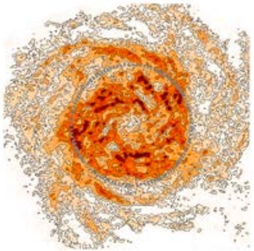
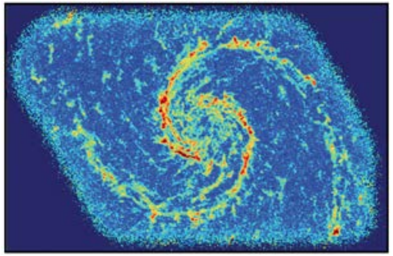
Next Generation Very Large Array Working Group 2


HI in M74: Walter+ '08

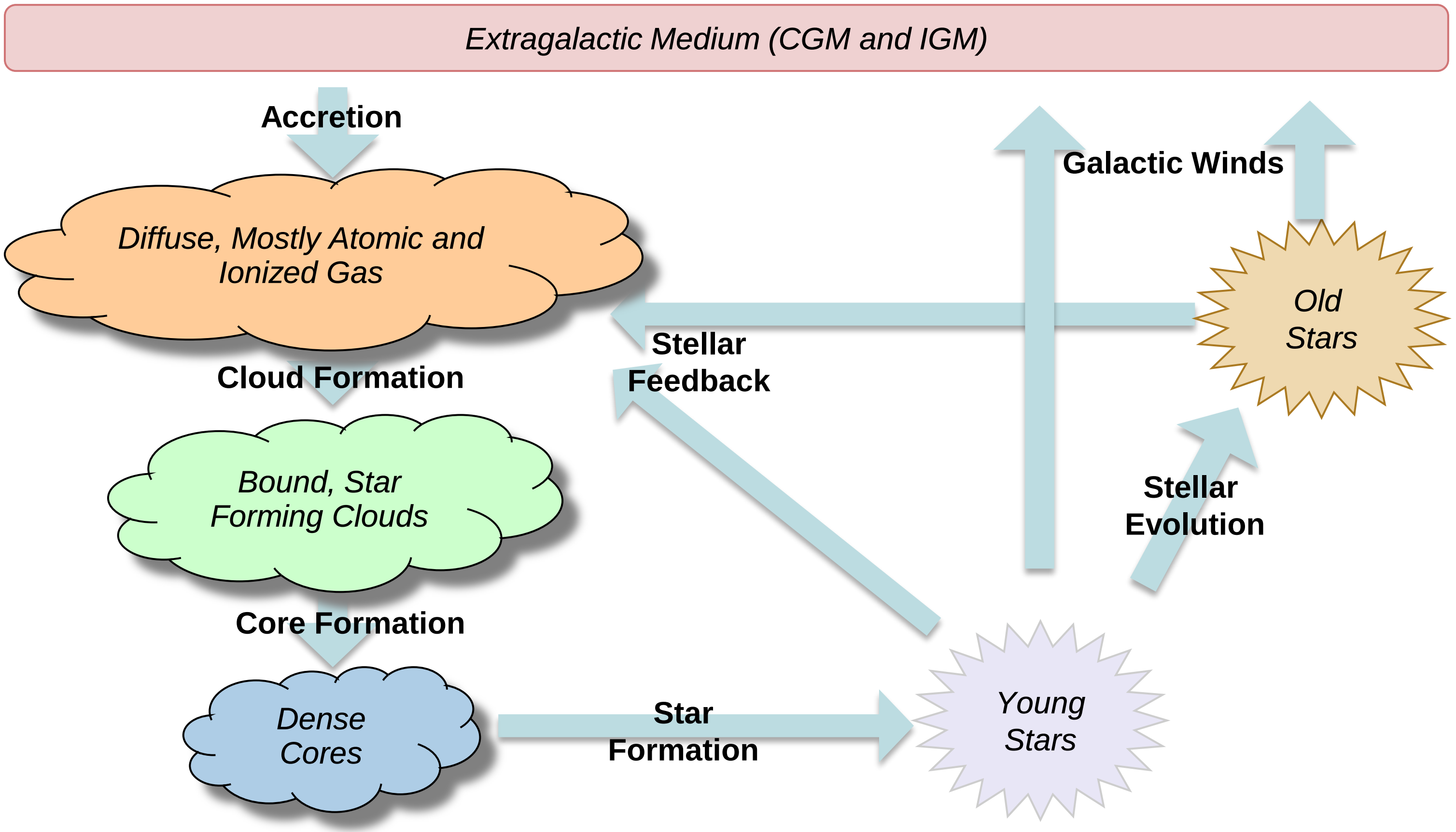

CO in M51: Schinnerer+ '13


Continuum in M82: Marvil & Owen

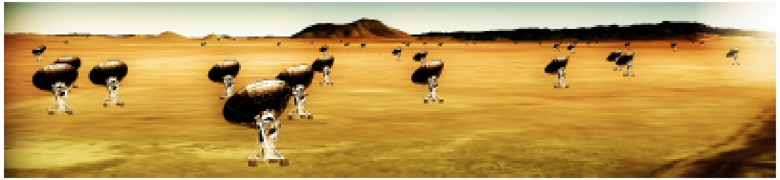
"Galaxy Ecosystems"

Adam Leroy (OSU), Eric Murphy (NRAO/IPAC) on behalf of **ngVLA Working Group 2**

Galaxy Ecosystems – the Matter Cycle In and Around Galaxies



Galaxy Ecosystems Working Group



Next Generation Very Large Array Memo No. 7
Science Working Group 2
"Galaxy Ecosystems" : The Matter Cycle in and Around Galaxies

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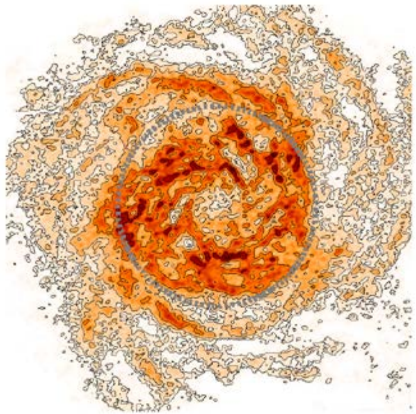
arXiv:1510.06431

- Contributions from a broad cross-section of community members.
- Outline gains in four areas:
  - cm-wave spectroscopy
  - continuum imaging
