The TOP-SCOPE survey of Planck Galactic Cold Clumps

Tie Liu (EACOA fellow)
liutiepku@gmail.com
2019-05-21

James Clerk Maxwell Telescope
East Asian Observatory

Image credit: Herschel/HiGAL

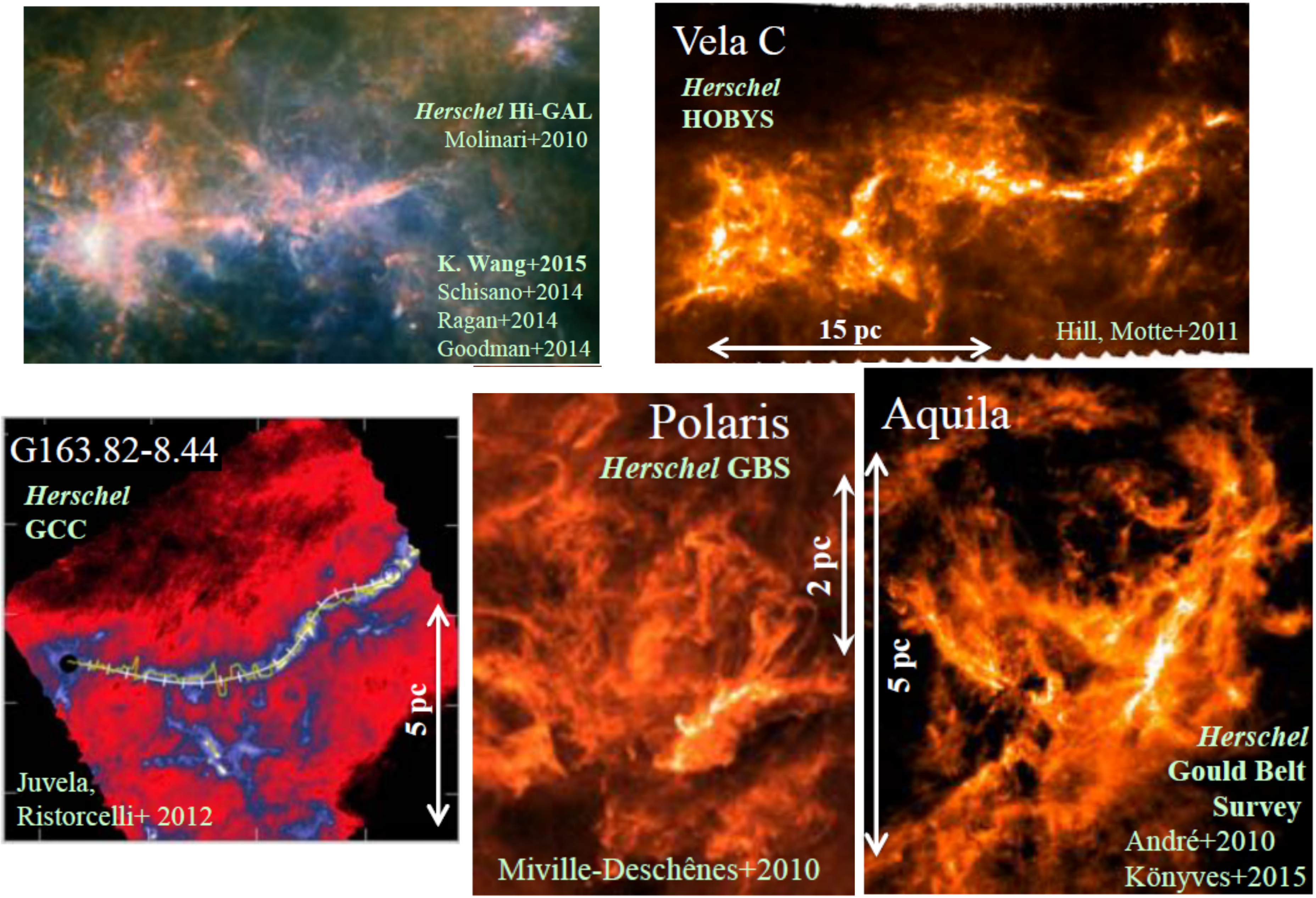
Korea Astronomy and Space Science Institute
한국천문연구원

Outline

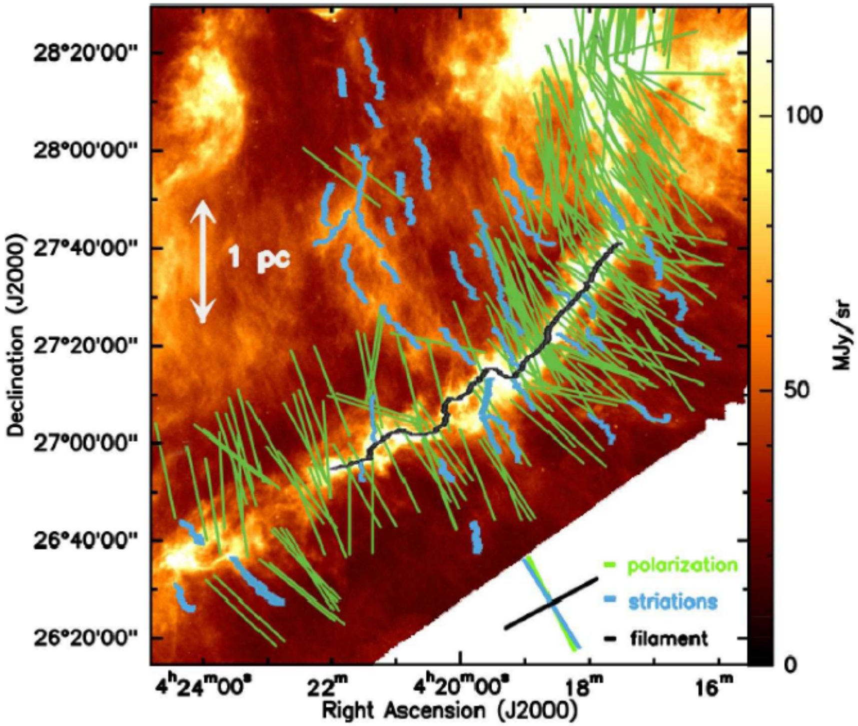
- 1. Introduction: the earliest phases in pre-protostellar evolution
- 2. The TOP-SCOPE Survey and follow-up observations of Planck Galactic Cold Clumps
- 3. Early results (some very preliminary)
- 4. Summary and Future plans

1. Introduction: the earliest phases in pre-protostellar evolution

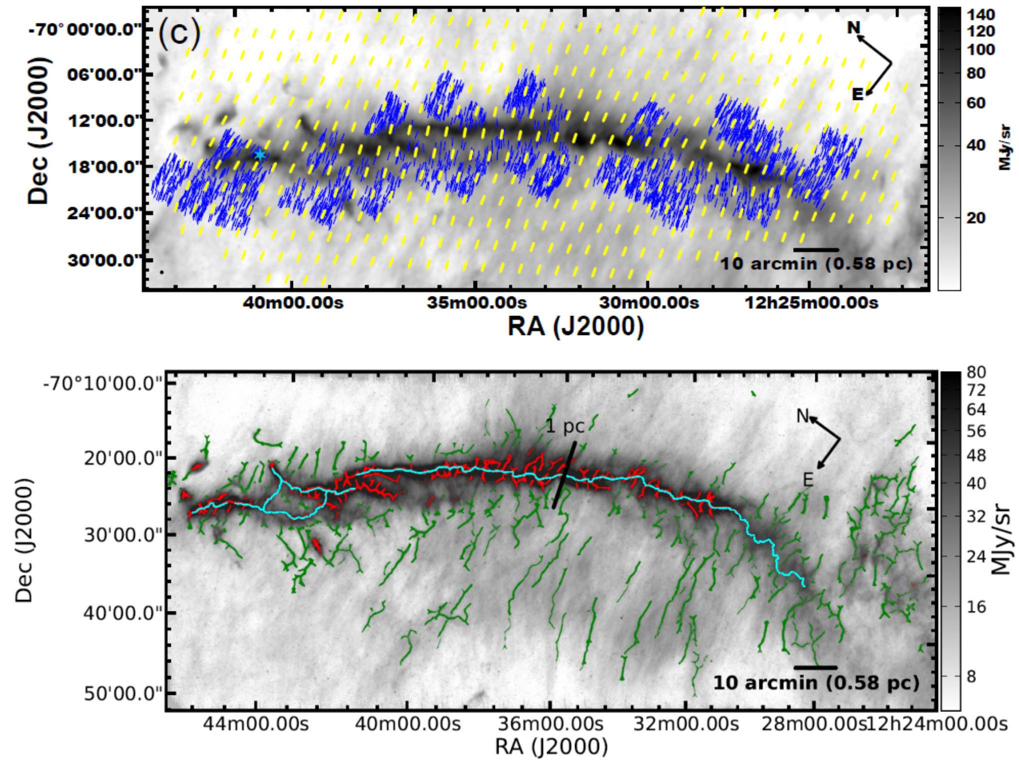
Herschel has revealed 'universal' filamentary structures in the cold ISM



Magnetic field in filamentary clouds



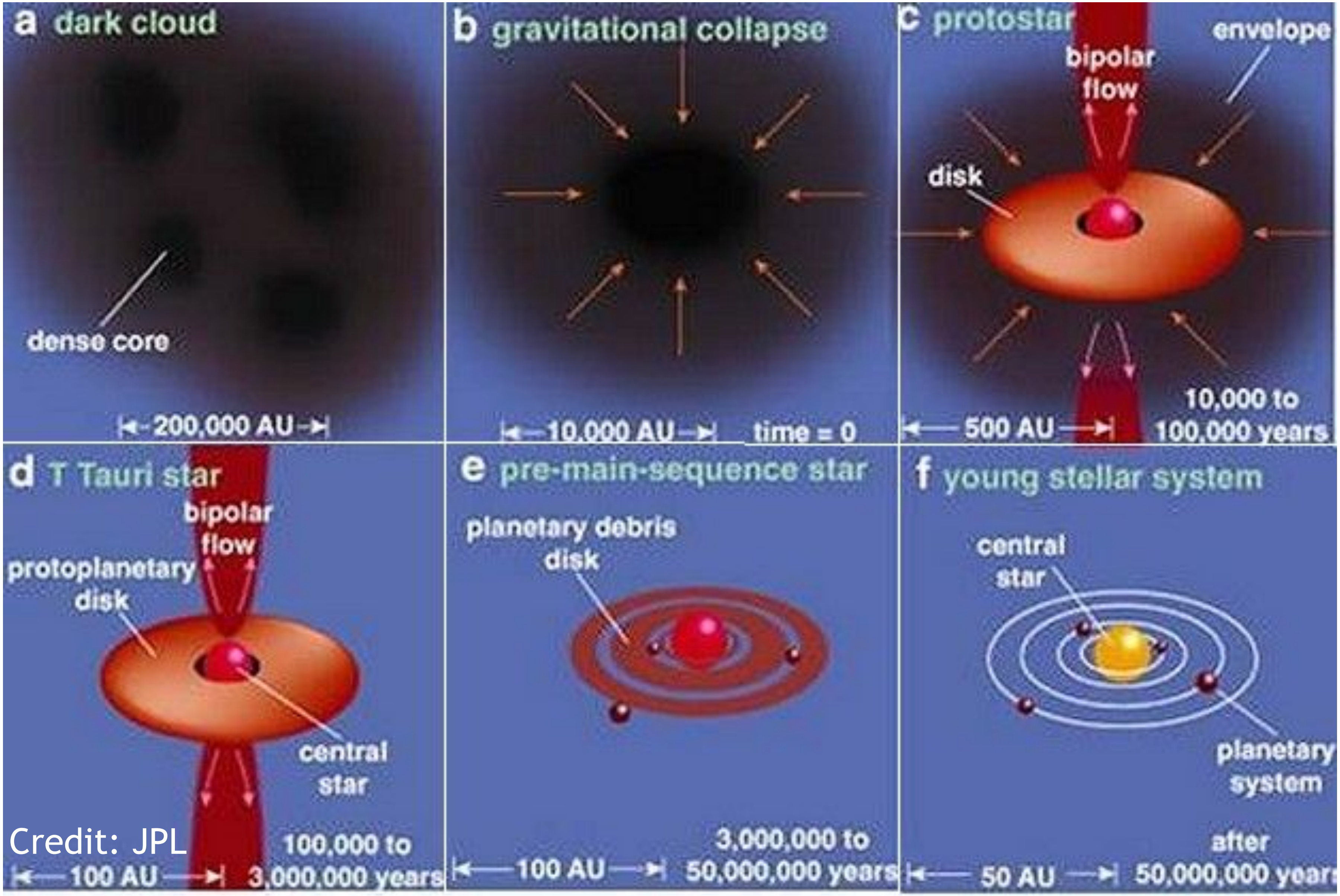
Magnetic field in Taurus (*Heyer et al.*, 2008; *Chapman et al.*, 2011)



