



## Next Generation VLA Science White Paper

Working Group 2: “Galaxy Ecosystems”

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**Abstract.** The “next-generation” Very Large Array (ngVLA) will be a powerful tool to study the detailed astrophysics of star formation both within the Milky Way and nearby galaxies. With an unprecedented combination of high angular resolution and both line and continuum sensitivity, this revolutionary facility will: (1) provide new insight on the fundamental physics behind radio emission; (2) allow detailed spectroscopic characterization of the interstellar medium in all sorts of astronomical systems; (3) directly measure the ionizing photon rate of newly formed massive stars with the ability to penetrate through high columns of dust for extremely compact, embedded systems; (4) study dust physics by accessing the cold/massive dust component that powers the Raleigh-Jeans tail of dust spectral energy distributions; and (5) directly study the role of magnetic fields on the star formation process by increasingly pushing into the Faraday-thin regime where polarization observations should begin to probe deep into star forming regions. The combination of sensitivity and astrometric accuracy promised by the ngVLA will further allow studies of the motions around black holes and at the

base of jets, measurements of proper motions in Local Group galaxies, and refinements to our knowledge of Galactic structure. In this White Paper, we discuss the qualitative gains expected for such Galaxy Ecosystem science using three key themes that will ultimately drive telescope specifications, namely: Spectral Line Imaging; Sensitive, Broad-Band Continuum Imaging; and Very High Resolution/High Sensitivity Imaging.

## 1. Introduction

Radio telescopes are essential to our understanding of “galaxy ecosystems,” here meaning the complex interplay of gas, stars, black holes, and dark matter in and around galaxies. They provide a main tool to study almost all phases of gas in galaxies: cool and cold gas (via emission and absorption lines), ionized gas (via free-free continuum), cosmic rays and hot gas (via synchrotron emission and the Sunyaev-Zeldovich effect). Thanks to the resolution of interferometers and the almost arbitrary frequency resolution of radio facilities, these telescopes are also able to study the motions of gas from the immediate vicinity of black holes and forming stars out to the dark-matter dominated halos of galaxies. The ability of radio interferometry to work across very long baselines also allows makes these telescopes among the best options to study the structure of the Milky Way, the Local Group of galaxies, and (by anchoring the distance ladder) even the structure of the universe. Over the previous decades, the Very Large Array and the Very Long Baseline Array have made fundamental contributions to each of these areas. The Atacama Large Millimeter/submillimeter Array is already doing the same in only its third year of operations.

A “next-generation Very Large Array” (ngVLA) that improves on the capabilities of the Very Large Array by a large factor in most important dimensions has been proposed as a natural next major directions for the U.S. astronomy community. In this document we discuss the motivation to build such a facility from the perspective of this broad “galaxy ecosystems” area. We describe how the ngVLA will emphasize the qualitative improvement in the diagnostic power of such a telescope. It would represent an enormous improvement even beyond ALMA as both a spectroscopic and continuum instrument. This order-of-magnitude leap in the relevant parameter spaces ensures that such a telescope would be a revolutionary tool. To show this, we highlighting the gains that we would expect in the areas of molecular ISM structure and massive star formation. We also present the very strong arguments for including a large amount of collecting area at very long baselines as a baseline part of the telescope design, highlighting how this will dramatically advance our knowledge of the structure of the Milky Way, the Local Group, black holes, and indeed the universe (via  $H_0$ ).

These goals do argue for different aspects of telescope design. In order to focus the discussion on the exact specifications of a proposed ngVLA, we describe in the text what aspects of such a telescope enable each advance. For this science area, recurring themes include the importance of surface brightness sensitivity (though not to the exclusion of good resolution), the utility of large bandwidth for both line and continuum science, the very strong drive to access the range  $\nu = 70\text{--}115$  GHz, and the advantage of building a very long baseline component into the baseline design of the telescope.

## 2. The Maturation of cm-Wave Spectroscopy

The last decades have seen enormous advances in our knowledge of interstellar medium structure in the Milky Way and other galaxies, and with it a better understanding of how stars are born and galaxies grow and die. However, these have come largely from bulk tracers of interstellar gas — tools like the H<sub>I</sub> or low- $J$  CO lines. These lines will remain essential to understand where the gas is, but they reveal comparatively little about the conditions within the gas. Detailed spectroscopic work on small regions (e.g., galactic nuclei, Galactic cores) has used a wider suite of molecular species to understand physical conditions in these restricted regions. The faint lines from these rarer species offer powerful diagnostics of temperature, excitation, density, shocks, and ionization. Studies that harness these lines have been severely limited in scope, though, because beyond the bulk gas tracers most cm- and mm-wave transitions are simply very faint compared to the sensitivity of current instruments.

A next generation VLA offers the chance to change this: it will make detailed cm- and mm-wave spectroscopy a survey tool, allowing it to be deployed to study all kinds of objects and not only a few bright regions. For example, if the telescope is optimized to this purpose it will be possible to

- Survey the whole area of active star formation in the inner part of the Milky Way at resolution  $\sim 1''$  and sensitivity to the entire range of physical processes granted by the rich cm- and mm- spectrum. At the distance of the Milky Way center and the star-forming Galactic Ring, this resolution is enough to resolve filamentary structure within molecular clouds and other aspects of detailed cloud structure. Doing so using an incredibly rich spectroscopic toolkit over, say, the whole Galactic Ring would offer a transformational view of Milky Way star formation.
- Survey a large sample of galaxies in tracers of shocks, gas density, excitation, ionization, and a host of other physical parameters at  $\sim 1''$  resolution. Such a survey would measure the life cycle of gas in galaxies, the impact of feedback on interstellar gas, and how stellar nurseries couple back to their galactic environments. For the nearest ( $\lesssim 20$  Mpc) galaxies such a survey would yield a highly detailed spectrum of each individual molecular cloud in each galaxy, providing a truly “top down” view of star formation using tools only previously accessible to Milky Way studies. For more distant galaxies, this sophisticated spectroscopic view would offer the best possible access to local physics.
- Use absorption against Galactic and extragalactic continuum sources background continuum sources across the sky (almost “for free” for some telescope designs) to assemble a detailed, unbiased probe of the extended molecular medium in the Milky Way, the dense areas around ultracompact HII regions, and (via absorption at the redshift of the source) the internal molecular medium around quasars and AGN.
- Measure the physical conditions in molecular gas beyond only dense molecular clouds. We know about molecular outflows driven by both AGN and star formation; diffuse, low-column molecular material; “CO-dark” molecular gas surrounding molecular clouds; and puffy, large scale height molecular disks in galaxies. All of these live outside the “molecular cloud” paradigm through which



brightest set of interesting diagnostic lines beyond CO (e.g., HCN, HCO<sup>+</sup>, CS, CN) are  $\sim 10$ – $30$  times fainter than CO, so that a similar quality map targeting these diagnostics would require an impossible 20,000–200,000 hours on the previous generation of forefront facilities. In very bright regions and through heroic efforts at lower resolution these diagnostics have been applied and explored, but their use as a general purpose tool remained limited by these simple sensitivity concerns.

This changes with ALMA, but in the  $\nu = 70$ – $115$  GHz range perhaps not as much as one would expect. ALMA's true strength lies in the sub-mm regime, where it shatters previous capabilities and it is a stunning tool to study dust emission, excited gas, and active regions. Though still revolutionary at  $\nu \sim 70$ – $115$  GHz, ALMA in its current (nearly final) form would still require  $\sim 15$  hours to produce a  $1''$  CO map of a nearby galaxy ( $\sigma = 0.2$  K,  $\Delta v = 5$  km s<sup>-1</sup>). To work with lines  $10\times$  fainter at matched signal to noise and resolution would require  $\sim 1000$  hours of observing time. There are ways to make this estimate more favorable (e.g., target poorer resolution or worse signal to noise) but the core fact is that ALMA is most transformational at sub-mm wavelengths, where the sensitivity in brightness temperature units is much better thanks to the Rayleigh Jeans scaling (and for fixed velocity resolution, a larger  $\Delta v$ ).

The range 70 to 115 GHz is uniquely powerful as a general spectroscopic tool. This region contains a high density of powerful diagnostic lines (SiO, HCN, HCO<sup>+</sup>, CS, RRLs, CO, CN, C<sub>2</sub>H, HNC, among others). Because these have low excitation requirements ( $h\nu/k_B \sim 4$  K), they are among the most generally useful and widespread transitions for each of these molecules. Indeed, for the very interesting, very cold ( $\sim 10$  K) component of the star-forming ISM these lines are almost the only option to explore the physical conditions. Compared to ALMA, the current VLA already has almost three times the collecting area ( $27 \times 25^2$  compared to  $\approx 40 \times 12^2$ ). An upgraded facility with performance similar to ALMA at 70–115 GHz,  $\sim 5$  times the collecting area of the VLA and  $\sim 12$  m dishes would then map the sky  $\sim 200\times$  more quickly than ALMA at matched frequencies (thanks to  $\sim 15\times$  larger collecting area). There are additional considerations, but even a gain of a factor of  $\approx 50$  in time qualitatively changes the kind of science that can be pursued in this regime, making a "key project" into standard PI science and enabling much more ambitious, transformational surveys.

**Considerations for ng-VLA optimized for cm-/mm-wave spectroscopy:** Spectral line mapping is fundamentally a surface brightness experiment. A large amount of collecting area on  $\sim$ km baselines (comparable to the current D configuration) still yields  $\approx 1''$  resolution in the 70-115 GHz range. Bandwidth aids this science via multiplexing (simultaneous observations of many lines) rather than the radiometer equation ( $\Delta v$  is set by the width of the line). Frequency coverage is essential: there are important diagnostic lines all the way from 1.4 GHz (Hi) through 115 GHz (CO 1-0). In particular, the diagnostic power in the range 20–50 GHz and 70–115 GHz are essential.