  - high resolution of thermal sources
  - very long baselines (very high resolution)
- Suggest benchmarks for the ngVLA to offer revolutionary capabilities.
- Highlight design elements key to this topic.
- Very much a "first look"

Radio Gives Us a Main Tool to Understand Galaxy Ecosystems



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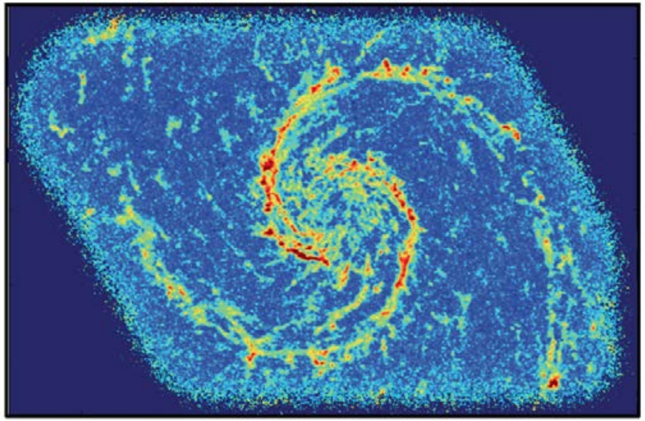
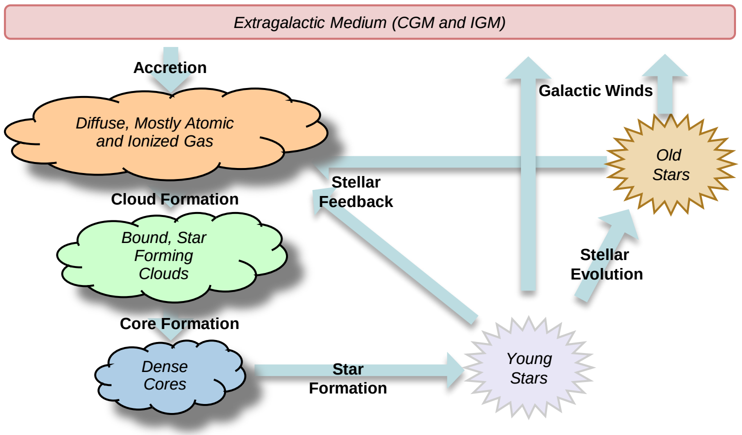


CO in M51: Schinnerer+ ‘13

Continuum in M82: Marvil & Owen

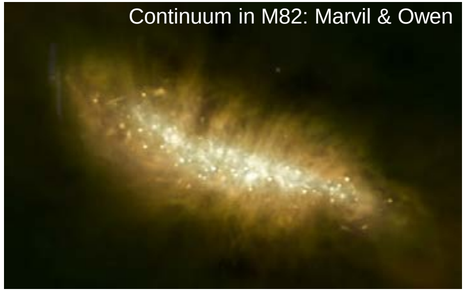
- Main way to observe distribution, motions, physical state of atomic (HI) and cold molecular (H_2) gas.
- Continuum contains information on recent star formation (ionized gas), cosmic ray electrons, magnetic field structure, and hot gas pressure (SZ effect).
- Astrometry and kinematics with extremely high precision to trace structure of the Milky Way and the Local Group.

