Premières phases de la formation des étoiles observées avec Herschel

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Sous la direction de
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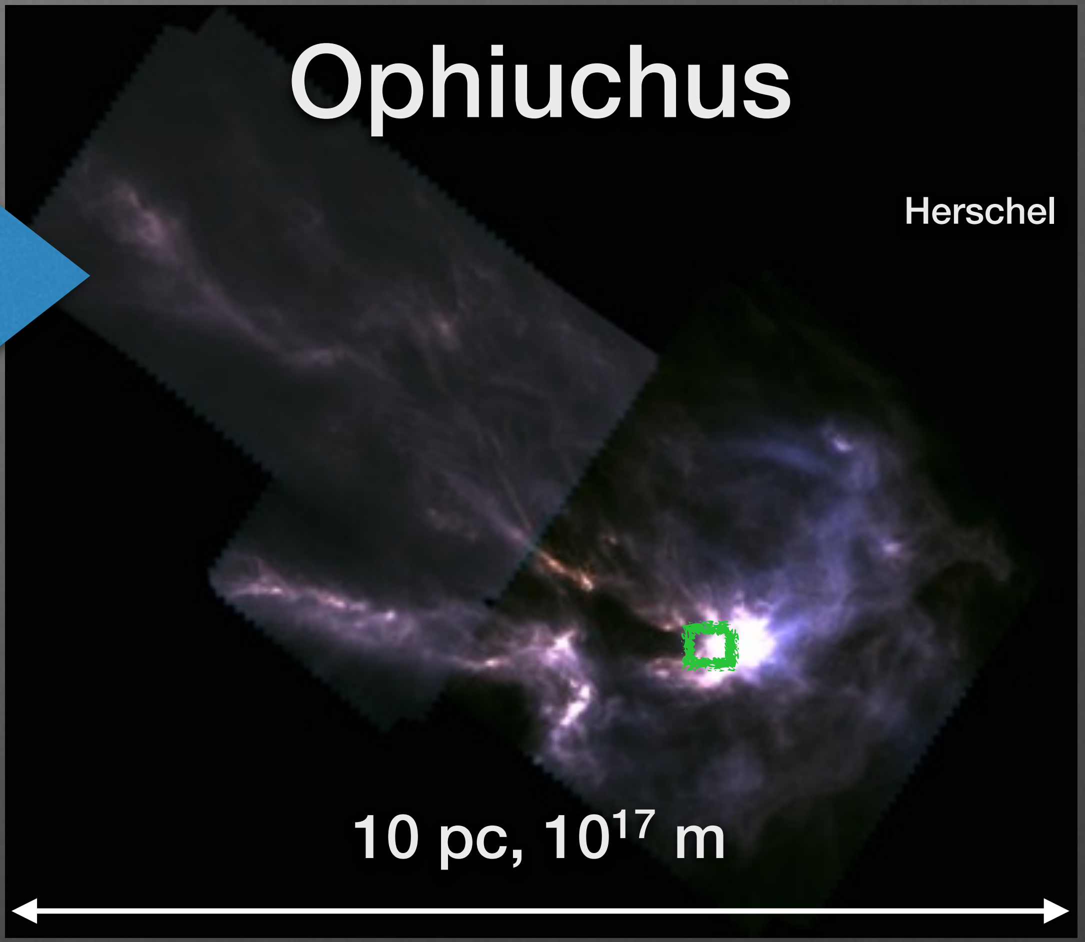
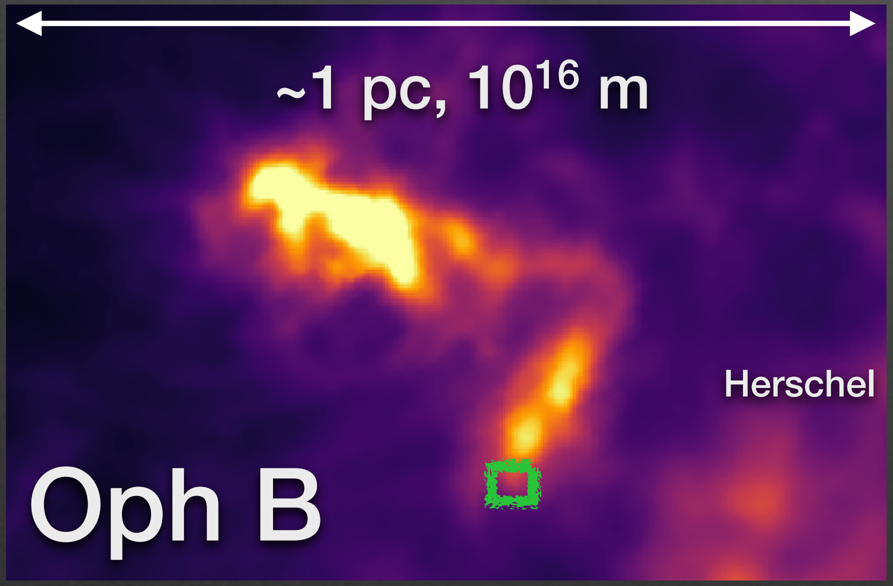
- Bilal Ladjelate

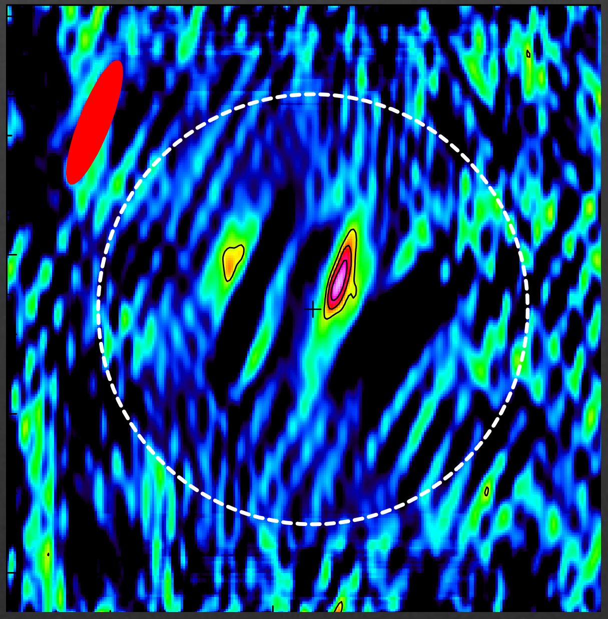
- ENS Paris puis M2 Astronomie, Astrophysique et Ingénierie Spatiale de l'Observatoire de Paris

- Suite à un stage en M1 au Harvard-Smithsonian Center for Astrophysics sur la formation des étoiles, j'ai décidé de poursuivre, plus tard, dans cette voie. Sur recommandation de mon directeur de stage d'alors, j'ai pris contact avec Philippe André pour poursuivre en stage puis en thèse.

Premières phases de la formation des étoiles observées avec Herschel

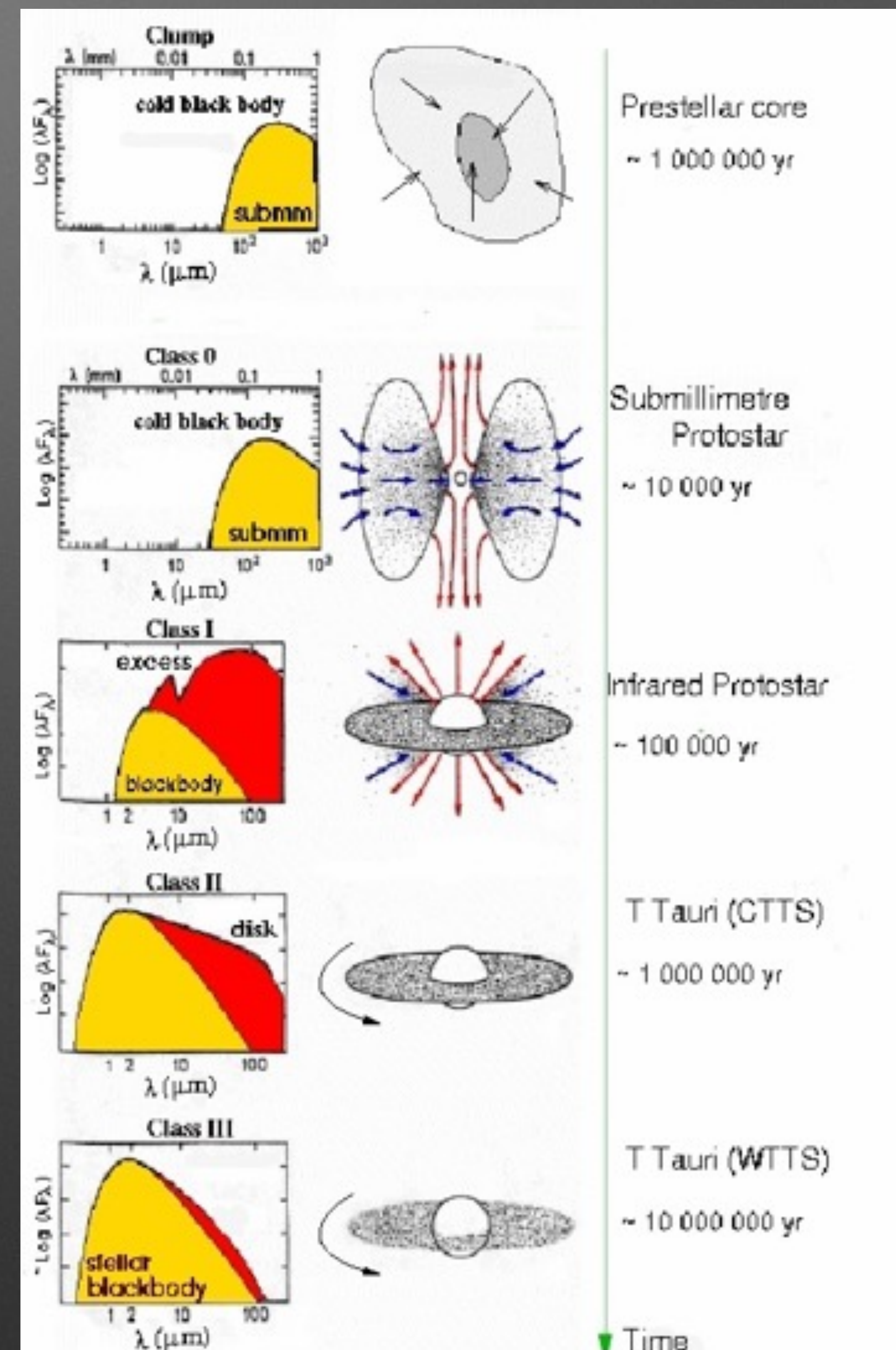






Introduction: A classical evolutionary scenario of the formation of low-mass stars

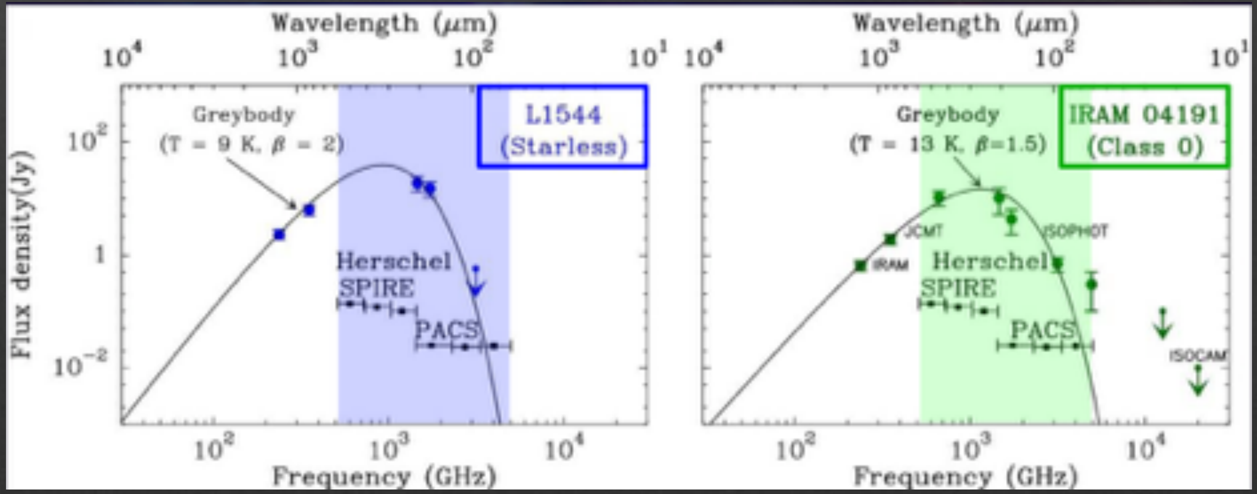
- Prestellar phase: a cold core accreting dust
- Class 0: the protostar is born, but its emission remains dominated by the envelope
- Class I: a disk is forming, and its emission dominates the emission of the young protostar
- Class II: The pre-main sequence star radiate more than its surrounding dust
- Class III: the emission is coming mostly from the star



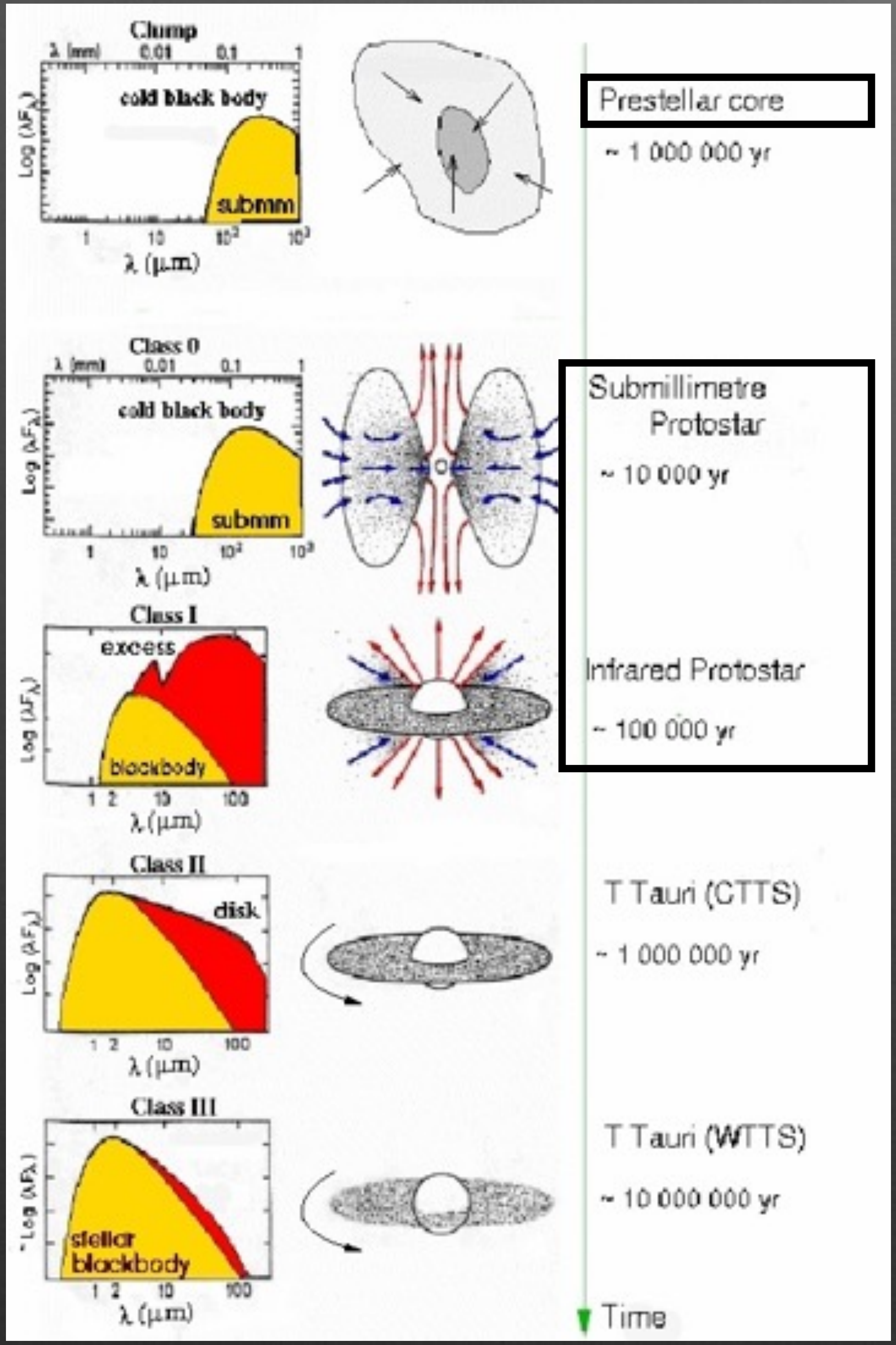
Lada, 1987
André, Ward-Thompson & Barsony, 1993, 2000

Introduction: Herschel Space Observatory

- Launched in 2009, operational until 2013 (Pilbratt et al. 2010)
- Primary mirror of 3.5m
- SPIRE: 250, 350 et 500 microns photometer (Griffin et al. 2010)
- PACS: 70, 100 et 160 microns camera (Poglitsch et al. 2010)



Introduction:
Wavelength and physical processes



- The prestellar phase is well covered from 160 to 500 microns. No detection at 70 and 100 microns.

- Class 0 and Class I protostars are detected at 70 and 100 microns because of the internal star.

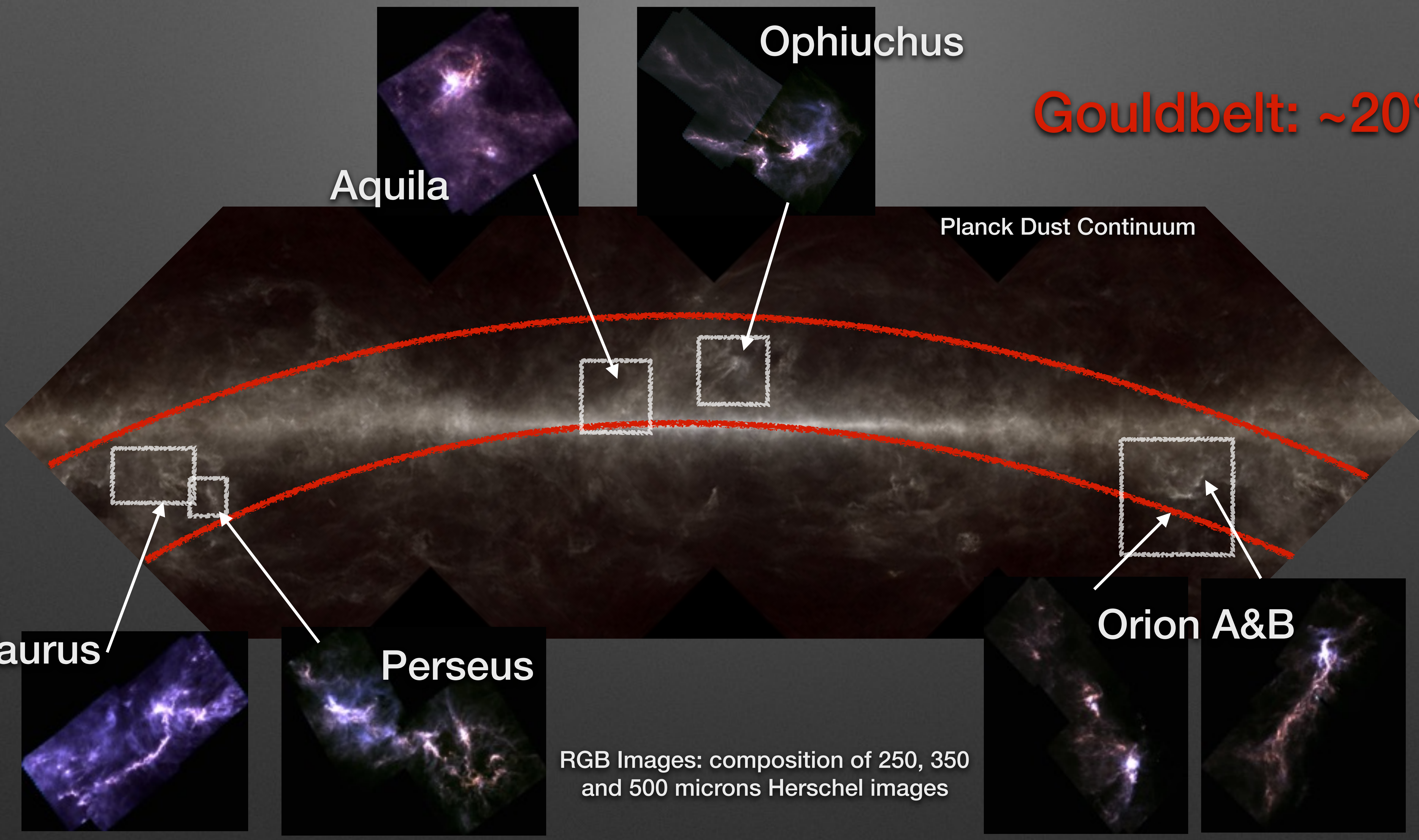
Lada, 1987
André, Ward-Thompson & Barsony, 1993, 2000

Introduction

- What is the origin of the stellar masses, and the link between the prestellar core mass function (CMF) and the initial mass function (IMF)?
- What is the link between the structure of molecular clouds and prestellar cores?
- Is the formation process of brown dwarfs similar to the formation process of low-mass stars?

