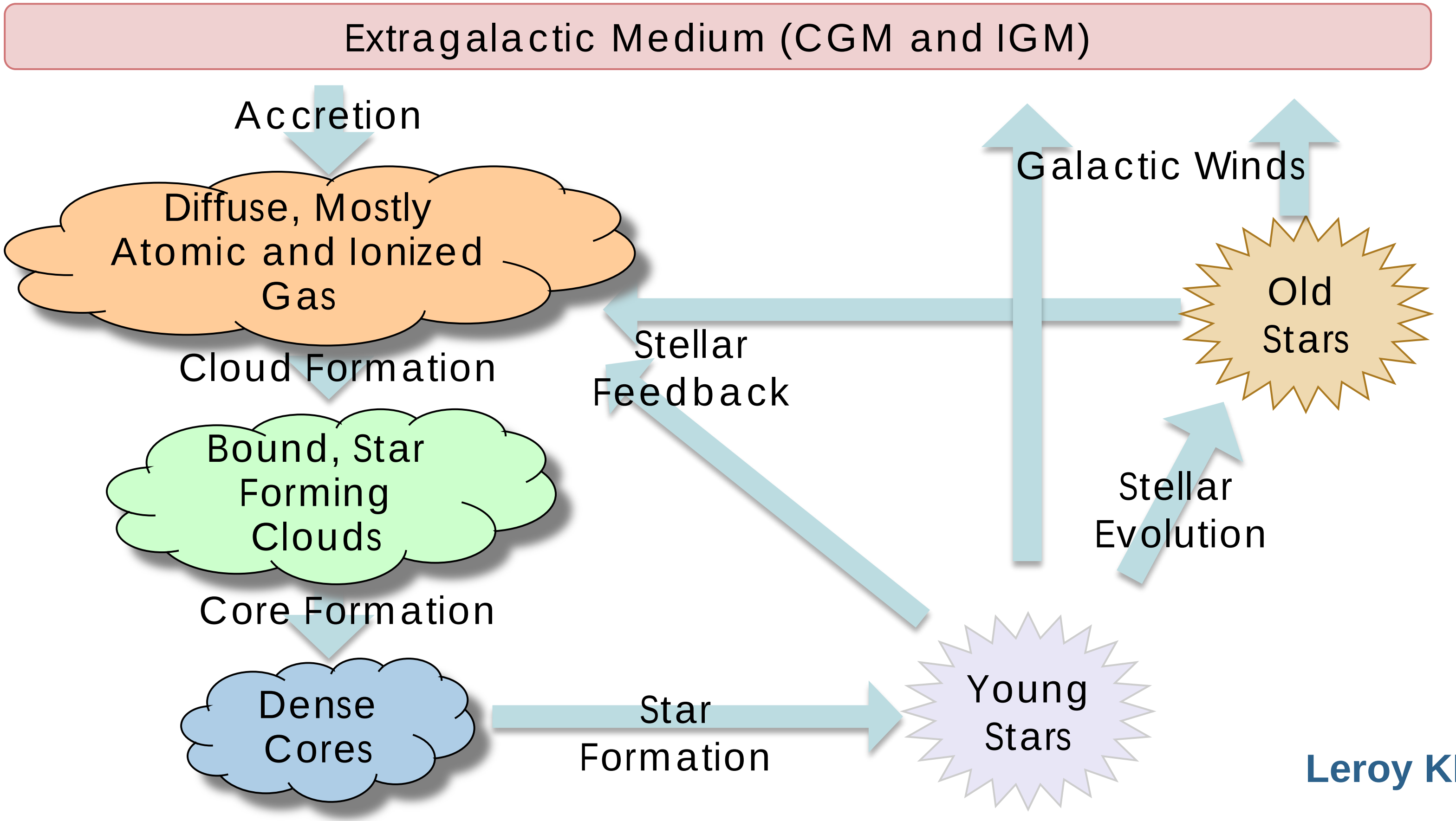
# The Next Generation Very Large Array:

