Earliest **P**hases **o**f **S**tar Formation

Resolving the seeds of star formation with Herschel

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(MPIA)

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The Earliest Phases of Star Formation (EPoS): A Herschel Key Program - The precursors to high-mass stars and clusters

Sarah Ragan, Thomas Henning, Oliver Krause, Jan Pitann, Henrik Beuther, Hendrik Linz, Jochen Tackenberg, Zoltan Balog, Martin Hennemann, Ralf Launhardt, Nils Lippok, Markus Nielbock, Anika Schmiedeke, Frederic Schuller, Juergen Steinacker, Amelia Stutz, Tatiana Vasyunina

(Submitted on 27 Jul 2012)

(Abridged) We present an overview of the sample of high-mass star and cluster forming regions observed as part of the Earliest Phases of Star Formation (EPoS) Herschel Guaranteed Time Key Program. A sample of 45 infrared-dark clouds (IRDCs) were mapped at PACS 70, 100, and 160 micron and SPIRE 250, 350, and 500 micron. In this paper, we characterize a population of cores which appear in the PACS bands and place them into context with their host cloud and investigate their evolutionary stage. We construct spectral energy distributions (SEDs) of 496 cores which appear in all PACS bands, 34% of which lack counterparts at 24 micron. From single-temperature modified blackbody fits of the SEDs, we derive the temperature, luminosity, and mass of each core. These properties predominantly reflect the conditions in the cold, outer regions. Taking into account optical depth effects and performing simple radiative transfer models, we explore the origin of emission at PACS wavelengths. The core population has a median temperature of 20K and has masses and luminosities that span four to five orders of magnitude. Cores with a counterpart at 24 micron are warmer and bluer on average than cores without a 24 micron counterpart. We conclude that cores bright at 24 micron are on average more advanced in their evolution, where a central protostar(s) have heated the outer bulk of the core, than 24 micron-dark cores. The 24 micron emission itself can arise in instances where our line of sight aligns with an exposed part of the warm inner core. About 10% of the total cloud mass is found in a given cloud's core population. We uncover over 300 further candidate cores which are dark until 100 micron. These are candidate starless objects, and further observations will help us determine the nature of these very cold cores.

Comments: Accepted for publication in A&A. 81 pages, 68 figures. For full resolution image gallery (Appendix B), see this http URL
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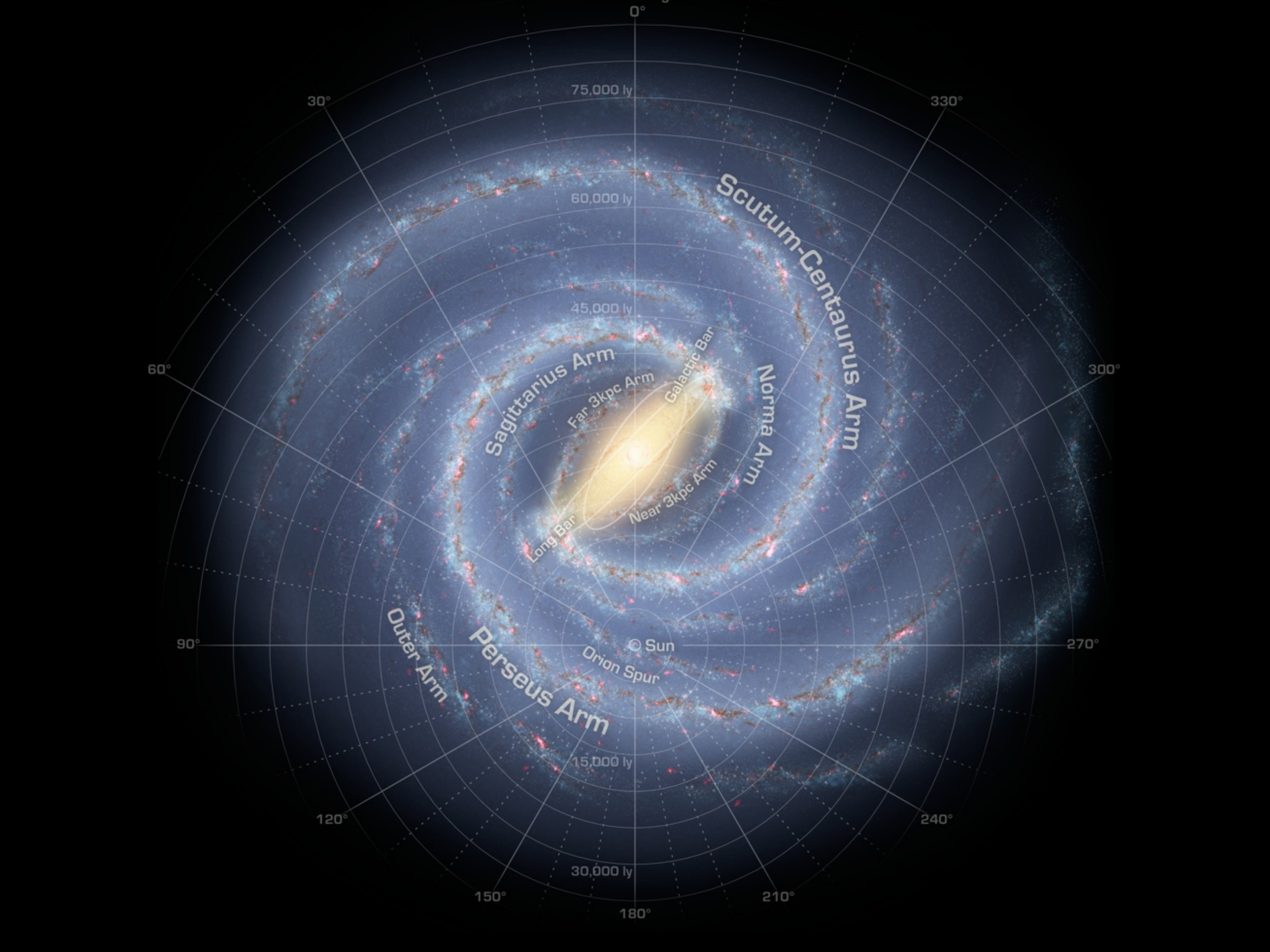
0°
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75,000 ly
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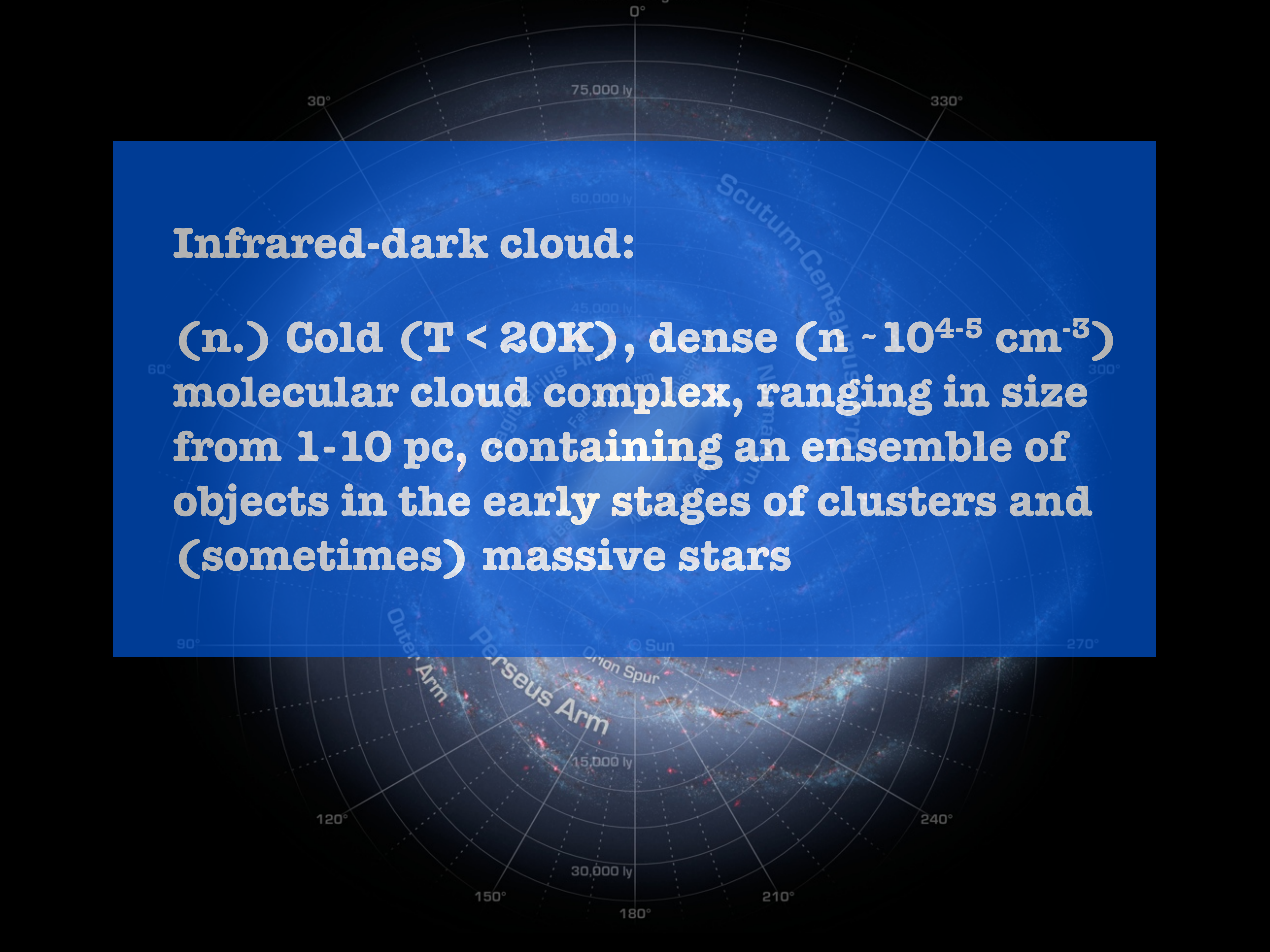
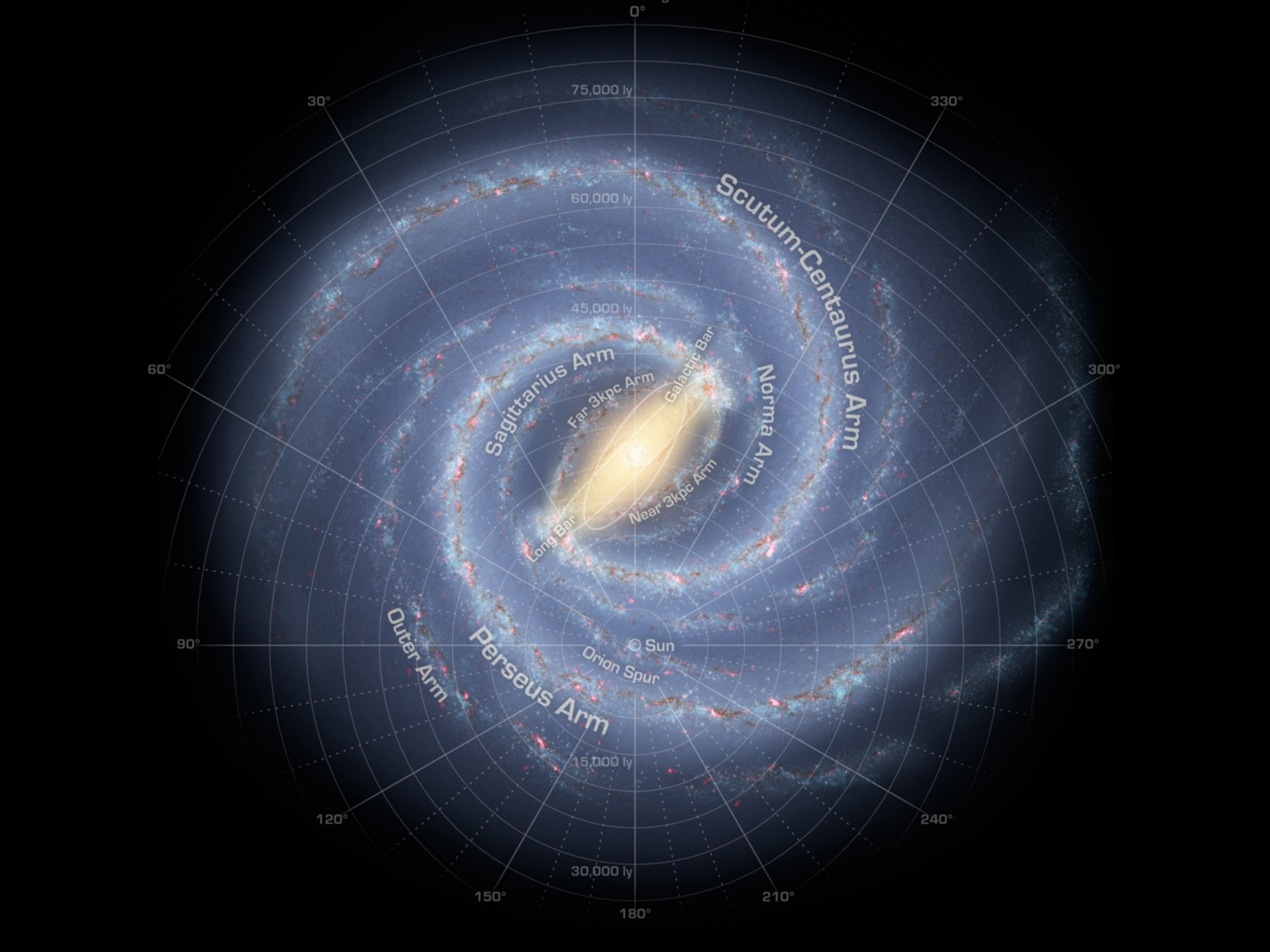
45,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Galactic Bar
Far 3kpc Arm
Norma Arm
Near 3kpc Arm
Long Bar
60°
300°
Outer Arm
Perseus Arm
Sun
Orion Spur
90°
270°
15,000 ly
120°
240°
30,000 ly
150°
210°
180°