Introduction:
Herschel Gould Belt Survey

http://gouldbelt-herschel.cea.fr

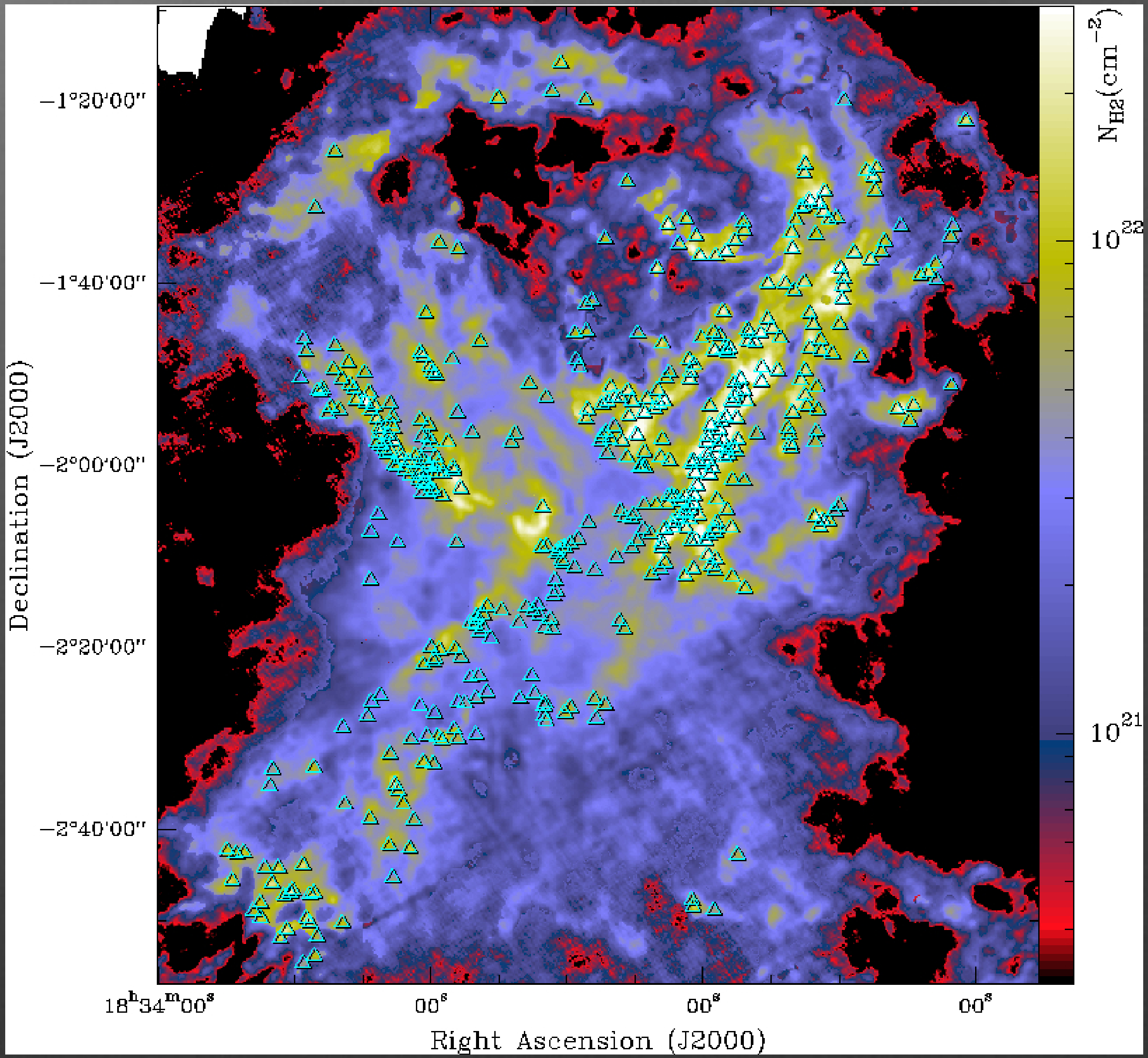


RGB Images: composition of 250, 350 and 500 microns Herschel images

Introduction:
Herschel Gould Belt Survey

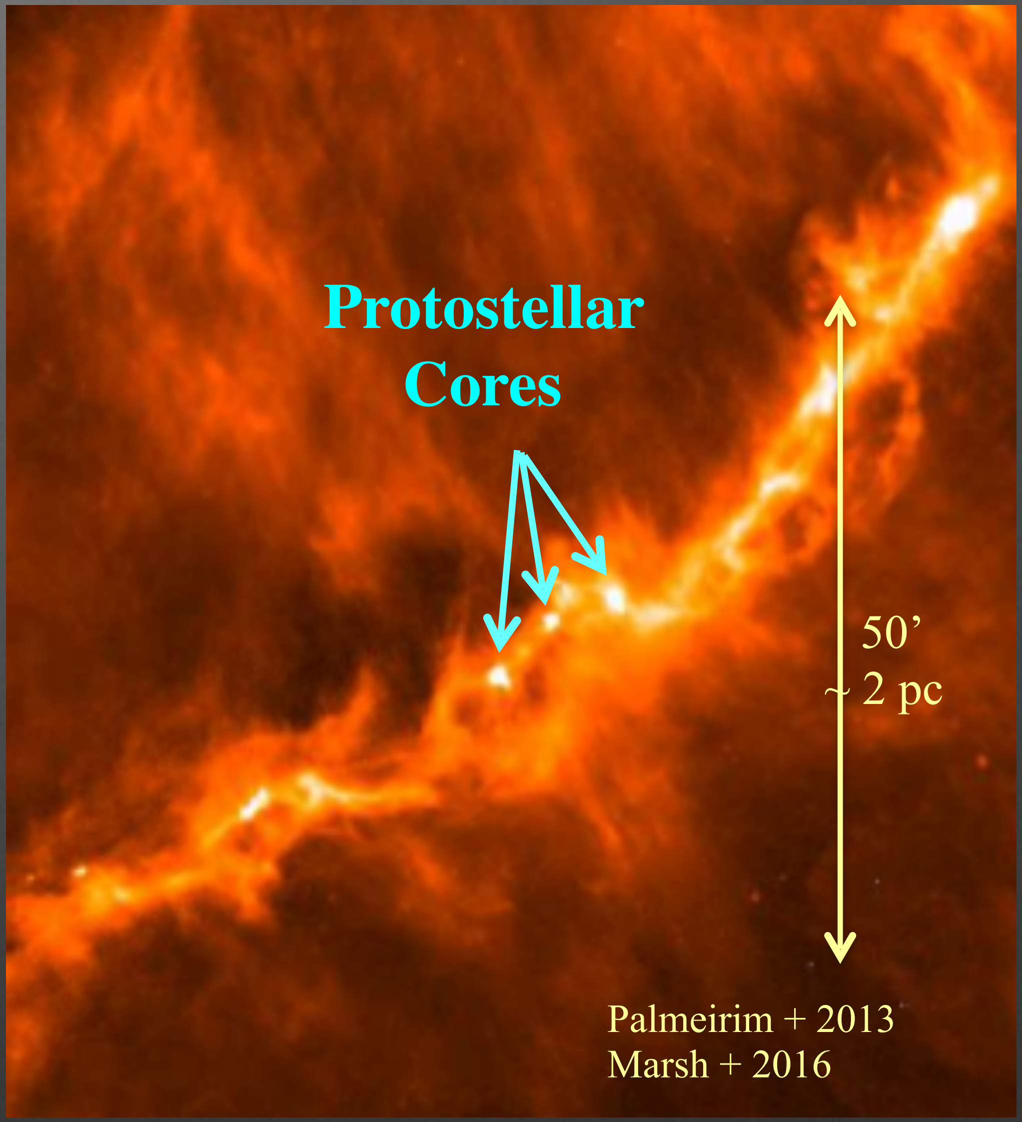
http://gouldbelt-herschel.cea.fr

- Highlights:
- André et al. 2010: connection between prestellar cores and filaments, connection IMF and CMF, star-formation threshold
- Arzoumanian et al, 2011: the distribution of width of filaments peaks around 0.1 pc
- Könyves et al. 2010, 2015: exhaustive core extraction in Aquila, quantitative results



Könyves et al. 2010

- Star-Formation in interstellar filaments? (Protostars & Planets VI, André et al. 2014)



Taurus B211/3 – *Herschel* 250 μm

Introduction:
Herschel Gould Belt Survey
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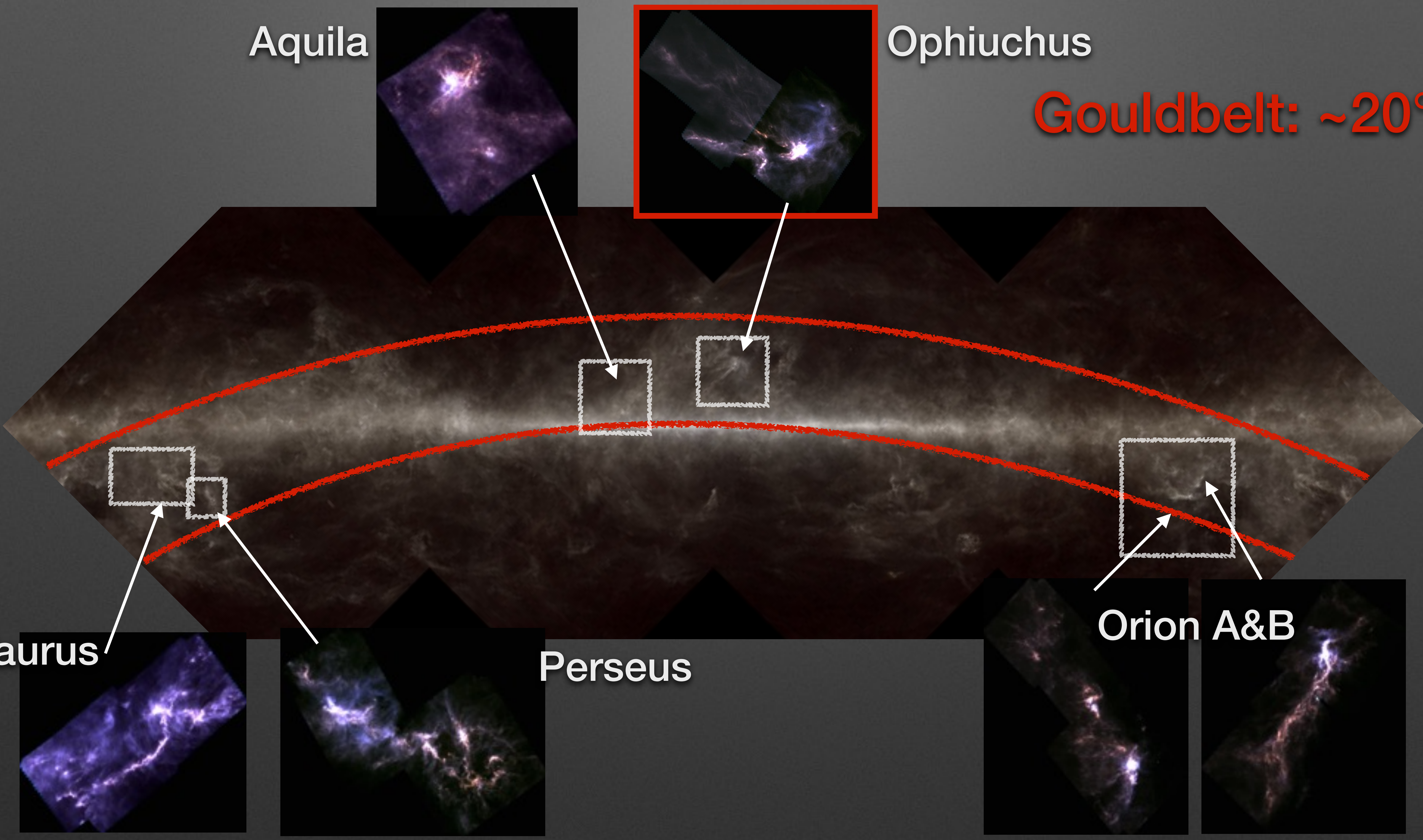
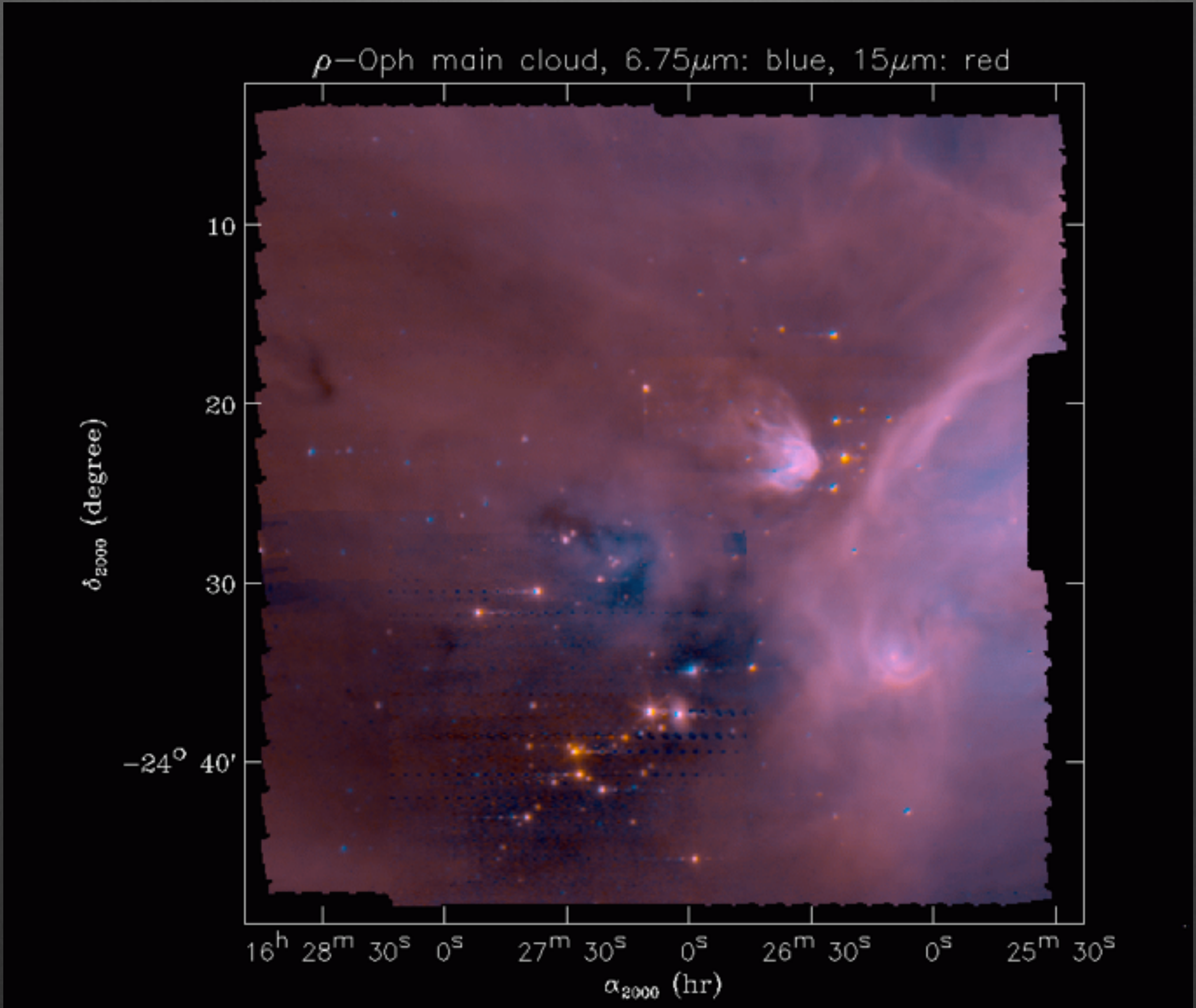
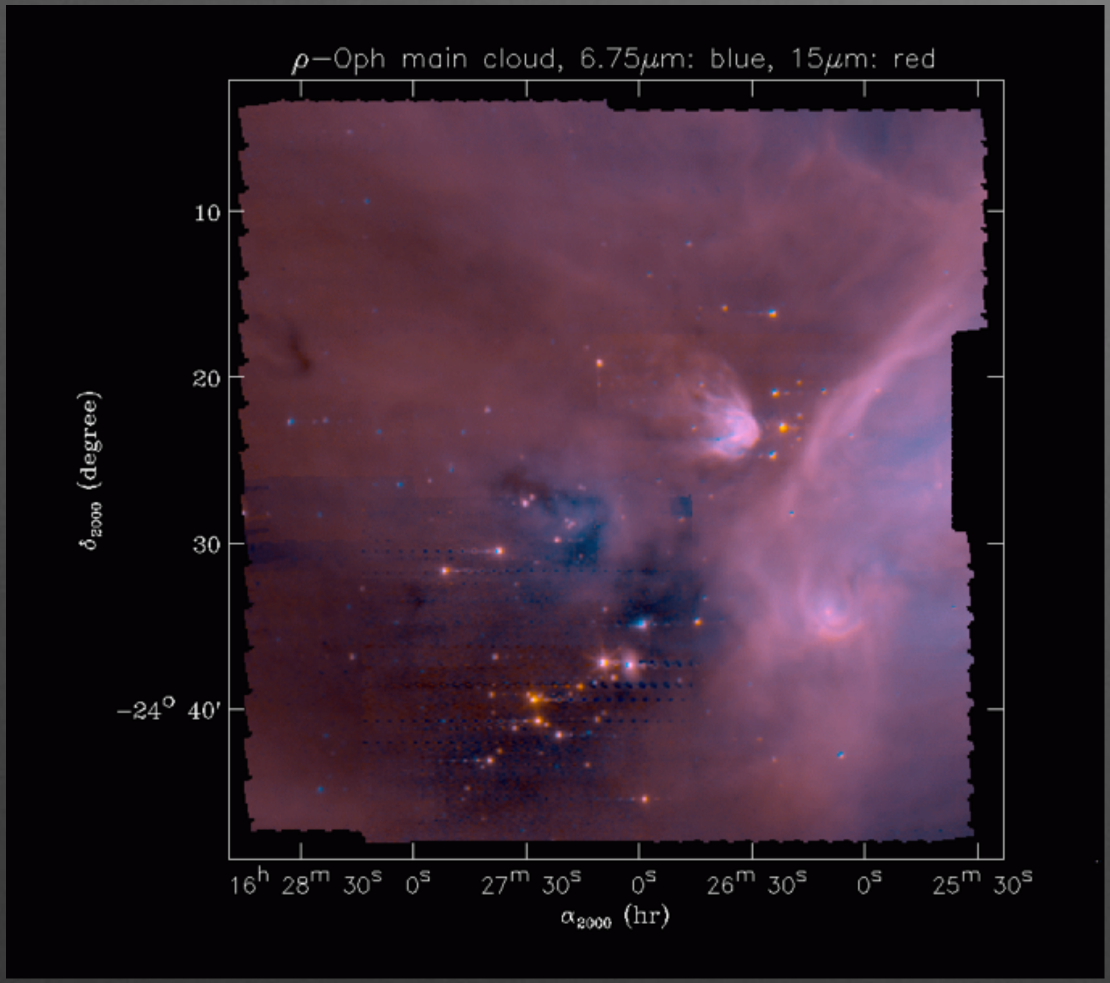


Introduction: Ophiuchus Molecular Cloud



ISOCAM composite image of Ophiuchus Main Cloud

Introduction:
Ophiuchus Molecular Cloud

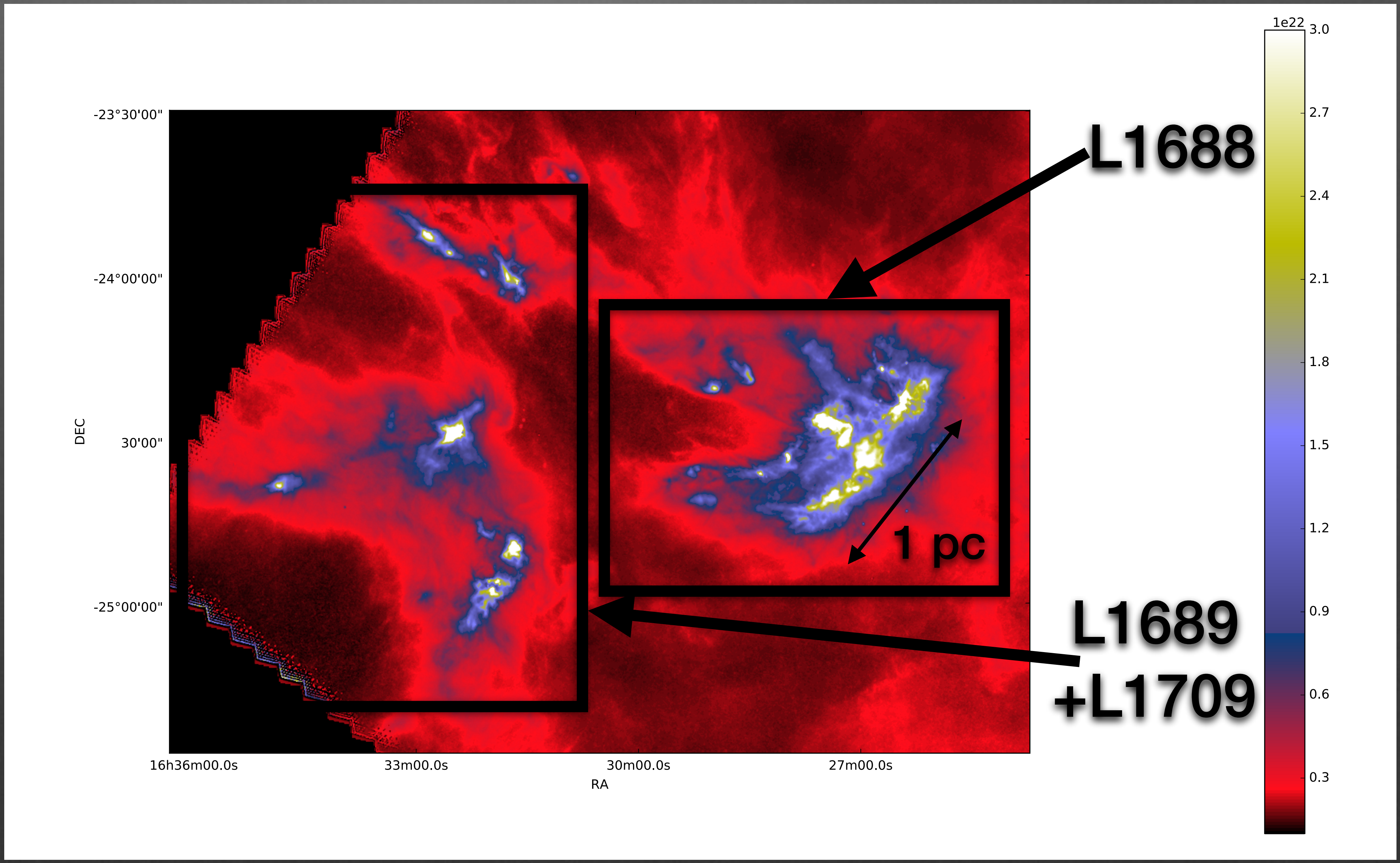


ISOCAM map of Ophiuchus Main Cloud
but also Lada, 1987, Loren et al. 1990, André et al. 1993, Motte et al. 1998, ...

