<u>1. Science aim/goal</u>: To measure the cooling power of molecular gas in star-forming regions throughout the Universe using the CO spectral line energy distribution, thus measuring the energy input directly.

2. <u>(i) Scientific Importance:</u> Warm ($T > 300$ K) and hot ($T > 800$ K) molecular gas is present toward every type of object showing active star formation, including nearby protostars, protoplanetary disks, out to more distant starburst galaxies and QSOs (Fig. 1). The Herschel Space Observatory opened our eyes to these vast reservoirs of warm/hot gas by observing highly excited rotational transitions of CO (J = 4 – 3 up to 50 – 49, 500 – 50 μm) that completely dominate the molecular line cooling budget and directly trace energetic input from forming stars. This discovery was a true surprise, and it is clear that with the Herschel observations we have only seen the tip of the iceberg, i.e. the brightest sources. This leaves the question of how much warm/hot molecular gas there is in star-forming regions throughout the Universe, and thus what is the global energy input from forming stars in a molecular cloud? In a galaxy? In the Universe? What is the origin of this energetic input, i.e. what are the dominant heating mechanisms?

Different types of heating mechanisms have already been proposed for explaining the warm/hot gas observed with Herschel, with most mechanisms falling in two camps: radiative heating through FUV, X-rays, and cosmic rays (PDRs, XDRs, CRDRs) or mechanical heating (shocks, turbulence). The model solutions are completely degenerate, however, and we still have no good picture of the origin of warm/hot gas, even toward nearby Galactic protostars, which have been studied extensively. What is needed to resolve these fundamental questions are deeper measurements at higher spectral and spatial resolution, so that we can disentangle the contributions from various physical regimes within a given source. Only with such measurements will we be able to directly measure and understand the energetic input from forming stars, and the fundamental role they play in the total galactic energy budget.

<u>(ii) Measurements Required:</u>

1. Sensitivity sufficient to detect CO transitions up to at least J = 30-29 toward the types of objects listed above; based on Herschel-PACS experience, the required sensitivity is ~ 10^{-19} W m^{-2}, i.e. about 1 – 2 orders of magnitude deeper;
2. A large fraction of the scientific objectives can be accomplished with spectrally unresolved lines. However, velocity resolution sufficient to spectrally resolve a CO $J = 30 – 29$ line profile with a resolution of 5 km s^{-1}, corresponding to R = 60,000 will discriminate between heating mechanisms;
3. The angular resolution must be high enough to spatially isolate the contributions from various components, i.e. 1” at 100 μm.

The sensitivity is set by the ability to detect warm and hot gas in extragalactic sources and protoplanetary disks. The spectral resolution is set by the ability to kinematically isolate various physical components contributing to heating; radiative processes are expected to produce narrow profiles toward nearby Galactic sources (< 5 km/s) whereas mechanical processes will give rise to broader (> 5 km/s) profiles. Finally, the spatial resolution must be high enough that distinct physical components can be isolated, and high enough that it is comparable to and compatible with lower-*J* CO observations performed with ALMA.

(iii) Uniqueness to 10μm to few mm wavelength facility: The best tracer of warm and hot gas is rotationally excited CO transitions as evidenced most prominently by the recent Herschel and earlier ISO measurements. These transitions have wavelengths in the range of 50 – 500 μm (transitions from $J = 50 – 49$ to $J = 4 – 3$) and these are some of the brightest CO lines (Fig. 1). There are currently no facilities that are able to address the above questions, as there are no facilities directly accessing the full CO ladder.

(iv) Longevity/Durability: ALMA covers wavelengths only down to ~ 165 micron (CO 16-15). SOFIA has very low line sensitivity compared to the requirement. JWST, WFIRST, E-ELT and related facilities do not cover the desired wavelength range at all. SPICA-SAFARI will have a similar wavelength range (50 – 200 μm) but will lack in sensitivity, spectral and spatial resolution compared even to Herschel. ALMA will be able to do these observations for highly redshifted objects, but only these.

3. Figure:

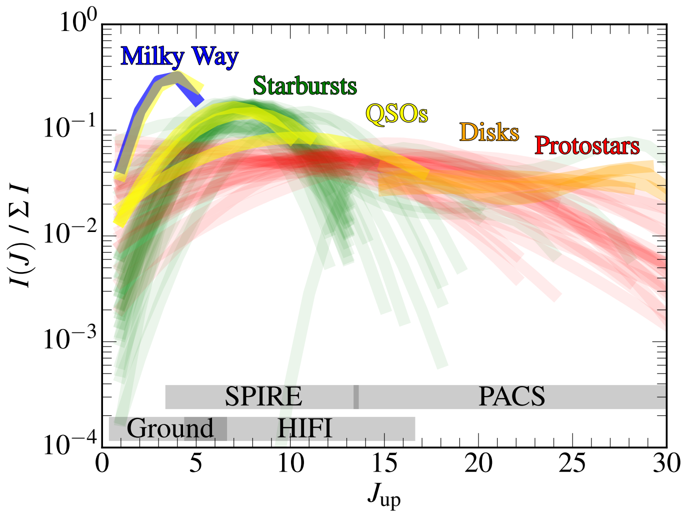

Figure 1. CO ladders observed toward various types of objects from the ground and with the Herschel SPIRE, HIFI, and PACS instruments (observations from many authors, compilation to appear in Kristensen & Harsono in prep.).

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	50-500		Covers CO J=4-3 to 50-49
Number of targets		100		
Survey area	deg.^{2}	N/A		
Angular resolution	arcsec	1		1" at 100 μm
Spectral resolution	λ/Δλ	5,000	60,000	Requirement: line detection, Desired: Spectrally isolate radiative and shock components (discrimation at 5 km/s)
Bandwidth		0.1 micron		300 km/s at 100 micron around a single line
Continuum Sensitivity (1 σ)	μJy	-		
Spectral line sensitivity (1 σ)	W m^{-2}	10^{-19}		
Signal –to-noise		20		
Dynamic range		-		
Field of Regard		10"		Most PACS emission is spatially compact at 10"
Cadence		N/A		