1. Science aim: Obtaining a comprehensive view of the multiphase ISM at the peak of cosmic star formation

2. (i) Scientific Importance:

Star Formation across Cosmic Time: Theoretical models of star formation in galaxies suggest that star formation is intimately tied to the overall lifecycle of the ISM. Stars form in cold, self-gravitating cores of molecular clouds, and then return this material to a hotter ionized phase via some form of energy injection. This self-regulation and interaction with the galaxy sets the star formation efficiency in galaxies. At z~1-3, when the bulk of cosmic star formation is happening, a consensus picture is emerging in which galaxies at a fixed stellar mass have larger star formation rates than those in the local universe. Why is this star formation more efficient than at low redshift? What physics in the ISM determines the star formation efficiency across the bulk of cosmic star formation history? What are the dominant feedback mechanisms that regulate star formation, and how does their relative importance evolve with galaxies at different masses and epochs?

There are as many theories as there are galaxy formation theorists. Some models suggest that radiative feedback from massive stars regulates star formation and sets the ISM structure. Others invoke kinetic energy input from supernova, while yet others require the accretion of cold gas from the intergalactic medium to set the turbulent structure in the ISM. Understanding the phase structure of the ISM can dramatically narrow the parameter space of underlying physical phenomena that set galaxy star formation rates/efficiencies at high-z.

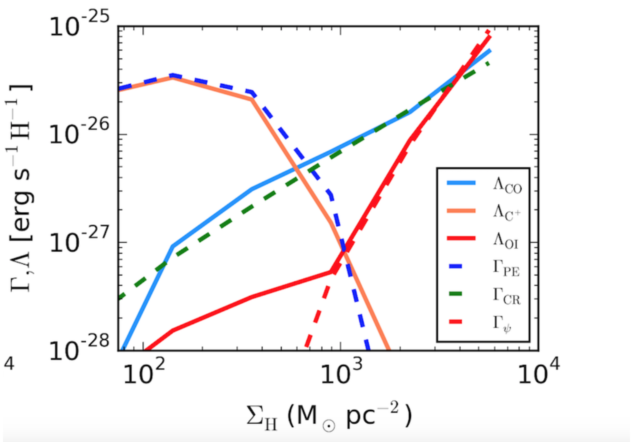
Extracting Physical Quantities: Cooling in the ISM is typically dominated by the FIR fine structure lines of [CII], [NII] and [OI], while the MIR PAHs trace the UV heating rate. This suite of lines directly constrains the physical conditions in the ISM. By quantifying temperatures, densities, surface densities and radiation fields characteristic of the gas surrounding dense molecular cores, we can reveal the physical conditions at the transition between the warm ionized medium, and dense, self-gravitating cores. What are the ratios of PDR masses to dense H_2 masses as a function of global galaxy property (e.g., SFR, sSFR)? How does this vary in extreme environments where the star formation efficiencies are potentially higher? How is gas heated by stellar feedback, and is this important in regulating star formation?

As an example, in the Figure below we show the results from a series of 1D thermal+chemical equilibrium PDR+molecular cloud calculations for clouds of different surface densities. Right away, we see that different physical conditions result in different cooling line strengths and sources of heating. While the current state of simulations are still in a nascent state, by 2030 we can imagine having comprehensive radiative transfer + chemical equilibrium models coupled with 3D galaxy formation models to train algorithms to determine the underlying physical properties that result in observed line ratios. The key point is that *only with access to the MIR and FIR lines can we probe nearly every phase of the ISM in a galaxy directly; without these, we will never understand how these give rise to the increased specific star formation rates at high-z.*

(ii) Measurements Required: What is needed are statistical samples of FIR fine structure lines in galaxies between z~1-4, comparable to the optical surveys of the 2000s. With these, we will be able to chart out *for the first time* how the phase structure of the ISM evolves with galaxy populations over cosmic time. We will be able to determine the luminosity-weighted physical conditions in the cold neutral, warm neutral, and warm ionized media. By selecting galaxies at a constant comoving number density, we can roughly chart how the ISM evolves for a *fixed* galaxy population, and determine how these conditions drive the rise in star formation efficiencies, followed by rapid quenching. As such, the FIRS will deliver a program that resembles the Sloan Digitized Sky Survey, but of the ISM at high-redshift that will provide a dataset that will enrich the community for decades.

What lines do we need?: We require lines that provide access to each phase of the ISM. The FIR fine structure lines of [OI] traces the diffuse warm neutral medium (as well as warm gas in clouds, though is dominated by the former in lower mass systems). [OIII] and [NII] each provide access to the ionized medium, while [CII] can be used to trace the parts of clouds that CO misses. There are additionally MIR lines accessible to the FIRS that can also be used to trace these phases of the ISM (e.g., [FeII], [SiII] for the neutral medium and, [NeII], [NeIII] [SIII], [SIV], and [OIV] for the ionized medium). While each are essential ingredients for understanding ISM phase structure, all but [CII] are only obtainable with the FIRS (and [CII] is impossible to get in the necessary statistical samples with ALMA; see below).

(iv) Longevity/Durability: (with respect to expected 2025-2030 facilities). FIRS will detect essentially all phases of the ISM related to star formation (CNM, WNM, WIM). While ALMA can do [CII] at *z*~2, it is infeasible to get statistical samples; we conservatively estimate <100 ALMA (U)LIRG detections per year (see appendix). Not only can FIRS obtain statistical samples of galaxies detected in [CII], it also provides the full suite of MIR and FIR lines necessary to probe multi-phases of the ISM.



3. Figure: The Lambda terms are cooling and Gamma are heating. PE is the grain photoelectric effect (so, UV heating), CR is cosmic rays, and Ψ is energy exchange with dust. From Narayanan & Krumholz 2016. The point is that the dominant coolant (and heating source) changes with cloud physical conditions, and that observations of the FIR lines (along with PAHs to trace the UV heating rate) can constrain physical conditions in the CO-dark portions of clouds.

4. Table:

Parameter	Unit	Required value	Desired Value	Comments
Wavelength/band	μm	20-500	20-500	[CII]->z~2 + other MIR/FIR lines
Number of targets		1e4	1e5	
Survey area	deg.^{2}	10	100	
Angular resolution	arcsec	2-3"	1"	Spectra so no confusion issues
Spectral resolution	Δλ/λ	3000	5000	
Spectral line sensitivity (1 σ)	W m^{-2}	3e-21	3e-22	1σ (to detect LIRGs out to z~3)

5. Key references:

Casey, Narayanan & Cooray 2014
Carilli & Walter 2013

Appendix:

Line sensitivity calculation: The science is based on detecting a suite of crucial MIR/FIR lines at z~1-3 in typical galaxies probing a range of star formation efficiencies. We need to detect LIRG-like galaxies over this redshift range. We assuming L[CII] ~ 0.5% LFIR and a 5 sigma detection over 5-7 channels to resolve kinematics of large clouds. For a fainter line like [OIV] in a LIRG, we expect L[OIV]=1e7 Lsun (following Spinoglio+2014) which has a flux at z~3 of 1e-21Wm-2 so requires an RMS of 3e-22Wm-2.

Note: Number of [CII] detections per year at z~2 expected by ALMA
If 1/2 of all the available time of ALMA in B8/9/10 during compact configuration were devoted to detecting [CII] at z~2, we estimate a conservative upper limit of ~100 galaxies a year, and in narrow redshift ranges due to the atmosphere. This is assuming an observing time of ~1 hour to detect each z~2 (U)LIRG (based on Herrera-Camus et al. 2015) and 200 hours total of B8/9/10 time per year.