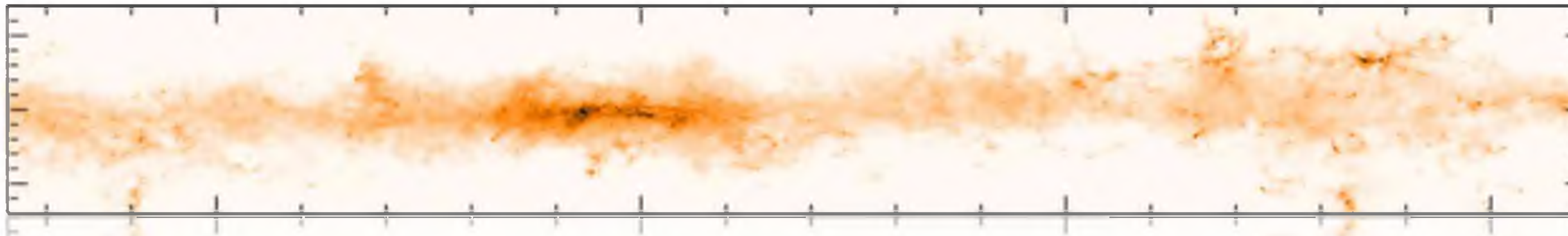

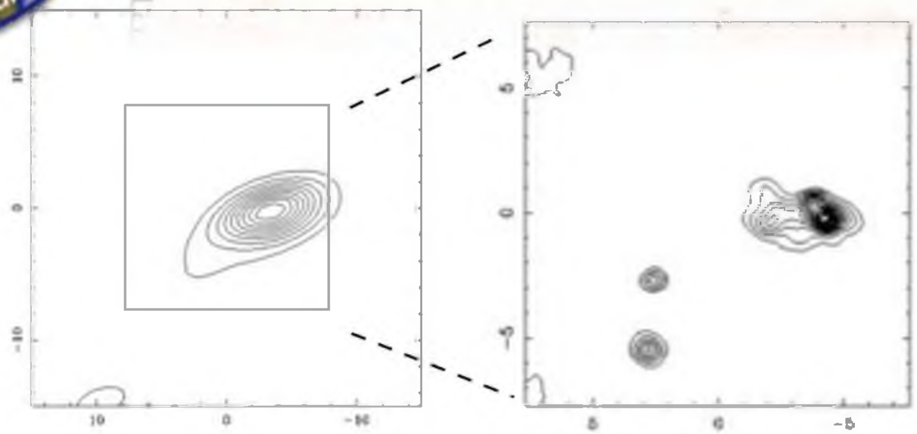

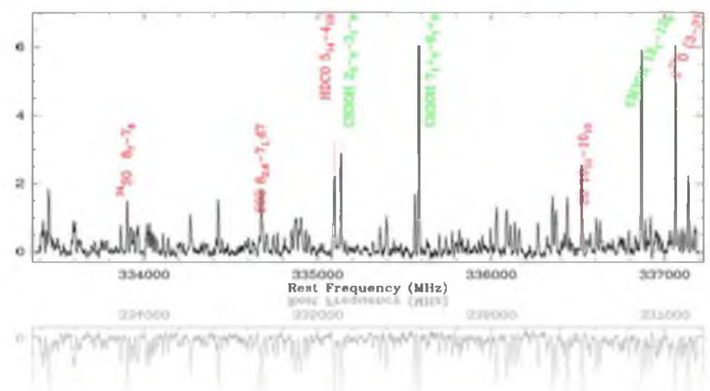

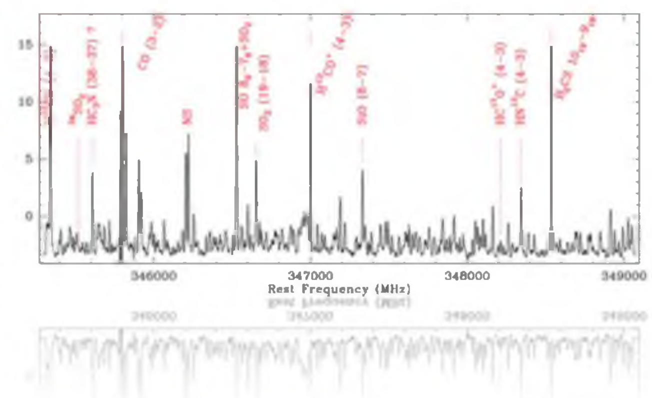

Max-Planck-Institut für Radioastronomie

MAX-PLANCK-GESELLSCHAFT

The hunt for young Galactic protoclusters

From ATLASGAL to SPARKS… and ALMA-IMF

Timea Csengeri
Laboratoire d'Astrophysique de Bordeaux, CNRS
Max Planck Institute for Radioastronomy, Bonn

ATLASGAL

MPG: Schuller (PI), Menten, Wyrowski, Urquhart, Csengeri, Beuther, Henning, Linz, Schilke
ESO: Walmsley, Bontemps, Cesaroni, Deharveng, Herpin, Lefloch, Molinari, Motte, Minier, Nyman, Reveret, Risacher, Russeil, Schneider, Testi, Zavagno
Chile: Bronfman, Contreras, Garay, Mardones

SPARKS

Csengeri (PI); Bontemps; Wyrowski; Menten; Urquhart; Leurini; Motte; Schuller; Testi; Bronfman; Beuther; Chapillon, Longmore; Commercon; Henning; Palau; Tan; Fuller; Peretto; Duarte Cabral; Traficante, Bouscasse, Lin

ALMA-IMF

Motte (PI); Ginsburg (co-PI); Sanhueza (co-PI); Louvet (co-PI); Bontemps; Csengeri; Herpin; Molet; Guzman; Bally; Battersby; Svoboda; Di Francesco; Galvan-Madrid; Bronfman; Nguyen Luong; Nakamura; Nony; López-Sepulcre; Gusdorf; Hennebelle; Braine; Ohashi; Tatematsu; Sakai; Lu; Chen; Reyes; Finger; Menten; Rosolowsky; Gomez;

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Origin of high-mass (proto)stars and clusters ?

Massive stars ($M > 8\ M_{Sun}$) play a crucial role in the life cycle of the ISM, and galaxies.

~ 100-10 pc

Dense c... -, intermediate mass stars

J... bility : $M_{env} \sim M_{Jeans} \sim 1\ M_{Sun}$

$M_{Jea...}$ ... $1/\sqrt{\varrho}$

thermal balance

... at high density

M_{Jeans} (0.05 pc)

associations

$_{nv} > 10\text{-}50\ M_{Sun}$

M_{Sol},~2000 au

Zhang et al. (2009),
...geri et al. (2011a,b)

(0.3 pc)

ciations/clusters

...her & Schilke (2004),
...t al. (2013), Urquhart
...Csengeri et al. (2017)

Where and how do the highest mass protostars form ?

Large area surveys AND high resolution interferometers are needed!

~ 0.1 pc

Outline

ATLASGAL

The largest sample of Galactic massive clumps

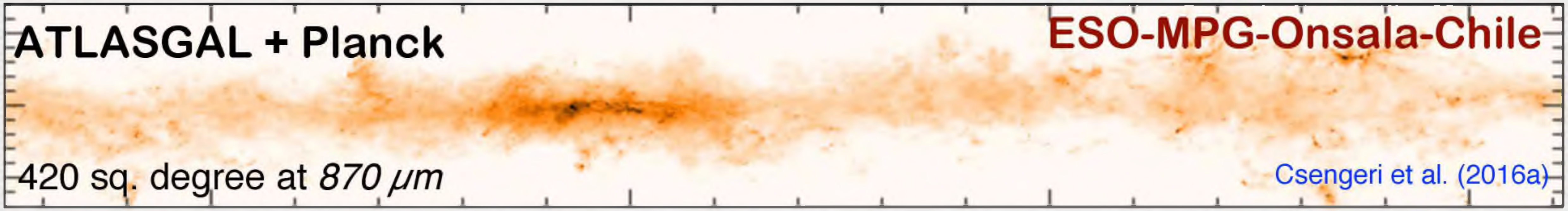
SPARKS

Formation conditions: fragmentation and kinematics

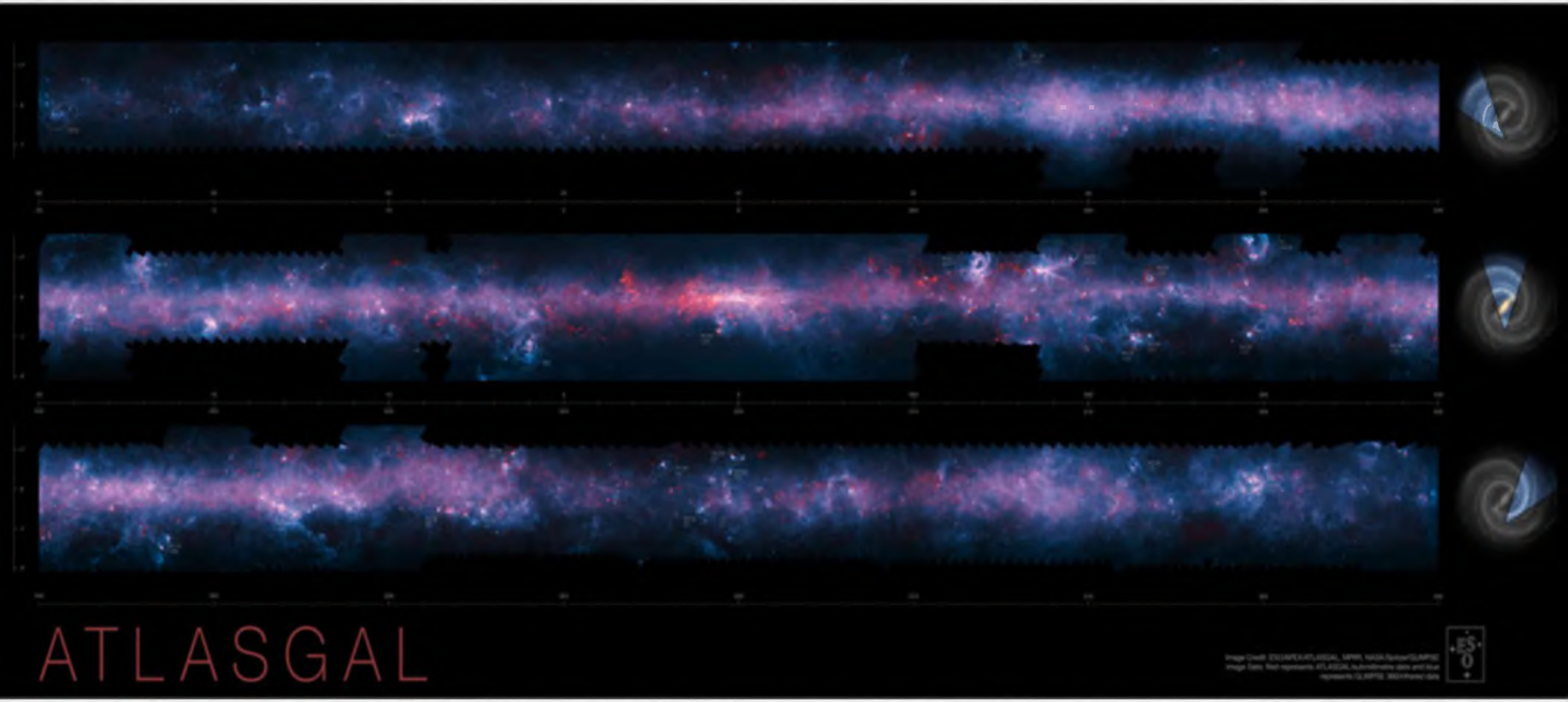
Infall and accretion: the case study of G328.25

