1. Science aim/goal
Establish the interstellar processes that maintain a multi-phase ISM, regulate the transition of gas between phases, and form molecular clouds.

2. <u>(i) Scientific Importance:</u>
The production of stars is a fundamental process that drives the evolution of galaxies over cosmic time. Newborn stars emerge from clouds of molecular gas that are embedded within a dynamic, multiphase interstellar medium (ISM) driven by rotational shear, magnetic fields, and mechanical and radiative feedback from supernovae and massive stars. Understanding the interactions and energy balance between each phase, how molecular clouds condense from the diffuse atomic gas interstellar component and how the rate and yield of stellar production depend on cloud properties are essential requirements to develop a more complete description of star formation and galaxy evolution.

(ii) Measurements Required:
To make significant progress, we require imaging of emission from well-defined tracers of the atomic and molecular gas phases of the ISM. Spectroscopic measurements in the mid- and far-IR are therefore critical since this wavelength regime contains the most important cooling lines (CII, OI, OIII, NII) as well as the H_2 rotational lines at 17 and 28 μm. Imaging of line emission from entire galaxies allows one to evaluate these gas phases with respect to kpc scale structures such as spiral arms, stellar bar potentials while reconnaissance in the Milky Way provides a high spatial resolution view of phase interactions. High spectral resolution is required to separate closely spaced velocity components in the Galactic plane while also providing key velocity information that can constrain theories of molecular cloud formation (Dobbs et al 2014).

The energy balance within the atomic and molecular gas phases is assessed from the measured luminosity of these cooling lines and the accounting of energy input from stars and supernovae. Imaging of galaxies and selected regions of the Milky Way in one or more of these cooling lines along with a census of heating sources provide direct measures of the energy balance within the neutral ISM. With the ability to resolve gas motions, one can evaluate the relative contributions of SNR-driven expanding shells and radiative output from massive stars to the ISM energy budget.

Gravity is an essential component to cloud formation as it acts to accumulate gas over large scales. Perturbations to the local gravitational potential conducive to cloud formation are generated by spiral density waves, the interface of large-scale (~10^2 pc) converging flows, and dense shells of swept up interstellar material.

Spectroscopic imaging of CII emission with high spectral resolution from nearby, face-on spiral disk galaxies would produce the data to evaluate these processes. In connection with H_2 rotational lines, CO and HI 21cm line data, these measurements would quantify the flow of atomic and molecular gas through the spiral potential -- allowing researchers to evaluate the gas velocities predicted by spiral density wave theory in each component, the location of developing molecular clouds (CO and dark H_2) with respect to the atomic material (CII and HI 21cm line) and downstream sites of star formation. One could also assess the amount of H_2 gas located within interarm regions that may also contribute to the assembly of larger molecular cloud structures upon entering the spiral arm. The variation of molecular gas fraction within and between spiral arms can further constrain the time scale of molecular gas. In the plane of the Galaxy, spiral arm streaming motions may be evident as absorption features against a continuum source (protostars in a spiral arm) at velocities forbidden by Galactic rotation.

Wide field spectroscopic imaging of CII emission (R>300,000) from diffuse clouds at high Galactic latitudes that avoids the confusion of the Galactic plane can evaluate the role of converging flows in the formation of molecular clouds. Such flows may be revealed by large-scale velocity gradients centered on peaks of CO emission

(iii) Uniqueness to 10μm to few mm wavelength facility:
High-resolution spectroscopy is essential to identify gas motions in the environments of developing molecular clouds, which are sites of enhanced extinction. This precludes the application of UV/optical measurements. The atomic fine structure lines are the major coolants in the neutral atomic medium, and in addition to being readily observable, are the best probe of the transitions between atomic and molecular gas phases in the ISM.

(iv) Longevity/Durability (with respect to expected 2015-2030 facilities):
The mid- and far-IR lines can only be observed from airborne or space-based facilities so observations of these critical lines are currently limited to SOFIA. Programs as proposed here are not feasible with SOFIA given the target sensitivity and area coverage. Millimeter-wave interferometers (ALMA and NOEMA) and large single dish telescopes (LMT, IRAM 30m, NRO 45m) will provide the measurements that resolve CO emitting molecular clouds in nearby galaxies and the JVLA will continue to image the HI 21cm line with high angular resolution.

