THE EARLIEST PHASES OF STAR FORMATION (EPoS): HERSCHEL AND APEX OBSERVATIONS OF THE PRECURSORS TO HIGH-MASS STAR FORMATION

Sarah Ragan, Thomas Henning, Henrik Beuther + EPoS team
Max Planck Institute for Astronomy - Heidelberg

Abstract. The question of how high-mass stars form relies fundamentally on the initial conditions. Due to the large distances to high-mass star-forming complexes and their precursors known as infrared-dark clouds (IRDCs), high-angular resolution is required to resolve individual cores. With the advent of *Herschel*, we now have access to the wavelength regime in which the cold dust comprising the clouds emits at its peak. As part of the *Herschel* guaranteed time key program "**Earliest Phases of Star Formation (EPoS)**" we obtained far-infrared maps of 45 IRDCs at all photometric bands from 70 to 500µm. Within these clouds we have isolated a population of 500 protostellar cores closely following the distribution of dense gas. Fitting spectral energy distributions (SEDs) to each core, we estimate their average properties. The cores are very cold (20K) and have a range of four orders of magnitude in mass. A counterpart at 24µm is common (67% of sample) and represents a more evolved sub-sample of cores. With follow-up, high-resolution (7.8") APEX/SABOCA observations at 350µm, we better constrain the Rayleigh-Jeans tail of the blackbody SED and also isolate colder and younger sources with no 70 micron *Herschel* component, indicating that they are pre-stellar/starless core candidates. These cold cores have masses up to 120 M⊙, bolometric luminosities below 50 L⊙, and bolometric temperatures below 30K. These datasets together provide the evolutionary sequence from starless to protostellar on small spatial scales. With a full census of the earliest phases of star formation in IRDCs, we connect the mode of star formation back to the large-scale cloud properties to determine the requirements for the most massive stars and clusters to form.

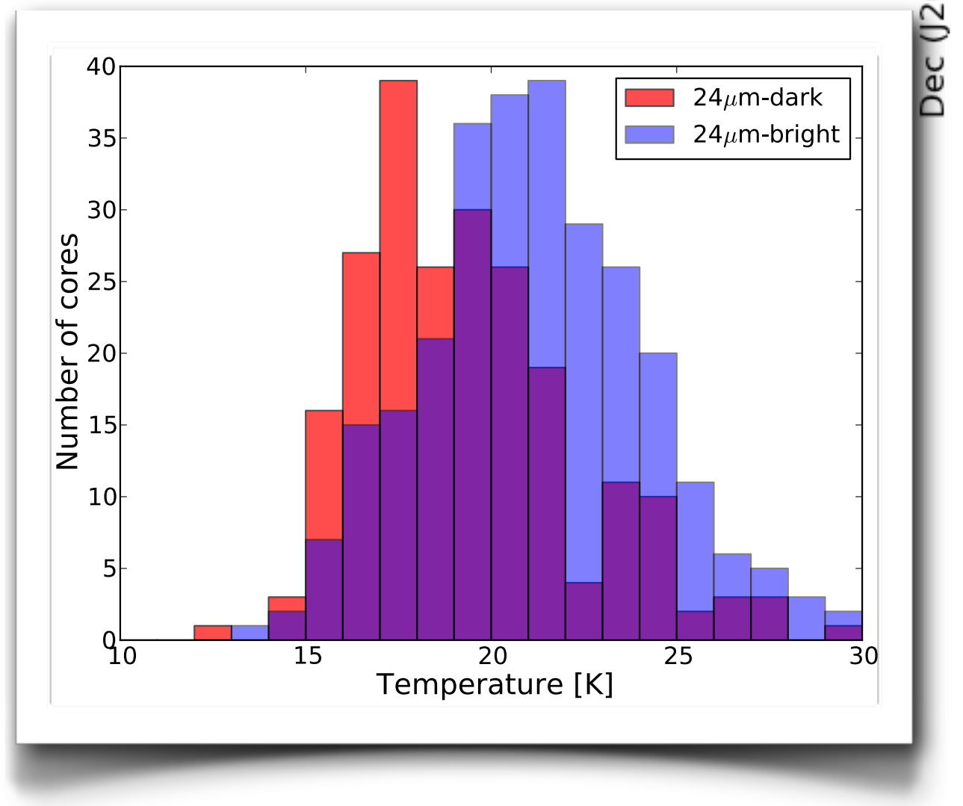
The Early Phases of Star Formation (EPoS)

