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Radio spectroscopic surveys provide us with a comprehensive picture of the Milky Way across many physical and chemical regimes. Spectral lines primarily probe the multi-phase gaseous interstellar medium (ISM) from its ionized to atomic and molecular phases, and constrain both local and galaxy-scale kinematics and structure through Doppler shifts. By investigating the physical and chemical properties and distribution of the ISM, the processes driving star formation and galaxy evolution can be studied in detail. This motivates line surveys of our Galaxy that allow us to use the range of physical conditions found in the Milky Way as a template for understanding star formation in extragalactic environments. In this chapter, we describe the science enabled by the spectroscopy of small molecules and radio recombination lines of atoms toward a range of Galactic environments with the SKA. We address questions concerning the processes that dictate the formation of molecular clouds (OH, CH), the properties of warm, ionized gas and the potential of H II regions in understanding the structure of the Galaxy (radio recombination lines), and the impact of CO-dark molecular gas across various density regimes on star formation and galaxy evolution (OH, H<sub>2</sub>CO). We propose a survey that includes the inner and outer Galaxy disk, characterized by a broad range of densities, temperatures, and metallicities. Deep, wide-field observations of small molecules will be uniquely accessible with SKA, providing key insights on the condition of interstellar medium in galaxies and its impact on star formation.

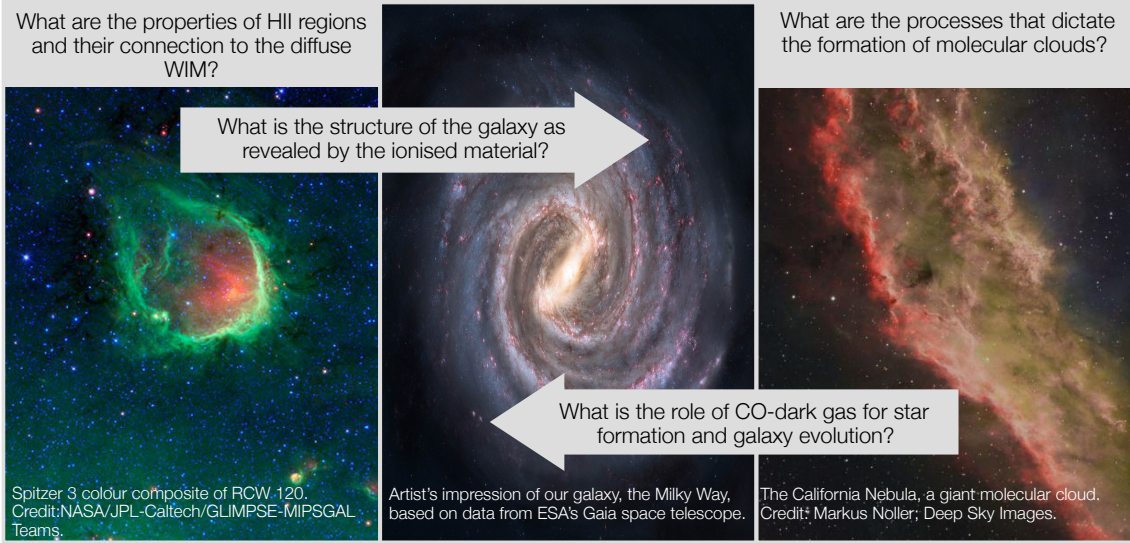
## 1 Introduction

The ISM is the lifeblood of galaxies. It provides the reservoir of raw material from which stars are formed, and to which they return much of their matter at the end of their lives. The cooling and condensation of warm ISM into cold molecular clouds directly determines conditions for star formation, a process that is driven both by galaxy-scale effects and by small-scale physics and chemistry. As young stars evolve, they heat and ionize the ISM, and enrich it with the dust and heavy elements responsible for cooling and shielding. The exchange of matter and energy between stars and the ISM thus forms a complex and interconnected system of self-regulating feedback that underpins the evolution of galaxies.

Our own Milky Way is an ideal laboratory for studying these connections and their dependence on environment in unprecedented detail, and provides a template for understanding the star formation and ISM lifecycle in extragalactic environments. Spectroscopic surveys are a key part of this picture – essential to understanding our Galaxy’s gas-phase constituents, linking the properties of the ISM to the processes of star formation, and connecting physical processes to environment. They provide kinematic information for the ionized, atomic and molecular structures of the Milky Way, revealing the physical and chemical processes underway as well as the distances to astronomical objects, all on spatial scales generally unobtainable in external galaxies. Combined with high-resolution continuum surveys, they are also uniquely suited to mapping the three-dimensional structure of the Galaxy in unprecedented detail. In this chapter, we focus on surveys of the ionized and molecular constituents of the Milky Way, noting that the atomic component is addressed in detail in [Miville-Deschênes et al. \(2026\)](#).

A key transition point in the stars–ISM lifecycle is the formation of molecules in cold, filamentary atomic clouds ([Krumholz et al., 2009](#)). Fundamentally, the ISM becomes molecular once density, temperature, and column density thresholds are met, which can occur due to both local and galaxy-scale processes. However, the details of how molecular cloud formation occurs, both on small scales and in the galactic context, remain uncertain. In particular, the connection between the physical conditions in the atomic gas and the propensity and mechanisms of molecule formation is not well constrained observationally (e.g. [Hafner et al., 2023](#); [Park et al., 2023](#)); nor are the details of molecular cloud assembly on sub-parsec scales. Additionally, there is growing evidence that H<sub>2</sub> exists at relatively low abundance throughout much of the cold atomic medium and is undetectable in the CO lines most commonly used to trace the molecular ISM ([Liszt and Lucas, 2000](#); [Busch et al., 2021](#); [Rybarczyk et al., 2022](#)). This apparently ultra-diffuse molecular component is still difficult to detect. However, it is likely the tail end of a much larger reservoir of diffuse, so-called ‘CO-dark’ molecular gas (e.g. [Grenier et al., 2005](#)), which may make up a considerable fraction of the H<sub>2</sub> budget, particularly in the outer Galaxy and in cloud envelopes (e.g. [Pineda et al., 2013](#); [Remy et al., 2018](#)). While CO-dark H<sub>2</sub> is unlikely to participate directly in star formation, it is critical as a marker of the earliest stages of chemical complexity, and may be important for the total molecular mass budget, particularly in the metal-poor outer Galaxy.

Within the Solar circle, roughly half of the interstellar gas mass resides in the molecular phase ([Scoville et al., 1987](#); [Bronfman et al., 1988](#); [Heyer and Dame, 2015](#)). However, the properties of the molecular gas and its ability to form stars change as a function of Galactocentric radius ( $R_{\text{Gal}}$ ),



**Figure 1:** The primary scientific goals of this work are illustrated here, highlighting the multi-scale and multi-physics impact of spectral line surveys.

from the Galactic center to the inner and outer Galaxy ( $R_{\text{Gal}} > 8.2$  kpc; [GRAVITY Collaboration et al. 2019](#)). In particular, the gradual decrease in metallicity (e.g., [Méndez-Delgado et al., 2022](#)) results in reduced abundances of dust and molecules heavier than  $\text{H}_2$  in the outer parts of the Milky Way ([Lê et al., 2023](#); [Patra et al., 2025](#); [Gigli et al., 2025](#)). The average flux of cosmic rays and the ultraviolet radiation field are also reduced ([Bloemen, 1987](#); [Padovani et al., 2020](#); [Sabatini et al., 2023](#)), but both penetrate deeper into clouds due to the reduced shielding, where they can heat and ionize gas ([Ossenkopf-Okada et al., 2025](#)). The decreased efficiency of gas and dust cooling affects the condensation and fragmentation of molecular clouds ([Glover and Clark, 2012](#)), and combined with the high fraction of atomic-to-molecular gas, is expected to lower the star formation rate per surface area ([Kennicutt and Evans, 2012](#)).

So far, spectroscopic surveys of the Galactic plane have mainly used carbon monoxide (CO) as the tracer of the bulk of the molecular gas mass. In the inner Galaxy, CO surveys have delivered a comprehensive census of molecular clouds ([Roman-Duval et al., 2010](#); [Barnes et al., 2015](#); [Duarte-Cabral et al., 2021a](#)), mapped their association with spiral arms ([Roman-Duval et al., 2010](#); [Colombo et al., 2022](#)), and studied the connection between clump properties and star formation ([Eden et al., 2013](#); [Urquhart et al., 2021](#)). Similar surveys in the outer Galaxy, however, have shown a weaker association of star formation with spiral arms ([König et al., 2021](#); [Urquhart et al., 2024, 2025](#)), which may be related to the presence of supershells or other dynamical processes within the disk, such as flaring and scalloping, as revealed by  $\text{H I}$  observations ([Kalberla and Kerp, 2009](#); [Soler et al., 2022](#)). Since CO can be efficiently photodissociated by UV radiation from young stars, alternative tracers are necessary to reveal the hidden, CO-dark molecular gas in the ISM and its relation to star formation.

Once stars have formed, they have an immediate effect on their surroundings, in particular via the intense ionizing radiation emitted from the most massive stars. The  $\sim 10^4$  K ionized ISM consists

of H II regions surrounding high mass stars and a pervasive, diffuse Warm Ionized Medium (WIM) that fills the volume of the disk and extends far from the plane (Lyne et al., 1985). As signposts of active star-formation, H II regions have historically been used as tracers of the Milky Way’s spiral structure (Georgelin and Georgelin, 1976). While the dominant source of ionization for the WIM is believed to also be high mass stars (Haffner et al., 2009), confirmation requires connecting the plasma properties and distribution in the dense zones surrounding H II regions with those in the diffuse WIM.

The diffuse WIM can be detected spectroscopically using optical lines such as H $\alpha$ , but extinction severely limits the utility of such measurements in the Galactic plane. Radio recombination lines (RRLs), primarily of H but also He and C, are detected throughout the entire volume of the Galactic disk (Anderson et al., 2021; Khan et al., 2024) and provide velocities to H II regions that, when combined with models of Galactic rotation, can result in kinematic distance measurements. They are very effective tracers of the  $\sim 10^4$  K ionized ISM, providing constraints on the star-formation and stellar feedback processes via measurements of electron temperatures, the level of turbulence and (indirectly) metallicity, and the association between ionized gas and natal molecular material (e.g., Veena et al., 2017).

