

# Mapping Turbulent Energy Dissipation through Shocked Molecular Hydrogen in the Universe

A whitepaper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

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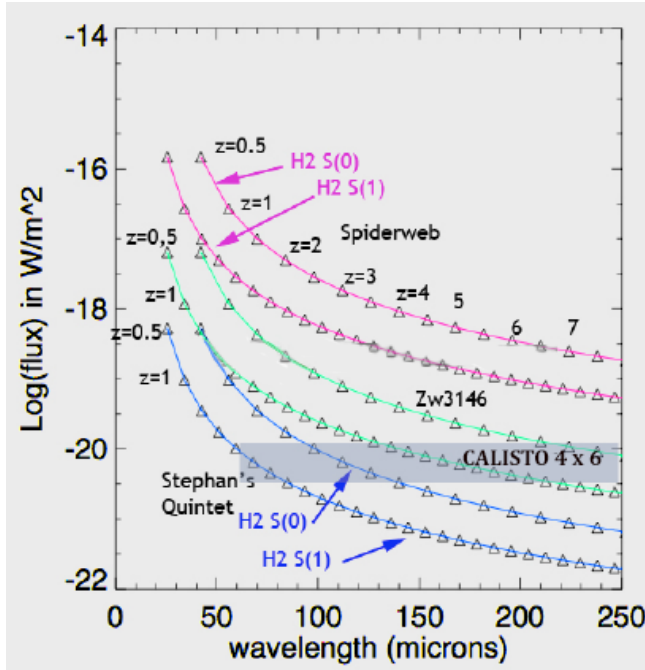
**Cover Images:** *(Left)* Shock-excited 0-0S(1) molecular hydrogen (blue) emission from Stephan's Quintet, *(Right)* The most extreme warm H<sub>2</sub> emitter found by Spitzer just before it ran out of cryogen--The "Spiderweb" proto-cluster at  $z = 2.16$ .

**Background and Motivation:** Probing the growth of structure in the Universe is arguably one of the most important, yet uncharted areas of cosmology, ripe for exploration in the next few decades. Molecular hydrogen ( $H_2$  and HD), along with the first heavy metals born in the first supernovae, played a vital role in cooling the primordial gas (e. g. Santoro & Shull 2006), setting the scene for the formation of first large-scale baryonic structures. The IGM enrichment by heavy elements also led to the formation of dust, which in turn almost certainly led to a rapid acceleration of  $H_2$  formation on grains for redshifts  $z < 15$  (Cazaux & Spaans 2004). Almost all the primary cooling channels for gas at  $z > 2$  occur in the far-infrared/sub-mm bands, including dust and Polycyclic Aromatic Hydrocarbons (PAH) emission, the mid-IR rotational lines of molecular hydrogen (e. g. 0-0 S(3)9.7 $\mu$ m, S(1)17 $\mu$ m, S(0)28 $\mu$ m), and the far-IR lines of [O I]63 $\mu$ m, [Si II]34.8 $\mu$ m, [Fe II]25.9 $\mu$ m and [C II]157 $\mu$ m. **The far-IR is therefore a critical window for the study of the initial growth and evolution of gas in the universe over cosmic time.**

During the *Spitzer* mission, it was discovered that there exists a population of galaxies exhibiting extremely strong emission from warm (typically  $100 < T < 500$  K) molecular hydrogen (Ogle et al. 2010). One of the most striking examples was found in the giant intergalactic filament in Stephan's Quintet (Appleton et al. 2006, Cluver et al. 2010), where the mid-IR molecular hydrogen lines were unusually bright (Cover page). This warm molecular gas is believed to be tracing the dissipation of mechanical energy in shocks (Guillard et al. 2009) and turbulence, caused by the collision of a high-speed intruder galaxy with a tidal filament.  $H_2$  emission dominates the gas cooling in the Quintet's filament, being enhanced relative to other important coolants (Appleton et al. 2013). Thus molecular hydrogen seems to be a powerful coolant, even in the local universe where metals are more abundant than in the early universe. Other nearby examples have also been found, where the  $H_2$  appears to be heated by collisions between galaxies (Peterson et al. 2012, Cluver et al. 2013, Steirwalt et al. 2014). Furthermore, Ogle et al. (2010) showed that 20% of nearby 3CR radio galaxies also showed excessively high warm  $H_2$  emission, most likely from shocks caused by the passage of the radio jets through the host galaxy (see also Nesvadba et al. 2010; Nesvadba et al. 2011). Guillard et al. (2012) demonstrated that radio galaxies exhibiting strong HI outflows also showed similar characteristics. In some cases, the warm molecular hydrogen provides clues about the suppression and removal of gas in the inner regions of galaxies containing AGN (Ogle et al. 2014). **Studying emission from warm molecular hydrogen can provide a direct measure of the properties of the gas cooling, which sets limits of timescale for the dissipation of turbulent energy. This is likely to be important for understanding the physical conditions that lead to negative ISM feedback on star formation in the universe.**

