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# THE HOBYS KEY PROGRAM: WHEN HERSCHEL LINKS HIGH-MASS STAR FORMATION TO CLOUD STRUCTURE

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**Abstract.** With its unprecedented spatial resolution and high sensitivity in the far-infrared to submillimetre regime, Herschel is revolutionizing our understanding of star formation. The HOBYS key program is an Herschel mapping survey dedicated to the formation of OB-type stars (Motte, Zavagno, Bontemps et al. 2010; see http://hobys-herschel.cea.fr. HOBYS aims at 1) discovering and characterizing the progenitors of high-mass stars, 2) making the link between the latters and their filamentary background, and 3) assessing the importance of triggering. Among the HOBYS highlights is the discovery of "mini-starburst ridges" defined as high-density dominating filaments supersonically contracting and efficiently forming clusters of high-mass stars. Their existence is predicted by dynamical models of cloud formation such as converging flows and is favoring a (high-mass) star formation scenario involving gas flows and global infall. The present star formation rate measured within these ridges is high enough for these 1–10 pc$^2$ regions to be considered as miniature and instantaneous models of extragalactic starbursts.

Keywords: dust, ISM: clouds, ISM: structure, stars: formation, submillimeter, IR: Herschel, H II regions

## 1 Introduction: From cloud to high-mass star formation

High-mass stars (OB-type, $M_\star > 8\ M_\odot$) play a major role in the energy budget and enrichment of galaxies but their formation remains poorly understood. The picture which is starting to emerge states that *OB stars form through very dynamical processes* such as (1) a powerful accretion driven by a high degree of turbulence (e.g. McKee & Tan 2002; Hosokawa & Omukai 2009) or (2) colliding flows initiated by competitive accretion or cloud formation (e.g. Bonnell & Bate 2006; Hartmann et al. 2012). From a purely observational point of view, gravitational streamers and shearing motions have been reported from the cloud to the protostellar scales in a few high-mass star-forming regions (on $10 - 0.1$ pc scales; Schneider et al. 2010a; Csengeri et al. 2011). These pioneering studies suggest that the formation of OB stars is tightly linked to the density and kinematics of their parental cloud.

At the dawn of *Herschel*[i], our knowledge of high-mass star formation and the evolutionary sequence of their earliest phases was still rather schematic. Bright *IRAS* sources embedded within massive envelopes have been recognized as high-mass protostellar objects (HMPOs) containing evolved high-mass protostars (e.g. Beuther et al. 2002). Cold massive dense cores (MDCs) associated with weak mid-infrared emission, but with clear signposts of OB-type protostars, have been qualified as IR-quiet and observed to harbor high-mass class 0 protostars (Motte et al. 2007; Bontemps et al. 2010b). Controversy was remaining about the existence and the lifetime of high-mass analogs of prestellar cores, since infrared dark clouds (IRDCs) are numerous (e.g. Peretto & Fuller 2010) but only a few harbor starless, massive, and dense enough cores (Motte et al. 2007; Russeil et al. 2010). Large surveys covering the far-infrared to millimeter continuum regime were thus required to improve the statistics of these studies and constrain models proposed for the formation of high-mass stars. Ground-based submillimeter surveys such as ATLASGAL (Schuller et al. 2009) started to help but they need to be completed by *Herschel* imagings.

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[i] *Herschel* is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.