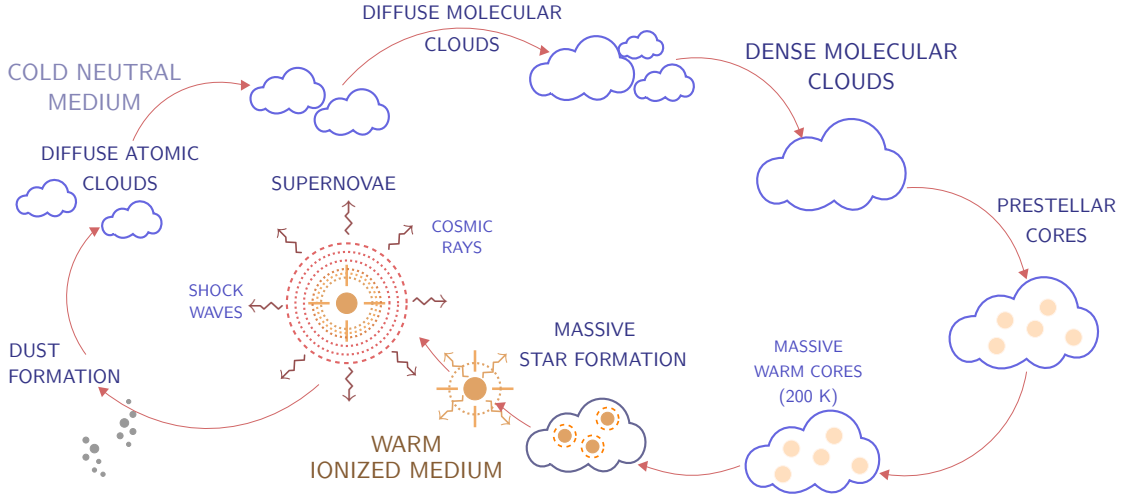
Large-scale line surveys of the Milky Way with the SKA provide the opportunity to study the physics of the ISM and its links to star formation using several complementary species: hydroxyl (OH), methylidyne (CH), formaldehyde (H<sub>2</sub>CO), and radio recombination lines of hydrogen, helium, and carbon (H, He, C). In this chapter, we propose an SKA survey that allows us to link the evolution of the ISM with star formation and galaxy evolution. The key science themes include: (i) understanding how cold atomic gas conditions impact molecular gas formation as a function of  $R_{\text{Gal}}$ , including the role of CO-dark gas, (ii) characterizing the warm, ionized gas surrounding H II regions and its connection to the diffuse WIM, (iii) constraining the structure of the Galaxy using kinematics from radio recombination lines, and (iv) establishing the role of CO-dark gas across various density regimes, constrained with H<sub>2</sub>CO, for star formation and galaxy evolution (see also Fig. 1).

In Section 2, we describe the science motivation for the line survey of the Milky Way. Section 3 provides a description of each of the tracers and their utility for the proposed science. In Section 4, we discuss the potential scope of the survey in terms of the coverage within the Milky Way and its feasibility. In Section 5, we provide a summary and outlook.

## 2 Linking the evolution of the ISM with star formation and galaxy evolution

The ISM exhibits a complex thermal, ionization, and density structure with multiple phases in approximate pressure equilibrium (McKee and Ostriker, 1977). These include: the hot ionized medium (HIM;  $T \sim 10^6$  K; Cox and Smith 1974), the warm ionized medium (WIM;  $T \sim 10^4$  K; Reynolds 1983), the warm neutral medium (WNM;  $T \sim 10^4$  K; Kulkarni and Heiles 1987; Dickey and Lockman 1990), the cold neutral medium (CNM;  $T \sim 100$  K), and molecular clouds ( $T \sim 10$  K). The flow of material between these phases reflects the balance of heating and cooling, and the energy input from stars. Transitions in and out of the densest, coldest molecular gas phase directly determine star formation rates.

## GAS LIFE CYCLE IN THE ISM



**Figure 2:** Schematic illustrating the lifecycle of baryonic material in the ISM, tracing its evolution from diffuse atomic gas to molecular clouds, the collapse into dense star-forming regions, the birth and evolution of massive stars, and their eventual return of enriched material back to the ISM.

## 2.1 From cold atomic to molecular gas

In the interests of clarity, we will begin by defining terminology. The term ‘cold neutral medium’ (CNM) is used variously in the literature to refer to anything from purely atomic cold gas, to all ISM below  $\sim 100$  K, including both diffuse-molecule dominated regions and dense star-forming molecular clouds. Here we will use CNM to refer to cold gas that is *primarily* atomic, but that may contain molecules at low abundance. This reflects historical usage of the term to refer to one of the two thermally stable phases of the atomic ISM (in opposition to WNM, [Wolfire et al., 1995](#)), and a rich history of its study via the H I 21 cm line (e.g. [Heiles and Troland, 2003](#)). However, we acknowledge that even primarily-atomic ISM may contain a non-negligible molecular fraction (see e.g. [Busch et al., 2021](#); [Rybarczyk et al., 2022](#)), noting that the process of molecule formation can begin at relatively low column density (e.g. [Wolfire et al., 2003](#)) and that molecules may be stirred into otherwise atomic gas via turbulent mixing (e.g. [Valdivia et al., 2016](#)). In our definition, CNM does *not* include H<sub>2</sub>-dominated regions – these we refer to as ‘molecular gas’ or ‘molecular clouds’. But we note that CNM structures may host molecular gas within them.

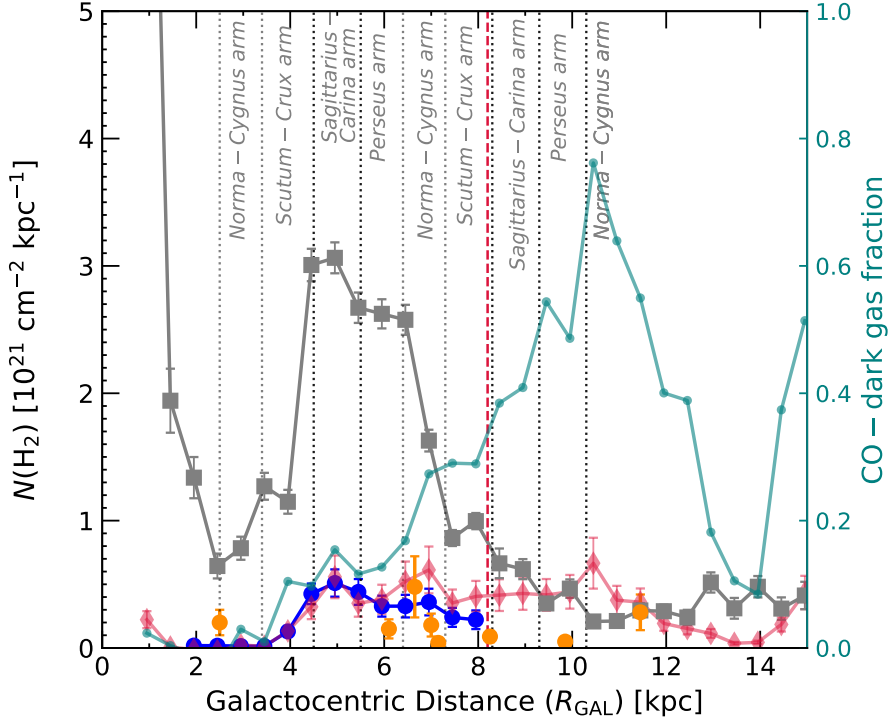
With terminology defined, we begin by recognizing that molecular clouds form when the cold atomic medium accumulates to sufficiently high volume and column densities to (self-)shield against photodissociation, enabling the formation and survival of H<sub>2</sub> ([Draine and Bertoldi, 1996](#); [Krumholz et al., 2008, 2009](#); [Glover and Mac Low, 2011](#); [Sternberg et al., 2014](#)). This process may be driven by various mechanisms, including turbulent flows, cloud mergers, and gravitational instabilities, and is governed by environmental factors such as pressure, metallicity, and dust shielding, as well as local physical conditions ([Elmegreen, 1989](#); [Blitz and Rosolowsky, 2006](#); [Leroy et al., 2008](#); [Krumholz and Burkert, 2010](#); [Sternberg et al., 2014](#)). Since molecular clouds require CNM as a

precursor to their formation, examining the relationship between the physical state of the CNM and the properties of any associated molecular gas is critical to understanding the conditions for star formation (Fig. 2). This must be done across a range of column density regimes, from low  $A_V$ , partially molecular gas, to dense and well-shielded molecule-dominated regimes, across a range of Galactic environments, and with sufficient number statistics to deduce robust correlations from inherently scattered data.

While the galaxy-scale processes responsible for molecular cloud formation are relatively well understood (e.g. Krumholz et al., 2009), and the global column density thresholds governing the H I-to-H<sub>2</sub> phase transition are well constrained (e.g., Bellomi et al., 2020), the manner in which the transition occurs on small (sub-pc to pc) scales remains less clear. Yet these are precisely the scales on which many of the key physical processes shaping the interstellar medium operate. For instance, the rich ~pc-scale filamentary structure observed in the CNM (e.g., McClure-Griffiths et al., 2006; Clark et al., 2019) is thought to arise from thermal instabilities in the magnetized, turbulent ISM, which naturally organize the CNM into filaments and clumps on characteristic scales of  $\lesssim 0.1\text{--}10$  pc (Audit and Hennebelle, 2005; Inoue and Inutsuka, 2016). However, while structure formation within the CNM sets the starting conditions from which molecular clouds are born, we lack a good description of how CNM structure couples to the star formation process; for example, it is unclear if atomic filaments are the direct precursors of self-gravitating molecular filaments that are widely observed in star forming regions (Arzoumanian et al., 2011; André et al., 2014; Hacar et al., 2023). Similarly, while the physical conditions required for molecule formation must arise from the physics of the atomic medium, our ability to link the thermal, structural and chemical properties of associated atomic and molecular gas is still limited – both by sample size and complexity (e.g. Syed et al., 2020; Hafner et al., 2023; Park et al., 2023; Soler et al., 2023).

One key place we lack understanding is the role of diffuse, CO-dark H<sub>2</sub> in molecular cloud formation. Often referred to as ‘dark molecular gas’ (DMG), CO-dark H<sub>2</sub> exists in warmer low-extinction environments ( $A_V \lesssim 1$ ), where limited (self-)shielding prevents the survival of a substantial amount of CO (Grenier et al., 2005; Wolfire et al., 2010; Shull et al., 2021), but the transition from H I to H<sub>2</sub> is well underway. The fraction of CO-dark H<sub>2</sub> to total H<sub>2</sub> in the ISM ranges from ~20% at  $R_{GC}$  of 4 kpc to ~80% at 10 kpc (Figure 3), and significant areas of the sky associated with OH emission are CO-dark (e.g. Pineda et al., 2013; Busch et al., 2019, 2021). Regions dominated by DMG may mark the earliest stages of molecular cloud formation, but DMG also exists in the envelopes of CO-bright clouds (e.g. Traficante et al., 2014; Remy et al., 2018; Liszt et al., 2019), and may even be well-mixed with H I (Liszt and Lucas, 2000; Busch et al., 2021; Rybarczyk et al., 2022). How such mixing could be achieved is an open question. Numerical models suggest that transient turbulent overdensities allow for rapid formation of H<sub>2</sub>, which may then be mixed into the more diffuse surroundings (e.g. Glover and Mac Low, 2007; Valdivia et al., 2016). However, observational results so far are unable to distinguish between this scenario and the presence of tiny, unresolved dense cloudlets (e.g. Pringle et al., 2001). In any case, the distribution of DMG on these small scales has direct implications for models of molecular cloud assembly.

