

Probing the cold Milky Way---  
Follow-up observations of Planck cold clumps

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On behalf of the TOP-SCOPE collaboration

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1. Kee-Tae Kim will take the place of Tie Liu to coordinate Korean collaborators when Tie Liu leaves Korea in future.

### Coordinators for Joint surveys:

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And more than 150 team members!

# Outline

1. Introduction of On-going surveys
2. Preliminary results and suggestions for SMA
3. SMA case studies of PGCC G192.32–11.88
4. Summary

# 1. Introduction of On-going surveys

# What are Planck galactic cold clumps?



Planck is a third generation space based cosmic microwave background experiment, operating at nine frequencies between 30 and 857 GHz

Planck Catalogue of Galactic Cold Clumps (PGCC), *13188 clumps*

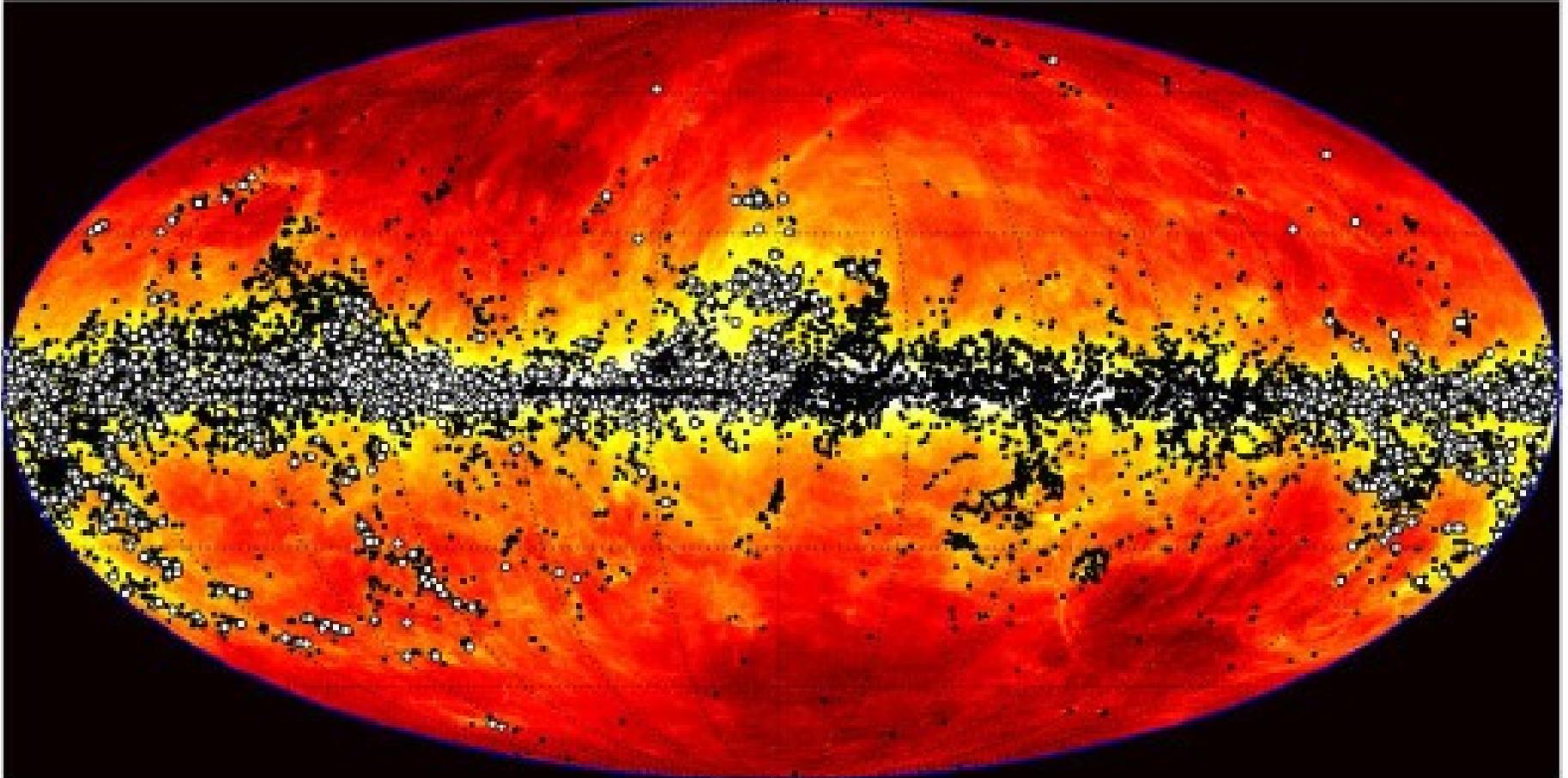
The early cold core (ECC) sample: *915*  
sample  $T_d < 14 \text{ K}$ ,  $\text{SNR} > 15$

## Why Planck cold clumps?!

Planck collaborators et al. (2016)

*“We believe that the PGCC catalogue, **covering the whole sky**, hence probing wildly different environments, represents a real goldmine for investigations of the early phases of star formation. These include, but are not limited to: i) studies of the evolution from molecular clouds to cores and the influence of the local conditions; ii) analysis of the **extreme cold sources**, such as the most massive clumps or those located at relatively high latitude; iii) characterization of the dust emission law in dense regions and the role of the environment. ”*

# Galactic distribution of targets



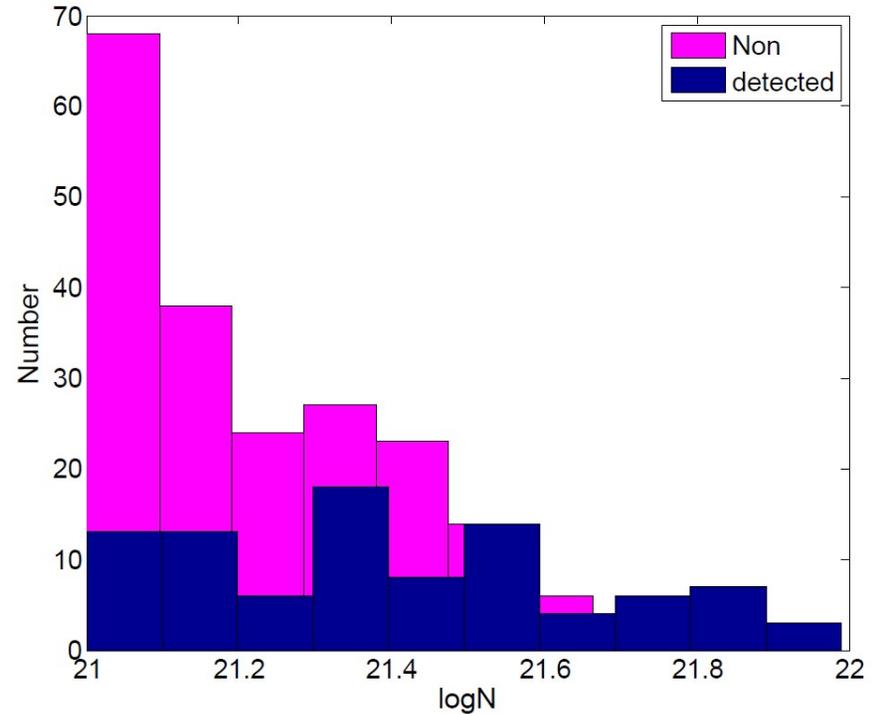
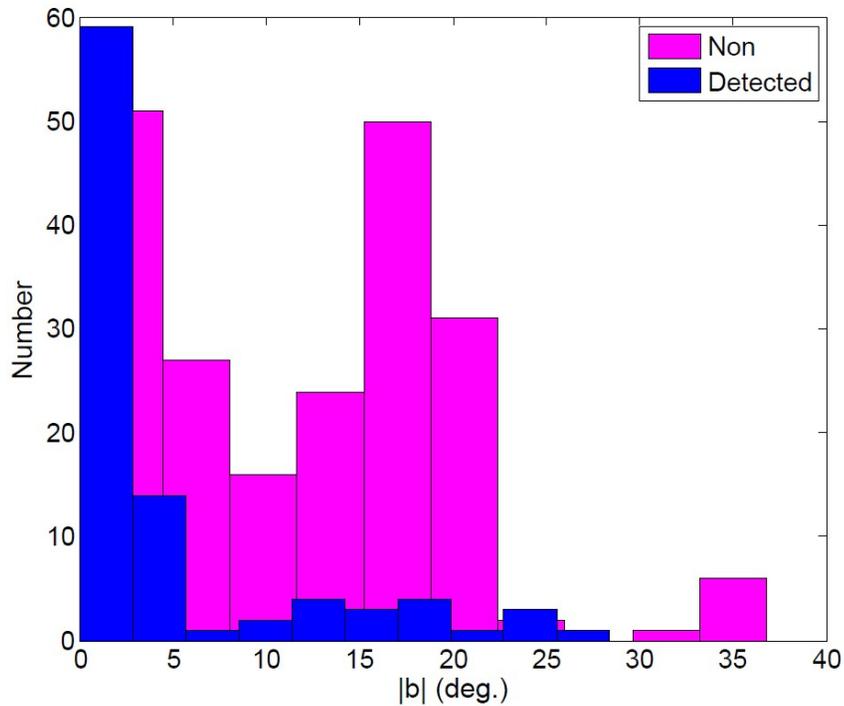
All-sky distribution of the 13188 PGCC sources (black dots) and the 2000 selected PGCC sources (open dots) overlaid on the 857 GHz Planck map (credit: M. Juvela).