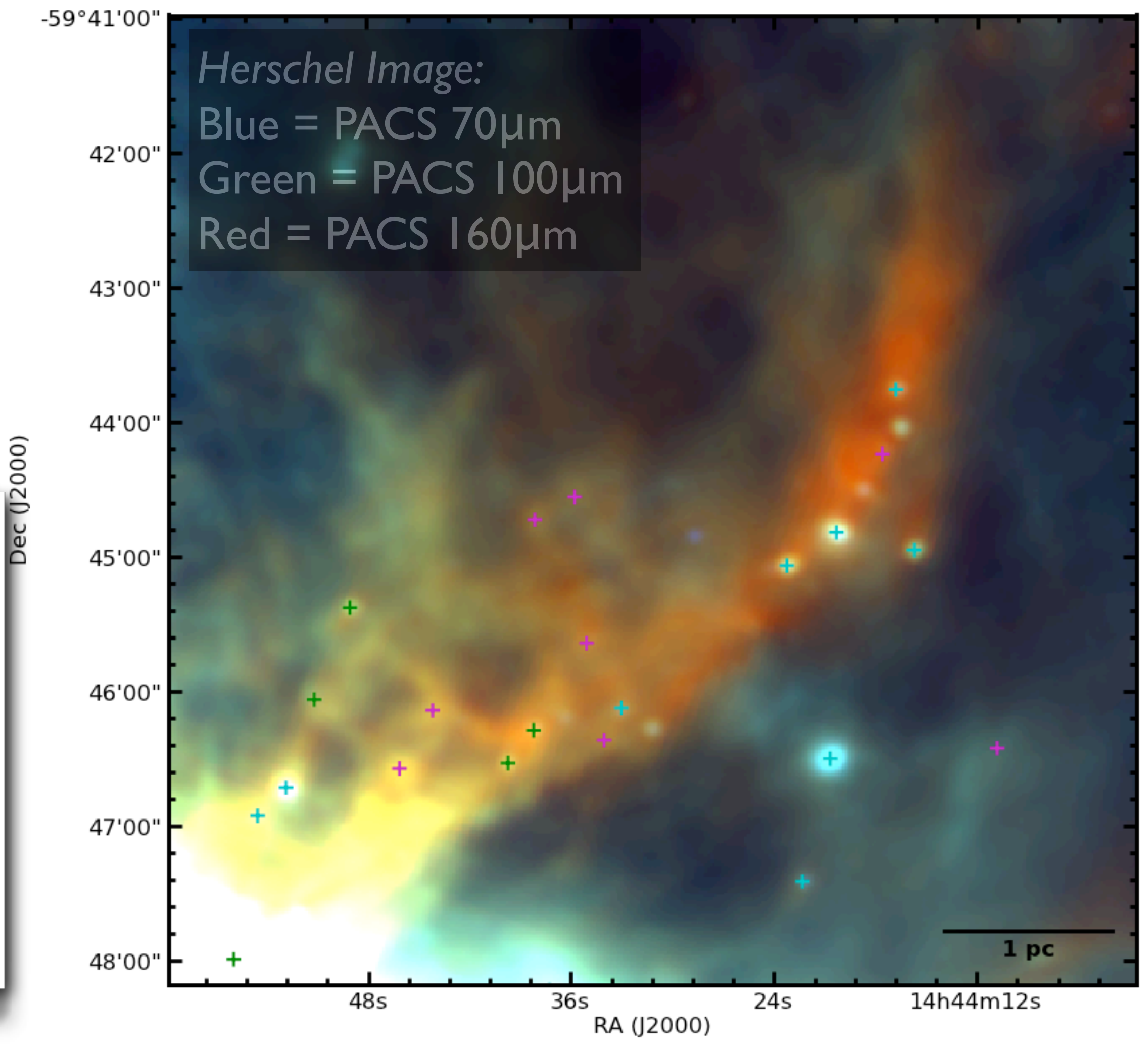
A Herschel guaranteed time key program

We survey **45** cold, massive molecular clouds with PACS at 70, 100, and 160µm and SPIRE at 250, 350, and 500µm. Figure 1 shows a three-color composite of one example filamentary IRDC. With these data, we probe the embedded core population at high angular resolution. We have detected ~500 embedded cores throughout our sample. We fit modified Planck functions to their SEDs, and derive their temperatures, luminosities, and masses. Figure 2 shows the distributions. We find the core luminosities and masses span 5 orders of magnitude, and the mean core temperature is 20K, independent of distance. Our radiative transfer models indicate that 24µm emission arises from warm dust near a central protostar, which heats the outer core probed by PACS.

Figure 1: Three color composite of IRDC G316.72+0.07. Green markers show locations of 24µm-bright protostellar cores. Blue markers are 24µm-dark cores. Magenta markers are 70µm-dark candidate cores.

Figure 2: Dust temperature from blackbody fits of the 24µm-bright (blue) and 24µm-dark (red) cores.





We fit the PACS 70, 100, and 160µm SED with a modified Planck function. The spatial resolution of *Herschel* at these wavelengths allows us to probe at "core" scales (r ~ 0.05 - 0.3pc) at PACS wavelengths at the distances to IRDCs. About 67% of the cores detected in the whole EPoS sample coincide with a 24µm counterpart. These cores are warmer on average than their 24µm-dark brethren. We conclude that cores detected at 24µm are protostellar in nature, such that an outflow cavity unmasks the MIR radiation. The 24µm-dark cores can also be protostellar (but with our line of sight along an optically thick region) or prestellar with intense external heating. 70µm-dark cores are superb targets for prestellar cores.