Figure 3 illustrates the radial distribution of the CO-dark gas across the Galactic plane as traced by [C II], CH, and OH, alongside the total molecular gas content traced by CO. These comparisons



**Figure 3:** Radial distribution of CO-dark molecular gas column density in the plane of the Milky Way as traced by varied tracers including [C II] (pink diamonds), CH (blue circles), and OH (orange circles) alongside the total H<sub>2</sub> column density as traced by CO (gray squares). The spiral arm crossings, typically encountered along the line of sight toward a background continuum source in the fourth Galactic quadrant, are indicated assuming a spiral-arm width of 0.85 kpc. The vertical dashed red line marks the Sun’s galactocentric distance. The secondary y-axis (in teal) displays the CO-dark gas fraction as traced by [C II]. Adapted from [Jacob \(2023\)](#). Data sources: CO, [C II], CO-dark gas – [Pineda et al. \(2013\)](#); CH – [Jacob et al. \(2019\)](#); OH - [Jacob et al. \(2019\)](#); [Busch et al. \(2021\)](#).

clearly demonstrate that the CO-dark fraction (relative to the total molecular content) is significant along many sightlines, with especially large fractions in the outer Galaxy. The [C II] dataset is extensive – observed under the Herschel/HIFI key guaranteed program, GOT C+ ([Pineda et al., 2013](#)), covering ~500 Galactic sightlines. However, since [C II] exists in all phases of the ISM, there are challenges in isolating the CO-dark component from [C II] alone. The molecular species CH and OH have advantages in this regard, but measurements of both remain limited. A large fraction of the available CH and OH data come from absorption line studies of their FIR rotational lines observed with SOFIA ([Jacob et al., 2019](#)), and are restricted to only a handful of sightlines. OH in particular presents additional challenges, as its FIR lines are often optically thick. The radio OH lines at 18 cm have been extensively observed with single dish facilities (e.g. [Dawson et al., 2014, 2022](#); [Xu et al., 2016](#); [Li et al., 2018](#); [Busch et al., 2019, 2021](#)) and interferometers (e.g. [Rugel et al., 2018, 2025](#); [Hafner et al., 2023](#)), and are able to trace CO-dark H<sub>2</sub>. However, single-dish studies within the Galactic Plane present challenges due to in-beam and line-of-sight confusion ([Dawson et al., 2022](#)), and existing interferometric observations have generally not been sensitive enough to detect CO-dark gas. Sensitive OH and CH observations with the SKA, described below, will therefore be

crucial to characterizing the nature and distribution of this diffuse molecular component.

## 2.2 The Warm Ionized Medium

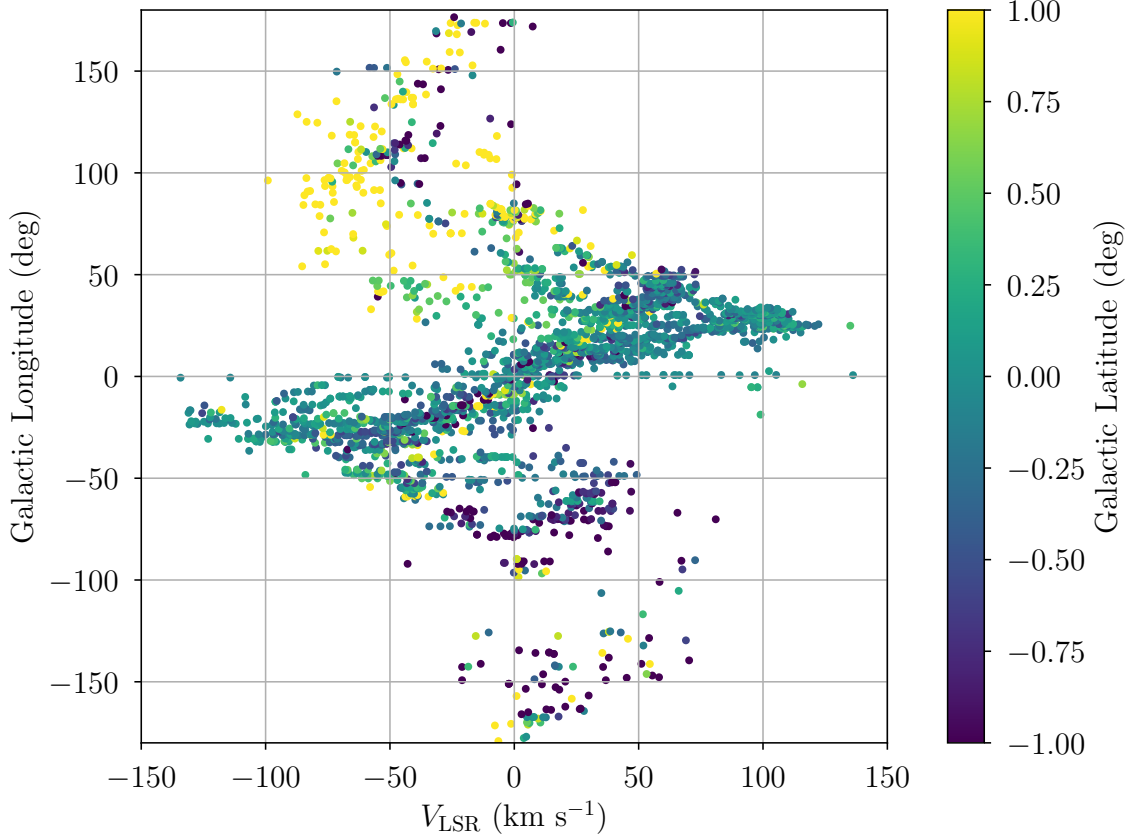
The warm ionized medium (WIM) is the  $\sim 10^4$  K ionized gas that pervades the volume of the Galaxy. Typically residing far from the Galactic Plane, a diffuse WIM component with densities as low as  $n_e \simeq 10^{-2} \text{ cm}^{-3}$  (Lyne et al., 1985) is detected using optical lines such as  $\text{H}\alpha$  (Haffner et al., 2003) or via pulsar dispersion measures. The densest portions of the WIM – the “dense warm ionized medium” (D-WIM; Langer et al., 2021) – are found just outside of  $\text{H II}$  regions, with electron densities  $10\text{--}30 \text{ cm}^{-3}$ , similar to those of  $\text{H II}$  regions (Roshi and Anantharamaiah, 1997; Heiles, 2001; Goldsmith et al., 2015), and containing up to a third of the WIM mass.

One of the major questions surrounding the WIM is the source of ionization. Based on energy considerations, the ionization of the WIM is most likely maintained by OB stars. Haffner et al. (2009) found that all of the energy from Galactic supernovae is required to maintain the WIM ionization, but only 15% of the energy from OB stars is required. The OB star hypothesis must be able to explain how OB star photons escape from their dense natal environments to reach large distances above the plane, ‘leaking’ through  $\text{H II}$  region photodissociation regions (PDRs) (e.g., Lockman, 1976; Anantharamaiah, 1986). The spectrum of the WIM differs from that of  $\text{H II}$  regions, however: it has characteristically lower  $[\text{O III}] / \text{H}\alpha$  and  $\text{He I} / \text{H}\alpha$  ratios as well as higher  $[\text{N II}] / \text{H}\alpha$  and  $[\text{S II}] / \text{H}\alpha$  ratios. Thus, if OB stars provide the requisite photons, the hardness of the radiation field must be modified as the photons leak from  $\text{H II}$  regions. To determine the source of ionization and how it is being softened, we need to trace the WIM from  $\text{H II}$  regions into more diffuse environments; with these observations we could show that the plasma properties can be explained as coming from individual  $\text{H II}$  regions (cf. Luisi et al., 2016).

Our present understanding of the WIM has been hampered by the lack of a facility that can connect these two regimes. Optical observations of the WIM are very sensitive, but suffer from extinction at locations where the D-WIM is found. Radio observations have lacked the necessary sensitivity, and so can detect the D-WIM, but not the more diffuse WIM. We need sensitive radio observations to investigate whether the WIM components have a common origin, determine their distribution, and to determine their plasma properties.

A connection between the D-WIM and  $\text{H II}$  regions was investigated by Anderson et al. (2015a), who found that the locations of large star-forming complexes in the inner Galaxy are correlated with the detection of multiple ionized gas components, which they interpreted as indicating the presence of the (dense) WIM preferentially toward massive star forming regions. Luisi et al. (2020) analyzed maps of RRL data and found that they could reproduce the extended ionized gas emission around the W43 star forming complex by assuming that all  $\text{H II}$  regions in the vicinity leak a percentage of their photons into the ISM. Because the kinetic temperature of the D-WIM is similar to that of the more diffuse WIM, the D-WIM is at a higher pressure.

The distribution of the WIM is also unclear, although it is well understood that the bulk of the dense gas is associated with high-mass star formation regions. Within the plane of the Milky Way, there appears to be a low-temperature (kinetic temperatures  $< 4,000$  K) component that is not associated with star formation. In a deep survey, taking  $\sim 20$  hours on source and  $\sim 200$  hours effective after



**Figure 4:** Galactic longitude, latitude, and LSR velocity ( $V_{\text{LSR}}$ ) distribution of 2,582 spectroscopic ionized gas measurements associated with 2,351 Galactic H II regions in the *WISE* Catalog of Galactic H II Regions (Anderson et al., 2014). An additional 21 measurements with  $|V_{\text{LSR}}| > 150 \text{ km s}^{-1}$  toward 20 nebulae (one at a Galactic longitude near  $\ell = 7.70^\circ$ , the rest near  $\ell = 358.75^\circ$ ) are excluded for clarity. Along sight-lines with multiple ionized gas velocity components, one or more of those components likely originates in diffuse ionized gas rather than a discrete H II region (Anderson et al., 2015b).

stacking 15 C-band RRLs, Bania et al. (2024) detected inner Galaxy diffuse ionized gas whose narrow line width implies very low electron temperatures. The emission may arise from cool diffuse plasma entrained in the Galactic bar, which would explain why it has no obvious sources of ionization, but does not provide an explanation for its cool temperature. To determine the extent and reasons for the low temperature of this component, very sensitive radio observations are required that are capable of tracing the ionized gas properties over a wide range of electron densities.

### 2.3 H II regions: deciphering Galactic structure

H II regions are formed around high-mass OB stars and are the classic tracer of spiral structure in galaxies (Rosse, 1850). In the Milky Way, the positions and kinematics of H II regions reveal structures that are interpreted as spiral arms (e.g., Georgelin and Georgelin, 1976; Hou and Han, 2014). For most Galactic H II regions, the distances to the nebulae are estimated kinematically by assuming a model of Galactic rotation (e.g., Anderson et al., 2012). These kinematic distances are subject to large, systematic uncertainties (Wenger et al., 2018; Peek et al., 2022). The three-

dimensional position and kinematic information provided by maser parallax observations constrain both the morphological structure as well as the kinematic structure of the Galactic disk (Reid et al., 2014, 2019). However, such measurements are only available for a few hundred nebulae, and are almost entirely confined to sources visible from the Northern hemisphere, due to the lack of Southern hemisphere facilities.