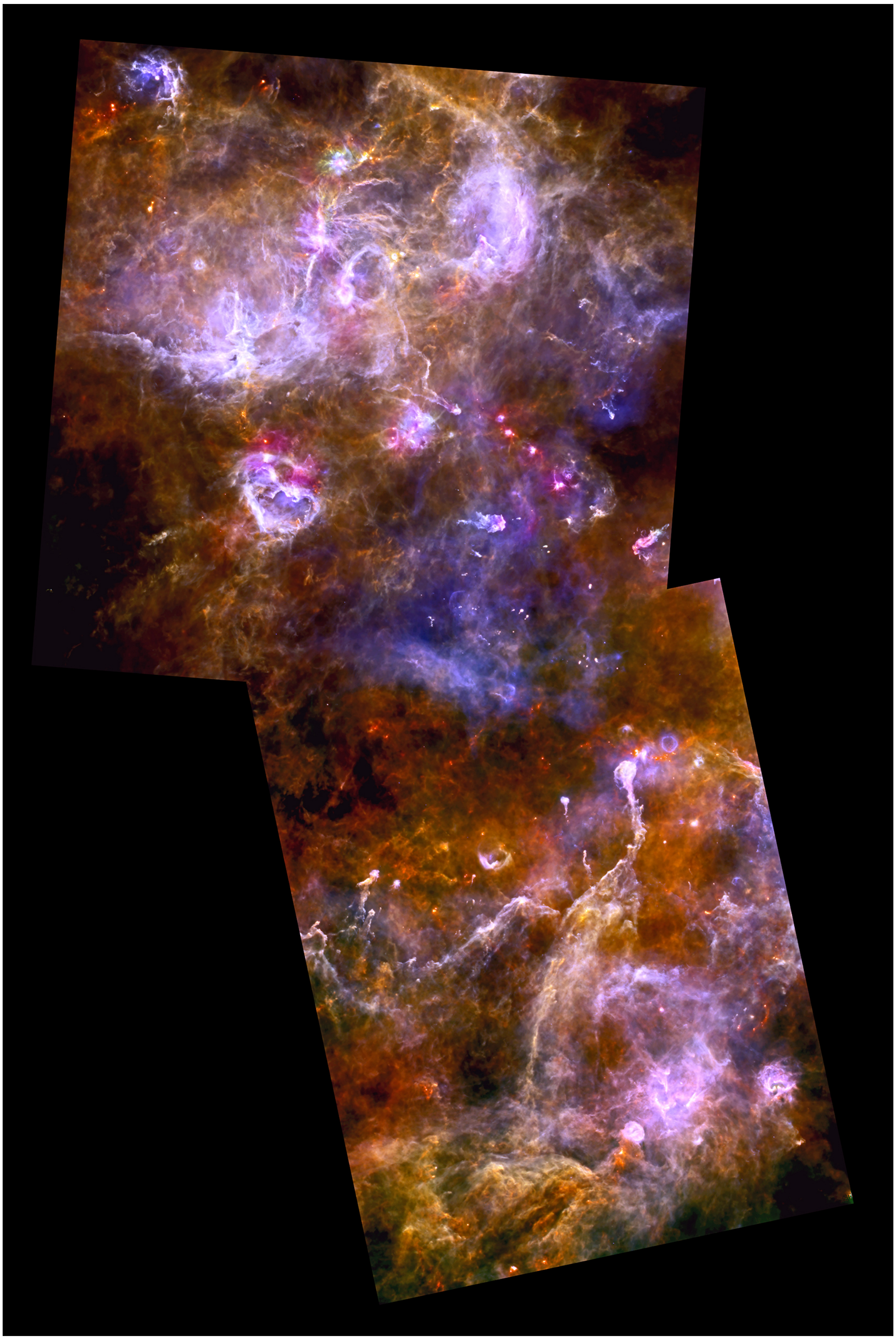

**Fig. 1.** Composite 3-color *Herschel* image of the Cygnus X molecular complex with red=250 $\mu$m, green=160 $\mu$m, and blue=70 $\mu$m (taken from Hennemann et al. 2012, and Hennemann et al. in prep.). The mosaic performed by the HOBYS key program approximately covers a $5^\circ \times 2.5^\circ$ or 120 pc $\times$ 60 pc area. The angular resolutions are $HBPW \sim 6''$ at 70 $\mu$m, $\sim 12''$ at 160 $\mu$m, and $\sim 18''$ at 250 $\mu$m. The diffuse blue emission in the center is an H II region powered by the Cyg OB2 cluster while earlier stage star-forming sites are seen as red filaments.

