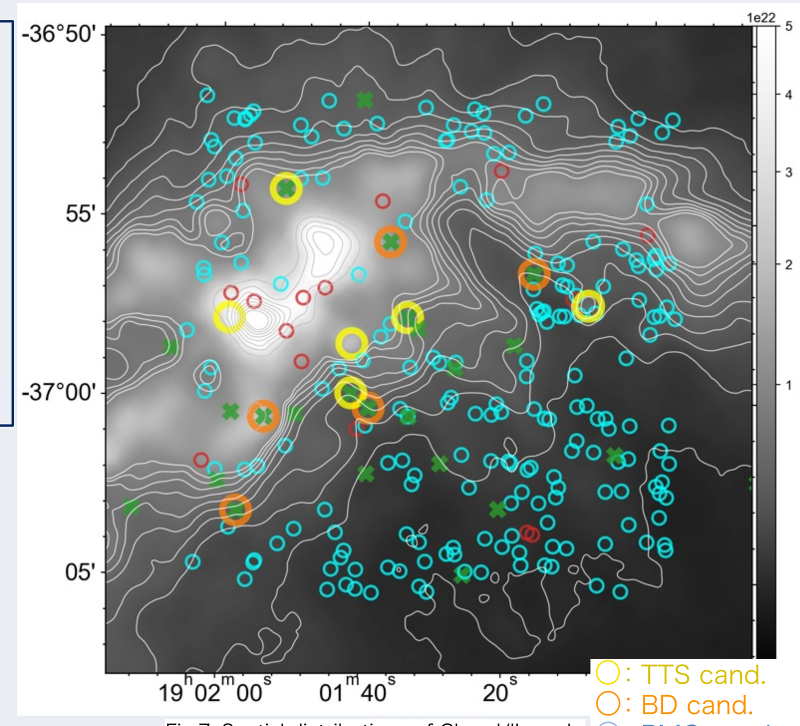

Fig.7: Spatial distributions of Class I/II cand. with Herschel H_2 column density map.

Does the local dust density affect the low-mass star formation?

Uncertainties in the photometric survey

- Background contaminations of extragalactic sources
- Age assumptions on the mass estimation