ALMA-IMF Large Programme

ATLASGAL: APEX Telescope Large Area Survey of the Galaxy



ESO PR 2016/1606



Searching for the precursors of massive stars and clusters

- **APEX/ATLASGAL survey: a complete view of the cold dust in the inner Galaxy**

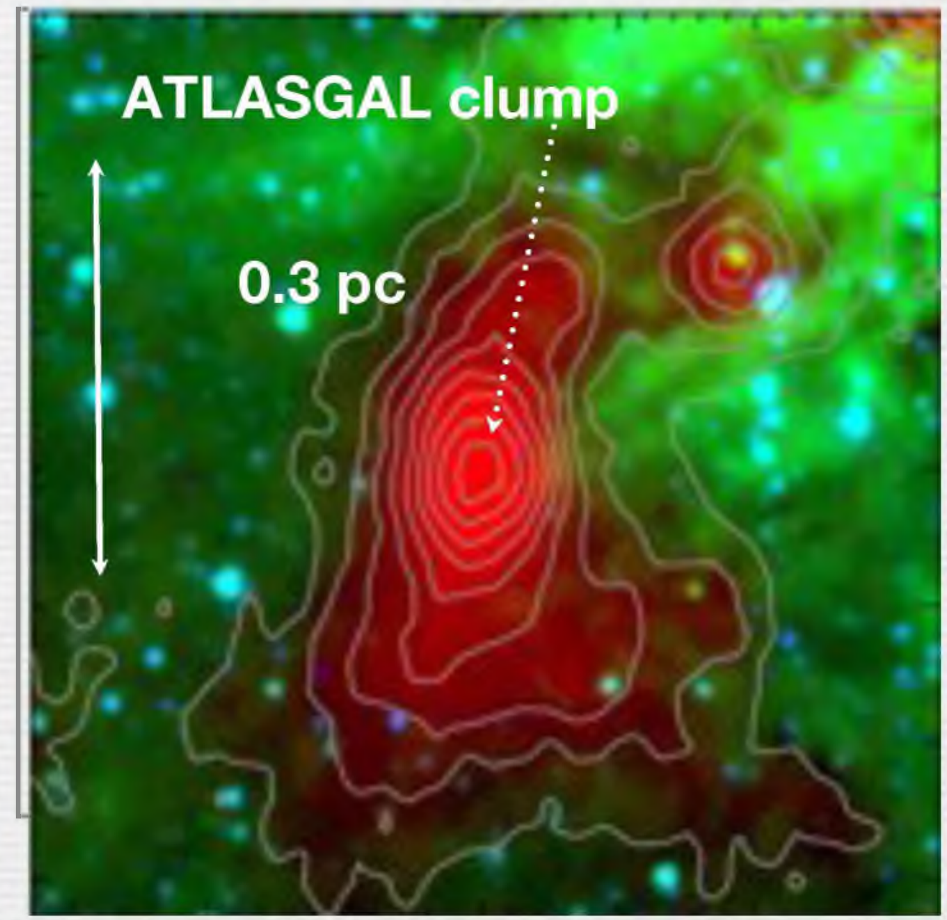
Catalogs of sources: *Schuller et al. (2009), Csengeri et al. (2014), Urquhart et al. (2018)*

Filaments: *Li et al. (2016), Mattern et al. (2018)*

Distances : *Wienen et al. (2012, 2015) Urquhart et al. (2018)*

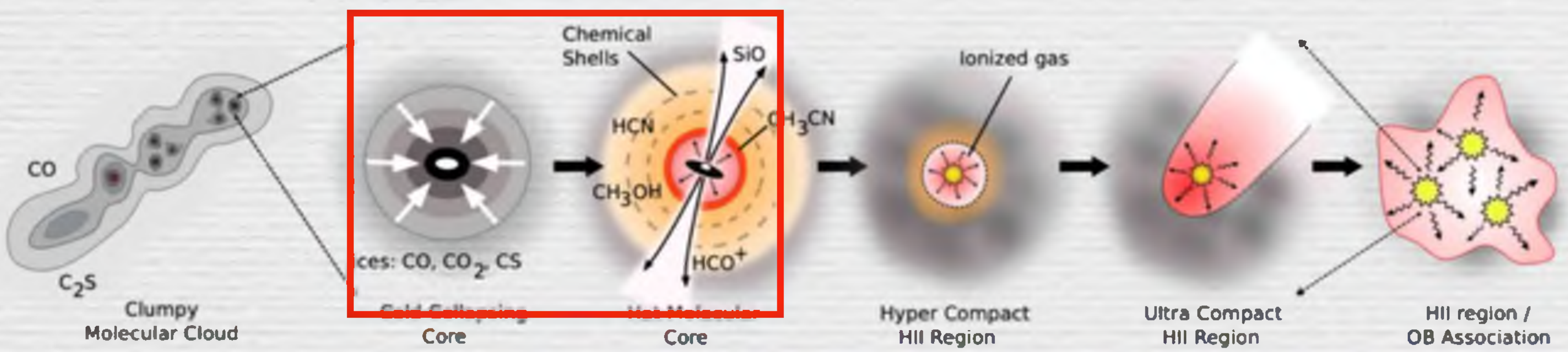
Dust properties: *König et al. (2017)*

Spectral surveys: *Giannetti et al. (2014) Csengeri et al. (2016b), Urquhart et al. (2019)*



870 micron (ATLASGAL) ; 22 micron ; 3.4 micron (WISE)

- **Precursors of rich clusters : flux limited sample of infrared quiet massive clumps with high surface density** *Csengeri et al. (2017a)*



from C. Purcell http://www.physics.usyd.edu.au/~cpurcell/professional/figures.php

ATLASGAL: identify the youngest precursors of OB type stars and clusters

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SPARKS

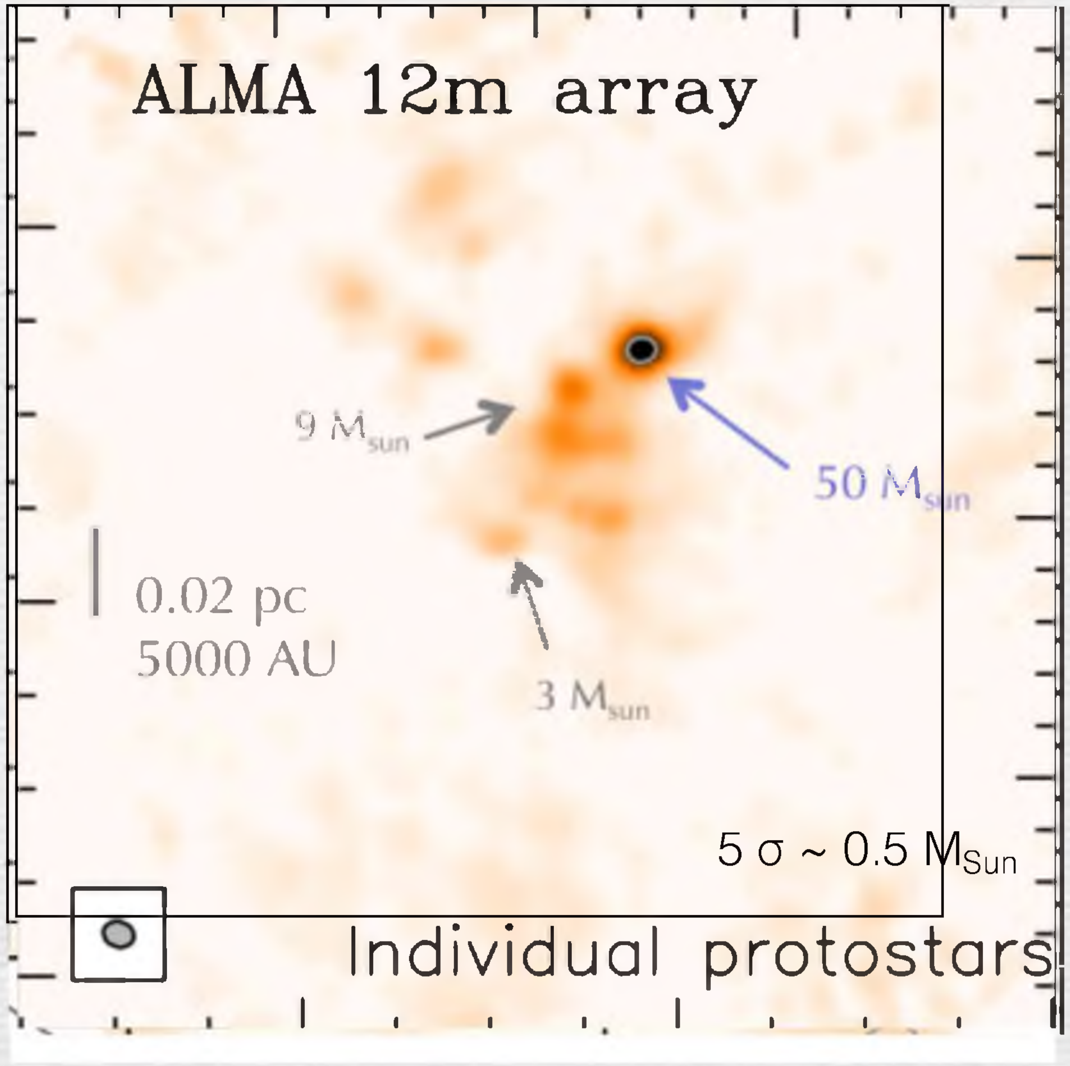
Search for high-mass Protostars with ALMA Revealed up to Kilo-parsec Scales