## Science in Nearby Galaxies

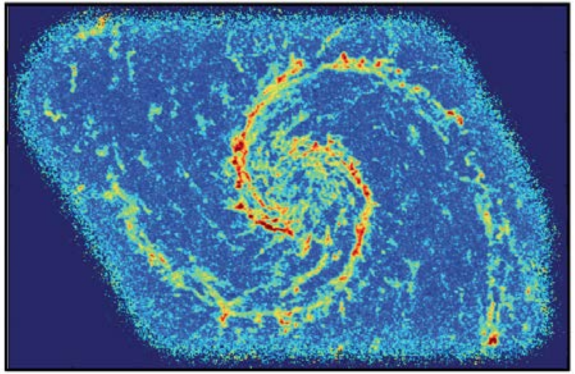
Eric J. Murphy for the Galaxy Ecosystem Working Group
(Caltech/IPAC)

# Gastrophysics: Multi-Process and Multi-Scale




Leroy KISS talk

# Game Changing, Qualitative Gains for Studies of Nearby Galaxy:



## Spectral Line Mapping:

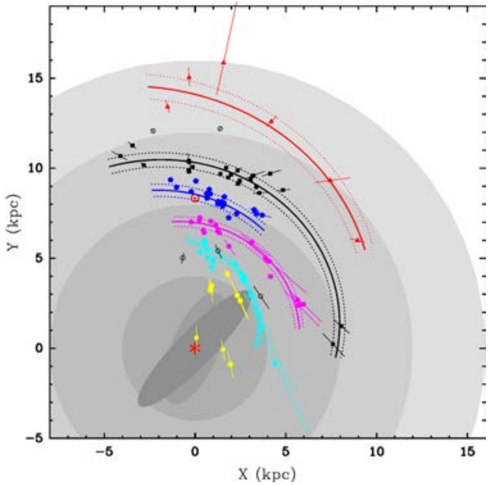
Map the diagnostic fingerprints of molecules and atoms in the cool ISM ~50x faster than ALMA

Enable major advances in our understanding of:
- astrochemistry
- the interstellar medium
- star formation
- dynamics

## Wide-Band Continuum Imaging:

Simultaneously capture all major radio emission mechanisms in a single observation (synchrotron, free-free, dust, SZ effect)

Enable major advances in our understanding of:
- the physics of cosmic rays
- ionized gas
- dust
- hot gas around galaxies.

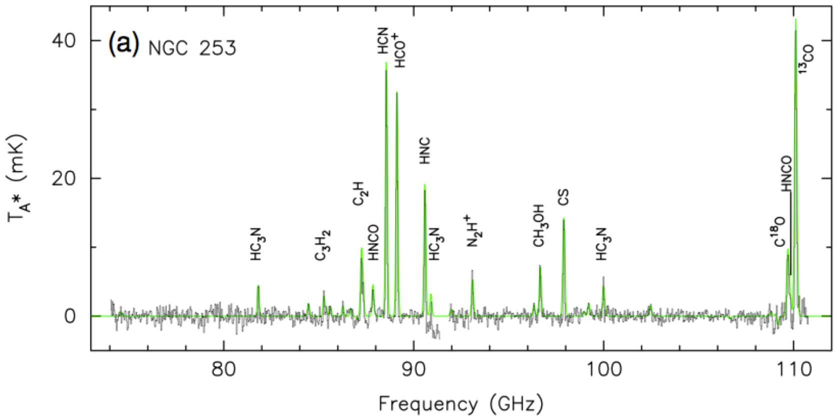



## Very High Resolution Imaging:

- obtain a complete view of the Milky Way’s structure
- resolve actively forming high mass stars and track their motion
- resolve three dimensional motions of forming stars and nearby galaxies

# Spectral Line Mapping Beyond ALMA

*The range 1.2 - 116 GHz offers a stunning range of diagnostic power with minimal sensitivity to temperature effects. The ngVLA is the next logical step beyond ALMA in spectroscopy.*