Infrared-dark cloud:

(n.) Cold ($T < 20K$), dense ($n \sim 10^{4-5}$ cm^{-3}) molecular cloud complex, ranging in size from 1-10 pc, containing an ensemble of objects in the early stages of clusters and (sometimes) massive stars




0°
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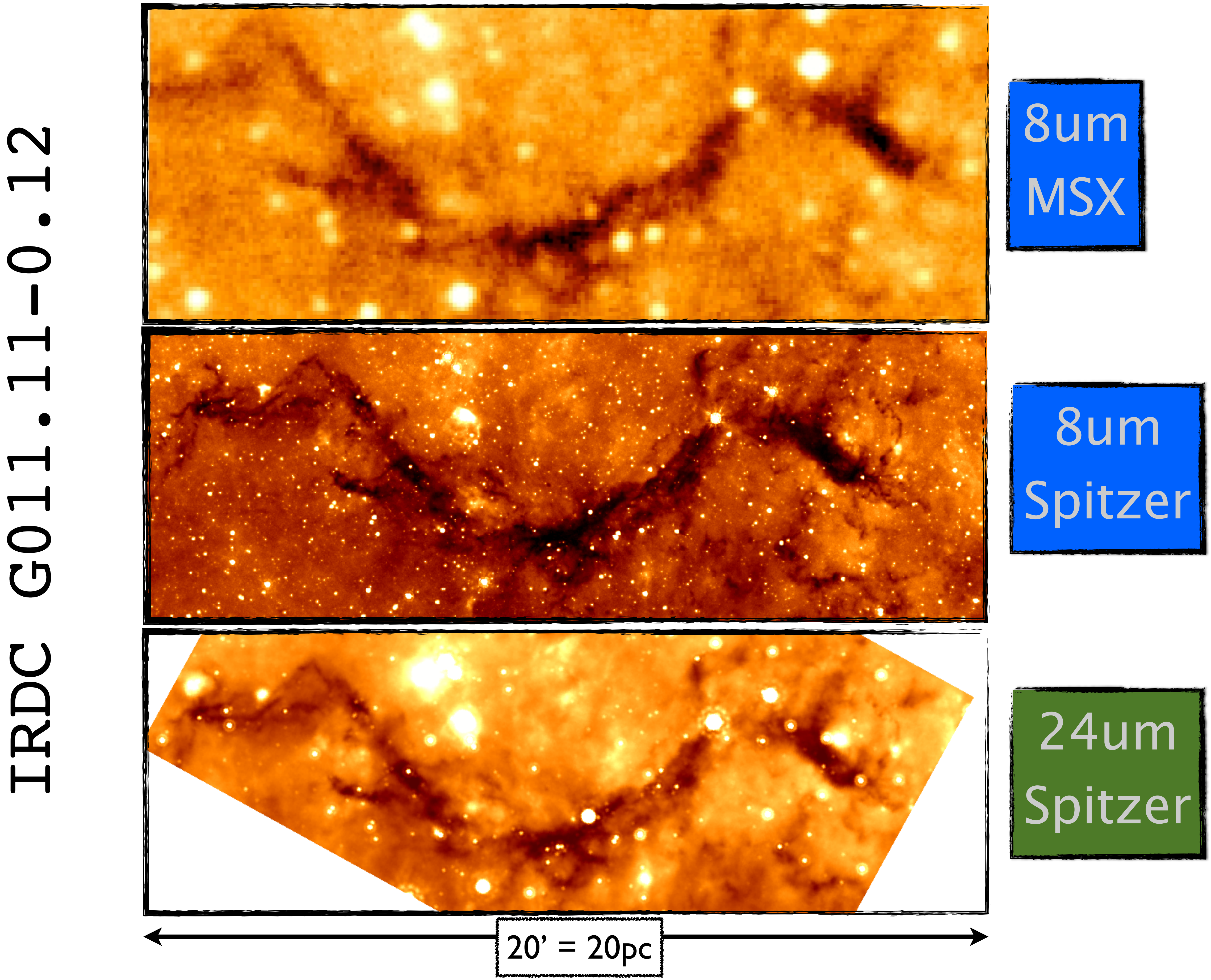
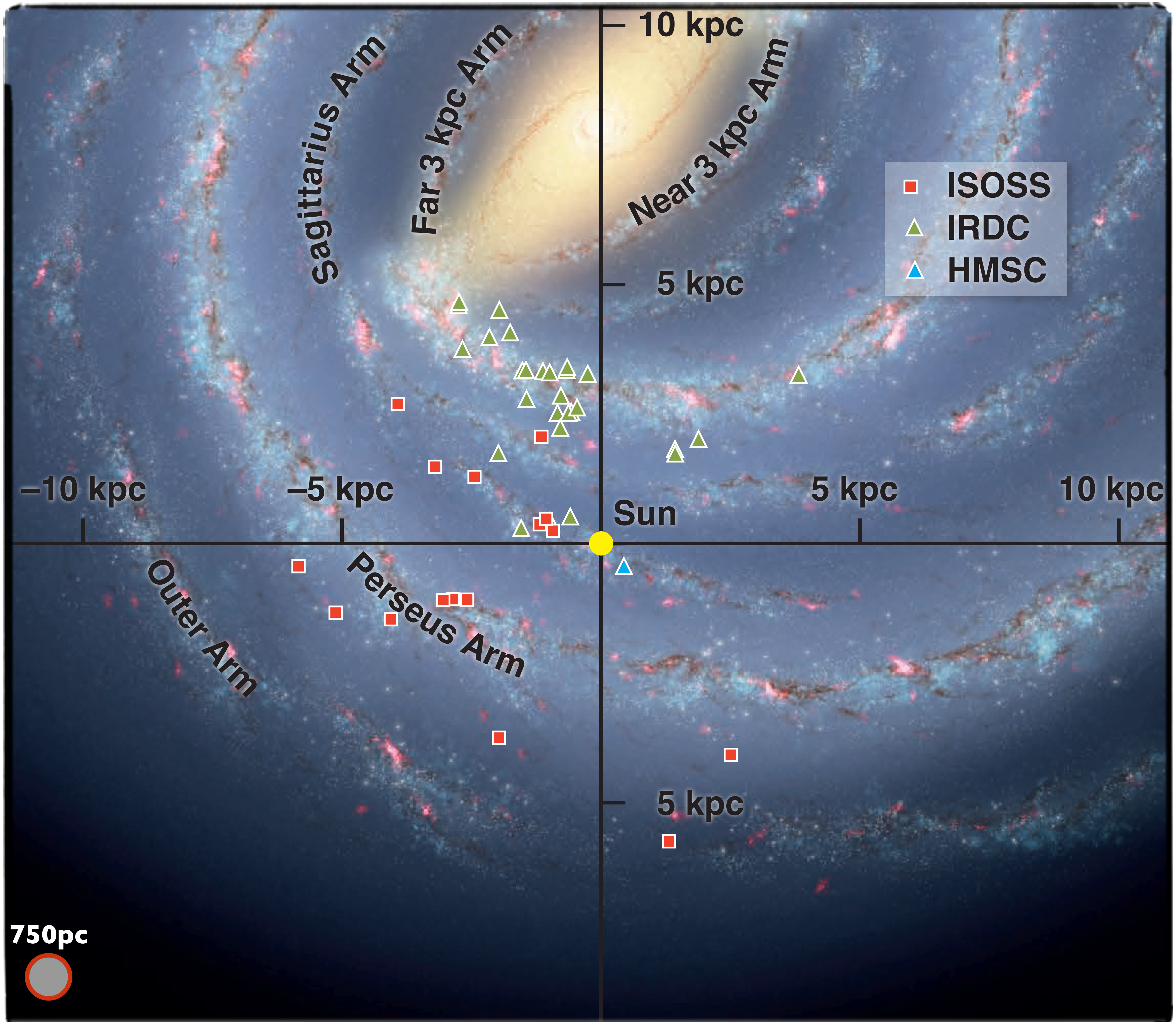
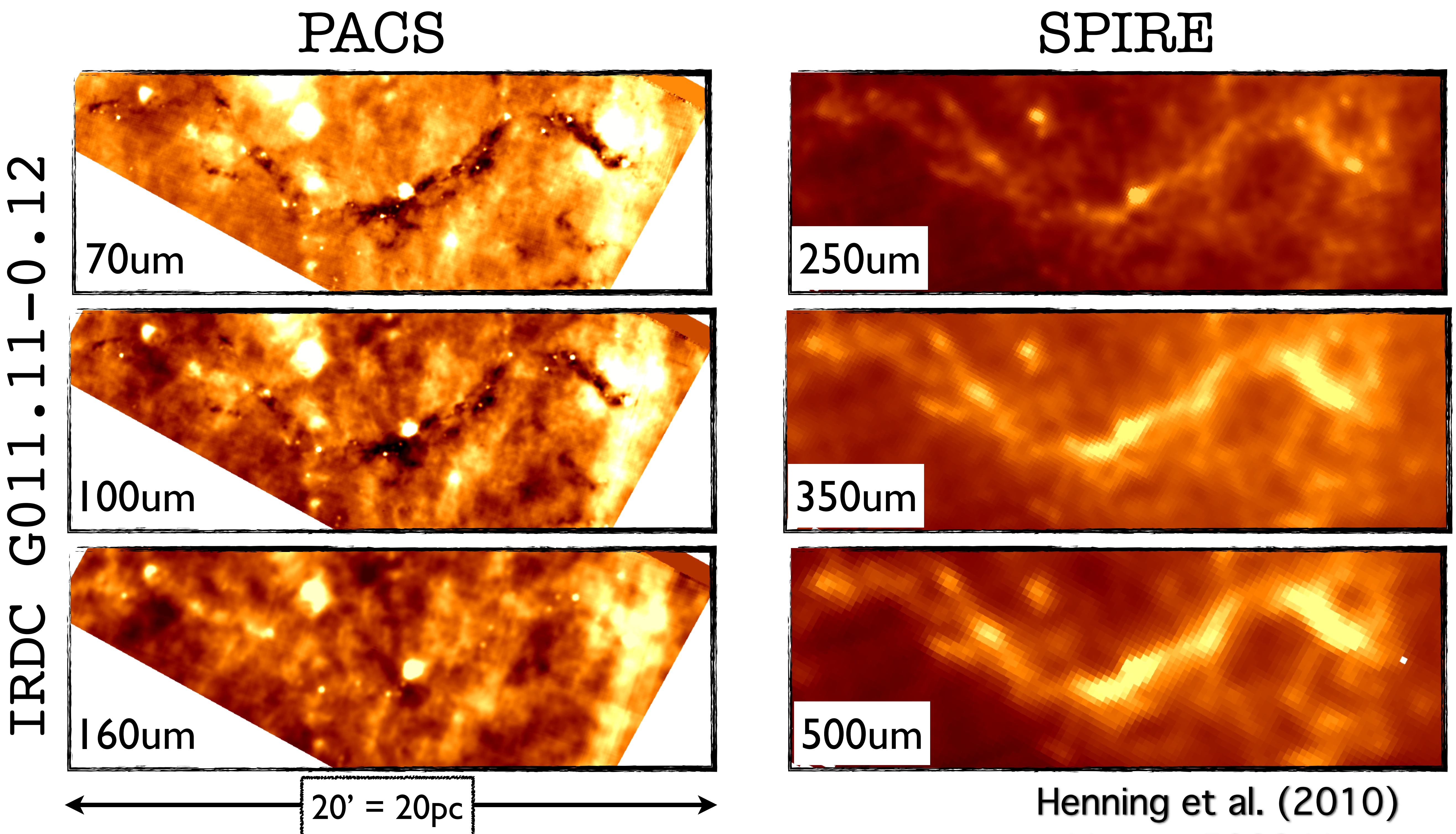
Pre-Herschel infrared view