- Nearest low-mass star-forming region (~140 pc)
- Classification of protostars was made in this region (Lada et al. 1987, André et al. 1993)
- ~200 young stellar objects in all wavelengths

Introduction: Ophiuchus Molecular Cloud

Moon to scale (0.5°)



Herschel column-density map

Plan

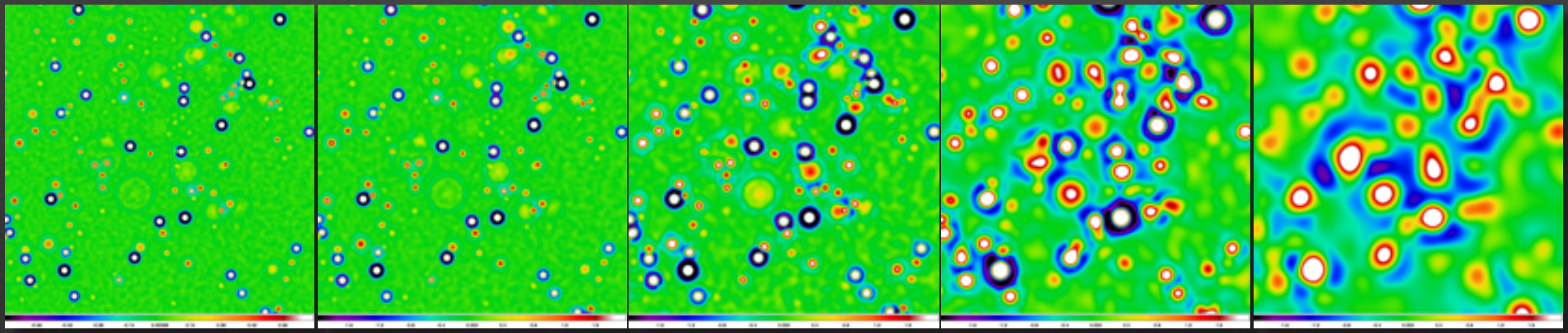
A. Identification and classification of prestellar cores and link with dense interstellar filaments

B. Observation and analysis of pre-brown dwarfs candidates

Core extraction

- getsources (Men'shchikov et al. 2012) is a multiwavelength, multi scale source extraction algorithm taking advantage of the high dynamic of Herschel images.

- The photometry of a source on its whole spectrum allows us to derive temperature and mass of this object (modified blackbody fitting)



getsources single scale decomposition

Core extraction

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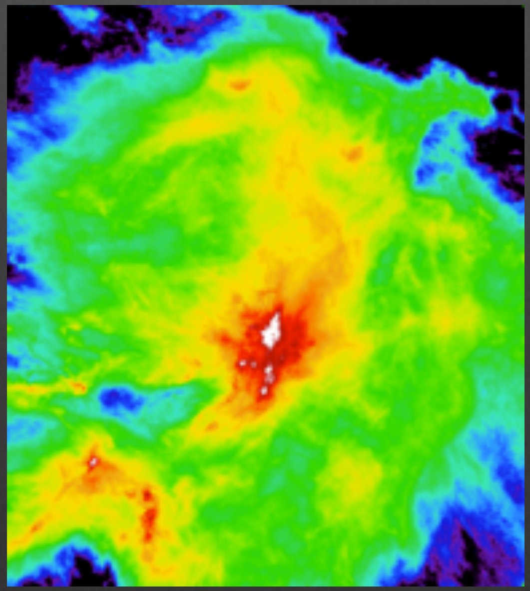

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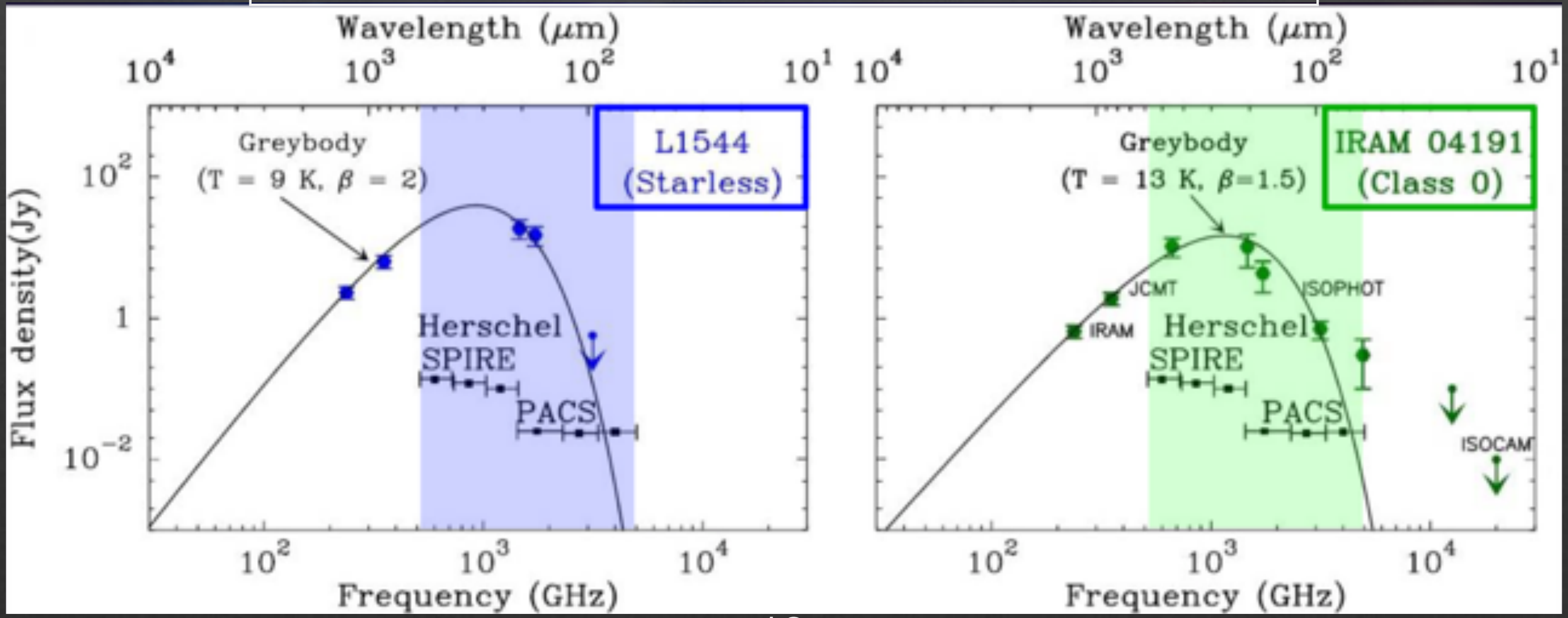
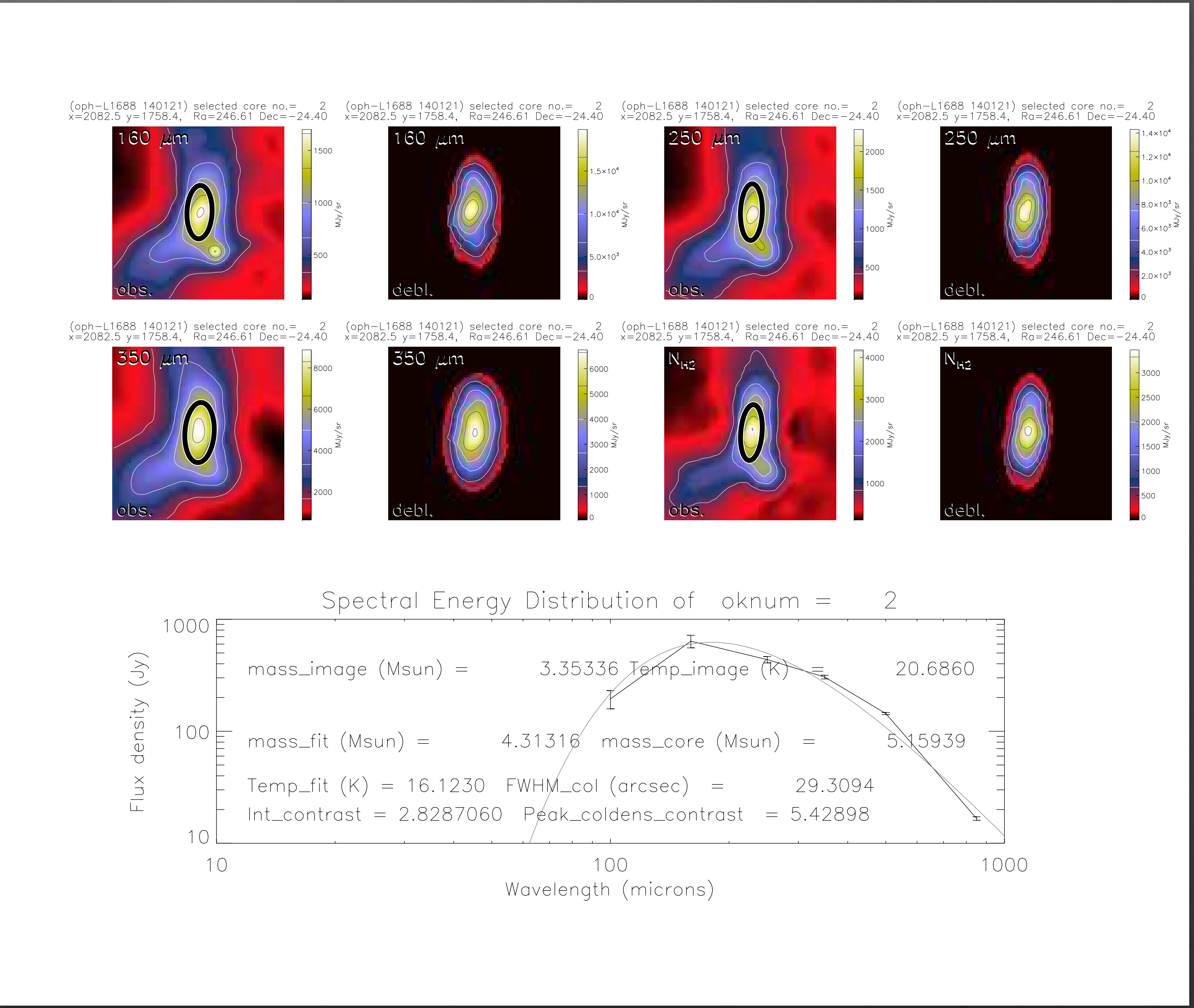


Core extraction

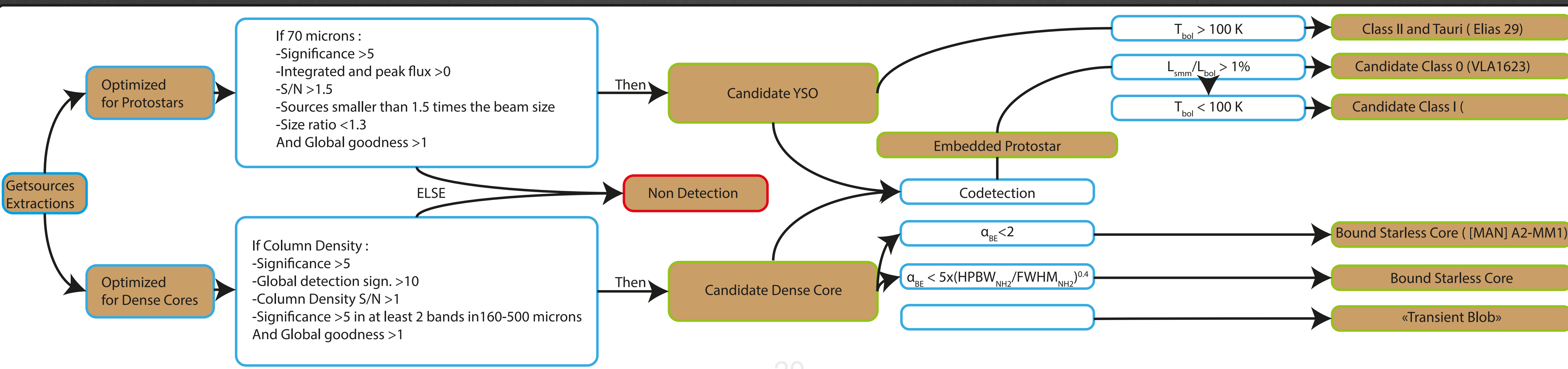
- Example of extracted core
- getsources extract the core from the parent cloud and measure its properties (size, flux, background, ...)



Core classification

- Prestellar cores are sources detected from 160-500 microns

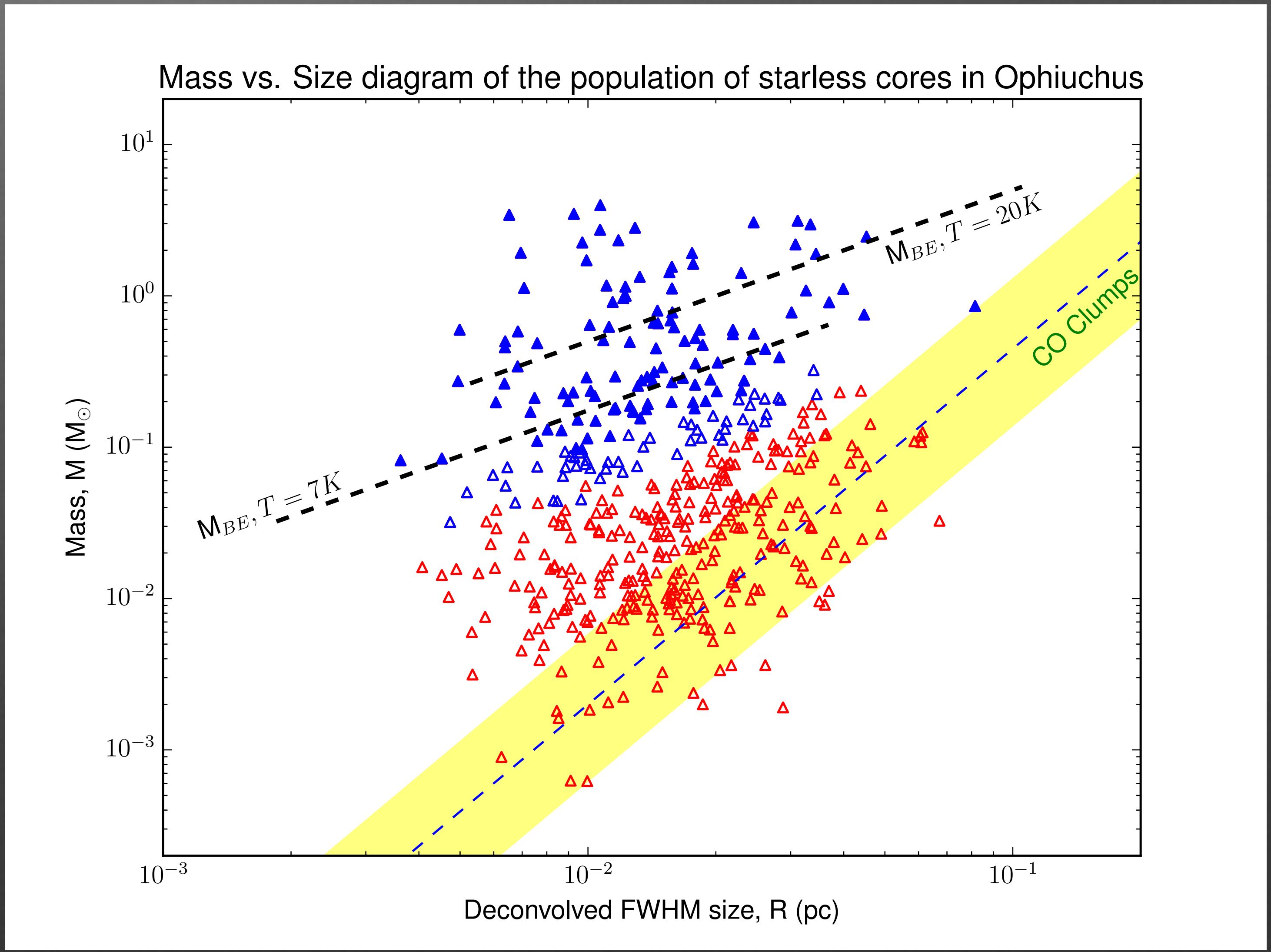
- Protostars and young stellar objects are detected at 70 microns (and 100 microns when available)



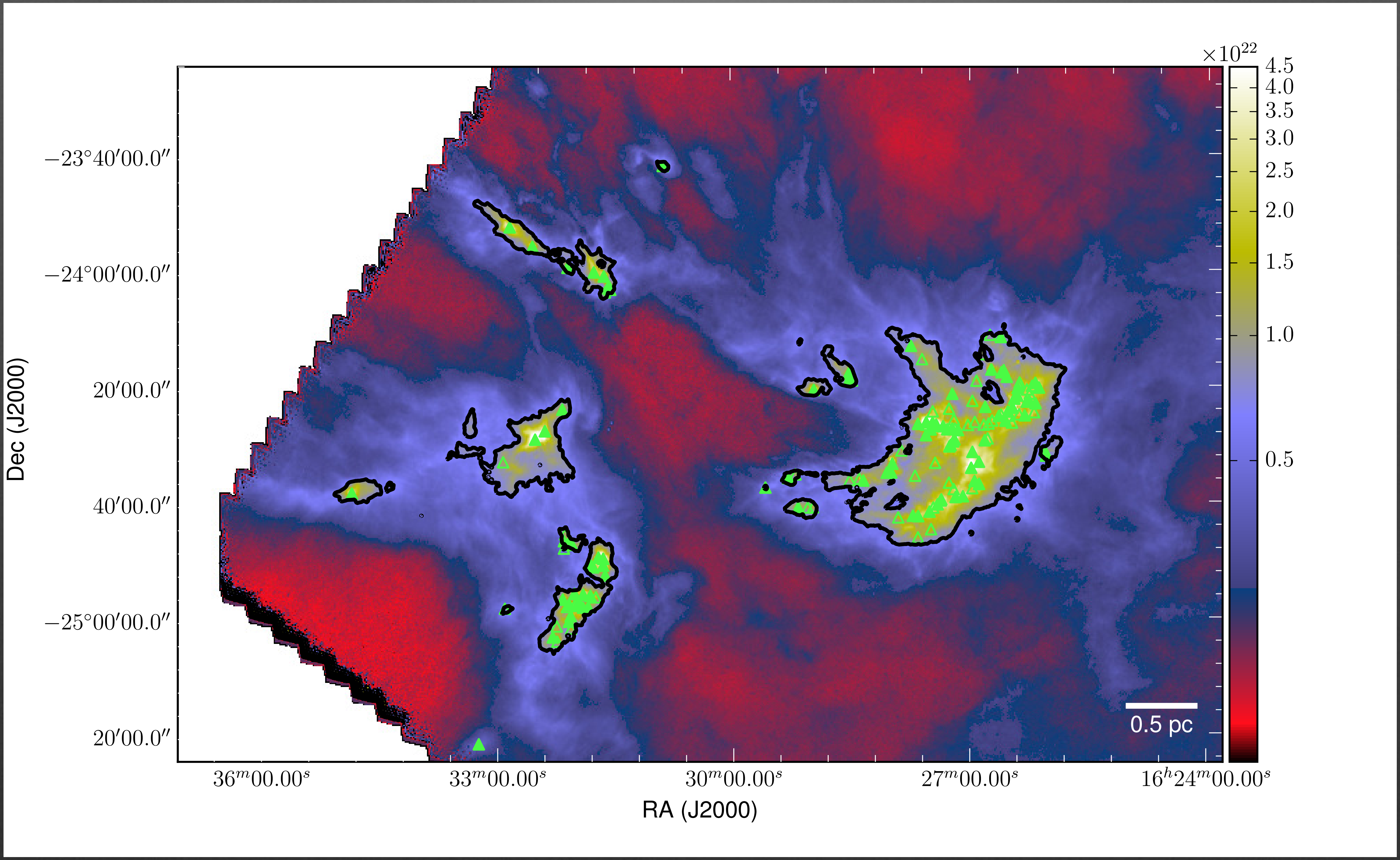
Distinguishing between bound and unbound cores

- Our most recent getsources extraction in Ophiuchus finds 300 cores (detections at wavelengths longer than 160 microns)

- The physical density of a core is a good diagnostic to classify it as a self-gravitating object (prestellar core) or unbound object (transient?).