- **35 ATLASGAL selected infrared quiet clump observed with ALMA**
  - 70% of all such objects within 5 kpc (flux limited sample!)
  - homogenous, representative sample of early stage massive clumps

- **Band 7 at ~2000 au resolution**
- **Continuum and lines**

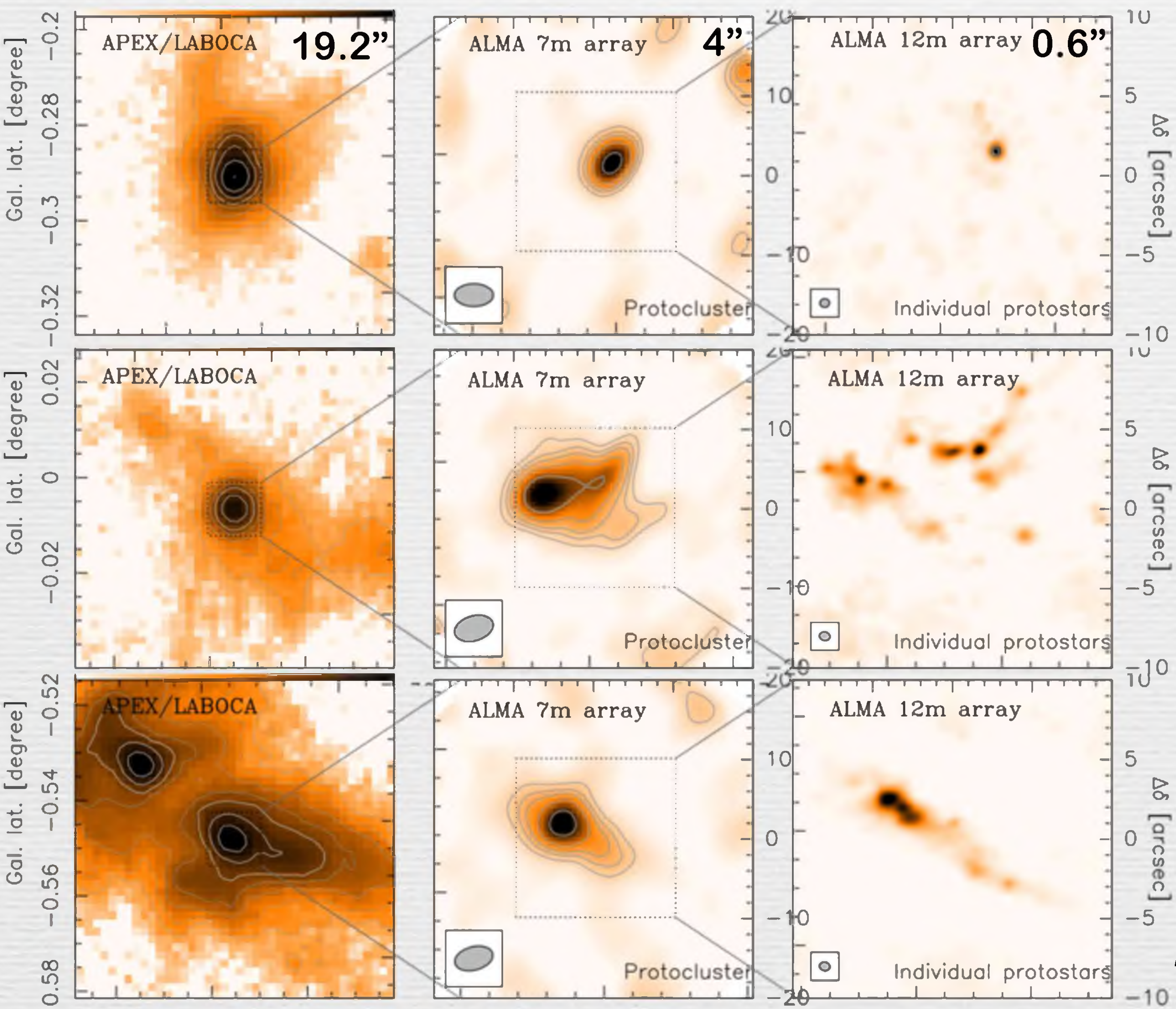
↓

Fragmentation, outflows, kinematics, chemistry on all scales



SPARKS: fragmentation

APEX (clumps) | **ALMA 7m (cores)** | **ALMA 12m (protostars)**



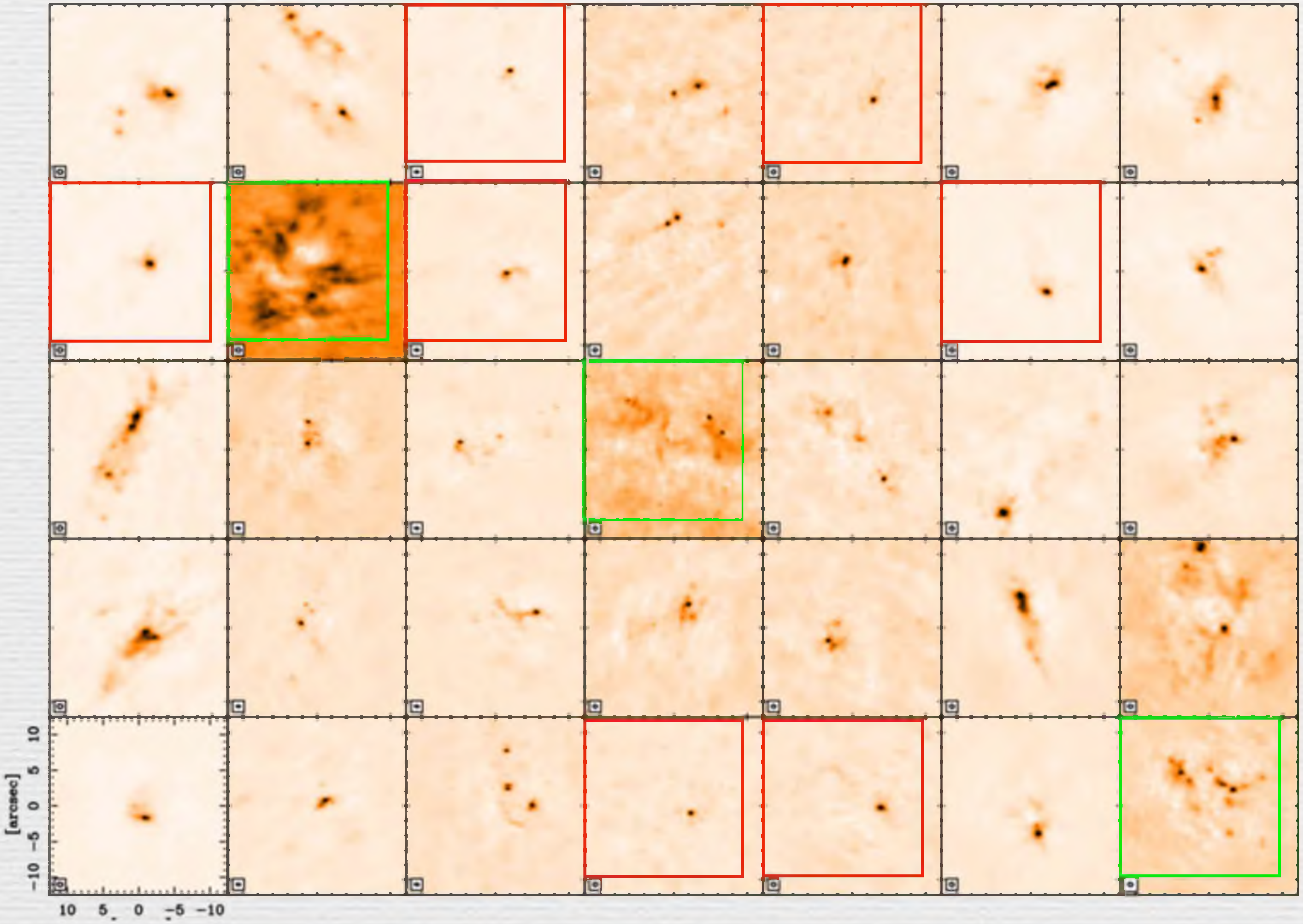
Limited fragmentation

Low-mass cluster

Massive protocluster

Line free continuum at 345 GHz

SPARKS reveals high-mass protostars



Line free continuum at 345 GHz

Statistically constrain the properties of high-mass protostars

- >60 protos. M_{env} > 10 M_{sol}
- ~30 protos. M_{env} > 30 M_{sol}

Envelope size

~ 3000 - 5000 au

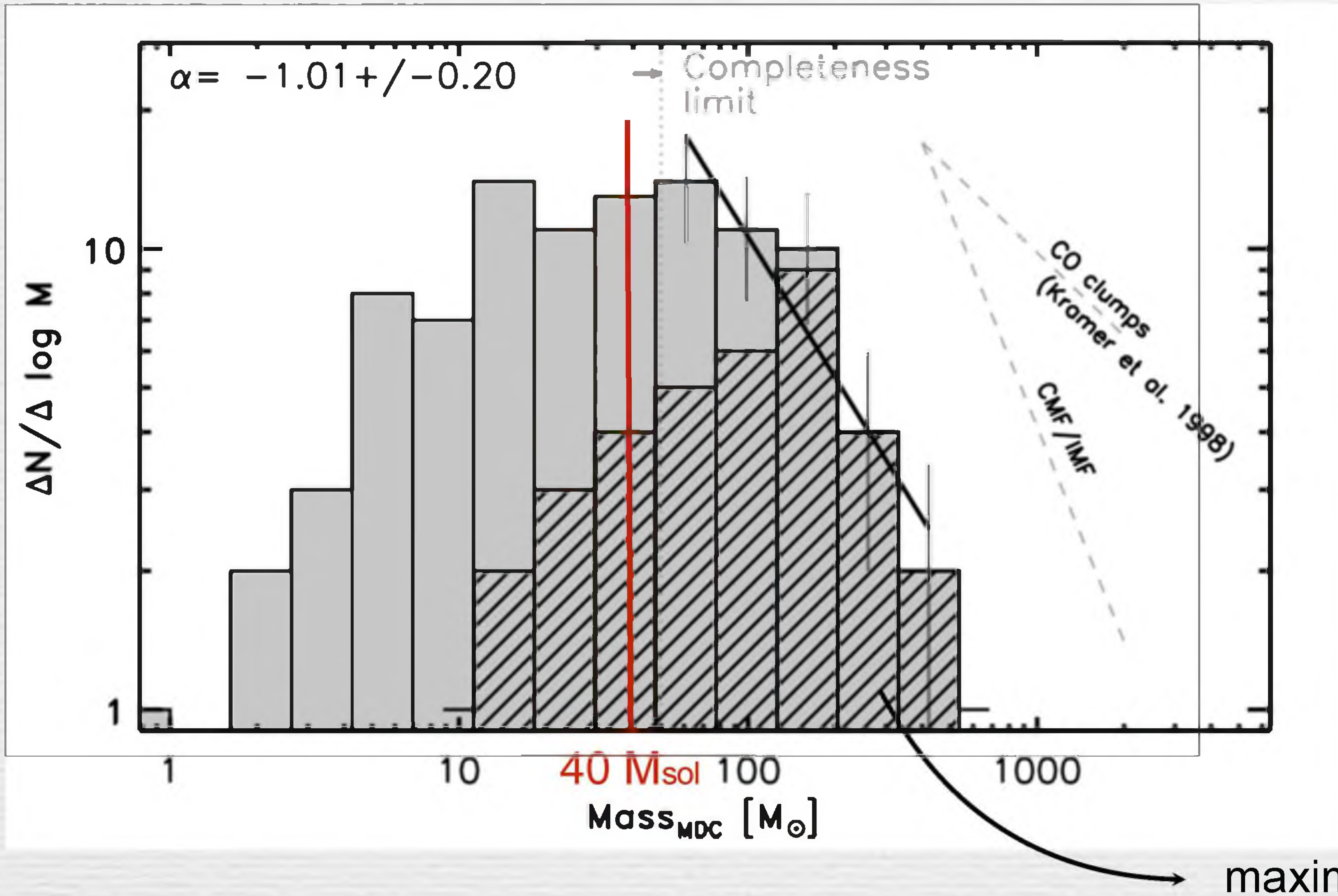
Fragmentation

- Single fragments: 7 (20%)
- Low-mass cluster: 3 (9%)
- Few massive fragments: 71%