Magnetic field and striations in Musca (*Cox et al. 2016*)

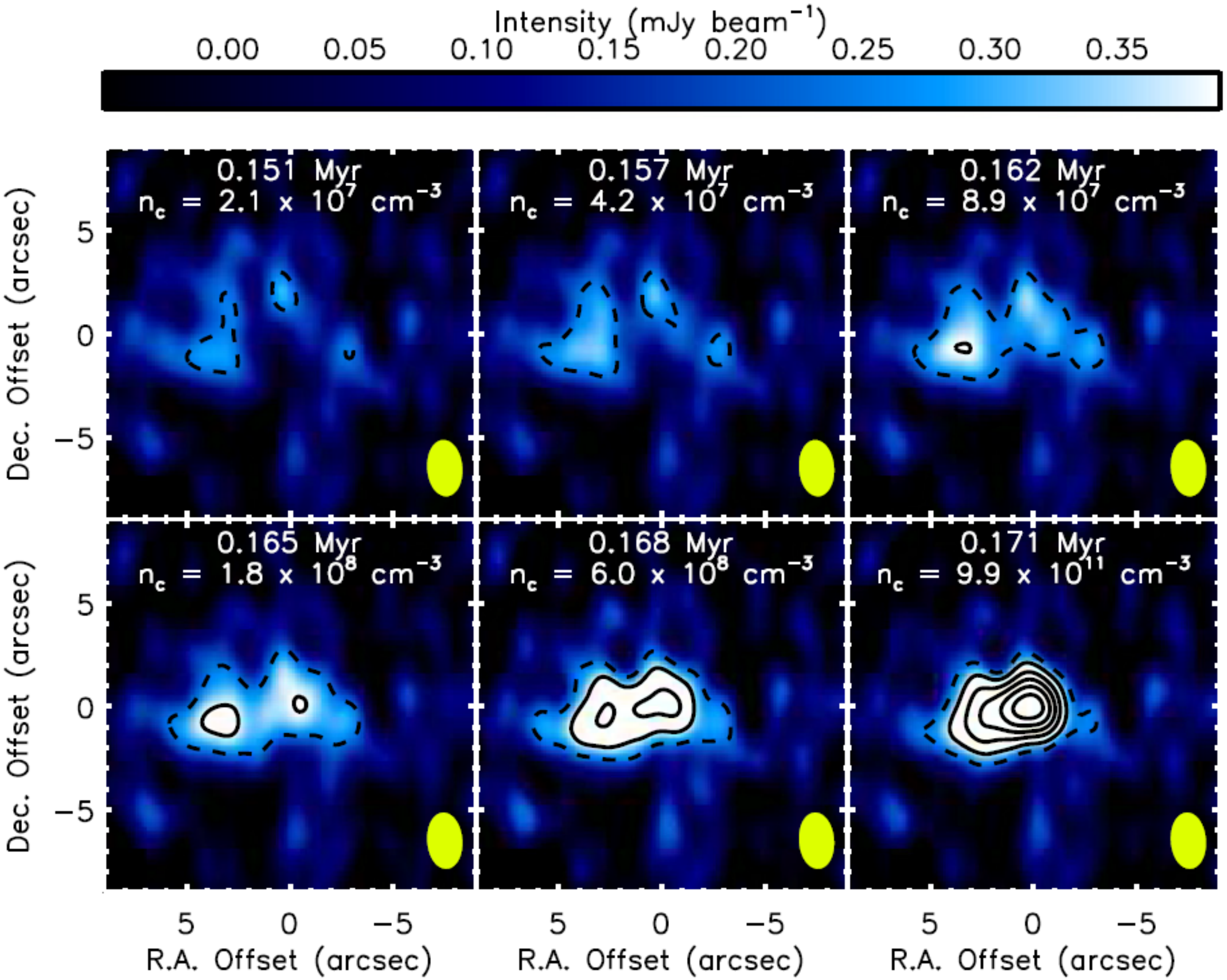
Polarization observations of nearby filamentary clouds suggested a scenario in which local interstellar material in this cloud has condensed into a gravitationally-unstable filament (with "supercritical" mass per unit length) that is accreting background matter along field lines through the striations (*Cox et al. 2016; see also Planck collaboration papers*).

Low-mass star formation



Do high-mass ($M > 8M_{\odot}$) stars or very low-mass ($M < 0.2M_{\odot}$) stars form in the same way?

Fragmentation and substructures of starless cores in turbulent fragmentation

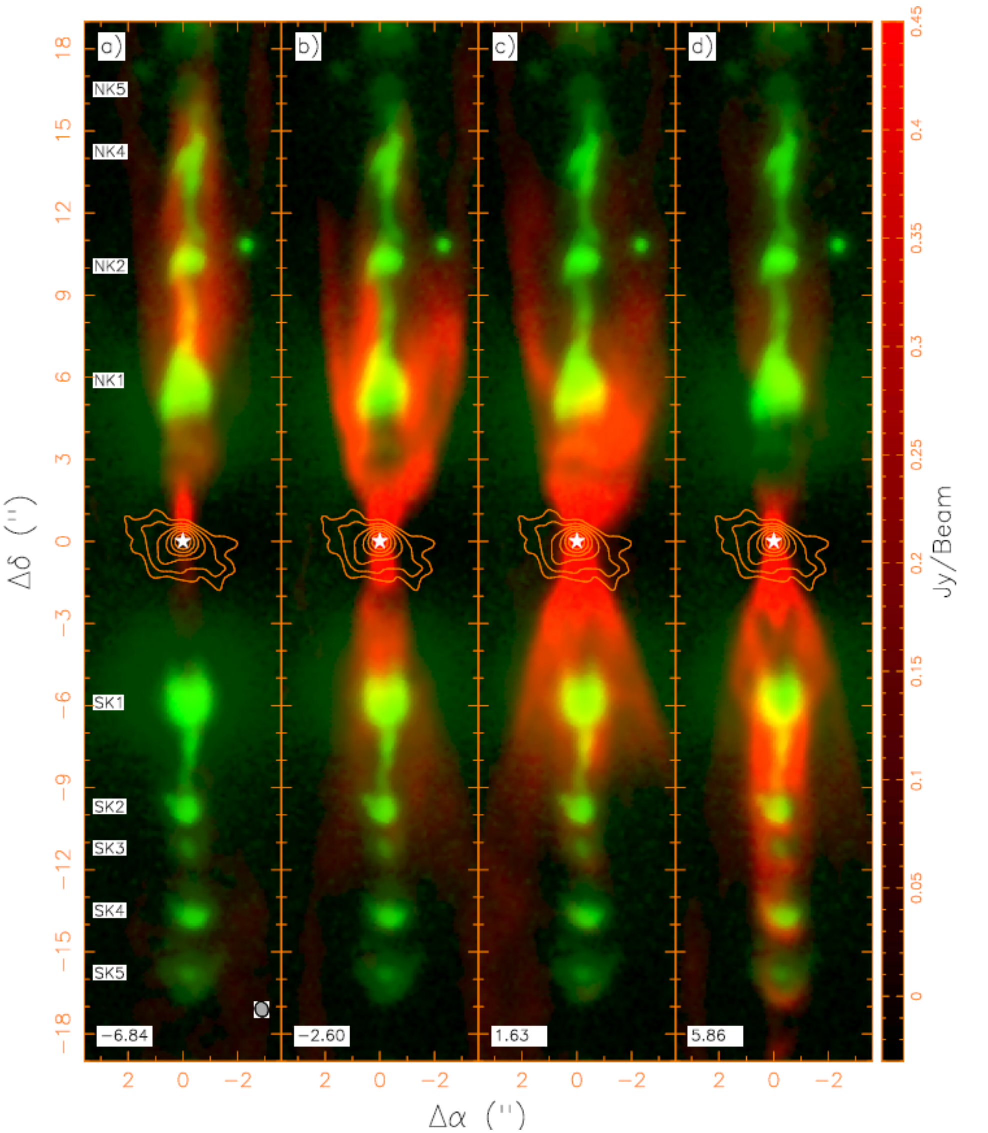


Synthetic ALMA 106 GHz continuum observations of the turbulent fragmentation simulation (Dunham+2016). ALMA is able to detect substructures for starless cores with peak density exceeding 9E7 cm-3

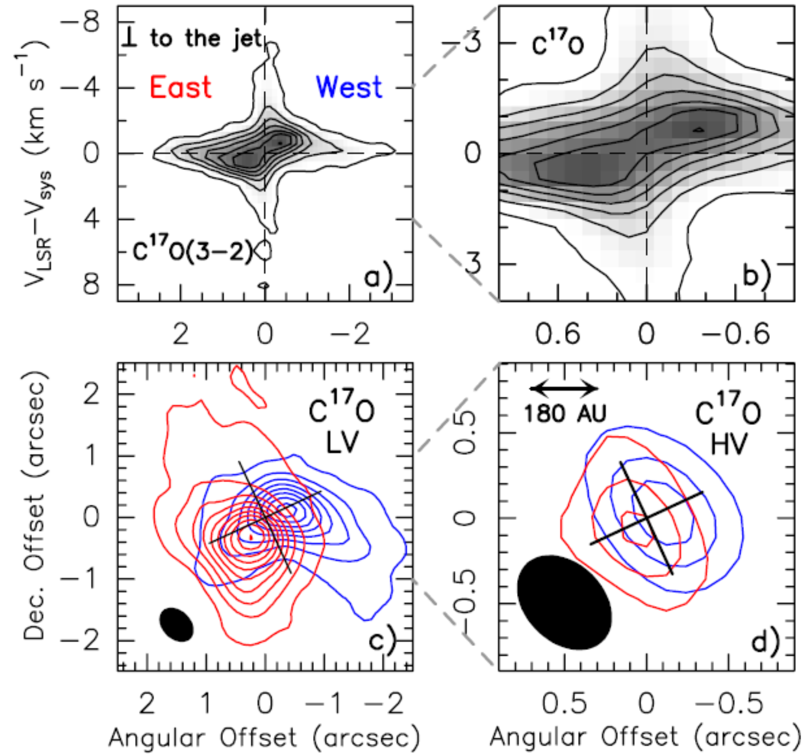
The process by which turbulent fluctuations in a dense core become Jeans unstable and collapse faster than the background core is the dominant mechanism responsible for forming multiple systems, and that the fragmentation begins in the starless core stage (Offner et al. 2010).