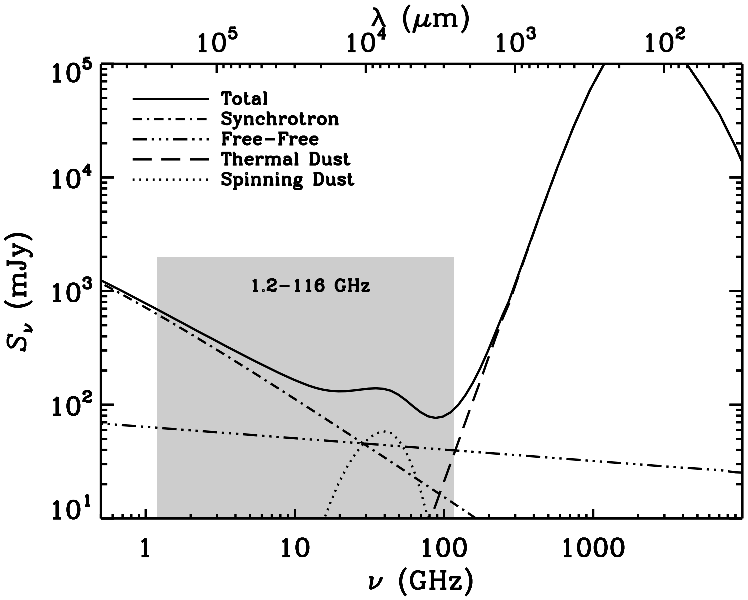
Galaxy Ecosystems – the Matter Cycle In and Around Galaxies



- How does gas move in and out of galaxies?
- How does the chemistry and physical state of the ISM depend on galaxy and environment?
- How do black holes and stars change the state and chemistry of the surrounding gas?
- How are high mass stars and clusters of stars formed, in detail?
- How does the state and chemistry of gas affect its ability to form stars?
- What is the structure of hot gas halos and magnetic fields in galaxies?

The Range ν=1-116 GHz Contains a Stunning Array of Diagnostics





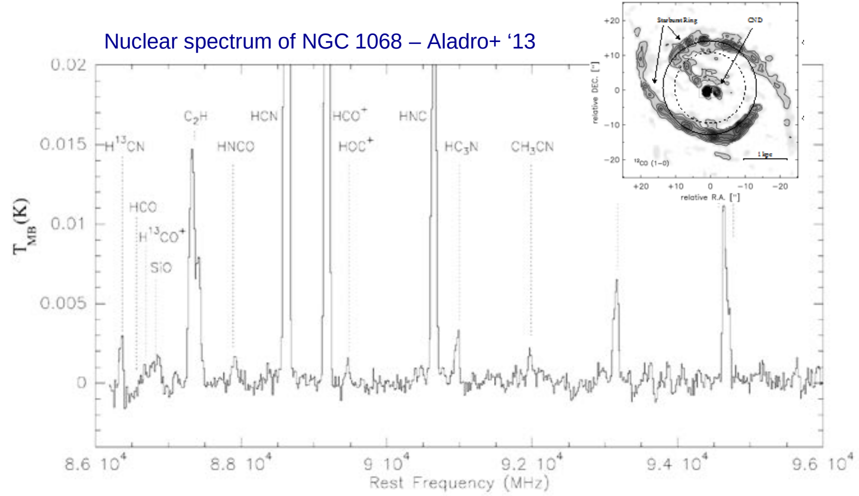
In this range (uniquely) all major continuum processes can be dominant:

- Synchrotron from cosmic ray electrons
- Rayleigh Jeans dust emission
- Thermal free-free emission
- Spinning dust grains

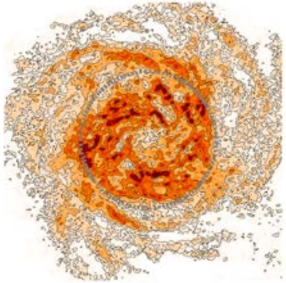
Polarization traces magnetic field structure.

