In Dust we Trust, from Orion to Andromeda

Molecular clouds from our Galactic backyard to Andromeda's neighbourhoods

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Smithsonian Astrophysical Observatory

In Dust we Trust, from Orion to Andromeda

'Nearby' molecular clouds in M31 with the Submillimeter Array

1) For star formation studies, *dust* observations define the "ground truth"

2) Locally, it is difficult to obtain large, resolved samples of clouds.

3) Comparable resolved extragalactic observations are so far limited to CO.

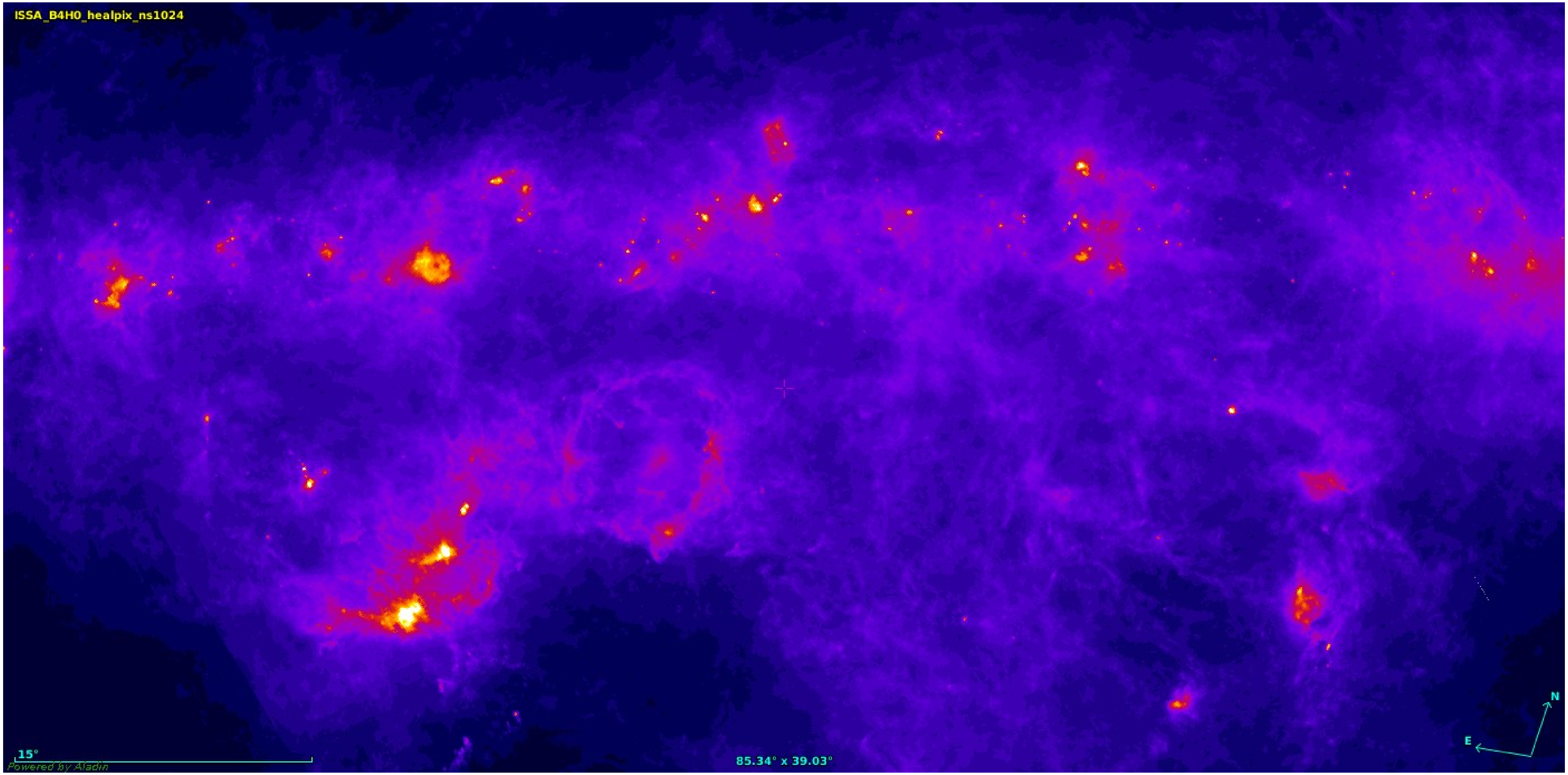
4) The SMA upgrade provides a unique opportunity to remedy that: in M31.

5) First resolved dust observations of GMCs in external disk galaxy (*and* CO)!

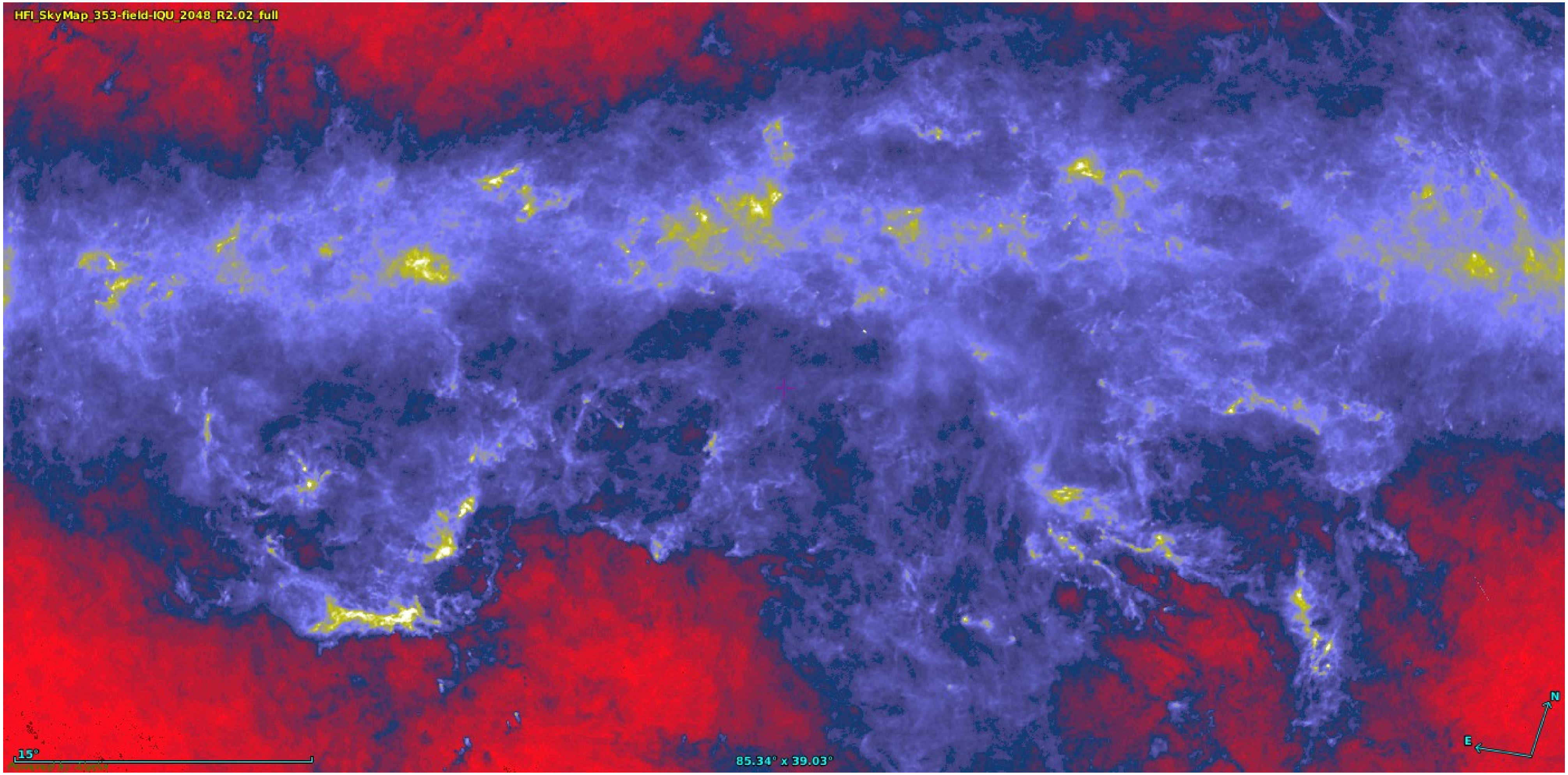
6) These will place Milky Way and extragalactic studies of GMCs *on the same footing.*

7) For star formation science, the wSMA upgrade will be transformational.

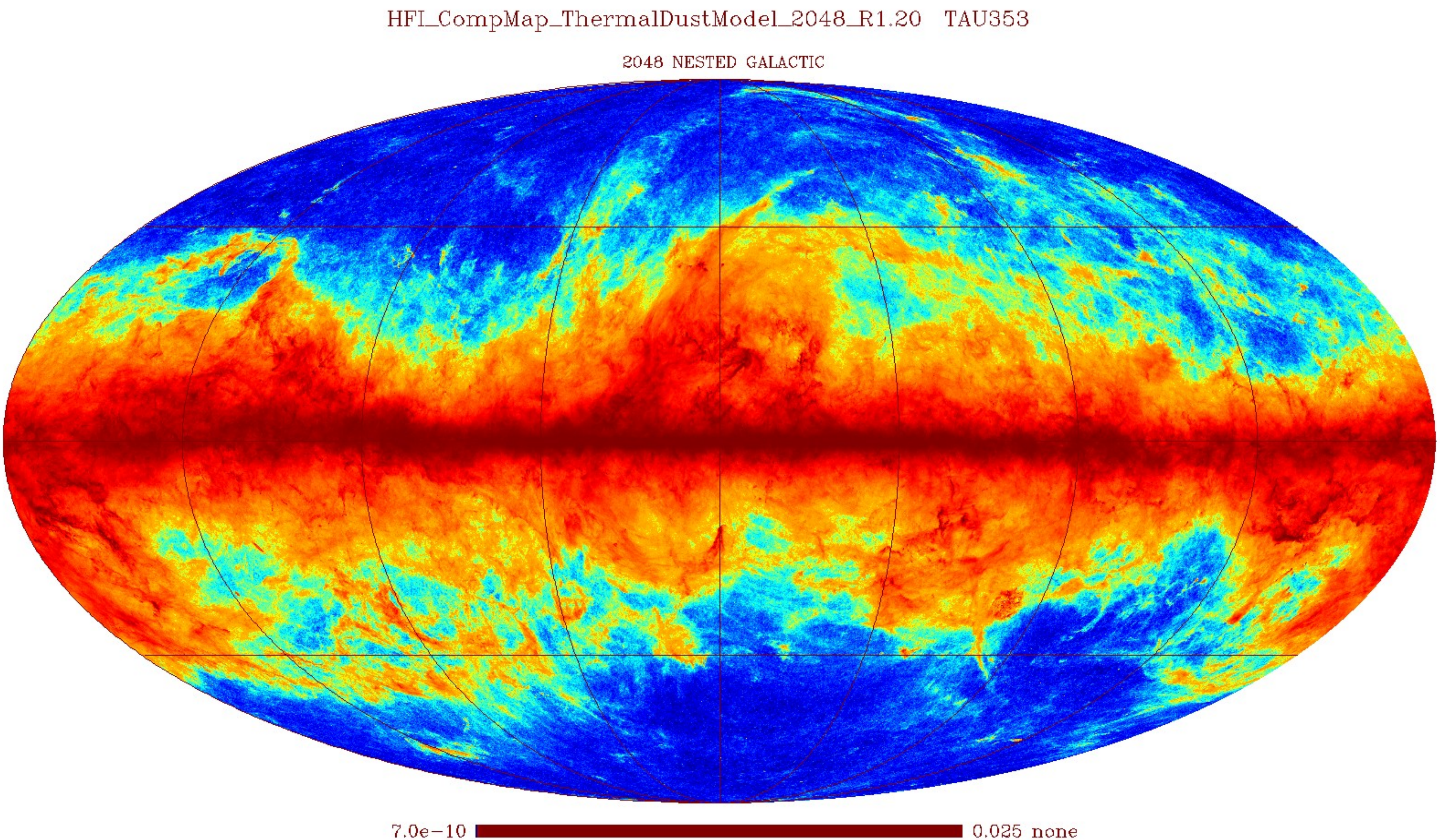
Stars form in **molecular clouds**



IRAS 100 μm

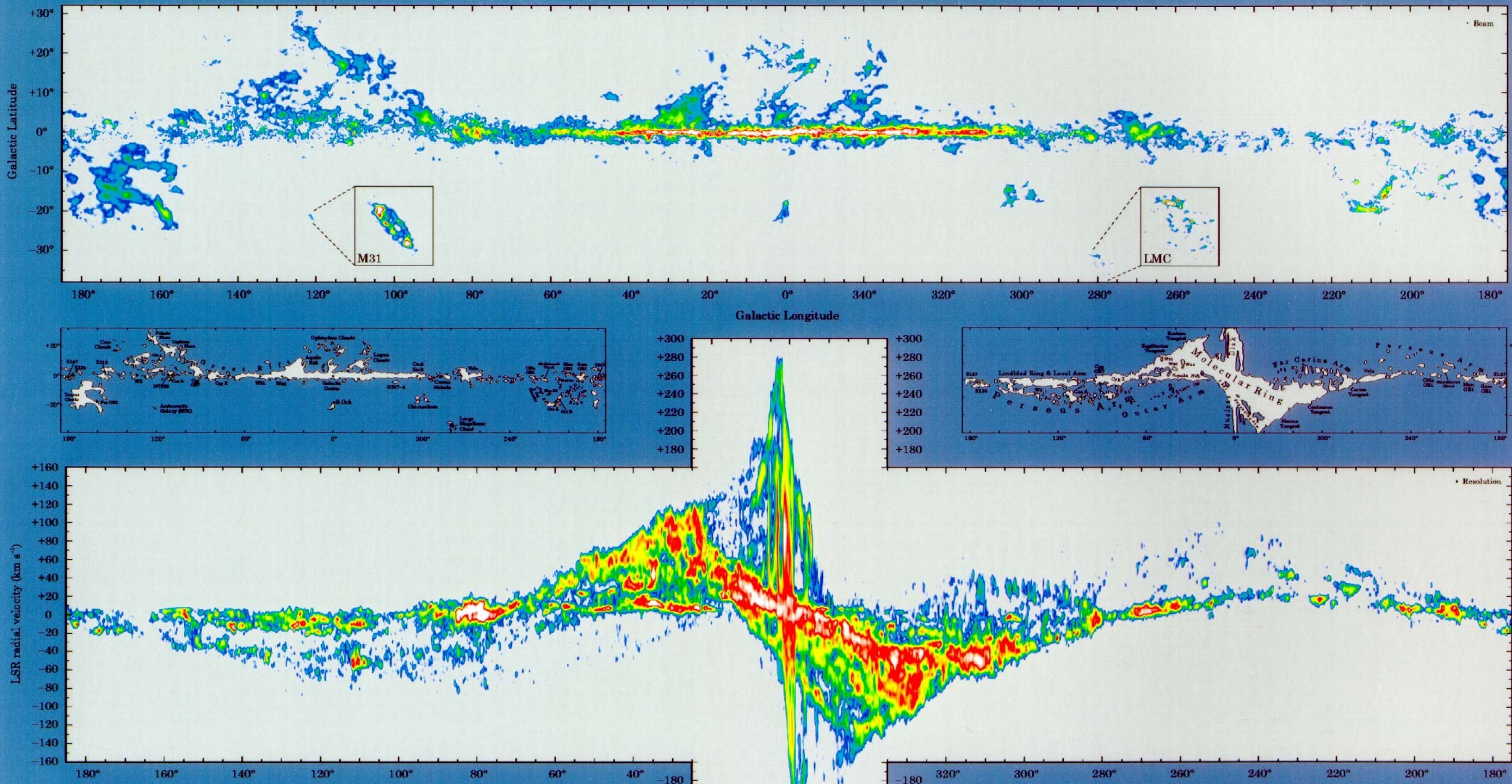


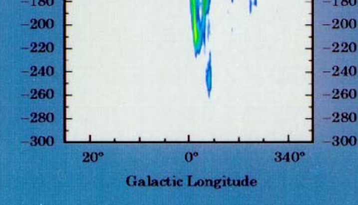
Planck 850 μm



Planck Collaboration

The Milky Way in Molecular Clouds





The Milky Way and its nearest neighbors, the Andromeda galaxy (M31) and the Large Magellanic Cloud (LMC), as observed in the 115 GHz line of carbon monoxide (CO), the best tracer of interstellar molecular clouds. These clouds, the location of essentially all star formation, are composed almost entirely of molecular hydrogen and atomic helium, both nearly impossible to detect.