In the absence of parallax measurements or other independent distance estimates, the position-velocity (ppv) distribution is the fundamental observable dataset for Galactic structure tracers like H II regions and H I emission. For example, Figure 4 shows the Galactic longitude-velocity distribution of every nebula in the *WISE* Catalog of Galactic H II Regions (Anderson et al., 2014). This distribution encodes both the underlying three-dimensional structure of the tracer as well as the velocity structure along the line-of-sight. Traditionally, the kinematic distances to structure tracers are inferred under the assumption of an axisymmetric rotation curve (Wenger et al., 2018). Deviations from a simple Galactic rotation model, as seen in the Perseus arm, are known to systematically bias kinematic distance estimates and create “features” in the ppv distribution (Peek et al., 2022). Such features correspond to velocity caustics rather than true enhancements in the tracer density. With (1) a sufficient sample of Galactic structure tracers like H II regions, (2) a sophisticated model of Galactic morphological and kinematic structure, and (3) probabilistic inference tools like Markov chain Monte Carlo (MCMC) techniques, the degeneracies between three-dimensional density enhancements and velocity caustics in the ppv distribution could be broken *probabilistically*. Sufficiently sampled, the ppv distribution *constrains* models of Galactic structure.

In the inner Galaxy, an axisymmetric Galactic rotation curve causes an ambiguity in the inferred kinematic distance. There are two distinct distances at which matter is predicted to have the same radial velocity. This problem is known as the kinematic distance ambiguity (KDA). Since H II regions emit broadband thermal radio continuum, the presence of absorbing material in the foreground of an H II region can resolve the KDA (Anderson and Bania, 2009; Brown et al., 2014). Given the prevalence of cool H I in the Milky Way disk, H I emission/absorption observations are commonly used to resolve the KDA (Kuchar and Bania, 1994; Kolpak et al., 2003; Urquhart et al., 2012). Unless the KDA is resolved, the kinematic distances of H II regions are worse than unreliable: they are degenerate.

The continuum survey with SKAO in Band 5b covering the 10-15 GHz frequency range with a sensitivity of approximately  $20 \mu\text{Jy}$  and a resolution of  $\approx 0.07''$  is designed to identify hundreds of thousands of compact radio sources (Traficante et al., 2026). In particular, these catalogs will be sensitive enough to detect all H II regions across the Galactic disc from the youngest and smallest ones, the so-called hyper-compact H II regions, up to the more evolved and extended classical H II regions, providing a complete census of their population as well as their evolution. In addition, the statistical lifetimes of their early stages will be robustly determined.

However, H II regions are expected to account for only about 1% of the compact radio sources detected in these continuum surveys; thus, classifying them requires additional information. RRLs observed with SKA will play a crucial role in confirming H II region candidates identified from positional correlations with infrared and submillimeter catalogs (e.g., WISE Anderson et al. 2014;

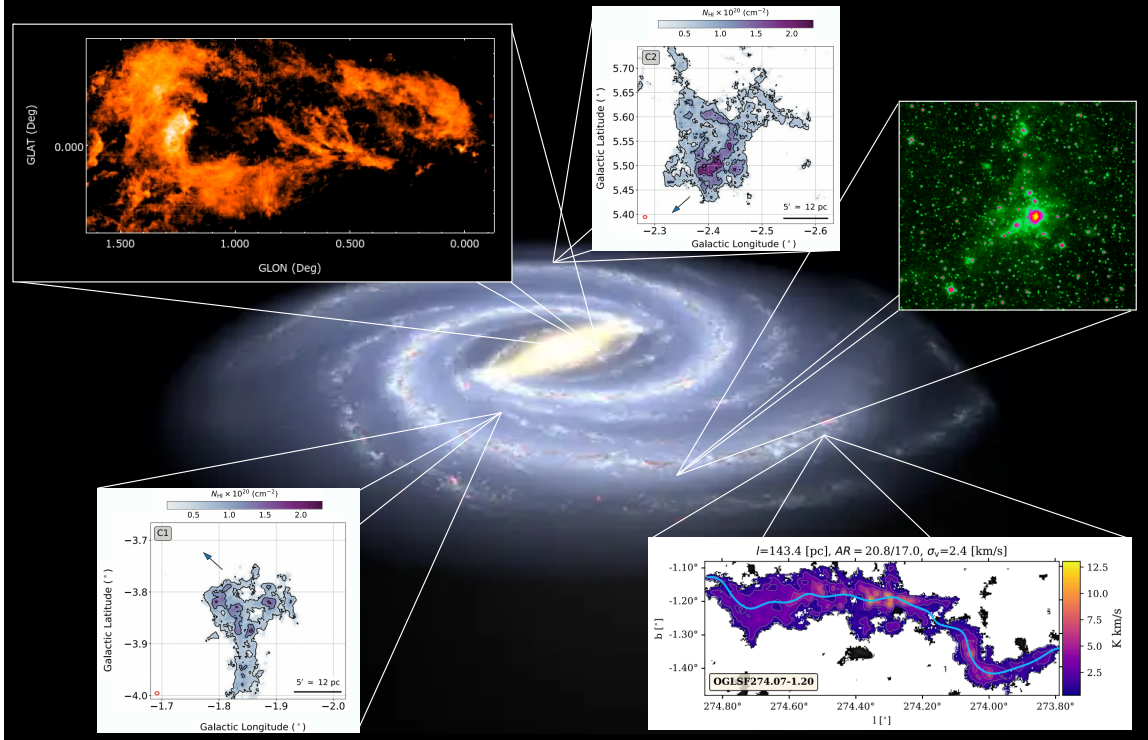
and Hi-GAL; Elia et al. 2017, 2021) and in their subsequent characterization. The detection of an RRL confirms that a source is Galactic, allows the distance to the H II region to be determined, and thus establishes its location in the Galaxy. The line-to-continuum ratio can be used to derive the electron temperature, while the line width provides information on the ionized gas kinematics and pressure broadening effects. The velocity of the line emission also makes it possible to identify the natal molecular material and to study the interaction between the molecular and ionized gas.

## 2.4 The Milky Way’s star formation in the context of galaxy evolution

The formation of stars occurs in molecular clouds that constitute the coldest and densest part of the ISM in galaxies, with kinetic temperatures  $T_{\text{kin}} \sim 10$  K and H<sub>2</sub> number densities  $n_{\text{H}_2} > 30$  cm<sup>-3</sup> (Kennicutt and Evans, 2012). Gravitational collapse of, and turbulent mixing in, molecular clouds leads to fragmentation, and the formation of smaller substructures: clumps – the birthplaces of stellar clusters ( $n_{\text{H}_2} \sim 10^4 - 10^5$  cm<sup>-3</sup>; sizes  $\sim 0.7$  pc, Traficante et al. 2015; Urquhart et al. 2018), and dense cores, forming individual stars or close multiple systems of stars within those clumps ( $n_{\text{H}_2} > 10^5$  cm<sup>-3</sup>; sizes  $< 0.1$  pc, Pineda et al. 2023). The rate of star formation is closely linked with the available reservoir of molecular gas, and this relationship seems to hold all the way from the size scales of dense clumps in the Milky Way (Wu et al., 2005, 2010) to those of starburst galaxies (Gao and Solomon, 2004).

Nevertheless, recent cloud-scale nearby galaxy observations (from e.g., the ‘Physics at High Angular resolution in Nearby Galaxies’, PHANGS survey) have shown that star formation is strongly regulated by the local environment, rapid cloud evolution, and stellar feedback (Schinnerer and Leroy, 2024). Molecular clouds appear short-lived, with lifetimes of roughly 10 to 30 Myr, inferred from spatial offsets between CO, H $\alpha$ , and UV emission, implying rapid cycling between cloud assembly, star formation, and dispersal (e.g. Kruijssen et al., 2019; Chevance et al., 2020). Stellar feedback from young clusters plays a central role in dispersing clouds and regulating the star formation process, preventing runaway collapse and maintaining low integrated efficiencies (e.g. Kim et al., 2022). As a result, only a few percent of molecular gas is converted into stars per free-fall time, allowing galaxies to sustain star formation over Gyr timescales rather than exhausting their reservoirs rapidly (e.g. Sun et al., 2020; Leroy et al., 2021).

These low SFEs have been observed to be mostly connected to the effects of large-scale dynamics, such as spiral arm streaming motions (e.g. Meidt et al., 2013), bar inflows (e.g. Egusa et al., 2018; Maeda et al., 2020; Hogarth et al., 2024), shear in galaxy centers (e.g. Leroy et al., 2013; Utomo et al., 2017; Hatchfield et al., 2020; Henshaw et al., 2023), and gravitational potentials from spheroids (e.g. Colombo et al., 2018) that increase the molecular cloud stability threshold and reduce gas fragmentation. Energetic processes, including active galactic nuclei and feedback from massive stars, can also contribute by heating the gas to temperatures unsuitable for the formation of stars. Indeed, the interplay between molecular gas availability and the ability to turn this gas efficiently into new stars is one of the main factors that establish the evolutionary stage of a galaxy (e.g. Saintonge et al., 2017; Colombo et al., 2020; Villanueva et al., 2024; Pan et al., 2024; Colombo et al., 2025). However, to establish which effect dominates requires a precise knowledge of the bulk of molecular gas available in a given star forming region in the Milky Way.



**Figure 5:** Galactic environments spanning the metallicity and dynamical diversity of the Milky Way, so far observed only in the CO-bright gas, forming the target sample for the proposed SKA line survey. Clockwise from top-left: high-velocity gas stream tracing bar-driven inflow in the Central Molecular Zone (Veena et al., 2024); an HVC toward the northern lobe of the nuclear outflow (Noon et al., 2023); the G195.722-0.120 high-mass star-forming complex in the far outer Galaxy (Urquhart et al. 2026, in prep.); the Falkor large-scale molecular filament in the outer Galaxy (OGLSF274.07-1.20, Colombo et al. 2021, Rodrigues da Costa et al. in prep.); and an HVC toward the southern lobe of the nuclear outflow (Noon et al., 2023).

Placing our understanding of Galactic star formation into its extragalactic context, we find that the Milky Way might not be the most efficient star forming engine, but instead a galaxy that is slowly reducing its star formation activity, on the way to becoming a retired object (e.g. Mutch et al., 2011; Licquia et al., 2015). This could stem from the dichotomy of observed inner and outer Galaxy behaviors: while the inner Galaxy appears to be actively forming stars, the outer Galaxy is generally quiescent. In fact, the Milky Way hosts a number of environments spanning a range of metallicity and dynamical properties such as the nuclear outflow, bar-driven inflow, and far outer Galaxy filaments and clumps (see Fig. 5). Therefore, by looking at the Milky Way we have the opportunity to understand not only how stars form, but also how stars stop forming, peering into one of the most important galaxy evolution processes at the highest level of detail possible.