EPoS high-mass sample



EPoS: Earliest Phases of Star formation

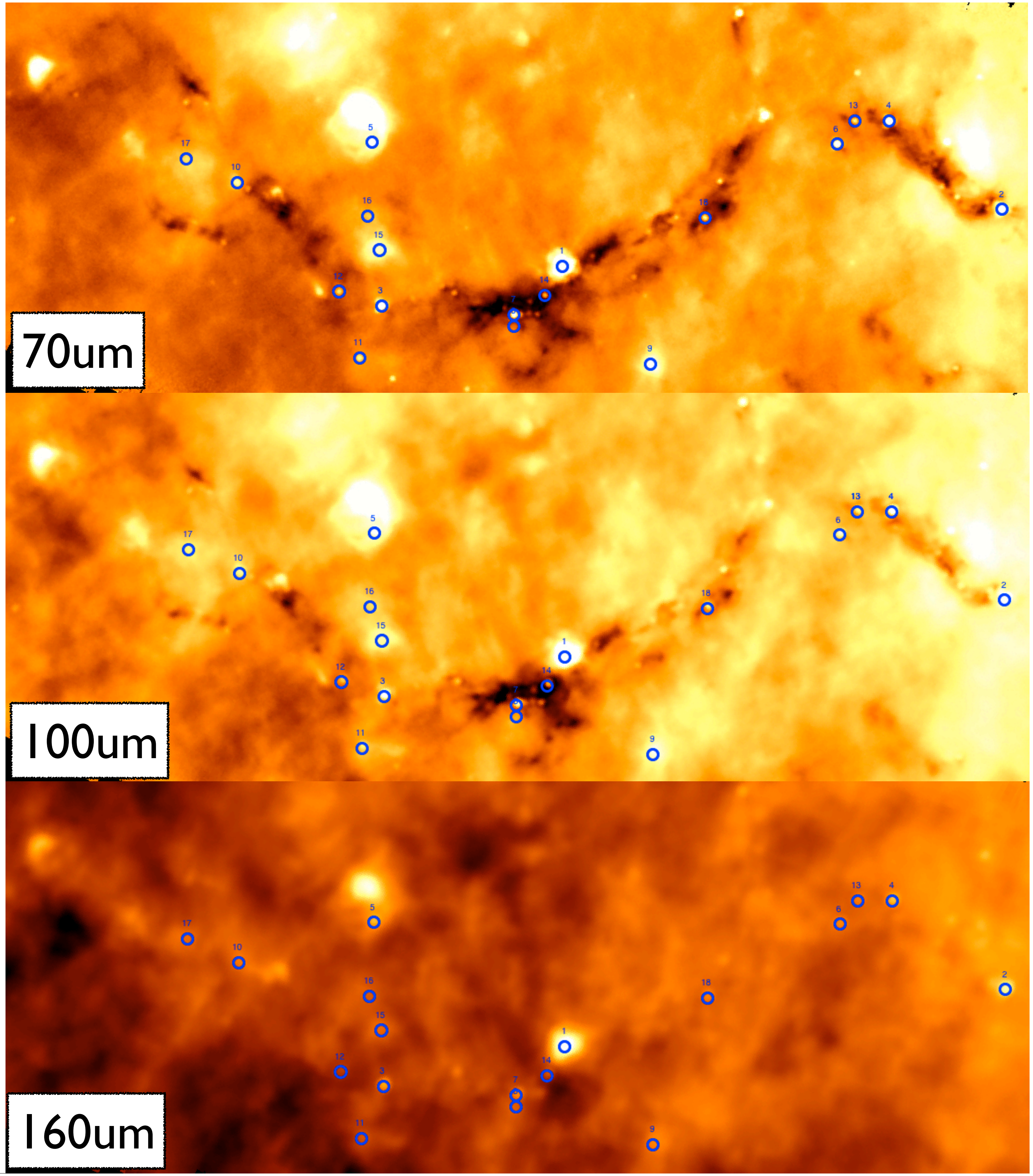


Henning et al. (2010)