The starless core non-detections (Schnee et al. 2010, 2012; Dunham et al. 2016; Kirk et al. 2017) indicate that either most of the starless cores are not collapsing, or that the starless cores are more accurately described by models that develop less substructure than predicted by the turbulent fragmentation scenario, such as Bonnor–Ebert spheres.

Keplerian rotating disk formed at Class 0 phase?



HH212: CO: red, H2: green, 350 GHz continuum: contours (Lee+2015)



A rotating disk of ~90 AU around a $0.3 \pm 0.1\ M_{\odot}$ source.

The rotating disk is possibly Keplerian.(Codella+2014)

Resolved disk-like rotation:
L1527 , VLA 1623, HH212, and L1448-NB
(Ohashi et al. 2014, Murillo et al. 2013; Codella et al. 2014a; Tobin et al. 2016a)

Open questions on the earliest phases of pre-protostellar evolution

- *1. Filaments in molecular clouds*
- How common are filaments in molecular clouds and how do they form?
- What is the role of filament in dense core or star formation?

- *2. Low-mass star formation*
- Substructure and fragmentation of starless cores
- Do first hydrostatic cores exist?
- Disk formation at Class 0 phase

- *3. High-mass star formation*
- Do massive starless cores exist?
- Are massive pre-clusters undergoing global collapse?

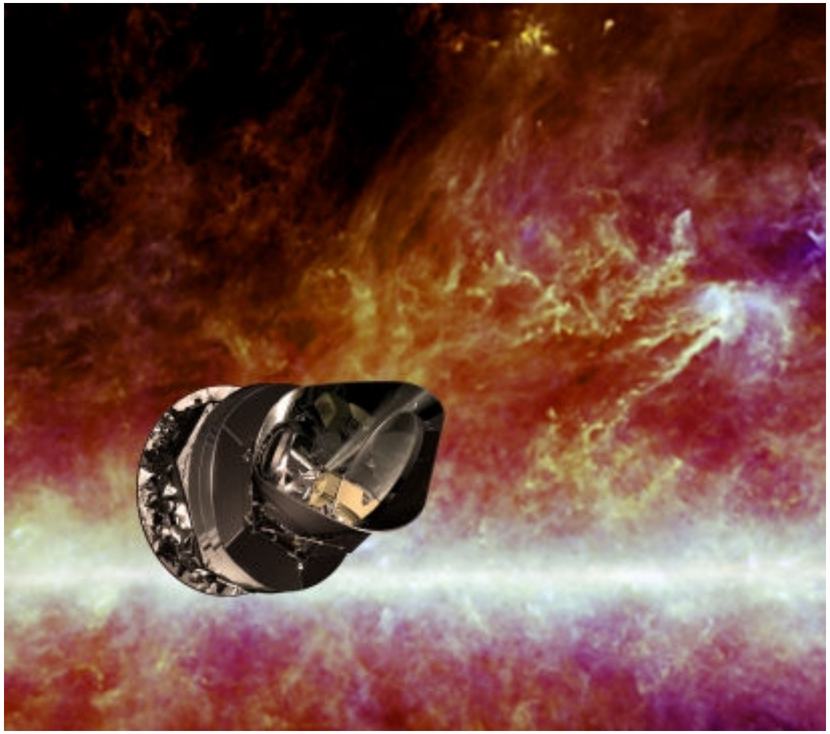
- *4. Very low-mass star (brown-dwarf) formation*
- Do they formed in the same way as their low-mass counterparts? Or do they form with other mechanisms?

- *5. Environmental effect on star formation*
- Is there a universal star formation law in different kinds (metallicity; UV radiation; density; temperature…) of clouds?

- *We need a large sample of cold clumps/cores that represent the very initial conditions of star formation and are located in widely different environments.*

2. The TOP-SCOPE Survey and follow-up observations of Planck Galactic Cold Clumps

Surveys of Planck Galactic Cold Clumps

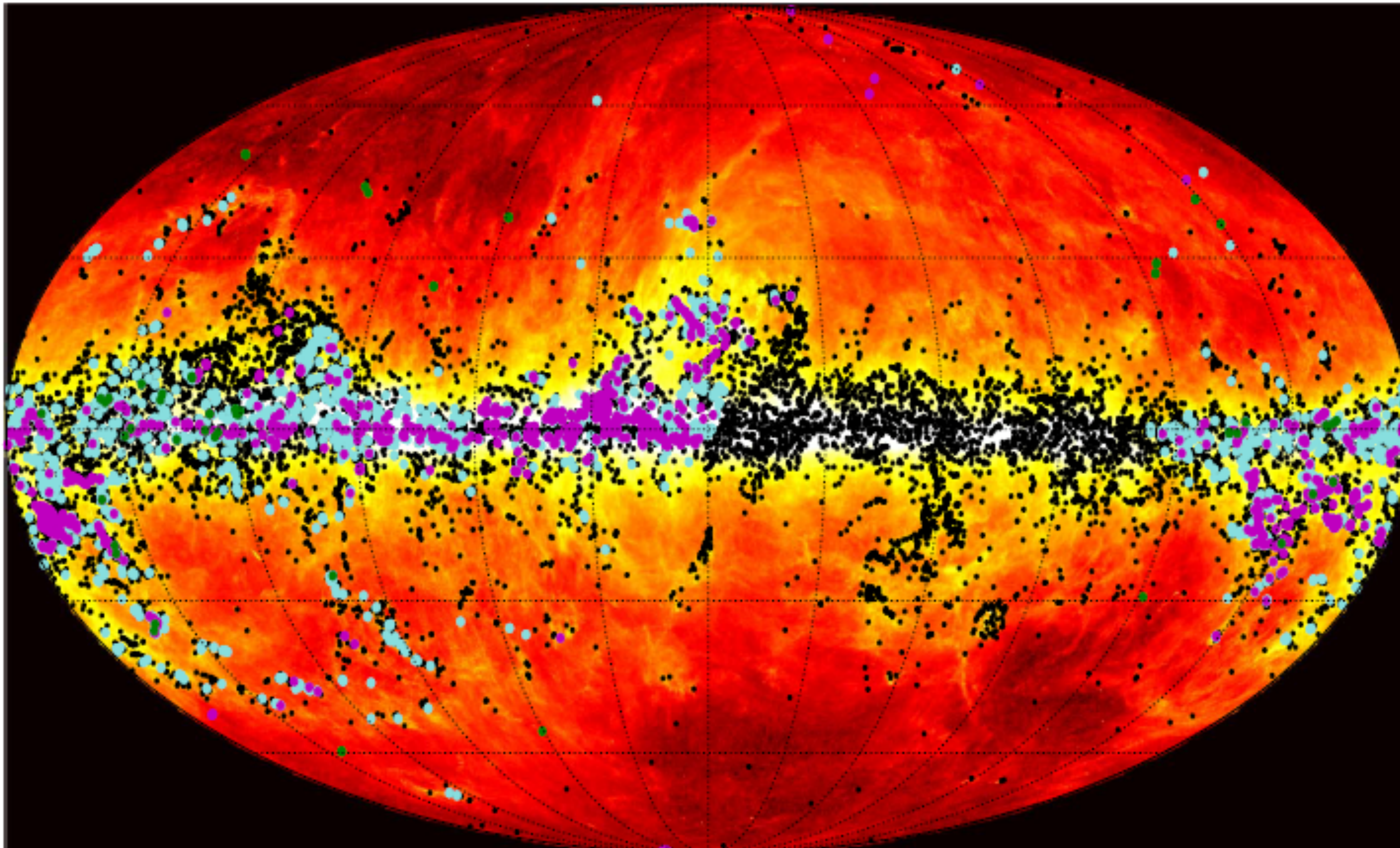


Planck is a third generation space based cosmic microwave background experiment, operating at nine frequencies between 30 and 857 GHz

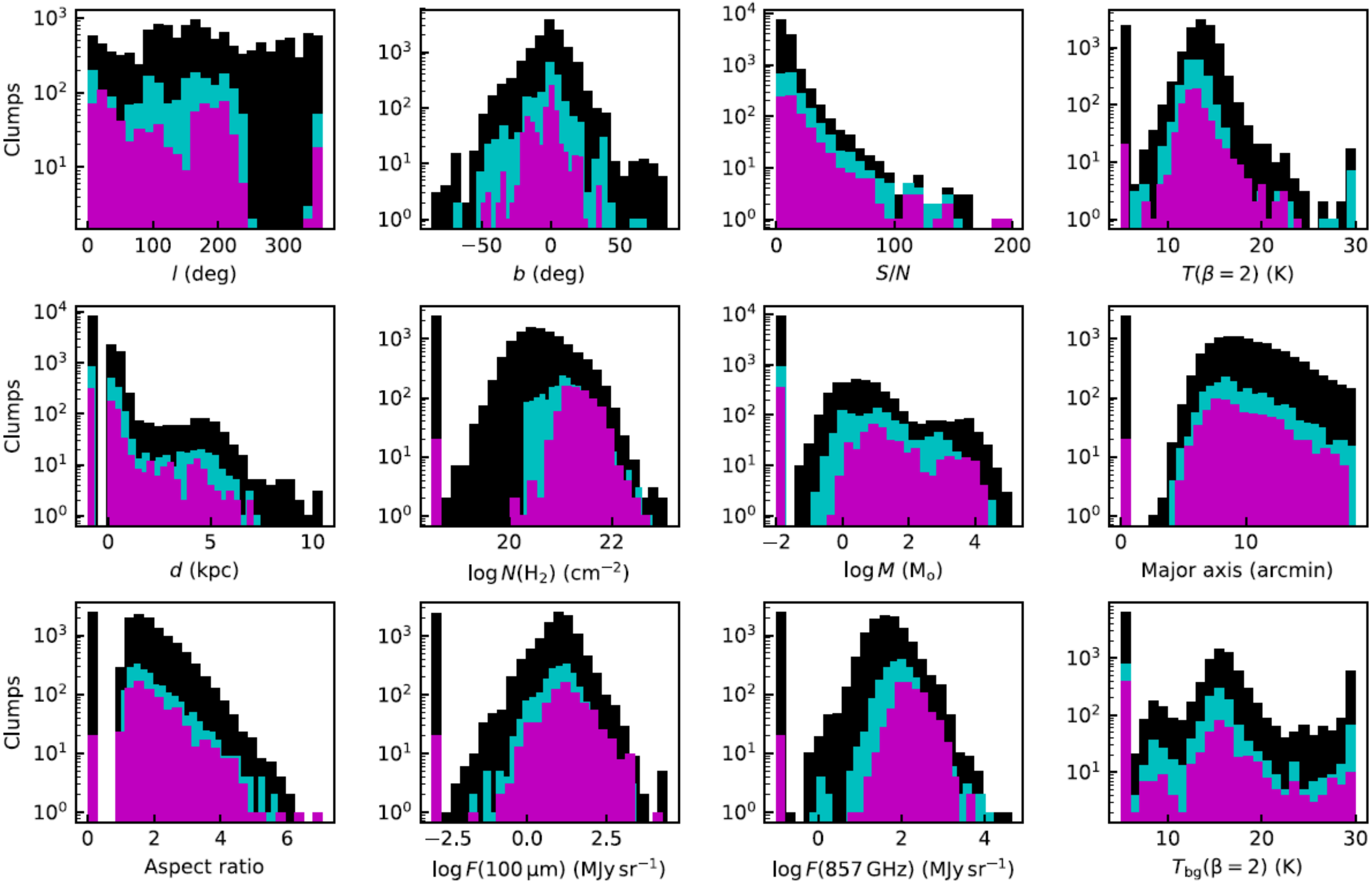
Planck Catalogue of Galactic Cold Clumps (PGCC), *13188 clumps*

The PGCCs are cold (T_d~14 K) clumps and thus represent the very initial conditions of star formation and molecular cloud evolution

We have an international team that includes more than **150 experts** all over the word (China; Japan, S. Korea, U.K., Taiwan, U.S., Canada, France, Finland…) to follow-up observe **1000-2000** PGCCs with multiple state-of-the-art telescopes (TRAO 13.7-m, PMO 13.7-m, JCMT 15-m, NRO 45-m, SMT 10-m, KVN, IRAM 30-m, **SMA, ALMA**, **SOFIA**, **BLAST-TNG**, Effelsberg 100-m, TianMa 65-m, FAST 500m…) in order ***to investigate the initial conditions of star formation in widely different environments and to address the questions raised in the introduction part***.