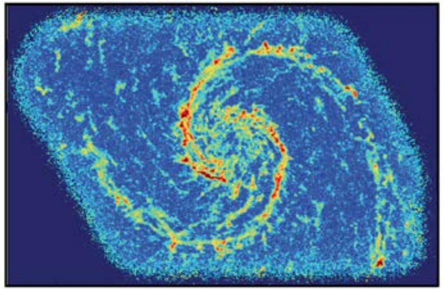
With enough sensitivity, the Sunyaev Zeldovich effect can be seen, perhaps even from the halos of normal galaxies.

The Range v=1-116 GHz Contains a Stunning Array of Diagnostics



Nuclear spectrum of NGC 1068 – Aladro+ '13



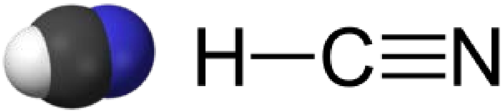


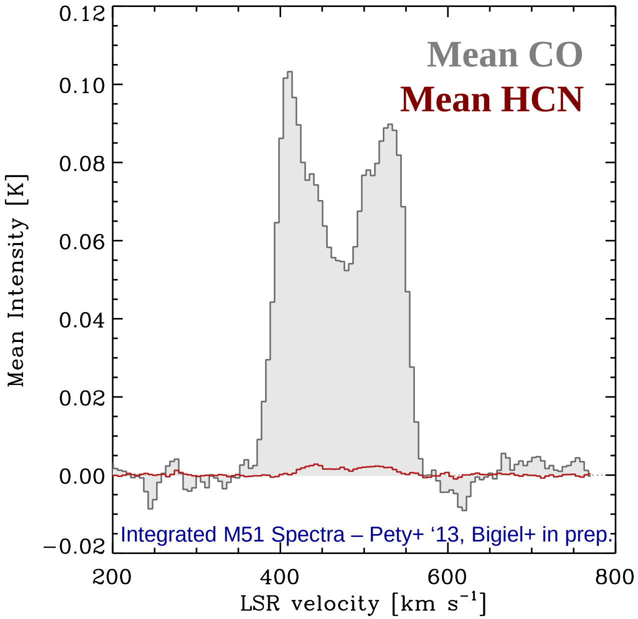
Multi-line spectroscopy, especially in the range 20-116 GHz can probe the distribution and physical state of the cold gas (as low as ~10 K) in a cloud or galaxy, including measuring:

- Excitation and temperature
- Density
- Presence of shocks
- PDR/XDR/CRDR balance

And can assess local chemistry, including the presence of complex organics.

Most of these Diagnostics are Sensitivity-Starved at Present

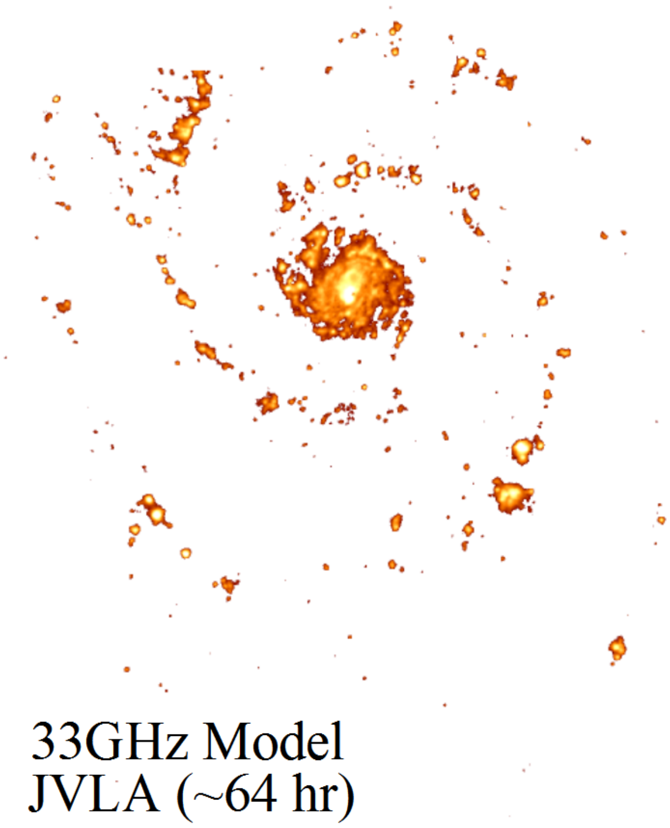




HCN, with a high critical density and reasonably high abundance, is one of the most commonly used tracers of dense gas.