M_{cloud} ~ 5000 M_{sun}

Point source extraction

IRDC G011.11-0.12

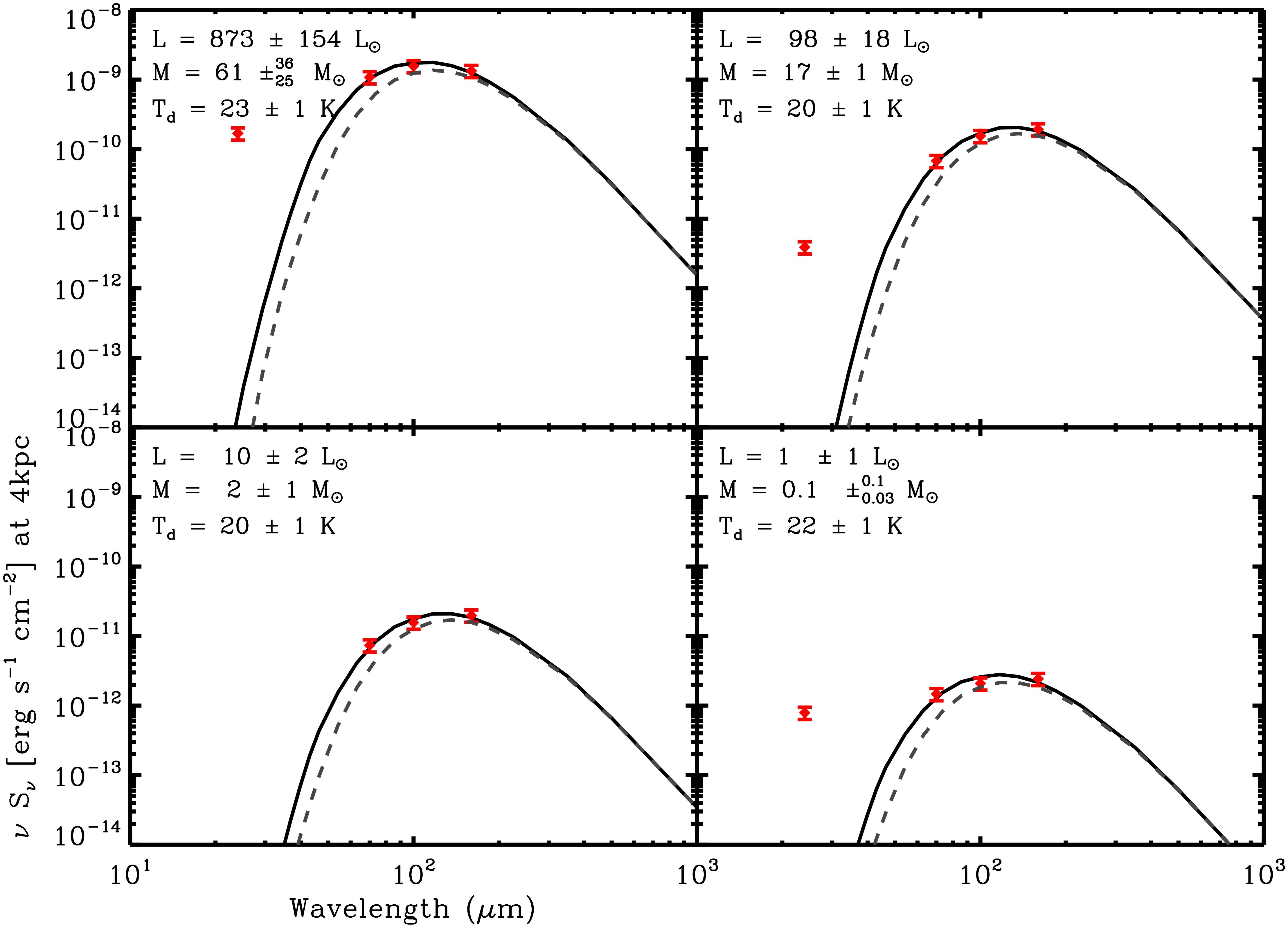


(1) Independent source extraction in each PACS band: require detection in all 3 bands
(2) Construct SEDs
(3) Fit modified blackbody function (T_{dust}, M, L)

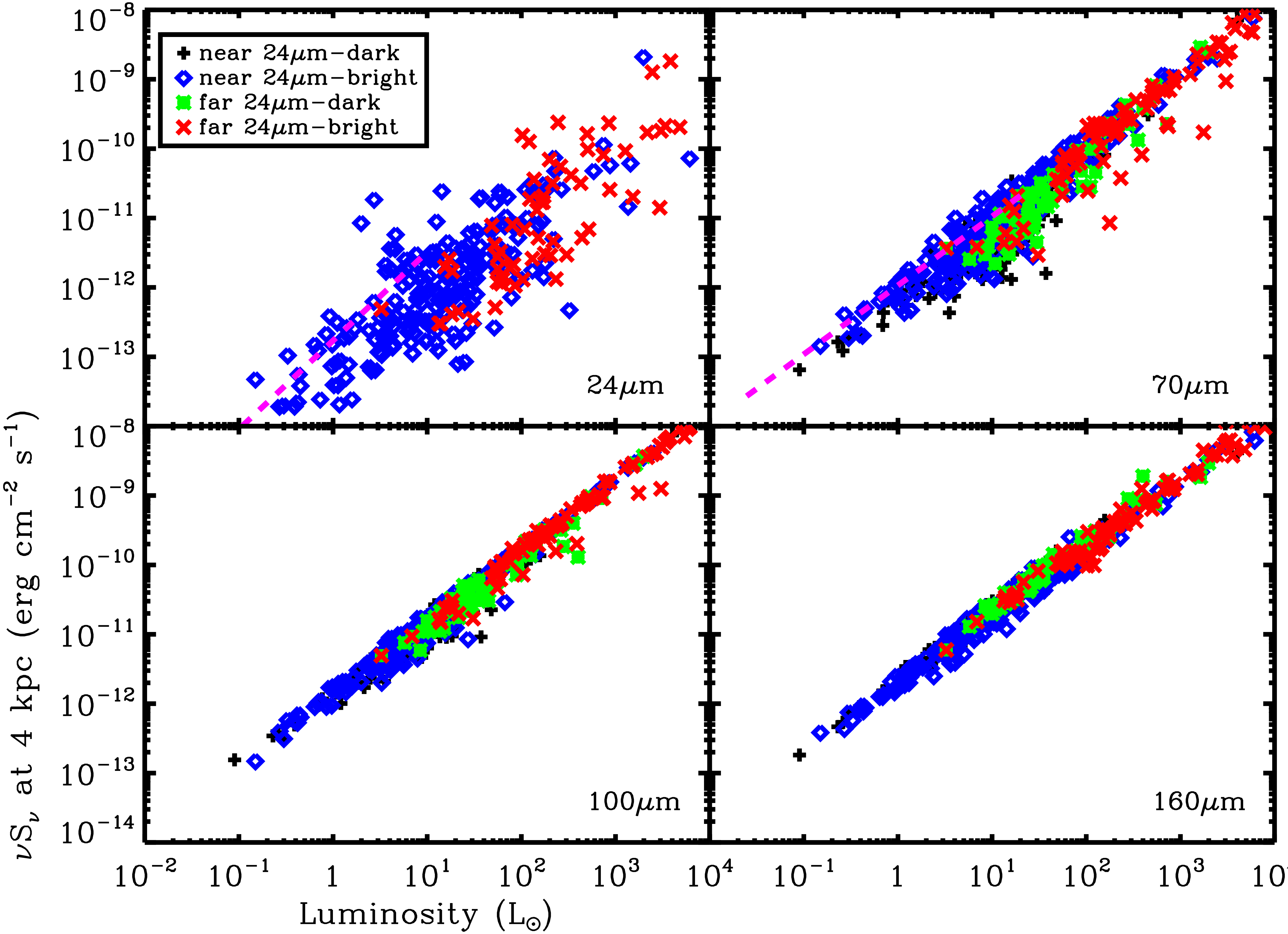
Results

★ 496 protostellar cores in full sample of 45 IRDCs
★ Size ~ 0.05 to 0.3pc
★ 65% have 24um counterparts

Typical core SEDs



What does this flux trace?



Modeling

Radiative transfer testing relative impact of protostars and external heating

Transphere-1D (Dullemond)

Black + Draine ISRF

Scenario 1

★ Internal heating source + ISRF heating

Conclusions

★ Internal heating source (protostar) dominates SED

★ ISRF only marginally influences the SED at $\lambda > 100$ µm

Scenario 2

★ No internal heating source + ISRF heating

Conclusions

★ Starless cores require external heating by an amplified ISRF (>100x) to exhibit typical PACS SED

★ External heating won't to produce 24um counterpart for a core

Modeling

Radiative transfer testing relative impact of protostars and external heating

Transphere-1D (Dullemond)

Black + Draine ISRF

Scenario 1

- ★ In
  IS
- ★ In
  (p
- ★ ISRF only marginally influences the SED at λ > 100 µm

Scenario 2

- ★ No internal heating source +
- amplified ISRF (>100x) to exhibit typical PACS SED
- ★ External heating won't to produce 24um counterpart for a core