# Summary of joint surveys/follow-ups

1. PMO/TRAO 13.7-m telescope survey in the J=1-0 transitions of CO isotopologues  
TRAO Observations of Planck cold clumps (TOP): **400hrs/yr for 3 years**  
**Goals: large scale structure & kinematics**
2. SMT 10-m telescope survey in the J=2-1 transitions of CO isotopologues (**600 hrs/3yrs**).  
**Goals: CO excitation, column density and depletion, kinematics**
3. SCOPE: SCUBA-2 Continuum Observations of Pre-protostellar Evolution (**300 hrs for first phase**)  
**Goals: dense cores and filaments**
4. KVN 21-m telescope survey in dense gas tracers (e.g. HCN, HCO+, N<sub>2</sub>H+) (**pilot survey done, 2016B proposal accepted; large proposal to be submitted soon**)  
**Goals: chemistry & kinematics of dense cores**
5. NH<sub>3</sub> follow-up survey with Effelsberg 100-m and TianMa 65-m ( **~30 hrs at 100-m.**)  
**Goals: kinetic temperature & turbulence**
6. HI survey with Arecibo 300-m and future FAST 500-m telescopes  
**Goals: HI abundance and chemical evolution of molecular clouds**
7. Follow-up observations with NRO 45-m ( **~150 hrs in 2015B; 2016B proposal accepted**)  
**Goals: Chemistry**
8. Follow-up observations with the SMA (**four standard proposals submitted or accepted**)  
**Goals: Fragmentation and small scale structures/kinematics**
9. Polarization and molecular line follow-up observations with the JCMT (**2017A: submitted**)
10. SOFIA proposal submitted (**Tie Liu**)

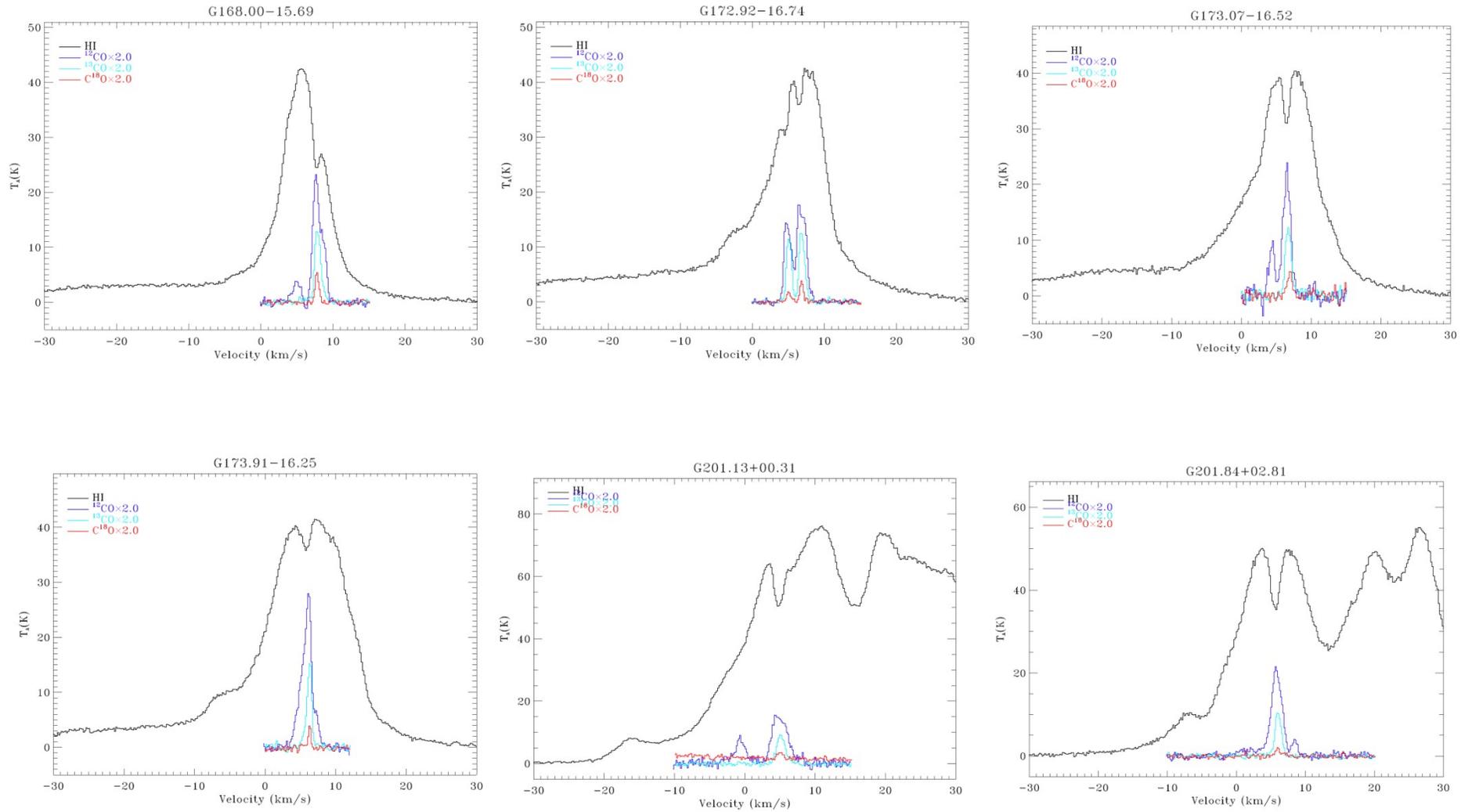
## 2. Preliminary results and suggestions for SMA