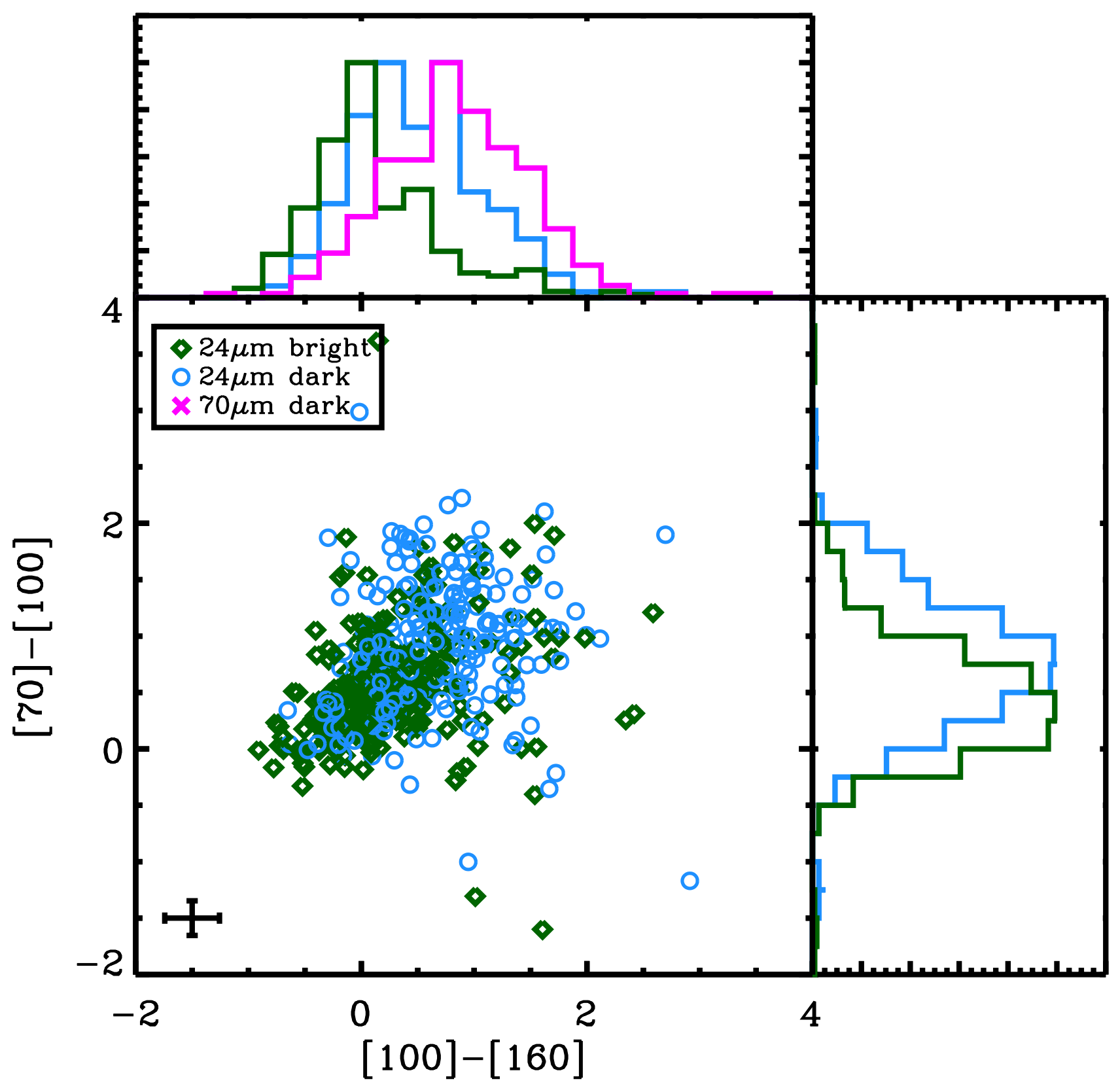


Figure 3: With the 70, 100, and 160µm fluxes, we construct a PACS color-color plot. Large numbers on color axes correspond to "redder" objects. Physically, "red" objects are associated with colder, younger objects. Our work confirms that these point sources are consistent with internally heated cores of protostellar nature. In the case of 70µm-dark cores (magenta histogram), these are consistent with younger sources which have minimal/no contribution from internal heating, making them excellent candidates for massive prestellar cores.

Ragan et al. (2012)
A&A, 547, 49

Questions? Find me! Email me: ragan@mpia.de

SABOCA 350µm observations with 7.8'' resolution

The **A**tacama **P**athfinder **Ex**periment (APEX) is equipped with SABOCA, a 39-channel bolometer array operating at 350µm. The 12-meter collecting area of APEX makes it well-suited to observe the cold dust in IRDCs at a superior spatial resolution (7.8'') compared to the SPIRE resolution at the same wavelength (24.9''). We employ the `dendrogram` (Rosolowky et al. 2008) tool to decompose the maps. For our purposes, we focus on just the "leaf" structures, or the highest contour feature above a local background or envelope structure.