A key point for spectral line science is that it often depends on ratios of lines. As with any ratio science using interferometers,  $u - v$  coverage matching becomes a concern. The proposed enormous frequency range (perhaps as much as 1–100 GHz) and the desire to do line ratio-oriented science argue strongly for an array designed with this goal in mind (either via movable dishes or a carefully designed array pattern).

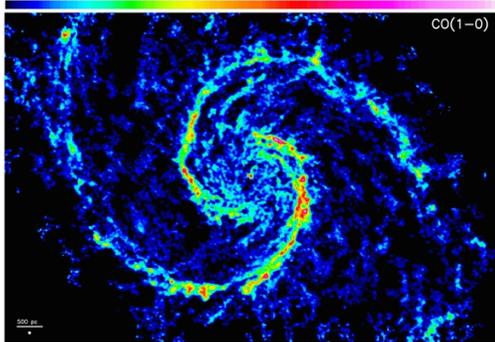


Figure 2. **State of the Art - CO.** This stunning  $1''$  image of CO in M51 (Schinnerer et al. 2013) took  $\approx 200$  h of high quality time to construct using the Plateau de Bure Interferometer and would still take  $\approx 15$  h using ALMA. The powerful cm-wave diagnostic lines are  $\sim 10$ – $30$  fainter than CO, so that an equivalent map, e.g., of CS, would require order 1000 hours even with ALMA. The ngVLA would change that, allowing this kind of map to be made using diagnostics of physical conditions not only bulk gas tracers like CO.

### 3. Chemistry and New Diagnostics from cm-Wave Low Excitation Transitions

The molecular ISM is the agent that transmits macroscopic changes in the structure and environment of a galaxy to the local star formation process. The molecular spectrum of galaxies are observed to be impressively rich (e.g. Figures ?? - 3). Recent surveys of the mm and cm spectrum reveal that chemical lines are not exotica confined to very peculiar locations in the Universe (Martin et al. 2006, Nakajima et al. 2011, Snell et al 2011, Aladro et al. 2011, 2013). As a result, chemistry is a treasure trove of information on the structure, properties and evolution of all parts of the molecular ecosystem in galaxies.

Chemical probes available to the ngVLA that are important and bright enough to survey across a range of galaxy types and star formation rates:

— Gas Excitation Tracers (CO and its isotopologues [110, 115 GHz],  $\text{NH}_3$  [23 - 28 GHz],  $\text{H}_2\text{CO}$  [4.83 GHz]): These lines are excellent probes of kinetic temperature, particular when observed at high spatial resolution. Gas temperature is vital for characterizing gas energetics and thermal pressures. See below for more discussion. The 1–0 transition is also the key molecular for measuring the total molecular mass budget.

— Dense Gas Tracers ( $\text{HCN}$  [88.6 GHz],  $\text{HCO}^+$  [89.2 GHz],  $\text{HC}_3\text{N}$  [numerous lines between 9.1 - 110 GHz],  $\text{HNC}$  [90.7 GHz],  $\text{CS}$  [49.0, 98.0 GHz]): These high dipole moment species require densities  $\sim 10^5$  or larger to excite and hence trace gas that is ready to form stars (e.g. Gao & Solomon 2004). Excitation of these low J transitions trace cooler, dense gas than regularly do ALMA and Herschel.  $\text{HC}_3\text{N}$ , with its numerous available closely spaced lines, is especially powerful for measuring gas excitation in very high density gas.

— Shock Tracers (thermal  $\text{SiO}$  [43.4, 86.8 GHz], thermal  $\text{CH}_3\text{OH}$  [48.4, 96.7 GHz], and  $\text{HNCO}$  [22.0, 44.0, 87.9, 110 GHz]): These are species whose gas-phase

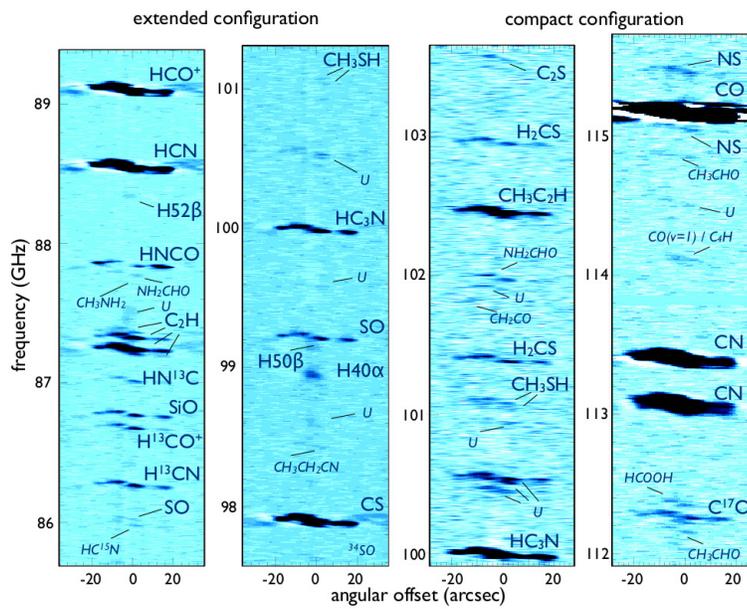


Figure 3. An imaging survey of the nucleus of NGC 253 at 85 - 116 GHz made with ALMA (Meier et al. 2015). The figure displays the spectral line data as if it were taken with an optical spectrograph oriented along the major axis of the nuclear bar. The horizontal axis is position and the vertical axis is frequency. The resolution is  $\sim 2''$  for the extended configuration, while  $\sim 5''$  for the compact. There is an extremely rich spectrum of molecular lines that observed that exhibit a complex and extended distribution.

abundance are particularly sensitive to shocks. SiO because of shock sputtered silicate grain cores and CH<sub>3</sub>OH and HNCO as bright shock liberated ice mantle species (also these species may be evaporated from grains by local heating sources). Inter-comparisons between shock tracers like these provide insight into shock strength and the presence of photodissociation. Line ratios between transitions of the same species constrain excitation of the shocked component directly.

— Photon- / X-ray - / Cosmic Ray-dominated region Tracers (CN [113 GHz], C<sub>2</sub>H [87.3 GHz], c-C<sub>3</sub>H<sub>2</sub> [18.3, 21.6, 46.8, 85.3 GHz], CH [3.33 GHz], HNC [90.7 GHz]): These species that are catalyzed in the presence of ions (especially C<sup>+</sup>) and maintain significant abundances in regions where ionization sources are strong. The depth of penetrate of the ionizing radiation is the main difference between PDRs and XDRs / CRDRs, with the later influence large columns.

— Complex Organics (CH<sub>2</sub>CO, HCOOH, CH<sub>3</sub>CHO, NH<sub>2</sub>CHO, CH<sub>3</sub>C<sub>2</sub>H, CH<sub>2</sub>CH<sub>2</sub>CN, CH<sub>2</sub>CH<sub>2</sub>OH and HCOOCH<sub>3</sub> [numerous transitions]): As the molecules gets larger, more circuitous reaction pathways become involved, challenging the predictions of theoretical astrochemical modeling. Moreover conditions capable of showing these species become rarer, though evidence is observed that these species are detectable in external galaxies and maintain high abundances on 100s of pc scales (Meier et al. 2015).

**Differentiated Chemistry Across Galaxy:** Mapping of the distribution of chemistry on scales larger than GMCs, the building blocks of the large-scale molecular ISM, demonstrate that gas chemistry and gas morphology are coupled (e.g. Meier & Turner 2005, Meier et al. 2012, 2015, Martin et al. 2015), making it a prime link tying microphysical processes to the macroscopic astrophysical drivers. Chemistry in the ISM is influenced by coherent dynamical processes on a wide range of scales, heating by individual low mass stars and turbulent dissipation within molecular clouds on the sub-parsec scale, clump - clump collisions, nearby massive star formation and protostellar outflows on 1-10 pc scales, up to varying cosmic ray ionization rates, spiral / bar perturbations and mergers / interactions on kpc and larger scales. Use of the information content provided by the rich spectrum to become available to the ngVLA will allow an unprecedented look at the regulating mechanics of galaxy evolution in the molecular ISM directly. How do these different mechanisms 'talk to each other'? To characterize such questions we need very high resolutions and sensitivities as well as wide field coverage to sample all relevant scales. The ngVLA is perfect in this respect. Also the large-scale structure of the cool, dense medium is less well constrained than the warm, dense phase because given the small fields of view, and low sensitivity, the focus has been dominated by chemistry in energetic environments. Watching the evolution of dense gas across spiral/bar arms promise to show how galaxies' main driver of secular evolution controls star formation. Where along the arms does star formation occur? How far downstream? In spurs? Are density changes or radiation responsible for the transition between the atomic and molecular phases and back again? What about the morphology of shocks in interacting / merging systems? Do they match the position and width expected from numerical simulations, which are sensitivity the detailed microphysics and expected star formation rates of multi-phase ISM models?