We begin with the generally quiescent outer Galaxy, where a significant amount of molecular gas might be CO-dark. The sub-solar metallicity allows for less shielding, and greater penetration of UV photons. The consequences of this are warmer dust grains (van Loon et al., 2010) and more efficient photodissociation of molecules such as CO (Wolfire et al., 2003). This effect was demonstrated by far-IR observations of the H II region 30 Doradus in the Large Magellanic Cloud (LMC), where

75% of the molecular gas mass is suggested to be undetected with CO (Chevance et al., 2020). The outer Galaxy has a similar metallicity to the LMC, but an at least 10–100× lower UV radiation field (Browning et al., 2003; Abdo et al., 2010), thereby allowing us to disentangle the impact of both factors on the DMG properties. Building on the radial trends discussed in Section 2.1, and the evidence from absorption studies of HCO<sup>+</sup> and other molecules in the direction of the Galactic anti-center showing that large-scale CO surveys are not sensitive to H<sub>2</sub> columns associated with the dark neutral medium (Liszt and Lucas, 2000; Liszt and Gerin, 2023), we consider their implications for star formation efficiency across Galactic environments. A large scale survey of OH with the SKA, covering regions selected from the ‘Outer Galaxy High Resolution Survey’ (Colombo et al., 2021; Urquhart et al., 2025) CO survey of the entire third Galactic plane quadrant (180 < *l* < 280 deg), will be able to pinpoint the importance of CO-dark gas in the outer Galaxy and extend our understanding of the star formation efficiency trend from the inner to the outer Galaxy.

Turning to the more active inner Galaxy, DMG may also be expected in gas associated with bar-driven inflow and vertical fountain flows, especially in the diffuse material feeding or surrounding the CO-bright central molecular zone (CMZ). The non-circular motions driven by the Galactic bar redistribute gas inward, while elevated turbulence, shear, and cosmic-ray ionization can alter the chemical balance of the interstellar medium. In particular, high cosmic-ray ionization rates can selectively reduce the CO abundance even where H<sub>2</sub> is abundant (Bisbas et al., 2015), making some fraction of the inflowing molecular gas difficult to trace with standard CO emission. To understand how the Galaxy supplies material to its nucleus and regulates star formation there, it is therefore essential to directly constrain the molecular gas participating in these bar-driven inflows, including the CO-dark component. Within longitudes  $|l| \leq 10^\circ$  and latitudes  $|b| \leq 2^\circ$  (Fig. 2, Henshaw et al., 2023), bright H I and CO features ( $|V_{\text{LSR}}| > 100 \text{ km s}^{-1}$ ) trace streams of material flowing along the Galactic bar toward the central molecular zone (CMZ). These inflows play a decisive role in the growth and evolution of the CMZ, which itself contains the largest reservoir of dense molecular gas in the Milky Way and is the main driver of nuclear star formation. Although CO emission is clearly present in these streams (Gramze et al., 2023; Su et al., 2024; Veena et al., 2024), a significant fraction of the molecular component in the central regions is expected to be CO-dark because the cosmic-ray ionization rate in the CMZ is enhanced by up to 2–3 orders of magnitude compared to the Solar neighborhood (Ravikularaman et al., 2025), leading to the dissociation of CO and a parallel enhancement of OH through ion–molecule chemistry. As a result, OH absorption becomes an especially powerful probe of the molecular content in the bar inflows, offering the means to quantify the fraction of CO-dark H<sub>2</sub> in the gas that is actively feeding the CMZ. Indeed, the CMZ and inflowing streams both show evidence for copious OH absorption in single dish observations (Sawada et al., 2004; Yan et al., 2017; Dawson et al., 2022). However, the estimation of CO-dark fractions from these observations is extremely challenging, since the relative line-of-sight distributions of the emitting continuum and absorbing molecules are poorly constrained (see Dawson et al., 2022). These difficulties are mitigated for interferometric absorption, since the extended Galactic synchrotron emission is resolved out, there is far less confusion, and discrete background sources (with associated distance estimates) can be identified.

A complementary regime is provided by low and intermediate-latitude fountain flows (e.g., Di Teodoro et al., 2018; Noon et al., 2023; Veena et al., 2023), where gas is lifted from the disk by

stellar feedback and subsequently cools and returns. These structures contain moderate metallicity, partially shielded gas where molecules may either survive ejection or reform during descent. OH absorption toward compact continuum sources at  $|b| \leq 5^\circ$  allows the molecular content of vertically circulating gas to be mapped as a function of height above the plane. This provides a direct test of whether the CO-dark molecular phase is primarily created during vertical transport or reassembled following cooling, and therefore links feedback-driven outflows to disk re-accretion and long-term gas cycling. These regions would be covered by the proposed OH Galactic Plane survey discussed in Section 4.1, and the expected detection rates in these bright inner Galaxy regions are well represented by the source modeling presented there.

Star forming regions in the Galaxy might show a reduced star formation rate even though a substantial amount of molecular gas is present. Through understanding inner and outer Galaxy (enhanced and quenched) star formation, we are able to place our local example into its extragalactic context, enabling a better understanding of the ‘microphysics’ driving evolution of external galaxies. SKA will be essential for estimating the amount of DMG in a variety of environments and establish its role for star formation and galaxy evolution.

### 3 Molecular and atomic lines accessible with SKA

Among the tracers accessible to the SKA, the spectral lines of the simple hydrides OH and CH offer the most promising probes of molecular gas physics and formation, particularly that of CO-dark gas. OH and CH are able to trace molecular gas throughout its lifecycle, from the DMG (Wannier et al., 1993; Barriault et al., 2010; Allen et al., 2012, 2015; Li et al., 2018; Busch et al., 2019; Jacob et al., 2019; Busch et al., 2021; Jacob et al., 2021), through to dense star-forming clouds (e.g. Turner, 1979; Dawson et al., 2014, 2022; Rugel et al., 2018, 2025; Jacob et al., 2024; Cappellazzo et al., 2026). A denser molecular component of the ISM can be characterized in terms of mass and density using  $\text{H}_2\text{CO}$ , providing key advances in understanding of star formation efficiencies in galaxies (Mangum et al., 2008; Zeiger and Darling, 2010; Darling and Zeiger, 2012; Ginsburg et al., 2015; Gong et al., 2023). Radio recombination lines of atoms, primarily H, He, and C, are useful tools to both pinpoint the CO-dark gas and to identify the sources of ionization in the warmest components of the ISM. Table 1 lists the key lines of all of these species available to the SKA.

#### 3.1 The OH lines: widespread absorption detections with matched HI absorption

The 1.6 GHz HFS lines of OH are observed throughout the molecular ISM in ‘quasi-thermal’ (i.e., non-LTE but not strongly masing) emission and absorption (Turner, 1979; Dawson et al., 2014, 2022; Rugel et al., 2018, 2025; Beuther et al., 2019). The low transition probabilities ( $A \sim 10^{-11} \text{ s}^{-1}$ ) of these lines combined with the low relative abundance of OH ( $N_{\text{OH}}/N_{\text{H}_2} \sim 10^{-7}$ ) mean that the optical depths of these OH lines are generally small, and their surface brightness in emission is exceptionally low. Even the brightest OH ‘quasi-thermal’ emission detections, utilizing sensitive receivers on single-dish radio telescopes, are typically no more than a few hundred mK, and may be an order of magnitude fainter in the CO-dark regime (Allen et al., 2012, 2015; Busch et al., 2019, 2021; Busch, 2024). Our ability to detect OH with an interferometer therefore comes primarily from absorption line studies against bright continuum sources, including point-like extragalactic sources and resolved HII regions – both of which are copious at 1.6 GHz.

**Table 1:** Frequencies and spectroscopic properties of the key transitions

Species	Transition		Frequency [GHz]	$E_1$ [K]	SKA Band
	$N, J$	$F' - F''$			
OH	1, 3/2	$1^+ - 2^-$	1.6122	0.00259	Band 2
		$1^+ - 1^-$	1.6654	0.00000	
		$2^+ - 2^-$	1.6674	0.00259	
		$2^+ - 1^-$	1.7205	0.00000	
CH	1, 1/2	$0^- - 1^+$	3.2637	0.00072	Band 4
		$1^- - 1^+$	3.3354	0.00072	
		$1^- - 0^+$	3.3491	0.00000	
	1, 3/2	$2^- - 2^+$	0.7016	25.72766	Band 1
		$2^- - 1^+$	0.7039	25.72751	
		$1^- - 2^+$	0.7224	25.72766	
		$1^- - 1^+$	0.7247	25.72751	
H I	$^2S_{1/2}, F = 1-0$	1.4204	0.00000	Band 1	
H RRL <sup>a</sup>	$265\alpha - 184\alpha$	0.3513 – 1.0470	–	Band 1	
H RRL	$190\alpha - 155\alpha$	0.9512 – 1.7489	–	Band 2	
H RRL	$112\alpha - 92\alpha$	4.6188 – 8.3094	–	Band 5a	
H RRL	$92\alpha - 75\alpha$	8.3094 – 15.2815	–	Band 5b	
o-H <sub>2</sub> CO <sup>b</sup>	$N_{K_a, K_c}$				
		$1_{10}-1_{11}$	4.82966	0	Band 5a
		$2_{11}-2_{12}$	14.48848	6.75919	Band 5b

<sup>a</sup> RRL lines discussed in this Chapter cover Band 2 and 5b; the lines in additional bands are listed for completeness. <sup>b</sup> Lower-level energies refer to the ground-state of the o-H<sub>2</sub>CO, shifted by  $\approx 15$  K from the ground-state of p-H<sub>2</sub>CO. Note: The line frequencies of the CH transitions were measured in the laboratory by [Truppe et al. \(2014\)](#) with uncertainties of  $\approx 20$  Hz, those for the other species were taken from the Cologne Database for Molecular Spectroscopy (CDMS; [Endres et al., 2016](#)) and the Jet Propulsion Laboratory Molecular Database ([Pickett et al., 1998](#)).

As motivated in Section 2, a detailed understanding of the formation of molecular gas from the cold neutral medium (CNM) requires a statistical census of molecular and atomic gas properties across a large number of sightlines and a wide range of evolutionary stages. Comparisons between H I and OH absorption can achieve this, allowing us to constrain the thermal and physical properties of molecular and atomic gas on a component-by-component basis – including CO-dark diffuse H<sub>2</sub>. Literature comparisons are limited – always in sample size, often in sensitivity, and also in the degree to which the relationship has been explored. [Hafner et al. \(2023\)](#) measured OH and H I absorption toward 38 sightlines using a combination of data from the Arecibo 305 m telescope and the Australia Telescope Compact Array. They report a CNM H I column density threshold for molecular gas formation (a result also noted by [Li et al. \(2018\)](#), using largely the same Arecibo

sample), but no correlation between the physical properties of their H I and OH components, suggesting a potential decoupling of the atomic and molecular gas post-transition. [Rugel et al. \(2018\)](#) detect OH absorption toward 42 sightlines in the VLA THOR survey, confirming that OH and CO are generally well correlated, but do not perform a detailed comparison with H I. [Rugel et al. \(2025\)](#) analyze OH and H I absorption together with CO and [C II] emission toward 3 Galactic H II regions at a sensitivity 5 times better than THOR, discovering only one completely CO-dark component, but noting moderate molecular gas fractions toward many, and stressing the importance of deeper observations to widely detect DMG. The GASKAP-OH survey ([Dawson et al., 2024](#)) on the Australian Square Kilometre Array Pathfinder will reach similar sensitivities, and increase the sample size via a large Galactic Plane survey, but will still be an order of magnitude shallower than the SKA survey we propose in Section 4.