4. Table:

Parameter	Required value	Desired Value	Comments
Wavelength/band	17-205 μm	17-205 μm	H_2 to NII
Number of targets	10	>100	Select from LVL survey
Survey area	4-25 arcmin^2 900 arcmin^2	4-25 arcmin^2 3600 arcmin^2	per galaxy; depends on size; Milky Way clouds
Angular resolution	5" @158 μm	2" @158 μm	Resolve spiral arm segments and arm/interarm regions at 10 Mpc
Spectral resolution	R=100,000	R=500,000	Resolve streaming motions > 10 km/s and resolve Galactic components
Sensitivity	$2x10^{-9}$ W/m^2/sr $\sigma(T_{mb})$=0.05 K	$4x10^{-10}$ W/m^2/sr $\sigma(T_{mb})$=0.01 K	in 5 km/s wide channels @158 μm

5. Key references, (Optional, at most three, reviews preferred):
Dobbs, C.L., Krumholz, M., Ballesteros-Paredes, J., Bolatto, A., Fukui, Y., Heyer, M., Mac Low, M., Ostriker, E., Vazquez-Semadeni, E. 2014, in *Protostars and Planets VI*, Arizona Press, eds. Beuther, H., Klessen, R.S.,Dullemond, C.P., Henning, R. p. 3

Appendix

Molecular Clouds from Spiral Density Waves

Spiral density waves are mechanisms that amplify the gravitational potential over large scales (> kpc) and modulate the flow of gas and stars through the spiral arms of a galaxy. As gas surface density increases, gravitational instabilities can be triggered that rapidly configure the gas layer to higher volume densities. The action of spiral density waves can also increase the rate of collisions between existing, smaller molecular cloud fragments allowing the assembly of larger, molecular cloud structures.

Quantifying the amplitude of these gas motions (departure from purely circular motion) is critical to understanding the formation of molecular clouds and stars in disk galaxies with varying degrees of spiral structure. Detecting such streaming motions with the HI 21cm line is challenging owing to thin and thick disk components of the atomic gas layer that can create confusion along the line of sight in a face-on galaxy. The CII emission line is more localized and therefore, offers a less confused view of the gas and kinematics in the thin disk from which molecular clouds develop.