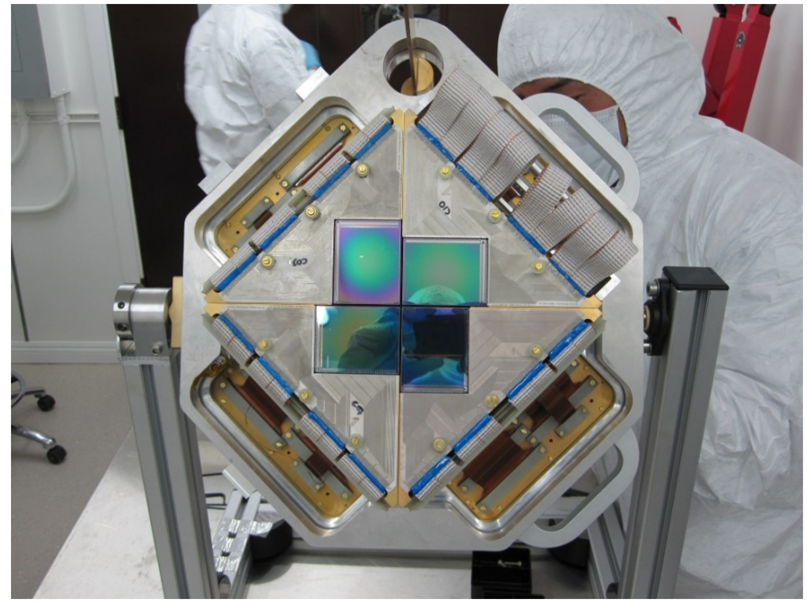
All-sky distribution of the 13188 PGCC sources (black dots), the 2000 PGCC sources selected for TOP (blue dots), and 1000 for SCOPE (pink dots) overlaid on the 857 GHz Planck map (Liu et al. 2018, ApJS, 234, 28)



Black: All PGCCs; Blue: TOP; Pink: SCOPE (Liu et al. 2018, ApJS, 234, 28)

SCOPE: SCUBA-2 Continuum Observations of Pre-protostellar Evolution

A JCMT legacy survey using ~400 hrs of SCUBA-2 time to observe ~1300 Planck Galactic Cold Clumps (PGCCs) in 850 micron continuum



With a diameter of **15m** the James Clerk Maxwell Telescope (JCMT) **operated by EAO** is the largest astronomical telescope in the world designed specifically to operate in **the submillimeter wavelength** region of the spectrum.

SCUBA-2 (Submillimetre Common-User Bolometer Array 2) is a **10,000 pixel** bolometer camera operating simultaneously at **450 and 850 micron.** The camera has in total eight TES arrays, four at each wavelength band. With each array having 32×40 = 1280 bolometers there are in total 5120 bolometers per wavelength.

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): (PI: Tie Liu, 1400hrs for 3 years)
2. **SCOPE: SCUBA-2 Continuum Observations of Pre-protostellar Evolution (PI: Tie Liu, 400 hrs; completed)**
3. SMT 10-m telescope survey in the J=2-1 transitions of CO isotoplogues (**PI: Ke Wang, 600 hrs/ 3yrs**).
4. KVN 21-m telescope survey in dense gas tracers (e.g. HCN, HCO+, N2H+) (**PI: Kee-Tae Kim, pilot survey done, 2016B & 2017A completed; large proposal to be submitted soon**)
5. Carbon chain molecular lines follow-up survey with Effelsberg 100-m and TianMa 65-m (**PIs: Yuefang Wu; Mengyao Tang**)
6. HI survey with Arecibo 300-m and FAST 500-m telescopes (**PI : Di Li**)
7. Follow-up observations with NRO 45-m (**PI: Ken Tatematsu, ~150 hrs in 2015B & 2016B**)
8. Follow-up observations with the SMA (**five filler/standard proposals conducted**)
9. **Three ALMA proposals accepted in cycle 4s/5; one accepted in cycle 6 (PI: Tie Liu)**
10. **JCMT HARP and POL-2 follow-ups in 2017B, 2018B,2019A (PIs: Tie Liu; Archana Soam)**
11. **Joint large proposal toward ~200 SCOPE dense cores accepted to NRO 45-m and Effelsberg 100-m in 2018A, 2019A semester (PIs: Ken Tatematsu; Victor Toth)**
12. **Two APEX proposal accepted in 2018A (PI: Mika Juvela)**
13. **Three SOFIA proposals accepted in 2018A,2019A**
14. **Four IRAM 30-m proposals accepted in 2018A, 2019A**
15. **Three Effelsberg 100-m proposals accepted in 2018B, 2019A**
16. **One BLAST proposals accepted in 2018B (PI: Mika Juvela)**
17. **Eight ALMA projects asking for 100 hrs for 12-m array and 70 hrs for ACA submitted in cycle 7**

JCMT future instruments

- 1. SCUBA-3
- 10 times faster survey speed? Observe All PGCCs (outside GP) within 300 hrs
- Bigger FOV and higher sensitivity for polarization? Statistical studies of B-field in a large sample of molecular clouds
- Recover faint large-scale structures

- 2. HARP-2 (>100 pixels)
- Interest for chemistry and kinematics studies in molecular clouds
- Structure of the gaseous Milky Way

3. Early results of the TOP-SCOPE survey

- 13 refereed papers published; 4 under review; more working papers

- About **3000 cold cores** were identified, most of which are either starless cores or Class 0/I protostellar cores (Liu+2018, ApJS, 234, 28; Eden+2019, MMRAS, 485, 2895)

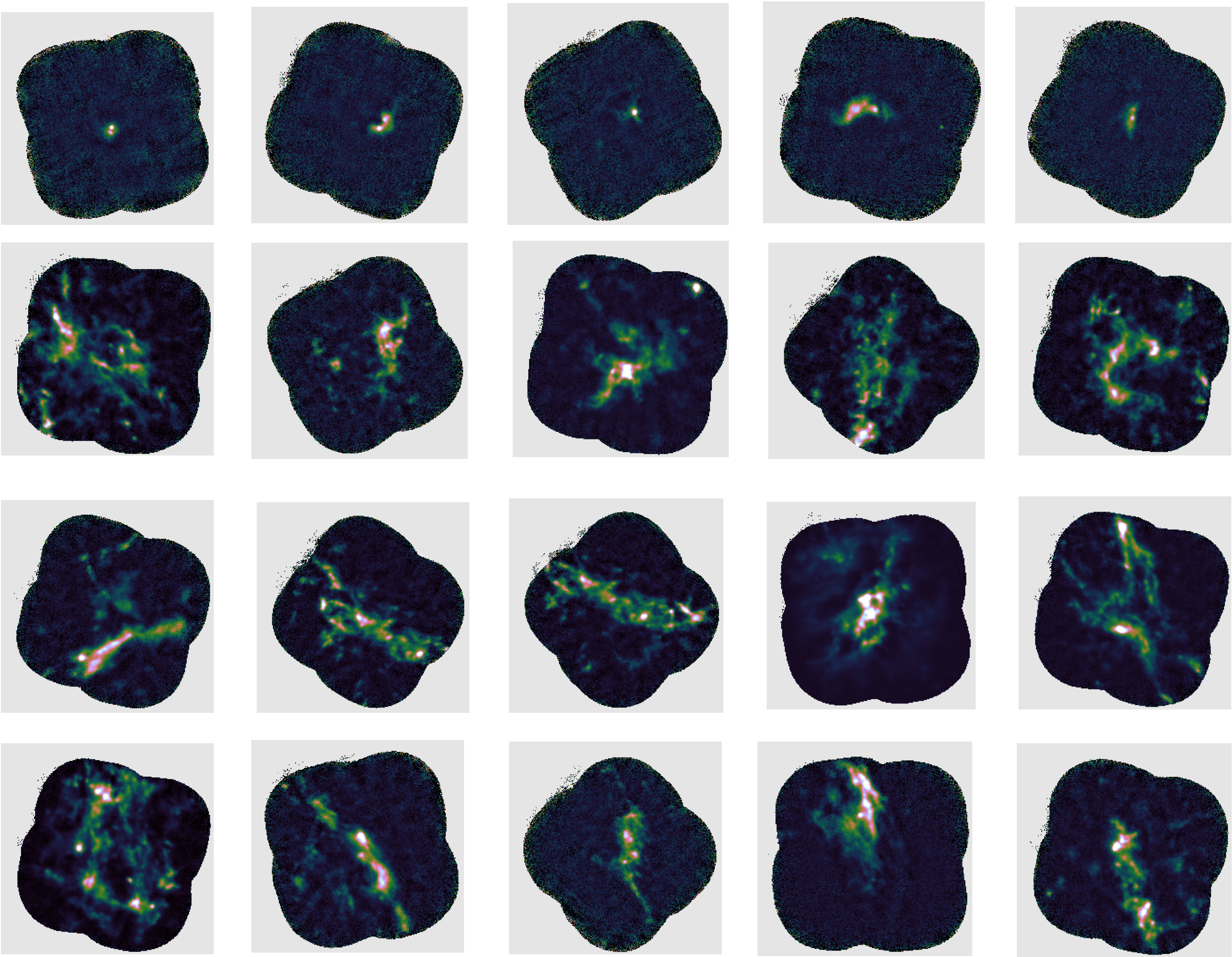
- The TOP-SCOPE survey discovered several tens of filaments that formed due to large-scale compression flows; Ordered magnetic field are revealed toward massive filamentary clouds for the first time (Liu+2018, ApJ, 859, 151; Juvela+2018, A&A, 620, 26; Soam+2018, submitted)

- A population of extremely young dense cores (starless and class 0) were identified in **NRO 45-m** and **ALMA** follow-up survey of SCOPE cores (Tatematsu+2016; Liu+2019, in preparation)