Diverse fragmentation properties

Palau et al. (2013),
Beuther et al. (2018) – CORE NOEMA Large Programme,
Lin et al. (2019) – SABOCA study

Massive dense cores form at an early stage



A large fraction of the cores are massive

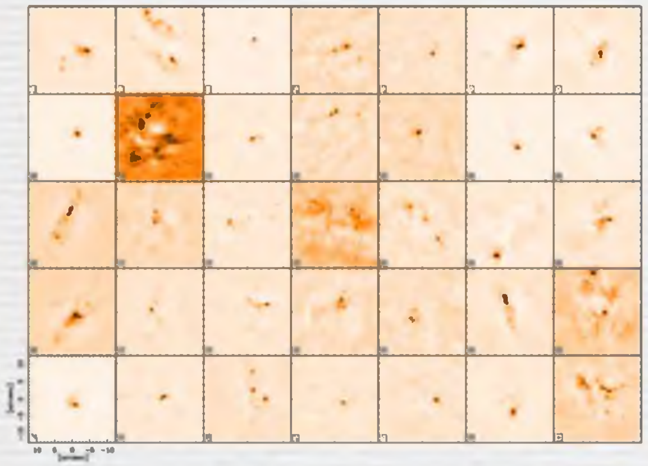
- Most clumps (80%) host already massive dense cores (MDCs)
  - MDCs are formed early on
- MDC mass distribution is shallower than the IMF

see also Motte et al. (2018), Nature Astronomy

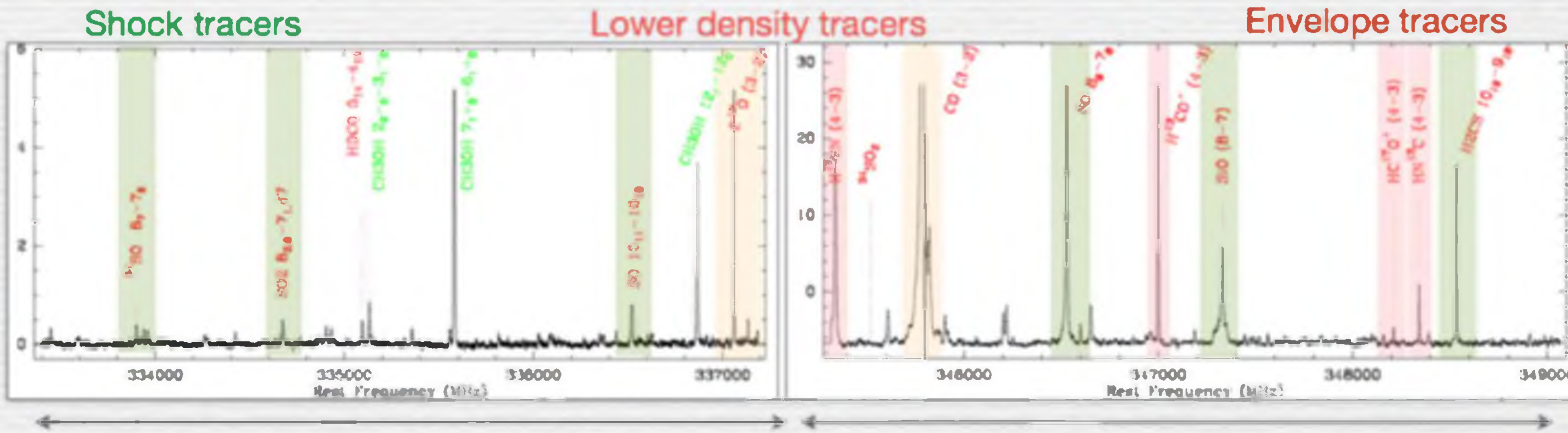
Conclusions:

- limited number of fragments, early appearance of MDCs: fragmentation is not compatible with pure gravo-thermal processes
- compatible with a fast collapse setting in at parsec scales : exceptionally strong B field or turbulence needed for viral equilibrium

High-mass envelopes: organised velocity field



Line free continuum at 345 GHz



7.5 GHz instantaneous spectral coverage

- **Tracers of dense gas:**

  $H^{13}CO^+$ (4-3) & $HN^{13}C$ (4-3)