- Ratios of CO-to-HCN in the disks of galaxies are often ~ 30-to-1.
- HCN is one of the brightest non-CO 3mm molecular lines. Many key diagnostics are much fainter.
- Imaging these species takes 1000 times longer than CO.

Most of these Diagnostics are Sensitivity-Starved at Present



Thermal free free emission yields a map of the distribution of ionizations with no concern for extinction:

- For star-forming galaxies, free-free dominant from ~30 to 200 GHz.
- But this emission is faint: in an image simulated for the JVLA from an Hα map spiral arms are barely visible in 60+ hours.
- Subtle decomposition and SED modeling requires even higher signal to noise.

For Thermal Sources, Sensitivity Also Limits Resolution

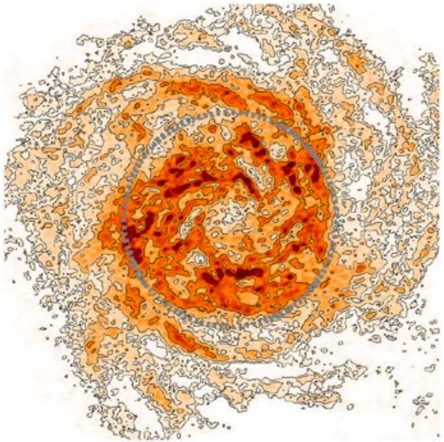
There are also enormous gains to made from improved resolution with existing tools: resolving forming high mass stars, distant filaments, clouds in other galaxies, etc.

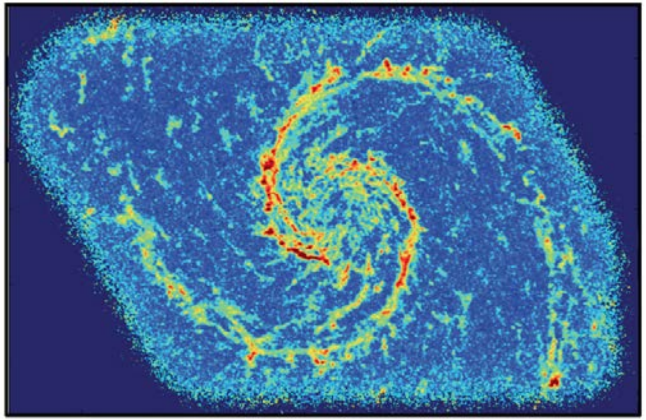
- For a fixed array + brightness:

$$\tau_{\text{int}} \propto \theta^{-4}$$

- So for fixed (e.g., 0.1 pc) res.:

$$\tau_{\text{int}} \propto d^{4}$$





For much galaxy ecosystem science, surface brightness sensitivity is the figure of merit. For a given telescope, the time to reach a fixed brightness sensitivity goes as resolution to the $^{-4}$.

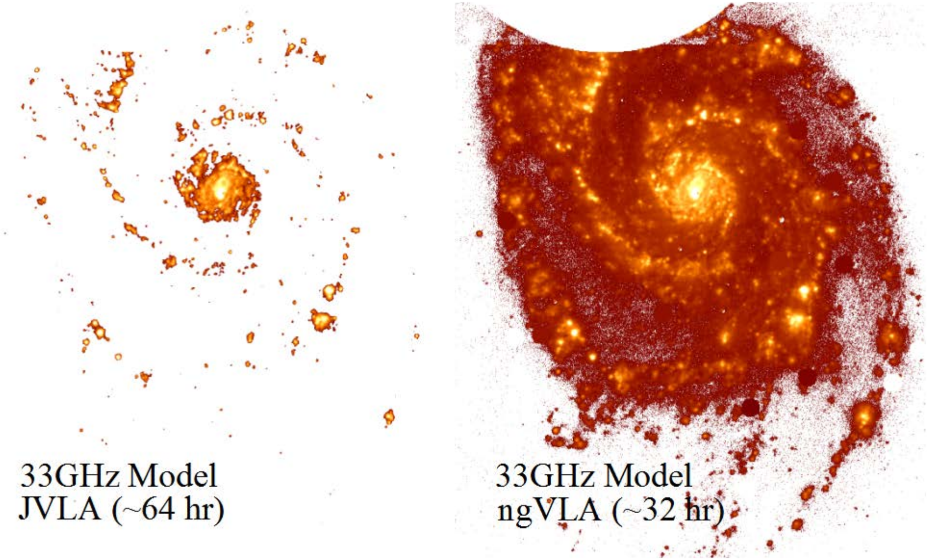
This is why we don't regularly image HI a (sub)-arcsecond resolution in A configuration. And it is why the first arcsecond resolution CO map of a big part of a galaxy came only 3 years ago.