# Dense core detection rate in SCOPE

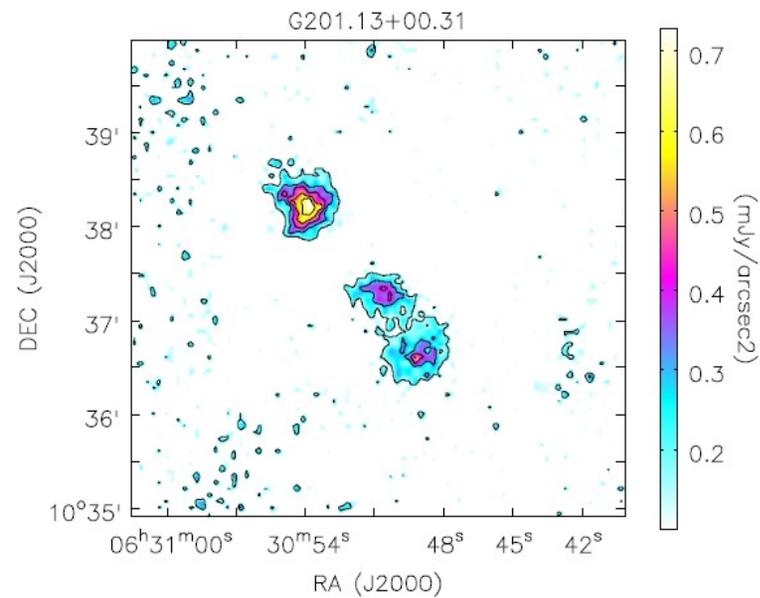
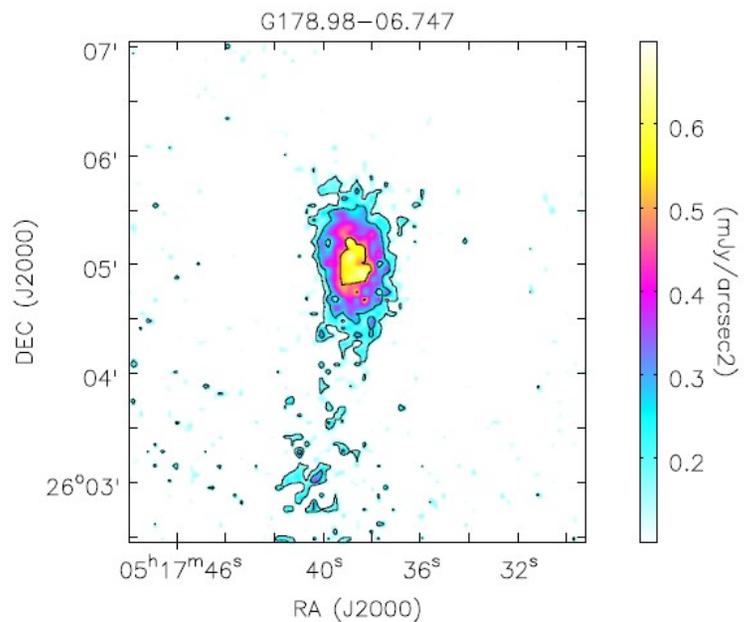
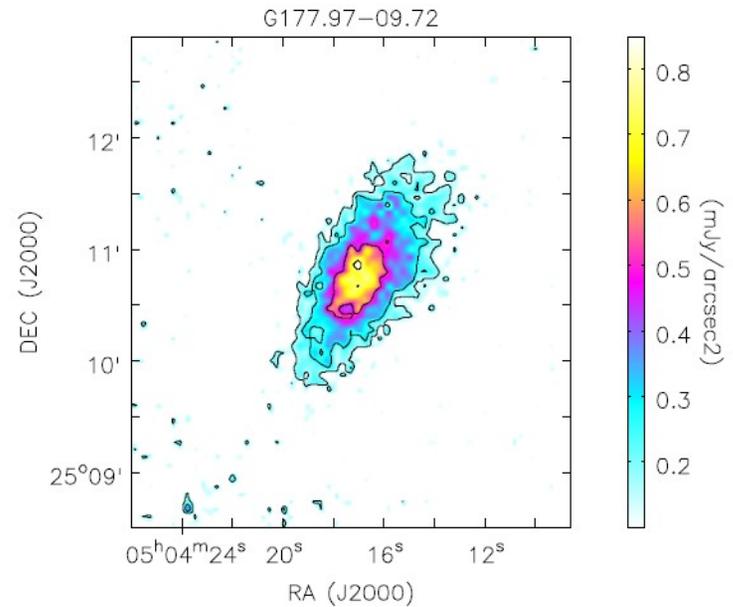
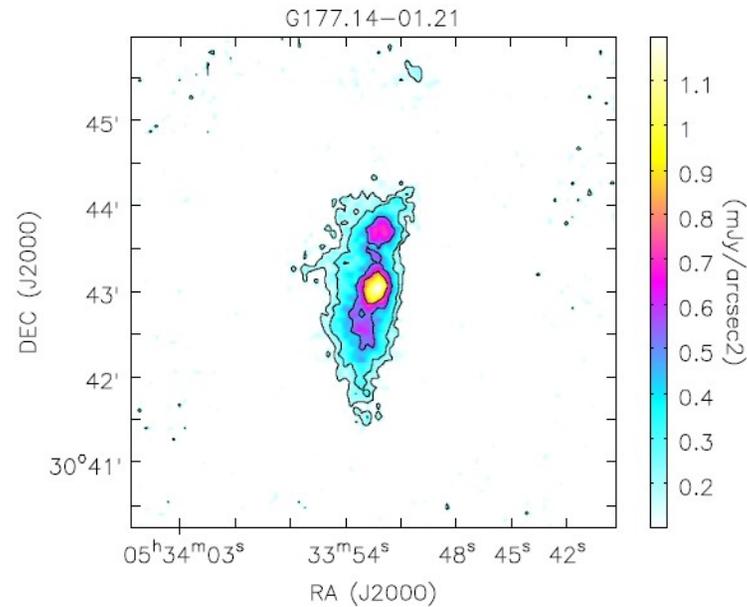


Cores prefer to form in dynamically active and dense environments

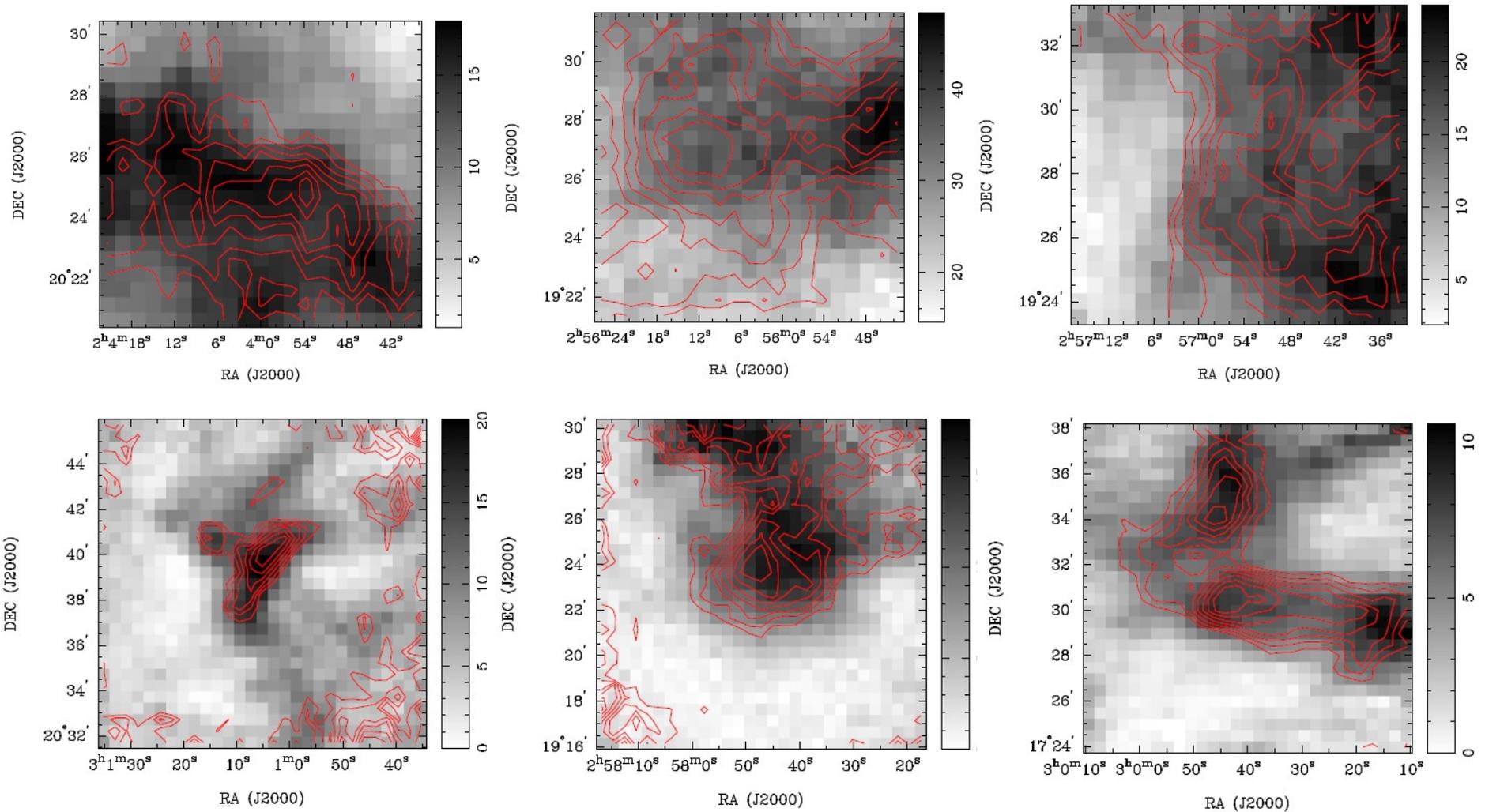
# HINSA detections with Arecibo 300-m (Di Li)