**The Care and Feeding of Supermassive Black Holes (SMBHs):** If the black hole mass - bulge relationships (Magorrian et al. 1998) have taught us anything, it is that SMBHs must effectively regulate star formation well beyond their direct dynamical influence, possibly via jets or winds interacting with inner bulge gas. If this is true then

imaging surveys of these AGN-dominated chemicals should resolve this extended influence during the SMBH's most active phases. A number of recent studies observe molecular outflows from AGNs (Alatalo et al. 2011, Aalto 2013 for a review) and others have argued for a number of nuclei with AGN influenced chemistry based on XDR line ratios of HCN, HCO<sup>+</sup> and HNC (e.g. Kohno et al. 2001, Aalto et al. 2002, Usero et al. 2004, Garcia-Burillo et al. 2012). Sub-mm ALMA observations are powerful probes of the energetic outflows close into the SMBHs. But these outflows much carry momentum out further into the nuclear / inner bulge environment. The low excitation ngVLA sampled lines will follow the influence out further to where it blends in with the existing ISM, giving us the chemical sphere of influence of the SMBHs. In the nearest systems, ngVLA in its more extended guise should easily resolve the 'molecular torii', determining its chemical and physical conditions. Very sensitive chemical surveys of absorption against the AGN cm / mm continuum will simultaneously probe gas chemistry from the very innermost AGN environs out to galactic halos along the line of sight.

**The Organic Universe:** Large molecules, many of potential pre-biotic importance, preferentially present lines in the cm regime. Taken together with the fact that the spectral line density in the cm tends to be lower, the cm accessible to ngVLA, has the potential to improve species identification. But more importantly, these large molecules are prime species for constraining the degree of chemical complexity reached in the ISM. Where do the large molecules form? Organics likely are delivered to Earth via comets, asteroids and other similar solar system bodies. Are the larger molecules formed in situ in the solar system or just collected there from the ISM? Do they vary with location in the galaxy, that is, are there 'chemical galactic habitable zones'? Initial hints tantalizing us with the implications for widespread life. Large molecules are also sensitive to the abundance of atomic pools, which change with metallicity. Finally, the cm lines of larger molecules are more sensitive to stimulated emission, making non-lte more common. Where modeled, larger molecules are more prone to flip between emission and absorption and characteristic densities ( $\rho$ ). This suggests they may ultimately be precision probes of gas density.

**Hiding Hydrogen:** The virtual invisibility of H<sub>2</sub> is perhaps the most frustrating eventuality associated with understanding the astrophysics of the molecular phase of the ISM. Two key proxies for H<sub>2</sub>, CO [115 GHz] and dust emission are both respectable in standard ISM locales (Bolatto et al. 2013), but the robustness of these two tracers become less clear in the extreme environments associated with very dense and diffuse, low density / low metallicity gas. Opacity, grain depletion in the dense case and photodissociation in the diffuse case limit the diagnostic power of these probes. At extreme high densities other molecular line probes available to the ngVLA come to the rescue (e.g. HNC [90.7 GHz], HC<sub>3</sub>N, and N<sub>2</sub>H<sup>+</sup> [93.2 GHz]). However, in the diffuse gas case the situation is more difficult, which is currently problematic, since this is a very important regime. It is here that the molecular - atomic ISM phase transition occurs, halos of galaxies reside and low metallicity systems. CH [3.33 GHz] is the molecule of interest here (Magnani & Onello 1995). CH is formed from radiative association of C<sup>+</sup> and H<sub>2</sub>, potentially directly tracing H<sub>2</sub> where C is not in the molecular phase. CH is expected to trace a narrow range of extinctions, between  $\sim 0.5 - 3$ , so if visual extinctions reach this level CH should be observable. The faintness of the line makes detection of this transition possible only in the Galaxy and the brightest and closest galaxies. Because of the increased sensitivity of the ngVLA coupled with the large primary beam at 3 GHz, a single deep observation of CH is expected to be capable of mapping the diffuse phase of the ISM of an entire nearby galaxy at GMC scales in one shot, as well as survey

significant solid angle on the Galaxy. These observations will naturally complement observations of the atomic phase (HI) as well as the ionized phase (free-free continuum and RRLs).

#### 4. Molecular ISM Structure in the Milky Way and Other Galaxies

Our interest in the structure of the molecular ISM arises because of its intimate link to the process of star formation, which is the fundamental agent of secular galactic evolution at  $z = 0$ . We have attacked the problem of star formation from both ends of the size scale: on large scales by relating how a galaxy forms stars to its total molecular content through the (Kennicutt-Schmidt) Star Formation Law and from the smallest scales through case studies of star forming structures like cores and filaments. In the middle ground lies the physical connection between galactic evolution and an individual star-forming event and that middle ground is mediated by the structure of the molecular ISM. This structure is sculpted by a mix of physical effects in unknown proportion, with hydrodynamical events (winds, shells and flows), magnetic fields, radiation, gravitation, and turbulence all thought to contribute significantly. Star formation emerges from this physical shaping, but we have only the coarsest understanding of how different combinations of physics would influence the resulting process. This limitation stems from our lack of a rich census of molecular cloud structure in different environments across a wide range of scales. This census is best conducted in the 1-118 GHz band as these transitions are most frequently excited in the relatively diffuse phases of the molecular ISM.

Better imaging enriches our understanding of the physics at play in the ISM. Low-resolution mapping led to a description of the molecular ISM governed by “clumps.” The community’s interest in filamentary structure has been driven by *Herschel*’s unrivaled dynamic range in imaging dust emission from the ISM. In creating comparable, velocity resolved imaging of the diffuse molecular ISM, we can identify the tell-tale structural signatures that will point back to the essential physics that governs the evolution of the ISM.

Fundamentally, the ngVLA will enable wide-area mapping of a suite of essential molecular gas tracers at  $\sim 1''$  resolution. These include both the 3 mm diffuse (OH, CO) and dense gas tracers as well as the cm-wave gas structural tracers such as formaldehyde and ammonia that measure physical parameters such as density and temperature. Using high quality maps to unravel the multiple physical effects practically means a detailed, statistical comparison with the outputs of numerical simulations. Additionally, several key science cases are directly and exclusively enabled by the ngVLA.

**Beyond A Certain Point of View:** Our ability to connect ISM structure to the wider galactic environment is severely limited by our restrictive point of view within the disk of our Galaxy. A rich understanding of the detailed influence of dynamical features such as spiral arms and bars has long been hampered by line of sight blending in the Milky Way. With high-fidelity, high-resolution mapping of thermal molecular emission throughout nearby galaxies, we will finally understand how molecular gas structure connects to the local galactic environment. Moving beyond our internal perspective on the physics at high resolution will answer questions like: How does molecular gas evolve through different types spiral arms? How do clouds evolve between spiral arms? How important is “triggered” star formation? How is star formation suppressed in some molecule-rich environments, such as our own Galactic Center?

**Magnetism across the Molecular ISM:** Magnetic fields are known to be important in molecular ISM evolution. A few star forming filamentary structures are seen to lie perpendicular to magnetic field lines. Field strength is comparable to other terms in the energy budget in molecular gas. However, we have only rudimentary measurements of the field strength and orientation in the molecular ISM. These observations rely on Zeeman active species such as CN and OH, both of which are in the ngVLA band. The dramatic improvement in sensitivity would move into the domain of Zeeman mapping where the field strength and orientation can be probed across wide areas in clouds, finally pinpointing how the field governs ISM evolution.

The ngVLA sensitivity also opens up mapping of the Goldreich-Kylafis effect, where rotational lines common species such as CO and CS show polarization at the few percent level, which will finally map the field strength and orientation in the bulk of the molecular clouds, spanning between the diffuse OH Zeeman maps with the dense-gas CN Zeeman maps. The Goldreich-Kylafis effect is maximized near the critical density of the lines in question, so a variety of lines can map the field strength through the molecular cloud.

**Formaldehyde and Ammonia to 5 Mpc:** Even in the ALMA-era, observing the weak emission lines of dense gas in the 3 mm window require a substantial investment of array time. Such studies are simply prohibitive when trying to observe down to scales comparable to dense, proto-cluster regions (1 pc) in other galaxies. With the ngVLA, we can identify the varied formation pathways for these protoclusters, by observing the emergent population of proto-clusters in the context of different cloud structures. Such observations will be aided by enabling observations of formaldehyde (4.8 and 14.4 GHz) and ammonia (23 GHz) in ordinary molecular gas beyond the Milky Way. These species represent essential components of our toolbox providing robust measurements of density (formaldehyde) and temperature (ammonia), that are comparatively immune to excitation and chemistry effects. Direct measurement of physical conditions will eliminate the suite of degeneracies that comes from inferring these conditions across wide frequency intervals with varying physical conditions (usually from multi- $J$  observations of rotational lines). While some parallel diagnostics can be identified in the submillimeter (methanol), these are biased toward the warmest parts of the ISM as opposed to tracing the structure of the pre-stellar molecular ISM.

**Proper Motions of the ISM:** Finally, with exquisite sensitivity used to observed bright lines toward nearby clouds, the ngVLA enables proper motion studies of *thermal* emission of the ordinary ISM. Even though such observations would require a substantial devotion of array time, they would, for the first time, observe the full 3D velocity structure of turbulence in the ISM. Such observations would directly answer a suite of questions about how the turbulent ISM leads to star formation: measuring compressive vs solenoidal motions or a direct measurement of the velocity power spectrum and its associated anisotropy.