The unprecedented sensitivity and resolution of the SKA can provide something that has never before been achieved: a statistical census of thousands of matched pairs of OH and H I absorption spectra. Together with complementary CO data from the wealth of existing CO surveys (e.g., [Duarte-Cabral et al., 2021b](#); [Colombo et al., 2022](#)), these can provide the most complete census to date of the cold ISM pre, post, and during its transition to the molecular phase – resolved on the sub-parsec spatial scales on which the key physical processes operate. While CO data is an important part of this picture, the combination of matched OH and H I absorption spectra provides a significant advantage: the common background source and high spatial resolution mean we can be sure that the two tracers are genuinely probing the same volumes of gas (a problem that plagues comparisons of H I and CO, particularly in the confused Galactic Plane). This means that our ability to assess the association of the two phases will be exquisite. Furthermore, we will be able to measure the physical state of both the CNM and molecular gas. For H I, the absorption can be combined with off-source emission measurements to return robust measurements of the physical state of the CNM ([McClure-Griffiths et al., 2023](#)). Although equivalent off-source OH emission spectra are not a realistic prospect, we have an alternative: the OH line ratios (particularly in the 1612 and 1720-MHz satellite lines) are sensitively dependent on environmental conditions, and can be modeled to constrain temperature, density, radiation field and column density (e.g. [Guibert et al., 1978](#); [van Langevelde et al., 1995](#); [Ebisawa et al., 2019](#); [Hafner et al., 2020](#)). We will further outline the details of a proposed OH Galactic Plane survey in Section 4.1.

### 3.2 The ground-, and first excited state lines of CH

Like OH, CH serves as a powerful probe of molecular interstellar clouds. Although CH holds the distinction of being the first molecule detected in space ([Swings and Rosenfeld, 1937](#); [McKellar, 1940](#); [Adams, 1941](#)) – via optical absorption near 4300.3 Å – its radio transitions near 3300 MHz, corresponding to the HFS lines of its ground electronic state, remained underutilized for many years despite being ubiquitously detected. This was because these lines were almost always observed in emission, even against bright background sources, and the relative intensities of the three HFS components often deviated from their expected values under conditions of local thermodynamic equilibrium (LTE;  $I_{3264 \text{ MHz}} : I_{3335 \text{ MHz}} : I_{3349 \text{ MHz}} = 1 : 2 : 1$ ). These anomalies indicated that the populations of the HFS lines of the CH ground-state  $\Lambda$ -doublet levels are inverted. The widespread detection of this population inversion across diverse environments suggested the presence of a

general pumping mechanism that preferentially populates the upper HFS levels of the ground-state  $\Lambda$ -doublet, largely independent of local conditions.

Recently, [Jacob et al. \(2021\)](#) performed detailed non-LTE radiative transfer modeling with the MOLPOP-CEP code ([Asensio Ramos and Elitzur, 2018](#)), incorporating the effects of preferential pumping from line overlap. Aided by a combination of HFS-resolved collisional rate coefficients for collisions between CH and o-/p-H<sub>2</sub> ([Dagdigan, 2018](#)), He ([Marinakis et al., 2019](#)), and electrons ([Jacob et al., 2024](#)), these authors were able to reproduce the observed intensities and level inversion (see [Rygl et al. 2026](#) for more information on CH excitation). The models were further constrained by column density measurements from CH FIR lines at 2 THz ([Jacob et al., 2019](#)). This joint modeling effort has significantly advanced our understanding of CH excitation and its observational diagnostics, and it now enables reliable interpretation of CH data even in the absence of complementary FIR column density estimates—highlighting that, despite the lack of current SKA support for S-band observations, pursuing CH remains a particularly fruitful venture given that its lines are almost always optically thin. Presently the only ‘large-scale’ study of the ground state lines of CH is being carried out under the framework of the MPIfR-MeerKAT Galactic Plane survey (MMGPS; [Padmanabh et al., 2023](#)).

In addition to the ground-state lines, the HFS transitions of CH in its first excited state at 700 MHz are particularly important for constraining the pumping scheme of the ground-state maser. To date, these lines have been detected only in the ISM, toward the W51 giant molecular cloud complex, first with the Arecibo 305 m telescope ([Ziurys and Turner, 1985](#)), and more recently with the upgraded Giant Metrewave Radio Telescope (uGMRT) by [Jacob et al. \(2024\)](#). Jointly modeling these lines with the ground-state lines has revealed that unambiguous detection of these lines requires targeting regions with strong 700 MHz continuum emission and moderately high gas densities—sufficiently high to excite the transition but not exceeding  $\sim 10^6 \text{ cm}^{-3}$  (on scales  $< 0.5 \text{ pc}$ ), as is often the case in high-mass star-forming regions. The principal limitation in detecting this line more widely has been sensitivity, yet such observations are essential for building a more complete picture of CH excitation in the ground state. Moreover, the 700 MHz HFS lines offer unique potential as probes of the line-of-sight magnetic field via the Zeeman effect, owing to CH’s unusually large Landé  $g$ -factor. This diagnostic is especially relevant at gas densities of a few  $\times 10^5 \text{ cm}^{-3}$ , comparable to the critical density of the rotational transition connecting the ground and first excited levels ([Bourke et al., 2026](#)). With its unprecedented sensitivity across Bands 1 and 2 (in the future), the SKA will provide the first real opportunity to study CH comprehensively in the radio sky, greatly extending its utility as a tracer of CO-dark molecular gas.

### 3.3 o-H<sub>2</sub>CO: a clean tracer of molecular gas masses and densities

The lowest two transitions of formaldehyde (o-H<sub>2</sub>CO at 4.8 and 14.4 GHz) accessible with the SKA-Mid Band 5 receivers open up a new path to determine gas masses and densities in molecular clouds. These transitions show anomalous absorption: their collisional excitation drives an ‘anti-inversion’ which cools the lines below the temperature of the cosmic microwave background (CMB); the transitions absorb CMB photons and appear in absorption against the CMB ([Palmer et al., 1969](#); [Townes and Cheung, 1969](#)). Since the CMB is isotropic, the absorption depends only on the total number of absorbing molecules and is distance-independent; thus, the gas masses can be accurately

determined.

The ratio of the 4.8 and 14.4 GHz lines is a useful tool to determine gas densities, since it is mostly determined by the volume density of H<sub>2</sub> (Mangum et al., 2008; Ginsburg et al., 2011). The anomalous absorption of H<sub>2</sub>CO lines has been considered to be unaffected by sub-thermal excitation, line trapping or optical depth effects, which often complicate the interpretation of the emission lines. However, recent calculations of collisional excitation, including collisions with electrons, demonstrate that the excitation of the low-frequency ortho-H<sub>2</sub>CO transitions might depend not only on H<sub>2</sub> density and kinetic temperature, but also on the electron fraction (Gerin et al., 2024). In particular, the 1<sub>10</sub>–1<sub>11</sub> transition at 4.8 GHz is predicted to have an excitation temperature below the CMB for low to moderate electron fractions ( $x(e) < 6 \cdot 10^{-5}$ ), but to exceed the CMB at higher electron fractions ( $x(e) > 10^{-4}$ ), potentially suppressing or reversing the anomalous absorption (Gerin et al., 2024). Thus, the interpretation of ortho-H<sub>2</sub>CO absorption also depends on the local ionization conditions, at least in the studies which focused on diffuse and translucent gas.

In Galactic studies, H<sub>2</sub>CO absorption is typically measured against either the CMB or bright Galactic continuum sources (e.g., H II regions), probing relatively short and well-defined path lengths through individual molecular clouds. In contrast, absorption against bright extragalactic continuum sources such as quasars provides pencil-beam lines of sight that integrate over all intervening material along the entire path through the Milky Way (and potentially beyond). These quasar lines of sight therefore probe diffuse and translucent gas components that may be missed in targeted Galactic observations, but they also introduce line-of-sight averaging over regions with potentially varying electron fractions, densities, and excitation conditions. As a result, given these newly computed collisional rate coefficients, the impact of electron excitation on the 4.8 GHz transition remains to be systematically explored in Galactic environments.

H<sub>2</sub>CO was successfully detected toward the Galactic Center (Zylka et al., 1992; Ginsburg et al., 2015) and several Galactic H II regions (Ginsburg et al., 2011; Gong et al., 2023), as well as star-forming galaxies (Mangum et al., 2008; Zeiger and Darling, 2010; Darling and Zeiger, 2012). However, the lines are faint and narrow, and therefore not suitable for large-scale surveys. Gong et al. (2023) report the results of the GLOSTAR survey toward the Cygnus-X star forming region. While widespread absorption is revealed in single dish Effelsberg maps, the high noise of the interferometric GLOSTAR observations (1.7 K per 0.5 km s<sup>-1</sup> channel) results in absorption on small scales only being detected toward the brightest continuum sources. Clearly, there is a need for much deeper interferometry to reveal molecular structures on small scales.

SKA will be able to detect H<sub>2</sub>CO in absorption toward a range of environments in the Milky Way, constraining physical conditions of denser ISM. Combined with OH observations, H<sub>2</sub>CO lines will help to establish the role of CO-dark gas for star formation across various density regimes in molecular clouds, characterized by different metallicities (see Section 2.4).

In addition, non-anomalous absorption is expected to be detected toward thousands of bright continuum sources both within the Milky Way and beyond (e.g. radio galaxies and H II regions; see Martin-Pintado et al. 1985; Arnal and Goss 1985; Kogut et al. 1989; Brunthaler et al. 2021). Since many H II regions will have accurately measured trigonometric parallaxes from associated maser

sources (Rygl et al., 2026), it might be possible to conduct 3D tomography of the molecular ISM by using a network of hundreds of known illuminating sources with well-characterized heliocentric distances.

### 3.4 Radio recombination lines of H, He, and C

RRLs are produced when ions and electrons recombine into an excited state and the electron transitions toward the ground state. They are the higher principal quantum number corollaries to  $H\alpha$  emission for hydrogen. RRLs can be used to derive plasma properties such as temperature and density, as well as kinematic distances to the emitting plasma using a Galactic rotation curve model. Because they are found throughout the radio band, and because their similar properties allow them to be stacked to increase sensitivity, RRLs are an excellent probe of ionized (for H and He RRLs) and neutral (for C) gas.

RRL emission does not suffer from extinction and with line-stacking can be quite sensitive (Beuther et al., 2016); it is therefore the ideal tool for investigating ionized hydrogen of the WIM and H II regions. Three recently completed single-dish surveys, SIGGMA (Liu et al., 2013; Liu et al., 2019), GDIGS (Anderson et al., 2021), and L-band FAST RRL survey (Hou et al., 2022), show the promise of fully-sampled RRL maps but lack the sensitivity and angular resolution to fully investigate the properties and distribution of the WIM.