The "*Herschel* imaging survey of OB Young Stellar objects" (HOBYS, Motte et al. 2010, see `http://hobys-herschel.cea.fr`) is a guaranteed time key program jointly proposed by the SPIRE and PACS consortia, and the Herschel Science Centre. Since October 2009, it used the SPIRE and PACS cameras (Griffin et al. 2010; Poglitsch et al. 2010) of the *Herschel* satellite (Pilbratt et al. 2010) to image essentially all of the regions forming OB-type stars at distances less than 3 kpc from the Sun ($d = 0.7 - 3.2$ kpc) and target a few prototypical regions of triggered star formation at the periphery of H II bubbles. Two other key programs have mapped massive young stellar objects (YSOs): EPoS targeting well-known HMPOs and IRDCs (Ragan et al. 2012) and HiGAL surveying most of the Galactic plane (Molinari et al. 2010). *HOBYS allows both a more statistically meaningful and more comprehensive study of cloud structure and YSOs at a fixed ∼0.1 pc resolution.* HOBYS images revealed networks of filaments and clusters of burgeoning YSOs (see Fig. 1) similar to those observed for the more nearby Gould Belt clouds (see André et al. 2010, $d = 100 - 500$ pc). The most obvious differences arise from the heating and structural impact of stellar clusters and H II regions associated/embedded within the HOBYS molecular cloud complexes (see e.g. Fig. 1). While triggered star formation is obvious around isolated H II regions Zavagno et al. (2010); Anderson et al. (2012); Deharveng et al. (2012), it is not yet unambiguously proven in cloud complexes (see however Schneider et al. 2010b; Hill et al. 2012, Minier et al. submitted).

## 2 HOBYS cloud structures: Ridges, the necessary conditions for clusters of high-mass stars to form

The cloud structure of HOBYS molecular complexes is investigated through column density images built from the far-infrared and submillimeter *Herschel* images. Indeed, the 160 $\mu$m PACS and 250/350/500 $\mu$m SPIRE images mostly trace optically thin emission of cold dust/big grains that follow the general density structure of the cloud. In contrast, the 70 $\mu$m emission originates from hot dust/small grains close to protostars or within H II regions/photo-dissociation regions. Dust temperature and column density maps (see e.g. Figs. 2b-c) were therefore drawn by fitting pixel-by-pixel spectral energy distributions (SEDs) for $\lambda > 160$ $\mu$m and using a modified blackbody model (see Hill et al. 2012, for a detailed description). Prior to fitting, the *Herschel* data were convolved to a common 37$''$ resolution and the zero offsets were applied to the individual maps (see details in Bernard et al. 2010). A dust opacity per unit mass given by $\kappa_\nu = 0.1$ cm$^2$ g$^{-1}$ $\times$ $(\nu/1000$ GHz$)^\beta$ and a dust spectral index of $\beta = 2$ (Motte et al. 2010) was used. HOBYS column density images generally display networks of filaments among which *a few well-ordered, dominating ridges which are privileged sites to form massive stars* (Hill et al. 2011; Nguyen Luong et al. 2011a; Hennemann et al. 2012). The DisPerSE algorithm (Sousbie 2011), based on Morse theory and the concept of persistence to identify topological structures, was used to take a census of the filaments/ridges (see dotted points in Fig. 2b).

Hill et al. (2011) studied the Vela C molecular cloud complex ($d = 700$ pc) and defined the two ∼3 pc-long filaments with column density above $10^{23}$ cm$^{-2}$ as "ridges". They showed that these high-density, elongated cloud structures are dominating and shaping their surroundings in marked contrast to other less-organized sub-regions of Vela C. Indeed, the density profile of ridges perpendicular to their crest suggests a (five times) larger radius of influence (∼0.5 pc) than averaged filaments. The multi-resolution distribution of the cloud shows a high concentration of the gas (∼40%, twice larger than in averaged regions) at scales smaller than 3 pc. Moreover, the column density probability distribution (PDF) has a high column density tail above $0.5 \times 10^{23}$ cm$^{-2}$, consistent with formation of the cloud through large-scale gas flows (e.g. Federrath et al. 2010). Hill et al. (2011) proposed that *ridges are both shaping and shaped by their surroundings as they represent a gravitational well and could have been formed by dynamical scenarios such as converging flows* (e.g. Heitsch et al. 2006). Minier et al. (submitted) showed that additional pressure arising from the ionization of the RCW36 OB cluster has helped shaping and could even be the main process responsible for making the Vela C center ridge denser. They compared the column density structure, mid-infrared and H$\alpha$ emission to numerical simulations (Tremblin et al. 2012) and located the RCW36 cluster at ∼1 pc from the center ridge of Vela C.