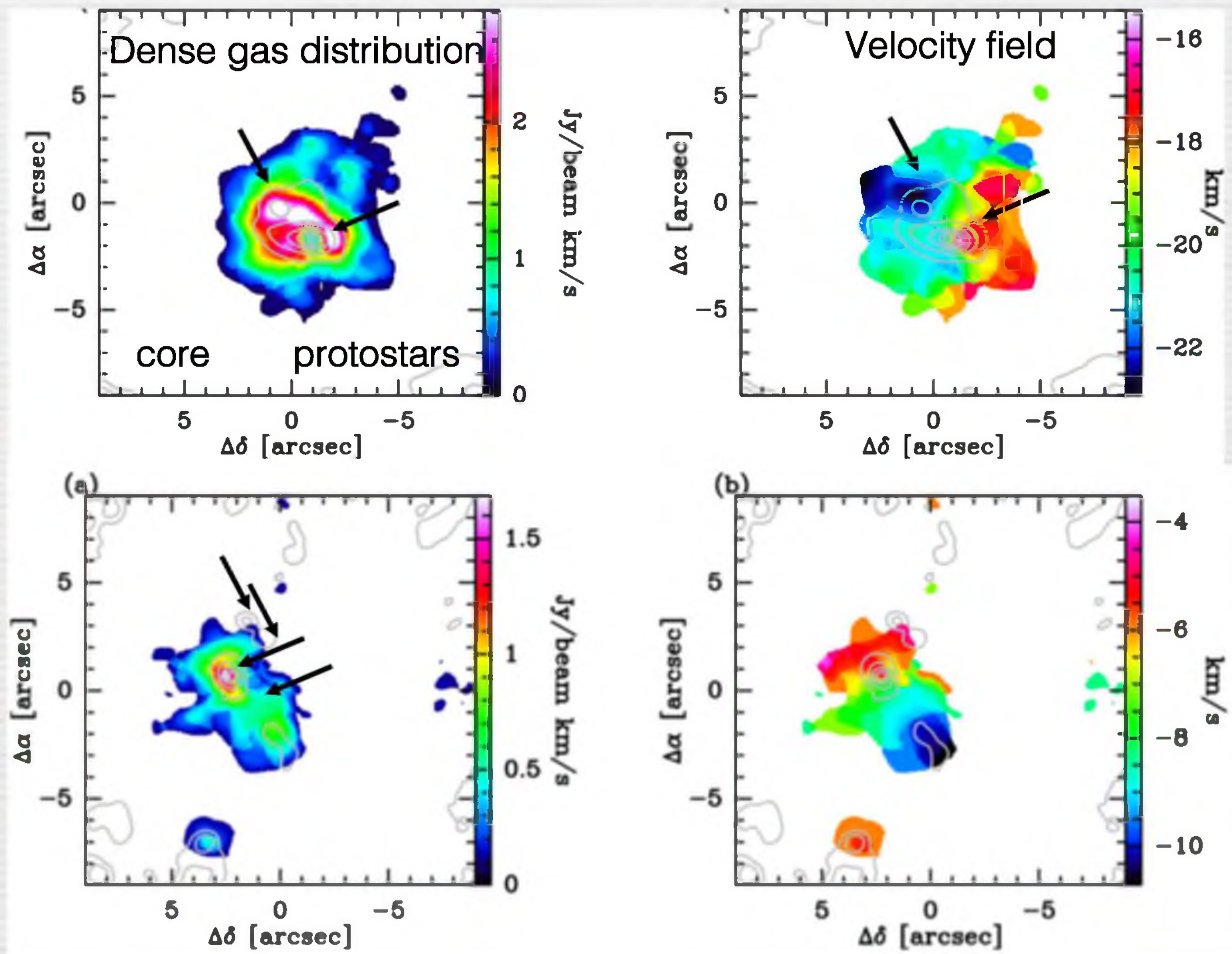
  n> 10^5-10^6 cm^{-3}

  $H^{13}CO^+$ (4-3) is the most extended

- **Kinematics of dense gas reveals highly ordered motions :** supersonic turbulence, but line-widths are relatively low $\bar{\Delta v} \sim 3\,\mathrm{km\,s^{-1}}$

- **Bonfand et al. (in prep) : Molecular content of high-mass envelopes**

Master thesis of L. Bouscasse



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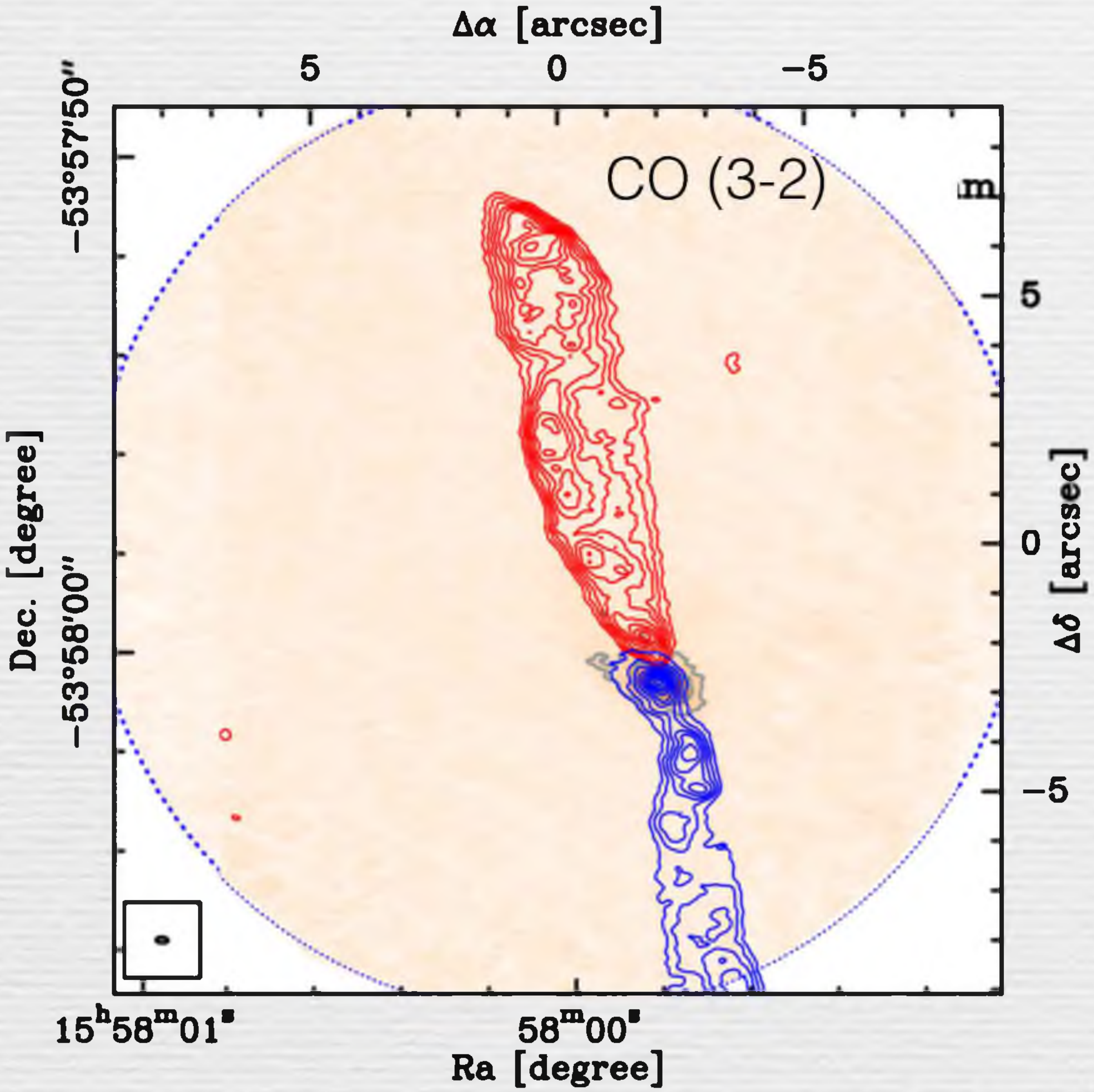
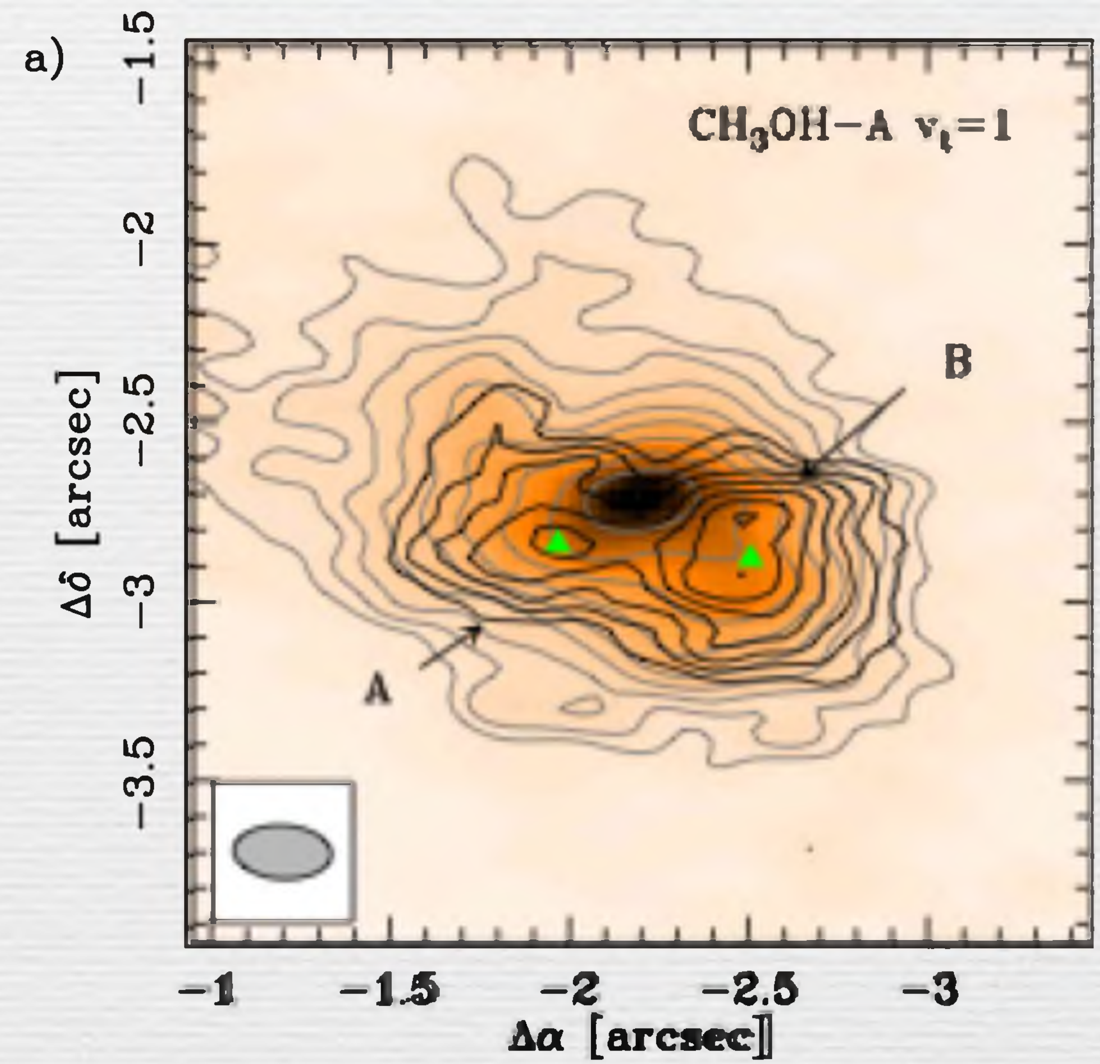
Case study: a high-mass protostar in its main accretion phase

- 650 M⊙ clump and a single compact object : current protostellar mass ~15 M⊙ (from L_{bol})
- M_{env} ~ 130 M⊙ ⟶ 50 M⊙ expected final stellar mass (O4-O5 type star)