# HINSA sources in “SCOPE”



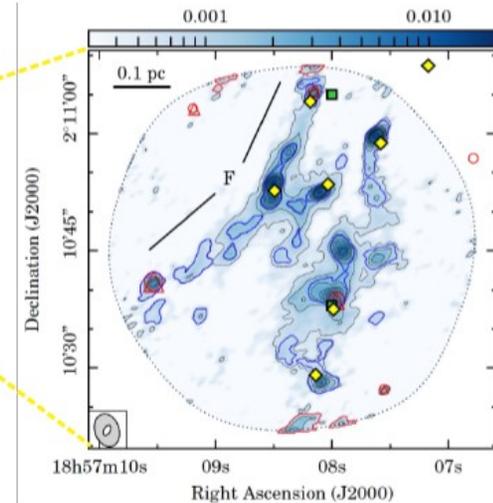
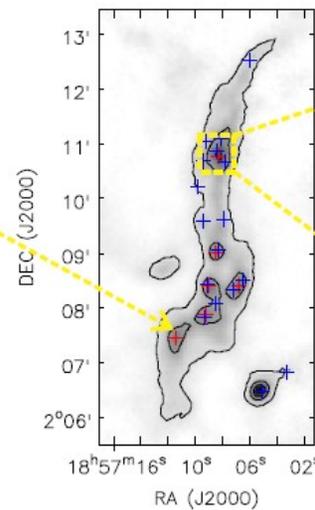
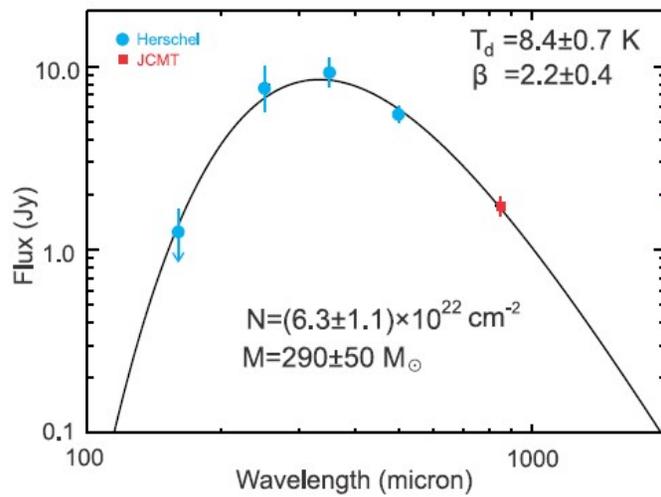
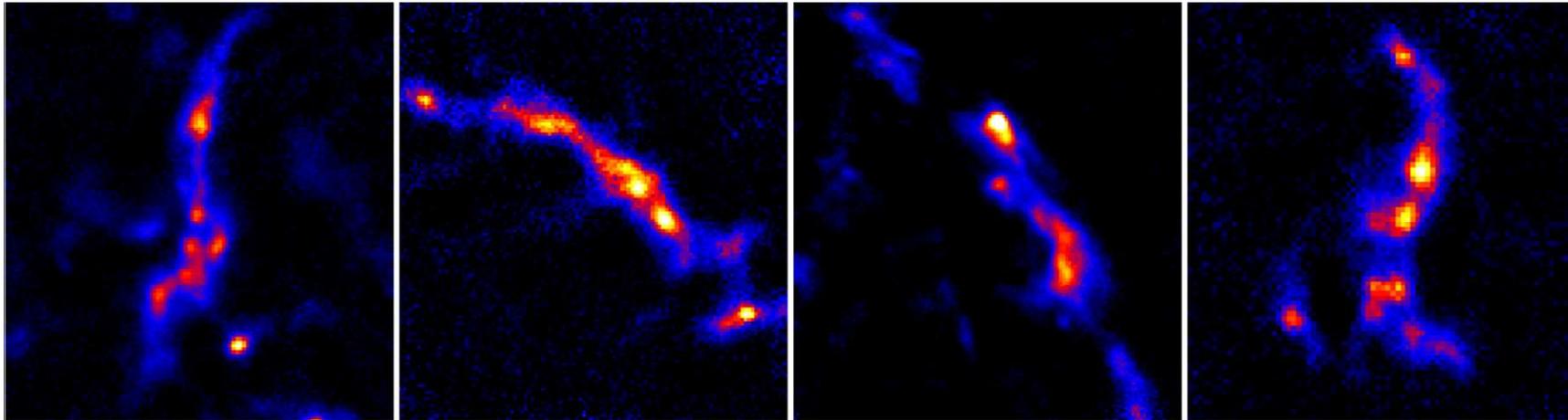
# High-Latitude clouds ( $|b| > 30$ deg.)



Dense gas clumps revealed in PMO/TRAO survey. But most of them have no SCUBA-2 detections. Density too low to form cores?

# Cold filaments

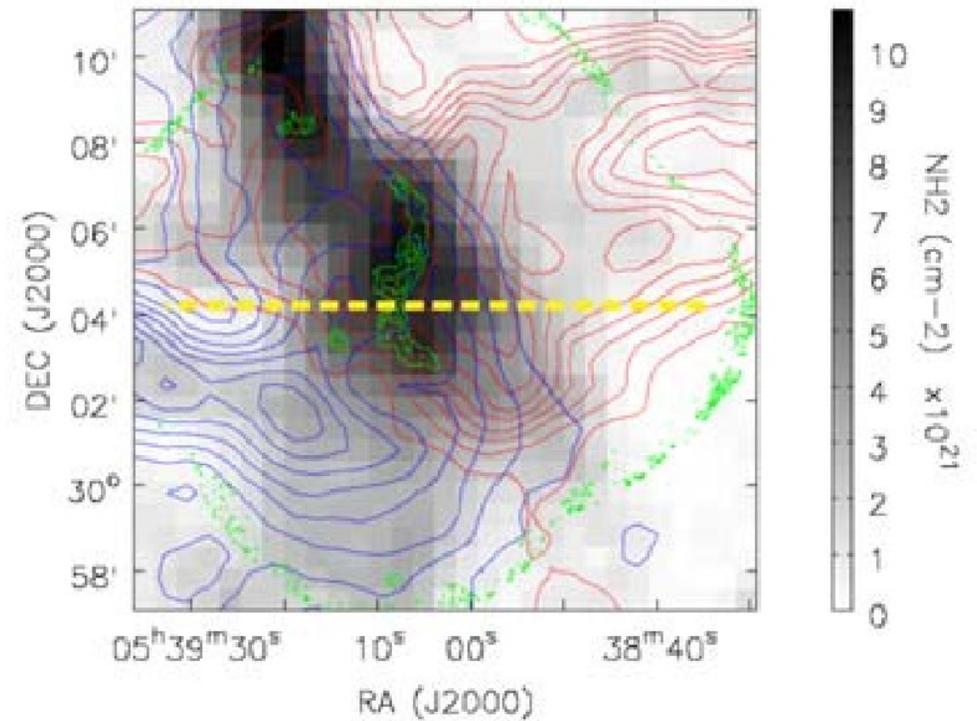
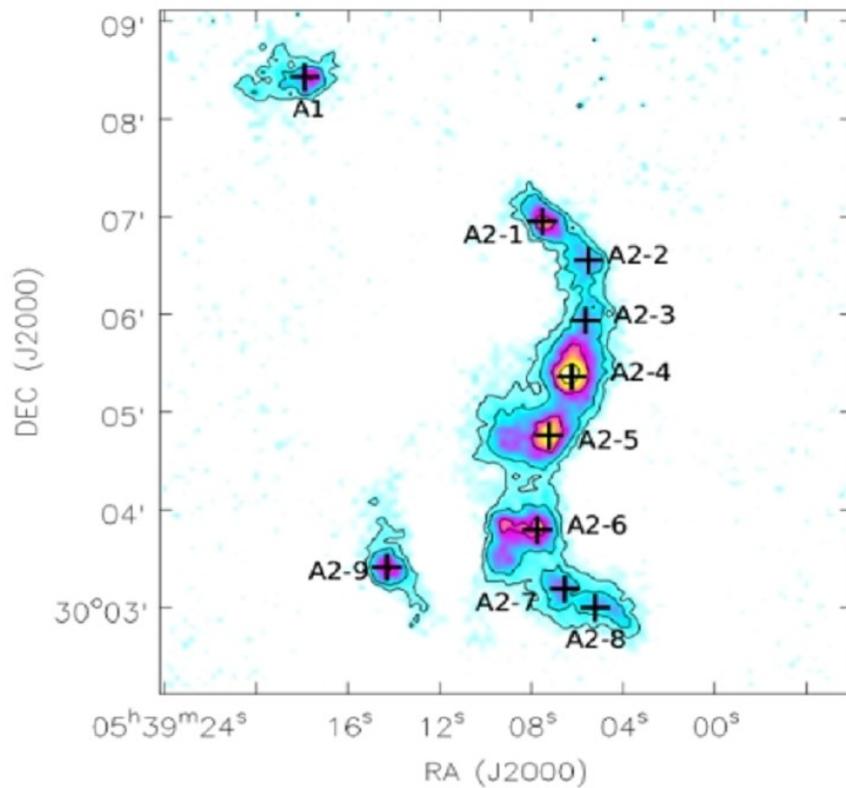
We detected several tens of very cold ( $T \sim 10$  K) and quiescent (starless) filaments