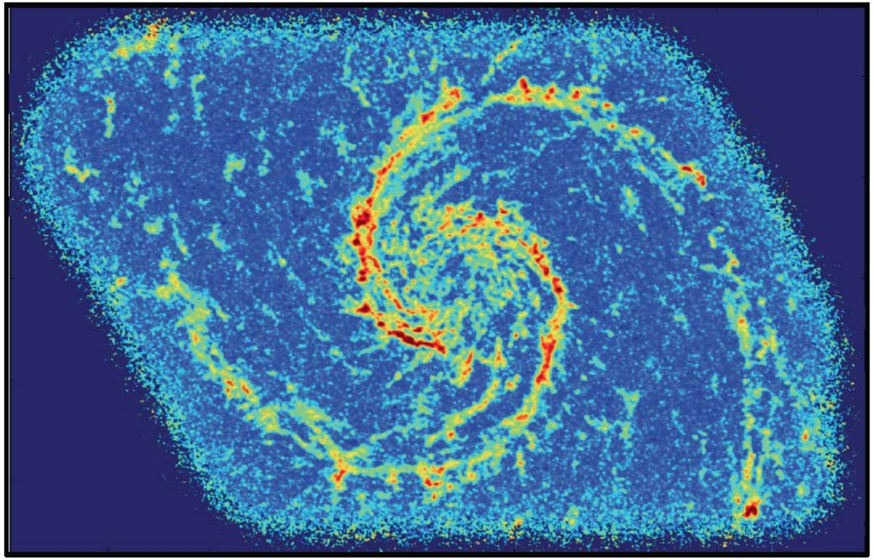



- **Molecular lines carry fingerprints of chemistry, temperature, density, presence of shocks, gas distribution, and kinematics.**
  *SiO, $NH_3$, HCN, $HCO^+$, CS, CO and a host of other molecules have their fundamental transitions in the range 1.2-116 GHz, which are faint (10-100x fainter than CO)*

- **Even with ALMA, spectroscopy is a major time investment (the level zero goal of <u>one</u> Milky Way at z ~ 3) take a day.**
  *Under any reasonable scenario mm-wave spectroscopy will remain a vibrant field over the coming decades because the observations take so much time and the insight into physical conditions is irreplaceable.*

# Spectral Line Mapping Beyond ALMA

| Machine | Image rms 1hr in a 1 km/s Channel | rms Brightness Temperature for a 1" Beam | Approximate Field of View (FWHM) |
|---|---|---|---|
| ALMA (40 dishes) - 345 GHz | 2.0 mJy/bm | 0.02 K | 16" |
| NGVLA (VLA x 5) - 100 GHz (assumes VLA dish quality) | 0.15 mJy/bm | 0.019 K | 56" |



**State of the Art**: M51 in CO (*J*=1-0) at 1" and ~1 K per km $s^{-1}$ - Schinnerer et al. (2013) **-- 200 hr with PdBI ~ 15 hr w/ ALMA ~** ***12min with ngVLA***

- ***For single lines in Band 3, the ngVLA is ~75x faster than ALMA***

- For Band 7, an upgraded VLA achieves similar rms over >10 times the area compared to ALMA – *and probes lower frequencies (lower ladder transitions) and so is less sensitive to the details of excitation.*
- This is a bit pessimistic: if the dishes and system were optimized for ~3-4mm observations, should be able to map CO ~>50x faster than ALMA in Band 7.
- ***Combining with bandwidth (~x3 due to multiple tunings), this machine is up to ~150 times faster than ALMA at mapping lines!***

# Key Considerations For Spectral Line Mapping

- **Surface brightness sensitivity** - to study the cold ISM line sensitivities ***need reach down into the K regime (even to <~ mK for exgal).*** It matters where the dishes sit, e.g., at 100 GHz the current "D" configuration is already ~ arcsecond.

- **Angular Resolution** - at the high end of the mm-wave band the angular resolution implied ***even by the current VLA configurations is very high*** ("A" is twice ALMA's maximum baseline already).