Hennemann et al. (2012) studied the DR21 ridge, the densest and most massive cloud structure of the Cygnus X molecular complex ($d = 1.4$ kpc, see Figs. 1-2): $M_{\rm total} = 15\,000\ M_\odot$ within a 4 pc $\times$ 1 pc elongated clump. This prototypical ridge contains 9 MDCs and is forming a cluster of ∼20 high-mass stars (Motte et al. 2007; Bontemps et al. 2010b). Schneider et al. (2010a) showed that the DR21 ridge is undergoing a global collapse and proposed it is fed by three sub-filaments called F1–F3. Hennemann et al. (2012) used the *Herschel* column density image to define the extent of the DR21 ridge by the $N_{\rm H_2} = 10^{23}$ cm$^{-2}$ contour and trace connected sub-filaments with DisPerSE (see Fig. 2b). The perpendicular column density profile of the DR21 ridge displays two peaks and the northern and possibly southern parts of the ridge show two extensions (see Fig. 2). These branchings and complex structure suggest the DR21 ridge could have been formed by dynamical scenarios such as the merging of several filaments (Hennemann et al. 2012). Schneider et al. (2012) similarly proposed that intermediate-mass star clusters in Rosette would preferentially form at the junction of filaments as predicted by Dale & Bonnell (2011). The DR21 sub-filaments display decreasing dust temperature towards the ridge, indicating the pile-up of material which cools down (see Fig. 2c). These sub-filaments are also gravitationally supercritical and indeed already form cores and protostars (see Figs. 2a-b). Given their mass, they merely represent remnant flows but *the accretion of both the cool gas and cores/protostars is probably helping building up a future cluster of high-mass stars within the DR21 ridge.* Such a dynamical scenario for cloud and then cluster formation is consistent with the kinematics measured in a few ridges and shocks observed with e.g. SiO (Schneider et al. 2010a, Motte et al. in prep., Nguyen Luong et al. in prep.).

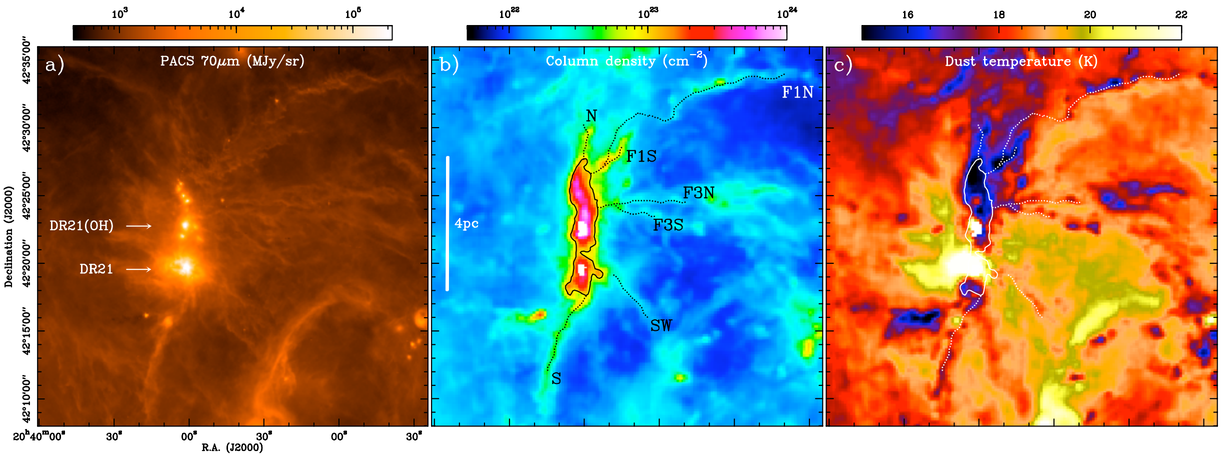


**Fig. 2.** *Herschel* maps of the DR21 environment showing a) 70 $\mu$m emission, b) column density, and c) dust temperature. The DR21 ridge is delineated by the $N_{H_2} = 10^{23}\,\mathrm{cm}^{-2}$ contour plotted in panels b) and c) and covering a 2.3 pc$^2$. The sub-filaments connected to the ridge are named and marked with dots along their crests in b) and c).