→ Follow-up Spectroscopy is necessary to derive mass/age of YSOs

Follow-up Spectroscopy

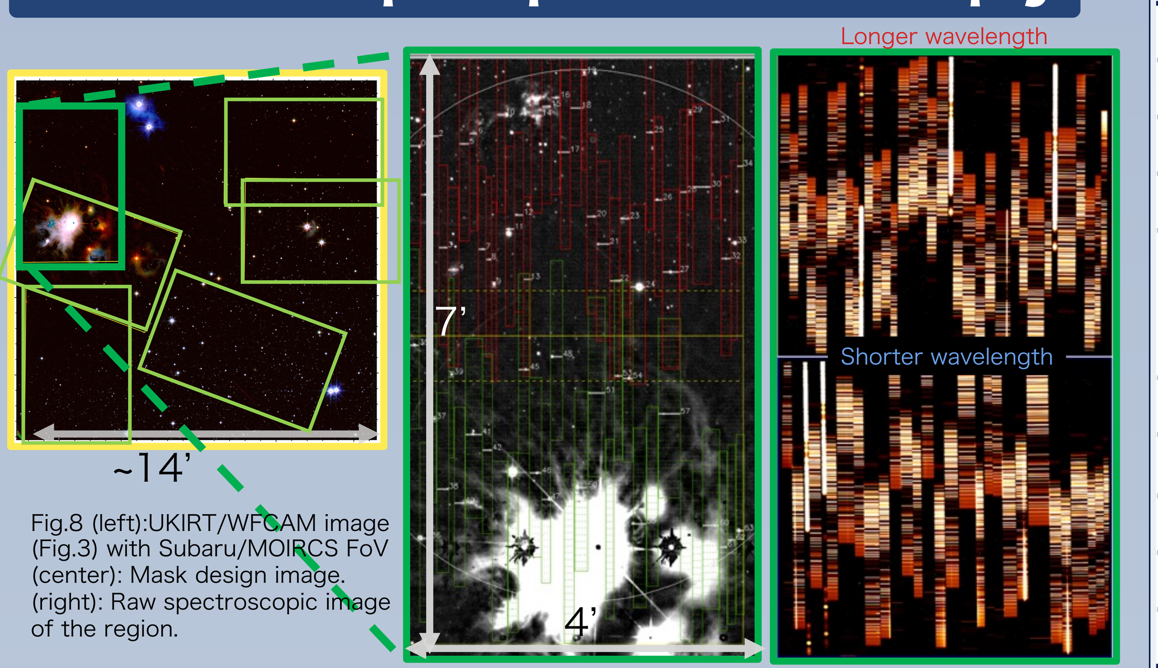

Fig.8 (left):UKIRT/WFCAM image (Fig.3) with Subaru/MOIRCS FoV (center): Mask design image. (right): Raw spectroscopic image of the region.

Observations

Telescope	Subaru
Instrument	MOIRCS
Observed bands	HK (1.3-2.3μm)
Resolution	~500
Date of observation	2020/09/02 2023/07/07,08 2024/05/22
Seeing	0.3 - 0.8"
Field of View	3.9'×6.9'×6 masks
Number of objects	319 (Analyzed:200)
Exp. time	1440-5280s
Target mag.	H < 20mag

1. Obtained spectra

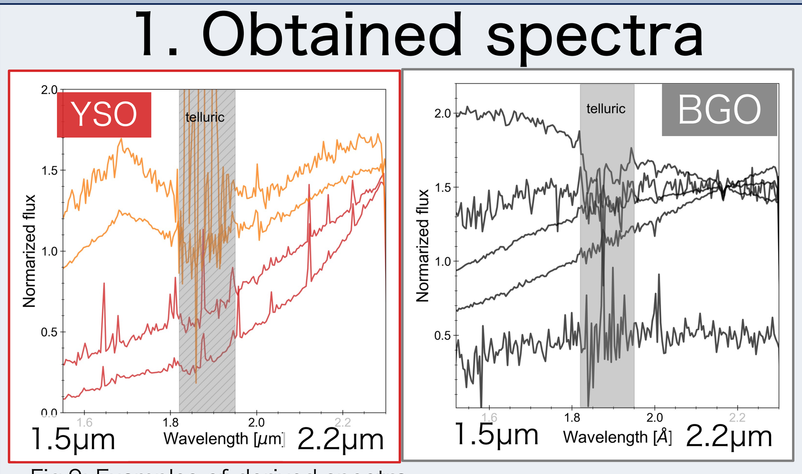

Fig.9: Examples of derived spectra.

Classified spectra from their features

○YSO

- Class I : Large IR excess
- H_2O:Water absorption bands in the H-band

○ Background objects (BGOs; stars or galaxies)

- Br γ absorption
- No significant features in the HK-band

Photometry	Class II candidates		Class I	Other
	PMO Cand.	BD Cand.		
Observed	80	4	13	222
Analyzed	46	4	12	138
Poor S/N	25	0	5	30

2. Determination of T_{eff}

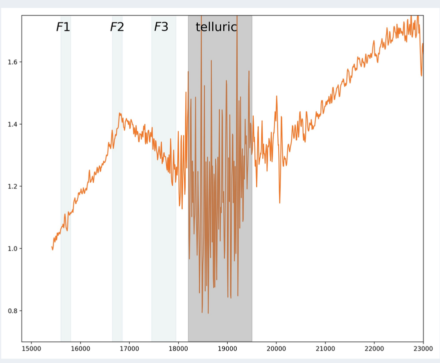

Fig.10 Wavelength range of index Q

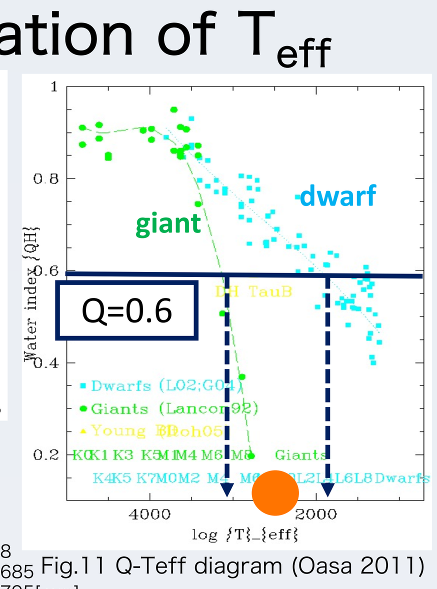

Fig.11 Q-Teff diagram (Oasa 2011)

$$Q = \left(\frac{F1}{F2}\right)\left(\frac{F3}{F2}\right)^{1.282}$$

F1=1.56-1.58, F2=1.665-1.685, F3=1.745-1.795[μm]

Teff of YSOs were determined from reddening independent water absorption index Q(Oasa 2011).