- **Spectral Resolution** - Galactic (or highly resolved extragalactic) work will require ***high (fraction of a km/s) spectral resolution*** across large parts (but maybe not all) of the band.

- ***uv* Matching** – over a decade in frequency means that a single physical telescope configuration produces a wide range of wavelength spacings - ***matching the upper and lower parts of the band.***

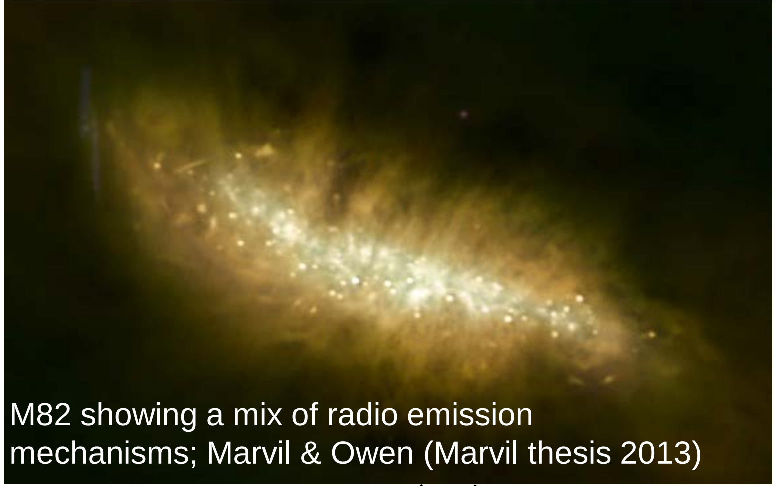
# Continuum Science Beyond the Jansky VLA

- **Why We Care:** between ~1.2 and 116 GHz all major radio emission mechanism contribute to the SED at similar levels. Sensitive, wide-band, high resolution observations in this regime let us understand the ***physics of dust, ionized gas, cosmic rays, magnetic fields, and hot gas.***

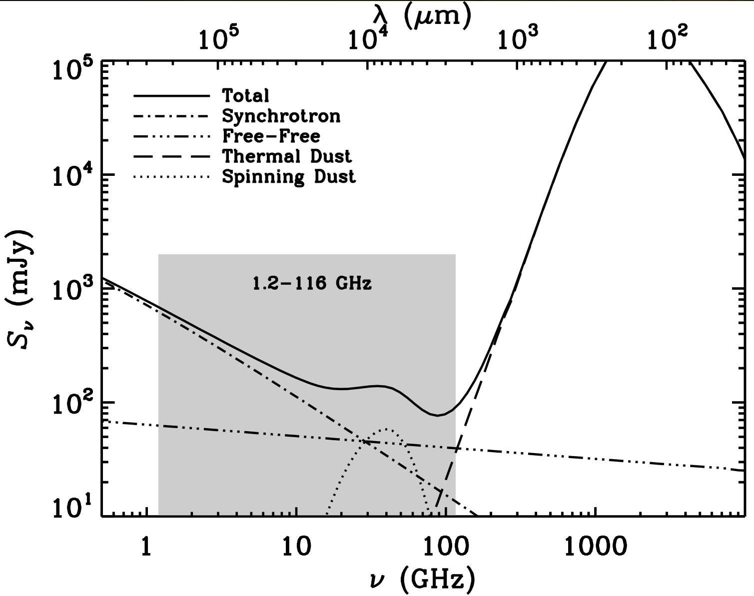
- **The Leap Forward:** The proposed instantaneous bandwidth, collecting area, and baselines (all ~5-10x VLA), should capture new regimes in continuum science: faint, extended emission, SZ effect in new places, full dust+thermal+non-thermal SED at once.

ngVLA is an **unprecedented** machine that uses the full radio continuum to study astrophysics. By contrast:

- ALMA is mostly optimized for dust emission
- SKA should be a synchrotron machine
- ***the ngVLA maps them all simultaneously, making it a physics tool!***