## 3 HOBYS YSO population: Short lifetimes for high-mass star precursors and burst of star formation

HOBYS identified thousands of YSOs in 8 molecular complexes of 50-100 pc sizes such as Cygnus X (see Fig. 1). *Herschel* compact sources were extracted using the multi-scale, multi-wavelength *getsources* algorithm (see Men'shchikov et al. 2012). At the detection step, the five *Herschel* images were decomposed into multi-resolution cubes as in the MRE-GCL method (see Motte et al. 2007). The five wavelength cubes were then combined, with greater weight being given to the higher resolution images, and the compact sources were detected within the resulting cube. At the measurement step, the initial *Herschel* and other complementary images, were used to compute the sources properties at their detected location, after the background had been subtracted and overlapping sources had been deblended. The strength of this approach is to allow the simultaneous detection, at all wavelengths, of compact but still resolved sources. In the final *getsources* catalogue, each *Herschel* compact source has a single position and one FWHM size (and integrated flux) at each of the wavelength considered. To limit the influence of different *Herschel* resolutions and restrict the study to the dense cores size ($\sim$0.1 pc), the fluxes at $\lambda > 160\,\mu$m were linearly scaled to the source size measured at 160 $\mu$m (procedure introduced by Motte et al. 2010; Nguyen Luong et al. 2011a). The spectral energy distributions of the extracted dense cores were compared to grey-body models to characterize their cold gas component. The bolometric luminosity, envelope mass, and submillimeter-to-bolometric luminosity ratio were estimated for each *Herschel* compact source.

HOBYS is therefore providing an unbiased census of intermediate- to high-mass dense cores, with $\sim$0.1 pc sizes, which can be used to start constraining the evolutionary sequence of OB-type YSOs. Mass-luminosity ($M_{\rm env}$ vs. $L_{\rm bol}$) diagrams were built to determine the low- or high-mass star potential and the evolutionary status (IR-quiet/class 0 versus IR-bright/class I) of protostellar dense cores (Hennemann et al. 2010, see also Bontemps et al. 2010a, Hennemann et al. in prep.). Among the preliminar but homogeneous and complete samples of massive YSOs, *no good candidate for being a high-mass prestellar core was yet found.* The few intermediate-mass starless dense cores discovered in Rosette suggest a statistical lifetime ($\sim 8 \times 10^4$ yr, Motte et al. 2010) intermediate between those found in nearby low-mass star-forming regions ($\sim 2 \times 10^5$ yr, Kirk et al.

2005) and high-mass star-forming complexes ($\sim 5 \times 10^4$ yr, Motte et al. 2007; Russeil et al. 2010). If confirmed, this result could suggest either that the prestellar lifetime depends on the final mass of the star that they will form or that statistical lifetimes cannot be used since star formation often proceeds in bursts.

As said above, ridges are the privileged sites for the formation of high-mass star clusters and YSO populations can be used to compute their star formation rate (SFR, see Fig. 3). Nguyen Luong et al. (2011a) counted YSOs in the G035.39–0.33 ridge (cf. Fig. 3a) and assumed a mass transfer efficiency from dense core to star depending on their mean density, typically 25% for MDCs. The clustering of IR-quiet MDCs and class 0 dense cores within the G035.39–0.33 ridge suggests they are simultaneously forming, probably just after the formation of the ridge itself (Vázquez-Semadeni et al. 2008). Nguyen Luong et al. (2011a) estimated a YSO lifetime close to the dense core free-fall time, typically $10^5$ yr, and assumed that the initial mass function of Kroupa (2001) applies. The resulting SFR estimates are very uncertain but remain *direct measurements* like those done from *Spitzer* YSOs counting (Heiderman et al. 2010) and in contrast to those made from the impact of OB-type stars/H II regions on the interstellar medium (e.g. Nguyen Luong et al. 2011b). They also correspond to *present SFRs* in opposition to the past SFRs measured within nearby galaxies or Gould Belt cloud from the infrared or centimeter emission of already formed stars. The star formation rate densities measured within the G035.39–0.33, W43-Main, and DR21 ridges are high: $\Sigma_{\rm SFR}$ $10 - 100$ $M_\odot$ /yr /kpc$^2$ on $1 - 10$ pc$^2$ areas (see Motte et al. 2003; Nguyen Luong et al. 2011a, Hennemann et al. in prep.). They are worthy of starburst galaxies usually defined by $\Sigma_{\rm SFR} > 1$ (Kennicutt 1998) and *ridges qualify as mini-starburst regions* (see Fig. 3b).