Water absorption bands are

- stronger for the cooler stars
- shallower for the reddened stars
  → using reddening independent index.
- sensitive to the surface gravity
  → T_{eff} of YSOs : average of $T_{eff\text{-}dwarf}$ and $T_{eff\text{-}giant}$.

3. Derive mass/age of YSOs

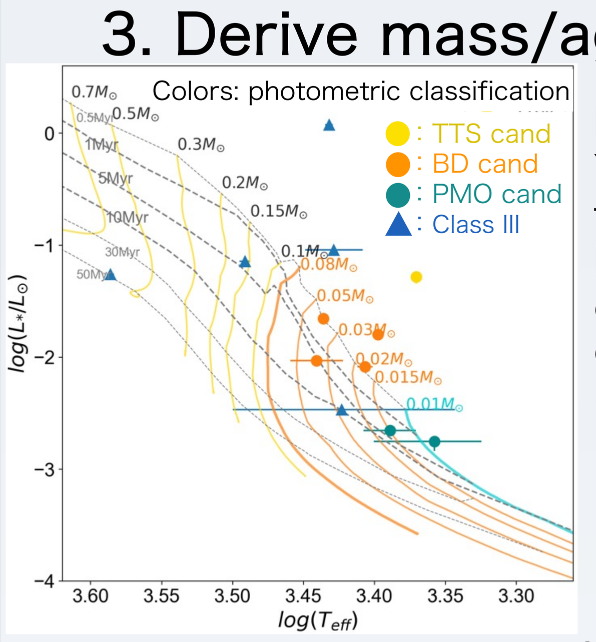

Fig.12: H-R diagram of spectroscopically confirmed YSOs

Masses and ages of YSOs were estimated from the bolometric luminosity and T_{eff} comparing with the evolutionary tracks (e.g. Baraffe et al. 2015).

- 8 young BDs
- 1 young PMO
- 5 Class I objects

were identified.

→ Identified first young PMO in the central part of R CrA region from spectroscopy

4. Spatial distributions of YSOs

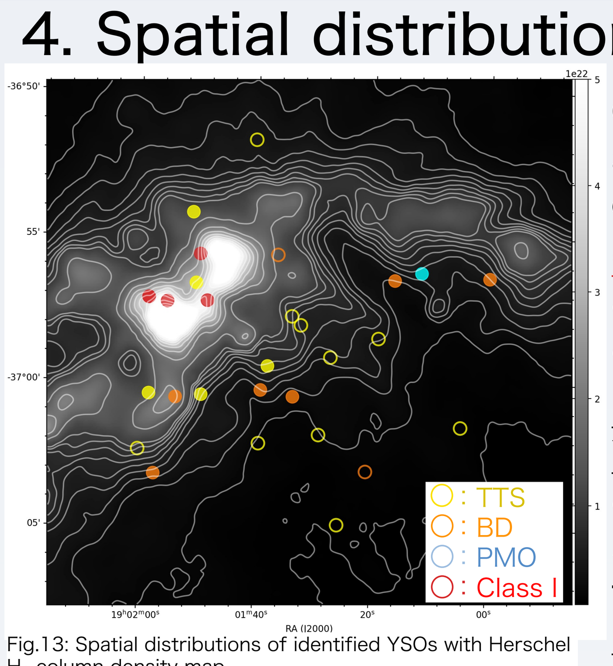

Fig.13: Spatial distributions of identified YSOs with Herschel H_2 column density map.