## 5. Continuum Science With A Next Generation VLA

The microwave spectrum of galaxies covering  $\sim 1 - 100$  GHz is powered by an eclectic mix of physical emission processes, each providing completely independent information on the star formation and ISM properties of galaxies. These processes include non-thermal synchrotron, free-free (thermal bremsstrahlung), anomalous microwave (e.g., spinning dust), and thermal dust emission, each of which become extremely faint in the

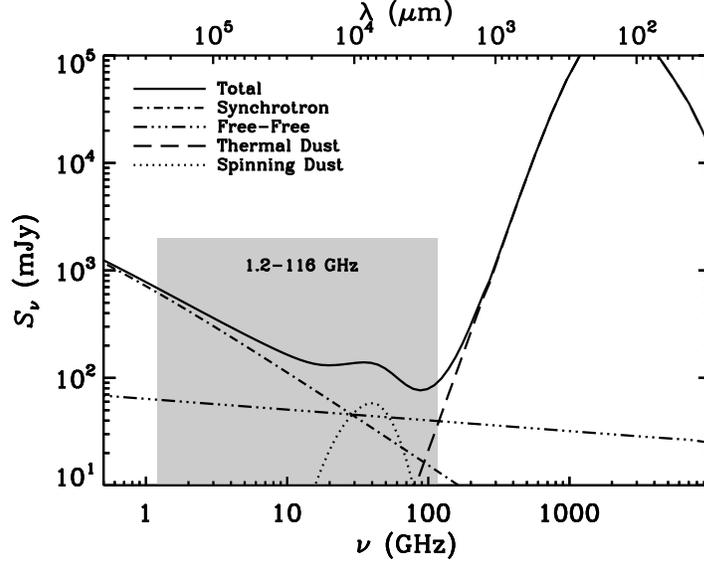


Figure 4. A model spectrum illustrating the various emission processes (i.e., non-thermal synchrotron, free-free, spinning dust, thermal dust) that all contribute to the observed microwave frequency range to be covered by the ngVLA. Frequency coverage between 1.2 – 116 GHz is highlighted.

$\sim 30 - 100$  GHz frequency range and therefore extremely difficult to map in the general ISM of nearby galaxies using current facilities. With the ngVLA, this entire frequency range will be covered almost simultaneously. Coupled with its nearly order of magnitude increased sensitivity compared to the current VLA, this new facility opens up this frequency window to investigate these distinct physical processes for large, heterogeneous samples of nearby galaxies for the first time. And, more importantly, having such a finely sampled spectrum over this entire frequency range will allow robust separation of these various emission components, which is currently the main uncertainty for multi-frequency radio studies.

- Non-Thermal Synchrotron Emission:** At  $\sim$ GHz frequencies, radio emission from galaxies is dominated by non-thermal synchrotron emission resulting from the end product of star formation. Stars more massive than  $\sim 8 M_{\odot}$  end their lives as core-collapse supernovae, whose remnants are thought to be the primary accelerators of cosmic-ray (CR) electrons, giving rise to the diffuse synchrotron emission observed from star-forming galaxies. Thus, the synchrotron emission observed from galaxies provides a direct probe of the relativistic (magnetic field + CRs) component of the ISM. As illustrated in Figure 4, the synchrotron component as a steep spectral index, typical scaling as  $S_{\nu} \propto \nu^{-0.85}$ . By covering a frequency range spanning 1.2 – 116 GHz, the ngVLA will be sensitive to CR electrons spanning an order of magnitude in energy (i.e.,  $\sim 1 - 30$  GeV), including the population of CRs thought to be responsible for driving the dynamically important CR pressure term in galaxies.

- **Free-Free Emission:** The same massive stars whose supernovae are directly tied to the production of synchrotron emission in star-forming galaxy disks are also responsible for the creation of HII regions. The ionized gas produces free-free emission which is directly proportional to the production rate of ionizing (Lyman continuum) photons. Unlike the non-thermal synchrotron emission, free-free emission has a relatively flat spectral index, scaling as  $S_\nu \propto \nu^{-0.1}$ . Globally, the free-free emission begins to dominate the radio emission once beyond  $\sim 30$  GHz, exactly the frequency range that the ngVLA will be delivering more than an order of magnitude improvement compared to any current or planned facility.
- **Anomalous Microwave Emission:** In addition to the standard Galactic foreground components (free-free, synchrotron, and thermal dust emission), an unknown component has been found to dominate over these at microwave frequencies between  $\sim 10 - 90$  GHz, and is seemingly correlated with  $100 \mu\text{m}$  thermal dust emission. Cosmic microwave background (CMB) experiments were the first to discover the presence of this anomalous dust-correlated emission, whose origin still remains unknown and presence as a foreground still hampers studies as the accurate separation of Galactic foreground emission in CMB experiments remains a major challenge in observational cosmology. At present, the most widely accepted explanation for the anomalous emission is the spinning dust model in which rapidly rotating very small grains, having a nonzero electric dipole moment, produce the observed microwave emission. The increased sensitivity and mapping speed of the ngVLA will allow for an unprecedented investigation into the origin and prominence of this emission component both within our own galaxy and others, ultimately helping to improve upon the precision of future CMB experiments.
- **Thermal Dust Emission:** At frequencies  $\gtrsim 100$  GHz, (cold) thermal dust emission on the Rayleigh-Jeans portion of the galaxy far-infrared/sub-millimeter spectral energy distribution can begin to take over as the dominant emission component for regions within normal star-forming galaxies. This in turn provides a secure hand on the cold dust content in galaxies, which dominates the total dust mass. For a fixed gas-to-dust ratio, this total dust mass can be used to infer a total ISM mass. Given the large instantaneous bandwidth afforded by the ngVLA, and more than an order of magnitude increase in mapping speed at 100 GHz compared to ALMA, such an observations will simultaneously provide access to the  $J = 1 \rightarrow 0$  line of CO revealing the molecular gas fraction for entire disks of nearby galaxies. Alternatively, combining H $\alpha$  observations (also available to the ngVLA) with  $J = 1 \rightarrow 0$  CO maps, one can instead use the thermal dust emission to measure the spatially varying gas-to-dust ratio directly.

Clearly, there is a broad range of continuum science applications that will be qualitatively improved upon with the constructions of the ngVLA. Simply taking the example of mapping a nearby galaxy in its free-free emission at 30 GHz illustrates how the ngVLA is truly a transformational telescope for the entire astronomical community. Much of what we know about star formation in nearby galaxies on  $1''$  scales is driven by observations of the H $\alpha$  recombination line Hydrogen. However, the interpretation of H $\alpha$  narrow-band imaging is severely complicated by the presence of contaminating nearby [NII] emission as well as internal dust extinction, both of which vary spatially

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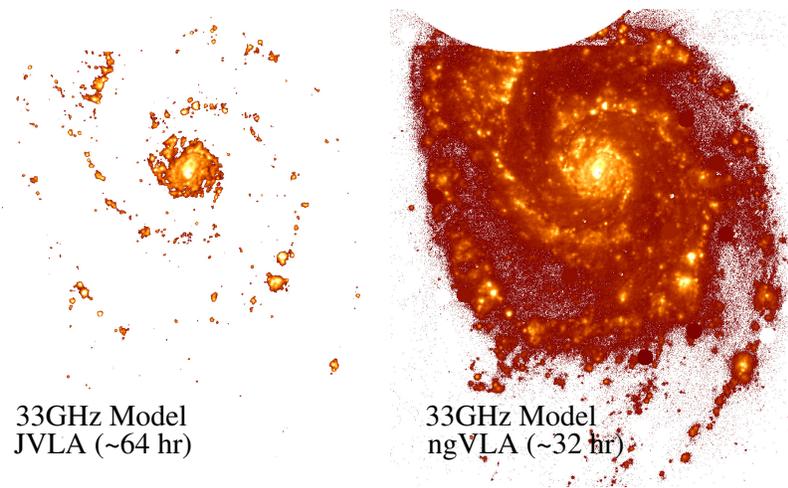


Figure 5. Both panels show a model 33 GHz free-free emission image of M51 based on an existing  $H\alpha$  narrow band image. The  $H\alpha$  image was first corrected for contamination from nearby [NII] emission, as well as Galactic and internal dust extinction. The left panel shows the emission that would be detected after a  $\approx 64$  hr total integration (mosaic with 2 hr per pointing; rms =  $4 \mu\text{Jy/bm}$  with  $\theta_S = 1''$ ) with the current VLA. The right panel shows what the ngVLA will deliver after integrating for a total of  $\approx 32$  hr (2 hr per pointing; rms =  $0.4 \mu\text{Jy/bm}$  with  $\theta_S = 1''$ , taking into account the factor of  $\gtrsim 2$  larger primary beam).

by large amounts within galaxy disks. Radio free-free emission maps at  $\gtrsim 30$  GHz provide a direct measure of the ionizing photon rate associated with massive stars without having to make simplifying assumptions about such effects, and thus will yield robust measures for the star formation activity within nearby galaxies disks on  $\sim 1''$  (i.e.,  $\lesssim 100$  pc) scales. Such maps will ultimately replace existing  $H\alpha$  maps as the workhorse for studying the distributed star formation on  $\lesssim 100$  pc scales in nearby galaxies.

M 51 (the Whirlpool Galaxy) is one of the most well studied galaxies in the nearby universe, providing a heavily used laboratory for detailed investigations of star formation and the ISM. With the ngVLA, one could map the entire disk of M 51 at 33 GHz down to an rms of  $\sim 400$  nJy/bm with a  $1''$  beam in  $\approx 32$  hr. A comparison of what can currently be delivered with the VLA for the same integration time per pointing is shown in Figure 5. To make a map to the same depth using the current VLA would take  $\sim 2500$  hr, the same amount of time it to take to roughly survey  $\sim 100$  galaxies. This is a game-changing step for studies of star formation in the local universe. This statement is independent of the fact that with such observations using the ngVLA, having its wide-bandwidth, a number of RRL's will come for free. The detection of such lines (individually or through stacking), coupled with the observed continuum emission, can be used to quantify physical conditions for the HII regions such as electron temperature. It is without question that the ngVLA will make radio observations a critical component for investigations carried out by the entire astronomical community studying star formation and the ISM of nearby galaxies.