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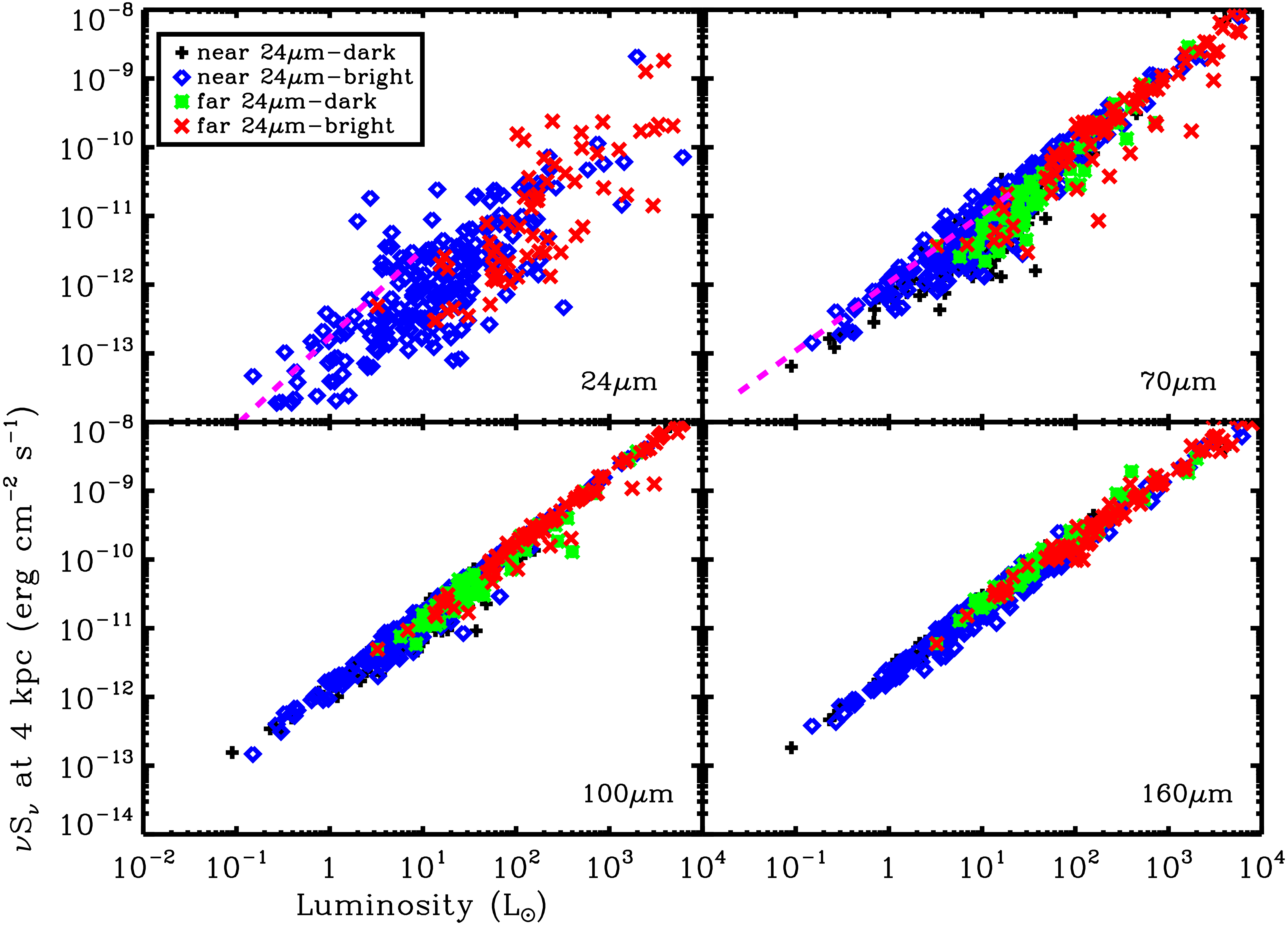
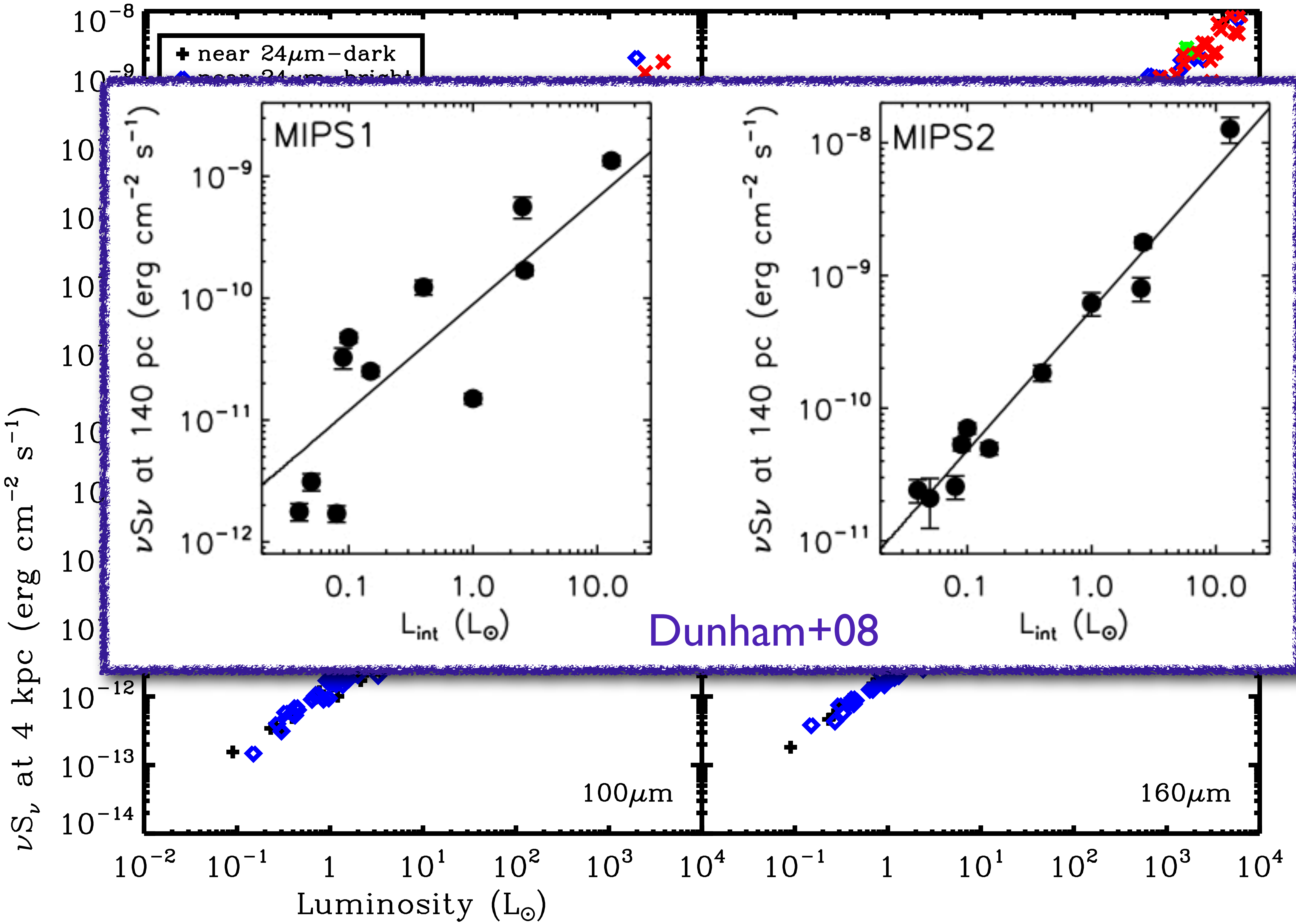
- ⋆ 24 µm detection requires presence of protostar
- ⋆ Presence/absence of 24 µm counterpart strongly depends on geometry
- ⋆ 70 µm detection can either be due to internal heating from a protostar or amplified external heating by ISRF (see Jørgensen+06, Nutter+09)

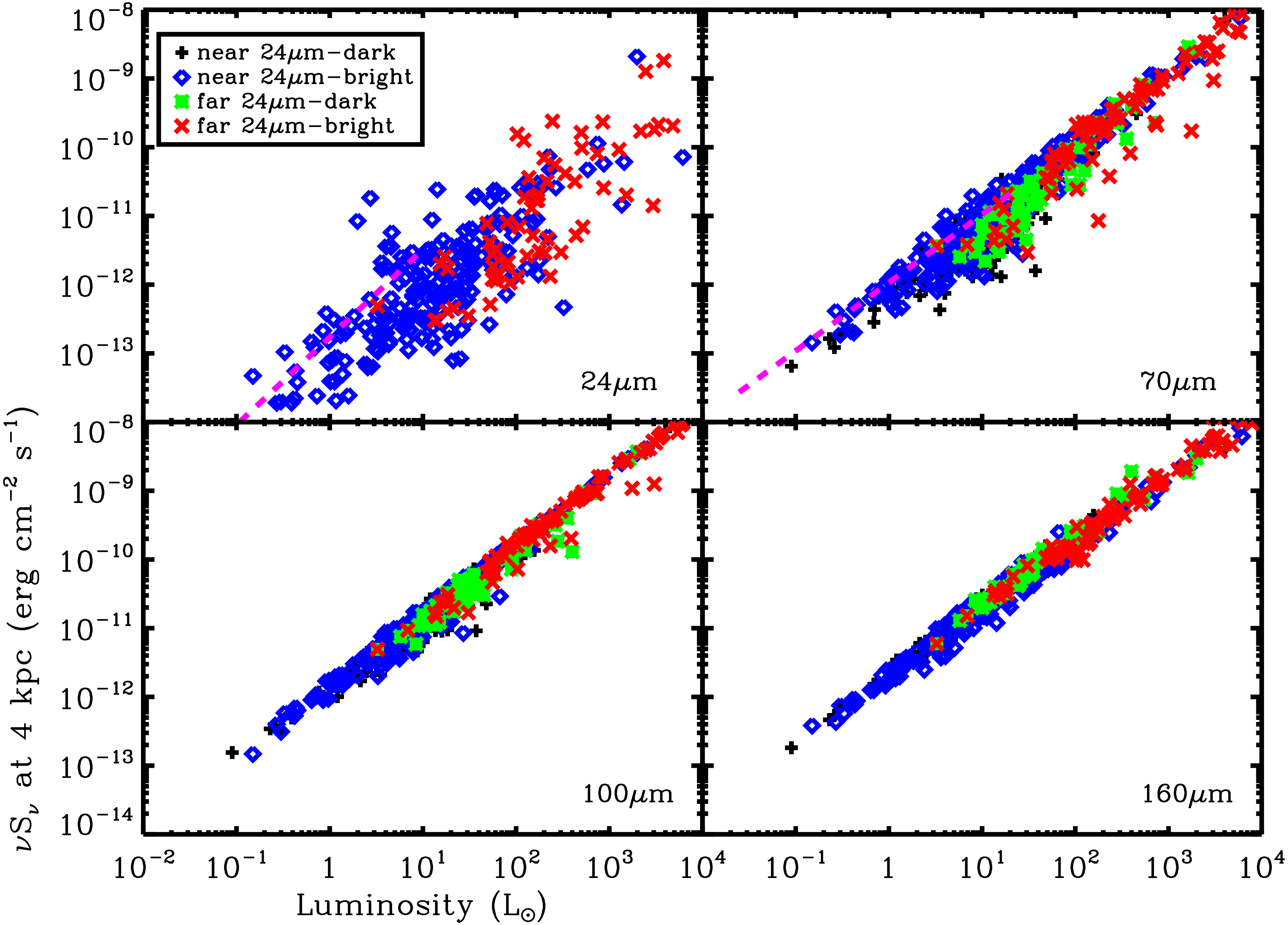
What does this flux trace?