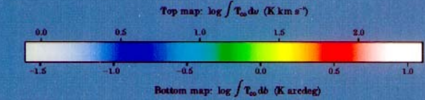
In the top map the colors, from dark blue (weakest) to white (strongest), represent the CO line intensity summed over all radial velocities, a measure of the total amount of molecular gas along the line of sight. The intense yellow-to-white horizontal strip at the center of the map is produced by the large number of molecular clouds in the inner spiral arms of the Galaxy, while elsewhere in the map individual nearby molecular clouds are prominent. Both the LMC and M31 are so weak in CO that their intensities have been scaled up by factors of 3 and 10, respectively. A finder chart is at the left.

The bottom map shows the distribution of the CO-emitting molecular clouds in radial velocity—crucial information lacking in continuum surveys. Here, the colors represent CO line intensity summed across a ~4° strip of Galactic latitude centered on the Galactic plane. Molecular clouds at higher latitude (and the LMC and M31) are therefore excluded. The observed radial velocities result mainly from the differential rotation of the Galaxy, except near the Galactic center, where a poorly understood outflow of molecular gas exceeding 200 km s⁻¹ occurs. A finder chart is at the right.

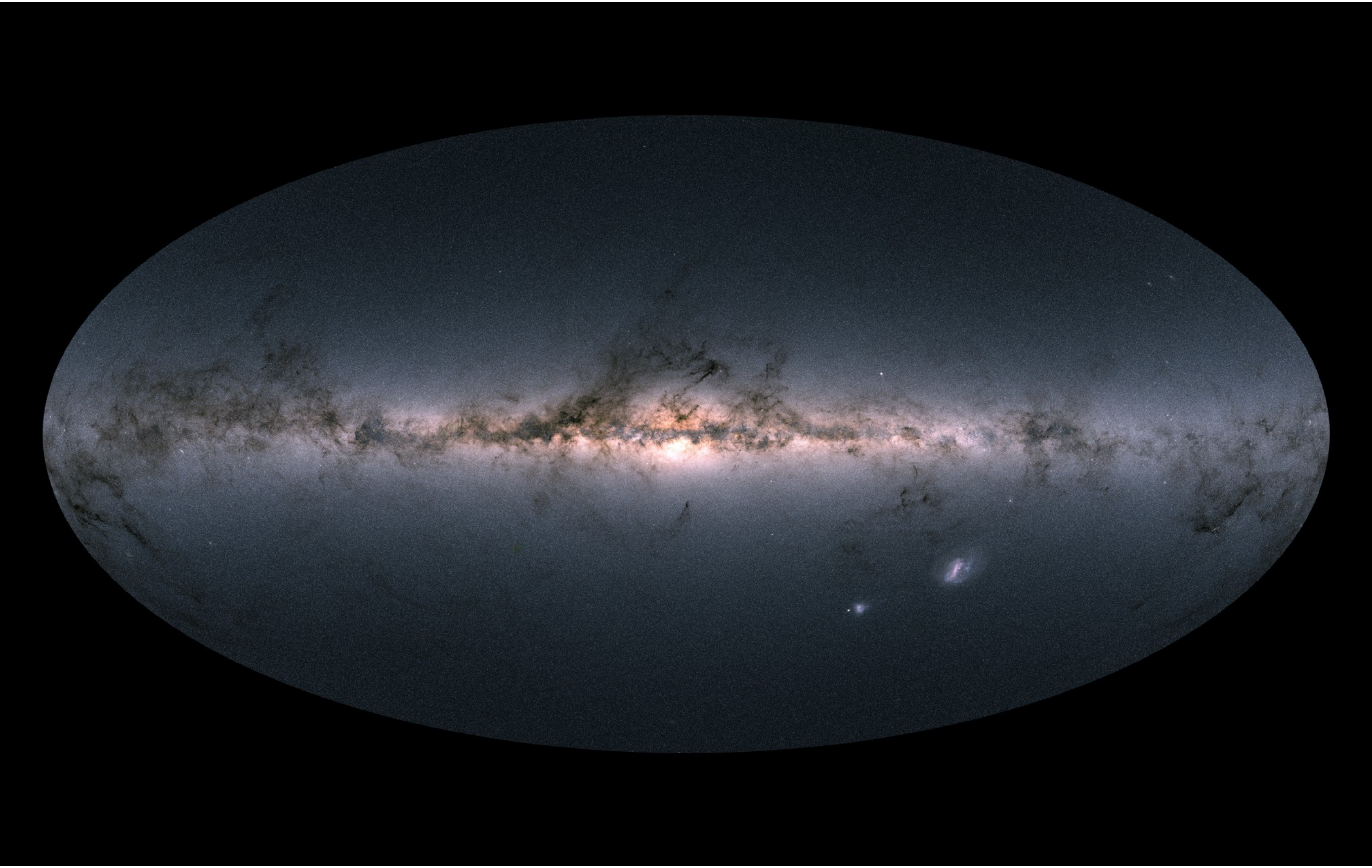
This poster is an update of one produced ten years ago which presented the first complete survey of the Milky Way in CO (first reference at right; also Dame 1988, *Sky & Telescope*, 76, 22). Since well before completion of that survey, done at an effective angular resolution of 0°.5, the same two 1.2 meter telescopes in Cambridge, Mass., and on Cerro Tololo, Chile, have been mapping the Galaxy and its nearest neighbors at several times higher angular resolution—every beamwidth (8.7 arcmin) or half beamwidth—and at 5 to 10 times higher sensitivity per solid angle. These instruments have now mapped in this way nearly the entire Galactic plane over a 4°–6° strip of latitude, as well as many local clouds at higher latitude. The maps above include these 270,000 new spectra; the original 0°.5 map is used in some high-latitude regions (e.g., Taurus) where full-resolution observations do not yet exist.

Roughly half of the new data have already been published as separate surveys of particular clouds or regions (see list at right), and since 1985 have formed the basis for 13 Ph.D. dissertations. The balance was obtained in the past few years in new large-scale surveys of the first and second Galactic quadrants.

This poster was supported by a generous grant from the Atherton Seidell Endowment of the Smithsonian Institution.



Harvard-Smithsonian Center for Astrophysics
T. M. Dame, Dap Hartmann, & P. Thaddeus



Schmidt's conjecture

We assume that no gas or stars enter or leave the region under consideration and that at $t = 0$ all mass was in the form of gas, so that $\mathfrak{M}_G(0)$ is the total mass density. The mass of gas left at time t is

$$\mathfrak{M}_G(t) = \mathfrak{M}_G(0) - \mathfrak{M}_T(t) + \mathfrak{M}_E(t) . \quad (9)$$

The above equations, except for some changes, were developed by van den Bergh (1957*b*).

It would seem most probable that the rate of star formation depends on the gas density, and we shall assume that the number formed per unit interval of time varies with a power of the gas density,

$$f(t) \sum_{M_v} \psi(M_v) = C[\mathfrak{M}_G(t)]^n . \quad (10)$$

Substitution of equations (7), (8), and (9) in equation (10) gives

$$f(t)\sum\psi = C\Big[\mathfrak{M}_G(0) - \sum \psi \mathfrak{M} \int^t f(t)\,dt + \sum \psi(\mathfrak{M} - 0.7) \int^{t-T} f(t)\,dt\Big]^n \quad (11)$$

$$\Sigma_{SFR} = k\Sigma_g{}^{\beta}\ (M_{\odot}/pc^2)$$

Schmidt (1959)

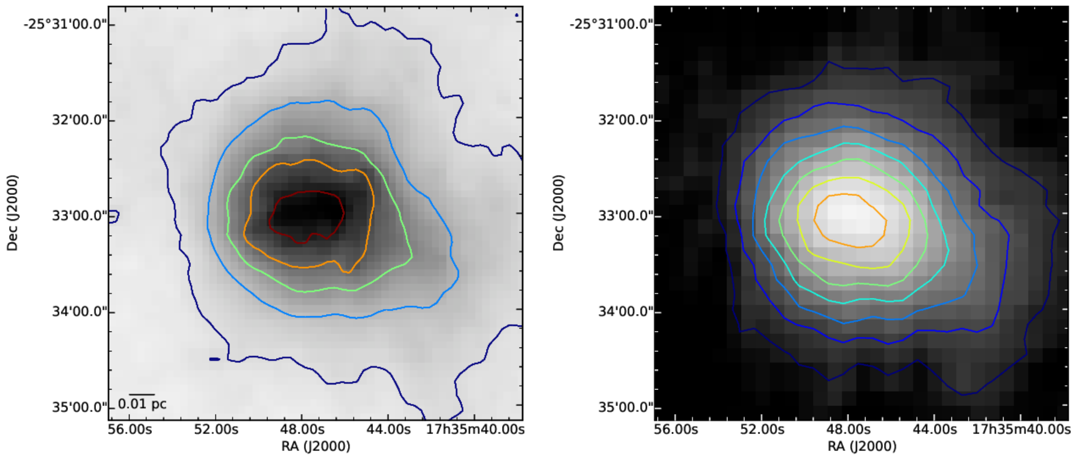
RATE OF STAR FORMATION

In a discussion with Sydney van den Bergh while I was still at Leiden, he inquired about our results on the gas density from the 21-cm work, wondering how long it would take star formation to exhaust the local supply of gas. I realized that there also would be a substantial return of gas to the interstellar medium from stars that evolve off the main sequence within a few billion years. It was not known how the rate of star formation depended on the gas density. I assumed that it would go as a power law of the gas density with power n. This made it possible to derive the density of stars and gas as a function of time, including the evolution of the metal abundance in stars. At the 50-year anniversary of the law celebrated in Tuscany in a NATO supported workshop, it appeared that the power law, with $n = 1.35$, fits remarkably well although it is not understood in detail why.

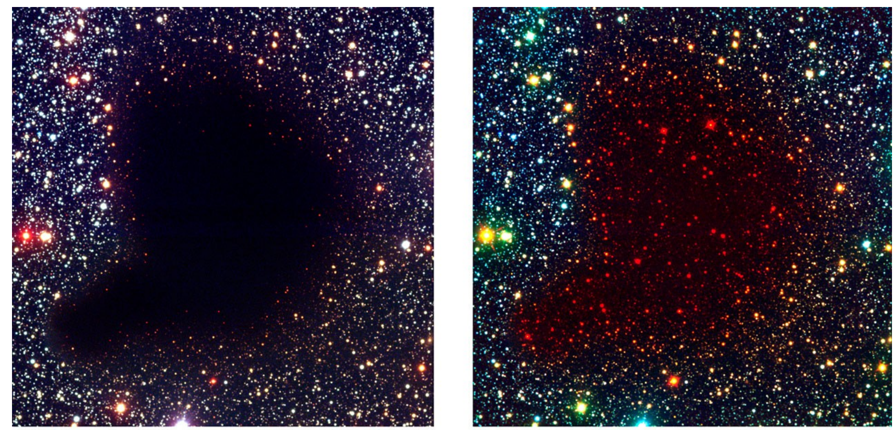
Schmidt (2015)

1) For star formation studies, *dust* observations define the "ground truth"

In Dust we Trust: extinction & emission



Forbrich et al. (2015)



B, V, I

B, I, K

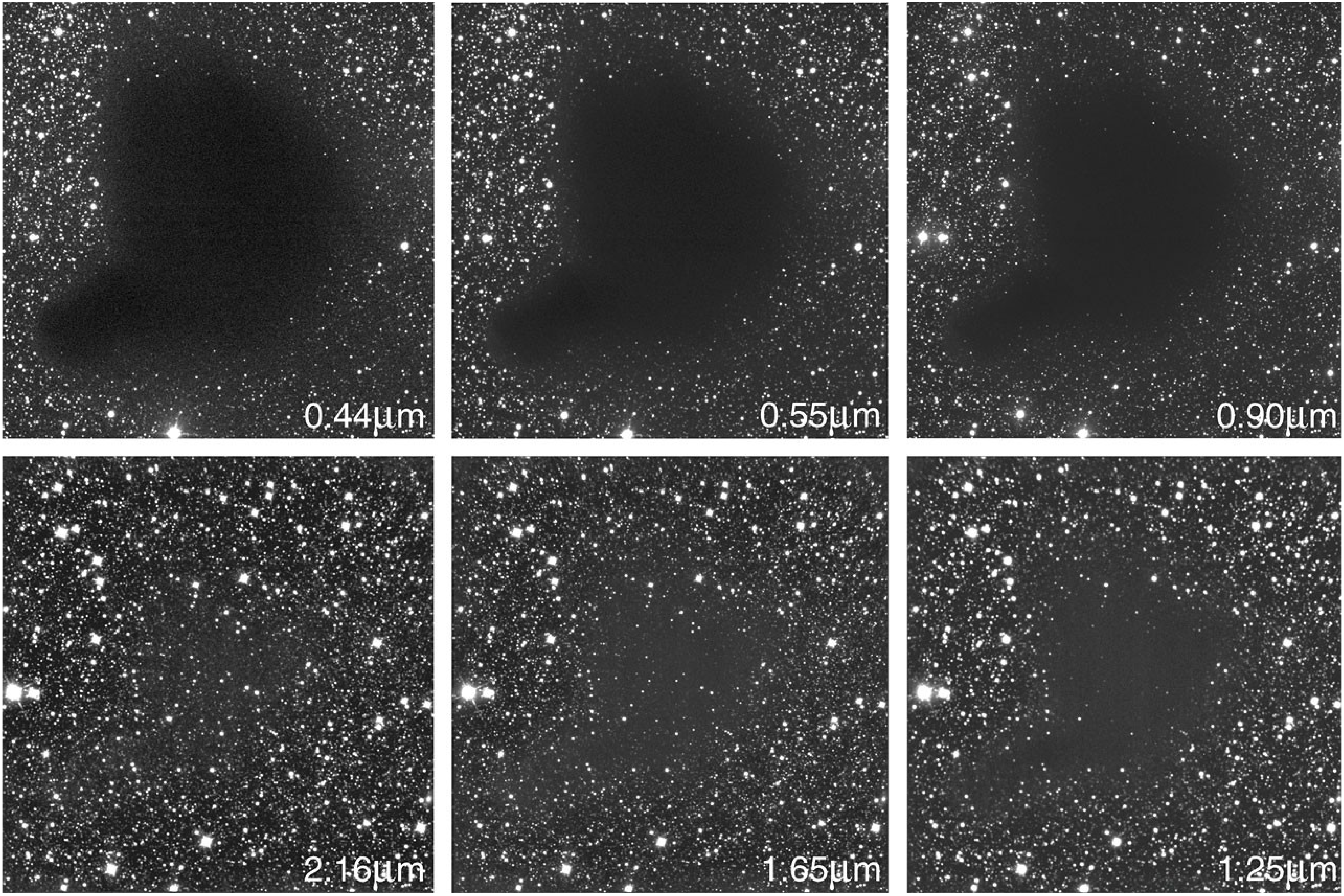
Alveset al. (2001)

Extinction: Precise and accurate (pencil beam) measurements of column density, but uneven spatial sampling, especially in high-density regions, and generally limited to nearby clouds.