## 6. The Sunyaev-Zeldovich Effect in Normal Galaxies: The Thermal Pressure Around Galaxies as a New Observable

The ngVLA offers the opportunity to observe galaxies at wavelengths from  $\lambda = 3$  cm to 3 mm with more collecting area and instantaneous bandwidth than has ever been possible. At low redshifts, this frequency range is the sweet spot for investigating the key radio wavelength emission processes: synchrotron, free-free and dust. It also covers the optimum frequency range for observing the Sunyaev-Zeldovich effect, i.e the modification of the CMB by Compton scattering. At ngVLA frequencies, intervening matter produces a reduction in the microwave background which can be used to measure the integrated thermal pressure along the line-of-sight. Most often this process has been observed at low spatial resolution in clusters of galaxies. ngVLA allows the possibility of making such observations at much higher resolution which would provide more detailed information of the structure of clusters. Furthermore, the potentially large improvement in continuum surface brightness sensitivity means that individual galaxies could also be detected.

However, such observations will only be possible if a large fraction of the ngVLA is configured in a very compact configuration so that it is optimized for high surface brightness sensitivity. This is because at 3mm, the natural resolution of an array the size of the current VLA D-configuration is  $\sim 1''$ , a rather high resolution for galaxies. Most spectral line work and even continuum observations will push ngVLA toward such resolution. Also large instantaneous bandwidths are needed for sensitivity, at least  $\sim 30$ – $40$  GHz. The combination of such parameters will allow revolutionary uses of ngVLA for SZ observations. Both the  $\nu = 10$ – $45$  and  $\nu = 70$ – $110$  GHz spectral windows would be useful for such observations.

Scaling from the current VLA exposure calculator, if  $\sim 5\times$  the current VLA collecting area was available on D-configuration baselines with  $\Delta\nu = 30$  GHz of bandwidth, then in 10 hours, one would reach rms sensitivities  $\sim 6 \times 10^{-3}$  mK. Using the CASA MSMFS imaging algorithm in the 3mm window, one reaches this sensitivity with  $\sim 1''$  resolution. Assuming a D-configuration-like distribution of baselines, at  $\sim 3''$  resolution, the rms sensitivity for these parameters approaches  $\sim 1 \times 10^{-3}$  mK, i.e. a microKelvin (see EVLA memo 162 for configuration sensitivity details).

A typical dense cluster observed at arcminute resolution produces  $\sim 0.5$  mK signal. The peak surface brightness should increase as the resolution increases, so a quite detailed image of cluster cores should be easily possible. Combined with X-ray imaging, such data would allow the likely complex, 3D distribution of density, temperature and turbulence to be inferred at 1-10 kpc resolution. Smaller objects should also be easily observable such as groups of galaxies and individual D-galaxies. A dense cluster has a pressure,  $P/k_B = nT$ ,  $\sim 10^5$  cm<sup>3</sup> K. Galaxies might well reach  $P/k_B \sim 10^6$  or more in their ISM over perhaps 10 kpc, about  $3''$  at  $z=0.2$ . For such pressures,  $P/k_B = 10^6$  cm<sup>3</sup> K, and path lengths of  $\sim 10$  kpc the expected signal will be  $\sim 2 \times 10^{-2}$  mK.

This integrated thermal pressure at high resolution would be a new observable for galaxies. Combined with other observations, other non-observables could be teased out of these results, such as the pressure from other sources, i.e. magnetic fields and turbulence. The enhancement in pressure due to galaxies being stripped in clusters could be estimated. The pressures in smaller in the disks of nearby star-forming galaxies might be measured. Stacking of results for smaller galaxies (or more observing time) might extend the measurements to smaller scales than 10kpc. This discussion just scratches the surface of possible SZ experiments with ngVLA if the array is configured to make such work possible.

## 7. Massive protostars and protoclusters with the ngVLA

### 7.1. Finding and resolving massive pre-stellar cores

Sensitive observations at centimeter to millimeter wavelengths at a range of angular scales are essential to understand the formation of massive protostars and protoclusters. On the largest scales, the network of infrared dark clouds (IRDCs) in the Milky Way span many arc minutes, typically containing multiple sites of active massive star formation. In recent years, the earliest phase of candidate massive pre-stellar cores have been identified within IRDCs in the form of low temperature ( $< 20$ K), high column density, compact (2000-5000 AU) objects prior to collapse of the first protostars. The kinematics of these objects will be best studied in the low-excitation molecular transitions in the 3-4 mm band, including key deuterated species. Because high surface brightness sensitivity is essential for spectral line imaging, the bulk of the collecting area at 3-4 mm will be best concentrated at baselines within about 8 km in order to obtain beamsizes of 0.2 arcsec (400-1600 AU at 2-8 kpc). Although ALMA can reach these baselines now, its total collecting area is insufficient to image such low brightness temperature sources. However, the proposed factor of 5 increase in collecting area for the ngVLA will amount to ten times ALMA's collecting area. This increase will enable spectral line imaging with a 1 K rms in 1 km/s channels in about 20 minutes. One could then survey entire IRDCs in all of their emission lines and continuum at a rate of

one square arc minute per hour, assuming a single feed receiver. Such surveys would pinpoint regions for higher resolution study with both ngVLA and ALMA.

## 7.2. Protoclusters and accretion

The collapse of massive prestellar cores leads to massive protostellar clusters (protoclusters), which consist of multiple deeply-embedded dust cores, some with hypercompact or ultracompact HII regions, clustered on scales of a few thousand AU. The detailed study of the accretion structures around individual massive protostars requires tracers of warm ( $> 100$  K), high density gas, whose high-J transitions are typically associated with ALMA wavelengths. However, when studying the central massive protostars and their accretion structures, long millimeter wavelengths (7-13 mm) are essential for penetrating the high continuum opacities from dust grains that hamper shorter wavelength ALMA observations. The transitions of thermal ammonia and methanol in the 10-13 mm range will be key probes of accretion kinematics, in addition to the many maser transitions of water, ammonia and methanol. At these wavelengths, the current VLA maximum baselines of 36 km are sufficient to reach scales of 0.08 arcsec (150-600 AU at 2-8 kpc), which is essential to resolve accretion onto a single massive protostar vs. a proto-binary. However, the increased collecting area of ngVLA is essential to utilize these longer baselines for thermal emission, since observations of thermal ammonia with the current VLA are insensitive for this purpose much beyond C-configuration. In contrast, the ngVLA will be able to reach a critical rms of 20 K in 1 km/s channels in about 12 hours. Although these size scales can theoretically be reached at the upper end of ALMA Band 1, it can only do so in continuum due to the reduced collecting area, and then only out to the distance of Orion, which is a relatively low luminosity region compared to the bulk of Milky Way massive star formation.

## 7.3. Ionized jets and hypercompact HII regions

The cm continuum emission from massive protostars traces bipolar ionized jets, such as those seen in Cepheus A, which along with molecular outflows provide feedback into the surrounding core. As they approach the main sequence, these stars power hypercompact HII regions which eventually expand and potentially impact the formation process of neighboring protostars. These ionized phenomena are best observed at wavelengths of 1-6 cm. In order to achieve matched resolution at the longest wavelengths with the molecular gas images at 1.3 cm, the ngVLA will require even longer baselines up to 150 km. In addition, because the ionized gas is of higher temperature ( $> 5000$  K), the 150 km baselines can also be exploited at shorter wavelengths for continuum. For example, at 1.5 cm, a beam of  $0.02''$  can be achieved, providing 40-160 AU resolution at 2-8 kpc. Such images can pinpoint the jet launching point and/or measure the size and of the hypercompact HII region, leading to accurate measurements of its density and pressure. Even with such a small beam, a more than adequate rms of 50 K (6  $\mu$ Jy) can be reached in just a few minutes with 8 GHz bandwidth.

## 7.4. Complete census of the protocluster population

Finally, and perhaps most importantly, the ngVLA will be able to detect the population of low-mass protostars and pre-main sequence stars forming in the midst of the massive protostars and thereby provide a complete census of the protocluster. In addition to dust emission from circumstellar disks around low-mass protostars, which will be visible at 3-8 mm, the more evolved pre-main sequence stars often exhibit chromospheric activity