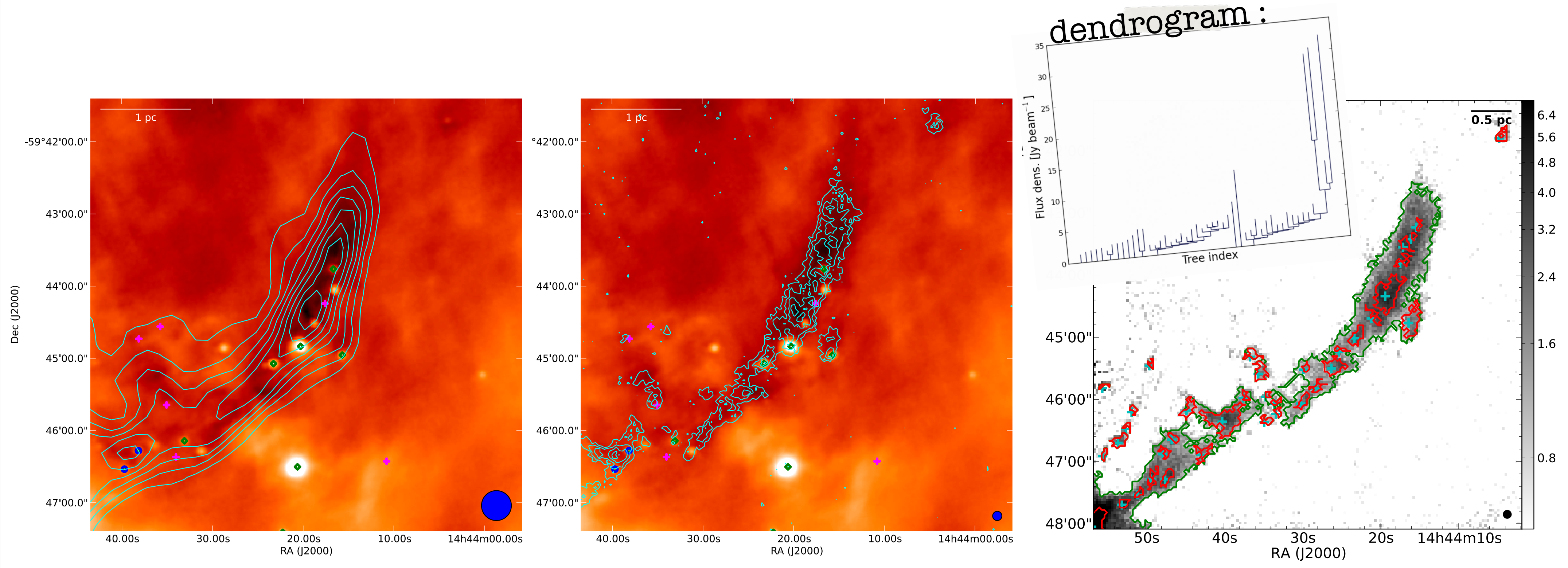


Figure 4: IRDC G316.72+0.07 PACS 70µm (image) overlaid with 350µm contours of SPIRE (left) and SABOCA (centre). The right panel shows the dendrogram decomposition of this IRDC, where green outlines the base "trunk" and red are the "leaf" structures (see inset tree structure diagram). The crosses mark all leaf positions. The respective beams are shown in the lower-right corners of the images.

Further constraining core populations with SABOCA

With information at similar spatial scales to PACS now at 350µm, we will have a more stringent constraint on the Rayleigh-Jeans tail of the core SEDs. We refit the SEDs of the recovered cores (see left side of the poster) with the SABOCA data included and find consistent results. We are also now be sensitive to colder cores, ones that were not detectable even at 70 or 100µm because their SEDs peak at longer wavelengths. These new cores are of particular interest because they represent an earlier evolutionary phase. They are plotted in magenta in Figure 5.