**Bridging to the high-redshift Universe:** Before *Spitzer* ran out of cryogen, it detected a number of very powerful  $H_2$ -emitting galaxies, including several central cluster galaxies (e. g. Zw 3146 at  $z = 0.3$ ; Egami et al. (2006)), where the  $H_2$  line-luminosity is an order of magnitude brighter than those seen in individual galaxy collisions. Shocks and or cosmic ray heating (Guillard et al. 2015; Ferland et al. 2008) may be responsible for some of these large luminosities, but by far the most powerful warm  $H_2$  emitting system was detected by Ogle et al. (2012) in the  $z = 2.15$  radio galaxy proto-cluster PKS1138-26 (known as the "Spiderweb": cover page). The luminosity in a single  $H_2$  rotational line (the 0-0 S(3) 9.66 $\mu$ m), was a phenomenal  $3 \times 10^{10} L_{\odot}$ , 100 x brighter than Stephan's Quintet. The existence of such extreme  $H_2$  emitters begs the question of whether  $H_2$  could be used to probe turbulence in the early universe (see Appleton et al. 2009). The molecular hydrogen lines therefore

represent an important window into turbulence that can only be explored in the far-IR. Although JWST's mid-IR capability will allow the study of the nearby universe in the higher-excitation H<sub>2</sub> lines, **the exploration of H<sub>2</sub> in the low-lying rotational lines (which traces the dominant mass and cooler temperatures) will be impossible beyond z > 2, without a large cool FIR telescope in space.**



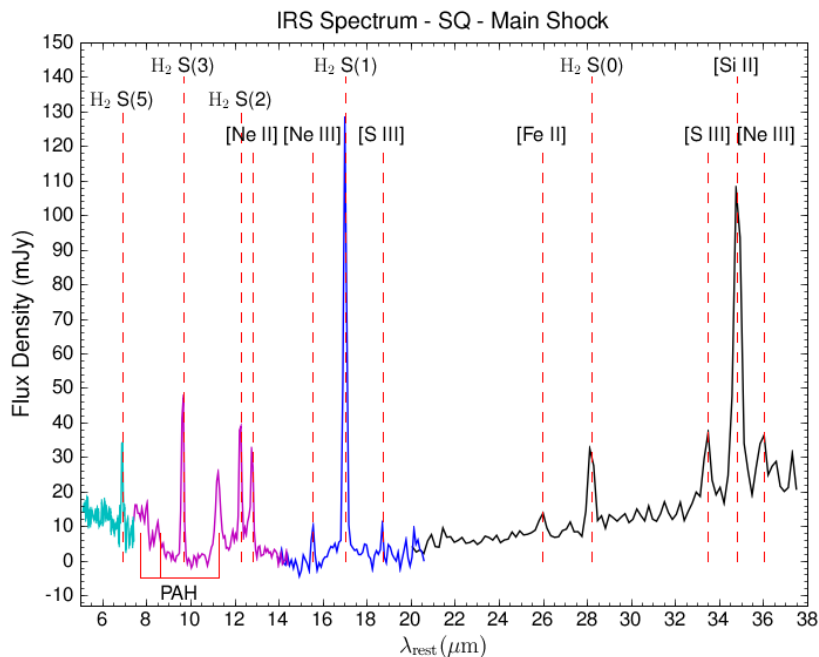
Estimates of the 0-0S(0)28 $\mu$ m and 0-0S(1)17 $\mu$ m ground-state pure-rotational H<sub>2</sub>-line fluxes ( $W m^{-2}$ ) for the Spiderweb (PKS1138-26) and the central cluster galaxy in Zw 3146 shifted in increments of  $z = 0.5$  as a function of observed wavelength.

The grey box shows the achievable sensitivity of the CALISTO telescope with the 4 x 6 element spectrometer discussed by C. M. Bradford in an associated white paper. These sources, if they exist at higher- $z$ , would be readily detected at  $z > 5-6$ . Compact group sources like Stephan's Quintet could be studied to  $z > 1$ .

Although the detection of individual proto-galaxies at redshifts  $> 10$  are probably beyond the reach of current instrumentation (see Appleton et al. 2009), the detection of powerful clusters at  $z > 4$  is quite feasible (see figure). These systems will provide an important insight into energy dissipation and galaxy formation in the most over-dense regions in the universe. CALISTO, a cold  $T \sim 4K$ , 5m class telescope which has been put forward for the FIR surveyor concept (see Bradford et al. whitepaper), is the only mission currently envisioned for the next decade capable of detecting the low-excitation H<sub>2</sub> gas that we associate with large-scale turbulence. Extra sensitivity could be gained by mapping around strong lensing systems, to dig deeper, and to avoid foreground confusion. This would allow exploration of limited volumes of the high- $z$  universe to greater depth. Potentially ALMA-Band 10 has a capability of reaching few  $\times 10^{-20} W m^{-2}$  in long integrations. However, the tiny primary beam (5 arcsecs at 850 GHz), and narrow fractional bandwidth ( $< 0.3\%$ ) would make the detection of shocked-enhanced primordial gas extremely difficult, requiring *a priori* knowledge of the precise target location and redshift. CALISTO, on the other hand, can potentially detect turbulent H<sub>2</sub> out to high redshift in many H<sub>2</sub> lines simultaneously because of its huge wavelength grasp. In addition, its larger beam would allow efficient mapping, especially if more than one beam is placed on the sky simultaneously (the 4 x 6 concept of Bradford et al.). At the highest  $z$ , the best way to detect primordial gas may be through the method of intensity mapping (e. g. Gong et al. 2013), where a CALISTO-like spectrometer could be used to map spatially and exploit spectrally, the faint statistical signals of proto-galaxies at  $z > 10$ . **A cold FIR telescope in space would provide a vital probe of heating and cooling processes at work in the youngest galaxies, greatly expanding NASA's portfolio, and providing a unique suite of tools for studying the Cosmic Dawn.**

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The IRS spectrum of the turbulent shock structure in the Stephan's Quintet Compact Group (Appleton et al. 2006; Cluver et al. 2010). The warm H<sub>2</sub> gas dominates the power from the region. [CII]157 $\mu\text{m}$  (Appleton et al. 2013) and [SiII] emission are the next most powerful line coolants. These lines are redshifted into the far-IR and sub-mm at high-z.