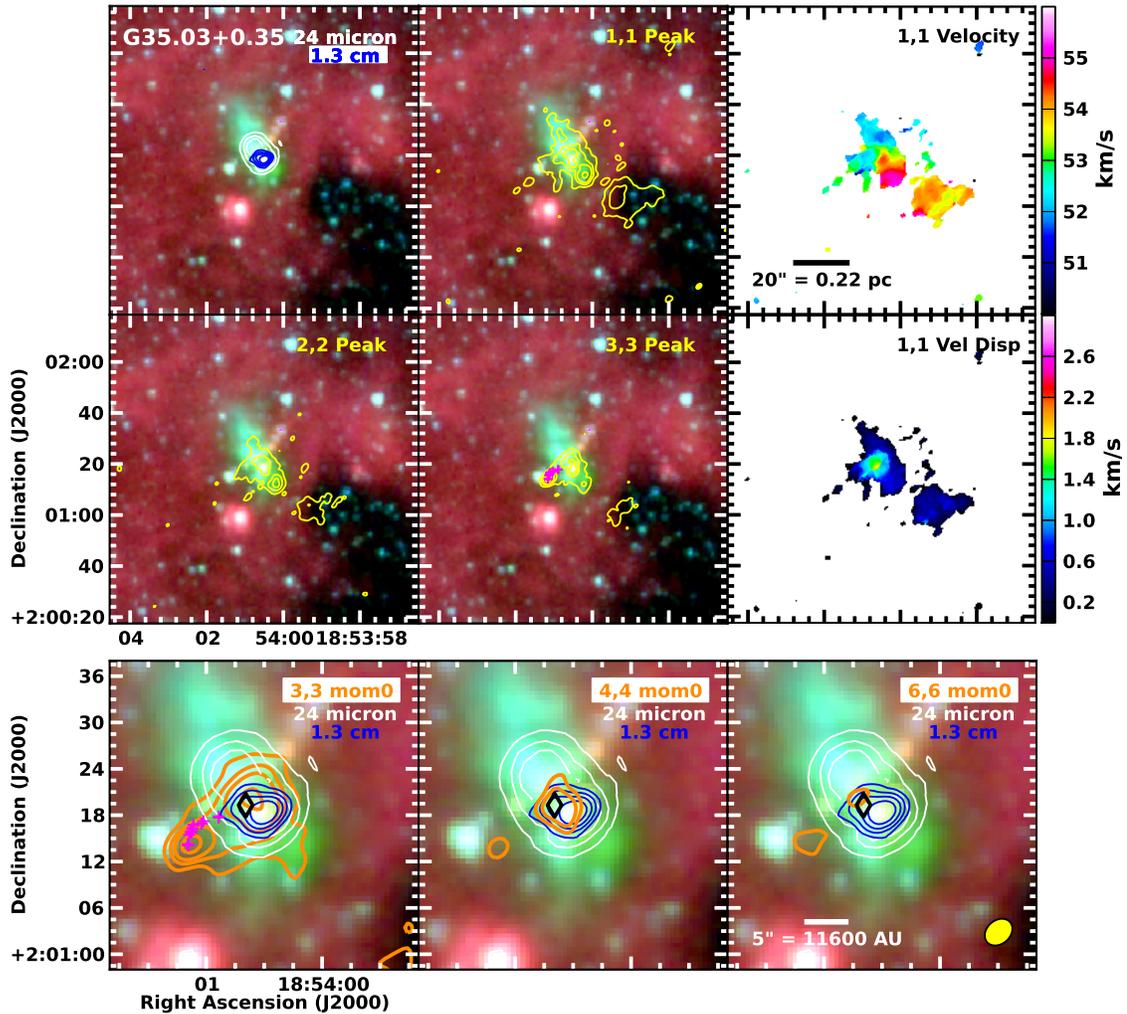


Figure 6. JVLA images of the  $\text{NH}_3$  transitions and continuum emission from the massive protocluster G35.03+0.35 using the D-configuration. While providing copious diagnostic information like temperature and kinematics, it is very time-consuming to push these types of observations to higher angular resolution due to surface brightness sensitivity limitations.

detectable in the cm range. For example, several dozen stars have been detected in M17 (at 2 kpc) down to 0.13 mJy and in Cepheus A (at 700 pc) at levels down to 0.3 mJy, which scales to 2.5 uJy at 8 kpc. With the ngVLA, ten sigma detections of these stars at 8 kpc (rms = 0.25 uJy) can be achieved in only 3 hours at 8 GHz with an 8 GHz bandwidth.

## 8. The Galactic Center in Unprecedented Detail

Species which give rise to abundant maser emission could be of particular use for high-resolution studies of gas kinematics (and their implications for star formation), given the non-thermal brightnesses of these lines. A particularly useful example of this may be 36.2 GHz collisionally-excited (Class I) methanol masers, which would be uniquely accessible to the NGVLA. Recent studies have shown (maser) emission from this line to be extremely abundant in clouds in the center of the Milky Way (Yusef Zadeh et al. 2013, Mills et al. ApJ accepted), and have detected it for the first time in an extragalactic source (NGC 253, Ellingsen et al. 2014). Using the 36.2 GHz methanol maser line as a tracer, it could be possible to trace sub-parsec structure (0.2-0.3 pc) in individual clouds in galactic nuclei out to Maffei2 / IC342 / M82 ( $d \sim 3-4$  Mpc), given an RMS of  $\sim 120$  K at 180 km baselines, with 10x the collecting area of the current VLA. For a single Galactic center cloud observed at comparable spatial resolutions with the VLA,  $\sim 50$  masers can be detected (5 sigma) with brightnesses 600 K (Mills et al. ApJ accepted). Thus far no other collisionally-excited methanol maser lines (e.g, those at 44, 84, or 96 GHz, which will be accessible to ALMA) have been shown to be similarly abundant in any Galactic sources, though the 84 GHz line has been detected as a megamaser in NGC 1068 (Wang et al. 2014).

Given the observed preponderance of these masers in Galactic center clouds, in environments where they are similarly common, these masers would allow for the kinematics and morphologies of individual clouds to be mapped on sub-parsec or "clump" scales, potentially revealing filaments or other substructure (see Figure 7). More quantitatively, the widths of these lines can be measured—these are expected to be intrinsically sub-thermally narrow, but are observed in practice to be much more broad, likely due to emission from multiple masers (e.g., Voronkov et al. 2014, Mills et al. ApJ accepted). This would allow for measurements of the turbulent spectrum of the gas down to sub-parsec scales, probing spatial variations of turbulence in across these galaxies (or their centers). Observed variations in the properties of turbulence in the variety of extragalactic environments accessible with the NGVLA could yield important insight on the resulting star formation properties as a function of these environments, as theory and observations suggest that the initial conditions for star formation (e.g., the distribution of gas volume and observed column densities) are set by supersonic turbulence (e.g., Vazquez-Semadini et al. 1994, Fedderath et al. 2010, Lombardi et al. 2008, Goodman et al. 2009, Kainulainen et al. 2009, Rathborne et al. 2015).

Other species (e.g., methanol at 36.2, 37.1 and 84 GHz) have also recently been observed to exhibit megamaser emission in the centers of nearby galaxies (Arp 200, Chen et al 2015; NGC 1068, Wang et al. 2014). Surveys for such sources are thus far incomplete (due to, for example, the historical dearth of Ka band receivers), and their incidence in the local universe is not well constrained. As maser emission is generally limited to a narrow range of physical conditions, variations in the in the chemical and physical conditions of Galactic nuclei can give rise to entirely different species and

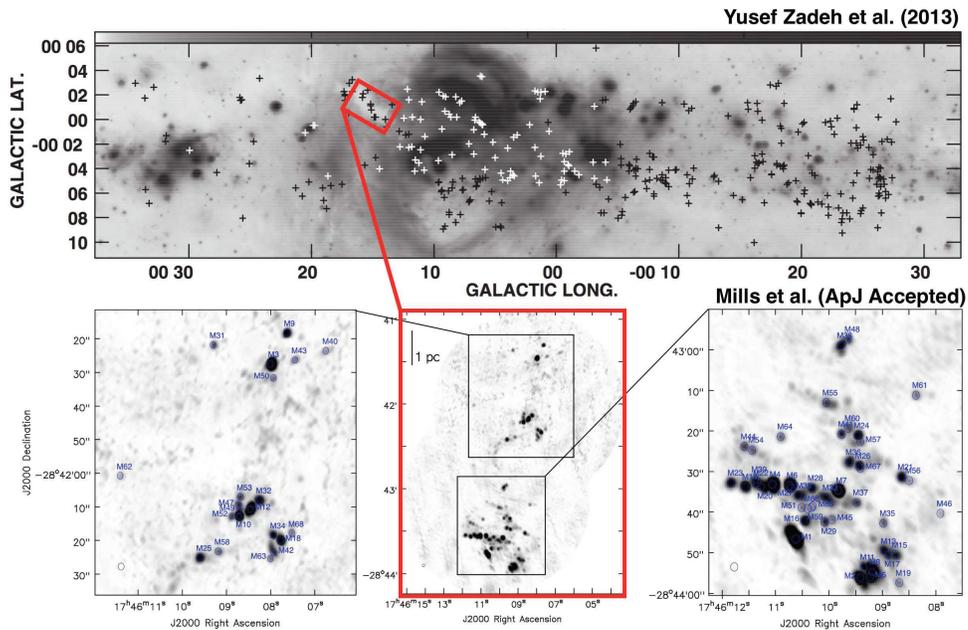


Figure 7. Top: Yusef Zadeh et al. (2013) find more than 350 36.2 GHz methanol emission sources in the central 150 parsecs of the Milky Way. Bottom: For one of these clouds, in which the lower spectral-resolution study of Yusef-Zadeh found 8 methanol sources, 0.1 pc and 1 km/s resolution VLA observations reveal nearly an order of magnitude more sources: 68 masers, all of which have brightness temperatures  $> 400$  K (Mills et al., ApJ accepted).

varieties of maser emission, e.g. OH or H<sub>2</sub>O (mega)masers (e.g. McEwen et al. 2014). A next generation VLA would offer unprecedented sensitivity at radio frequencies to search for and characterize a larger range of potentially megamasing transitions (e.g., CH<sub>3</sub>OH 24, 36, 44, 84, 96 GHz, see Voronkov et al. for other observed and potentially masing transitions) as well as more highly excited OH transitions observed to be masers in our Galaxy (at X and Y GHz). There thus remains a rich discovery space for the detection and characterization of additional megamasing transitions which will allow for a larger sample of sources for which accurate distances and black hole masses can be determined.