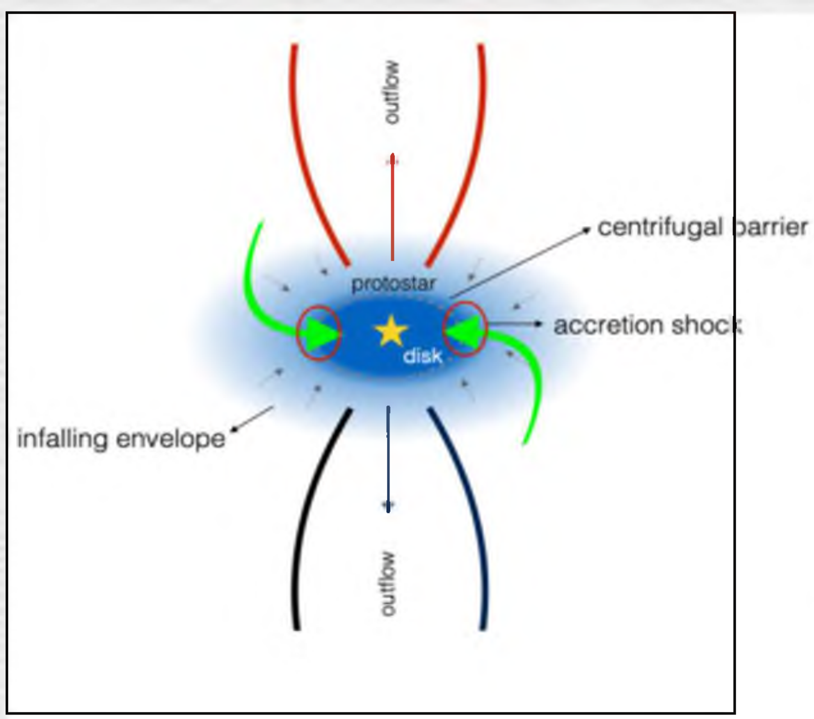
Csengeri et al. (2018)



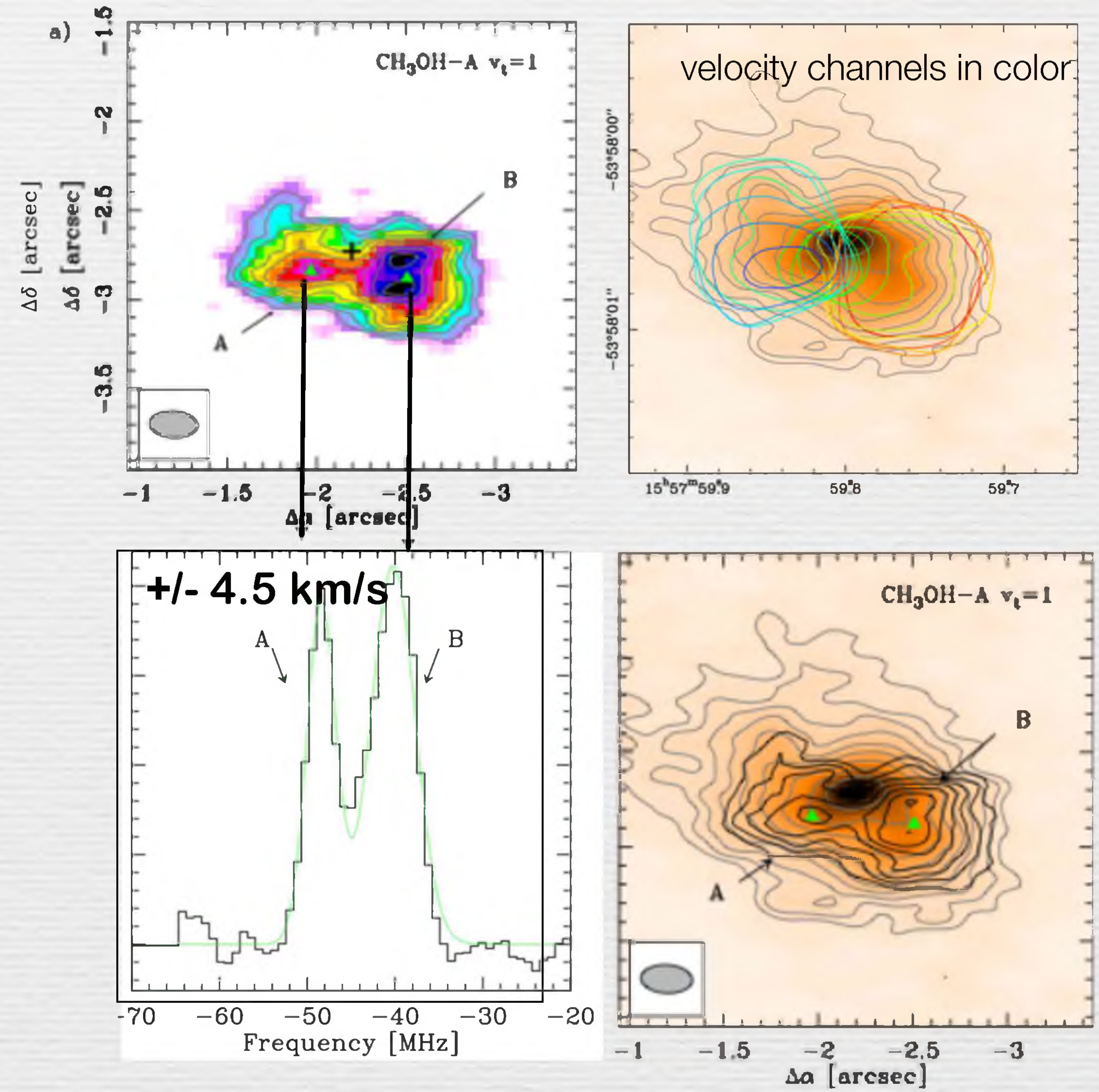
G328.2551-0.5321: Accretion shocks at the centrifugal barrier

- CH_3OH v_t=1 :
  - peaks offset from the protostar
  - two velocity components
- Increase of CH_3OH abundance by shocks

→ **centrifugal barrier**



(adapted from Sakai et al. 2014, Nature)

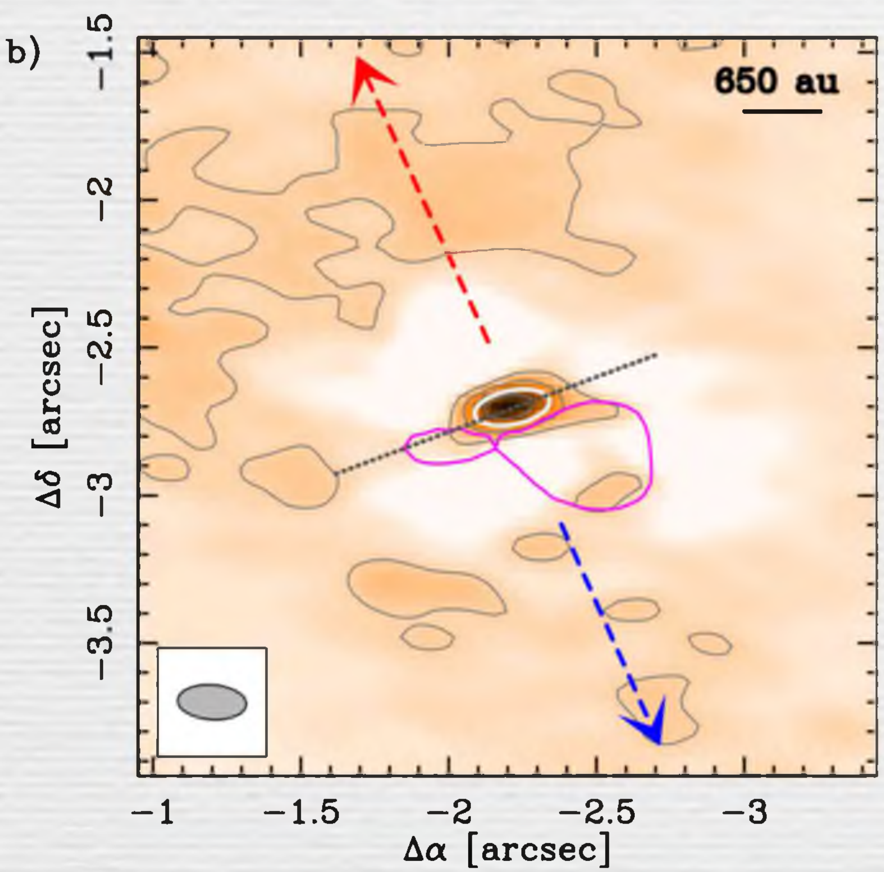


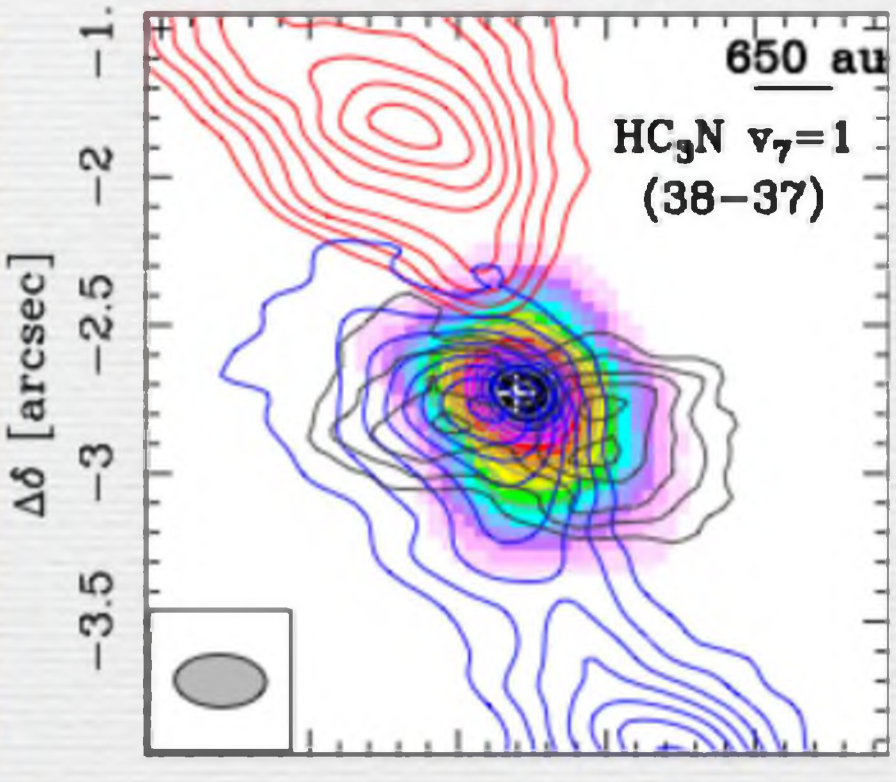
Csengeri et al. (2018)