Surface Brightness Sensitivity as a Key to Breakthroughs

A leap in surface brightness sensitivity would bring the powerful physical diagnostics in the range ν = 1-116 GHz in to regular use at high resolution, so that they could be applied to survey purposes and become regular tools for "P.I. science."

The best way to achieve this is a **massive gain in collecting area** at the relevant baselines compared to previous facilities. For the "thermal" science in the galaxy ecosystems area, the relevant baselines are roughly those of the current VLA, especially a few km.

Surface Brightness Sensitivity as a Key to Breakthroughs

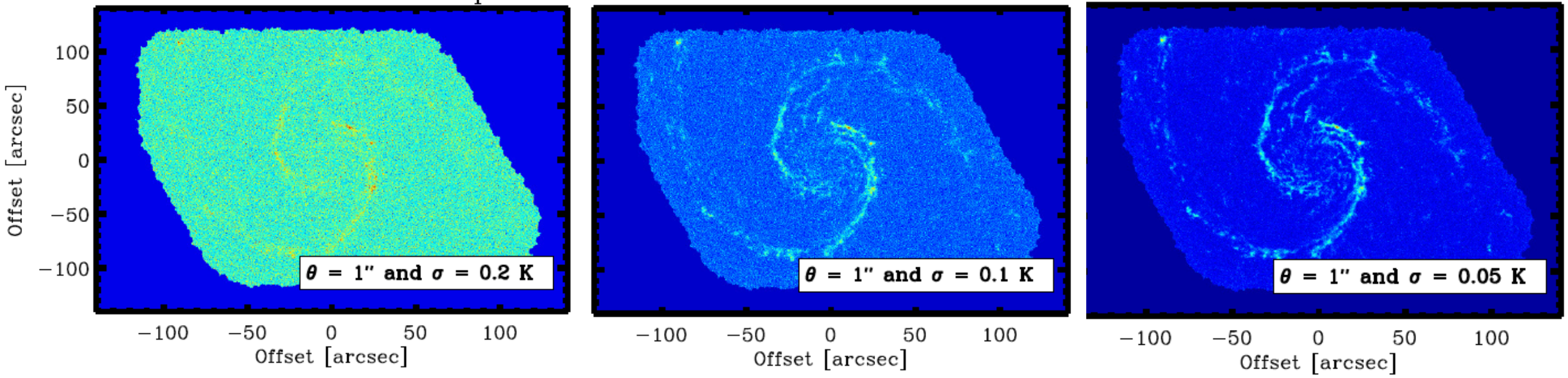


With approximately the version of the ngVLA proposed in the initial white paper, it would be possible to image thermal emission (indeed the whole SED) across a star-forming galaxy at ~1” resolution in ~30h. More, full, wide-band point-by-point SED modeling would be possible up to 100 GHz, not just for a few bright regions (or requiring 1000s of hours) as now.