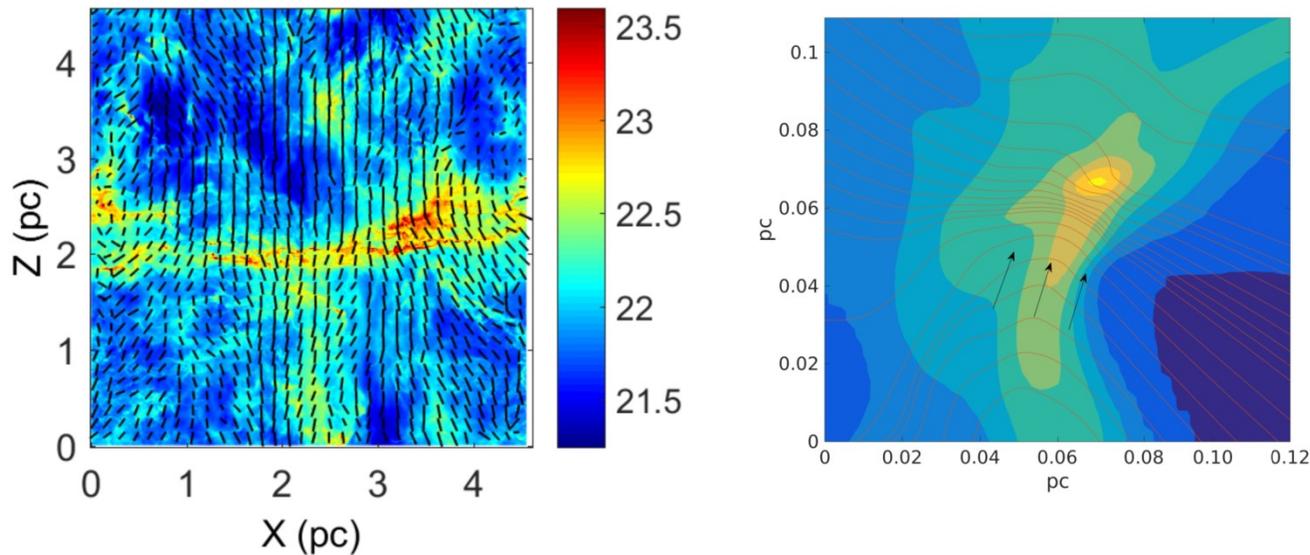
(Henshaw et al. 2016)

# Cloud-Cloud collision induced filament formation

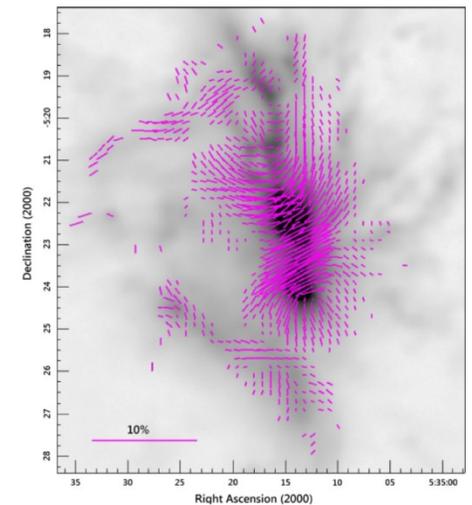
JCMT 850 micron



# Polarization observations of cold filaments with JCMT/POL-2 and the wide field & wide band wSMA

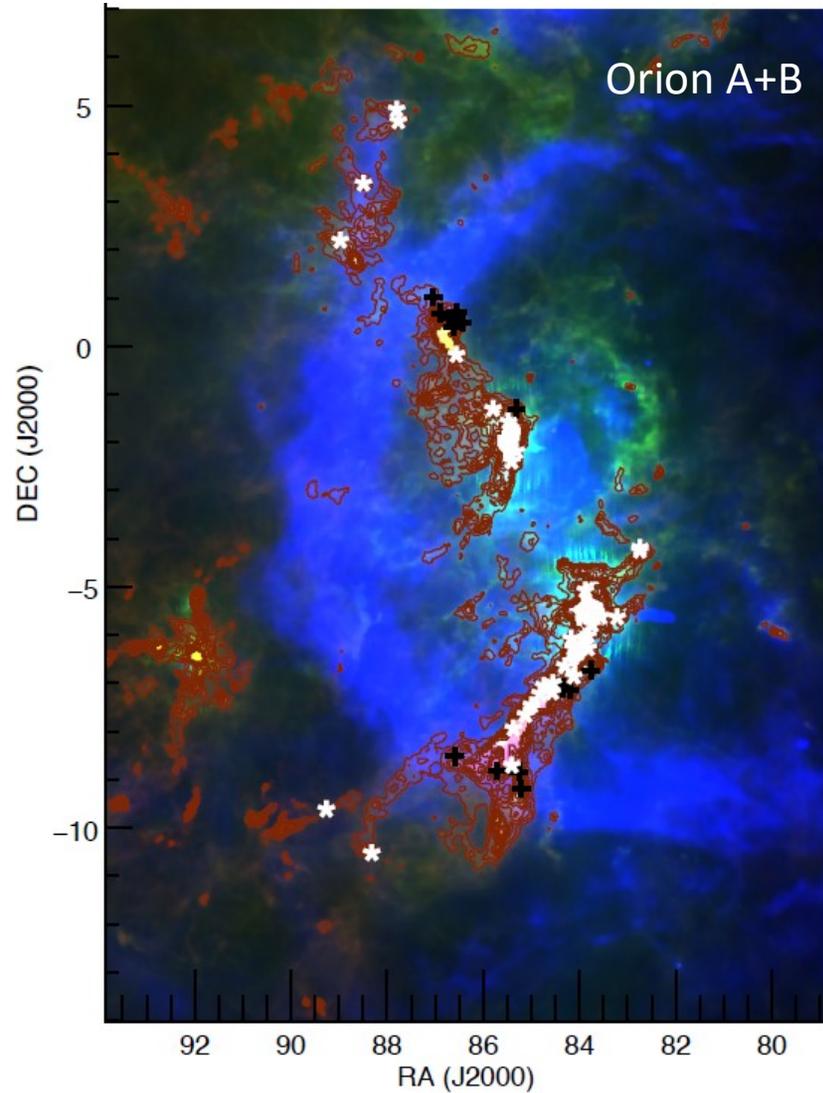
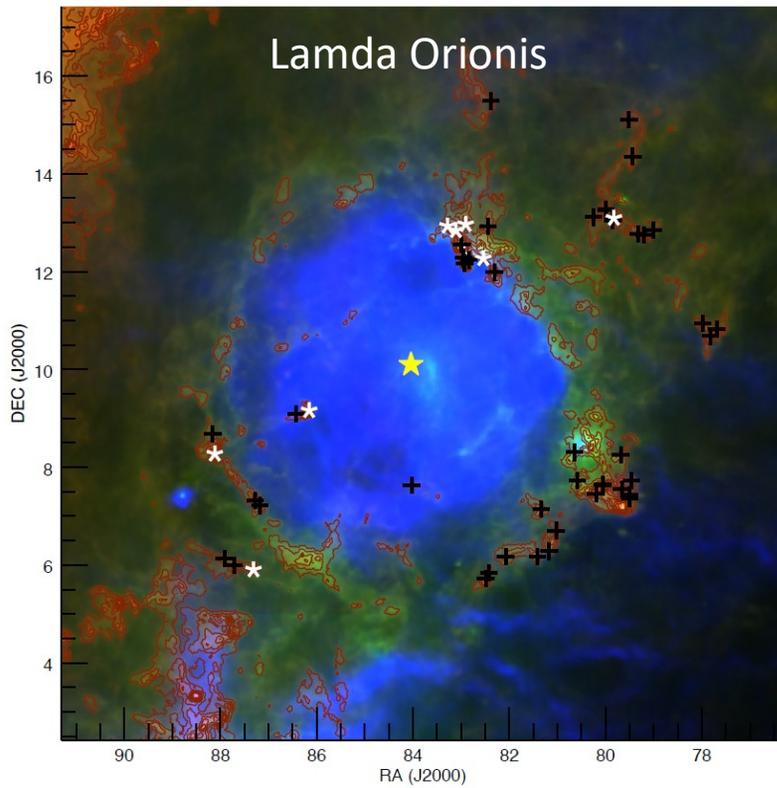