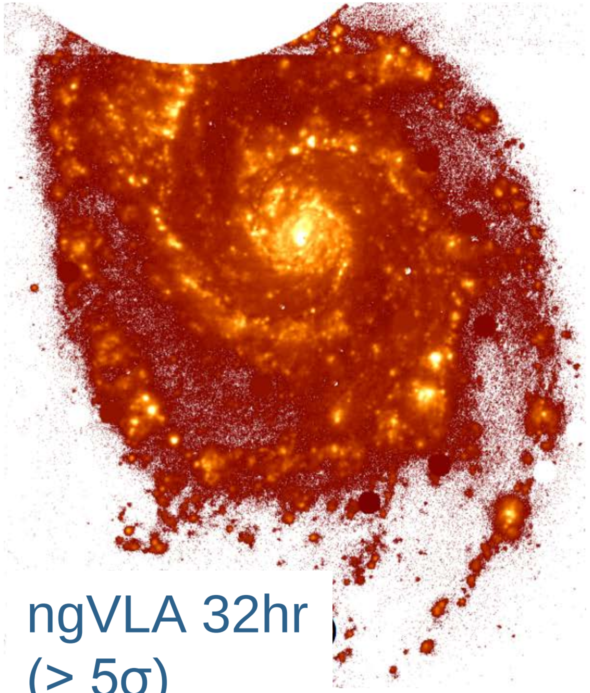
M82 showing a mix of radio emission mechanisms; Marvil & Owen (Marvil thesis 2013)



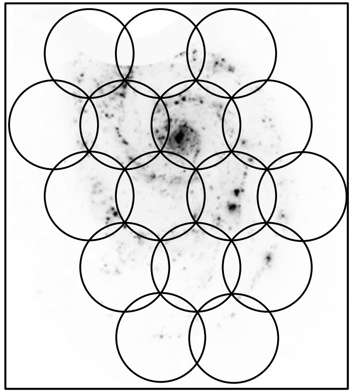
# Robust Maps of Star Formation in Nearby Galaxies

## M51 at 33GHz (free-free emission)

JVLA 64hr
(> 5σ)



ngVLA 32hr
(> 5σ)



Model 33GHz from Hα

- units: μJy/bm for $\theta_S$ = 1”
- 15m dishes
- 8GHz bandwidth
- 2hr/ptg: rms ~ 400 nJy/bm
- $\langle A_V \rangle$ ~ 3 mag (Scoville+ 2001)

- Equivalent map would take ~200 to 300x longer with JVLA ***(i.e., ~2500 hr !!!!).***

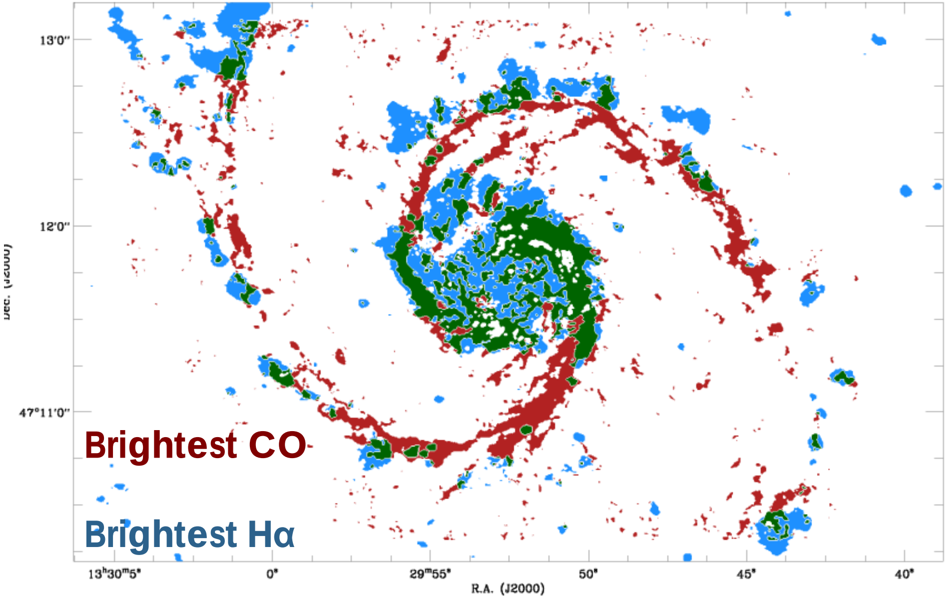
***Direct measure of ionizing photon rate without [NII] or extinction corrections***