Surface Brightness Sensitivity as a Key to Breakthroughs

M51 Simulated HCN Map

Simulations from scaling Schinnerer+ ‘13 CO map using 1-to-20 HCN-to-CO

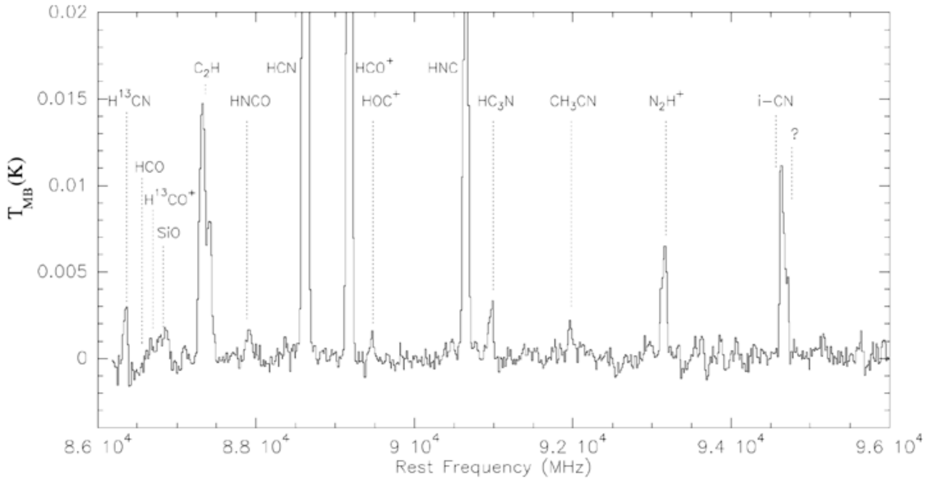


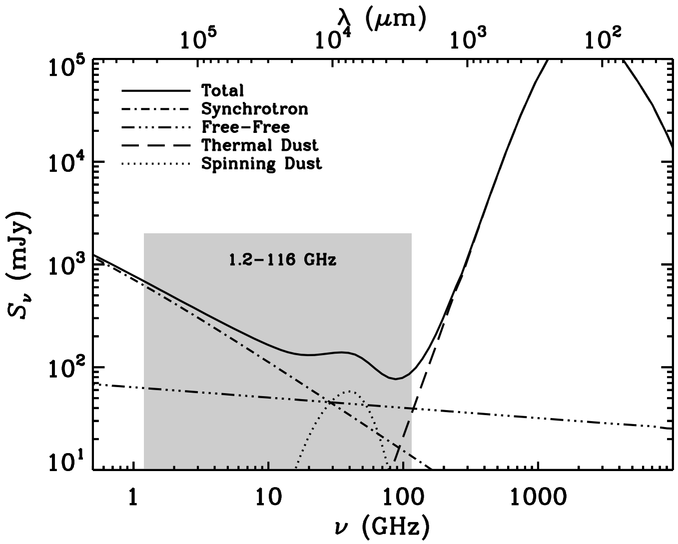
A similar demonstration of how improved surface brightness sensitivity at high resolution recovers simulated HCN emission (calculated from CO) for M51 at one arcsecond resolution. Sensitivities of ~50 mK (per ~5 km s^{-1}) recover structure at high signal to noise.

HCN is among the brightest (non-CO) extragalactic lines – high surface brightness sensitivity is essential to push sophisticated mm/cm-wave spectroscopy into common use.

Surface Brightness Sensitivity as a Key to Breakthroughs

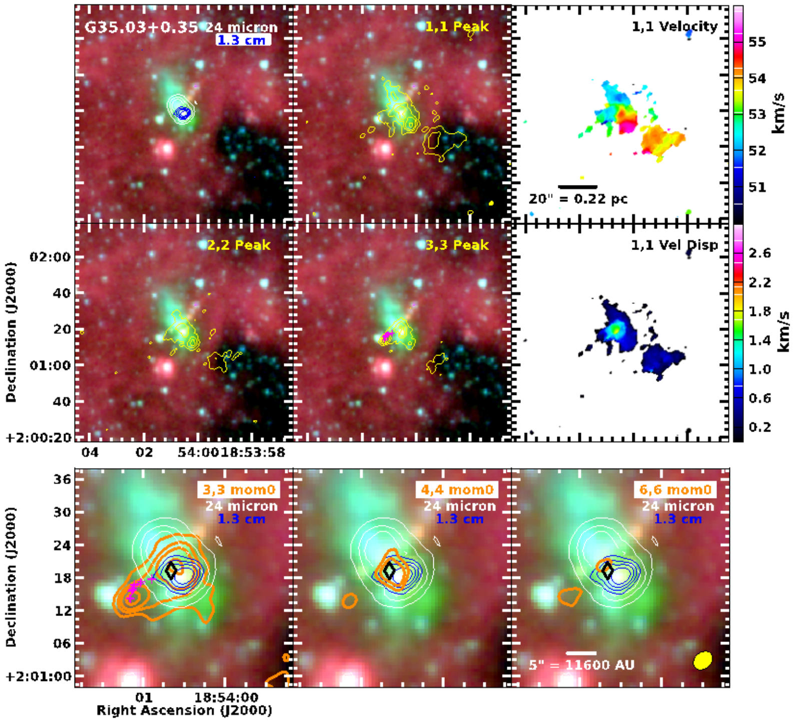
Nuclear spectrum of NGC 1068 – Aladro+ '13





With enough sensitivity *every synthesized beam* in a spectroscopic imaging observation will contain a large suite of spectroscopic diagnostics and detailed continuum information.

High Physical Resolution for Thermal Sources



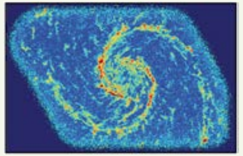
Brogan+ '11 and in prep. – Ammonia and continuum in protocluster G35.03+0.35

NH_3 largely restricted to VLA D by surface brightness considerations

With better surface brightness sensitivity, one will also be able to map tracers of excitation and density like ammonia and formaldehyde in distant, lower massive protoclusters and even in to other galaxies.