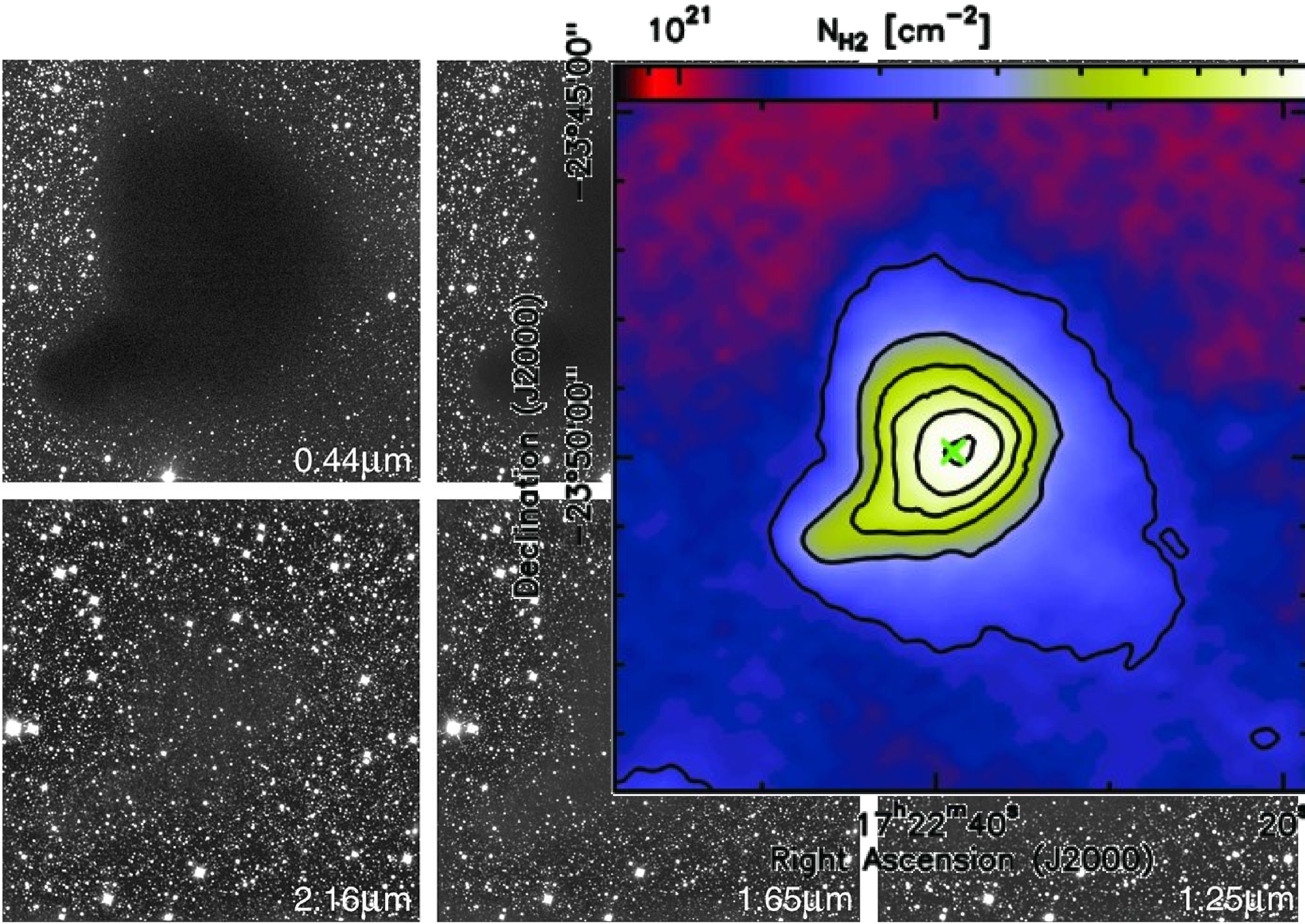
$$(m_{\rm obs} - m_*) = A_V = 1.086\tau_V$$

Emission: High resolution in high-density regions, low noise and full spatial sampling, but poor sky coverage at high angular resolution and T-τ degeneracy (LOS).

$$I_\nu = B_\nu(T_D)(1 - e^{-\tau_\nu}) \approx B_\nu(T_D)\tau_\nu$$



ESO



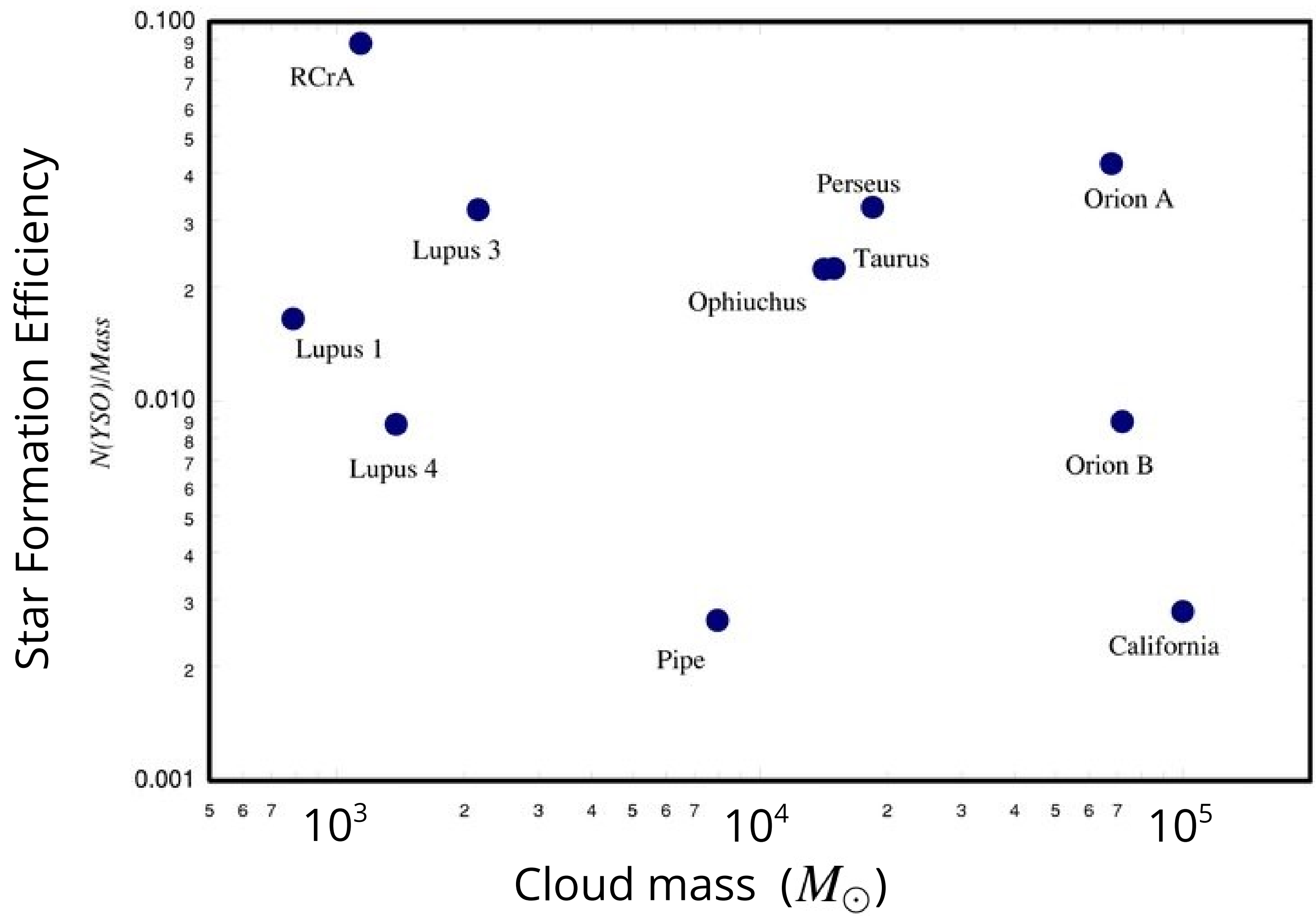
ESO, Roy et al. (2014)

ESO/S. Guisard

M(ρ Oph) ~ 2 M(Pipe), but SFR(ρ Oph) ~ 15 SFR(Pipe)

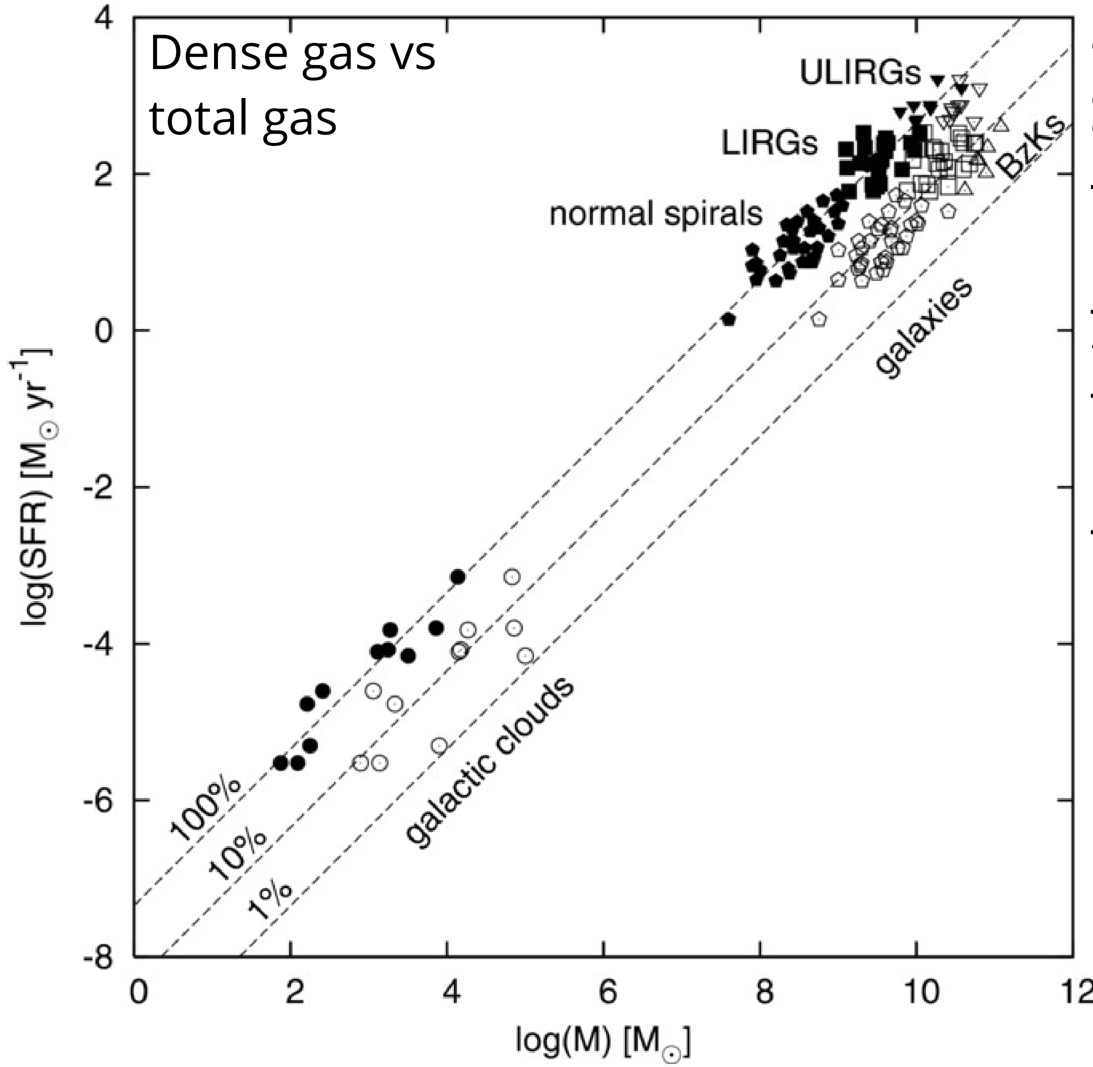
(YSOs: Forbrich et al. 2009, 2010, ISM: Forbrich et al. 2014, 2015)

A **star formation census** of nearby molecular clouds based on extinction mapping and YSO counting



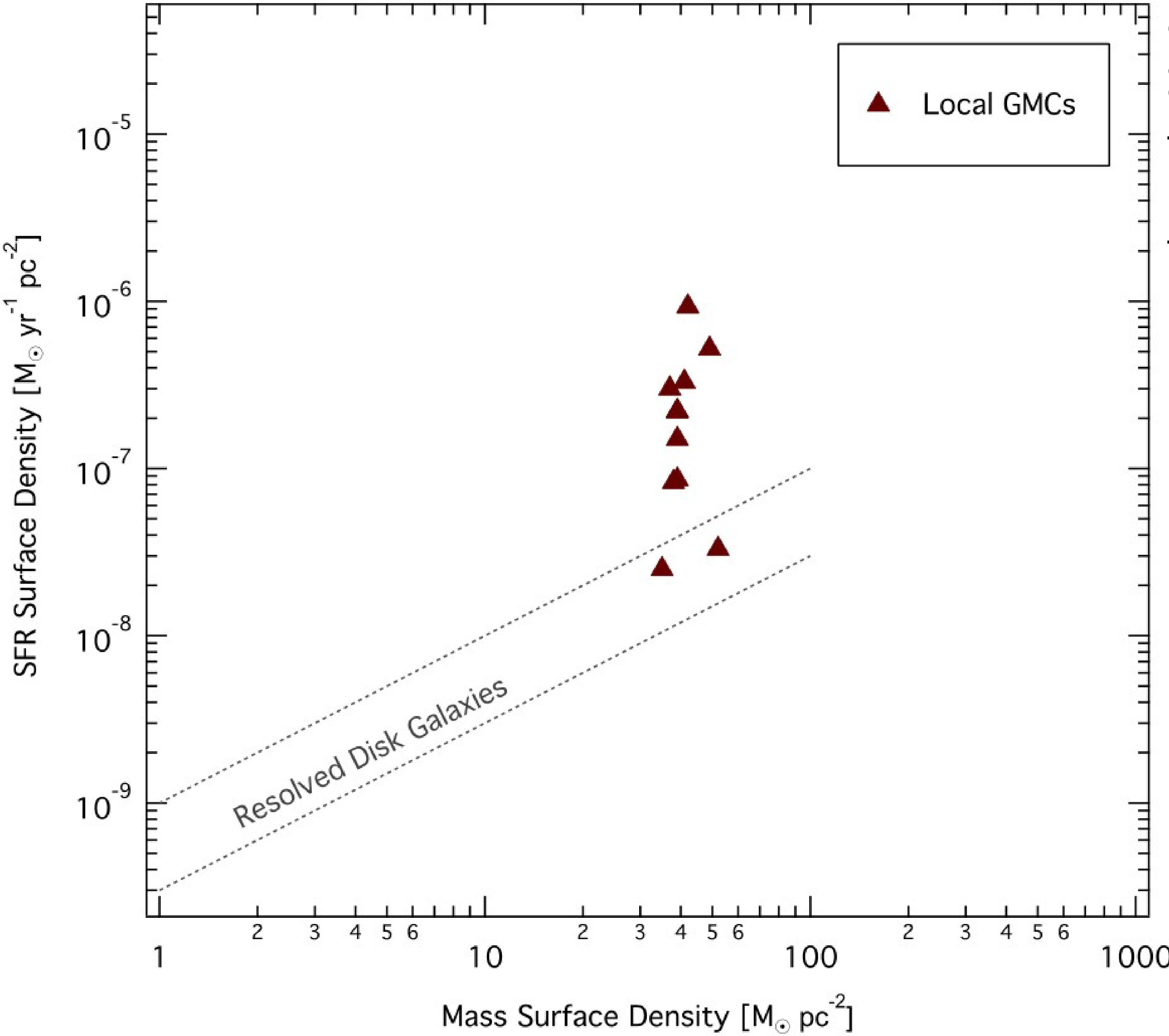
Lada et al. (2010)