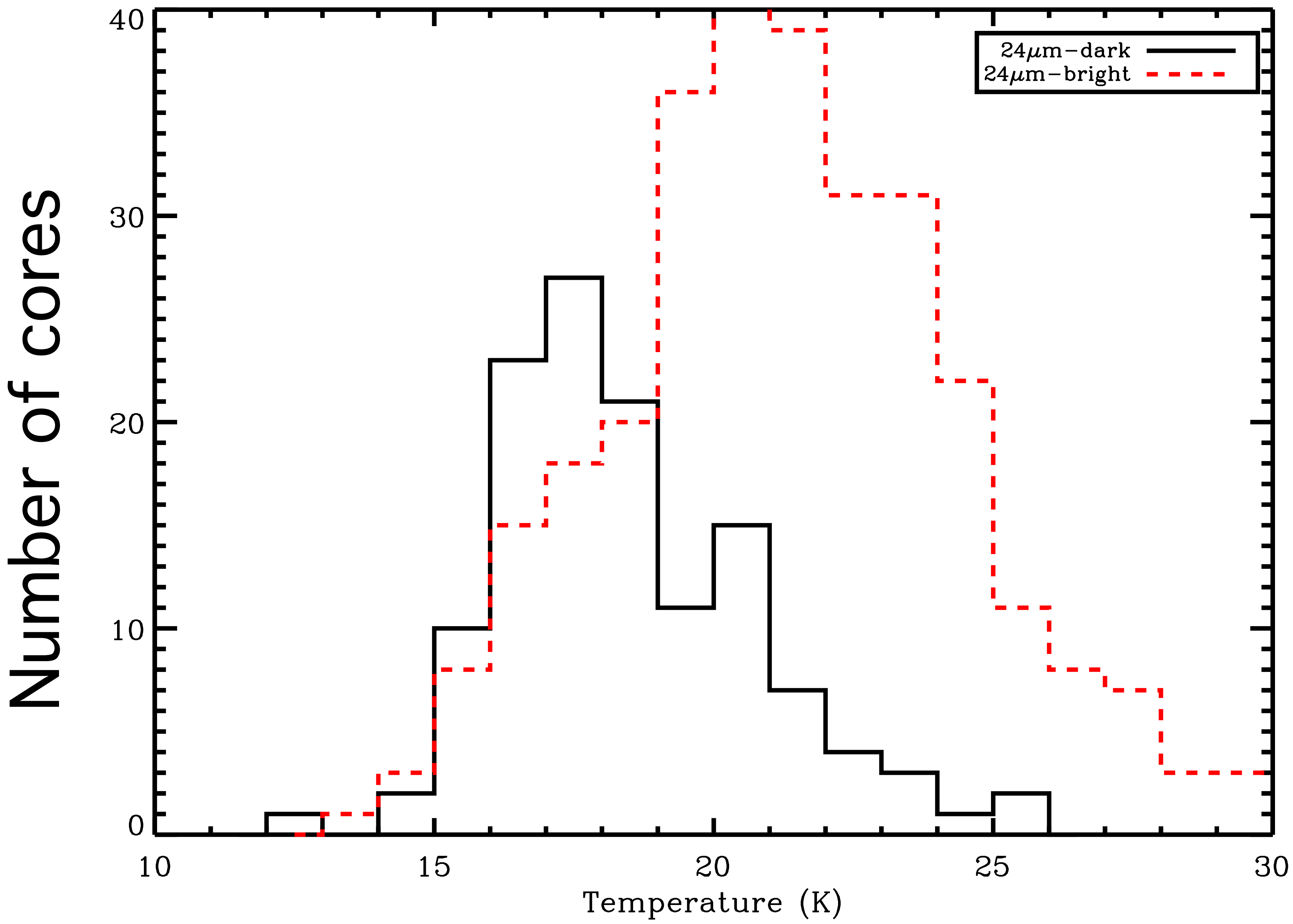
What does this flux trace?



What does this flux trace?

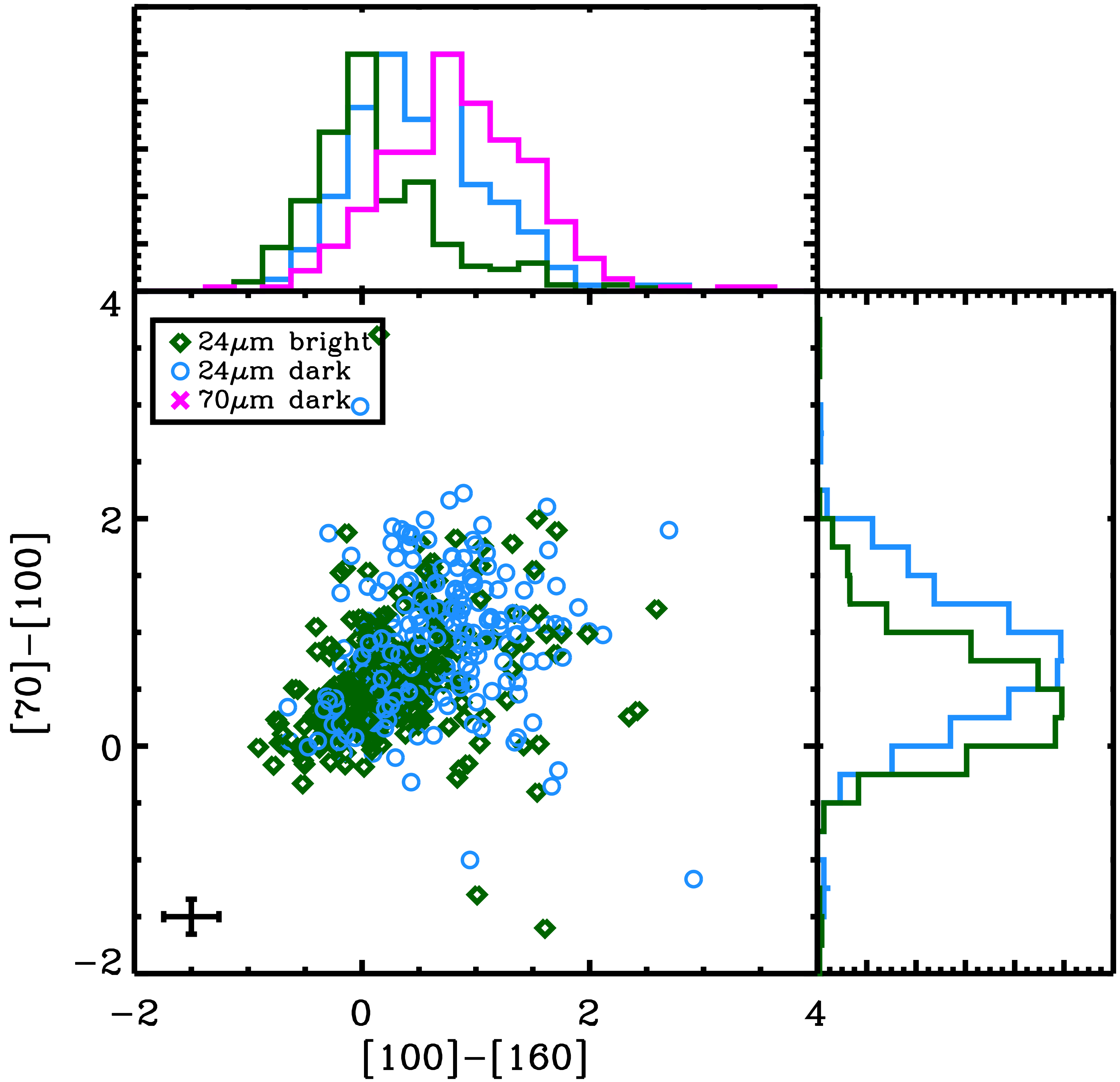


Core temperature distributions



PACS color-color diagram

Color as a proxy of core dust temperature



PACS color-color diagram

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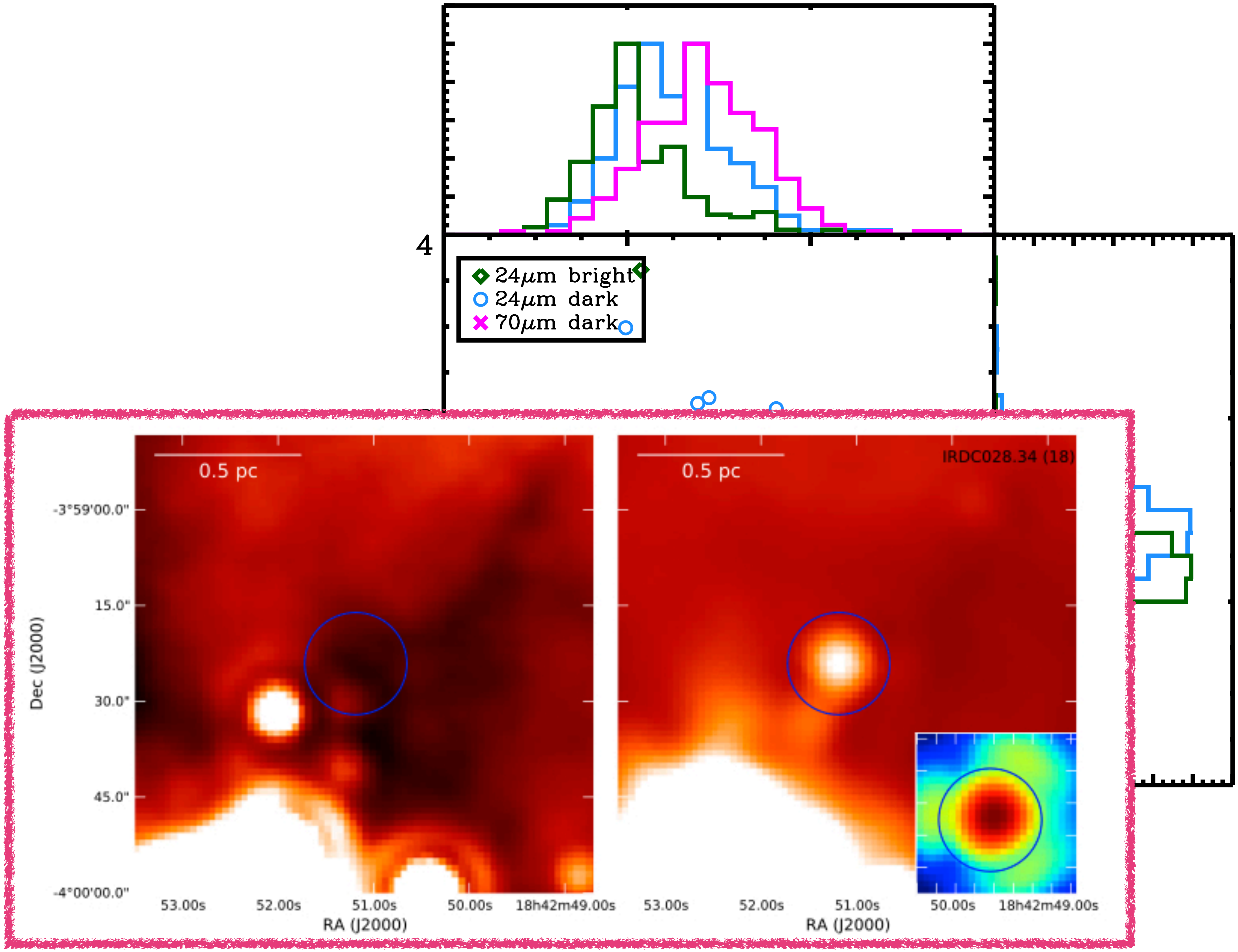