(Li et al. 2016, in preparation)



POL-2 obs of OMC1

# Environmental effects on core formation



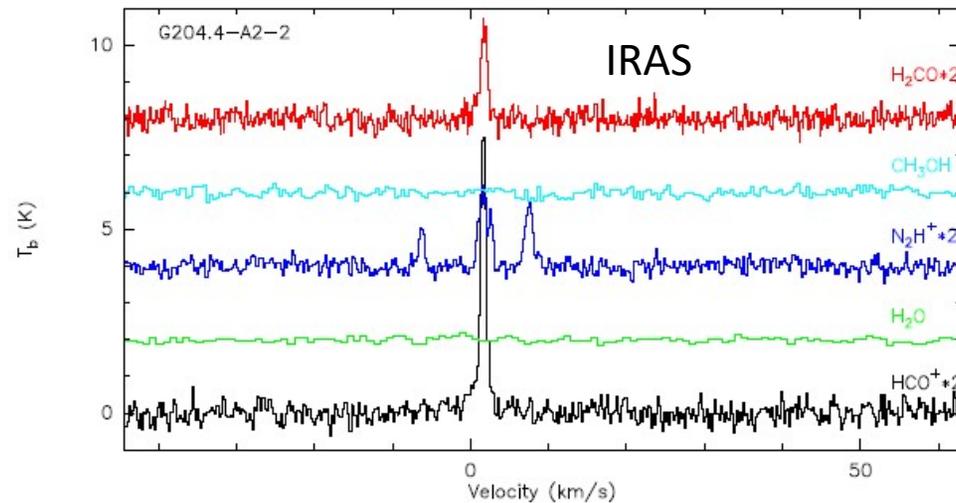
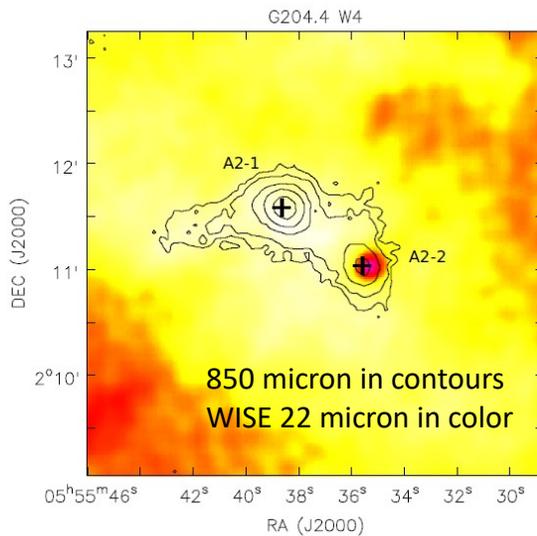
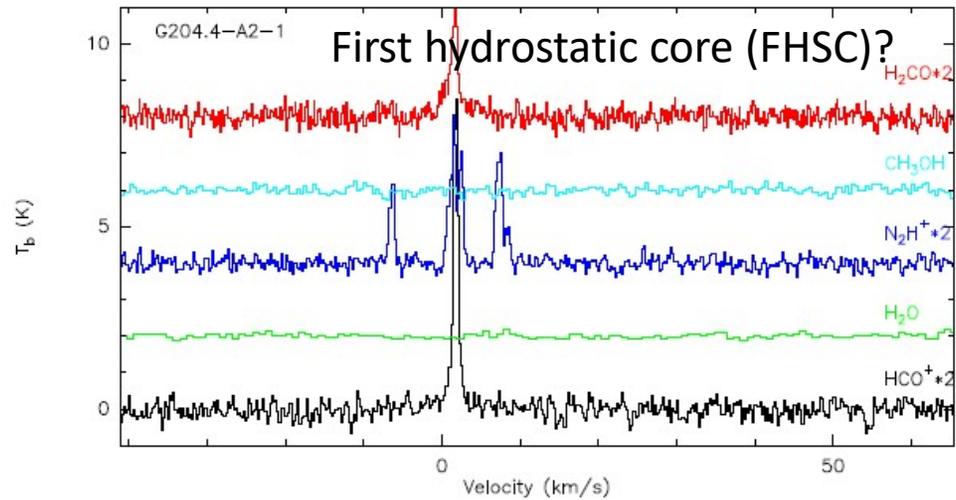
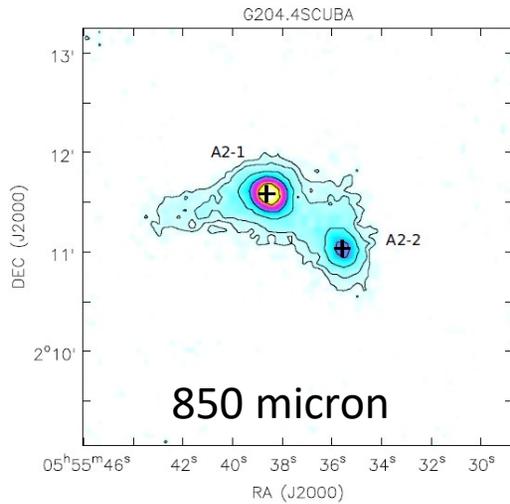
(Blue: Halpha, Green, IRAS 100 micron, red/contours: Planck 353GHz  
 Black stars: PGCCs without SCUBA-2 detections  
 White stars: PGCCs with SCUBA-2 detections)

region	Observed PGCC	Detected PGCC	Detection Rate
total	103	41	~39%
Lambda Orionis Complex	50	8	16%
Orion A	30	23	~76%
Orion B	16	9	~56%

11/5/2016

(Hee-weon Yi, in preparation)