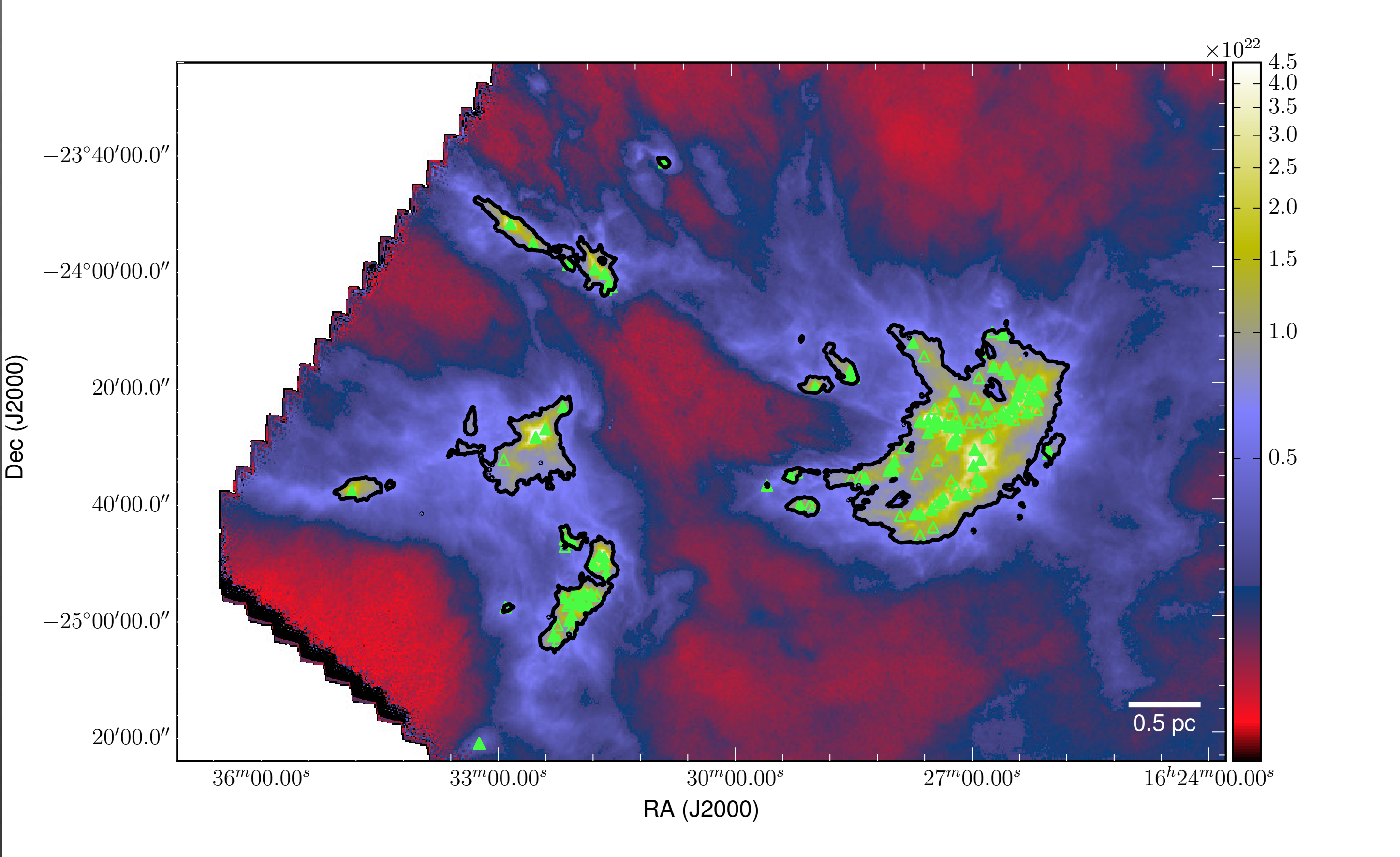
Spatial distribution of extracted starless cores



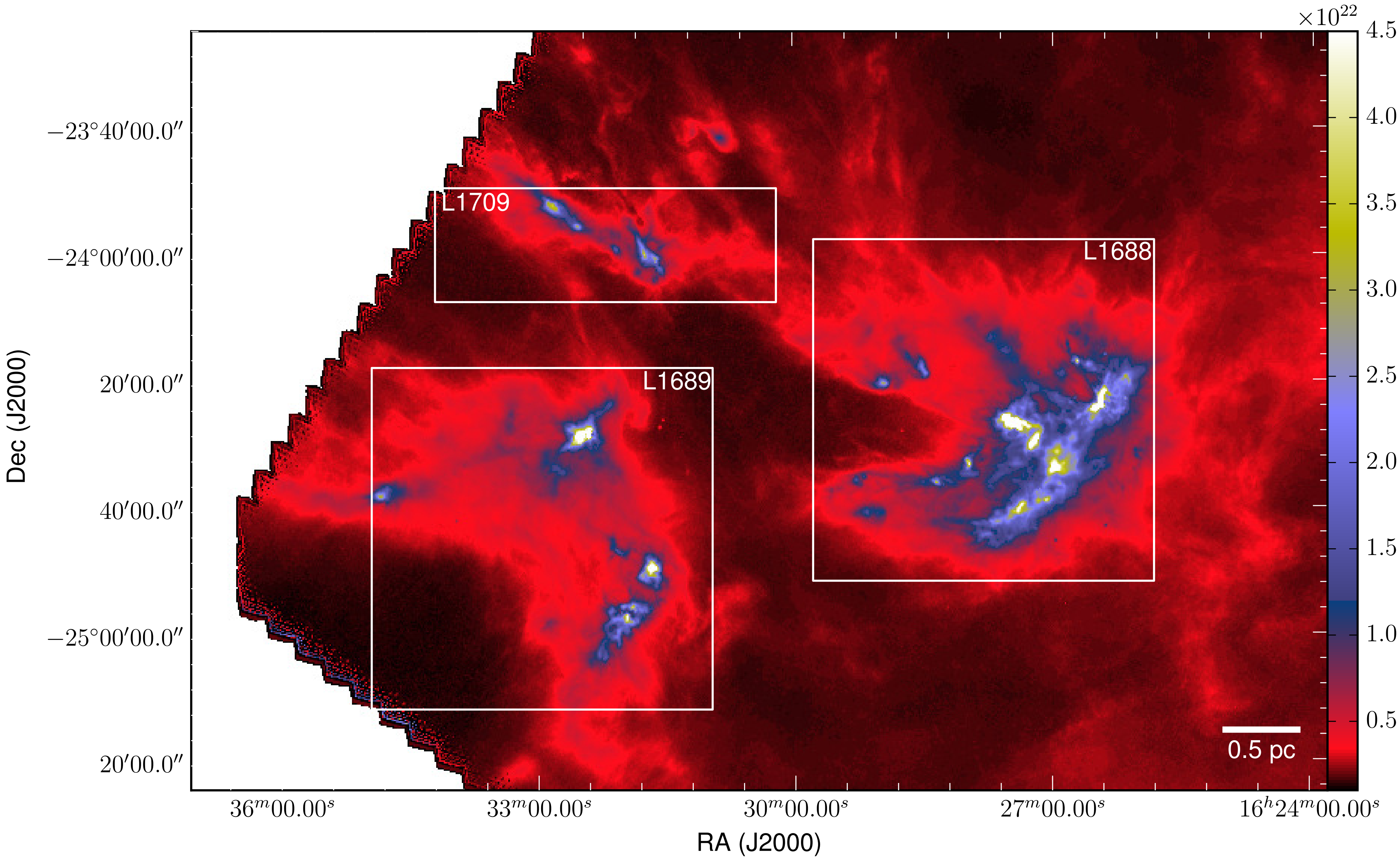
Herschel column-density map

Spatial distribution of extracted starless cores

- Among the starless cores detected with getsources, ~140 of them are gravitationally bound

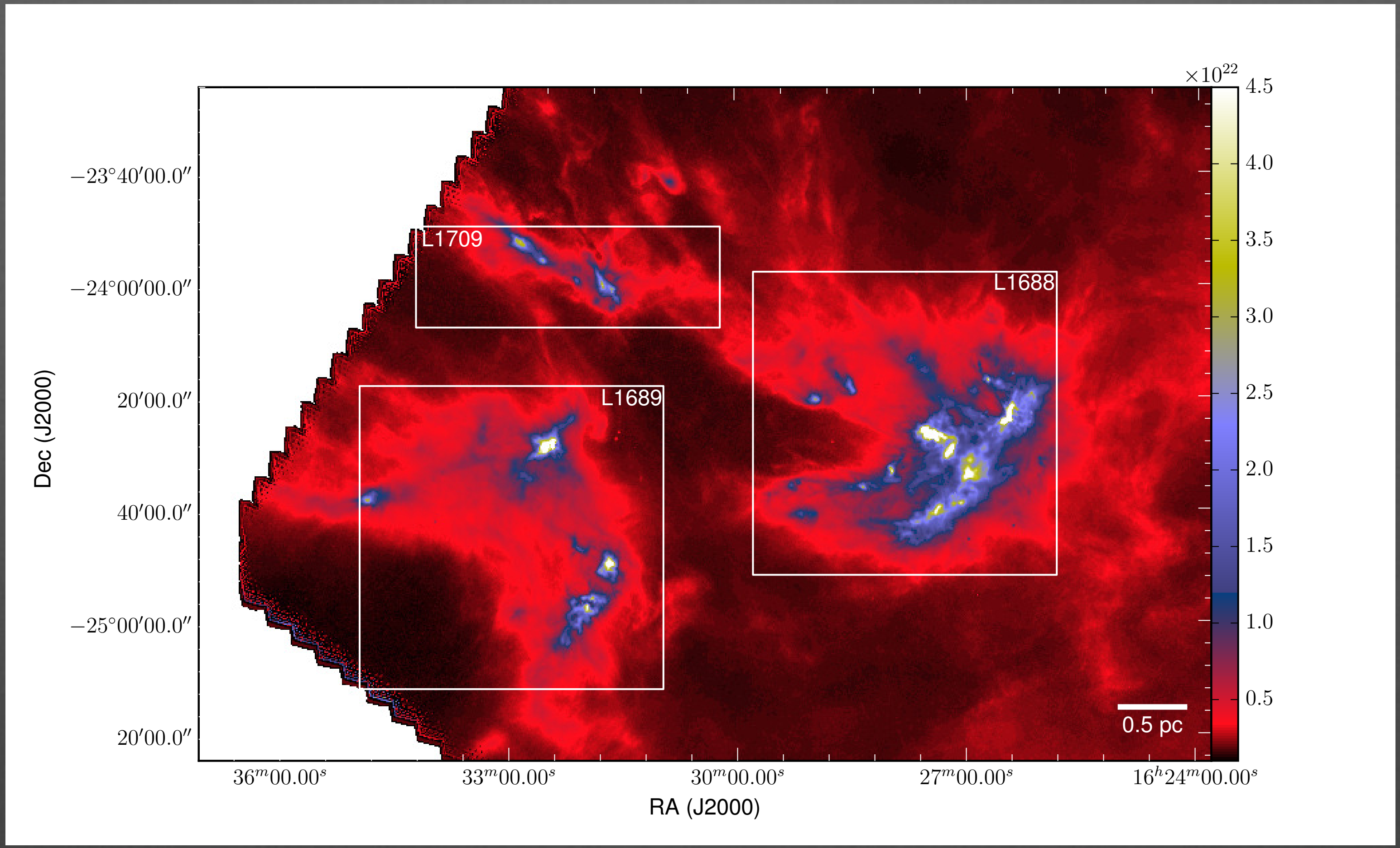


Structure of the Ophiuchus Molecular cloud



Herschel column-density map of L1688

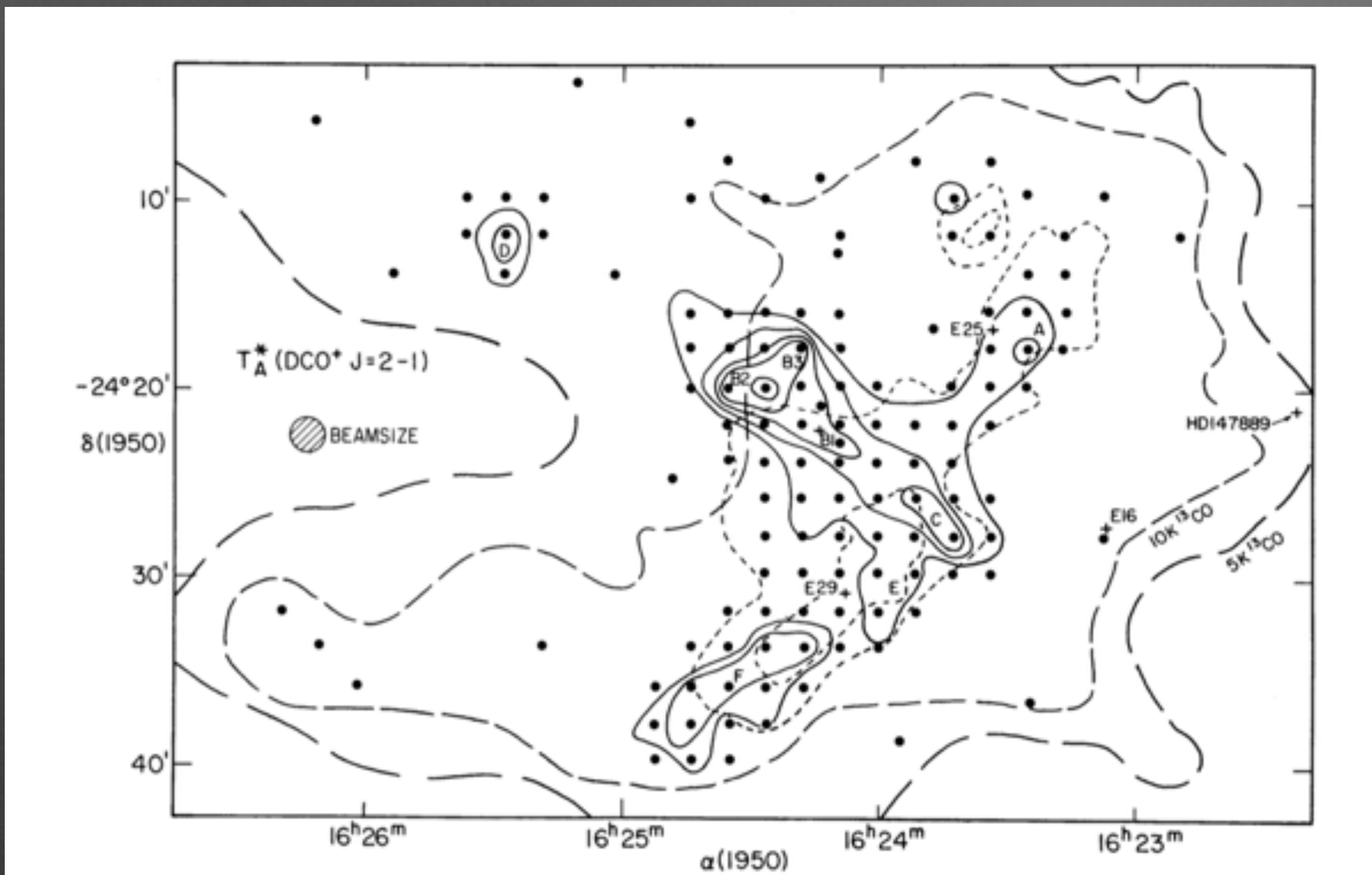
Structure of the Ophiuchus Molecular cloud



L1689+L1709
Total Cloud Mass: 880 Msun
Dense gas Mass : 258 Msun
Number of prestellar cores: 39
Ratio of prestellar core mass and total gas mass : 10.6%
Ratio of prestellar core mass and dense gas mass : 5.8%

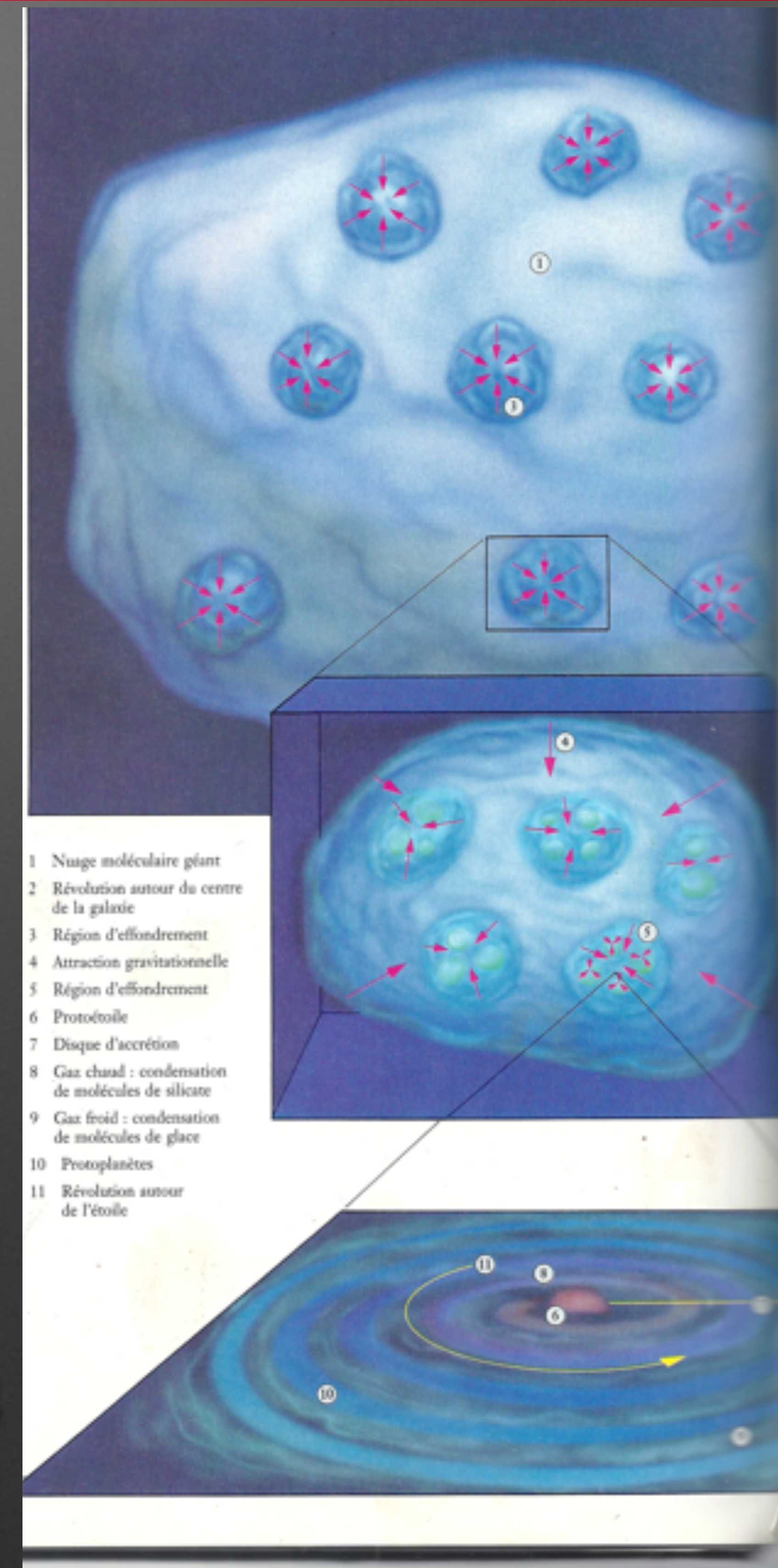
L1688
Total Cloud Mass: 950 Msun
Dense gas Mass : 500 Msun
Number of prestellar cores: 99
Ratio of prestellar core mass and total gas mass : 8.8%
Ratio of prestellar core mass and dense gas mass : 2.6%