PACS color-color diagram

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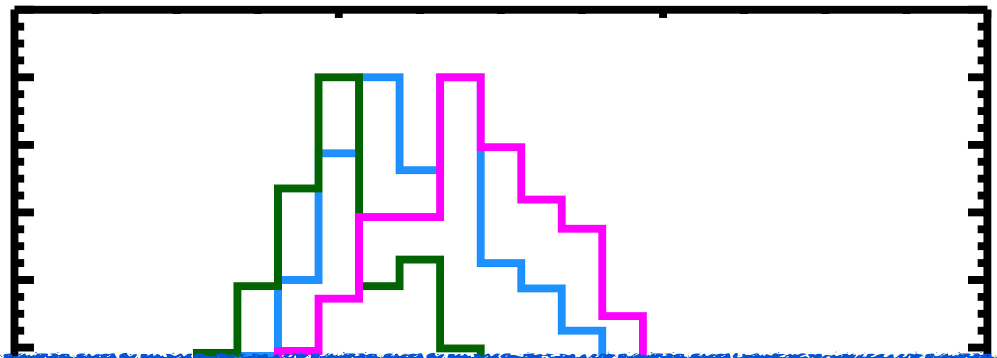
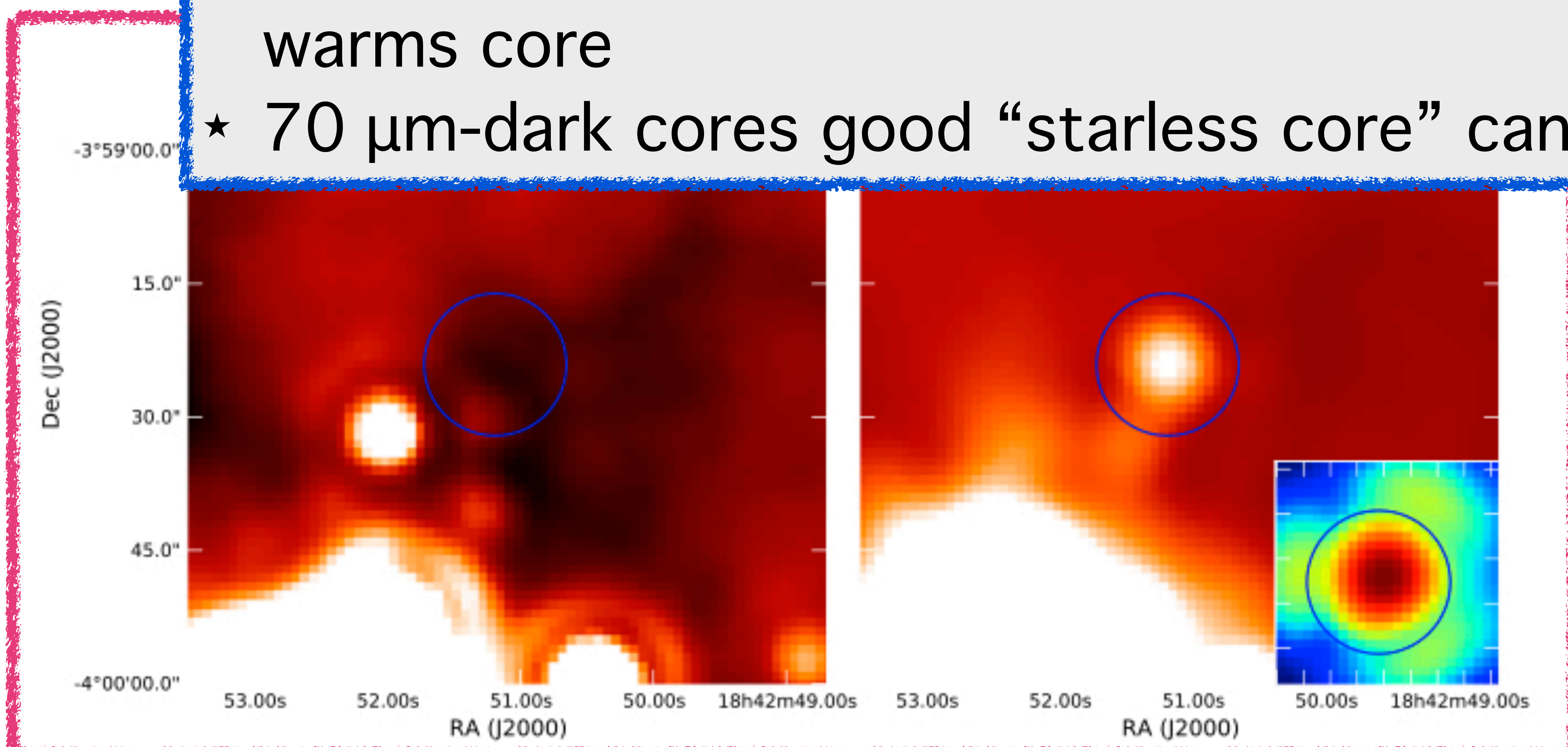
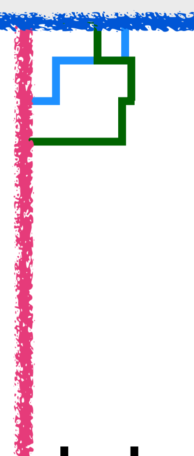
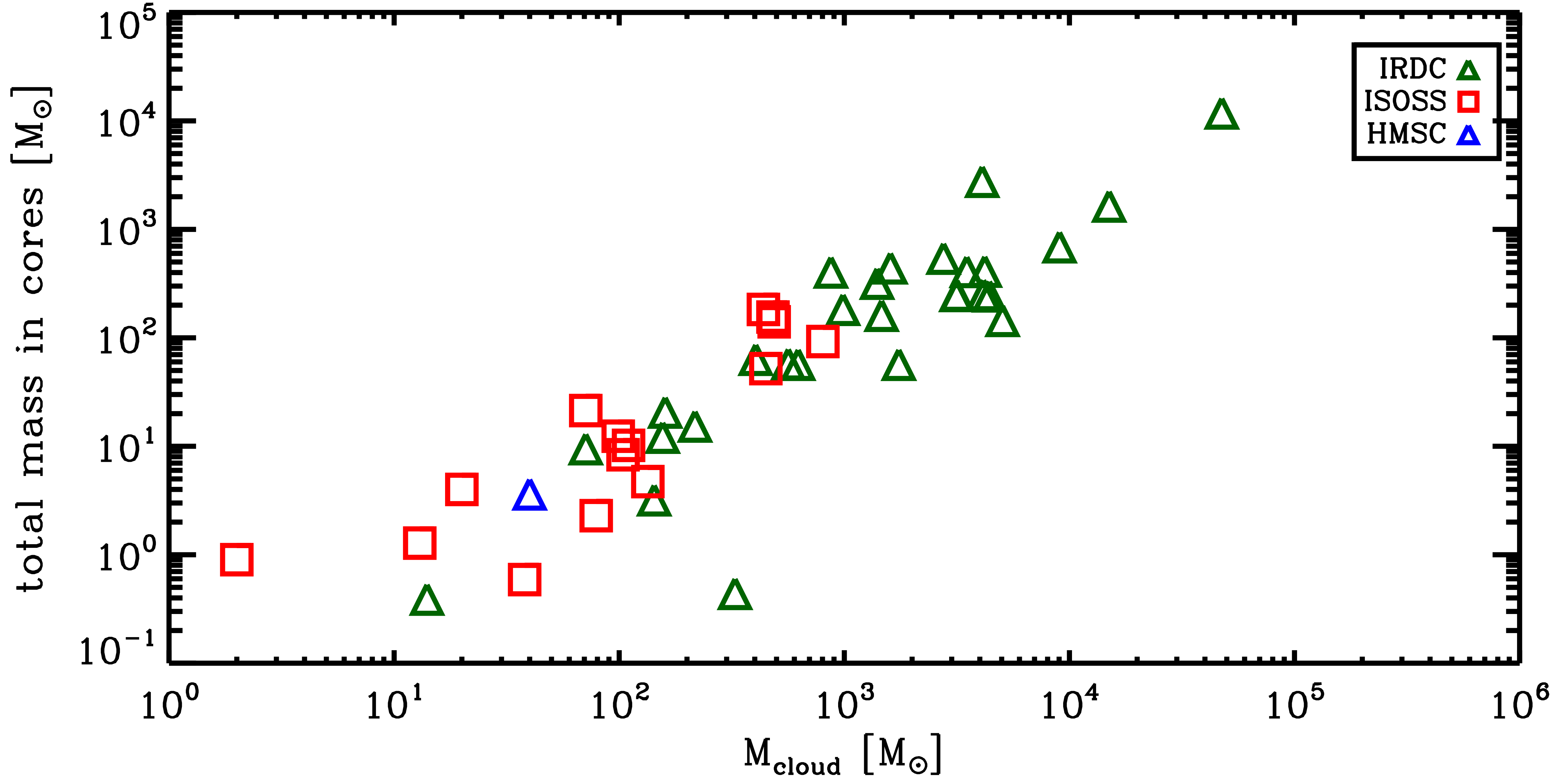


- ⋆ PACS SED gives the conditions in cold outer parts of the core
- ⋆ 24 μm counterpart is definite signpost of protostar, warms core
- ⋆ 70 μm-dark cores good “starless core” candidates