The **extragalactic connection**



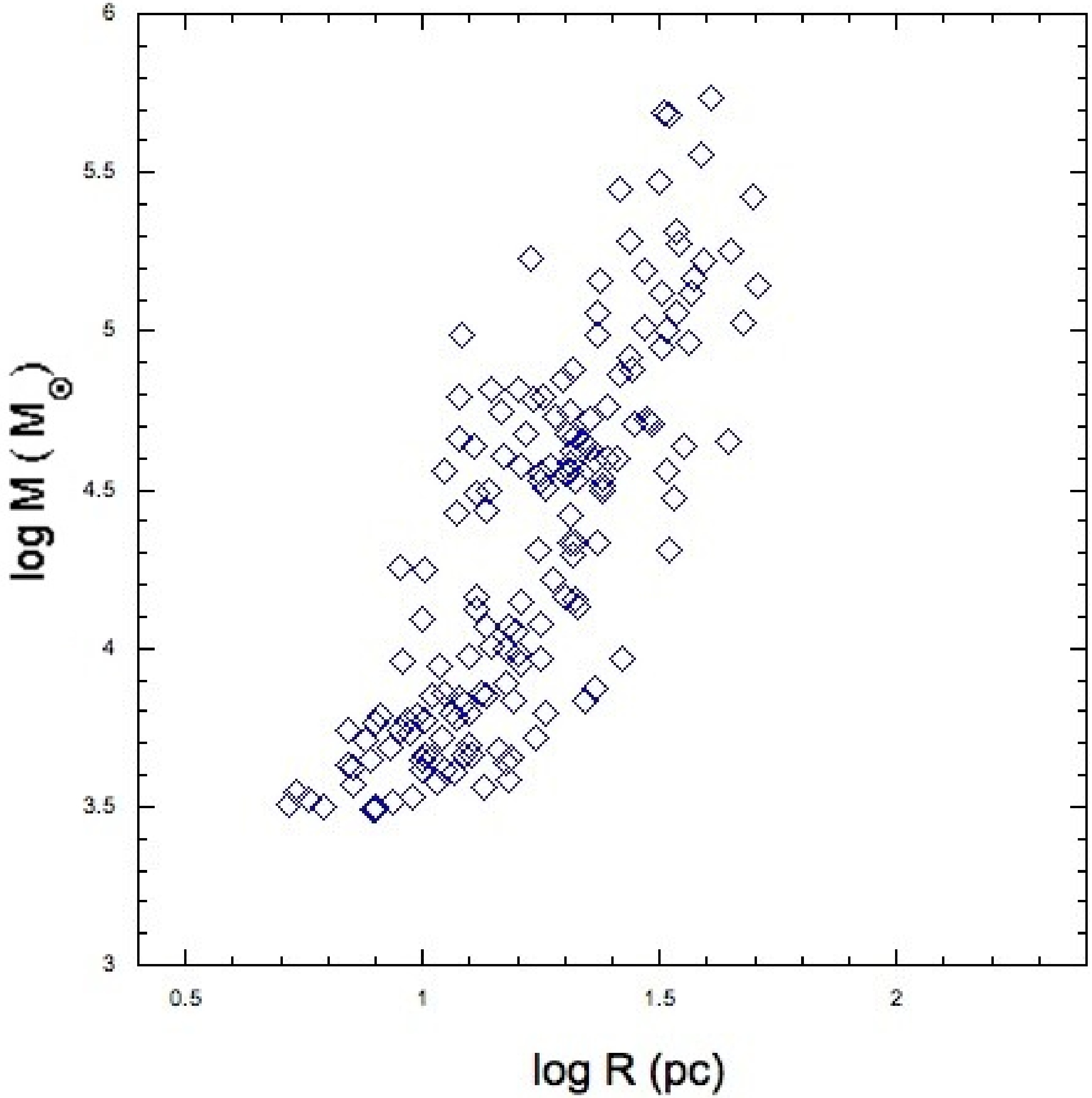
Lada, Forbrich et al. (2012)

The **extragalactic connection**



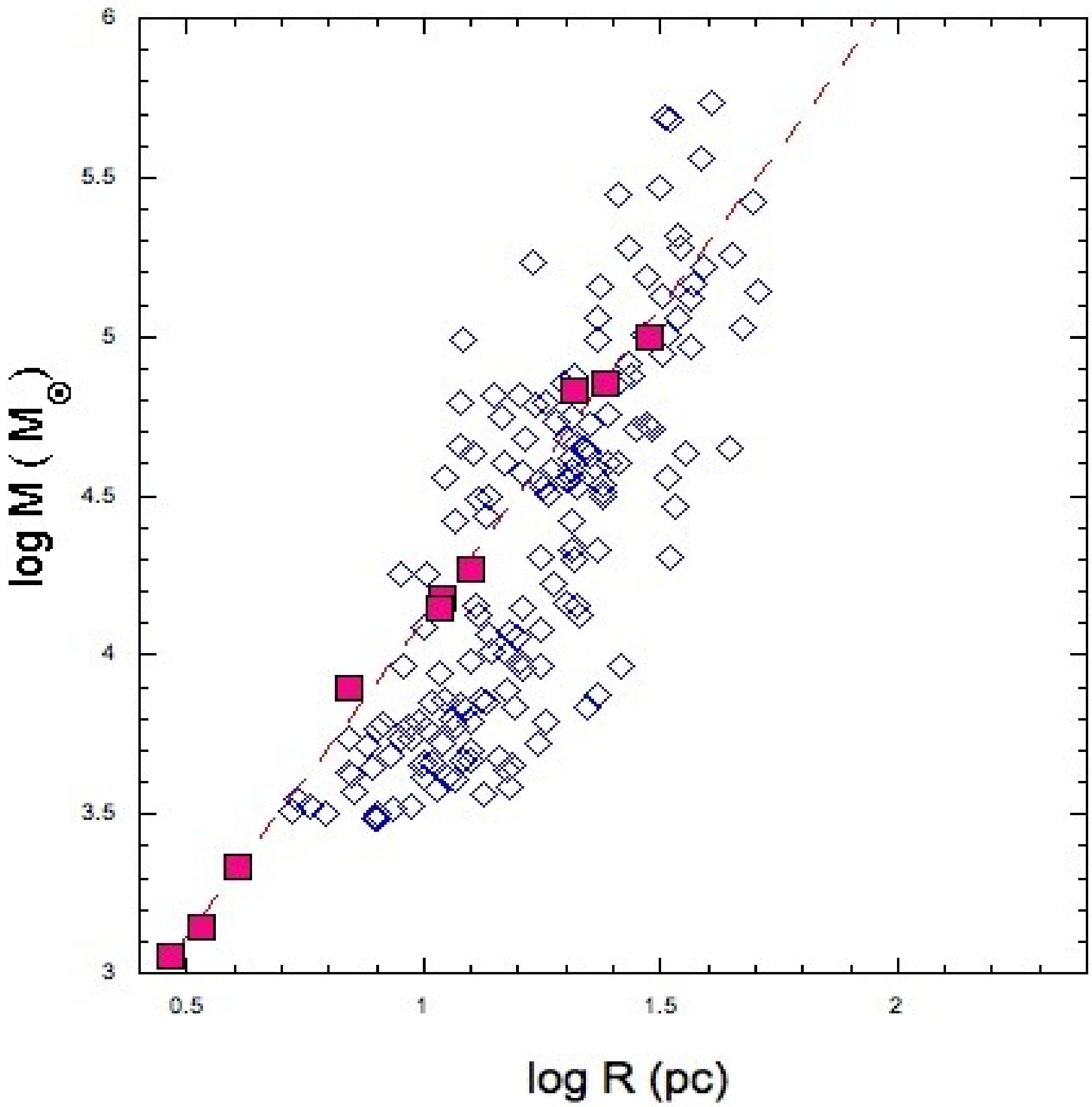
Lada et al. (2013)

GMC Mass vs Size Relation



Data: CO clouds within 3 kpc (Rice et al. 2016)

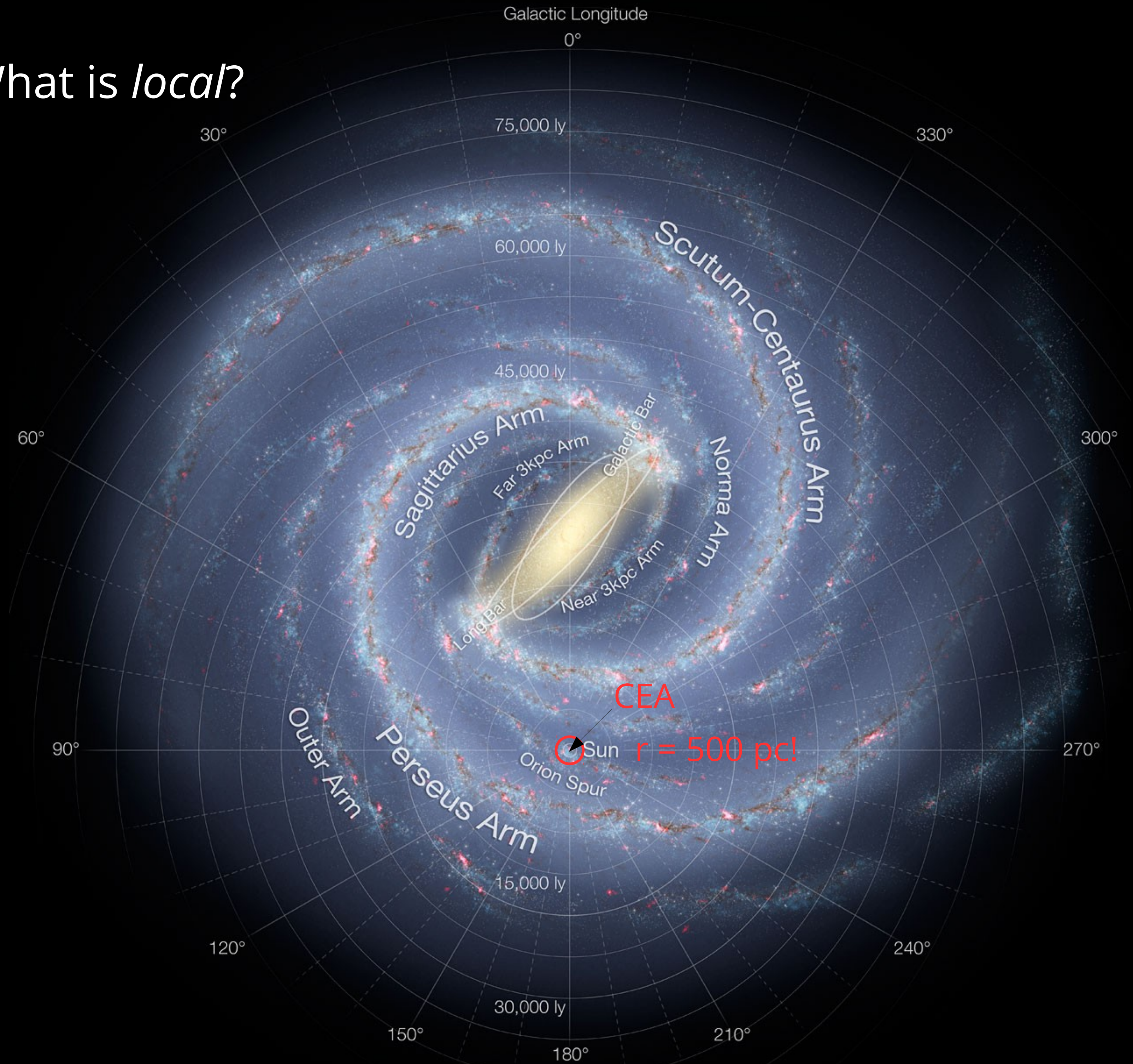
GMC Mass vs Size Relation



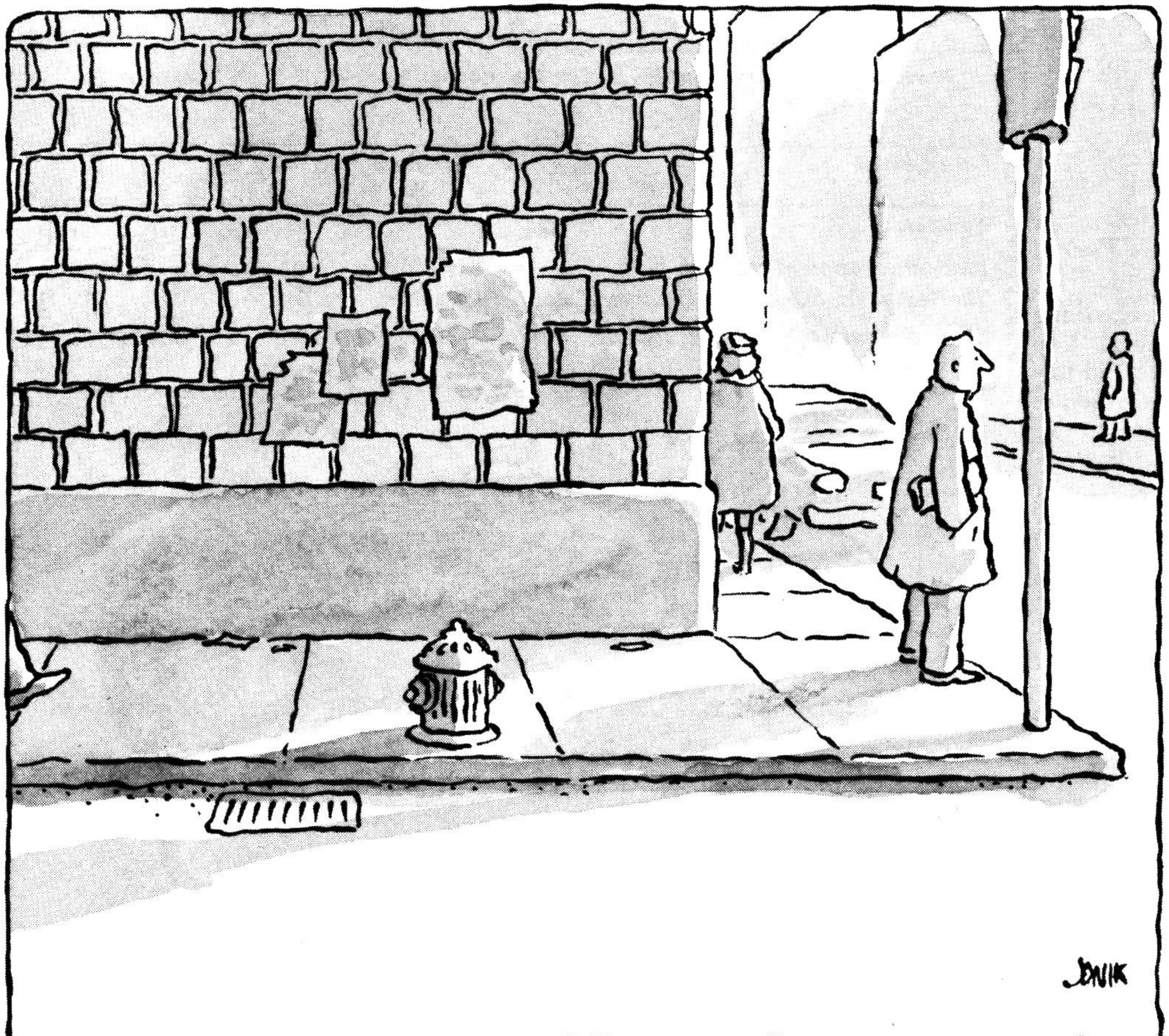
Data: CO clouds within 3 kpc (Rice et al. 2016); Lada et al. (2010)

2) Locally, it is difficult to obtain large, resolved samples of clouds.

What is *local*?