Filamentary structure in Ophiuchus

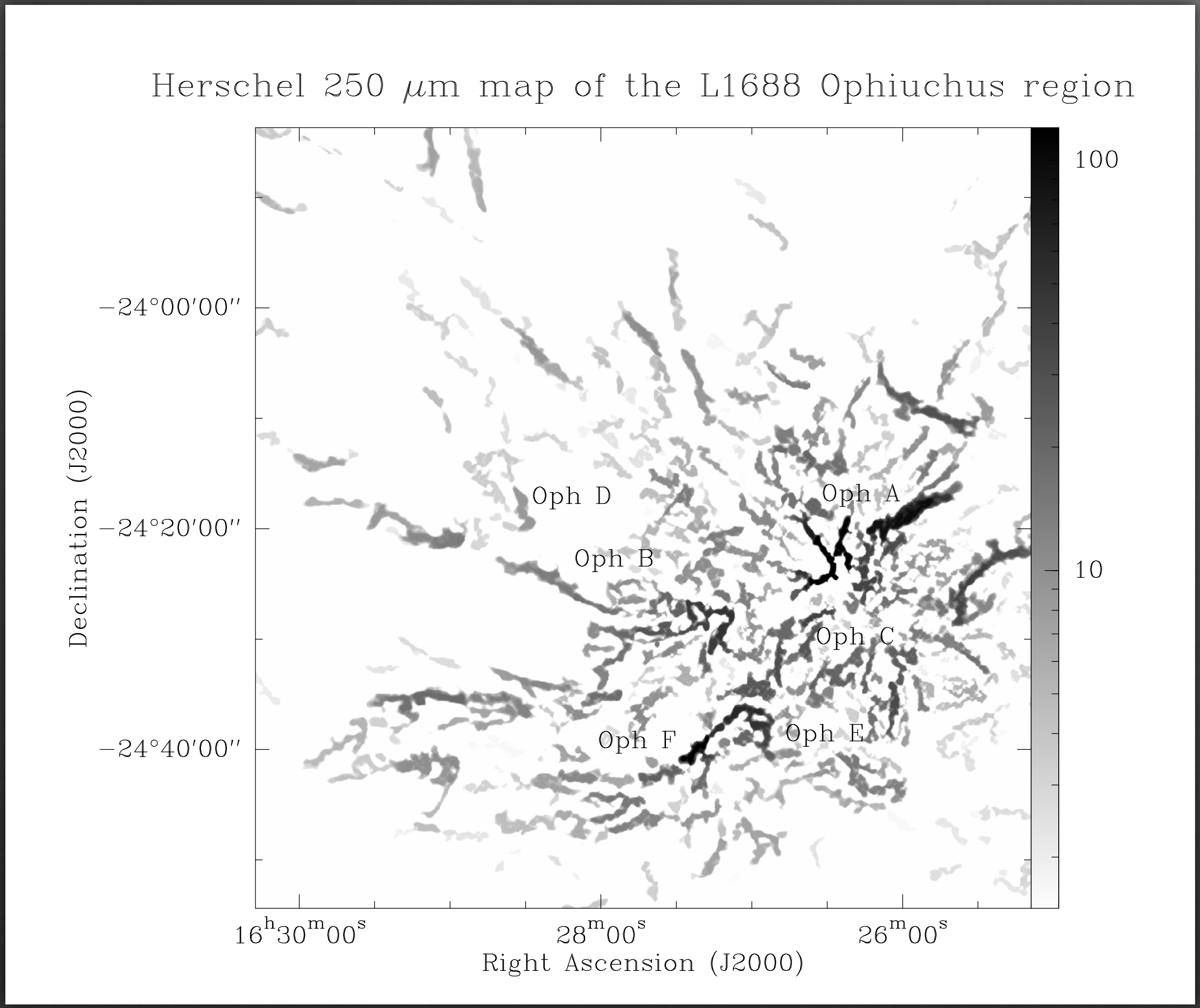


Loren et al. 1990

Astrophysique illustrée, 1993



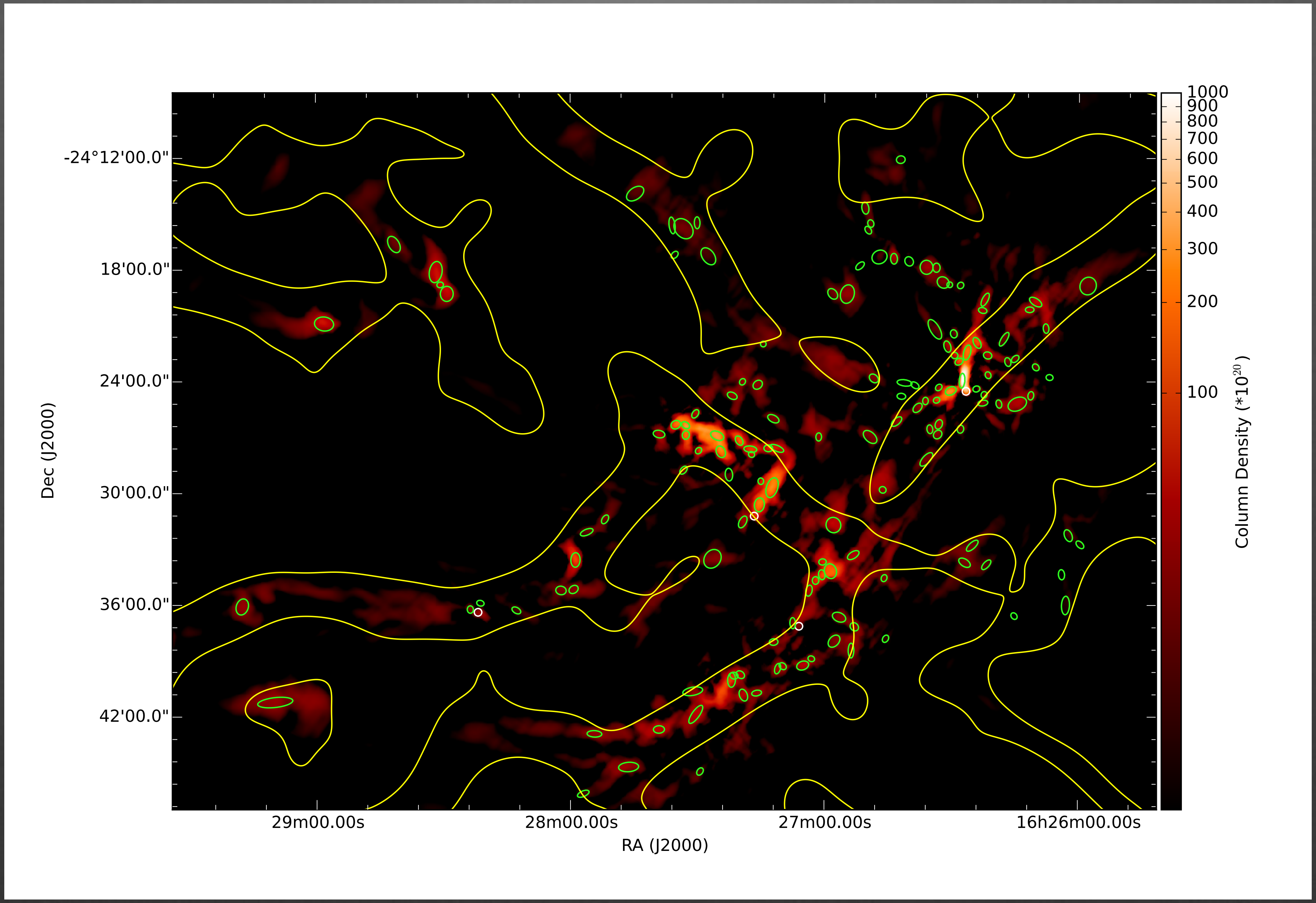
Filamentary structure in Ophiuchus



Filtered 250 microns map with getfilaments (Men'shchikov, 2013)

- Ophiuchus was not previously known as a filamentary region
- Loren et al. 1990, described the cloud with clumps
- We can extract the filaments of Ophiuchus with getfilaments

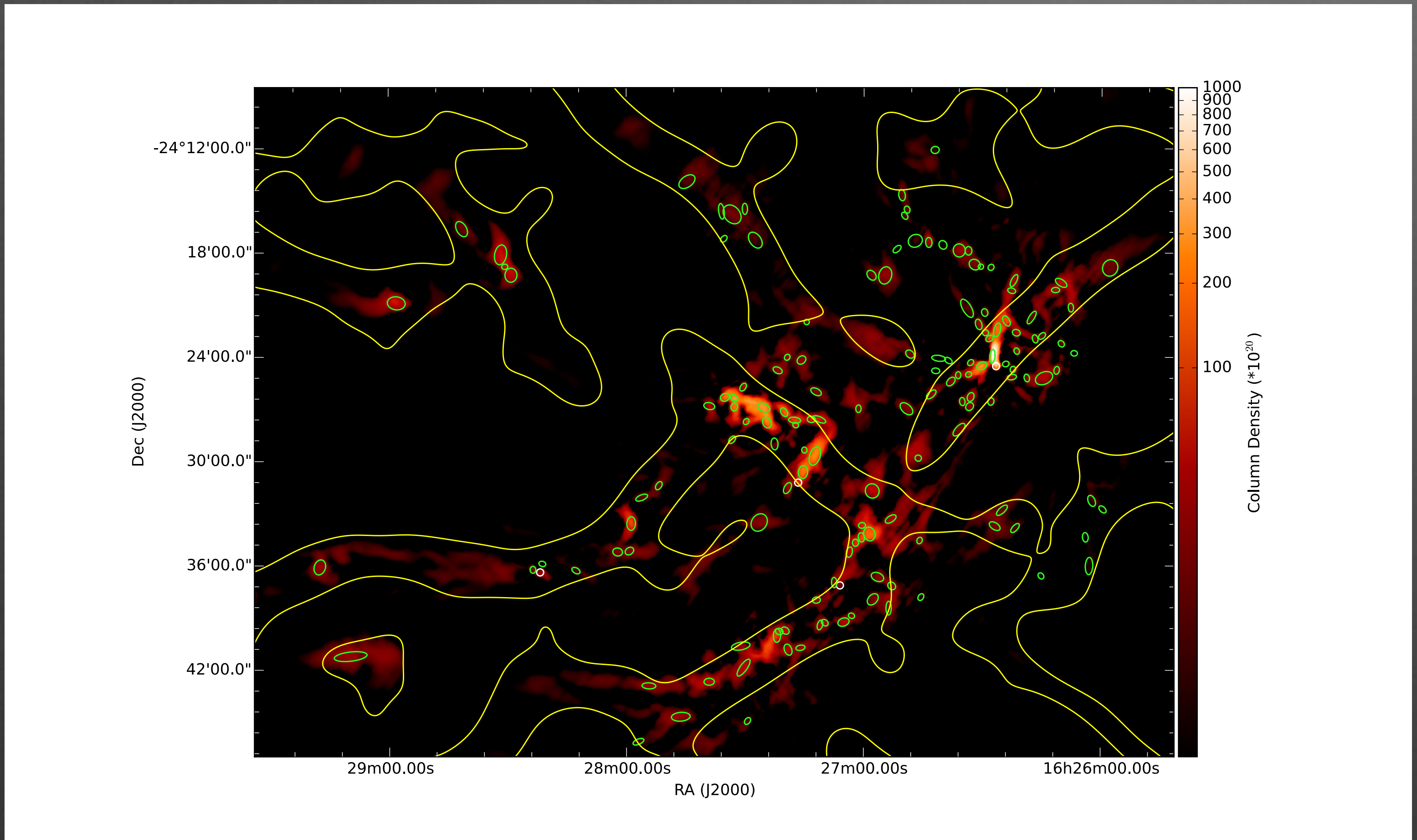
Connexion between prestellar cores and filaments in Ophiuchus



Ophiuchus Column-density filtered map by getfilaments. The yellow contour are a 0.1 pc smoothed getfilaments skeleton

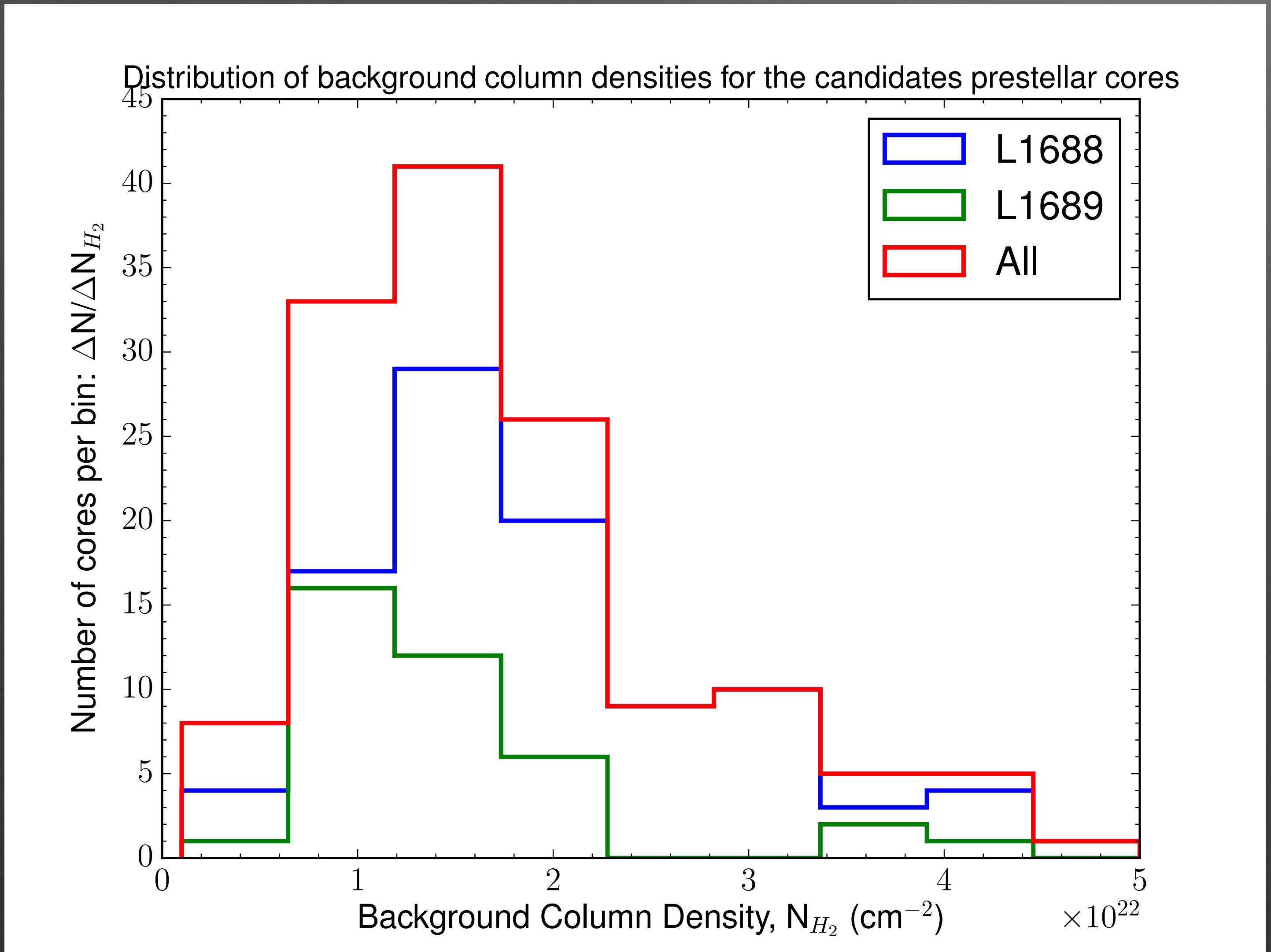
The green ellipses represents the bound prestellar cores extracted by getsources

Connexion between prestellar cores and filaments in Ophiuchus



- ~80% of prestellar cores are within dense filaments, similar to Aquila (André et al. 2010, Könyves et al. 2010, 2015)

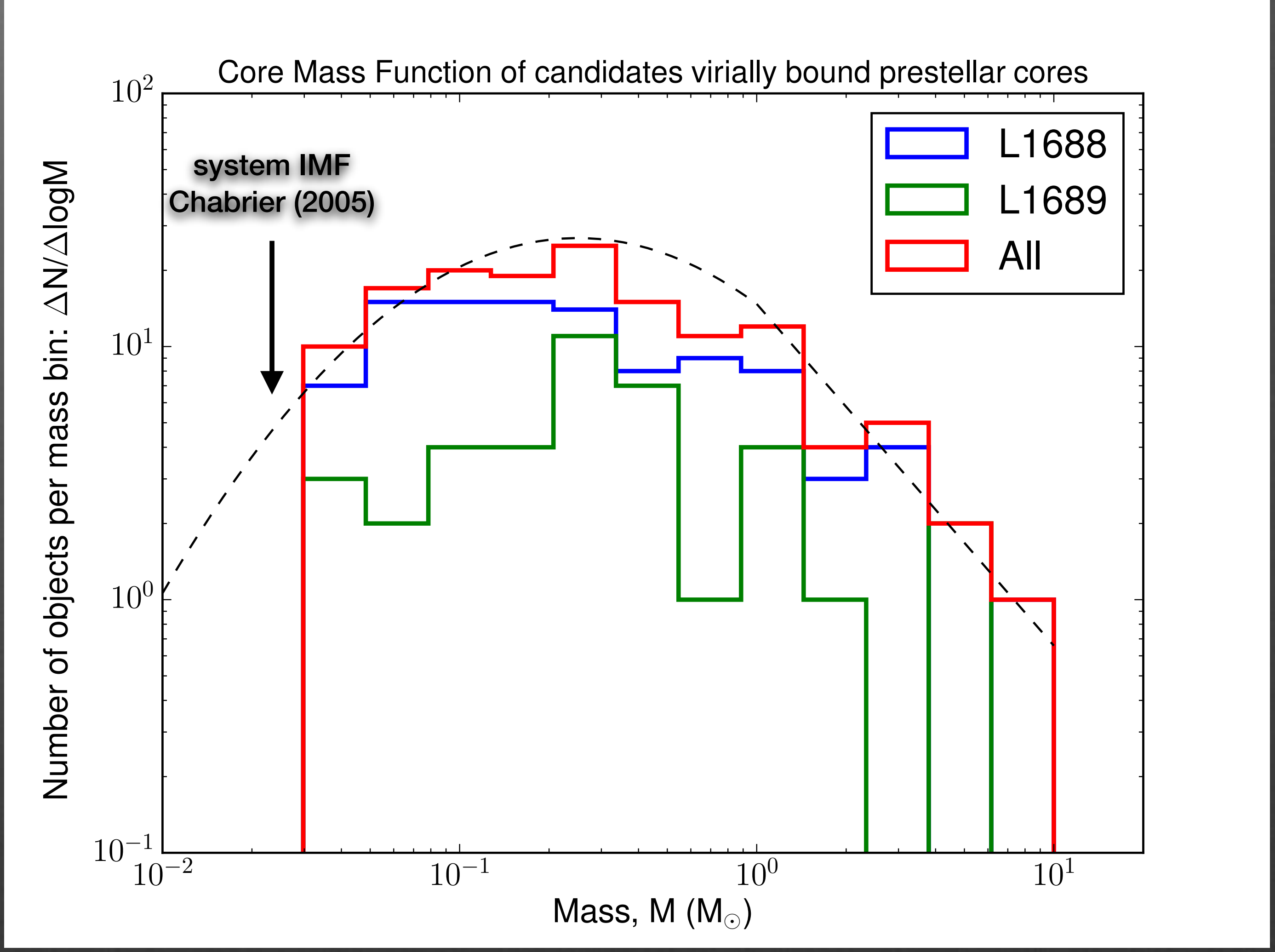
Core formation threshold in Ophiuchus



- Prestellar cores are for 99% detected above a column density threshold of ~7x10^21 cm-2
- Similar again to Aquila (André et al. 2010, Könyves et al.2015)