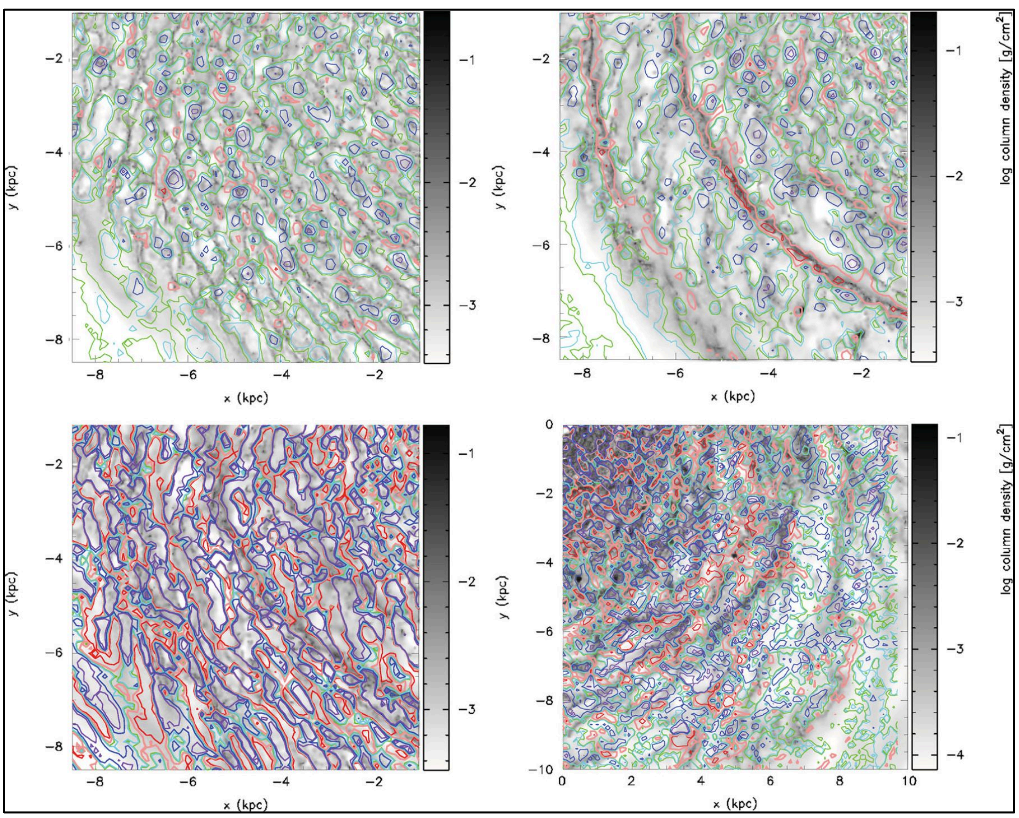

Figure 1 From Dobbs et al 2012. Contours of constant velocity divergence overlayed on an image of gas column density for 4 different models: (top left) no spiral; (top right) spiral density wave with 5% perturbation; (bottom left) spiral density wave with 20% perturbation; (bottom right) flocculent. The contours represent convergence on time-scales of 4 Myr (red), 10 Myr (orange), and 100 Myr (green) and divergence time-scales of 4 Myr (violet), 10 Myr (blue), and 100 Myr (cyan). Enhanced gas surface densities and likely the assembly of molecular clouds occur I regions of converging flows in response to the spiral potential.

The time-scale for molecular gas (as opposed to the lifetime of a given molecular cloud) is constrained by the molecular gas fraction and its variation with azimuth and radius within a galaxy (Koda et al. 2009, Koda, Scoville, & Heyer 2016). For example, if the molecular gas fraction increases on spiral arms and decreases within the interarm regions of spiral galaxies, then there is clearly a transition from atomic to molecular gas triggered by the spiral density wave and the molecular time is approximately a spiral arm crossing time. Conversely, if the molecular gas fraction is constant with azimuth for a given radius, then there are both molecular clouds within the spiral arms and interarm regions. In this case, giant molecular clouds are assembled in spiral arms from small, pre-existing molecular fragments and are disassembled back to small fragments when leaving the spiral arm. Since the molecular fragments must survive an arm-to-arm transit, the minimum molecular time scale is the time required to transit from arm to arm ($2\pi/[m (\Omega(r)-\Omega_p)]$ ~ 100-500 Myr, where m=number of spiral arms, Ω_p is the pattern angular velocity).

Previous studies to measure the molecular gas fraction have been limited to the conventional tracers of atomic (HI 21cm) and molecular gas (CO). With sensitive, well-sampled measurements of CII emission, along with HI 21cm, CO and far infrared thermal dust continuum emission, one can distinguish the dark-H_2 gas from the CO-defined H_2 gas and include it in the accounting of the molecular gas fraction.

Molecular clouds from converging flows of diffuse gas

The formation of molecular clouds from the converging flows of the diffuse ISM has been examined by many recent theoretical studies. Such convergent flows can be the product of spiral density waves, as shown in Figure 1, or the localized, longitudinal component of turbulent motions. The spatial scale of such flows are smaller than spiral density wave scales but are comparable to molecular clouds. Figures 2 and 3 are from Heiner et al. 2015, which show slices of atomic and molecular gas configurations and velocities that emerge from a simulation with decaying turbulence in a thermally bistable neutral medium. Molecular clouds develop where there are converging streamlines of atomic gas. Observations of CII emission can help separate the atomic and molecular gas components and identify the relative velocities. The primary targets for such a study clouds located at higher Galactic latitudes to reduce the confusion of velocity components along the sight that is most severe in the Galactic plane (|b|<5). To rigorously establish the role of such converging flows, one would need to sample many clouds (>10). If a large fraction of the target molecular clouds exhibit evidence for converging atomic flows circumscribing their domains, then this mode of molecular cloud formation becomes more credible.