# Key Continuum Considerations

- **Bandwidth:** ***Wide instantaneous bandwidth is a major enabler***, with resolution (beyond ~2 MHz or so) secondary.
- **Brightness Sensitivity:** As with lines (but not the same numbers) the ability to detect a diffuse, faint glow (at high resolution) is key to a lot of science and this means ***brightness sensitivity is key to a lot of science***. This comes from a more filled (compact) array.
- ***uv*** **coverage and frequency:** Again, the wide spectral coverage means that the ***interaction of frequency and antenna position might complicate creation of a continuous SED***. But this is a secondary concern.
- **Polarization:** For both line and continuum (but especially continuum), ***wide band polarization capabilities will be key*** to study the morphology and magnitude of magnetic fields.

# The Power of the ngVLA
# Bandwidth: Continuum and Lines at the same time
# High Enough Resolution to see Evolution

## M51 CO & Hα

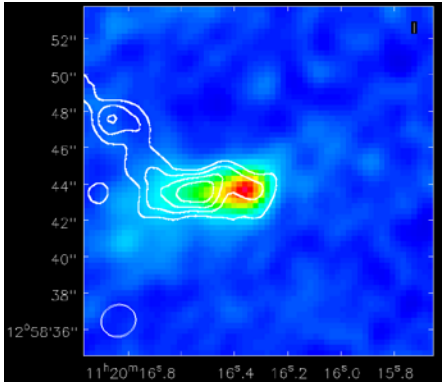



**Overlap**

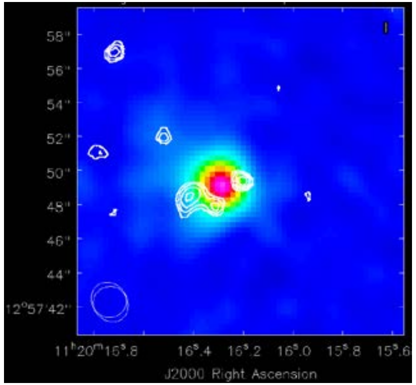
SCHINNERER ET AL. (2013), PETY ET AL. (2013) – S. MEIDT, HUGHES, LEROY ET PAWS IN PREP.