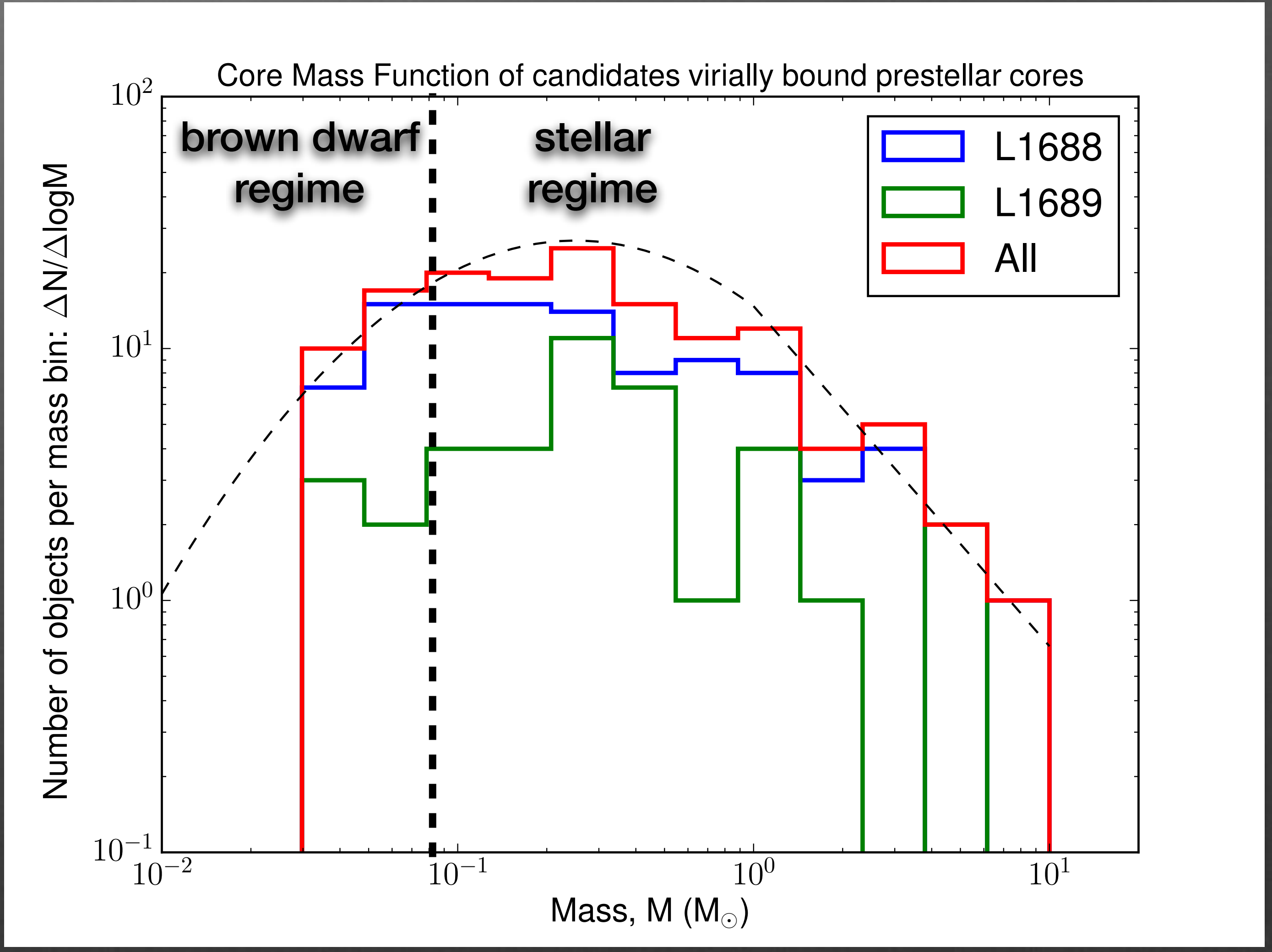
Prestellar Core Mass Function

- CMF: Core Mass Function
- Similar to the Initial Mass Function (confirmation of Motte et al. 1998) (pre-Herschel result)



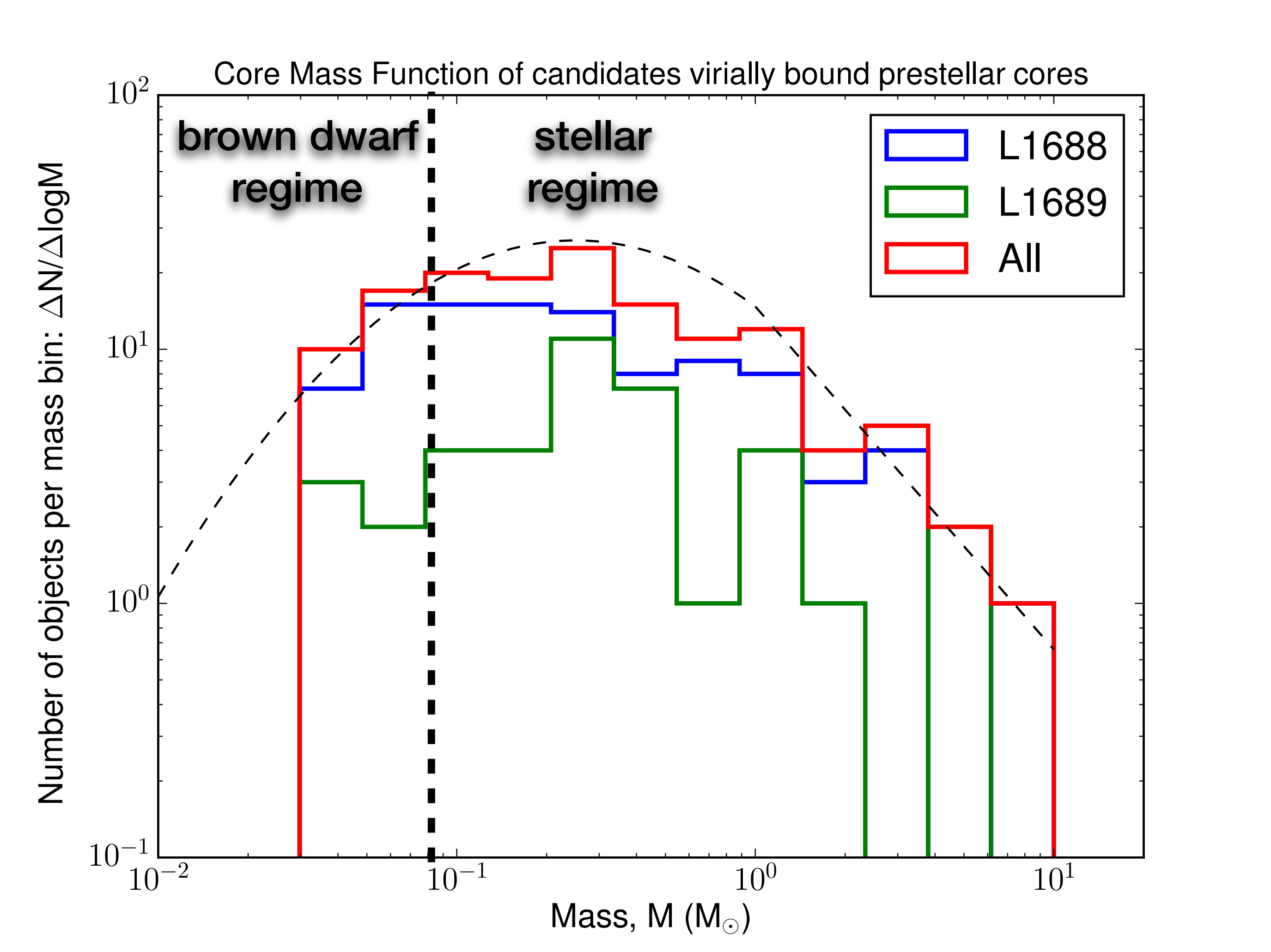
Prestellar Core Mass Function

- CMF: prestellar Core Mass Function
- Completness estimated with sources added to the data
- The sources are simulated with a radiative transfer code
- The completeness is just above the limit between the mass regimes of brown dwarfs and stars



Prestellar Core Mass Function

- Under 0.08 solar mass, the objects are too light to burn hydrogen.
- Intermediate between planets and stars



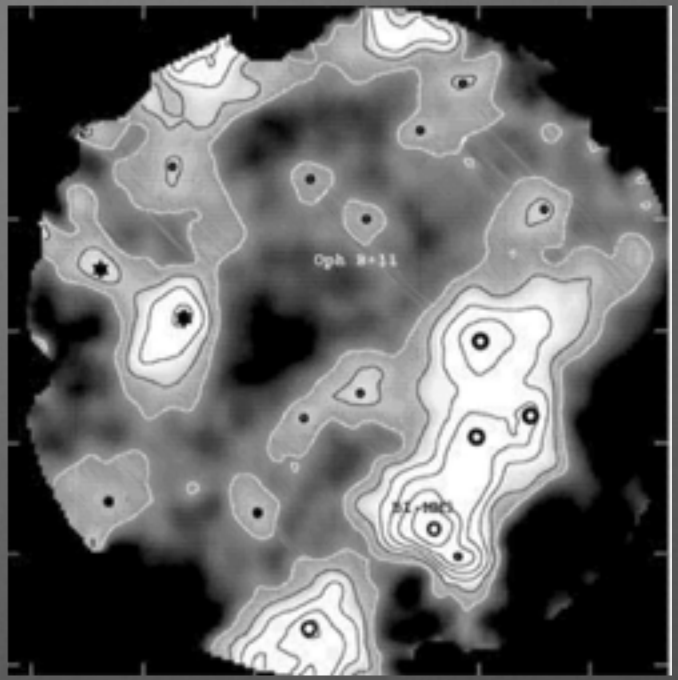
- Is it possible to detect and analyse precursors of brown dwarfs with Herschel?
- Can we have access to the behavior of the CMF at the lowest masses?
- What is the mechanism of formation of brown dwarfs

Oph-B11, a prototype

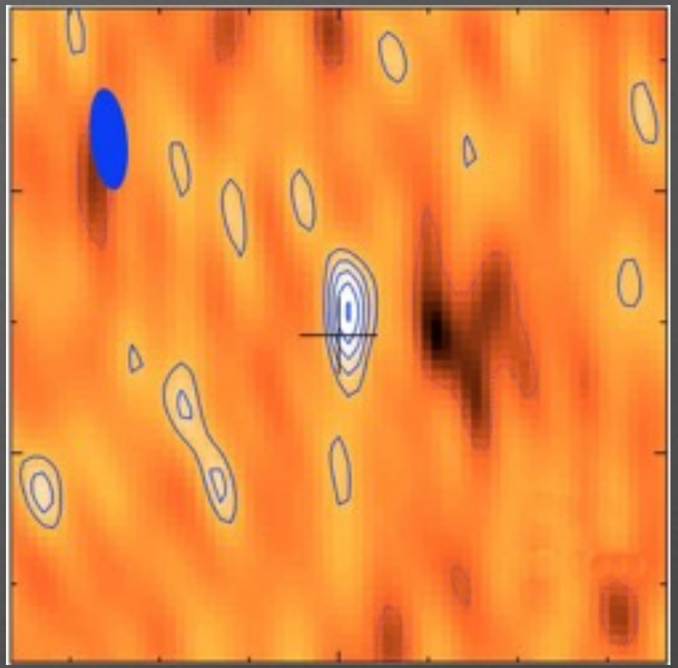
- Detected at 850 microns with the JCMT and at 3.2 mm with the IRAM interferometer

- ~ 0.03 solar masses

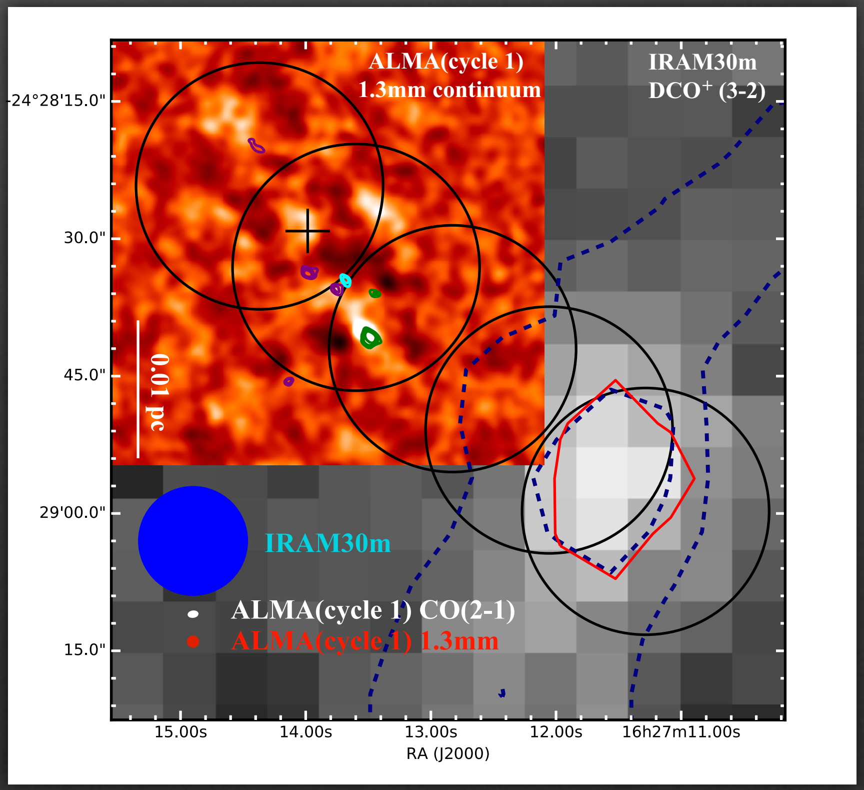
- ~ 1000 AU in diameter(4e-3 parsecs)



Greaves et al., 2003



André, Ward-Thompson & Greaves, 2012



ALMA and IRAM survey of Oph-B11

Oph-B11, a prototype

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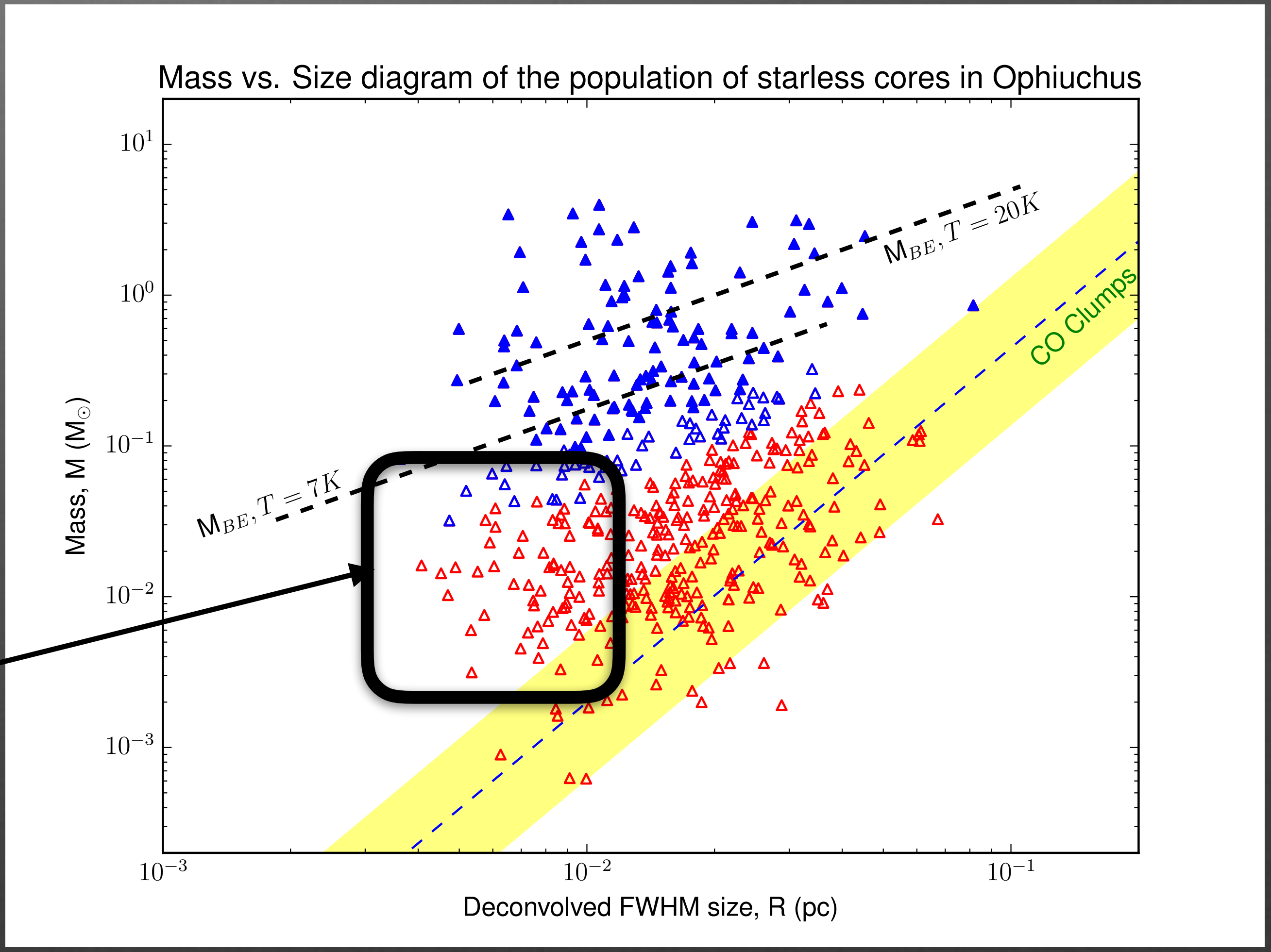
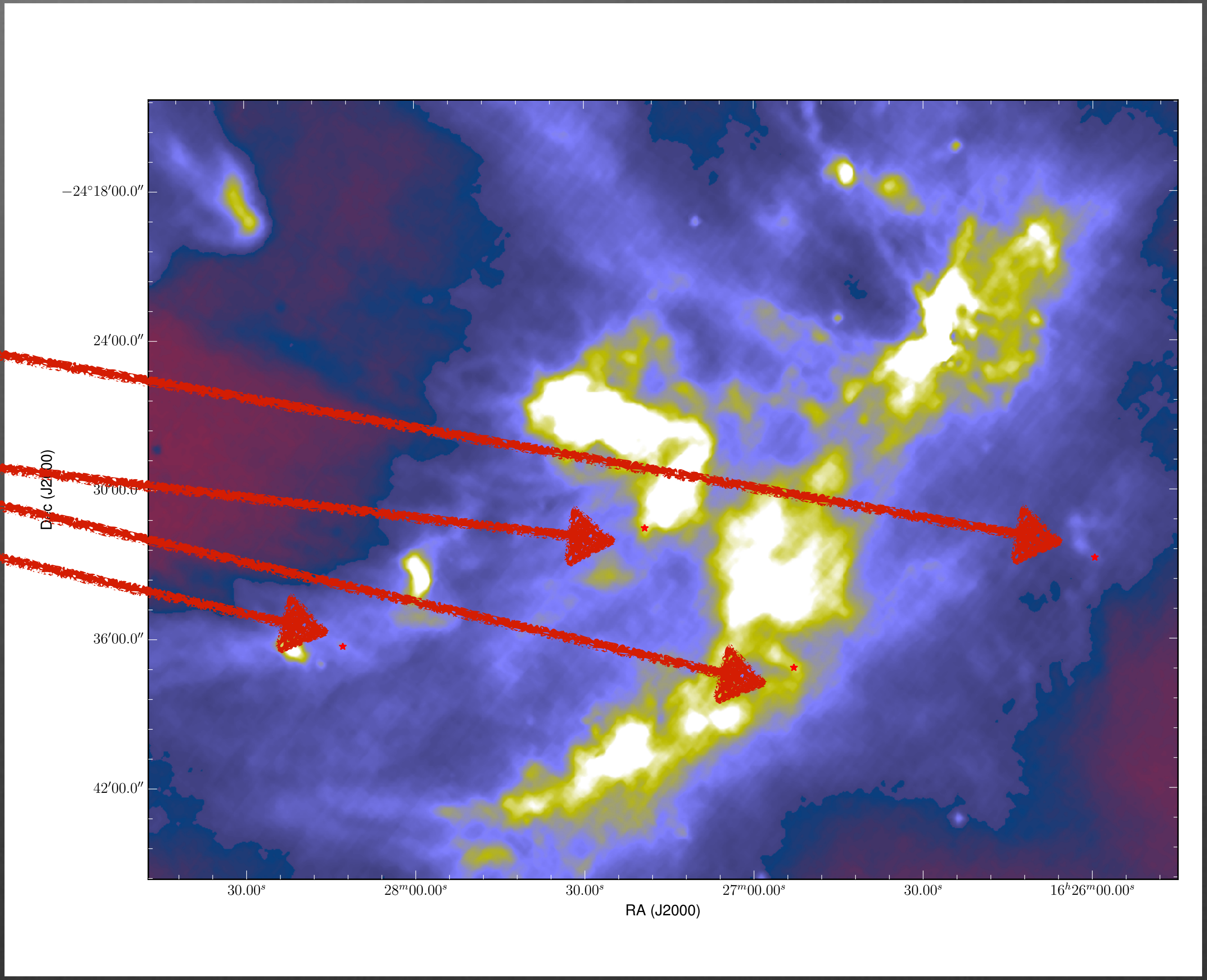