## 9. Science Opportunities for the Next Generation VLA with Very Long Baselines

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### 9.1. $H_0$

Precise knowledge of the value of the Hubble constant ( $H_0$ ) is key for evaluating cosmological models and, specifically, making progress understanding Dark Energy. Currently there are many approaches to determine  $H_0$ , including measurements of the cosmic microwave background, baryon acoustic oscillation, gravitation lensing, and megamaser galaxies. However, differences in estimates of  $H_0$  of about 5% still exist (Efstathiou 2014). Recently, the Megamaser Cosmology Project has obtained  $\sim 10\%$  accurate distance estimates for five galaxies in the Hubble flow, yielding geometric estimates of  $H_0$ , which are of particular value as they are direct measurements and independent of all other methods.

Megamaser measurements of  $H_0$  require mapping weak water maser emission from sub-parsec scale accretion disks surrounding supermassive black holes at the centers of the galaxies. There currently are  $\sim 50$  known megamaser galaxies at distances of 50 to 200 Mpc, which could yield independent  $H_0$  estimates. However, most are too weak to be observed with reasonable integration times on current telescopes. One needs micro-arcsecond precision maps and independent spectral monitoring (to measure maser accelerations) for spectral lines that are  $\sim 1$  mJy. Mapping details of an accretion disk that subtends a total of  $< 1$  mas requires the longest baselines available ( $\approx 8000$  km) and both mapping and monitoring observations require significantly more total collecting area than currently available. Both could be provided by a next generation VLA that spanned US territory.

### 9.2. Gravitational Waves

Gravitation radiation has been inferred from observations of the Hulse-Taylor binary pulsar. The dominant uncertainty in measuring the gravitational radiation damping of the binary's orbit comes from the need to correct for the effects of the Galactic (" $V^2/R$ ") accelerations of both the Sun and the binary (Damour & Taylor 1991), which contribute  $\approx 1\%$  to the *apparent* orbital period decay. In 1993 when the Nobel Prize was awarded in part for this work, the IAU recommended values for the Galactic acceleration of the Sun (from  $R_0 = 8.5 \pm 1.1$  kpc and  $\Theta_0 + V_\odot = (220 + 15) \pm 20$  km s<sup>-1</sup>). Using these Galactic parameters, improved pulsar timing data of (Weisberg, Nice, & Taylor 2010), and a pulsar distance of 9.9 kpc, the binary's orbital period decays at a rate of  $0.9982 \pm 0.0025$  times that prediction from general relativity (GR). With improved Galactic parameters

from VLBA mapping of the Galaxy (Reid et al. 2014), the GR test parameter accuracy improved by a factor of 4. Surprisingly, the new value of  $0.9962 \pm 0.0006$  now differs from unity (the GR prediction) by  $6\sigma$ . Given the improvement in the Galactic parameter values, the dominant uncertainty in the GR test now is the uncertain pulsar distance. A pulsar distance of 6.5 kpc would bring the GR test value to 1.0000. An accurate measurement of the parallax of the Hulse-Taylor binary pulsar, which could be made with a next generation VLA, could critically test this prediction.

In the near future, Advanced Ligo is expected to directly detect gravitation waves from coalescing compact stars, such as the merger of white dwarves that generate Type Ia supernovae and merging neutron star and black hole binaries. Ultimately, space instruments like Lisa should detect the inspiral of supermassive black hole binaries, predicted to a universal outcome of galaxy mergers across cosmic time. While gravitational wave detectors will open a new and exciting window for astrophysics, detecting and imaging the electromagnetic counterparts will provide invaluable information to illuminate the nature of these sources. Do gravitation wave sources accelerate matter to highly relativistic speeds and produce jets? Are these jets different from those associated with accretion of material onto stars and black holes? Since, the scales of the expected electromagnetic radiation would characteristically be  $< 1$  mas, the longest possible interferometric baselines are needed to image the emission.

### 9.3. Black Holes and Cosmic Accelerators

The formation and growth of supermassive black holes in the centers of galaxies is thought to play a critical role in the formation and evolution of galaxies. Powerful jet of plasma moving at nearly the speed of light are generated by accreting black holes and these jets can provide enough energy to the interstellar medium to affect star formation on galactic scales. Observations with the VLBA have revealed an extremely complex system, possibly involving a helical magnetic sheath that confines the plasma. However, fundamental astrophysical questions remain after decades of inquiry: Do these cosmic accelerators launch jets and how are these jets collimated?

Key observations would be image the base of jet with sufficient angular resolution and sensitivity to test long-standing theories (Blandford & Znajek 1977; Blandford & Payne 1982). However, synchrotron opacity at centimeter wavelengths usually obscures the central “core” from view. What is needed is observations at short enough wavelengths where the emission is optically thin. Currently, VLBI arrays with good imaging capabilities do not function well below 7 mm wavelength. A next generation VLA that operates at significantly shorter wavelengths could provide critical observational data to make progress on this difficulty problem.

As discussed above, VLBI observations of maser emission from sub-parsec scale accretion disks surrounding supermassive black holes yield detailed spatial–kinematic data. Usually, the masers are moving in nearly perfect Keplerian rotation about a central mass. This allows one to determine the masses of the central black holes with unprecedented accuracy and reliability. These “gold standard” black hole masses can be used to test the black hole–galaxy  $M - \sigma$  relationship, which is usually based on unresolved dynamical estimates of black hole mass. Megamaser black hole masses, which currently fall toward the lower end of the black hole mass range, suggest significant deviation from the  $M - \sigma$  relations (Greene et al. 2010). Currently, VLBI measurements are sensitivity limited to masers stronger than  $\approx 5$  mJy and therefore only  $\sim 10$  black hole masses have been measured. However, there are  $\sim 100$  known megamasers for which

masses could be measured with increased sensitivity as could be provided by the next generation VLA. Of course, sub-mas angular resolution is crucial for resolving details in these tiny disks.

Compact stars in binary systems with mass transfer (e.g. X-ray binaries) are often not well understood owing to highly uncertain distance estimates. For example, the distance to the archetypal black hole candidate, Cyg X-1 (the source of the famous wager between Hawking and Thorne), has until recently been uncertain by a factor of two from  $\approx 1.1$  to  $2.5 M_{\odot}$  (Caballero-Nieves et al. 2009). At the lower end of this distance range, the inferred mass of the compact object would be  $< 3 M_{\odot}$ , casting doubt on it being a black hole. However, a recent VLBA parallax established that Cyg X-1 was at a distance of  $1.86 \pm 0.12$  kpc (Reid et al. 2011) and that its mass is  $14.8 \pm 1.0 M_{\odot}$  (Orosz et al. 2011), firmly establishing it as a black hole.

Many X-ray binaries might contain neutron stars instead of black holes. Reliable measurement of distance is needed to firmly establish the masses of the compact objects (to determine neutron stars from black holes) as well as to determine if the emission is below, at, or above the Eddington limit, which provides important clues for the nature of accretion. More accurate distances to X-ray binaries are certainly needed, but few are as strong as Cyg X-1. The neutron star candidates are usually too weak for reliable parallax measurement with the VLBA ( $\sim 0.5$  mJy), and a significant increase in collecting area on long baselines is needed to for such parallax measurements.

#### 9.4. Mapping the Milky Way

Surprisingly, we know other galaxies far better than we know the Milky Way. Since we are inside the Milky Way, it has proven very difficult to properly characterize its structure, because dust obscures most of the Galaxy at optical, and to some extent at IR, wavelengths and distances beyond the extended Solar Neighborhood are often quite uncertain. Thus, we only have an “educated guess” that the Milky Way is a barred Sb or Sc galaxy, and even the number of spiral arms (2 or 4) is actively debated (Benjamin 2008).

Using the VLBA, the BeSSeL Survey is mapping the spiral structure of Milky Way out to distances of about 10 kpc (see Fig. 10). That leaves a significant portion of the far side of our Galaxy as “terra incognita.” Without a complete map, connecting nearby spiral arm segments in the 4<sup>th</sup> Galactic quadrant with their continuation in the 1<sup>st</sup> quadrant will be uncertain. With significantly increased collecting area compared to the current VLBA, parallax measurements of weak masers in very distant star forming regions could be made with better than 10% accuracy at distances of 20 kpc.

#### 9.5. Local Group Cosmology

The distribution of dark matter in galaxies and groups of galaxies is one of the major problems in observational cosmology. The Local Group provides the nearest and best system for detailed study. Various attempts to “weigh” the Milky Way and the Andromeda galaxy have resulted in inconclusive values. The major problem is that most studies work with only one-dimensional (radial) velocity components, introducing significant ambiguities and requiring statistical mass estimators, which suffer from small sample sizes and/or unknown biases from non-isotropic distributions. Clearly the most reliable way to derive mass distributions is from 3-dimensional velocity measurements through proper motions.

Understanding both the history and fate of the Local Group will require detailed knowledge of the space motion of Andromeda with respect to the Milky Way. If Andromeda has a negligible proper motion (with respect to the Milky Way), then these two dominant Local Group members will collide and merge over the next few Gyr. However, should Andromeda have a sizeable proper motion of order  $100 \text{ km s}^{-1}$ , as suggested by Loeb et al. (2005), the stellar disks would not collide and the two galaxies would pass by each other and not merge on this time scale.

Currently, proper motions of Local Group members, done optically, have achieved accuracies approaching about  $10 \mu\text{as y}^{-1}$ . These can yield reasonably significant space motions for close satellites of the Milky Way (eg, for the LMC see Kallivayalil et al. (2006)), but only marginally significant estimates for more distant galaxies associated with M31 (the Andromeda galaxy) (van der Marel & Guhathakurta 2018). However, VLBI measurements of water masers in Andromeda satellites M 33 and IC10 (Brunthaler et al. 2005, 2007) have achieved  $\approx 5 \mu\text{as y}^{-1}$  accuracy over time baselines of less than 5 years.