# Extremely young dense cores (SMA proposal submitted, PI: Naomi Hirano)



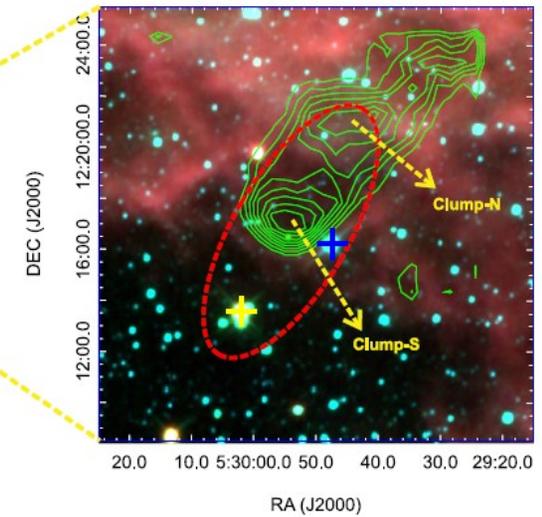
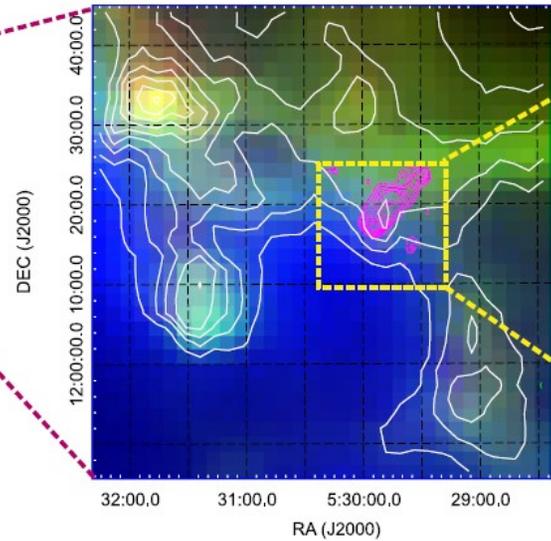
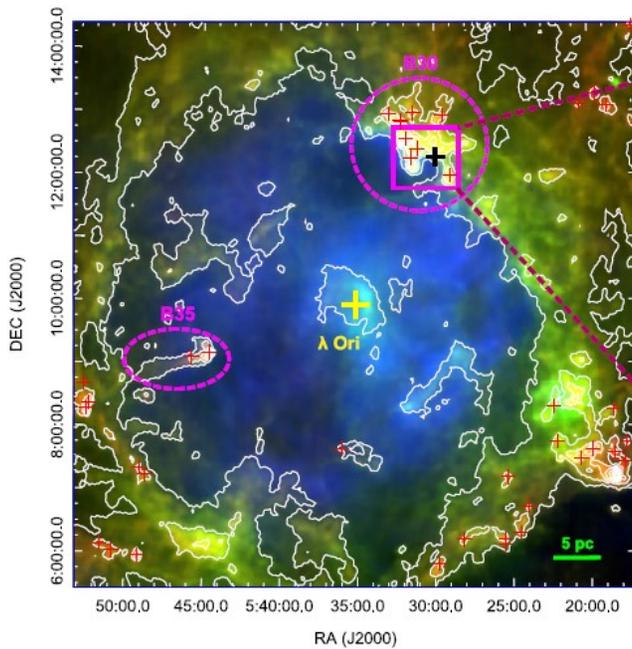
11/3/2010

# Follow-up observations of “SCOPE” cold cores with wSMA

- 1. KVN, Effelsberg 100-m and NRO 45-m of dense gas tracers (e.g., NH<sub>3</sub>, CCS, CCH, N<sub>2</sub>H<sup>+</sup>, N<sub>2</sub>D<sup>+</sup>, HCN, HCO<sup>+</sup>, DCO<sup>+</sup>) for chemistry studies toward 115 dense cores (proposals accepted). These observations will be extended to 1000 other dense cores in near future.
- 2. SMA follow-ups of Class 0/I protostellar cores in Lambda Orionis (submitted, PI: Tie Liu).
- 3. More follow-ups of SCOPE extremely young dense cores in different environments with the **wide-band** wSMA to study environmental effect on chemical and physical structures of dense cores on the verge of star formation.

### 3. SMA case studies of PGCC G192.32–11.88

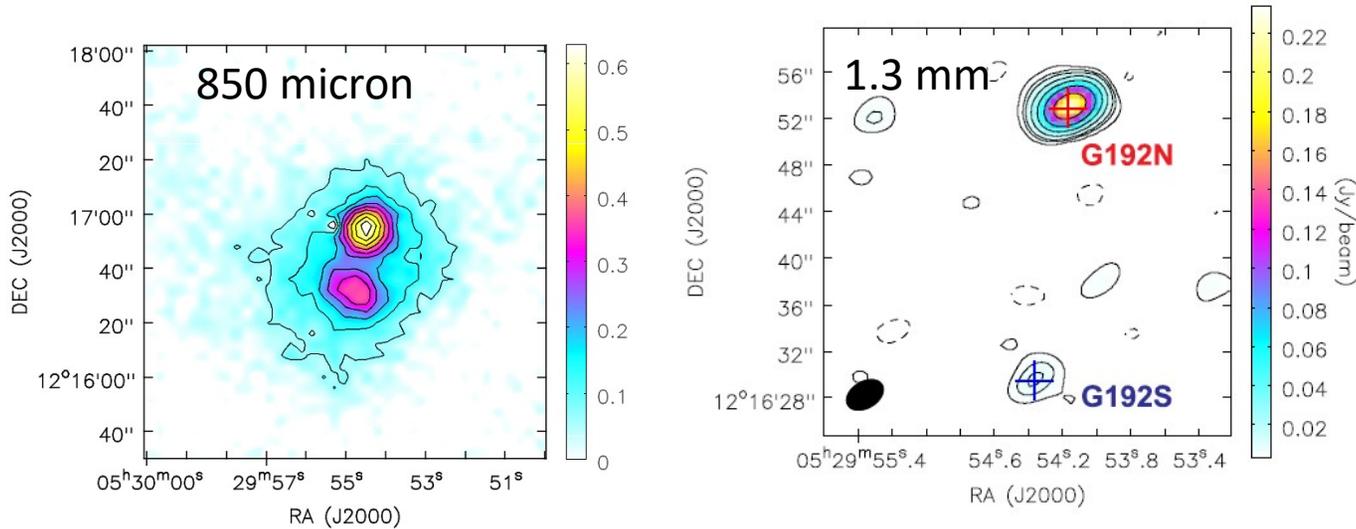
# Environment of PGCC G192.32–11.88



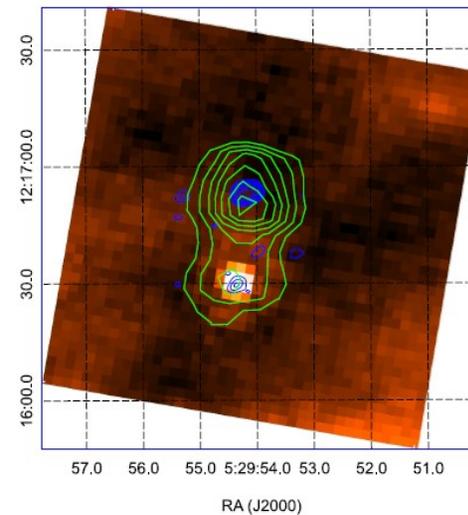
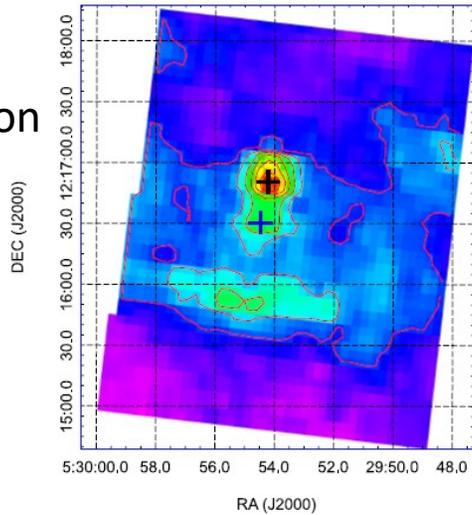
Three-color composite image (red: Planck 857 GHz; green: IRAS 100  $\mu$ m; blue: H $\alpha$ )  
White contours : Planck 857 GHz continuum emission.

Three-color WISE image  
(W1: blue,W2:green,W4:red)  
Green contour: H $_2$  column density

# brown-dwarf and very low-mass star formation (Liu+2016)



MIPS 70 micron



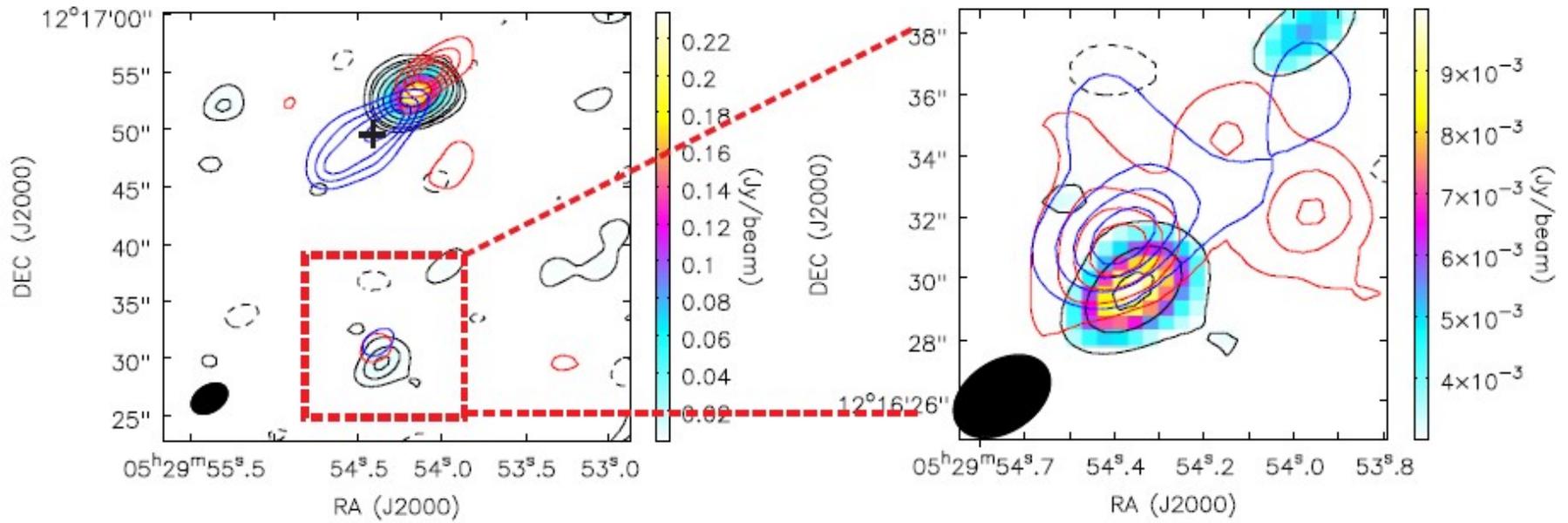
Green Contours: 70 micron  
 Blue contours: 1.3 mm  
 Color: 24 micron