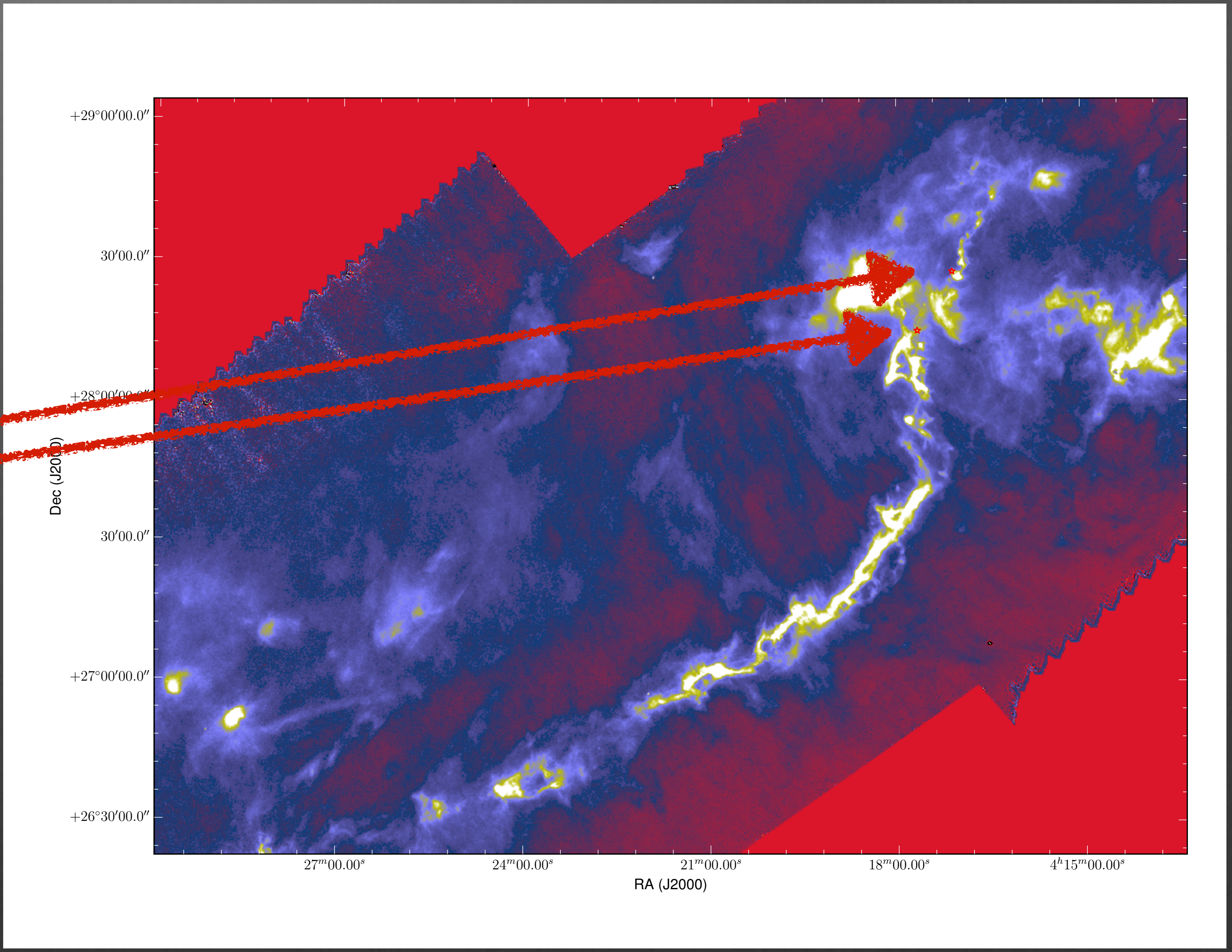
D'autres candidats?

- 4 candidates pre-brown dwarfs selected in Ophiuchus…
- Observed with the IRAM NOEMA interferometer (ex-PdBI)

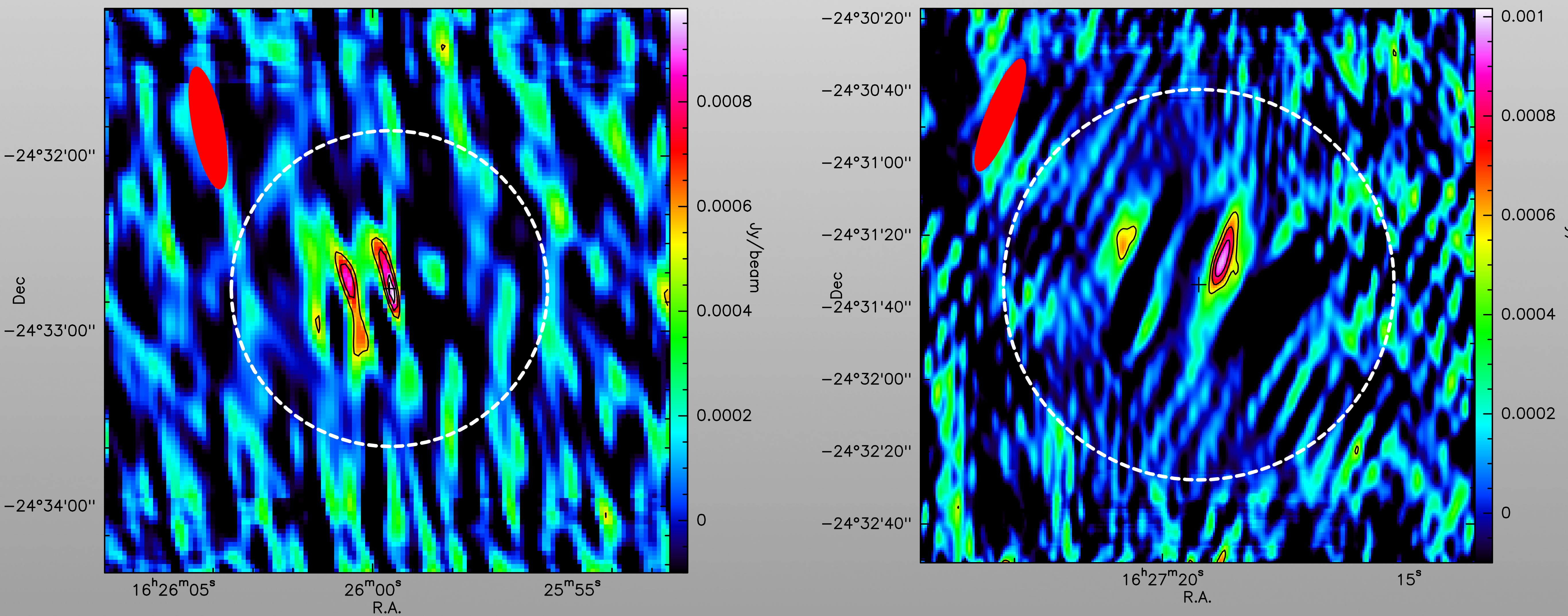


D’autres candidats?

- …and 2 in Taurus
- Observed with the IRAM NOEMA interferometer (ex-PdBI)

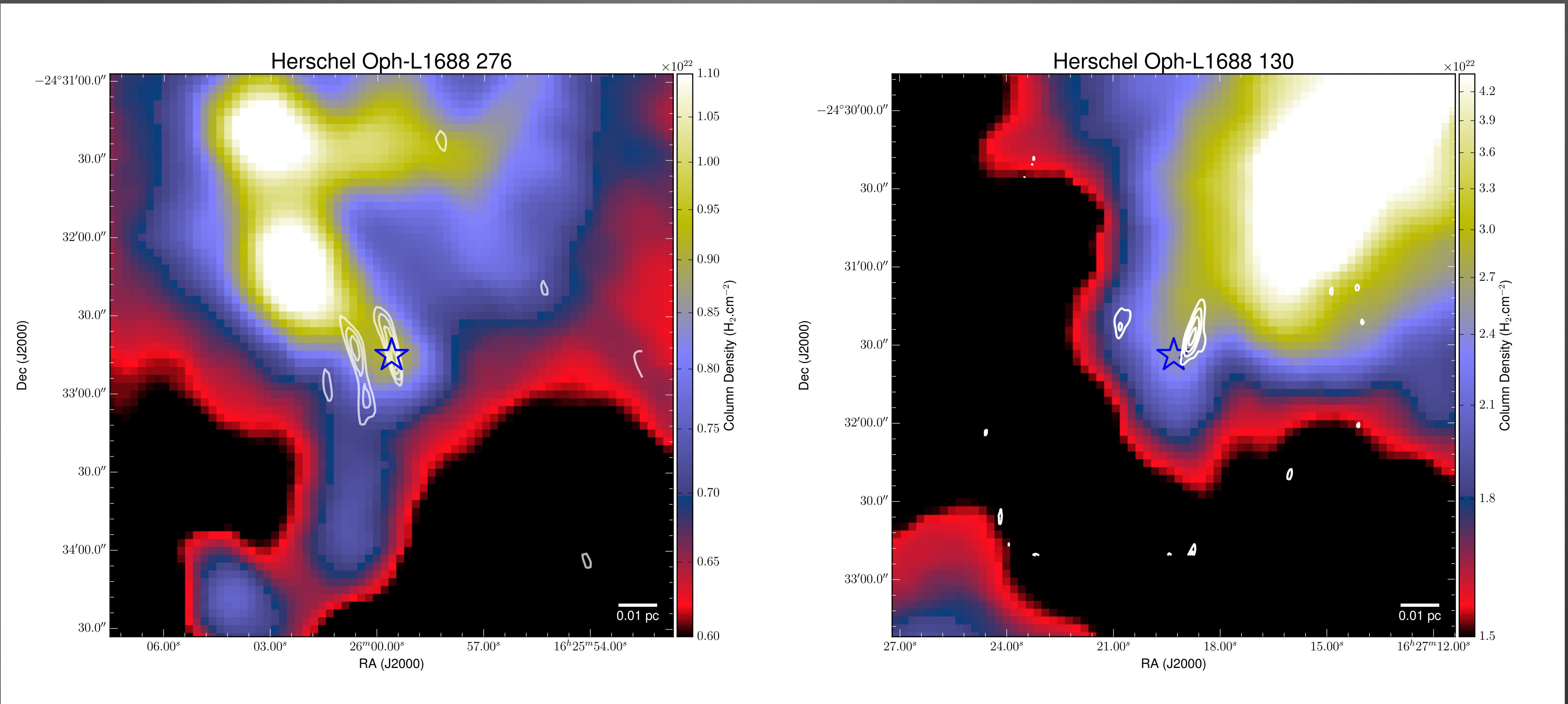


D’autres candidats?



NOEMA 3mm continuum observation

D'autres candidats?

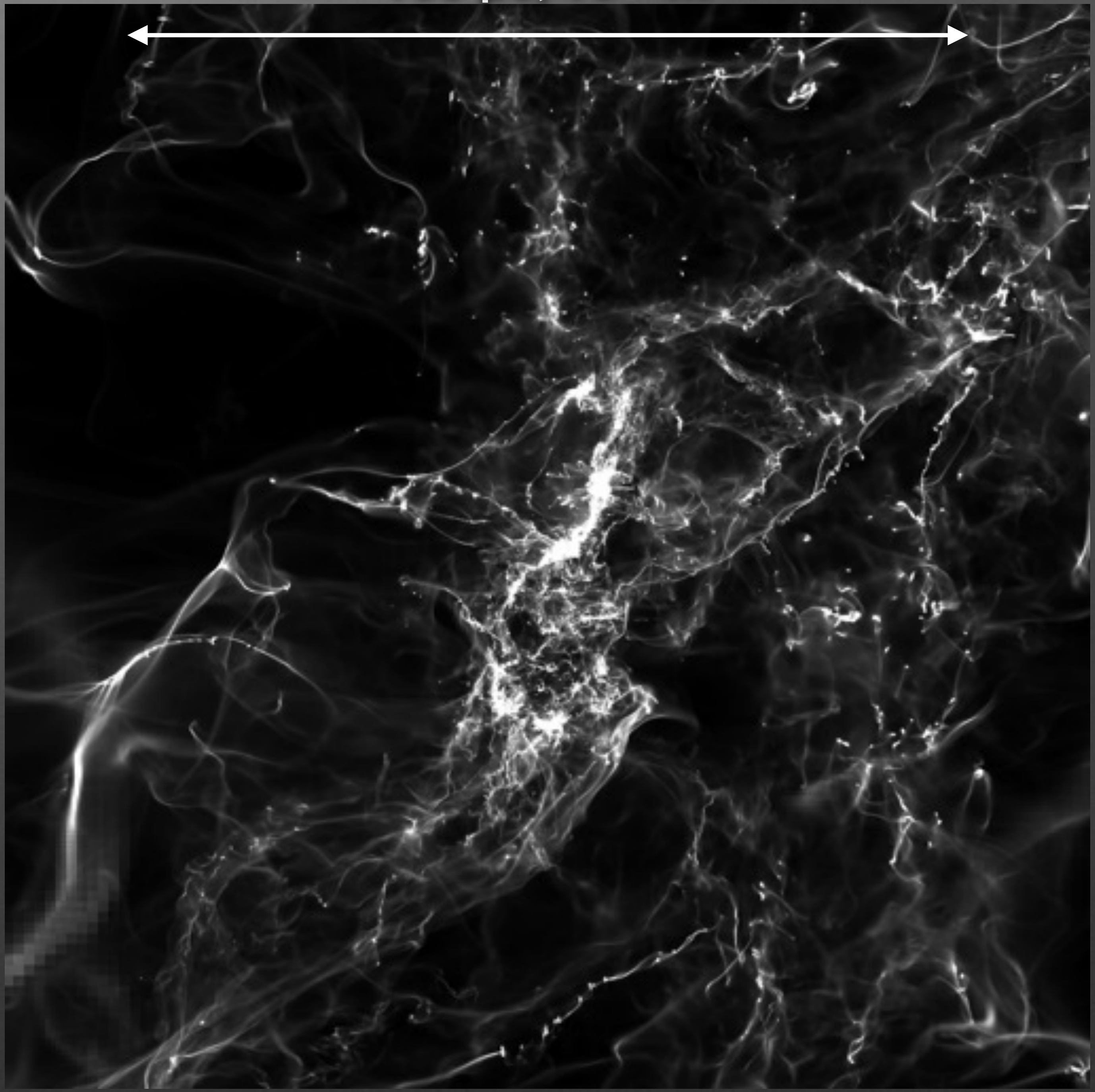


Observations still ongoing

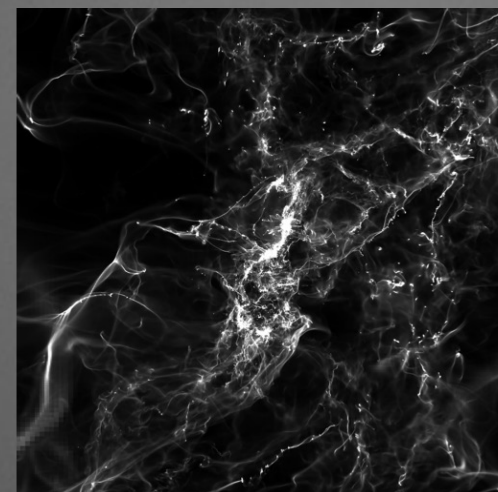
Simulating Observations

- RAMSES simulations of colliding flows (Hennebelle & Soler, in prep)
- Necessity to produce synthetic Herschel images in all bands to compare the observational results with the simulation results

100 pc, 10^{18} m



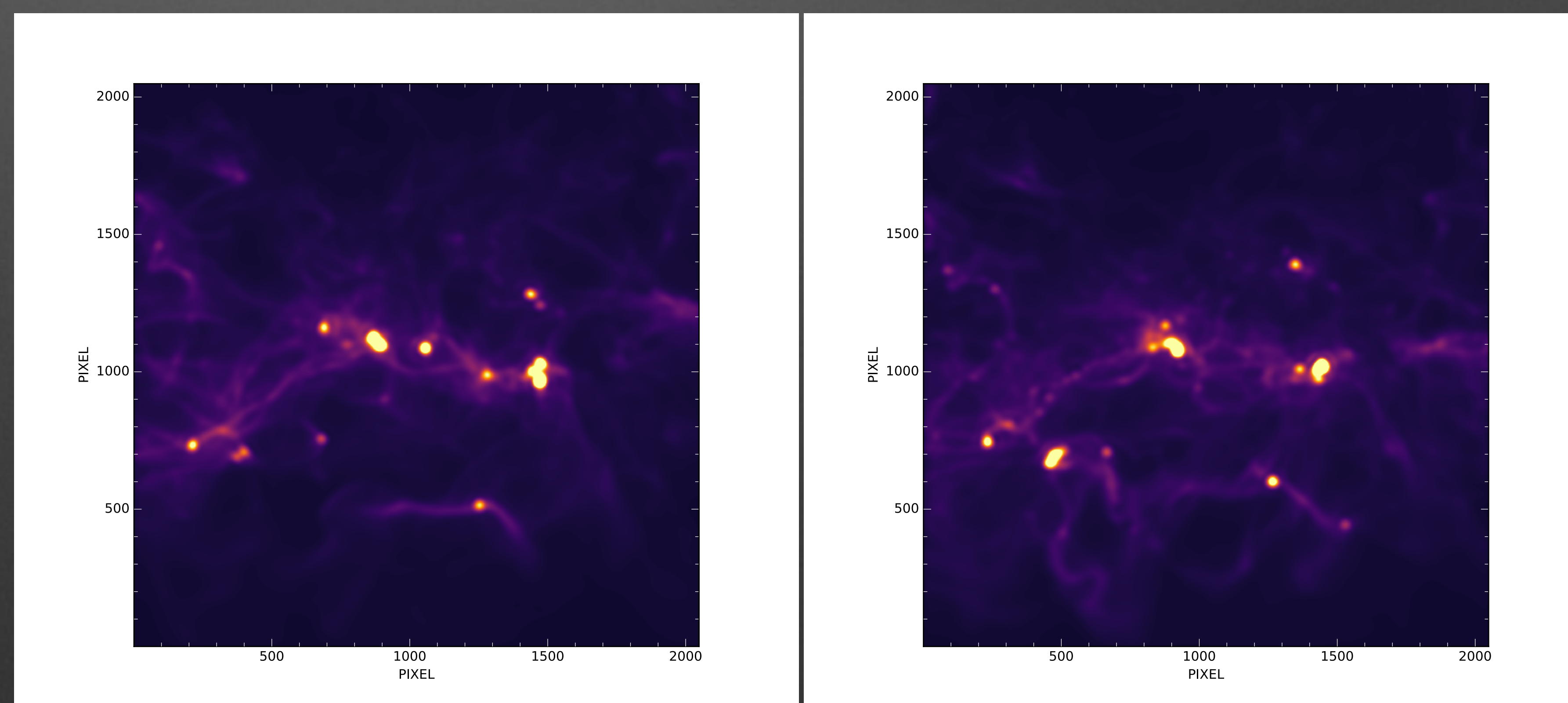
Observing Simulations



*Herschel PSFs and rescaling

- Adapting the same framework used in observations for simulations

- Possibility of confrontation between the physics of the simulations and the observational « reality »



SPIRE 250 microns synthetic images of FRIG simulations

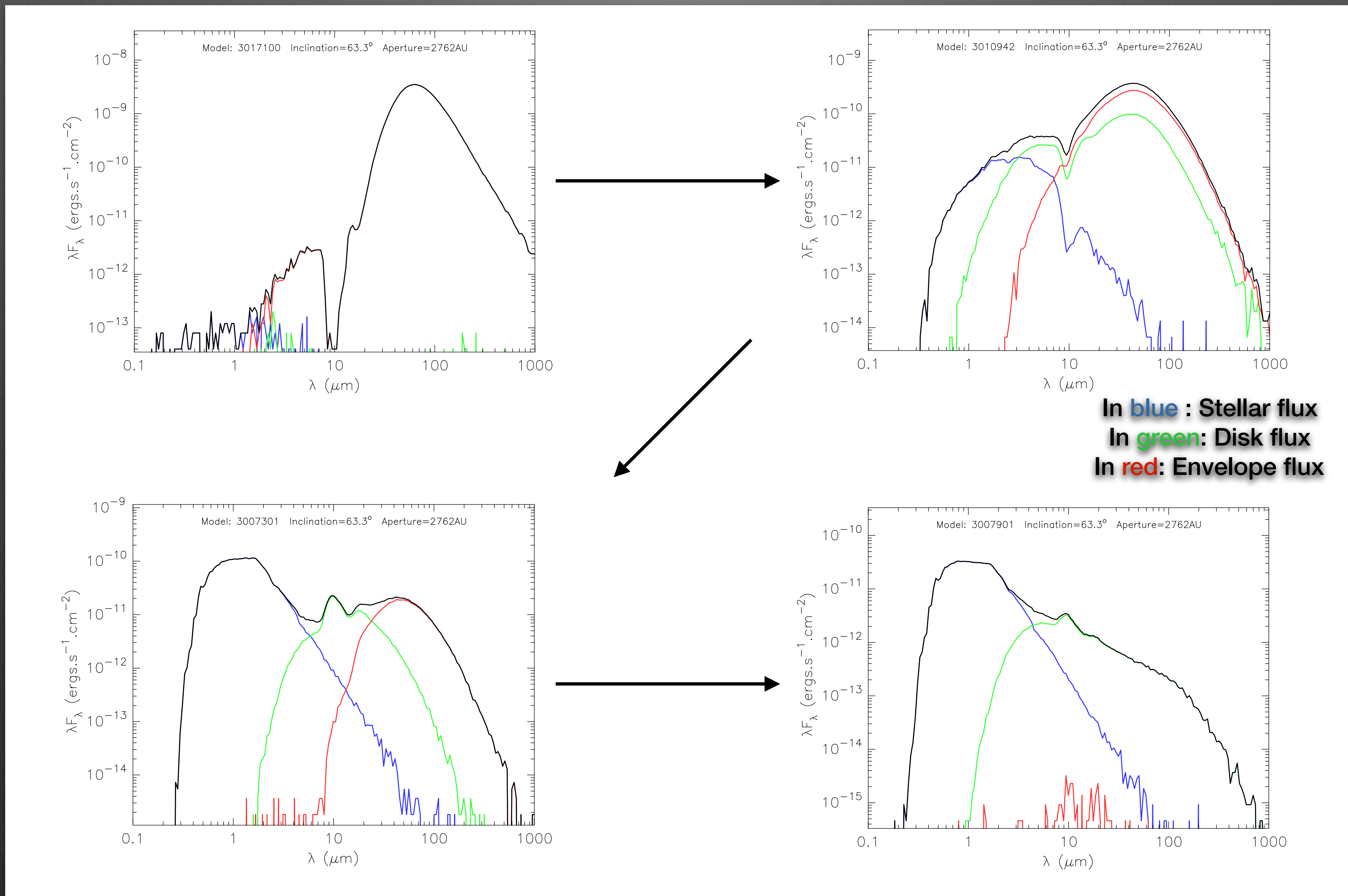
Conclusions

Conclusions

- A full survey of Ophiuchus allow us to count about 140 precursors of young stellar objects and derive their physical properties
- The results in Ophiuchus being similar to other galactic results, we have hints of universality of star-formation processes in the Milky Way
- The comparison between sub-regions of Ophiuchus, permitted by the extensive Herschel Survey of this region, give important results about the differences of star-formation activity between L1688 and L1689 (Ladjelate et al. in prep)
- While pre-brown dwarfs candidates can be observed at small scales with interferometers, lower scale might be more important to understand their environment of formation

Merci pour votre attention!