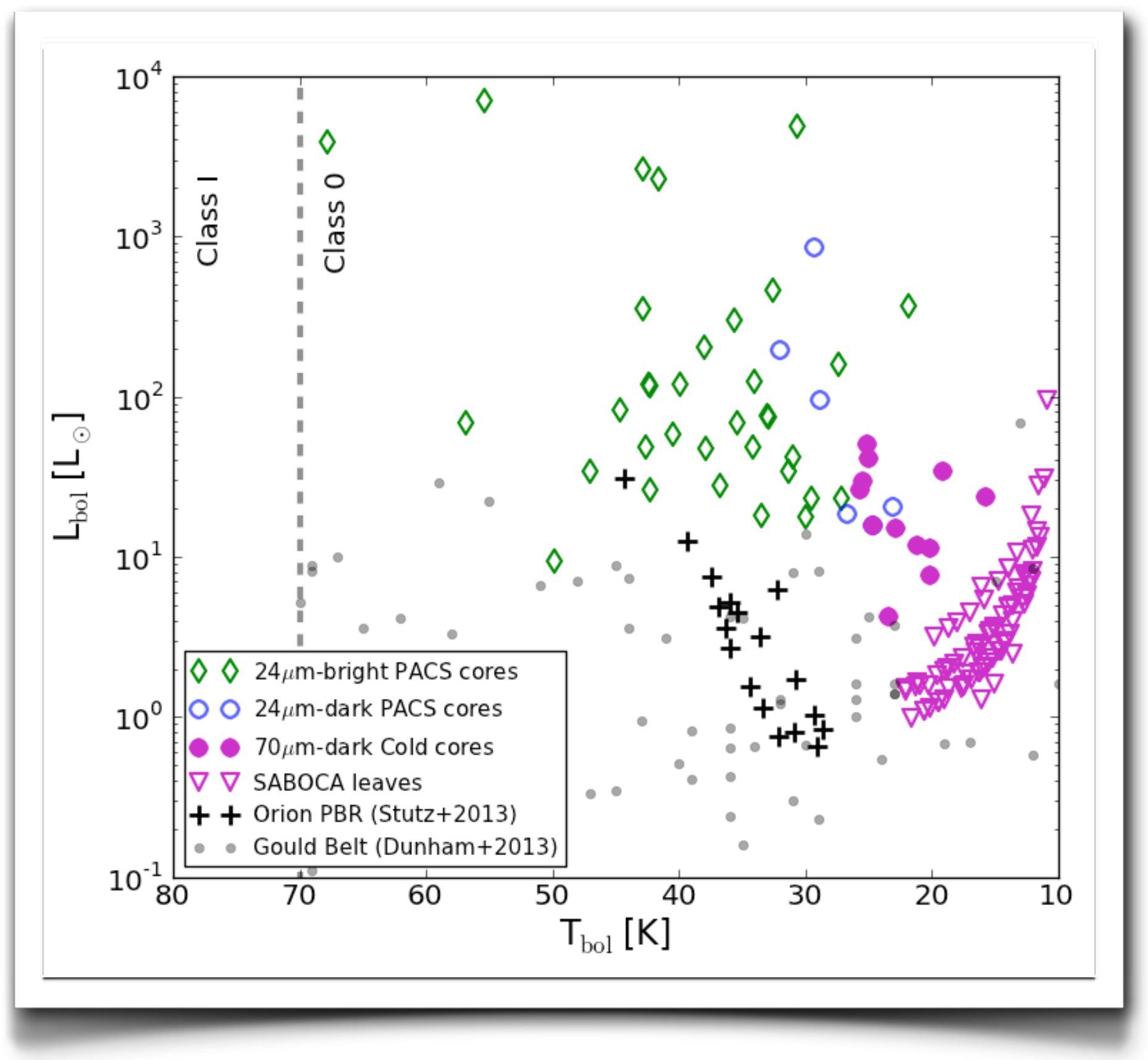


Figure 5: Bolometric luminosity versus the bolometric temperature of all cores recovered by SABOCA. The Class 0/I division in T_{bol} for low-mass cores is shown. The magenta triangles are upper limits in both L_{bol} and T_{bol}. The new population of PACS bright red sources in Orion (PBRs; Stutz et al. 2013) and a compilation of cores in Gould Belt clouds (Dunham et al. 2013) are shown for reference. IRDC cores exhibit a similar range in temperatures but higher luminosities.