## HII regions in M66

### ALMA + JVLA




**HCO+ contours on 33GHz**

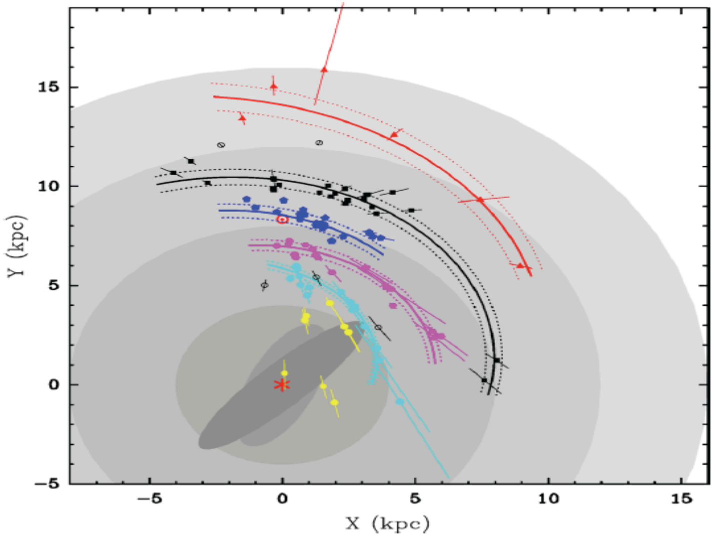


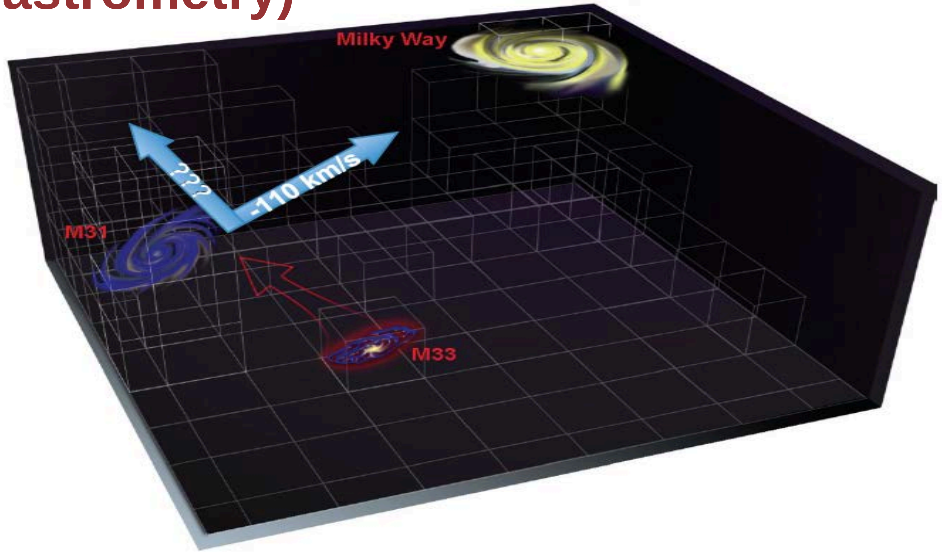

**HCN contours on 95GHz**

PEAKS OF CURRENT STAR FORMATION OFFSET FROM SITES OF FUTURE STAR FORMATION

MURPHY ET AL. IN PREP.

# Very Long Baseline Science Beyond the "HSA"
## (VLBI μas astrometry)




- We know very little about the far-side structure of the MW
- ngVLA will provide a complete view of the large scale structure of MW

- The orbits and fate of the Local Group galaxies remain uncertain – need proper motions ~10's of km/s at ~1Mpc
- ngVLA will deliver 3D imaging of dynamics of LG for dark matter, real-time cosmology

Much of the science requires ~20% of collecting area at long baselines.

# Key Very Long Baseline Numbers

- **Baseline length** - a few hundred km and a few thousand km offer qualitatively different science (few hundred km great for star formation, ***a few thousand needed for "super" version of current science***). Designing in very long baseline science offers advantages compared to post-hoc construction of next generation VLBI networks.

- **Frequency coverage** - ***high frequency might be less of a driver for the very long baseline applications***. It's possible that the key masers and continuum applications could be achieved with ~5 - 50 GHz coverage. Heterogeneous design? At least not a driver.

- **Spectral Resolution -** Spectral resolution is important (masers) but not necessarily over the whole band. It's not totally clear that the VLBI applications drive the frequency setup.

- **Collecting Area at Long Baselines** - sensitivity dominates considerations for VLBI science, ***to do qualitatively new work large amounts of collecting area*** at Earth-spanning baseline lengths are required.

# Food for thought and Implications for Design / Science Requirements:

- The current VLA is already ~3x ALMA's collecting area.
- A 5x VLA concept ~2x more collecting area than the re-baselined SKA1-MID
- Brightness sensitivity is key for many line and continuum requirements (D/C-configuration w/ a lot more collecting area already optimized for 100GHz "thermal" (~K) line science.
- *uv*-coverage matching complicates "ratio science" *(movable vs. lots of dishes)*
- Mapping speed / mosaicking - *small dishes*
- Frequency coverage - high end of the mm band a line driver, 100 GHz a driver for continuum but not 115 GHz, high frequency less key for VLBI applications.
- Spectral resolution - be ambitious with correlator / computing specs, this project will gestate for a long time
- Even in "next generation" mode, the HI and CO (+isotopologue) lines represent irreplaceable workhorse lines.