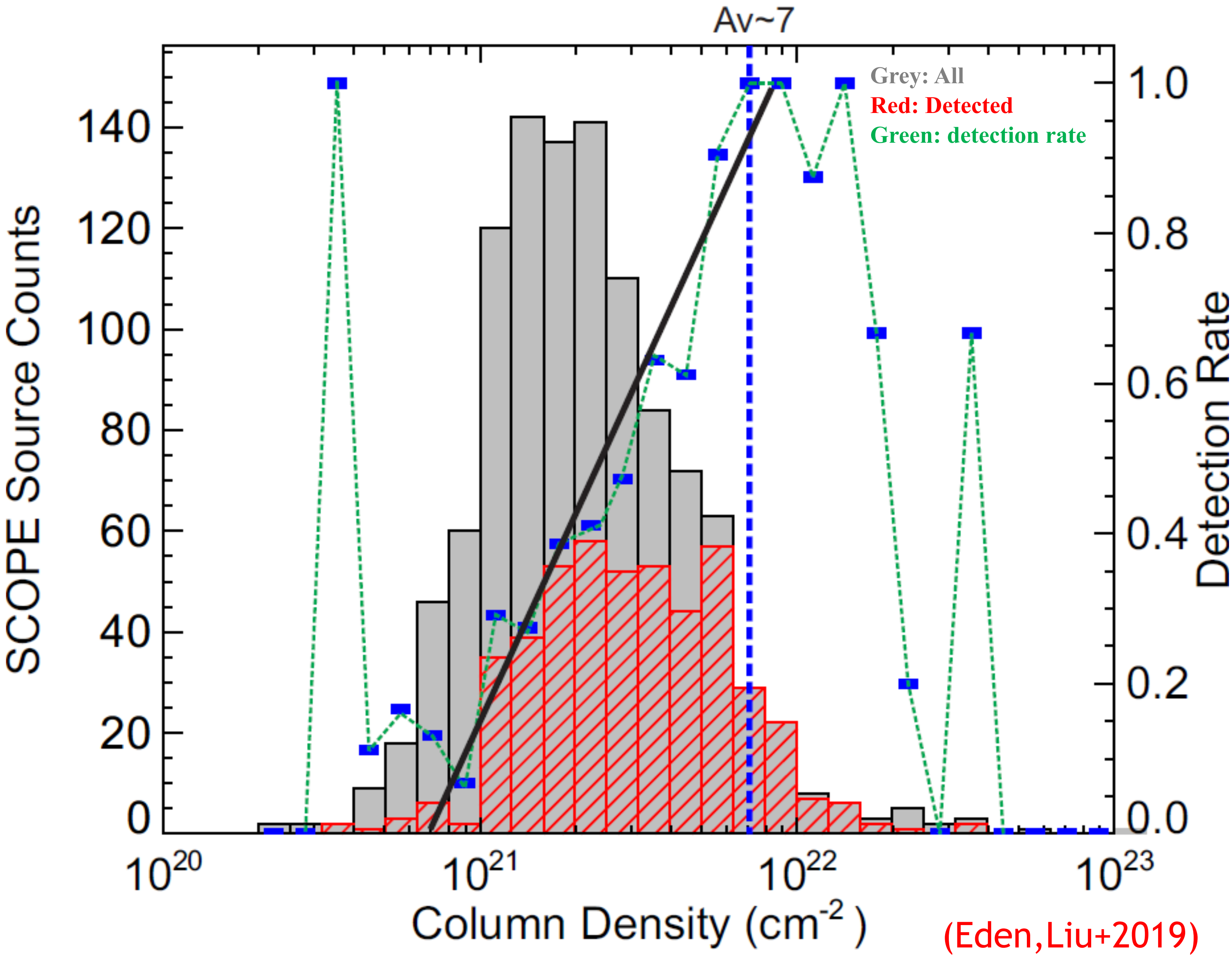
- First detection of a magnetized collapsing massive starless clump (Liu+2018, ApJ, 859, 151)

- First detection of a proto-brown dwarf formed due to photo-erosion of HII regions (Liu+2016, ApJS, 222, 7; Liu+2019, in preparation)

3.1 A census of dense cores across the Galaxy

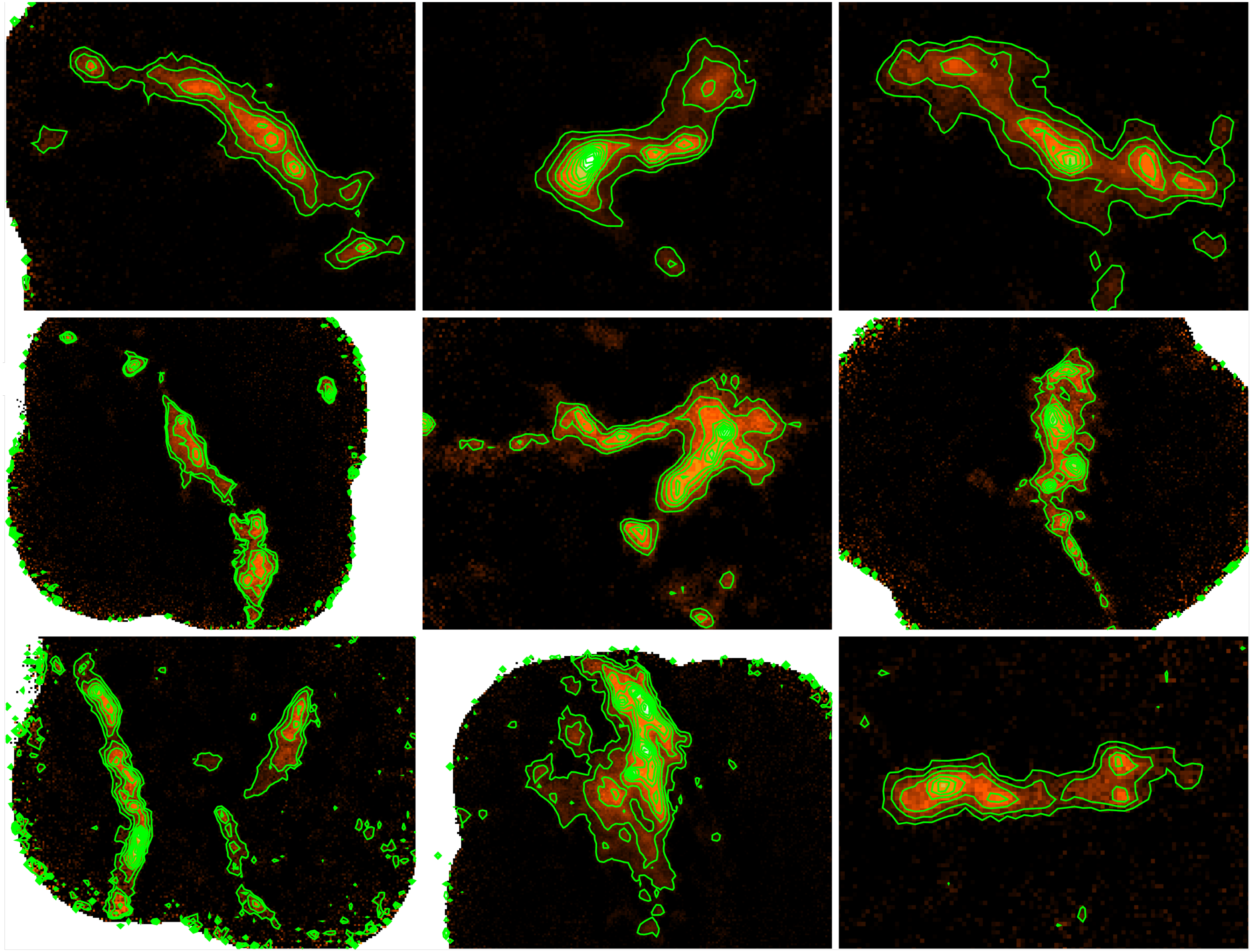


Dense core detection rate as function of background column density from Planck

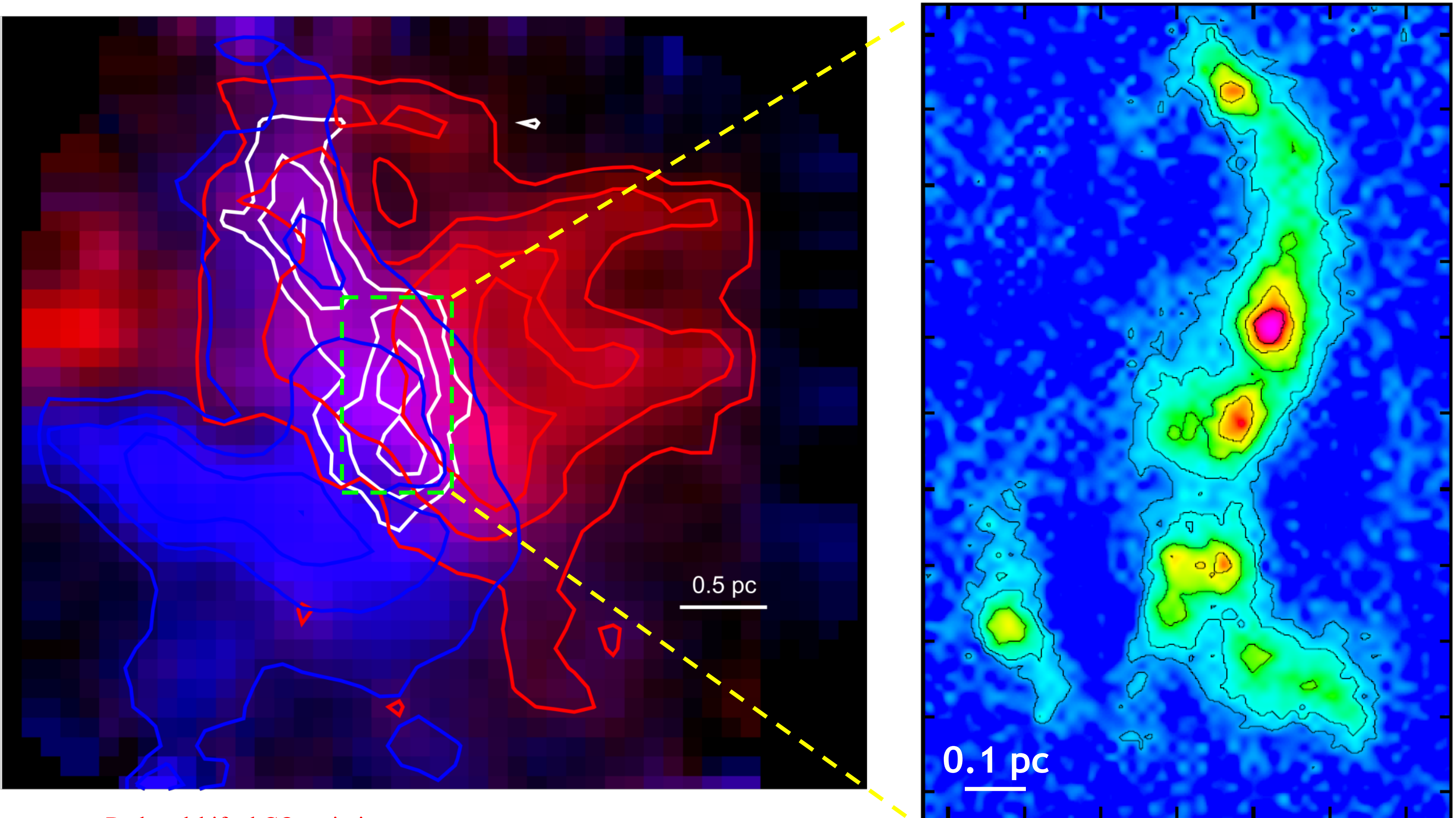


(Eden,Liu+2019)

3.2 Filaments in the TOP-SCOPE survey



Filament formed due to cloud-cloud collision?