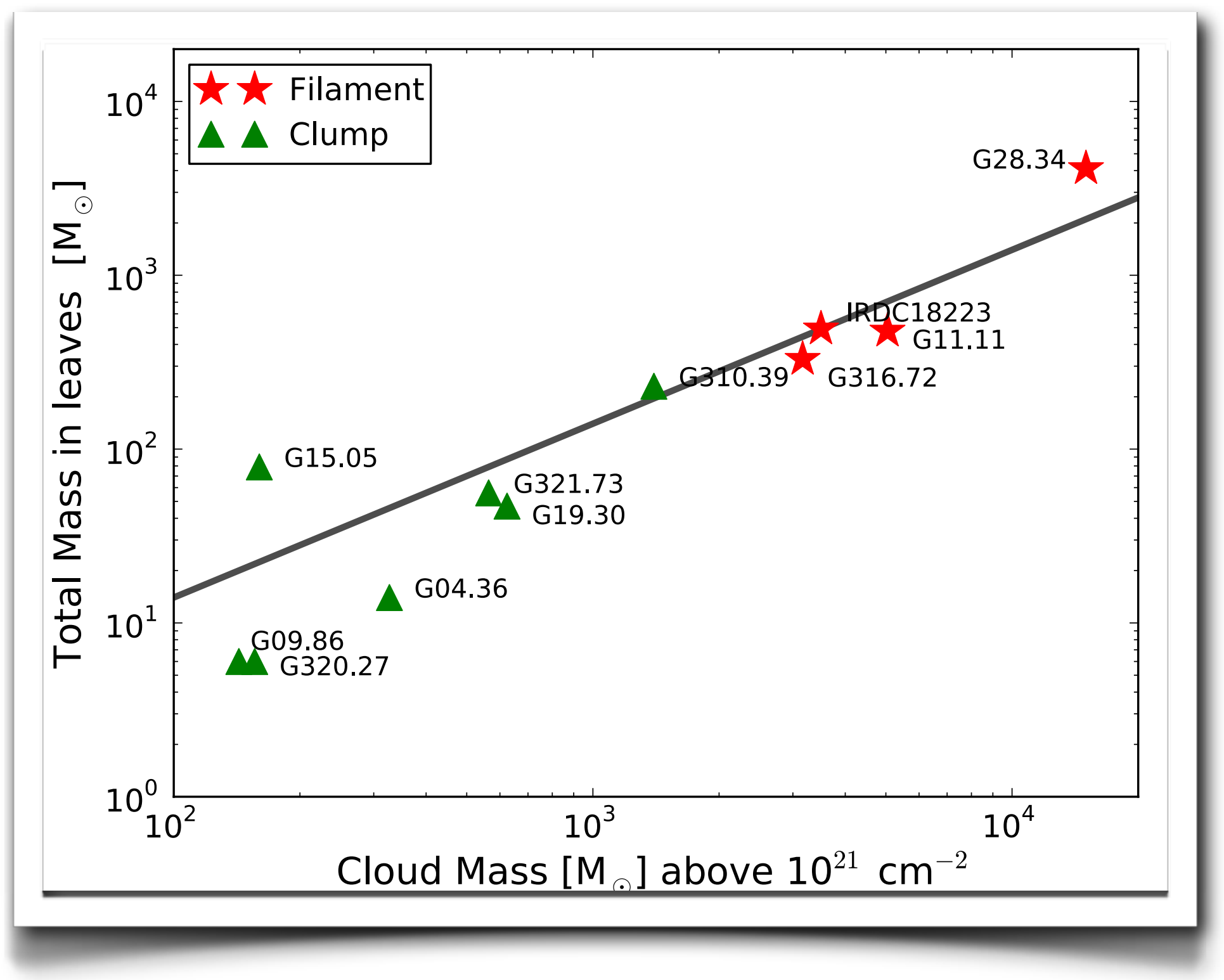


Figure 6: The total mass in dendrogram "leaf" structures as a function of total cloud mass. Filamentary clouds are plotted with red stars, and clumpy IRDCs are shown in green triangles. The mean "efficiency" of core formation is 14%.

Our SABOCA sample of 11 objects consists of a mix of clumpy to filamentary clouds. Regardless of morphology, the fraction of mass in core structures is between 10 and 20%.
Filamentary IRDCs are not only the most massive objects in our sample but are also more complex in their hierarchical structure.

Ragan et al. (2013)