Because the ionization potential of helium is nearly twice that of hydrogen, the ionic helium-to-hydrogen ratio,  $y^+$ , indicates the hardness of the radiation field. Within any RRL observation, the lines of He are shifted  $-122 \text{ km s}^{-1}$  from those of H, and so usually fall within the same bandpass. Observations have shown that  $y^+$  is similar between the WIM and the D-WIM (Luisi et al., 2019), which indicates that the ionizing radiation fields are similar. These observations have to date been limited to only dense plasmas; sensitive observations are required to determine  $y^+$  over the entire Galaxy.

Carbon RRLs are an excellent tracer of the atomic ISM. The ionization potential of carbon is less than that of hydrogen, so in areas where hydrogen is neutral we still find ionized carbon. C RRLs are therefore efficient tracers of the properties of photodissociation regions (PDRs; Salas et al., 2019), and a useful tool to identify CO-dark gas in low-metallicity regions. Like He RRLs, C RRLs are also usually in the same bandpass as H RRLs, shifted  $-150 \text{ km s}^{-1}$  from those of H.

SKA will enable a large-scale RRL survey of the Galactic midplane at  $\sim 20\times$  the sensitivity of GDIGS (see Section 4). This would allow us to trace RRL emission from H II regions into the ISM, test the hypothesis that OB stars provide the requisite photons for maintaining the WIM, determine the hardness of the radiation field through measurements of  $y^+$ , and allow for the determination of PDR properties using C RRLs. It would also allow for a thorough investigation of the cool WIM seen by Bania et al. (2024) and its connection to other Galactic features.

### 3.5 Note on H I self-absorption

While details of H I surveys are outside the scope of this chapter, it is worth briefly mentioning H I self-absorption (HISA). The SKA will map the H I 21 cm line at unprecedented resolution and surface brightness sensitivity, and in particular will provide a new census of self-absorption

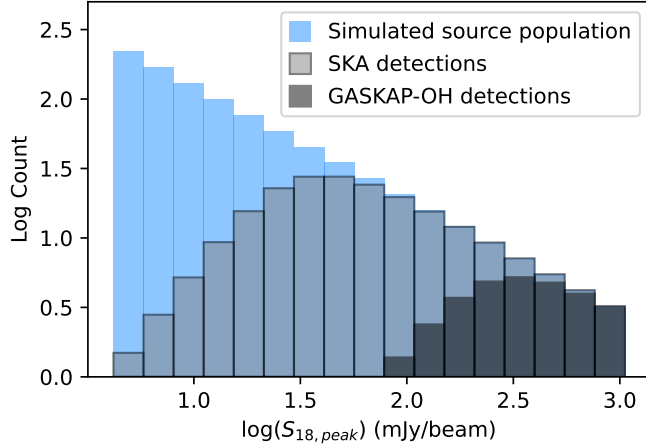
from regions where CNM is projected against the warm H I background emission (e.g., Gibson et al., 2000; Kavars et al., 2005). Observational studies have found HISA clouds to trace the structure of the CNM (e.g. McClure-Griffiths et al., 2006), to typically host molecular gas (as seen via associated tracers such as CO; e.g. Wang et al. 2020; Syed et al. 2023), but also to arise directly from molecule-dominated regions in the case of the narrowest HISA features (e.g., Li and Goldsmith, 2003). Indeed, recent simulations confirm that HISA may arise not only from the CNM but also from dissociated H<sub>2</sub> within self-gravitating molecular clouds, where the latter component is often missed through observational bias and highly susceptible to the structure of molecular clouds (Seifried et al., 2022). We refer the reader to Miville-Deschênes et al. (2026) for a more detailed discussion of H I with the SKA, and here simply highlight that observations of HISA will provide additional constraints on the structure of the CNM around molecular clouds and on the detailed process of the H I -to-H<sub>2</sub> transition.

## 4 Proposed observations

### 4.1 Galactic plane survey in OH

As discussed in Section 3.1, an SKA Galactic Plane survey in OH absorption – when paired with an equivalent H I survey – would provide a statistical census of thousands of matched pairs of OH and H I absorption spectra. Such a dataset would allow us to statistically track how the presence and properties of the molecular gas vary with CNM properties and with  $R_{\text{Gal}}$  and local Galactic environment. We would be able to pin down the CNM conditions required for molecule formation, including distinguishing DMG from CO-bright H<sub>2</sub>. We would be able to assess correlations between H I and H<sub>2</sub> physical properties, measuring the imprint of the CNM upon the molecular gas formed within it. We would be able to assess correlations both spatially (across resolved background sources) and spectrally (e.g., profile shapes, linewidths) to constrain the degree of mixing of the molecular and atomic phase, and compare our results with the predictions of H<sub>2</sub> formation models (e.g. Goldsmith et al., 2007; Sternberg et al., 2014; Seifried et al., 2017; Bialy et al., 2017) to comment on key properties such as the turbulent properties and degree of clumping of the host CNM (Park et al., 2023). These analyses coming together, in a statistical way across varied conditions that exist in the plane of the Milky Way, could constitute a generational change in our understanding of the transitions between the key phases and gas populations in our Galaxy.

The sensitivity of OH absorption measurements is driven by the flux density distribution of the background continuum source population. In the Galactic Plane this consists of both compact extragalactic sources and resolved H II regions and supernova remnants – the latter of which often dominate the bright source population, particularly in the inner Galaxy. The measured flux density distribution of resolved sources is strongly affected by  $uv$  coverage and imaging parameters and is therefore not straightforward to predict. The expected optical depth distribution of OH in the Galactic Plane is similarly not well constrained, but likely ranges from  $\lesssim 0.01$  (as seen in very diffuse, off-Plane sightlines; Li et al., 2018; Nguyen et al., 2018; Hafner et al., 2023) to  $\tau \sim 1.0$  as seen toward some star-forming gas associated with H II regions (e.g., Rugel et al., 2018; Koley et al., 2021; Cappellazzo et al., 2026). In order to constrain both of these distributions and make meaningful predictions about detection rates, we turn to Australian SKA Pathfinder (ASKAP) data



**Figure 6:** Simulated detection rate for OH absorption over a 600 square-degree SKA survey of the Galactic Plane. The simulated data is generated as described in the text. This treatment considers only the brightest position toward a simulated source, and is in that sense a lower limit. For extended bright sources, multiple/resolved detections are likely; for extended weak sources, integrating spatially to improve sensitivity could yield detections not modeled here. Conversely, the source population is modeled from a relatively bright region of the Galactic Plane (likely overestimating compared to a larger survey) but extending to  $|b| \lesssim 2.1^\circ$  – higher than an SKA survey likely would. While the exact numbers here are therefore subject to some uncertainty, the order of magnitude detection rate and improvement over GASKAP-OH (the closest competitor) are reasonable.

from the GASKAP-OH survey (Dawson et al., 2024). With baselines ranging from 22m to 6km and fairly dense  $uv$  coverage, particularly on shorter baselines, the appearance of the complex in-Plane continuum in ASKAP data is likely to be comparable to that of the AA4 array (though the imaging fidelity with AA4 should be superior). Dawson et al. (2024) report the OH detection rate as a function of optical depth sensitivity ( $\sigma_{e^{-\tau(v)}}$ ) for a single  $\approx 20$  square-degree GASKAP-OH field centered on  $l \approx 340^\circ$  and extending between  $|b| \lesssim 2.1^\circ$ . We take the continuum source peak flux density distribution ( $S_{\text{peak}}$ ) from the same data<sup>1</sup>, which are well described by a simple power law, and extrapolate down to a flux density limit of 5 mJy. We assume an on-source time of 600s and adopt reasonable imaging parameters to obtain a spectral sensitivity at 1.6 GHz of  $\sigma_v \sim 1$  mJy for a velocity resolution of  $0.75 \text{ km s}^{-1}$ . With optical depth sensitivity defined as  $\sigma_{e^{-\tau(v)}} = \sigma_v / S_{\text{peak}}$ , we thus can obtain a simulated source population and detection statistics for a hypothetical SKA survey.

Figure 6 shows the results of this simulation, together with a description of the caveats. In the inner Galaxy where the on-sky source density of HII regions and SNRs is high, we expect to detect OH absorption toward at least  $\sim 10$  sources/deg<sup>2</sup> (many with multiple spectral components), and to produce *resolved maps* of OH optical depth toward the brighter continuum complexes, enabling us to track small-scale variations in gas properties at a resolution of  $\sim 4''$  ( $\sim 0.05$  pc at a representative distance of 3 kpc). In the outer Galaxy where the source distribution will trend

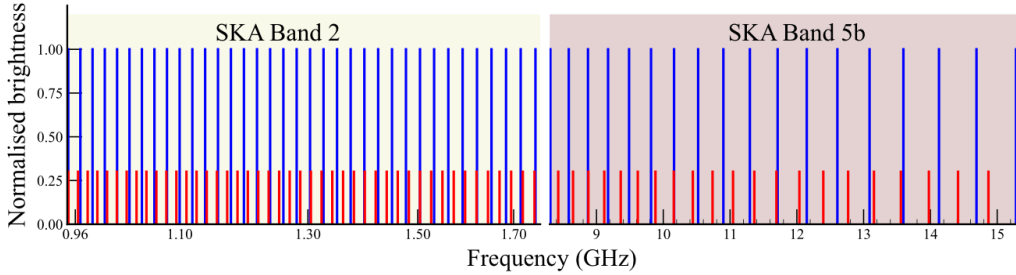
<sup>1</sup>Extracted from contiguous ‘islands’ of emission identified by the *Selavy* sourcefinder (Whiting and Humphreys, 2012)

toward the (generally weaker) extragalactic population, and the OH optical depth may be lower, the detection rate is expected to be correspondingly smaller. Alongside an unbiased survey of the inner Galaxy, deeper integrations toward targeted outer Galaxy fields would therefore be a more efficient use of telescope time.

Although the 3 GHz (Band 4) receiver remains unfunded at present, the exceptional sensitivity of the SKA offers a unique opportunity to probe the 700 MHz CH lines on a large scale for the first time. The excitation of these CH transitions is primarily dominated by collisions, and as a result they are expected to appear in absorption against the bright background envelopes surrounding the targeted star forming regions (see Sect. 5.3 of Jacob et al., 2024). Toward W51 E (the only known source toward which this line has been unambiguously detected), Jacob et al. (2024) detect absorption that is only a few % of the continuum. Therefore, a primary reason for its non-detection thus far has been due to sensitivity issues arising from the weaker background continuum emission at 700 MHz. SKA will allow us to probe down to 5 mJy, sufficient to detect CH absorption at a minimum of a  $3\sigma$  level (based on previous observations).