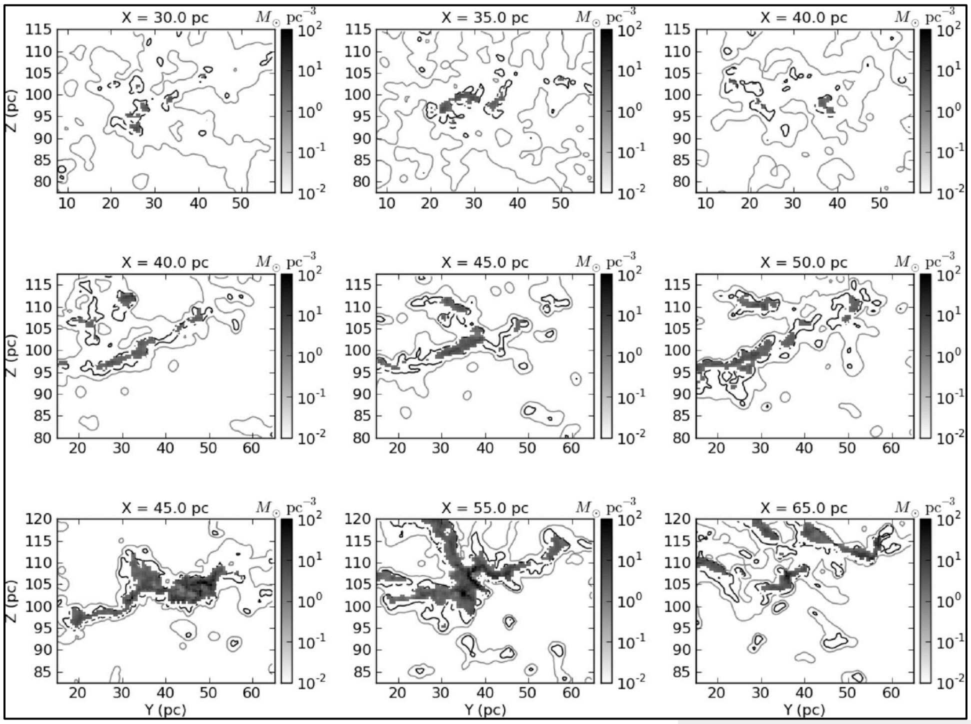

Figure 2 From the simulations of Heiner et al 2015. Y-Z plane of the atomic (contours) and molecular (grey-scale) mass density at different X axis depths for three different times: upper panels: t = 12.5 Myr; middle panels: t = 25 Myr; lower panels: t = 33.7 Myr.

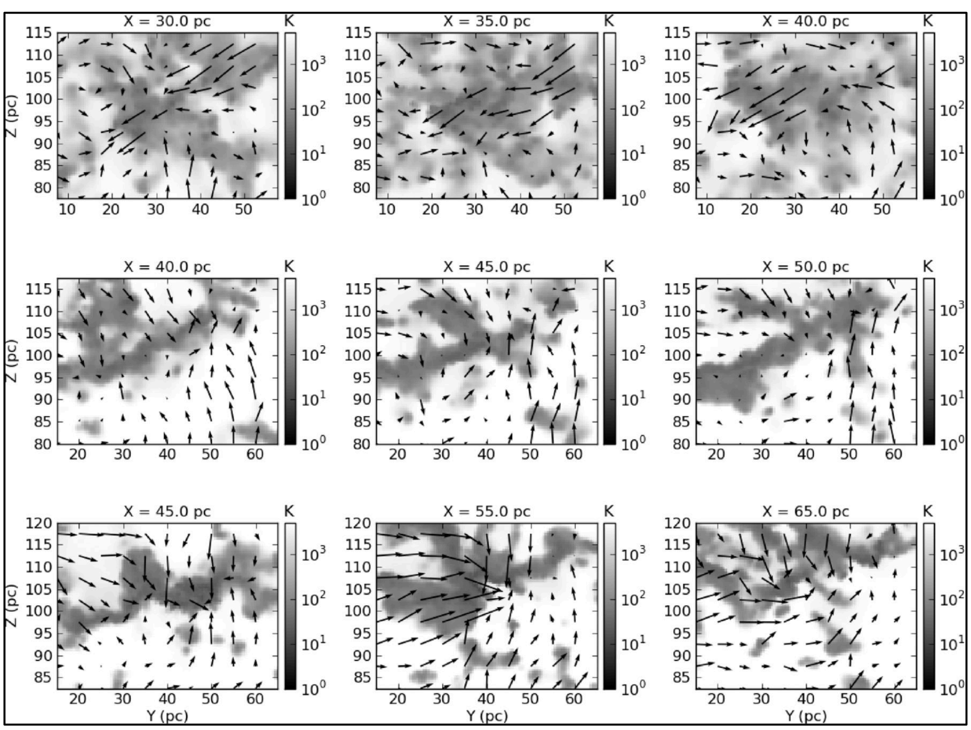

Figure 3 From Heiner et al (2015). Vectors representing streamlines of gas overlayed on images of gas temperature for different depths into the cloud along the X axis. Gas volumes with temperatures less than 50 K and visual extinctions greater than 1 are assumed to be molecular.