Compared YSOs and Herschel H_2 column density

Class I objects : concentrated in cloud core region

Most of Identified YSOs : distributed in the southern part of the cloud with lower Av values

Identified BDs are not embedded in the cloud
→ Located near the surface of the cloud

5. Spectroscopic mass vs cloud dust density

Compared YSO mass and cloud dust density in the R CrA region and NGC1333

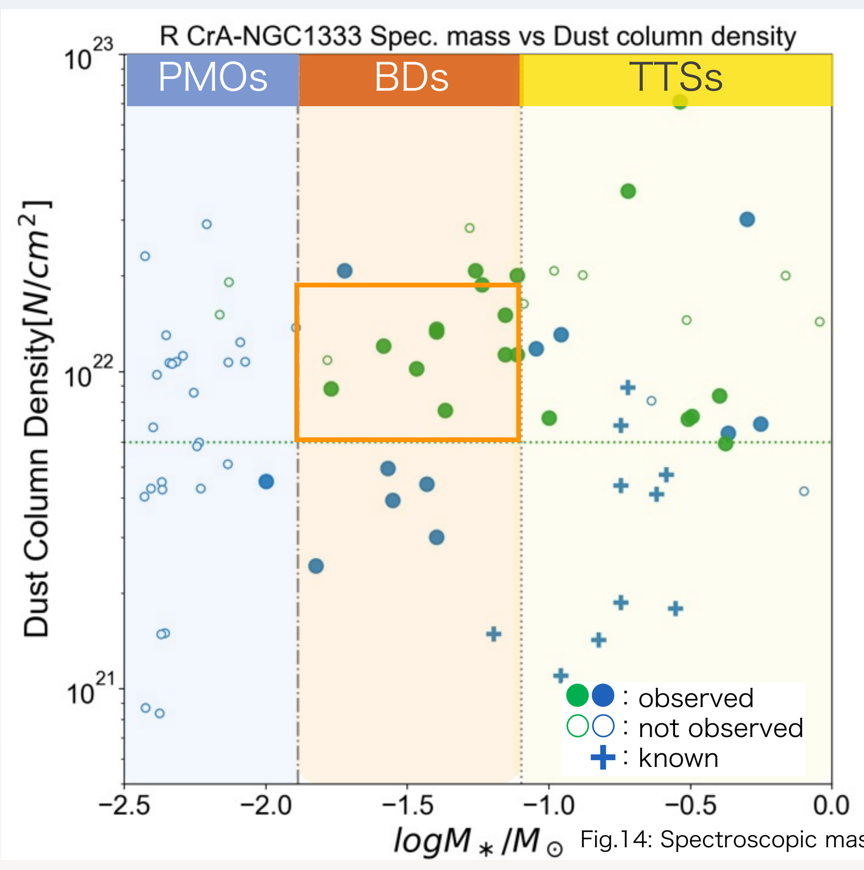

Fig.14: Spectroscopic mass of R CrA (blue) and NGC1333 (green) vs Herschel H_2 column density

○BDs in the R CrA region

- Not identified in N_{H2}=5-10×10²¹/cm²
- BD number density : 11/pc²
- Reddening : low (Av=0 to few mag)

→ located near the surface of the cloud

○BDs in the NGC1333 region

- concentrated in N_{H2}=5-10×10²¹/cm²
- BD number density : 36/pc²
- Reddening : high (Av~10mag)

→ Clustered inside the cloud

BD formations might be different with the local cloud properties (e.g. dust density)

Summary

We have conducted deep NIR photometric/spectroscopic observations of young very low-mass objects in the R CrA region.

○Photometric survey

- Identified ~200 VLMO candidates with NIR excess

○Follow-up spectroscopy

- Confirmed ~10 VLMOs and 5 Class I objects in 50 candidates
- BD formation might differ between R CrA region and NGC1333

Future works

- Observations and analysis of the other star-forming regions
- Efficient survey of VLMOs using H_2O NB filters aimed to detect H_2O absorption bands
  → proposed to KAKENHI Early-Careers
- Development of ULTIMATE-MOS Instrument

It is important to obtain NIR spectra (especially HK-bands) of VLMO candidates as many as possible for our follow-up observations to confirm young VLMOs.

→ Installing Auto-Guider on MOIRCS is necessary to continue NIR Multi-object Spectroscopy in the era of ULTIMATE-Subaru.