## 4.2 H II regions

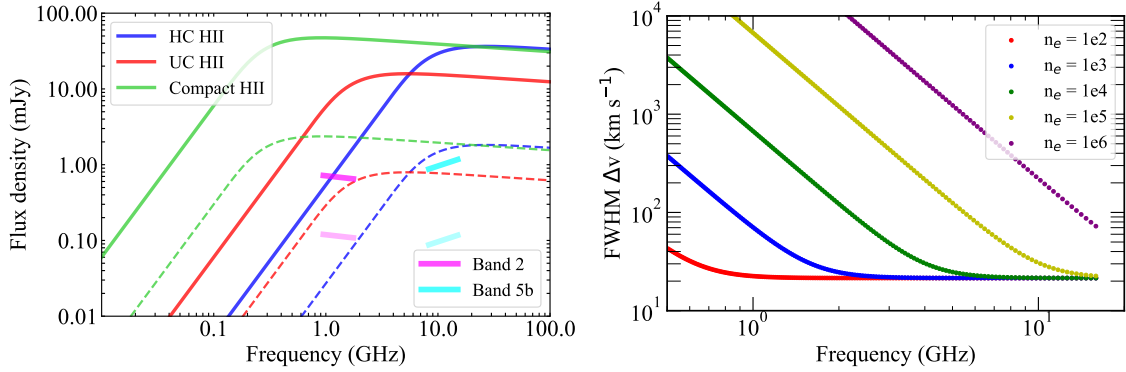
There are 36  $H\alpha$  RRLs available in Band 2 and 17 in Band 5b. Using the SKA sensitivity calculator with an integration time of 600 s and assuming a robust weighting of 1 gives a sensitivity of  $\sim 0.7$  mJy beam $^{-1}$  per 3.5 km s $^{-1}$  channel in Band 2 and  $\sim 1$  mJy beam $^{-1}$  per 4.5 km s $^{-1}$  channel in Band 5b, with beam sizes of  $\sim 1$  arcsec and  $\sim 0.1$  arcsec, respectively.



**Figure 7:** Schematic showing the RRLs within the SKA Bands 2 and 5b. The blue and red lines show the frequencies of the  $H\alpha$  and  $H\beta$  lines respectively. There are 36  $H\alpha$  RRLs in Band 2 (beige shaded region) and 17  $H\alpha$  RRLs in band 5b (pink shaded region).

The sensitivities in Band 2 can be improved by stacking RRLs (Figure 7). This is also possible in Band 5b, but the number of available lines within each 2.5 GHz window is much smaller, and the process is more complicated because the line intensity depends on frequency. However, the sensitivity in Band 5b can be straightforwardly enhanced by smoothing the data to a 1-arcsec beam.

In Figure 8, we show the expected continuum and RRL fluxes for the three most compact stages of H II regions located at a distance of 20 kpc, assuming a line-to-continuum flux ratio of 20. We also show the RRL sensitivities (brighter magenta and cyan bars) as well as the improved sensitivities achievable by stacking and/or smoothing the data. These results demonstrate that the SKA will be capable of detecting RRLs from all compact H II region stages; however, detecting the two most compact stages will be challenging in Band 2.



**Figure 8:** Left Panel: Predicted flux densities for the three most compact H II region stages. The solid and dashed lines show the continuum and RRL fluxes respectively. The bright magenta and cyan bars show the sensitivity to RRLs estimated from the SKA sensitivity calculator assuming a 600 second integration, robust weighting of 1 and channel width of  $\sim 3.5$  and  $4.5 \text{ km s}^{-1}$ . The pale magenta and cyan bars show the improvement to the sensitivity from stacking the RRLs in Band 2 and smoothing to 1-arcsec resolution in Band 5b. Right panel: Shows the impact of pressure broadening to the expected RRL line-width as a function of electron density and frequency.

A further complication arises from pressure broadening, which is significant for compact H II regions with high electron densities, particularly at low frequencies. This effect is especially severe in Band 2, leading to line widths of hundreds of  $\text{km s}^{-1}$  for moderate electron densities ( $\sim 10^4 \text{ cm}^{-3}$ ), and may limit the usefulness of Band 2 to the more extended compact H II regions. In contrast, pressure broadening is much less severe in Band 5b, which is better suited for probing the most compact H II regions. However, Band 5b is less sensitive to more extended H II regions, which are more easily filtered out.

The two bands are therefore complementary: Band 2 is more sensitive to larger H II regions with lower electron densities, while Band 5b is more sensitive to smaller, denser H II regions. Combining observations from both bands will be essential for achieving a complete census of the compact H II region population. We note there are a further 21 H $\alpha$  RRLs in Band 5a (i.e., 4.6-8.5 GHz) that can enhance the analysis and provide additional constraints on the evolutionary modeling but the focus of this chapter is on Band 2 and 5b.

### 4.3 Physical conditions of dense ISM with H<sub>2</sub>CO

Formaldehyde absorption at 4.8 and 14.4 GHz has been mapped with single-dish surveys for several regions in the Milky Way down to angular scales of  $\geq 1'$  (e.g., Zylka et al., 1992; Ginsburg et al., 2015; Gong et al., 2023), but wide area surveys at much higher angular resolution are more challenging. For example, to detect formaldehyde absorption lines from Galactic clouds requires a sensitivity of  $\sim 0.1$ - $0.2 \text{ K}$ , which takes at least a full 12-hour track with the VLA, yielding a synthesized beam of  $21'' \times 18''$  at  $\sim 4.8 \text{ GHz}$  (Evans et al., 1987). For comparison, the wide area GLOSTAR JVLA survey reaches an rms sensitivity of  $1.7 \text{ K}$  per  $0.5 \text{ km s}^{-1}$  channel for the 4.8 GHz formaldehyde line and so can only reveal the brightest components (Gong et al., 2023).

The SKA-Mid will fundamentally revolutionize this type of investigation across the Galactic plane,

combining sensitive and high angular resolution observations with a wide Field of View ( $\sim 12.5'$  and  $\sim 6.7'$  in Bands 5a and 5b, respectively; [Braun et al. 2019](#)). For instance, exploiting Band 5a receivers ( $\nu_0 = 4.8$  GHz, see Tab. 1;  $\Delta\nu = 6.72$  kHz), an rms noise level of approximately 0.2 K can be achieved in  $\sim 20$  hours using the AA4 configuration, yielding a synthesized beam of  $\sim 7''$  (Briggs; robust = 0), considerably smaller than the  $\sim 20''$  beam of VLA observations at these frequencies ([Evans et al., 1987](#)). This sensitivity will allow us to spectrally resolve the  $\text{H}_2\text{CO } 1_{10-1_{11}}$  lines, which have a typical FWHM of  $\sim 1 \text{ km s}^{-1}$ , as reported by [Evans et al. \(1987\)](#). In a comparable amount of time, an  $\text{H}_2\text{CO } 2_{11-2_{12}}$  detection will be feasible using the SKA-Mid Band 5b receiver ( $\nu_0 = 14.5$  GHz, see Tab. 1;  $\Delta\nu = 13.44$  kHz), achieving an rms of  $\sim 0.1$  K with a synthesized beam of  $\sim 3.5''$  (Briggs; robust = 1). This capability makes it feasible to survey the Milky Way’s molecular clouds at significantly better angular resolution than existing single-dish CO surveys, and without the excitation or optical depth issues that typically affect those CO observations.

## 5 Summary and outlook

The SKA will open a new discovery space in Galactic ISM studies by enabling wide-area, high-fidelity spectroscopic surveys that combine deep continuum mapping with simultaneous spectral line observations at high velocity resolution. By leveraging these capabilities, the proposed OH absorption line survey of the Galactic Plane, combined with matched H I data, will deliver the first large-scale statistical census of OH–H I absorption pairs. This dataset will quantify how molecular gas emerges from the CNM, including identifying the physical conditions that regulate  $\text{H}_2$  formation, distinguishing CO-bright and CO-dark molecular components, and directly measuring how the CNM structure and dynamics imprint on newly formed molecular gas. A future pathway for 3 GHz (Band 4) CH absorption line measurements will provide a complementary and highly sensitive tracer of diffuse molecular gas when this SKA receiver becomes available.

At the same time, targeted RRL observations across Bands 2 and 5b will provide a comprehensive view of the compact H II region population, tracing the evolution of ionized gas from the densest hyper-compact objects through to extended compact regions. The complementarity of the two bands – with Band 2 optimized for more extended, lower-density regions, and Band 5b sensitive to the youngest, densest regions less affected by pressure broadening – will be critical to constructing a complete evolutionary census. When combined with continuum survey products, even shallow per-pointing integrations can yield powerful RRL constraints through line stacking and beam-matched smoothing, demonstrating the efficiency of commensal survey strategies. Together, these experiments will deliver: (i) the largest absorption-based inventory of molecular gas tied directly to CNM properties; (ii) spatially resolved maps of OH opacity across key continuum complexes, probing sub-pc-scale ISM structure; (iii) empirical constraints on  $\text{H}_2$  formation models under realistic Galactic conditions; and (iv) a unified, multi-band RRL census of compact H II regions across the Milky Way.

More broadly, these observations showcase the unique impact of SKA’s multi-line, wide-band survey mode. Building on the legacy of VLA pathfinder programs such as THOR, GLOSTAR, and the L-band Local Group Survey, an SKA survey designed for commensal continuum and spectral line

science will not only maximize discovery potential, but will also directly inform optimal correlator configurations, survey cadences, and stacking strategies for next-generation ISM studies.

By simultaneously charting the molecular, atomic, and ionized phases of the Milky Way with unprecedented sensitivity and statistical power, the SKA will enable a step change in our understanding of phase transitions in the Galactic ecosystem – from how molecules first assemble in the diffuse ISM to how massive stars reshape their natal environments. This integrated view has the potential to redefine Galactic ISM studies for decades to come, while providing essential benchmarks for star-forming galaxy physics across cosmic time.

## **Acknowledgments**

A. K. acknowledges support from the Polish National Science Center SONATA BIS grant No. 2024/54/E/ST9/00314. A. M. J. and V. V. S. would like to acknowledge the support of the Max Planck Society. D. C., A. K., A. M. J., and V. V. S. gratefully acknowledge the Collaborative Research Center 1601 (SFB 1601 sub-project B3, A1, and B2) funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 500700252. M.P.B. is supported by a Jansky Fellowship provided by the National Radio Astronomy Observatory. The National Radio Astronomy Observatory and Green Bank Observatory are facilities of the U.S. National Science Foundation operated under cooperative agreement by Associated Universities, Inc. G. S. acknowledges financial support under the National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.1, Call for tender No. 104 published on 2.2.2022 by the Italian Ministry of University and Research (MUR), funded by the European Union – NextGenerationEU-Project Title 2022JC2Y93 Chemical Origins: linking the fossil composition of the Solar System with the chemistry of protoplanetary disks – CUP J53D23001600006 – Grant Assignment Decree No. 962 adopted on 30.06.2023 by the Italian Ministry of Ministry of University and Research (MUR); the project ASI-Astrobiologia 2023 MIGLIORA (“Modeling Chemical Complexity”, F83C23000800005); the INAF-GO 2024 fundings ICES, the INAF-GO 2023 fundings PROTOSKA (“Exploiting ALMA data to study planet forming disks: preparing the advent of SKA”, C13C23000770005) and the INAF Minigrant 2023 TRIESTE (“TRacing the chemIcal hEritage of our originS: from proTostars to planEts”; PI: G. Sabatini). V.V.S acknowledges the support of the Department of Atomic Energy, Government of India, under Project Identification No. RTI 4012.

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