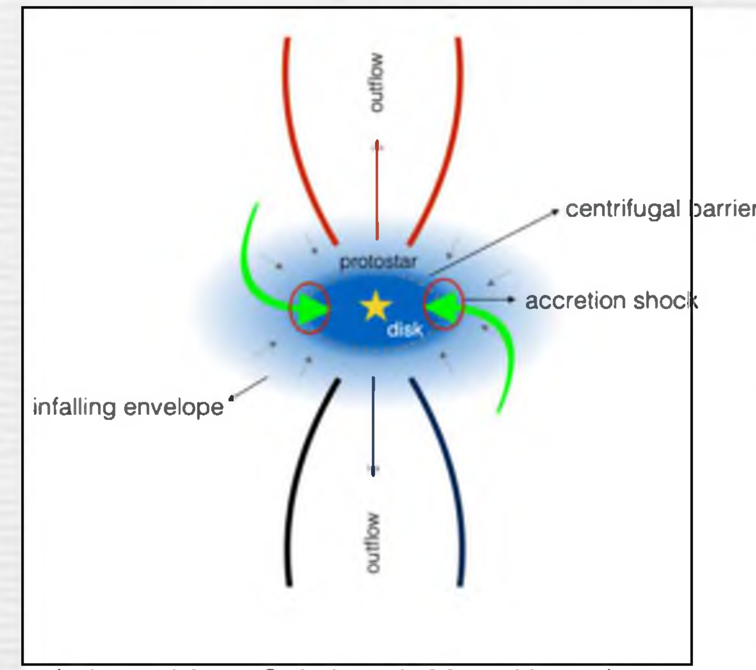
G328.2551-0.5321 : First hints for an accretion disk?

Image plane analysis: residual emission after a 2D Gaussian fitting

⟶ **Compact dust component**: deconvolved radius of ~ **250 au**





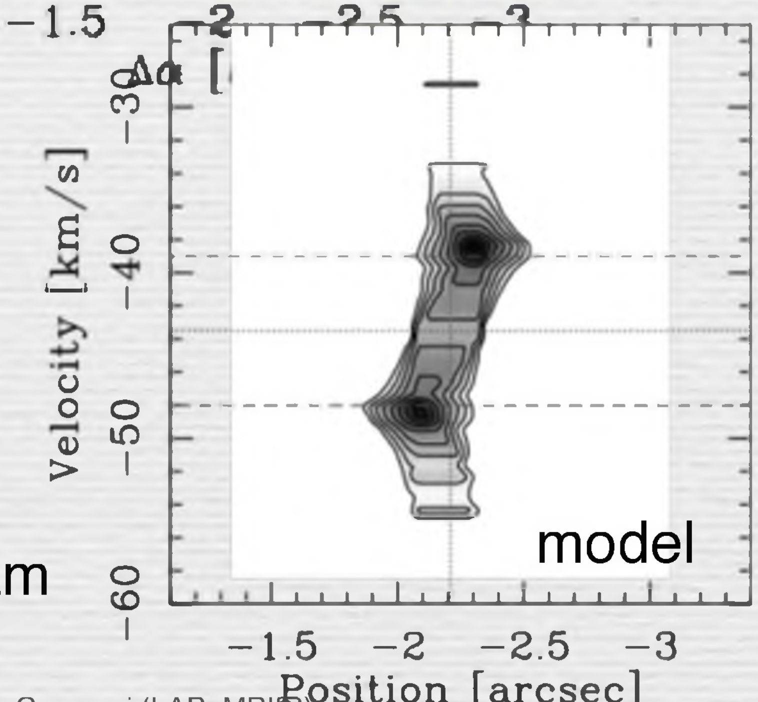


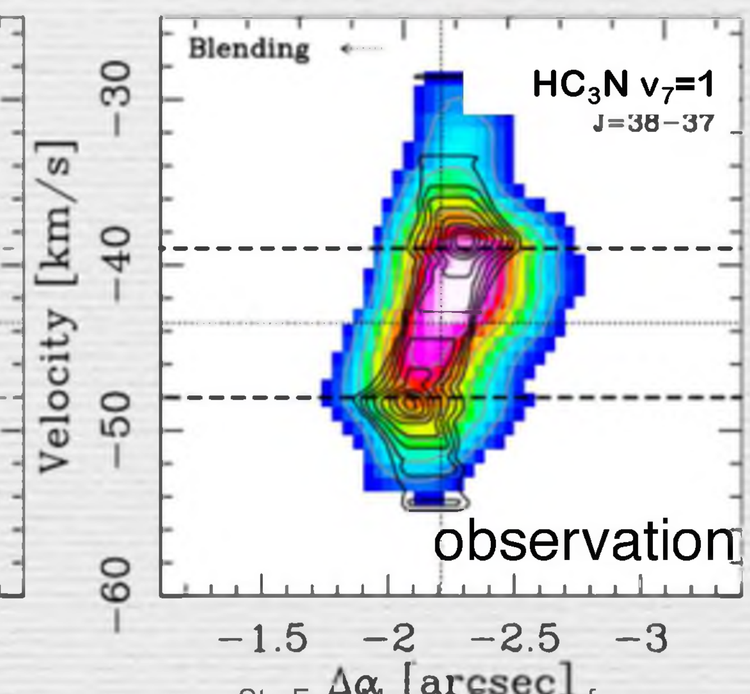
(adapted from Sakai et al. 2014, Nature)

- **HC$_3$N v$_7$=1 : peaks on the protostar**

Compatible with Keplerian disk models!

pv-diagram

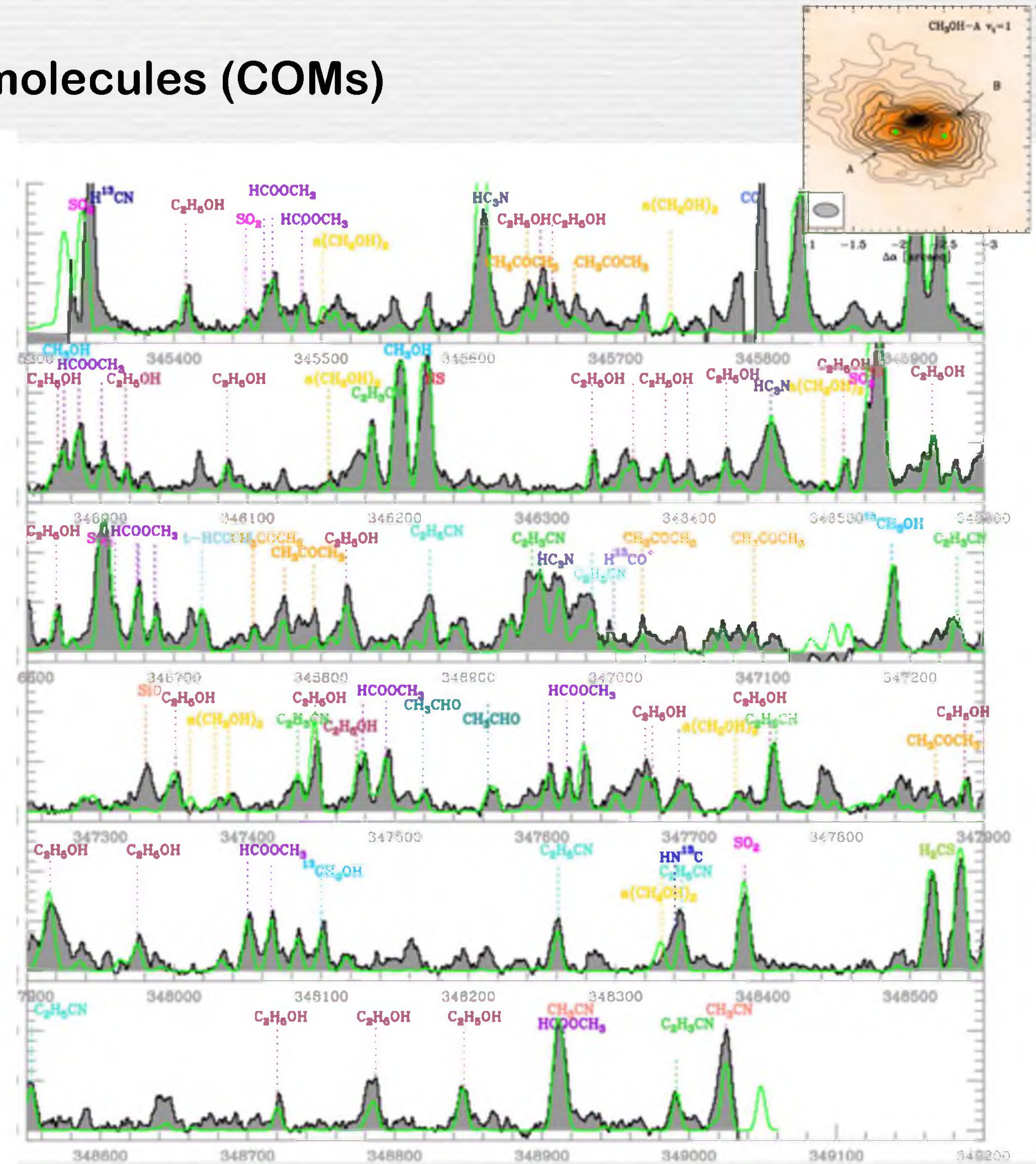




Case study: large abundance of COMs towards the accretion shocks

Significant emission of complex organic molecules (COMs)

- **Fitting through WEEDs:**
  - CH_3OH (methanol)
  - CH_3OCHO (methyl formate)
  - C_2H_5OH (ethanol)
  - CH_3COCH_3 (acetone)
  - a$(CH_2OH)_2$ (ethylene glycol)
  - t-$HCOOH$ (formic acid)
  - CH_3CHO (acetaldehyde)
  - C_2H_3CN (vinyl cyanide)
  - C_2H_5CN (ethyl cyanide)
  - $HC(O)NH_2$ (formamide)
  - HDO (deuterated water)
- **Physical conditions:**
  - T ~ 180 K, N (CH_3OH)~ 10^{19} cm^{-2}



Spectrum extracted towards one of the shock positions

Csengeri et al. (2019, subm.)