Extremely young Class 0:

G192N:  $M=0.43 M_{\text{sun}}$  (JCMT);  $M=0.38 M_{\text{sun}}$  (SMA);  $L_{\text{int}} \sim 0.2 L_{\text{sun}}$

Proto-brown dwarf:

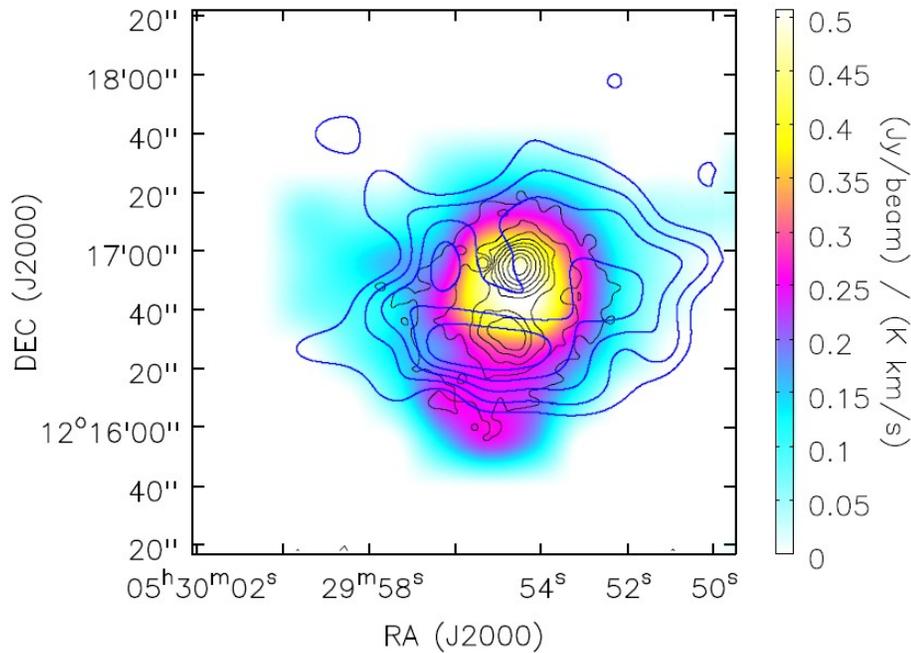
G192S:  $M=0.23 M_{\text{sun}}$  (JCMT);  $M=0.02 M_{\text{sun}}$  (SMA);  $L_{\text{int}} \sim 0.08 L_{\text{sun}}$



1.3 mm continuum in color image and black contours; CO outflows in red and blue contours

Lobes <sup>a</sup>	Radius <sup>b</sup> (10 <sup>3</sup> AU)	$V_{max}$ (km s <sup>-1</sup> )	Age (10 <sup>3</sup> yr)	Mass (10 <sup>-5</sup> M <sub>⊙</sub> )	$\dot{M}_{loss}$ (10 <sup>-8</sup> M <sub>⊙</sub> yr <sup>-1</sup> )	$F_{flow}$ (10 <sup>-7</sup> M <sub>⊙</sub> km s <sup>-1</sup> yr <sup>-1</sup> )	$\dot{M}_{acc}$ (10 <sup>-8</sup> M <sub>⊙</sub> yr <sup>-1</sup> )	$L_{acc}$ (10 <sup>-5</sup> L <sub>⊙</sub> )
G192N-Red	0.9	5	1.7	7.4	4.5	1.8	4.8	4.0
G192N-blue	1.8	14	1.2	45	36	22	58	430
G192S-red	0.8	3	2.6	1.6	0.6	0.2	0.5	0.1
G192S-blue	1.0	4	2.3	5.1	2.2	0.9	2.3	1.3

## Chemistry or accretion flow?

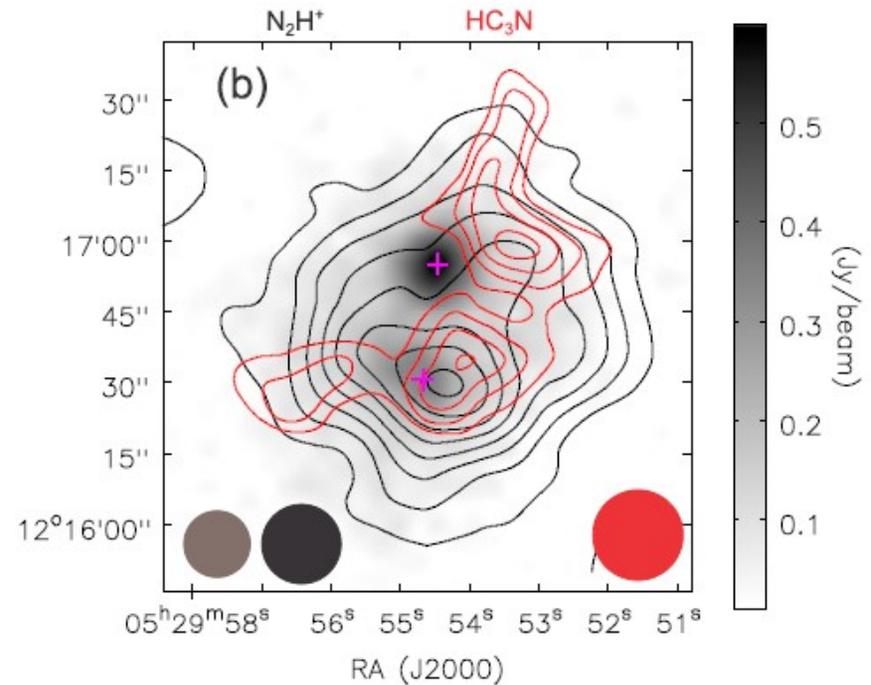


Blue: C18O (2-1)

Black contours: 850 micron continuum

Color image: 850 micron / C18O ratio

(Liu+2016)



Gray image: 850 micron continuum

Black: N<sub>2</sub>H<sup>+</sup> (1-0)

Red: HC<sub>3</sub>N (J=9-8)

(Tatematsu+2016,submitted)



# 4. Summary

- (1). We are conducting a series of surveys toward 1000-2000 PGCCs with multiple ground-based telescopes
- (2). From the JCMT legacy survey, we have discovered very cold filaments/cores and extremely young dense cores, which are suitable for future wSMA observations
- (3). We discovered an extremely young Class0 and a proto-brown dwarf candidate with the SMA.
- (4). We plan to observe more massive, quiescent and cold filaments with the wSMA to study the initial conditions of high-mass star formation, the role of magnetic field in filament fragmentation and the chemistry of extremely cold cores therein.
- (5). The “SCOPE” survey has also revealed a population of “starless” cores with centrally peaked continuum emission, high column density ( $> 10^{23} \text{ cm}^{-2}$ ), and extremely high abundance of deuterated species. These starless objects can be good candidates for first hydrostatic cores (FHSCs). We plan to observe more of them with the wSMA to investigate their physical and chemical properties. We have proposed the w**SMA** to observe one such core (G204NE; PI: Naomi Hirano; 2016B-A013).