Red: redshifted CO emission
Blue: blueshifted CO emission
White: $C^{18}O$ emission

SCUBA-2 850 micron continuum

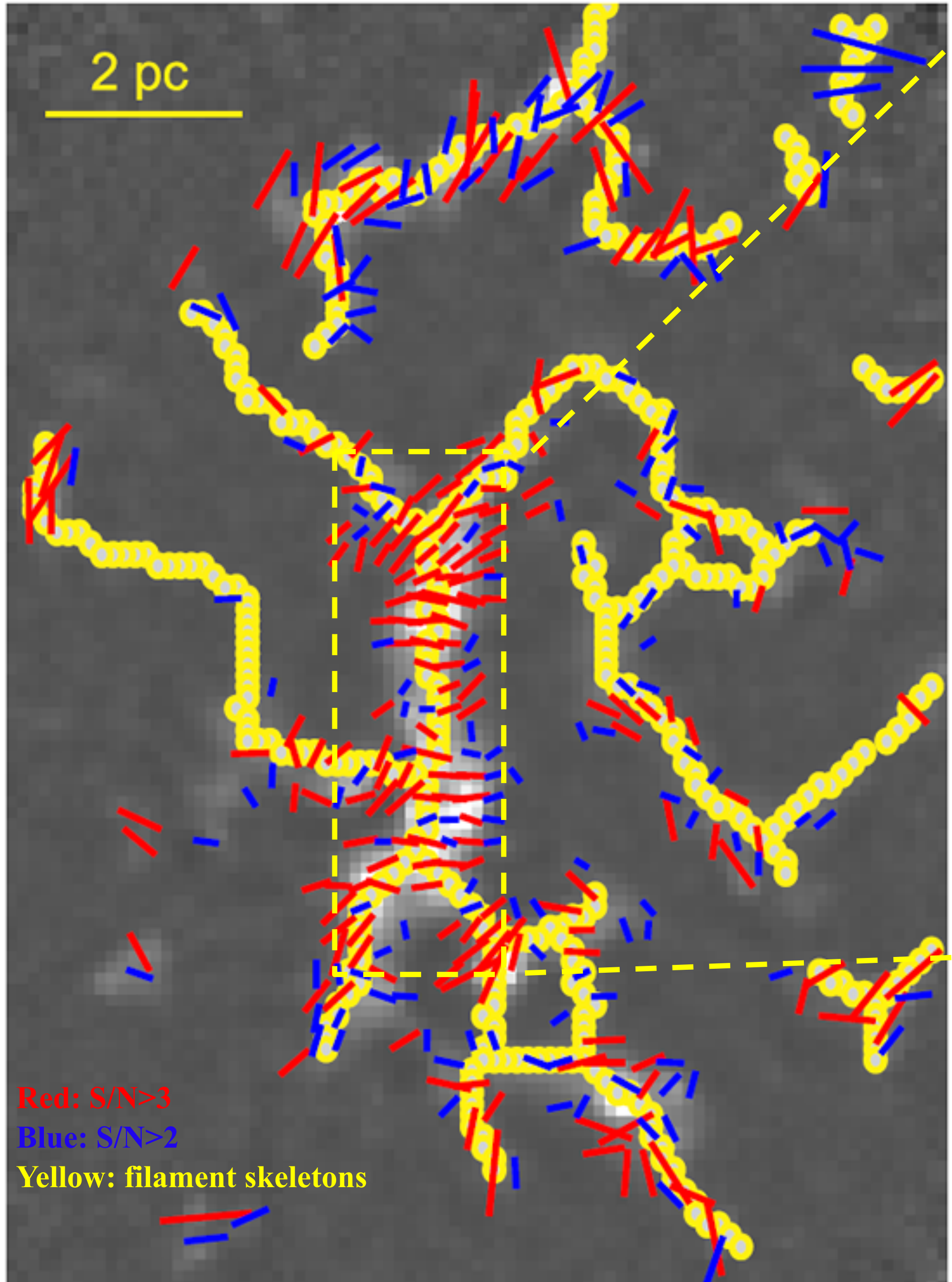
(Zhang et al. 2019; more examples in Dana et al. 2019; Liu et al. 2018b, ApJ, 859, 151)

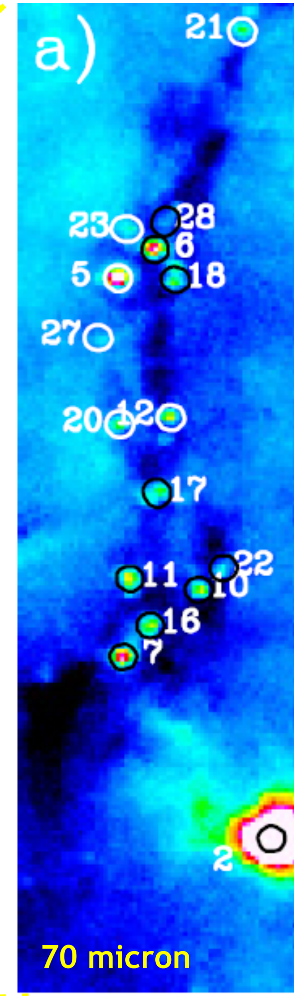
Magnetic fields in filamentary clouds

Cloud is highly filamentary

Magnetic fields (~100 μG) important but not sufficient to support filament or clumps against gravitational collapse

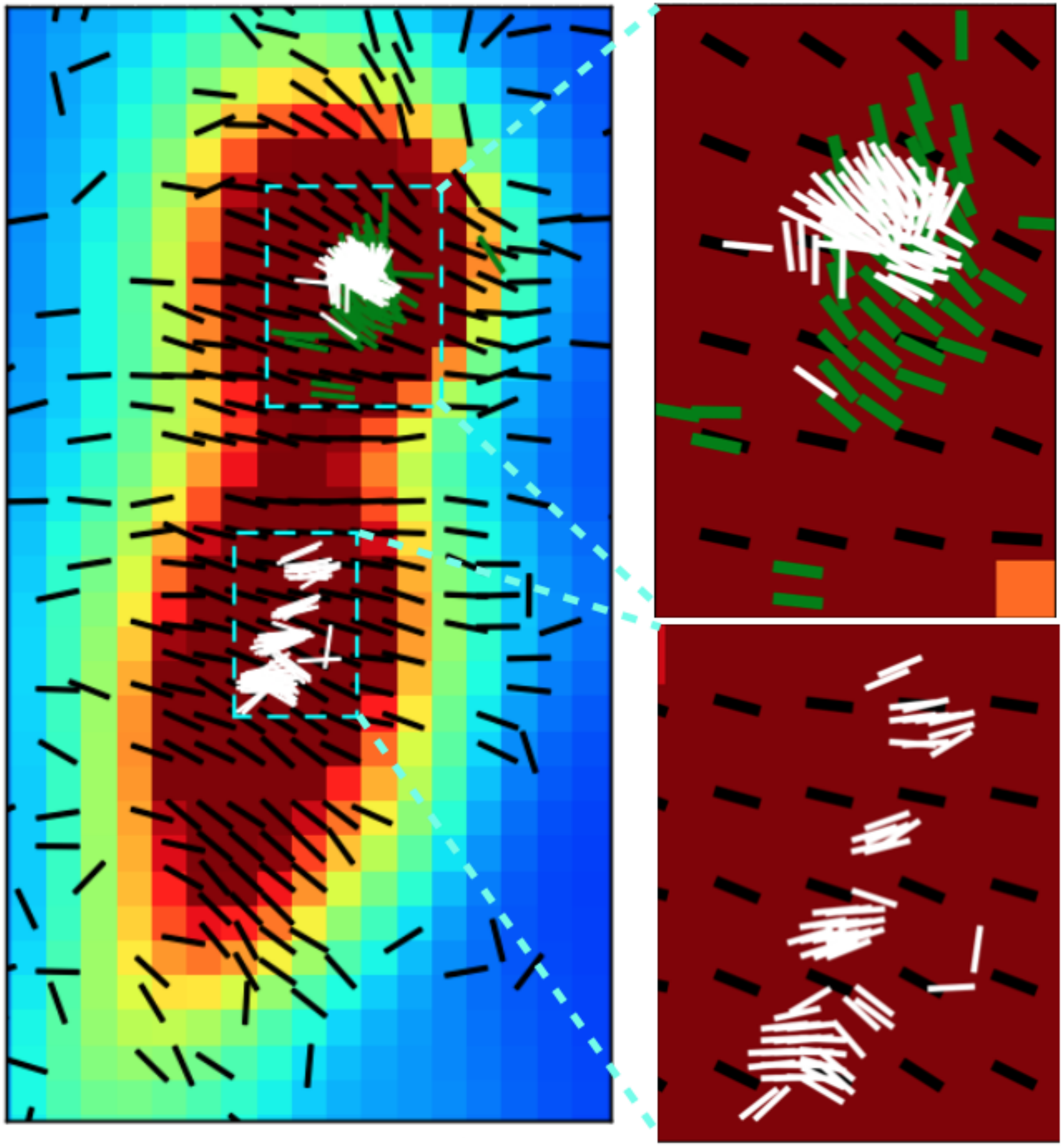
(Liu et al. 2018, ApJ, 859, 2)





(Nguyen Lu’o’ng+2011)