- (sub)-arcsecond atomic gas (HI) imaging would be possible, enabling "cloud-scale" work beyond the local group.
- Stunningly detailed views of galaxy nuclei would allow nearby galaxy nuclei to be studied like the Milky Way.
- It might even be (just) plausible to observe turbulent motions in 3-d (via proper motions).

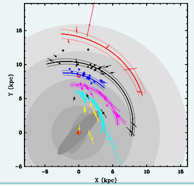
Suggested Benchmarks for Galaxy Ecosystems



Map lines 30 times fainter than ^{12}CO with ~1” resolution, high fidelity, and full flux recovery fast enough to survey many galaxies and large parts of the Milky Way.

Measure the radio spectral energy distribution at ~1” resolution with high fidelity and full flux recovery quickly enough to allow mapping surveys of galaxies.

Achieve sensitivity to thermal line and continuum processes at ~0.1” resolution quickly enough to allow surveys of many forming protoclusters and galaxy nuclei.

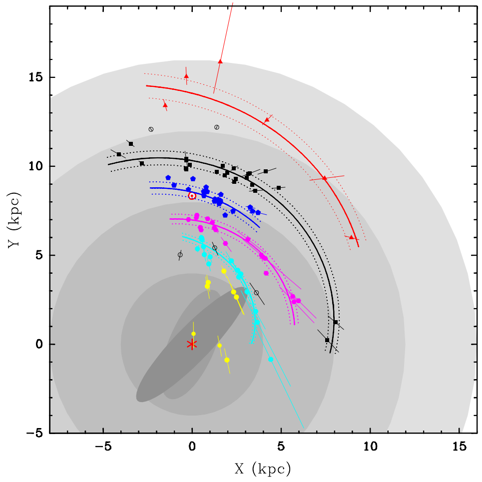


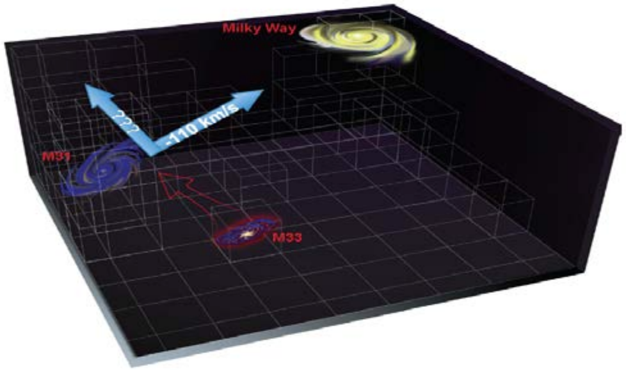
Measure the proper motion of galaxies at the level of ~ 0.1 uas yr^{-1} and distances to weak masers with ~10% accuracy at ~20 kpc.

Key Elements of Technical Design

- **A large amount of collecting area on few ~km baselines** is essential.
- Some plan for **short and zero-spacing data** built in to the baseline design is crucial.
- **Large instantaneous bandwidth** aids spectroscopy (many lines) and continuum science.
- Coverage all the way from **1 to 116 GHz** (HI to CO) is important.
- A plan for **very long baseline capabilities** built in to the array is important.
- Other considerations like a small dish size are desirable but not irreplaceable.
- u-v matching across frequency another issue to build in.

A Strong Case for Very Long Baseline Capabilities





Building very long baseline capabilities in to the design of the ngVLA would offer major gains in the area of galaxy ecosystems.

With added collecting area and VLBA baselines it will be possible to:

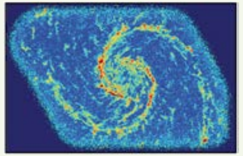
- Measure direct distances to star-forming regions on the other side of the Milky Way.
- Directly observe the three-dimensional motions of Local Group galaxies.

A Complement to ALMA

- ALMA is optimized for sub-mm, where it exceeds previous capabilities by orders of magnitude.
- At cm the picture is muddier: the current VLA has ~3 times the collecting area of ALMA already.
- Sub-mm is fantastic for things that are warm or forming. It struggles to capture the cold gas and continuum processes other than dust.
- ngVLA – “the matter cycle”, ALMA – “things forming”

(similar lines of discussion apply to the SKA)

Suggested Benchmarks for Galaxy Ecosystems



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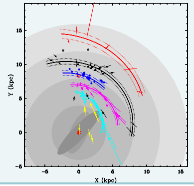

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