Chemical Differentiation on < 2000 au scales

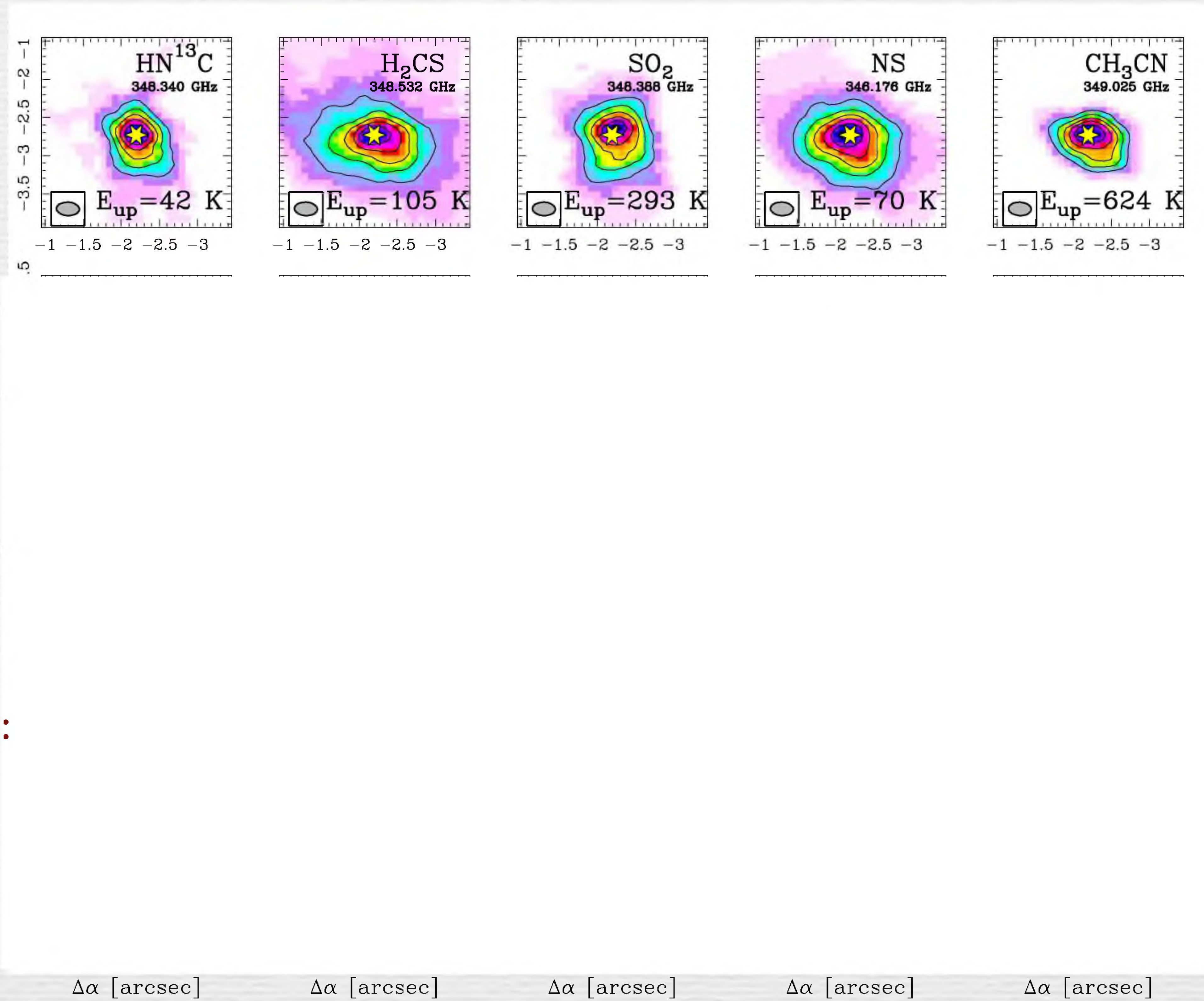
Most of the COMs arise from warm gas

Different spatial morphology between O-bearing an N-bearing COMs

Especially with CN group

3 physical components:

- **inner envelope**
- **Protostar+disk**
- **Accretion shocks**



Csengeri et al. (2019, subm.)

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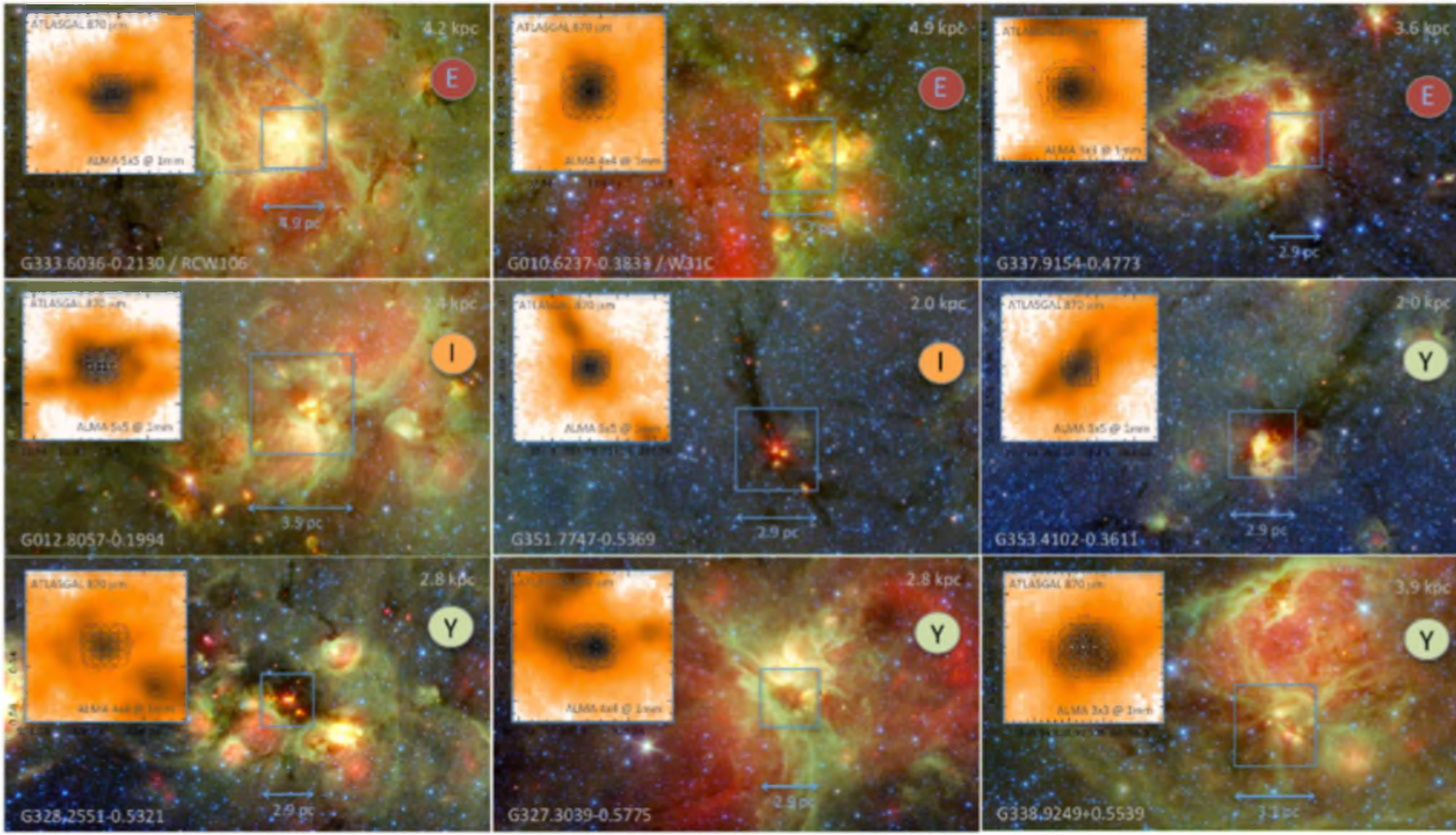
ALMA-IMF: Origin of the IMF?

Mapping 15 Galactic star forming regions over a range of evolutionary stage

Y → I → E

PI: F. Motte



Summary

1. Based on large area surveys statistical studies are now feasible at high angular resolution and high sensitivity with ALMA

- Statistically constrain fragmentation properties, and envelope properties
- SPARKS reveals a large number of high-mass protostars (Menv ~ 60 M_{sol})
- diverse fragmentation properties: single protostars vs. protoclusters

2. Case study: precursor of an O4-O5 star - physical properties

- **M_{env} ~ 130 M_{sol}** : single collapsing envelope
- **accretion shocks** at the centrifugal barrier, first indication for an accretion disk at 250 au

3. Case study: precursor of an O4-O5 star - chemical properties

- ~10 COMs identified
- **increase of temperature and abundance of COMs at the accretion shocks**
- **qualitatively similar picture to low-mass star formation**

Csengeri et al. (2017a,b, 2018, 2019, subm.)