Magnetic field in more evolved filaments

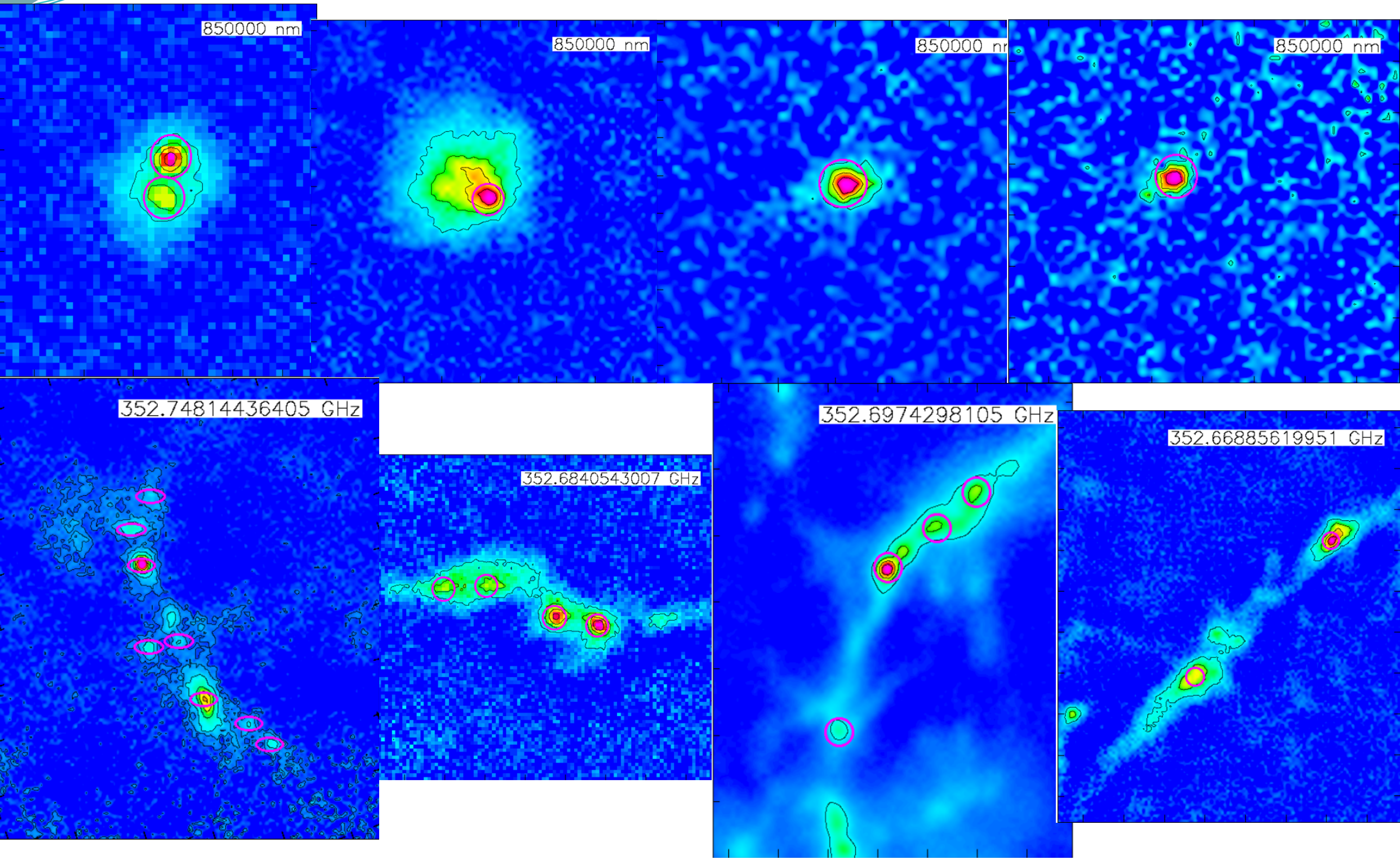


The consistency of field orientations at large scale (POL-2) and small scale (SMA and CARMA) indicates that magnetic fields are dynamically important in the self-similar fragmentation process of filaments (Soam, Liu+2019; see also Lee+2015).

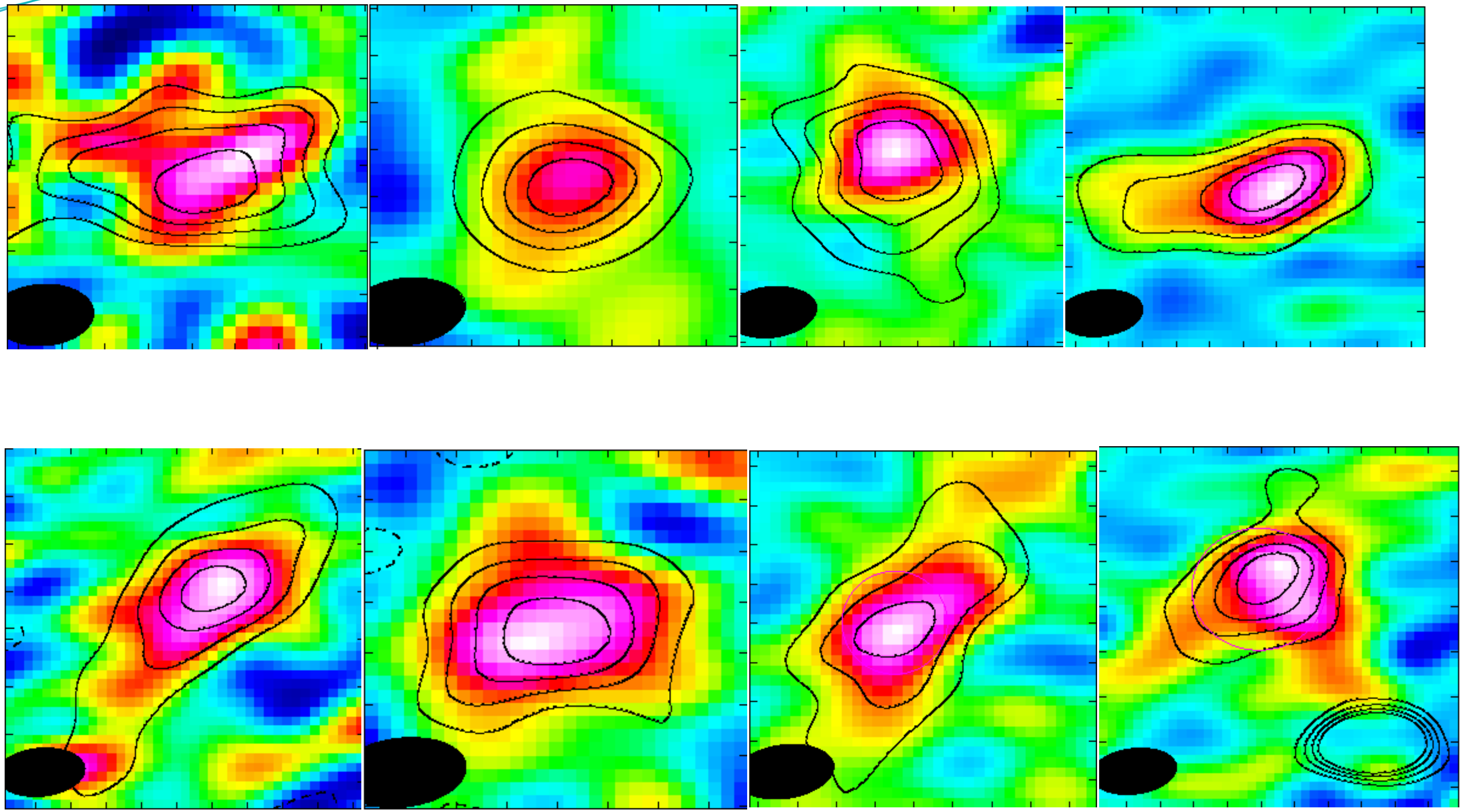
Black: POL-2 B-field segments
White: SMA B-field segments
Green: CARMA B-field segments
Circles: dene cores