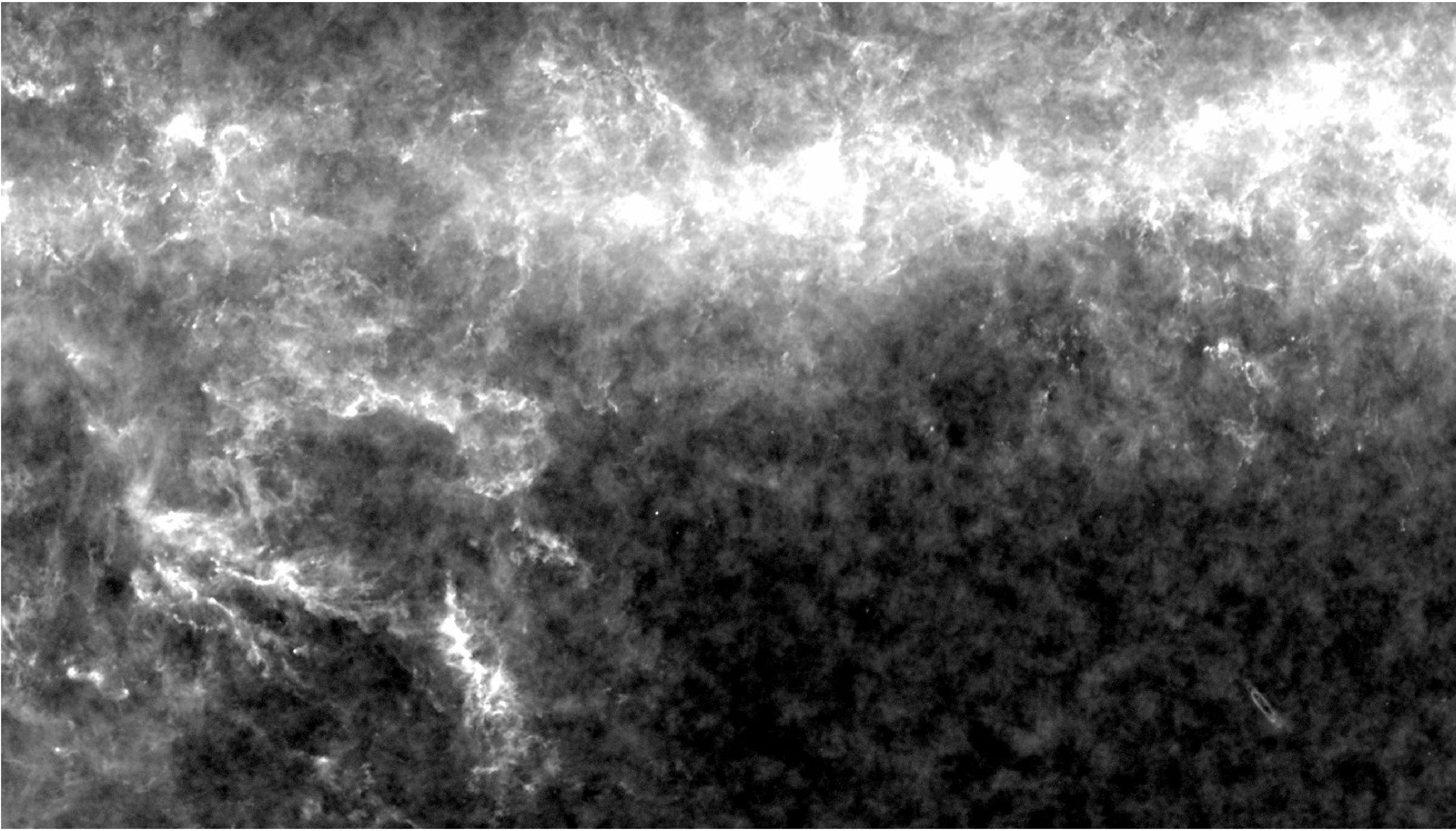


ESO



THE MILKY WAY
(Detail)

A *Planck* 217 GHz view of the Galactic plane



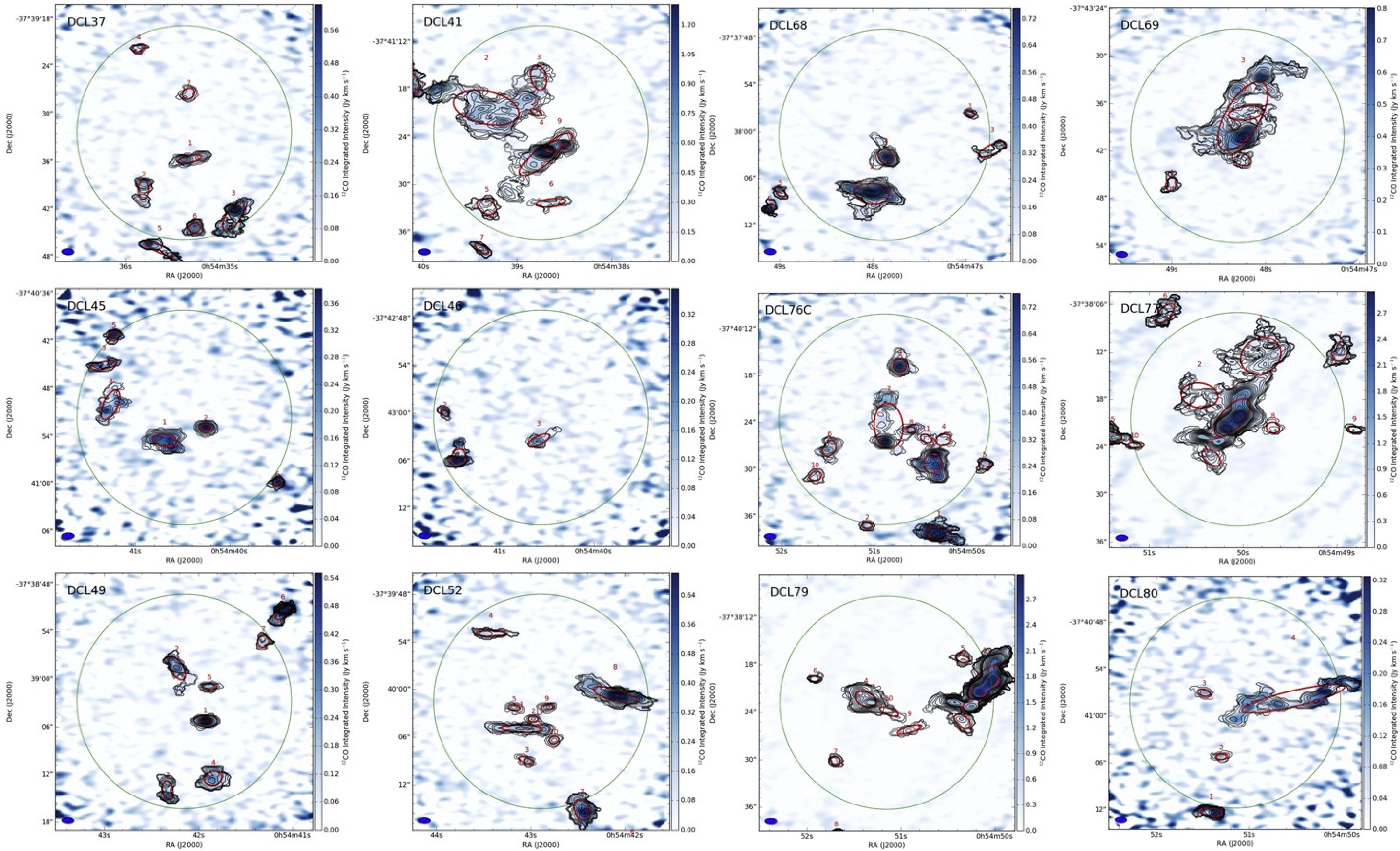
3) Comparable resolved extragalactic observations are so far limited to CO

ESO

The NGC 300 **GMC zoo**: ALMA, CO(2-1)

ESO

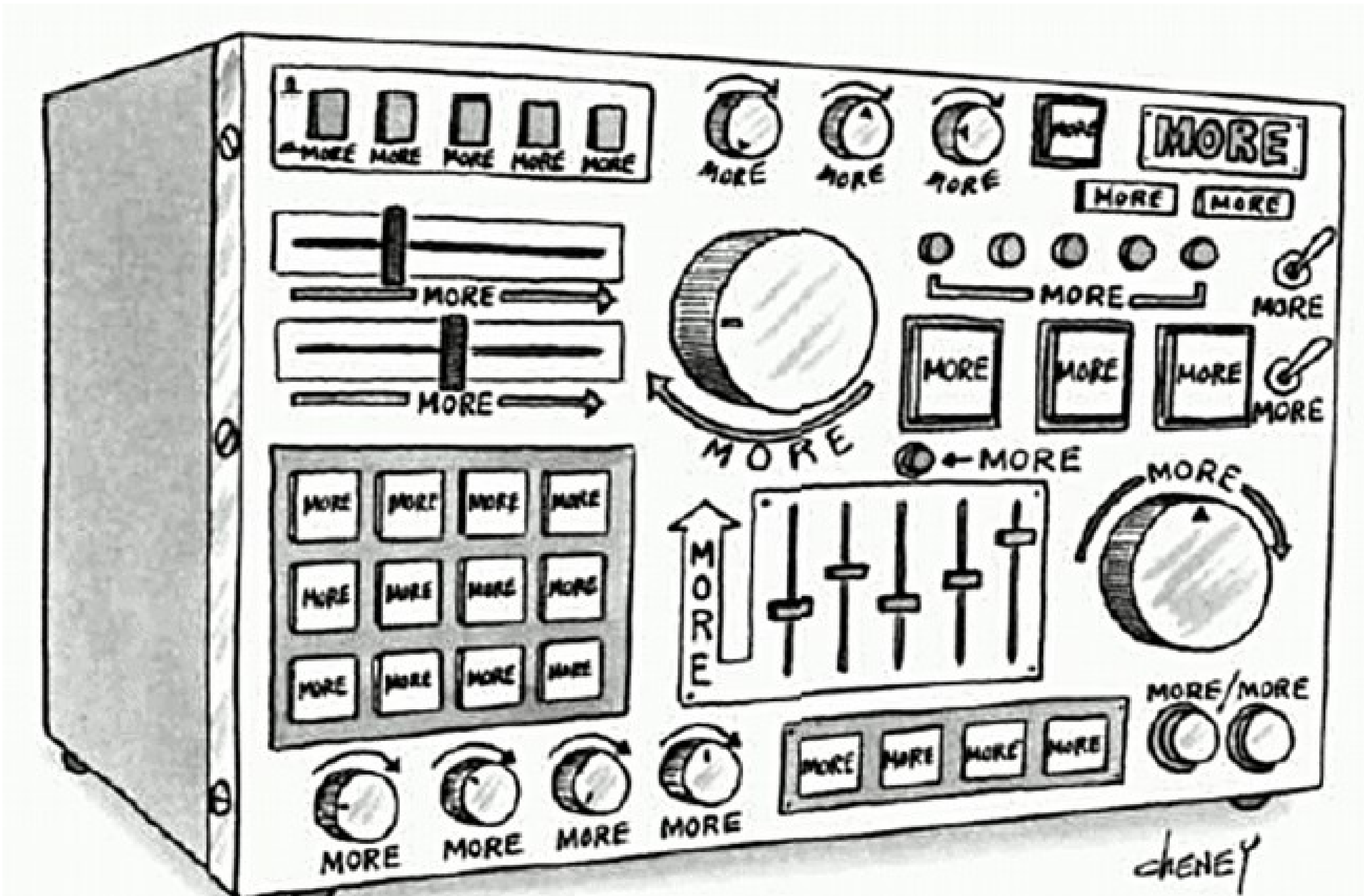
The NGC 300 **GMC zoo**: ALMA, CO(2-1)



Faesi, Lada, & Forbrich (2018)

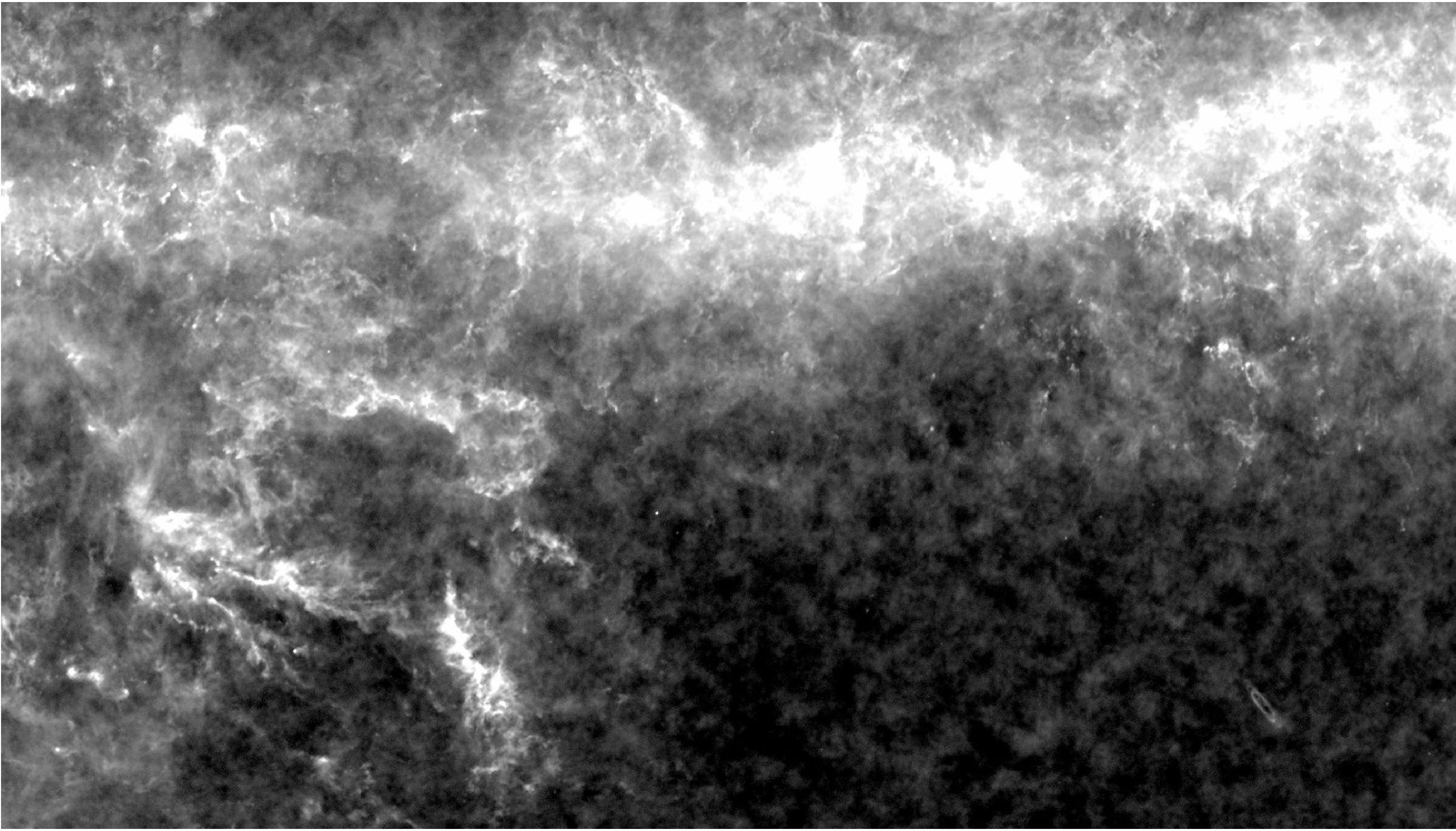
4) The SMA provides a new and unique opportunity to remedy that!