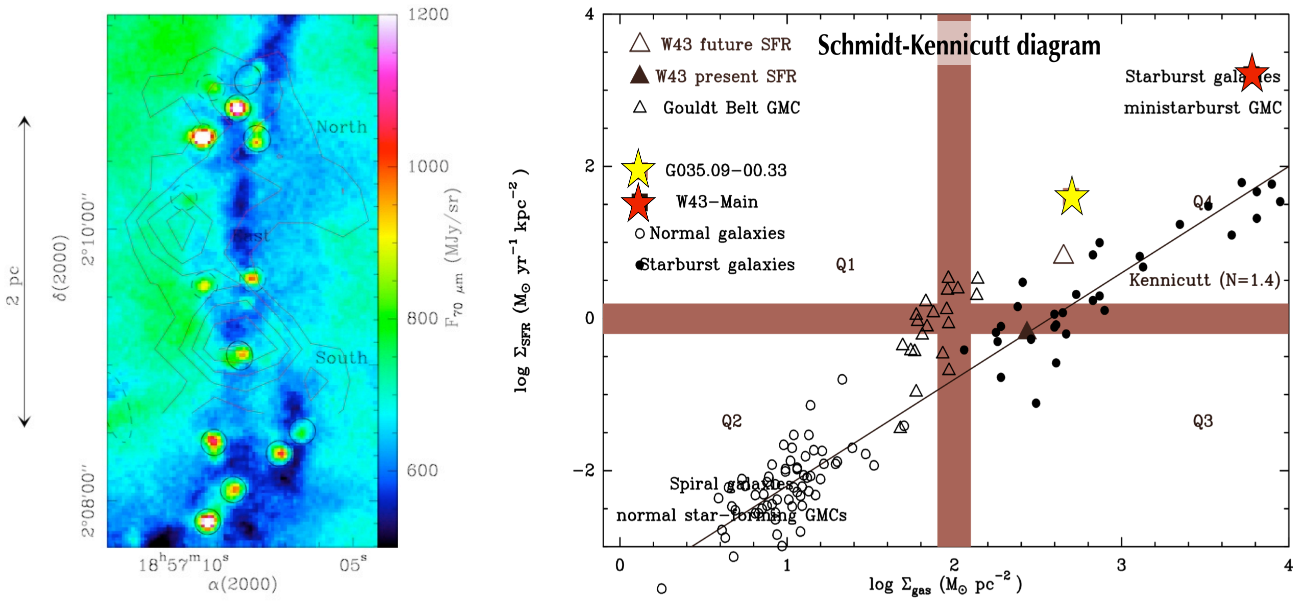


**Fig. 3. Left:** The G035.39–00.33 ridge seen at 70 $\mu$m (color) and in SiO (contours from Jiménez-Serra et al. 2010). The dense cores with mass >20 $M_\odot$ are indicated by continuous ellipses, those with mass <20 $M_\odot$ by dashed ellipses. **Right:** The G035.39–0.33 and W43-Main starburst ridges placed in the Schmidt-Kennicutt diagram, a plot of the star formation density as a function of mass density originally built to separate starburst and spiral galaxies.

## 4 Conclusions

HOBYS studies defined "ridges" as high-column density ($A_V > 100$ mag), elongated (several pc) cloud structures concentrating the mass of their surroundings and forming high-mass stars. With their filamentary structure, high density, and low temperature, ridges are extreme infrared-dark clouds. While turbulence could have formed most cloud filaments, more dynamic scenarios such as converging flows and/or filaments merging are advocated to form ridges. The HOBYS survey statistically showed that ridges are privileged sites for the formation of high-mass star clusters and are currently developing local bursts of star formation. In such a scenario, high-mass prestellar cores that will collapse independently from their surrounding cannot exist, in agreement with the lack of their discovery. The HOBYS survey is a necessary step towards Galaxy-wide studies of high-mass star formation since it will soon make the global study of cloud structure and star formation activity in the closest Galactic arm with the unmatched resolution of ∼0.1 pc.

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