3.3 Chemical and dynamical evolution of SCOPE dense cores

An ALMA survey of 72 Orion cores down to 100 AU

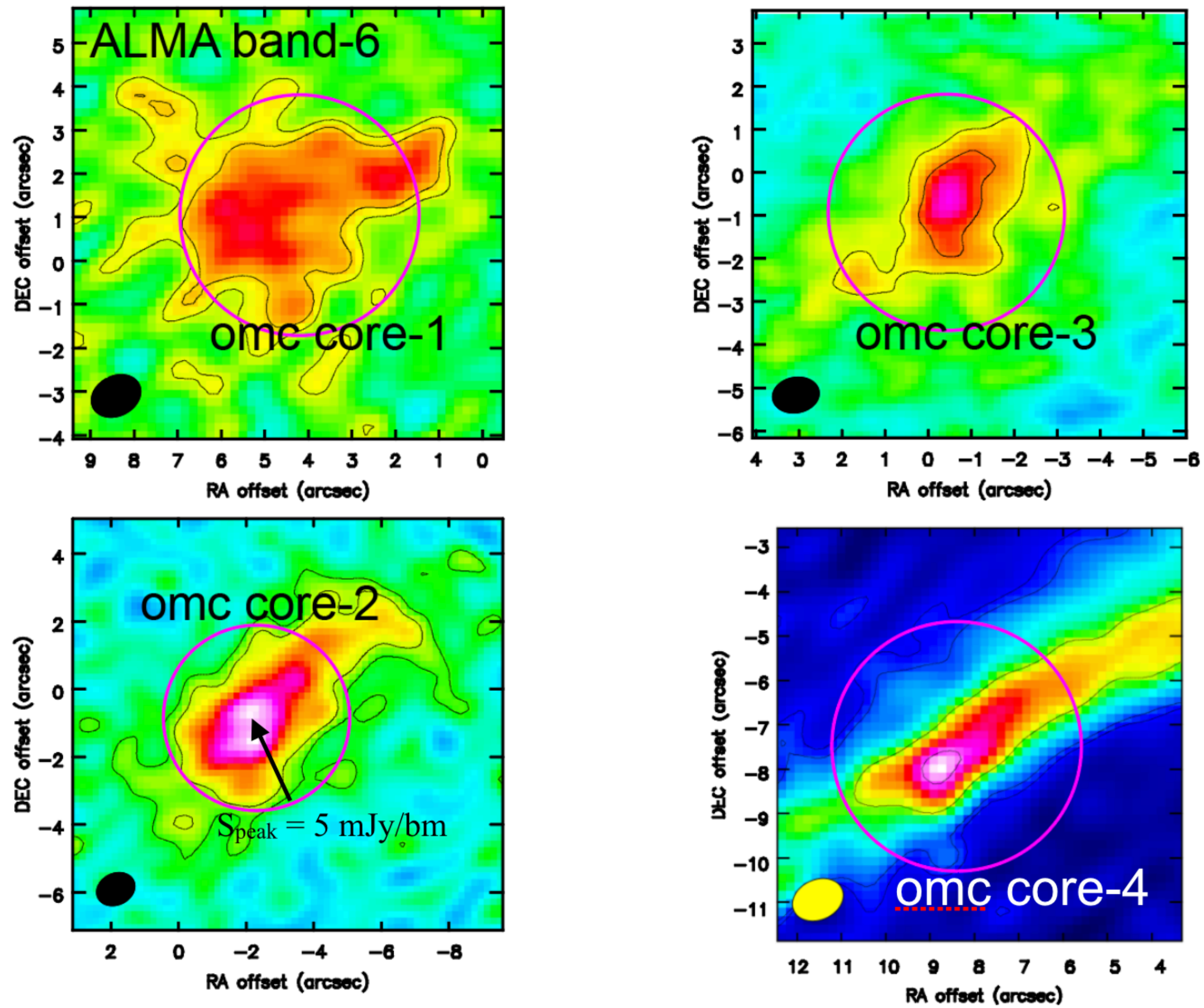


Starless cores with ACA

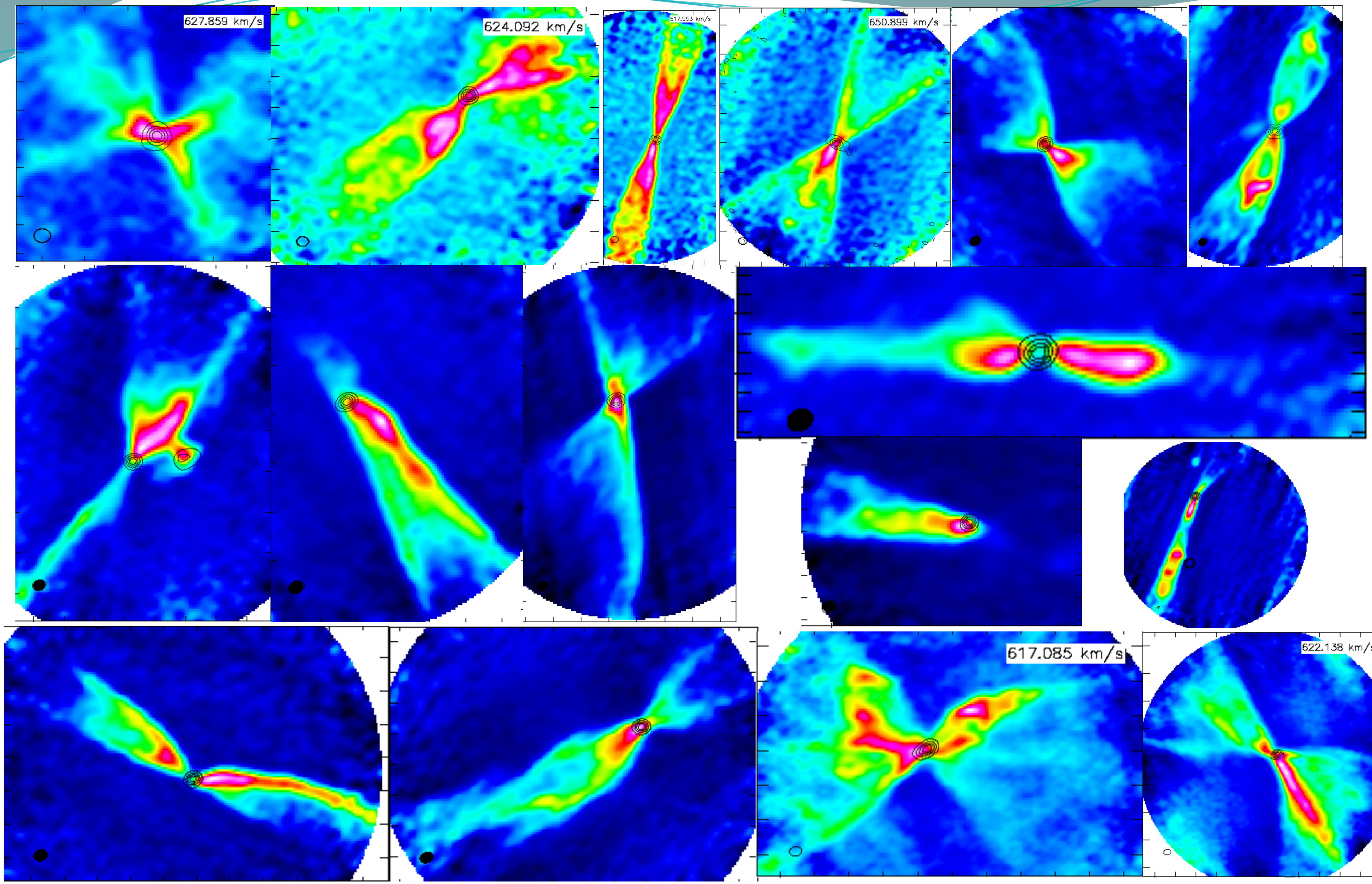


Color images: N2D+ (3-2); contours: 1.3 mm continuum

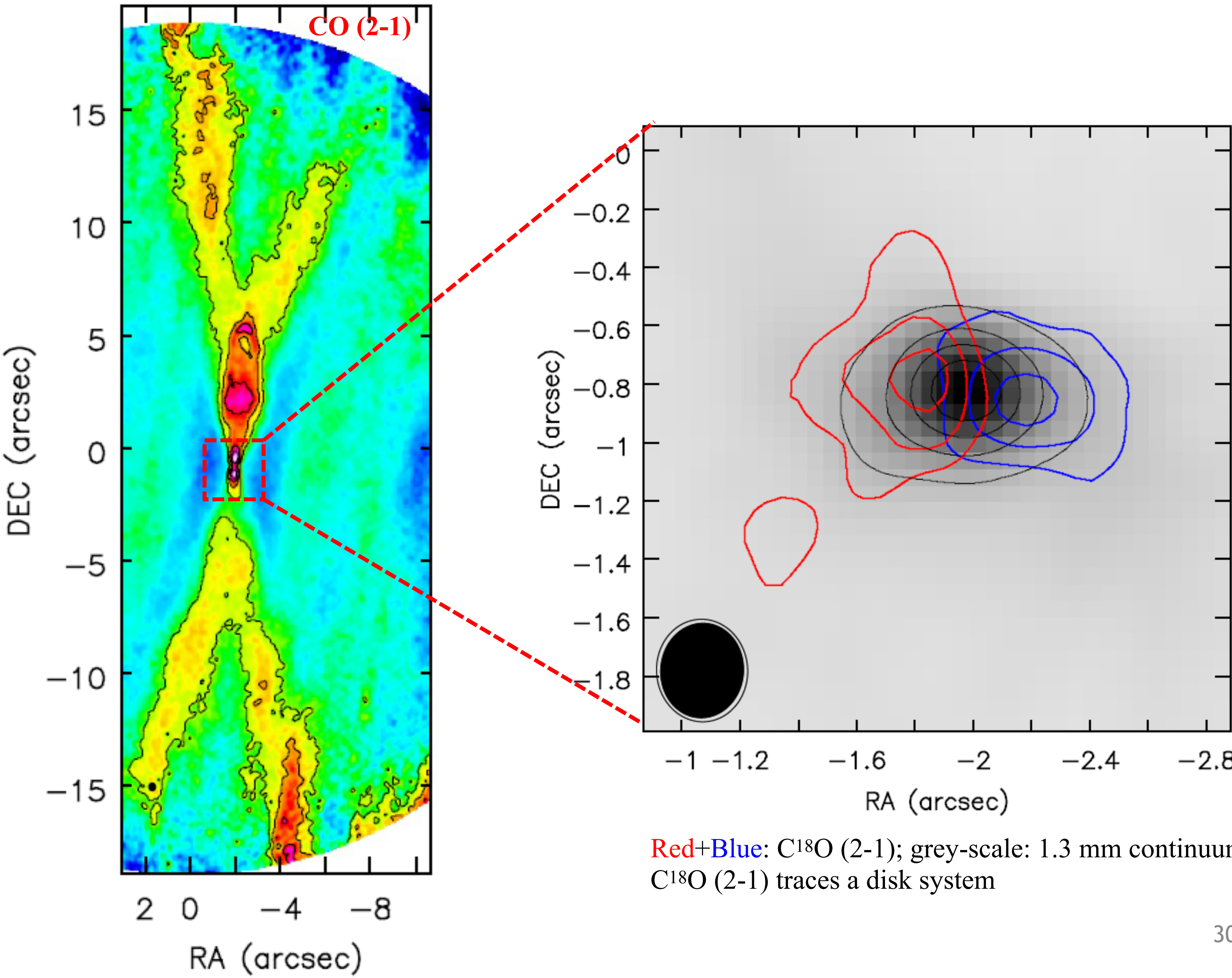
Substructures of starless cores with the 12-m array



Class 0 outflows



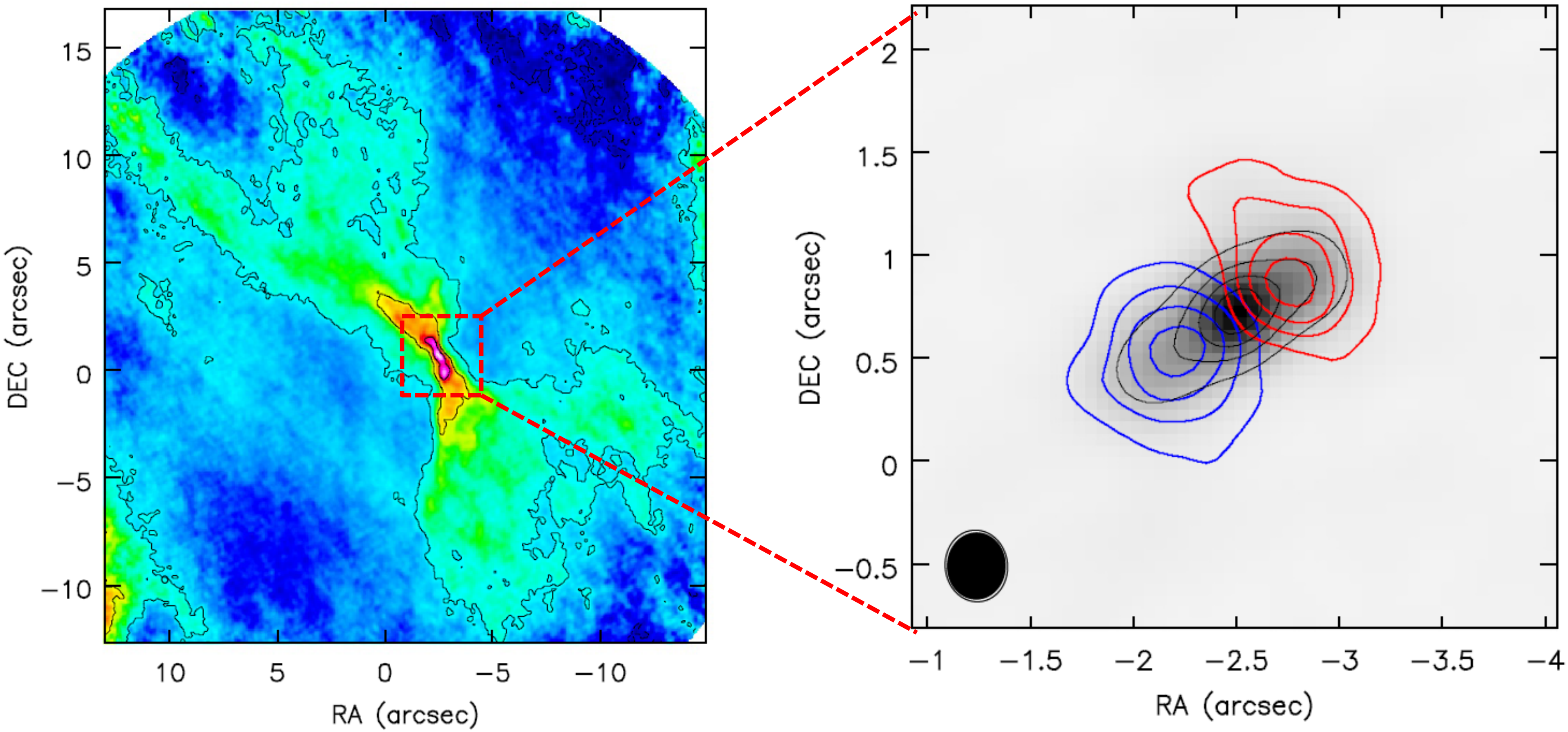
Disk+outflow system of young Class 0 protostar



Red+Blue: $C^{18}O$ (2-1); grey-scale: 1.3 mm continuum

$C^{18}O$ (2-1) traces a disk system

A more evolved disk+outflow system of Class 0 protostar



Preliminary results from an ALMA survey of 72 Orion cores (PI: Tie Liu)

Summary and Future Plans

- The TOP-SCOPE survey has detected a sample of cold filaments and dense cores that probes wildly different environments, and thus represents a real goldmine for investigations of the early phases of star formation.

- Study filament formation from molecular line and dust polarization observations and compare with MHD simulations

- Study the evolution of disks and outflows in the earliest phases with the ALMA and compare with MHD simulations

- Astrochemistry studies toward cold cores/disks with single-dish data and ALMA data (many lines detected like N_2D^+, H_2CO, DCO^+,DCN,$C^{18}O$, CH_3OH, SiO, HNCO, HC_3N…)

- Follow-up observe high-mass starless clumps and pre-/proto-brown dwarfs with the ALMA to study the initial conditions for the formation of high-mass ($M>8M_\odot$) stars and brown dwarfs ($13\ M_{Jupiter} < M < 75\ M_{Jupiter}$)

Collaborations are always welcome!