We are currently poised to make truly dramatic progress in understanding the dynamics, and hence dark matter mass distribution, of the Local Group. The proper motion of the Andromeda galaxy is the key measurement needed to understand the dynamics of the Local Group. There are two ways to measure Andromeda's proper motion: 1) directly via its AGN (M31\*) or 2) indirectly by measuring the motions of newly discovered water masers in Andromeda's disk. M31\* is weak ( $\sim 30 \mu\text{Jy}$ ) and variable, making it extremely difficult to detect with high signal-to-noise with current VLBI arrays. However, the next generation VLA with large collecting area and long baselines would be able to easily make the required measurements. Over  $\approx 10$  years, we could make measurements with accuracies of  $\sim 0.1 \mu\text{as y}^{-1}$  and thus measure the 3-dimensional velocities of galaxies in the Local Group with uncertainties less than  $1 \text{ km s}^{-1}$ ! Indeed, with this accuracy significant measurements of motions in other groups out to the Virgo Cluster could be made.

## 10. Synthesis

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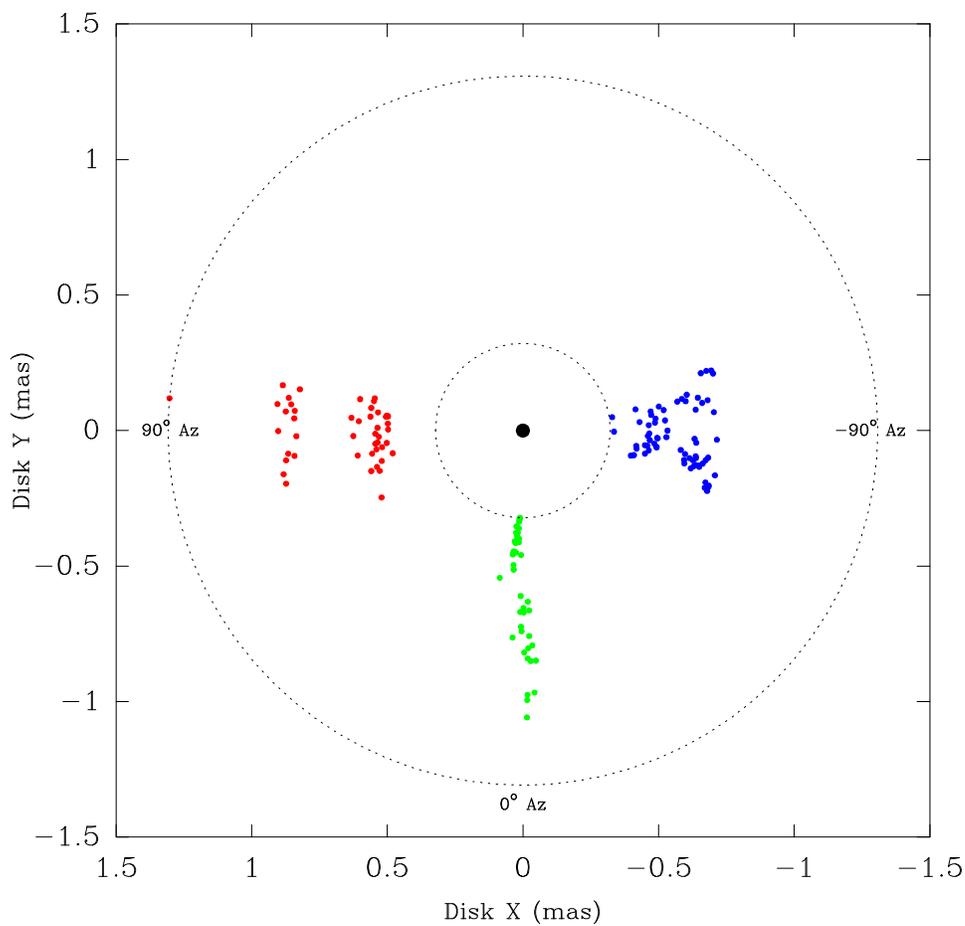


Figure 8. Location of water maser features in UGC 3789 projected in the plane of the accretion disk based on the best-fit model. The location of the central black hole is shown with a *black filled circle* at the origin. The observer is at a large negative Y location. *Red and Blue* dots indicate the red-shifted (toward disk azimuth  $\approx 90^\circ$ ) and blue-shifted (toward disk azimuth  $\approx -90^\circ$ ) high-velocity masers, respectively. *Green* dots indicate the systemic velocity masers (toward disk azimuth  $\approx 0^\circ$ ).

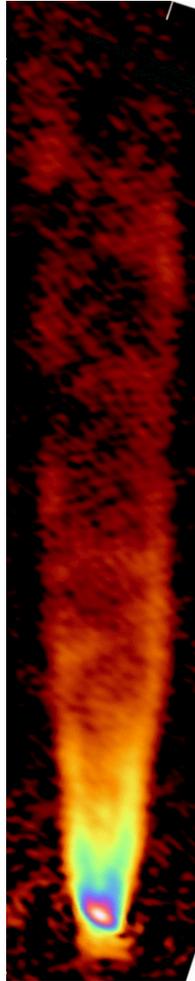


Figure 9. VLBA image of the jet launched from the supermassive black hole in M87. The bright “V-shaped” emission (green) comes from within  $\sim 300 R_{\text{Sch}}$ .

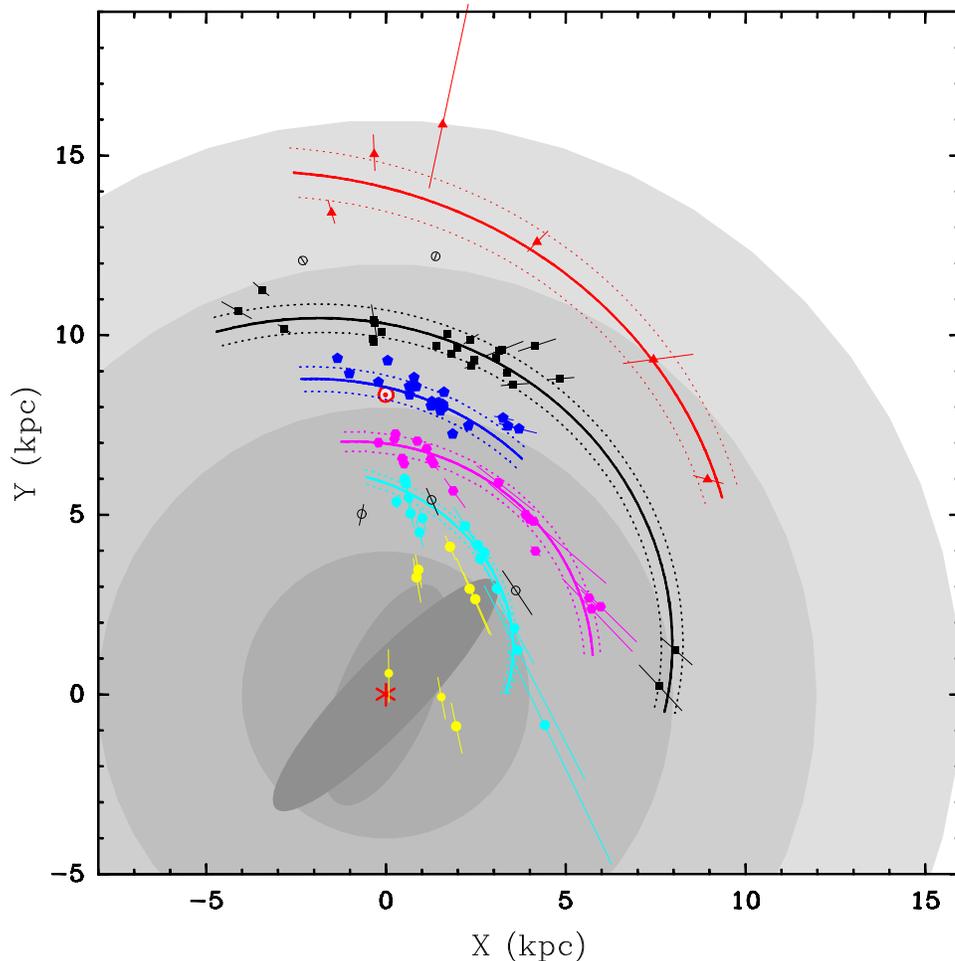


Figure 10. Plan view of the Milky Way showing the locations of high-mass star forming regions with measured trigonometric parallaxes. The Galactic center (*red asterisk*) is at (0,0) and the Sun (*red Sun symbol*) is at (0,8.34). Inner Galaxy sources, *yellow dots*; Scutum arm, *cyan octagon*; Sagittarius arm, *magenta hexagons*; Local arm, *blue pentagons*; Perseus arm, *black squares*; Outer arm, *red triangles*. Open circles indicate sources for which arm assignment was unclear. Distance error bars are indicated, but many are smaller than the symbols. The background grey disks provide scale, with radii corresponding in round numbers to the Galactic bar region ( $\approx 4$  kpc), the solar circle ( $\approx 8$  kpc), co-rotation of the spiral pattern and Galactic orbits ( $\approx 12$  kpc), and the end of major star formation ( $\approx 16$  kpc). The short COBE “boxy-bar” and the “long” bar are indicated with shaded ellipses. The *solid* curved lines trace the centers (and *dotted* lines the  $1\sigma$  widths) of the spiral arms from the log-periodic spiral fitting. For this view of the Milky Way from the north Galactic pole, Galactic rotation is clockwise.