Introduction:
A classical view of the formation of low-mass stars



Data from Robitaille et al. 2007

Introduction: Wavelength and physical processes

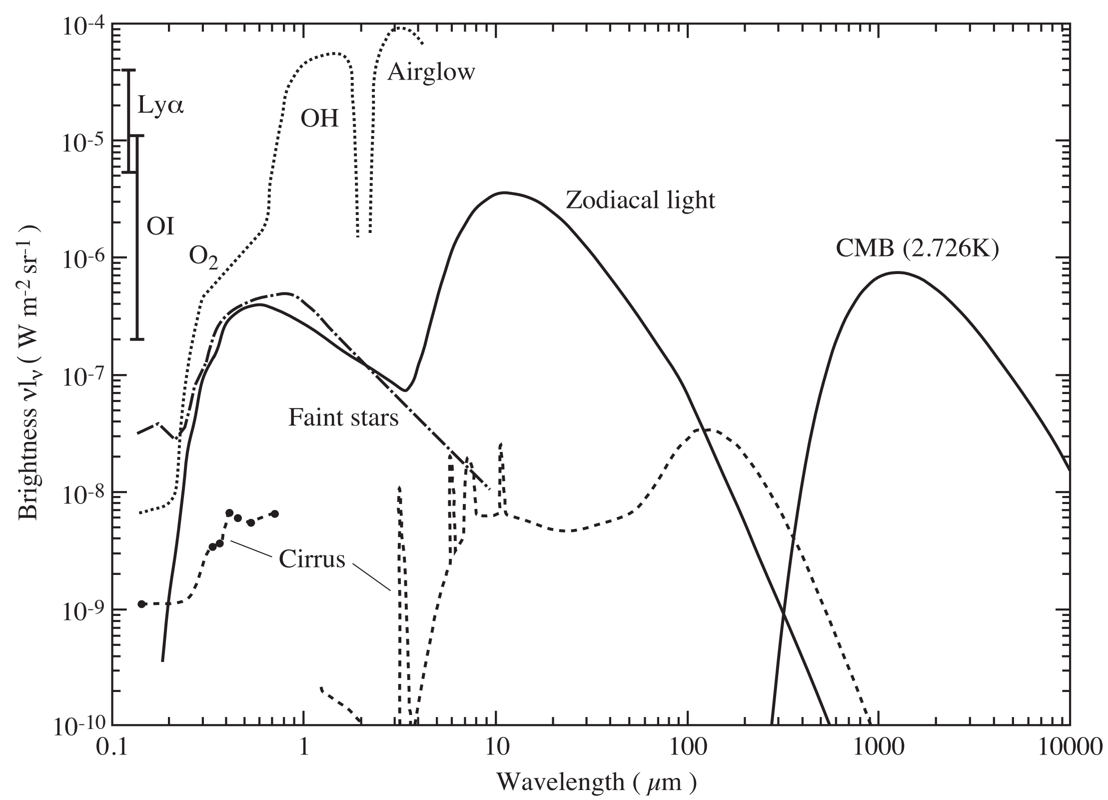


Fig. 1. Overview on the brightness of the sky outside the lower terrestrial atmosphere and at high ecliptic and galactic latitudes. The zodiacal emission and scattering as well as the integrated light of stars are given for the South Ecliptic Pole ($l = 276°$, $b = -30°$). The bright magnitude cut-off for the stellar component is $V = 6.0$ mag for $0.3 - 1$ μm. In the infrared, stars brighter than 15 Jy between 1.25 and 4.85 μm and brighter than 85 Jy at 12 μm are excluded. No cut-off was applied to the UV data, $\lambda \leq 0.3$ μm. The interstellar cirrus component is normalized for a column density of 10^{20} H-atoms cm^{-2} corresponding to a visual extinction of 0.053 mag. This is close to the values at the darkest patches in the sky. Source for the long-wavelength data, $\lambda \geq 1.25$ μm, are COBE DIRBE and FIRAS measurements as presented by Désert et al. (1996). The IR cirrus spectrum is according to the model of Désert et al. (1990) fitted to IRAS photometry. The short-wavelength data, $\lambda \leq 1.0$ μm, are from the following sources: zodiacal light: Leinert & Grün (1990); integrated starlight: $\lambda \leq 0.3$ μm, Gondhalekar (1990), $\lambda \geq 0.3$ μm, Mattila (1980); cirrus: $\lambda = 0.15$ μm, Haikala et al. (1995), $\lambda = 0.35 - 0.75$ μm, Mattila & Schnur (1990), Mattila (1979). The geocoronal Lyman α(121.6 nm) and the OI(130.4, 135.6 nm) line intensities were as measured with the Faint Object Camera of the Hubble Space Telescope at a height of 610 km (Caulet et al. 1994). The various references for the airglow emission can be found in Sect. 6

Leinert et al. 1998

Introduction:
Wavelength and physical processes

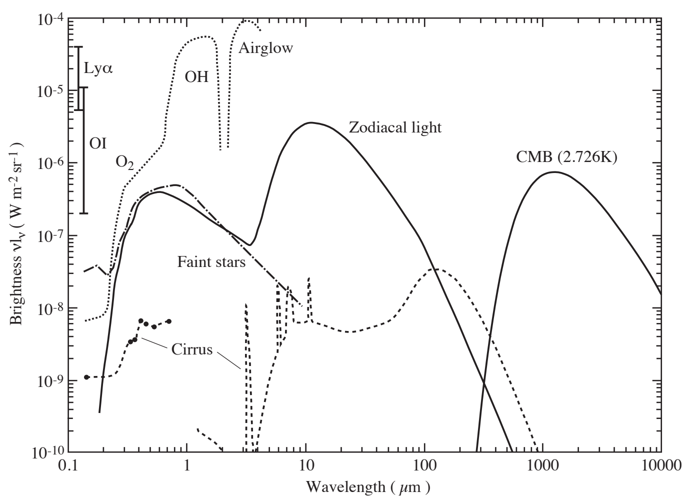
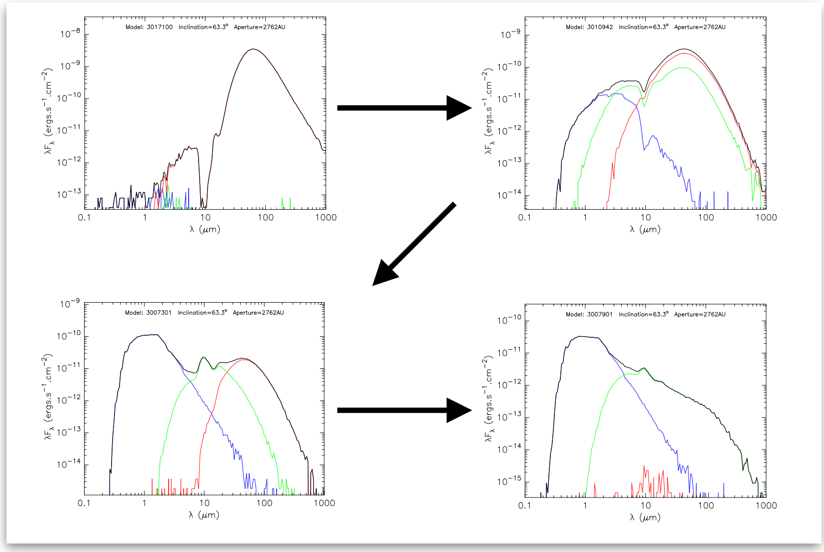


Fig. 1. Overview on the brightness of the sky outside the lower terrestrial atmosphere and at high ecliptic and galactic latitudes. The zodiacal emission and scattering as well as the integrated light of stars are given for the South Ecliptic Pole ($l = 276°$, $b = -30°$). The bright magnitude cut-off for the stellar component is $V = 6.0$ mag for $0.3 - 1$ μm. In the infrared, stars brighter than 15 Jy between 1.25 and 4.85 μm and brighter than 85 Jy at 12 μm are excluded. No cut-off was applied to the UV data, $\lambda \leq 0.3$ μm. The interstellar cirrus component is normalized for a column density of 10^{20} H-atoms cm^{-2} corresponding to a visual extinction of 0.053 mag. This is close to the values at the darkest patches in the sky. Source for the long-wavelength data, $\lambda \geq 1.25$ μm, are COBE DIRBE and FIRAS measurements as presented by Désert et al. (1996). The IR cirrus spectrum is according to the model of Désert et al. (1990) fitted to IRAS photometry. The short-wavelength data, $\lambda \leq 1.0$ μm, are from the following sources: zodiacal light: Leinert & Grün (1990); integrated starlight: $\lambda \leq 0.3$ μm, Gondhalekar (1990), $\lambda \geq 0.3$ μm, Mattila (1980); cirrus: $\lambda = 0.15$ μm, Haikala et al. (1995), $\lambda = 0.35 - 0.75$ μm, Mattila & Schnur (1990), Mattila (1979). The geocoronal Lyman α(121.6 nm) and the OI(130.4, 135.6 nm) line intensities were as measured with the Faint Object Camera of the Hubble Space Telescope at a height of 610 km (Caulet et al. 1994). The various references for the airglow emission can be found in Sect. 6

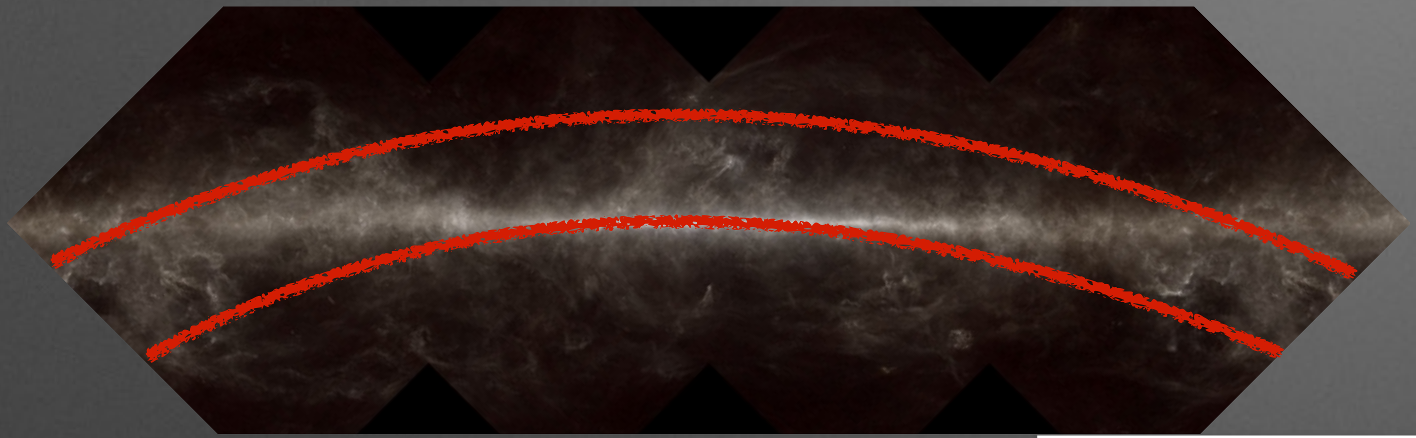


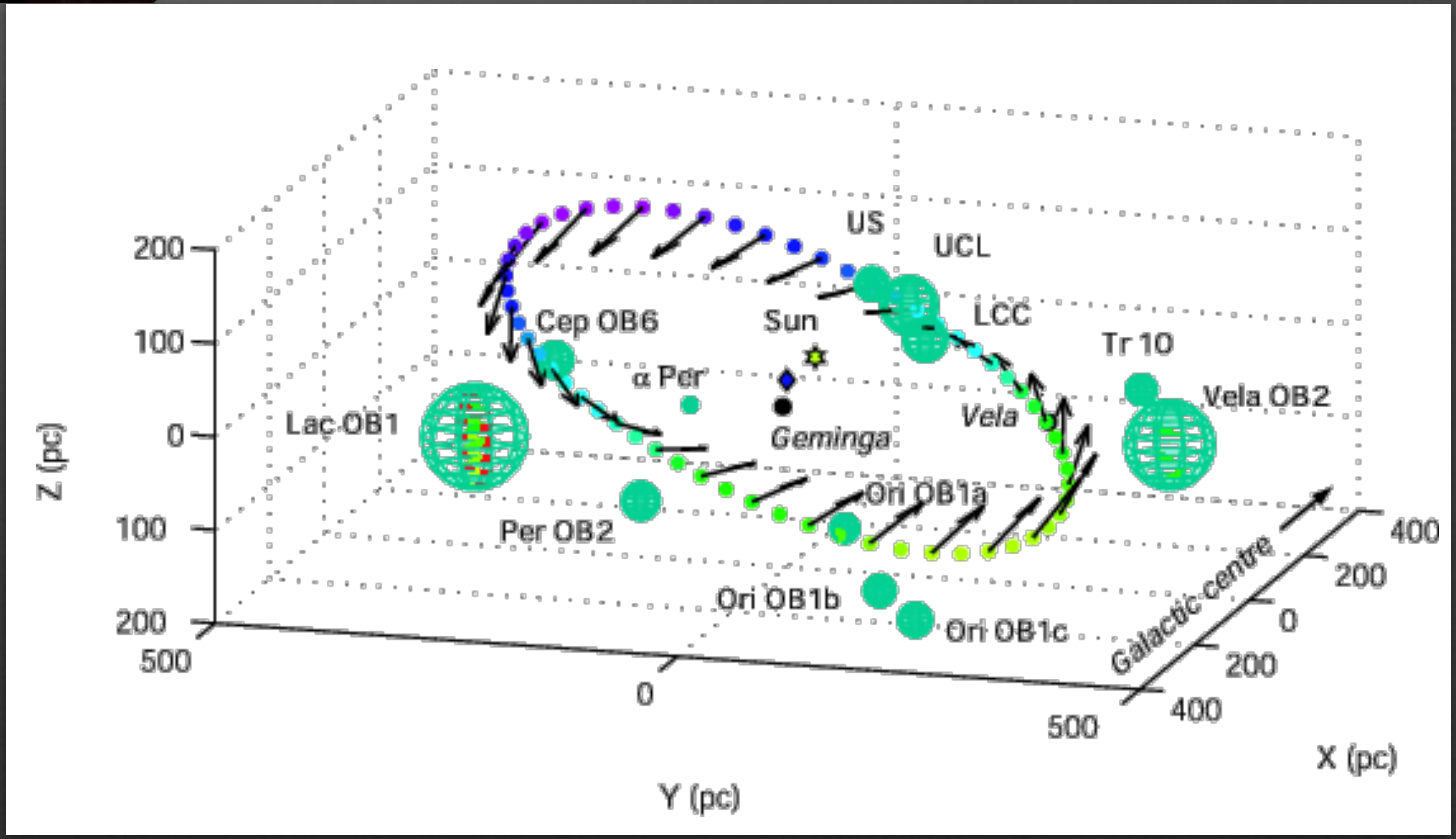
- The prestellar phase is well covered from 160 to 500 microns. No detection at 70 and 100 microns.
- Class 0 and Class I are detected at 70 and 100 microns because of the internal star.

Leinert et al. 1998
Robitaille et al. 2007

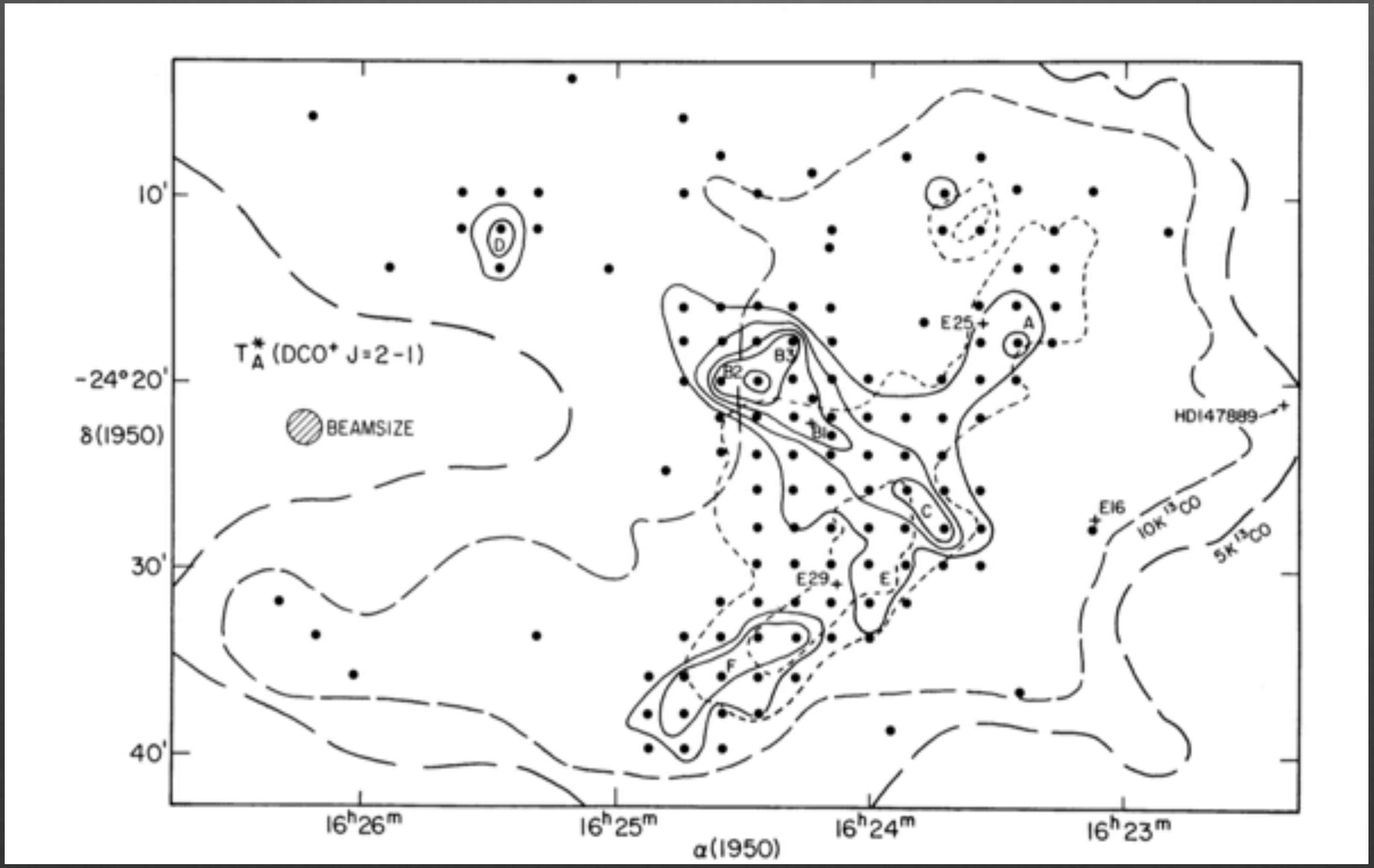
Introduction:
Herschel Gould Belt Survey

http://gouldbelt-herschel.cea.fr





Distribution of molecular gas in L1688



Loren et al. 1990