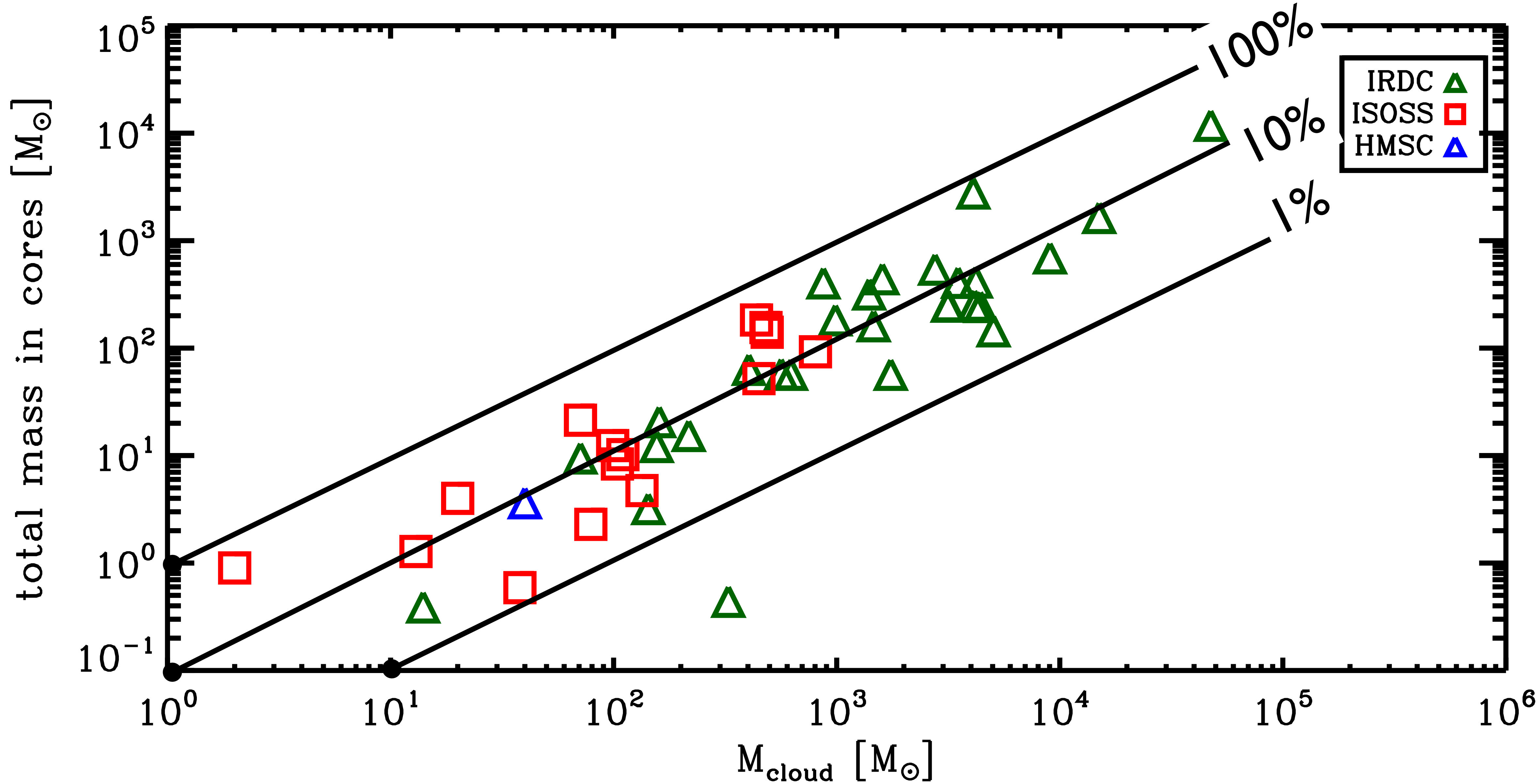




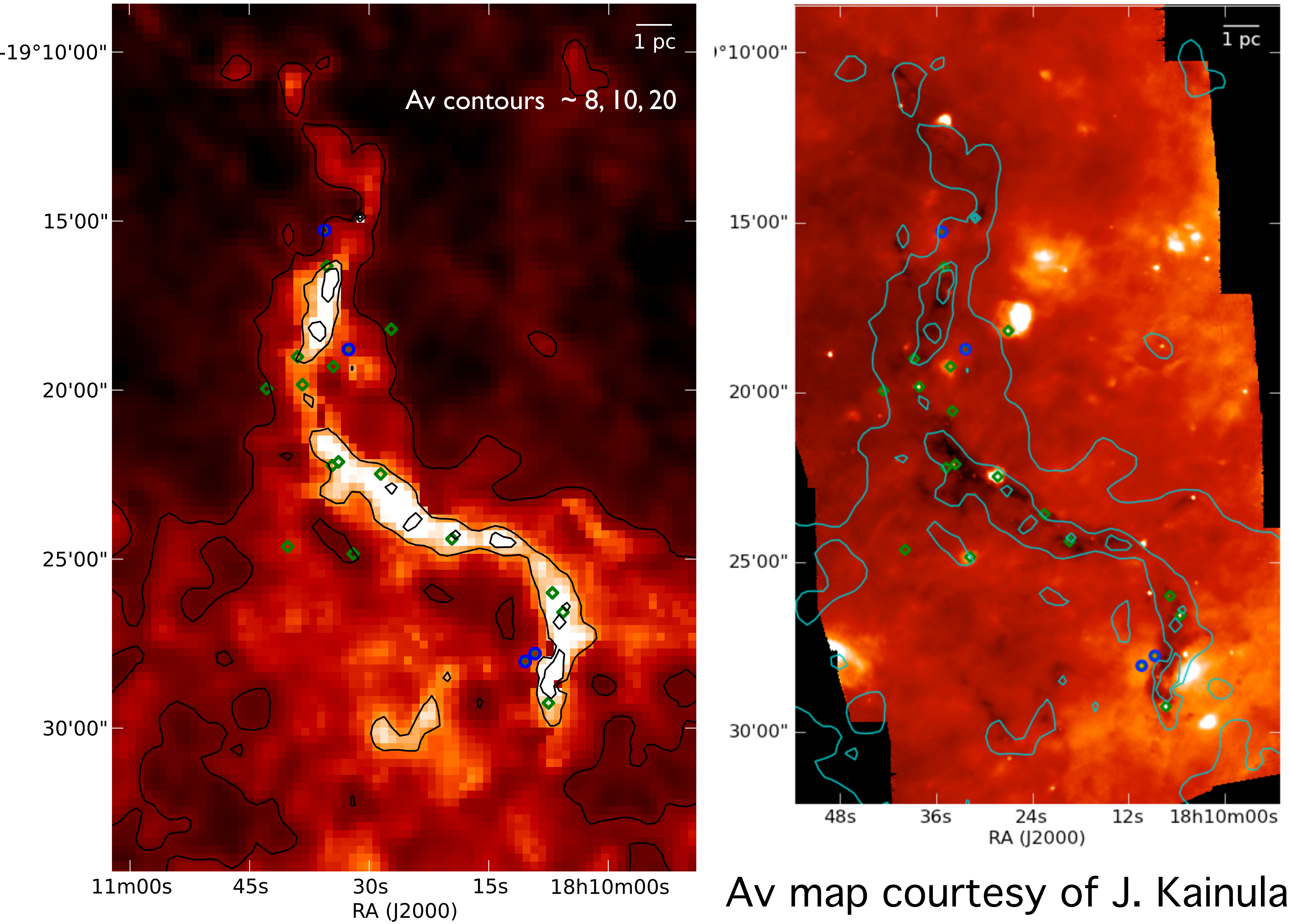
Core formation efficiency



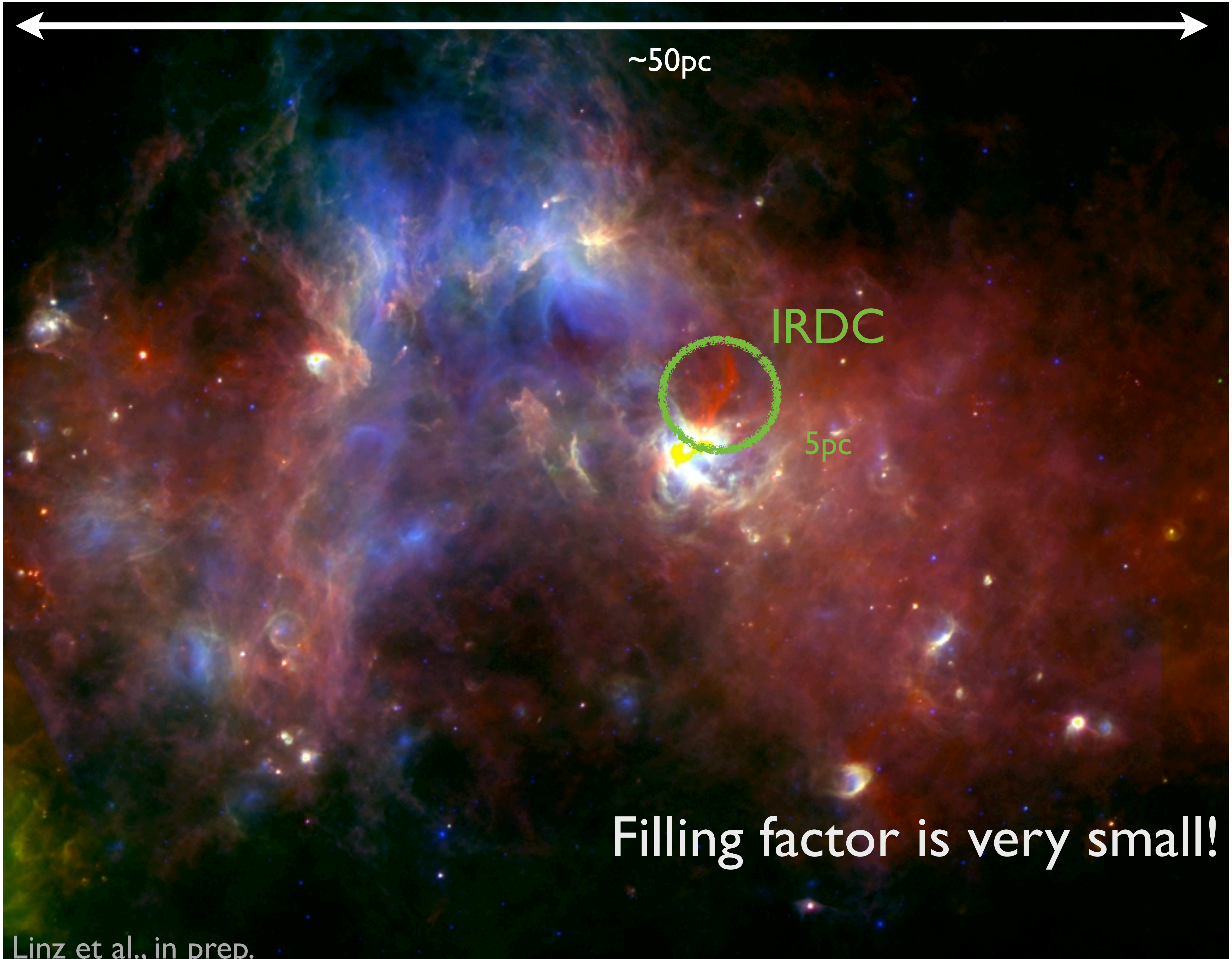
Core formation efficiency



IRDC environment



Av map courtesy of J. Kainulainen


~50pc
IRDC
5pc
Filling factor is very small!
Linz et al., in prep.

Summary

- ⋆ Herschel reveals deeply embedded protostellar cores in a range of evolutionary stages in IRDCs
- ⋆ External heating by ISRF can play a role
- ⋆ IRDCs produce cores with ~10% efficiency
- ⋆ IRDCs live in environments with a huge reservoir of Av ~ few
  - ⋆ Pressure confined??
  - ⋆ Filling factor must be quantified!

Linz et al., in prep.