Wideband **upgrades** of radio interferometers

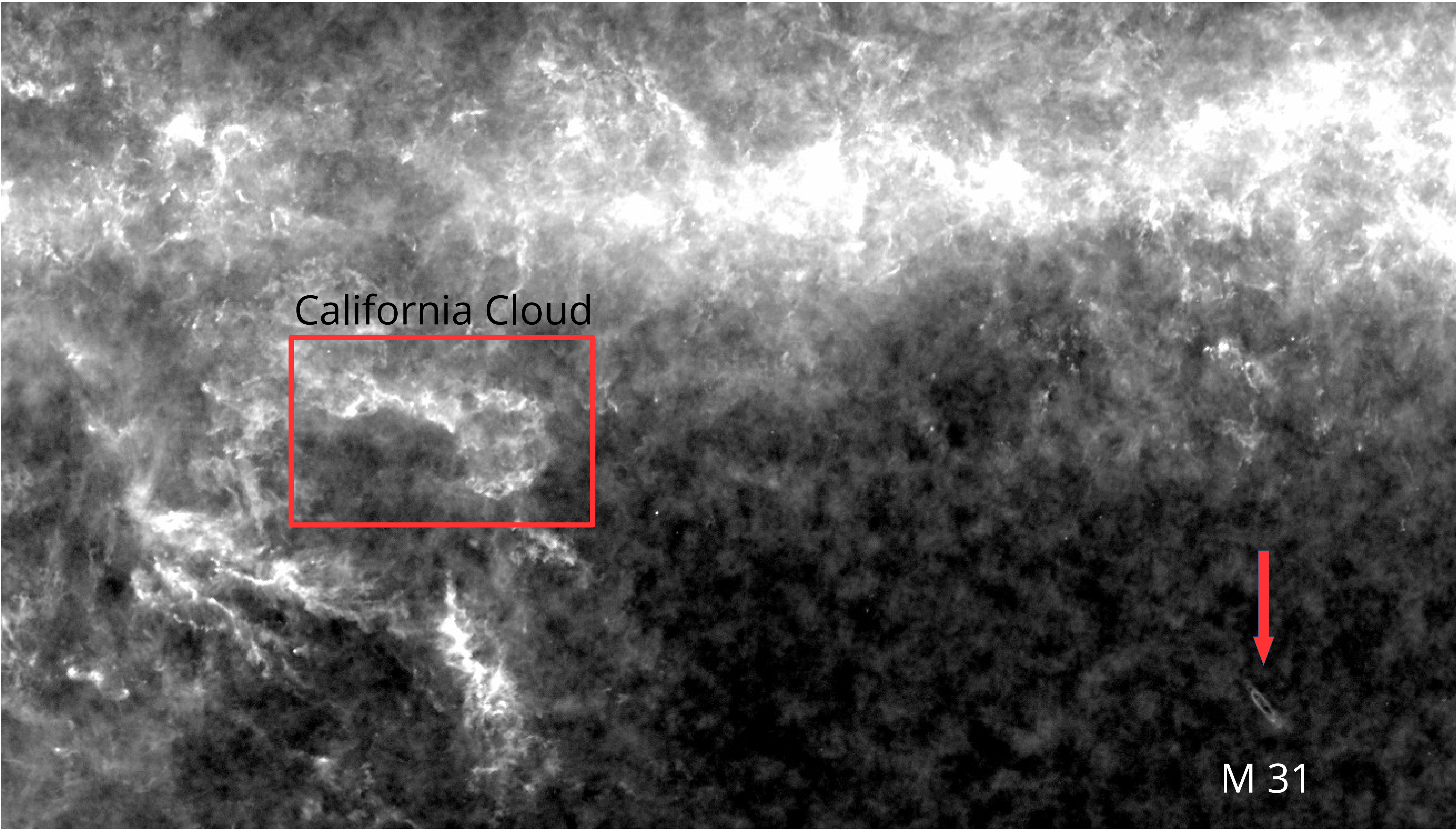


The New Yorker

A *Planck* 217 GHz view of the Galactic plane



A *Planck* 217 GHz view of the Galactic plane



= apparent size of moon

The **Submillimeter Array** (SMA)

The SMA Andromeda Dust
and Molecular gas Survey

The **Submillimeter Array** (SMA)

... is perfect for imaging GMCs in M31:

1 Resolution of 15 (10, 5) pc at 230 GHz in sub/comp/ext config
2 Primary beam of 55” or 200 pc, maximum angular scale ~100 pc
3 Continuum bandwidth of 32(+) GHz, *high sensitivity*
4 Discrete dust continuum and CO with *identical* (u,v) coverage, calibration, and *astrometry*
5 Observing at routine frequency for MK, long tracks (high Dec)
6 Ability to obtain data at 345 GHz with matched (u,v) coverage

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But what about ALMA?

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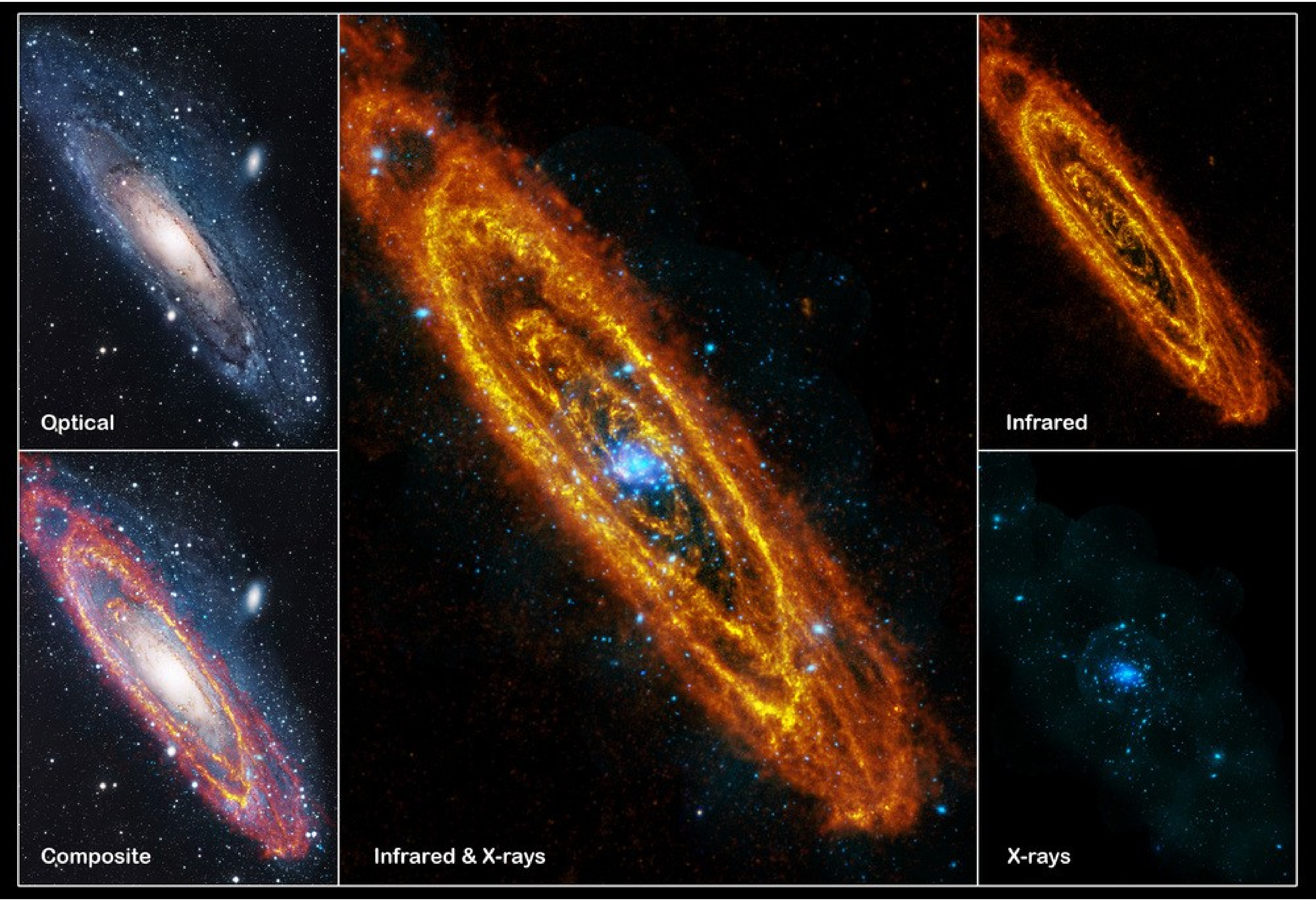
NGC 300 is the most nearby (small) spiral galaxy visible for ALMA, but it is almost 3x more distant and at lower metallicity, largely cancelling advantages: would only expect ~1 GMC per track

Buckley-Houston/Rahn/NASA/JPL-Caltech



see also Viaene et al. (2014)

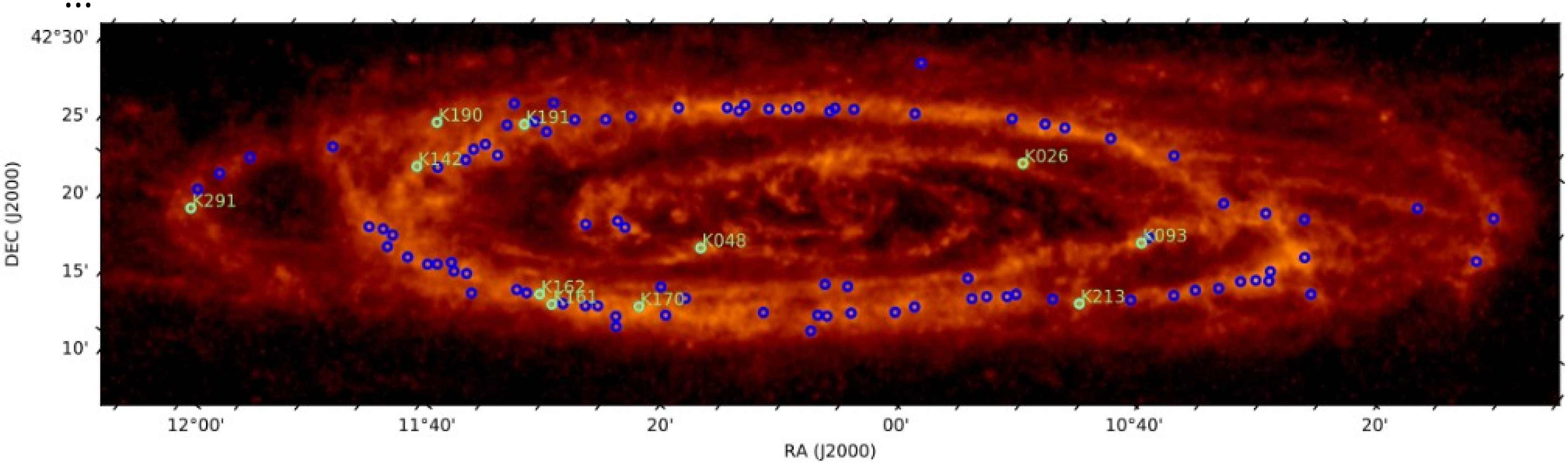
ESA

The SMA Dust Continuum-CO Survey of Resolved GMCs in Andromeda

Main goals:

1) Detect and resolve dust continuum and CO emission in **100 individual GMCs** in M31 in different environments,
2) directly **compare CO and dust emission** with same calibration and *(u,v)* coverage to measure X factor, search for any CO-dark gas,
3) use dust and gas data to test **Larson's relations** across M31, construct GMC dust-derived **mass function**,
4) selected measurements at 345 GHz to **constrain dust properties**,
5) measure **star formation laws** with ancillary data,
6) compare with NIR dust **extinction** mapping,

...



5) First resolved dust observations of GMCs in external disk galaxy (with *free* CO)!

First Resolved Dust Continuum Measurements from Individual Giant Molecular Clouds in the Andromeda Galaxy.

JAN FORBRICH,[1,2] CHARLES J. LADA,[2] SÉBASTIEN VIAENE,[3,1] AND GLEN PETITPAS[2]

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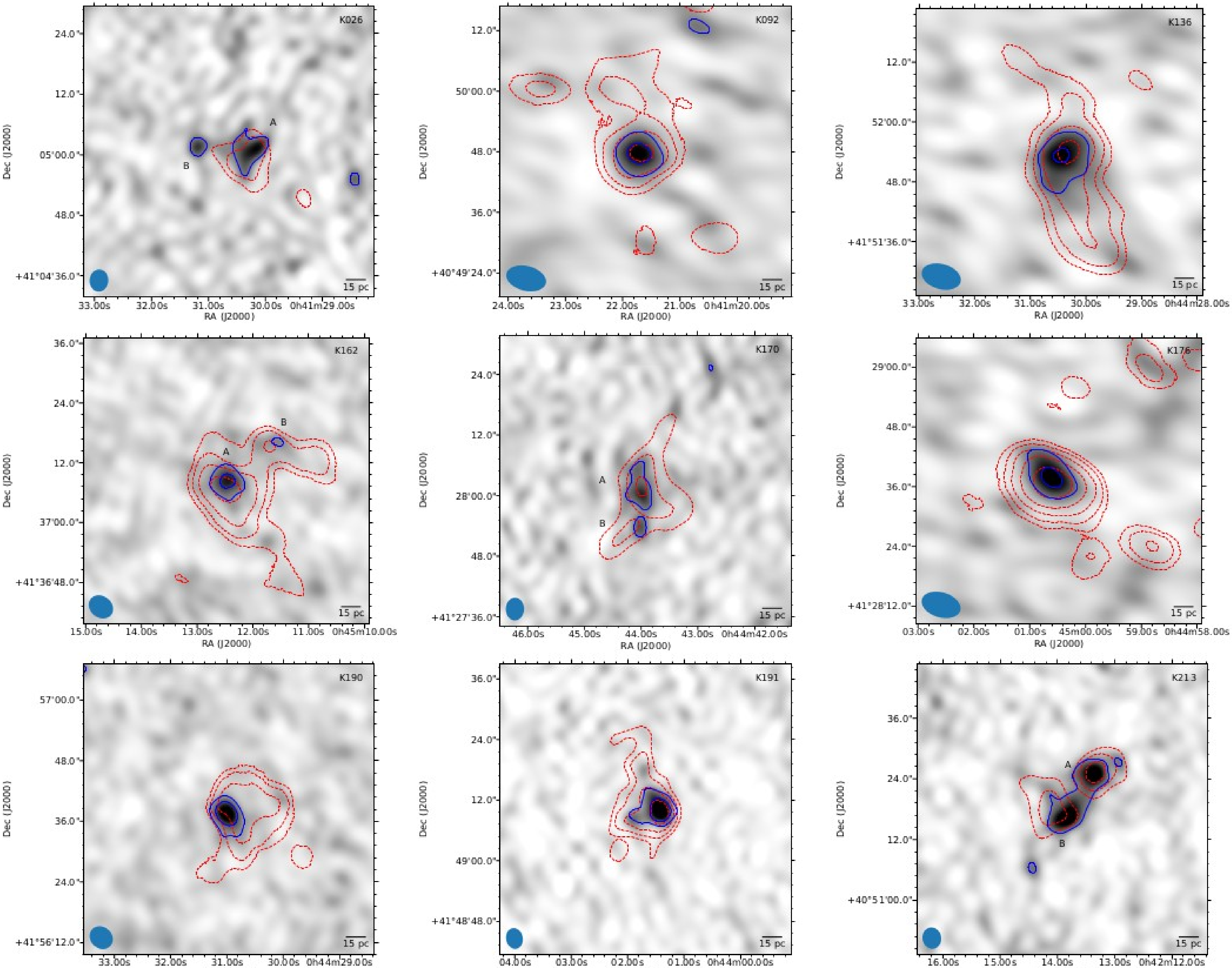
[2] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, MS 72, Cambridge, MA 02138, USA*
[3] *Sterrenkundig Observatorium, Universiteit Gent, Krijgslaan 281, 9000, Gent, Belgium*



Forbrich et al. (2020)

A direct measurement of dust vs CO

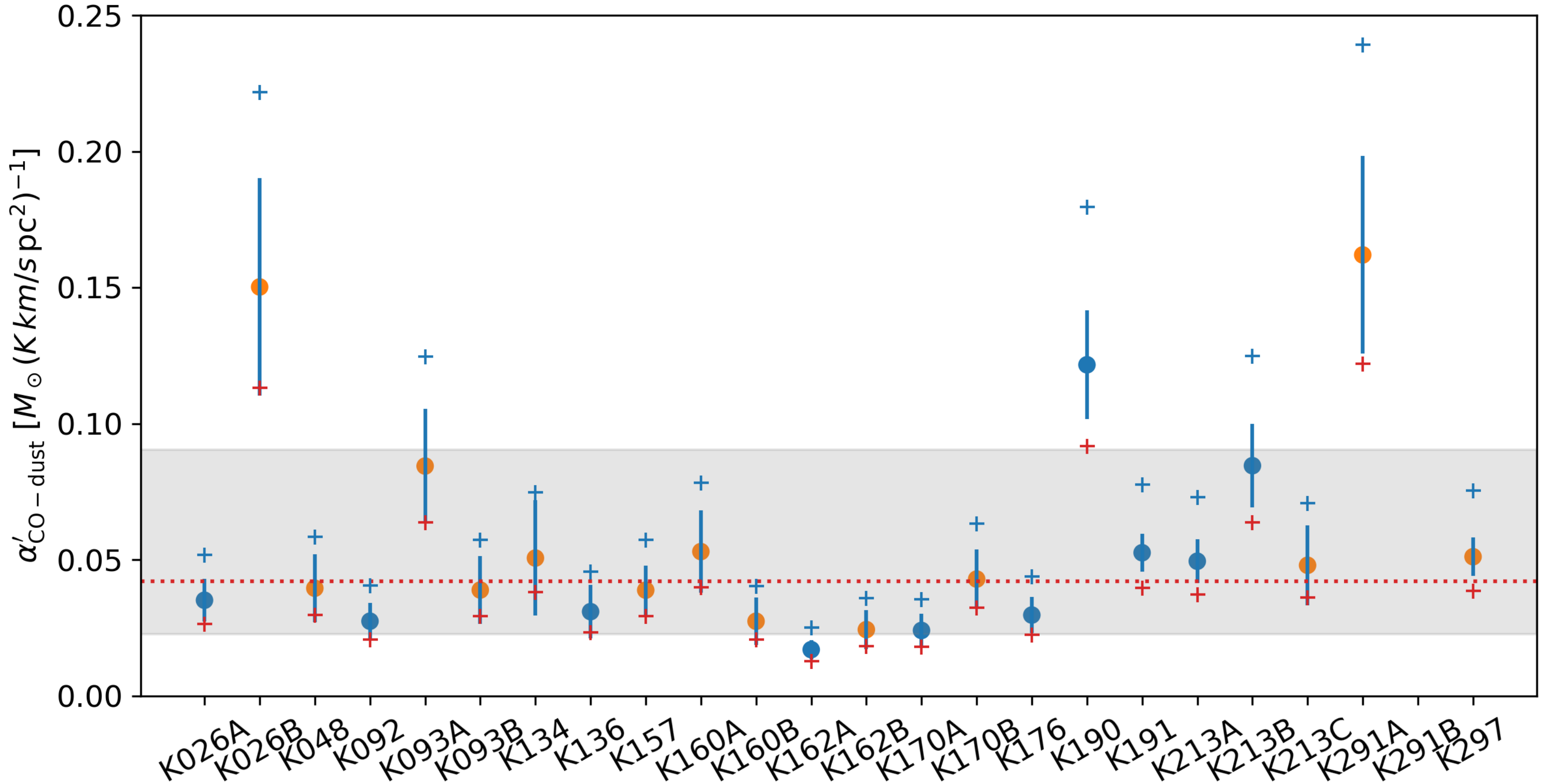
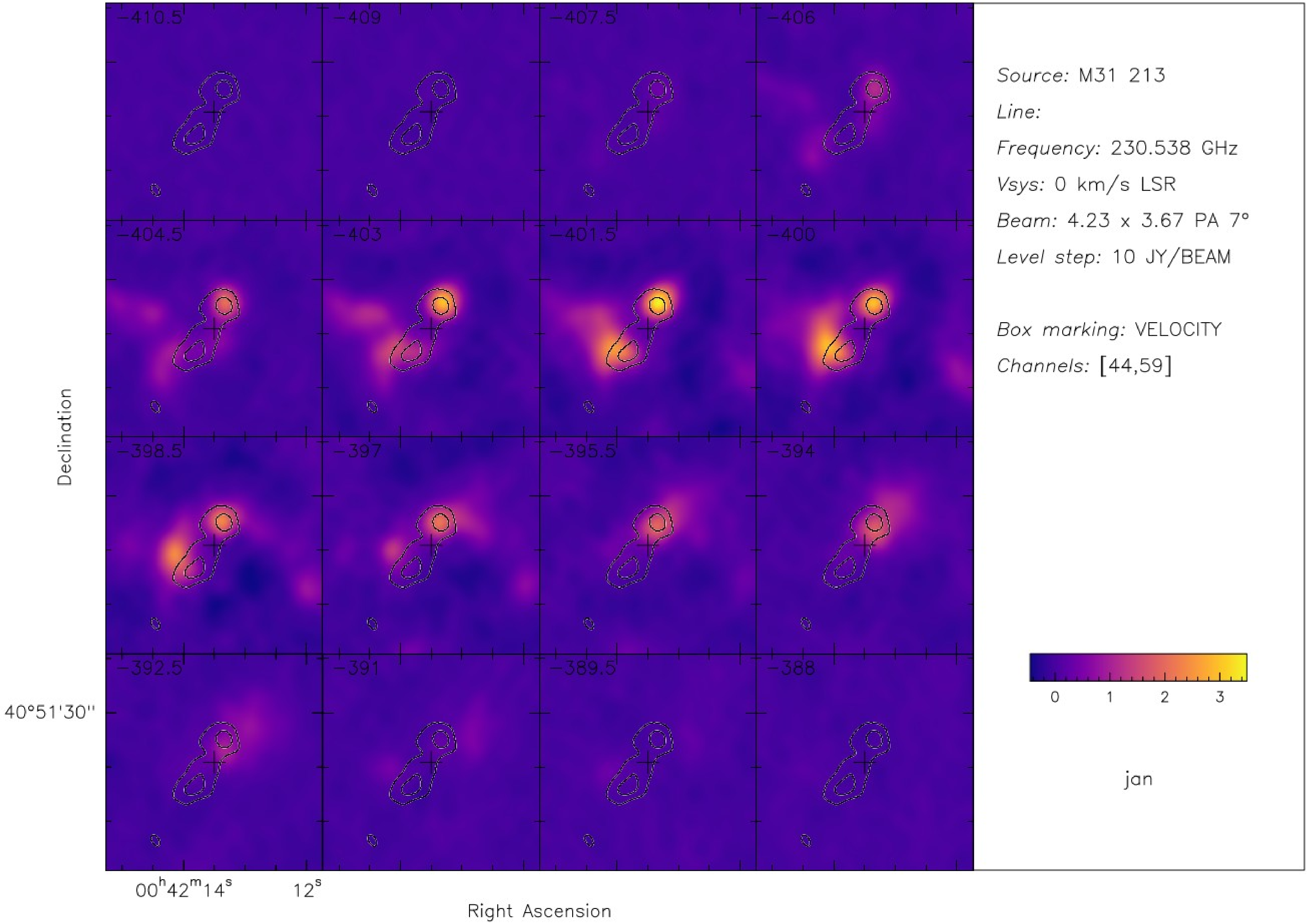


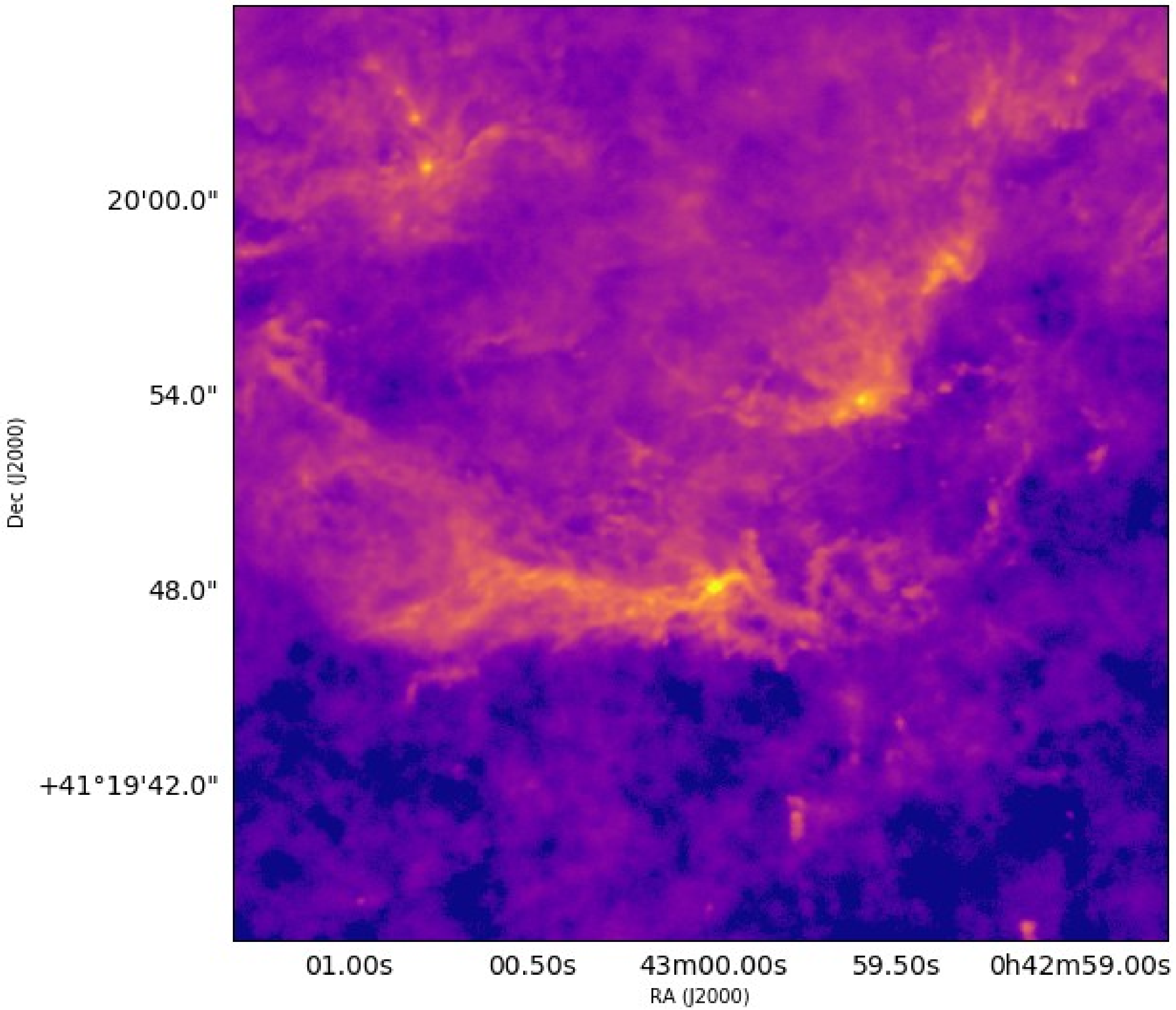
Figure 2. Direct $\alpha'_{\mathrm{CO-dust}}$ measurements per cloud, converting CO luminosity to dust mass. Blue dots indicate resolved sources, and orange dots indicate unresolved sources, both for $T_d = 20$ K. Red and blue crosses additionally show α_{CO} for $T_d = 25$ K and $T_d = 15$ K, respectively. The dotted line indicates the (clipped, see text) sample mean of $\alpha'_{\mathrm{CO-dust}} = 0.042\ M_\odot$ $(\mathrm{K\,km\,s^{-1}pc^{-2}})^{-1}$. For comparison, we divide the nominal Galactic value for the CO(2-1) transition (see text) of by a gas-to-dust ratio of 136 to find a near-identical value of $\alpha'_{\mathrm{CO-dust(gal)}} = 0.045\ M_\odot$ $(\mathrm{K\,km\,s^{-1}pc^{-2}})^{-1}$, and we indicate the corresponding range with an uncertainty of ±0.3 dex as a gray-shaded area. Note that K291B is off-scale (see Table 1).

Forbrich et al. (2020)


-410.5
-409
-407.5
-406
-404.5
-403
-401.5
-400
-398.5
-397
-395.5
-394
-392.5
-391
-389.5
-388
Source: M31 213
Line:
Frequency: 230.538 GHz
Vsys: 0 km/s LSR
Beam: 4.23 x 3.67 PA 7°
Level step: 10 JY/BEAM
Box marking: VELOCITY
Channels: [44,59]
0
1
2
3
jan
Declination
40°51'30''
00h42m14s
12s
Right Ascension

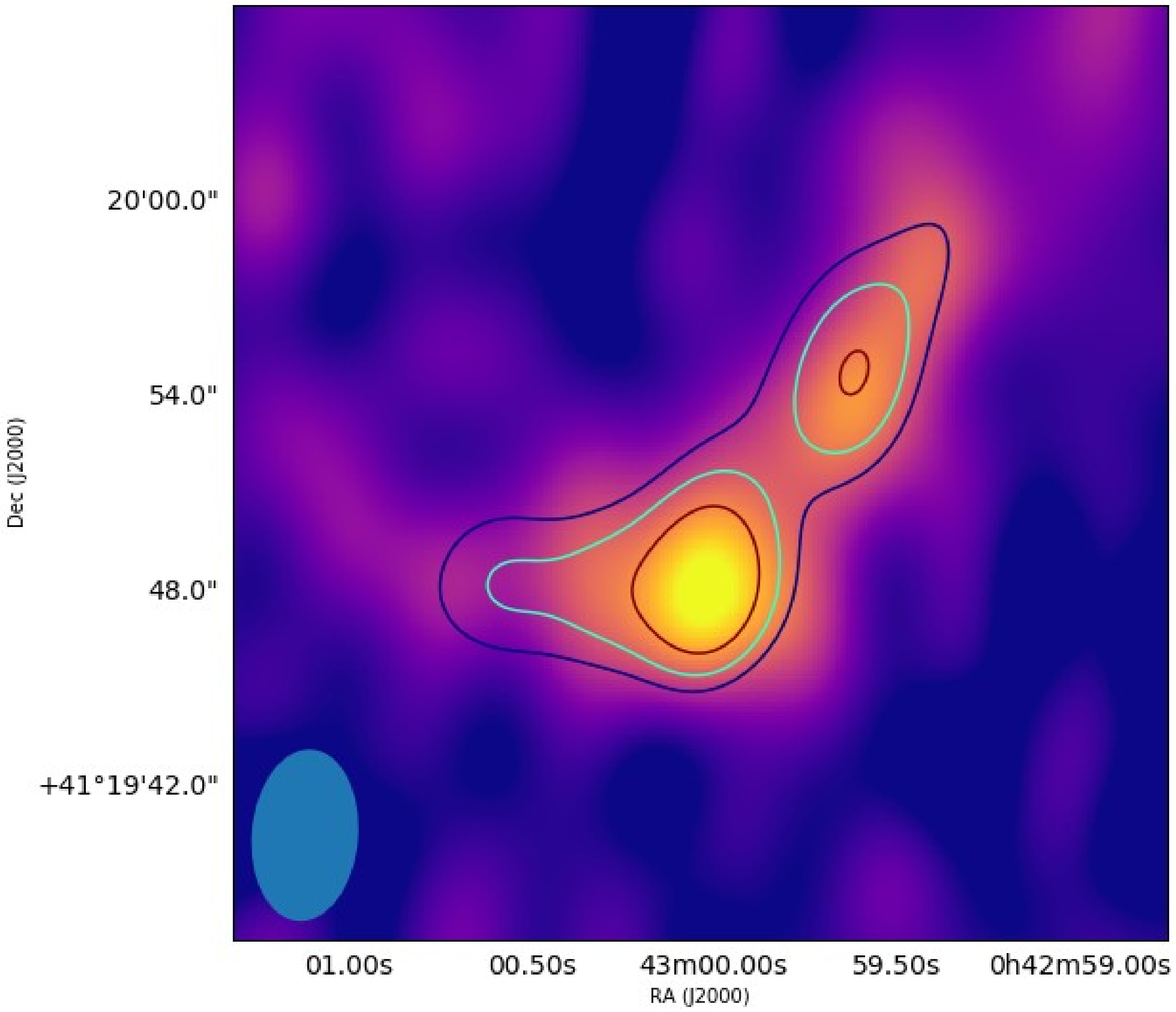
6) These results will place Milky Way and extragalactic studies of GMCs *on the same footing*.

What would **Orion** look like in M31?



Data: Planck Collaboration

What would **Orion** look like in M31?



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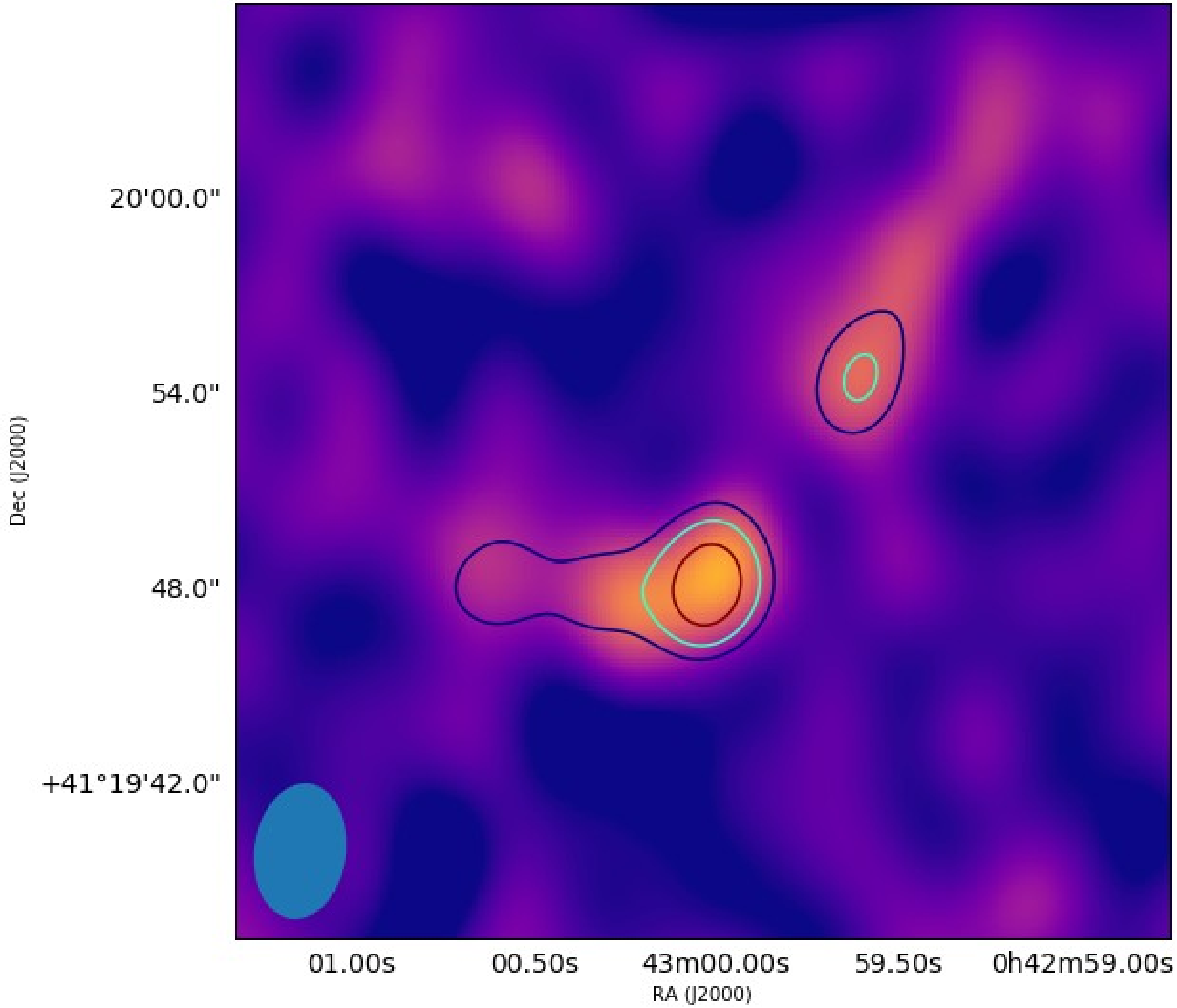

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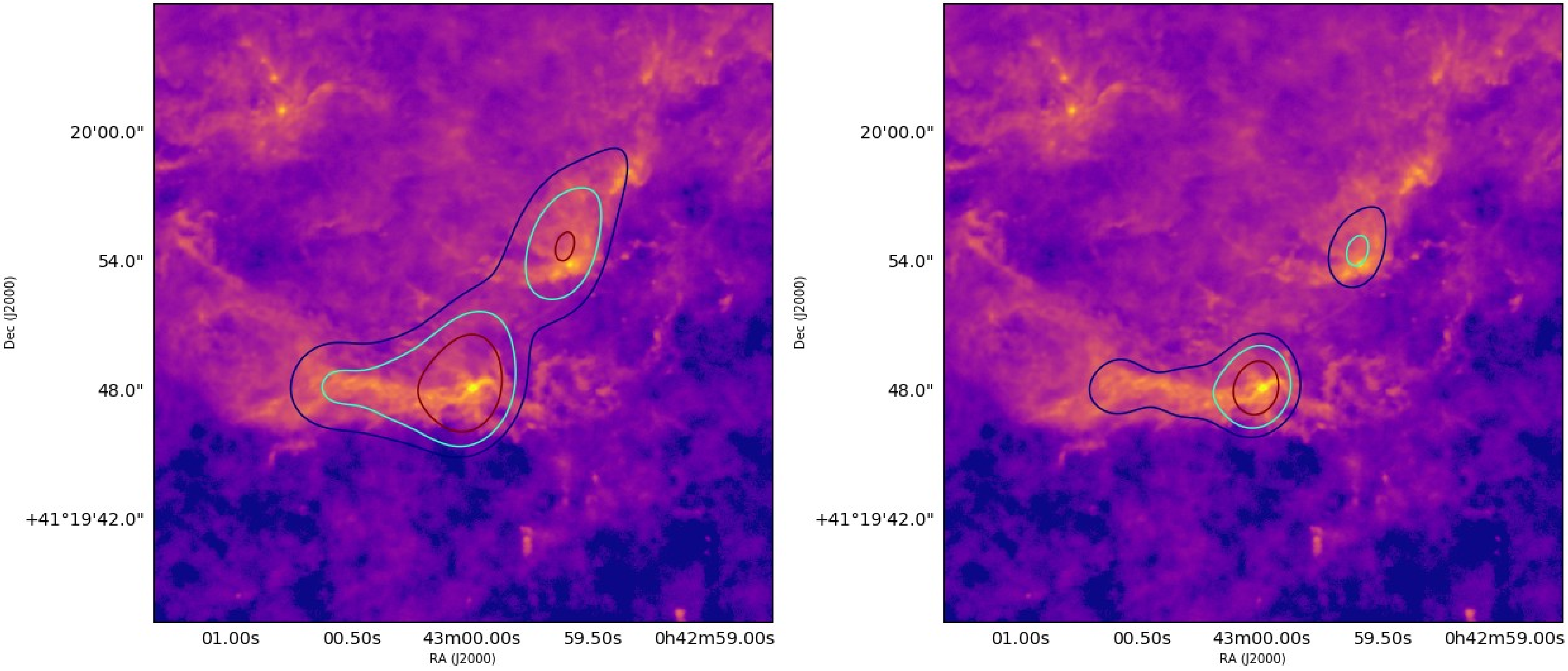

Data: Planck Collaboration

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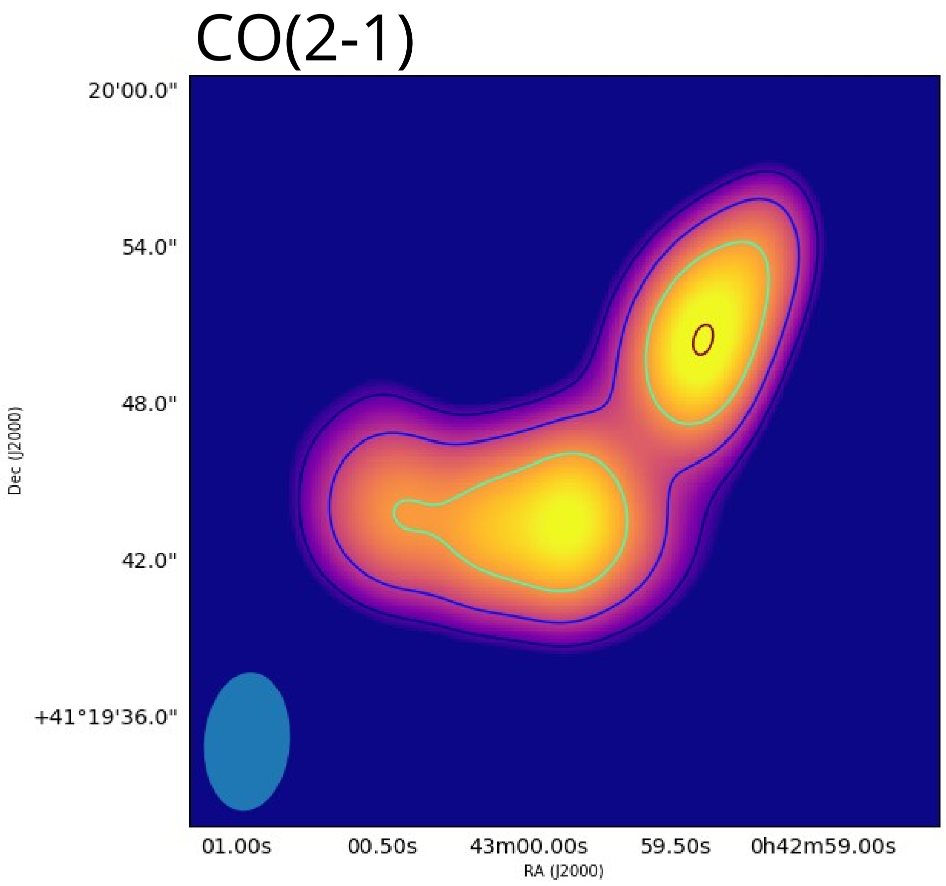
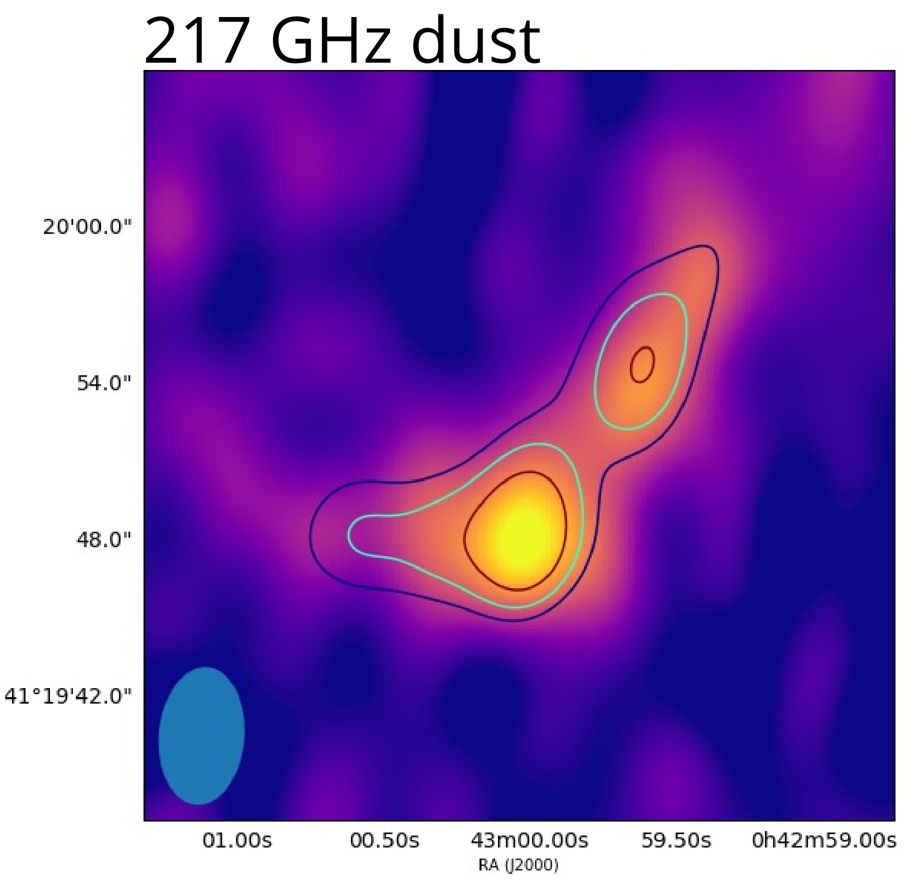
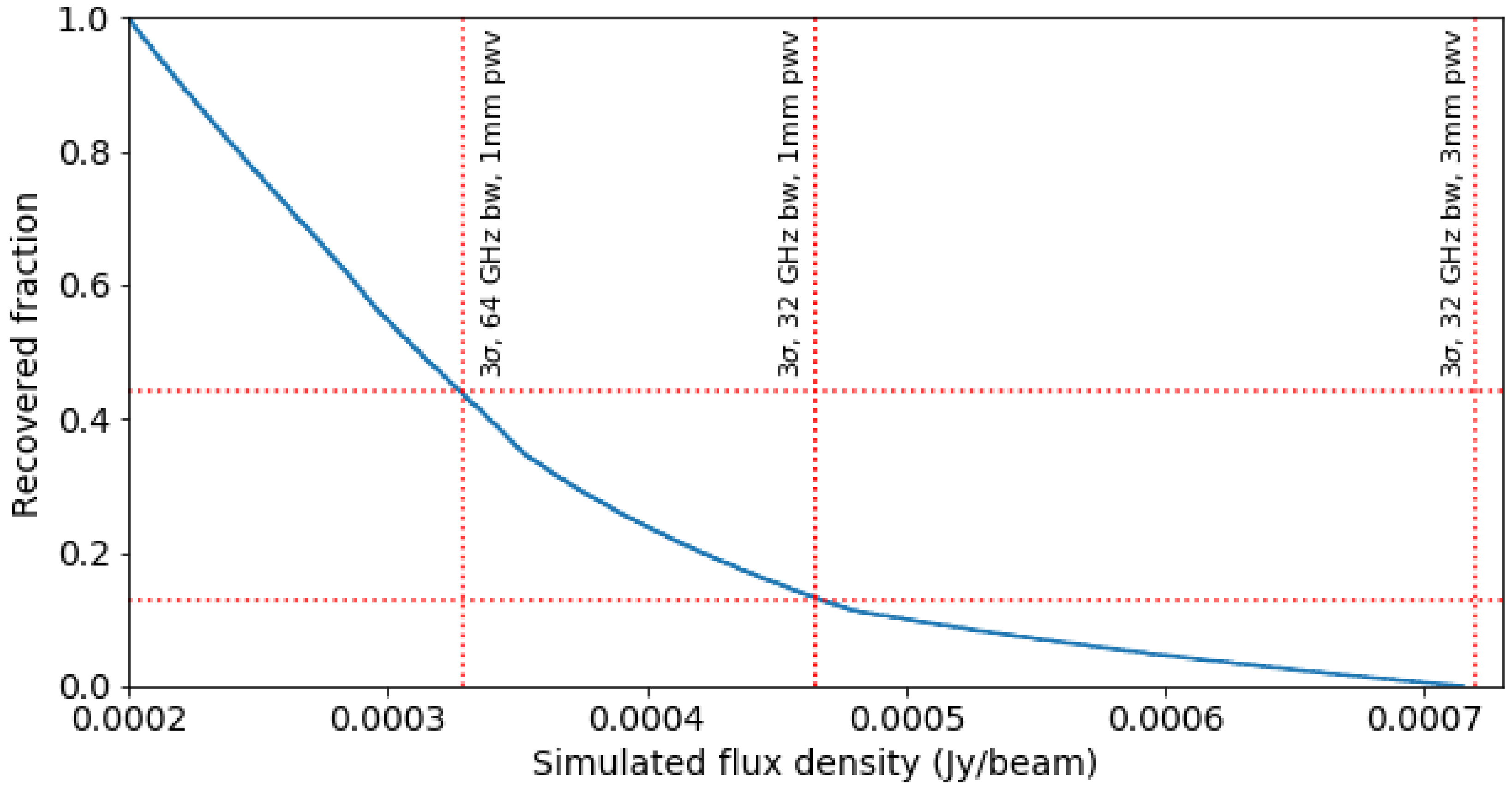




Data: Nishimura et al. (2015), Planck Collaboration

What would **Orion** look like in M31?




NASA/ESA

A VLA survey for **HII regions** in the GMAs of M31

- Survey of *all* 326 Herschel-identified Giant Molecular Associations in M31.
- To be carried out as a high-priority program in Q1/Q2 of 2020.
- Resolution-matched to SMA survey and pathfinder for SMA target selection.
- At these scales, the X-band radio flux is expected to be almost entirely thermal.
- Goal: identify equivalent of Orion Nebula (as small HII region) at S/N=10 in all GMAs
- Will provide sub-cloud-scale (13 pc) SFR constraints for a large and unbiased sample.
- PhD thesis project of Jonathan Toomey at U Hertfordshire

Summary

1 We have demonstrated that the SMA can detect dust continuum emission from many *resolved* individual GMCs in M31, guided by discrete concurrent CO measurements.

2 M31 is at a sweet spot for the SMA in terms of sensitivity, resolution, & spatial filtering, providing a unique opportunity that ALMA currently cannot easily replicate (cf. NGC 300).

3 With GMCs in M31 measured on an equal footing (dust) with respect to the local clouds, we can expand the local sample by including GMCs with a wider range of properties, reflecting different environmental conditions, but at similar metallicity.

4 In this role, the wSMA upgrade will be transformational!