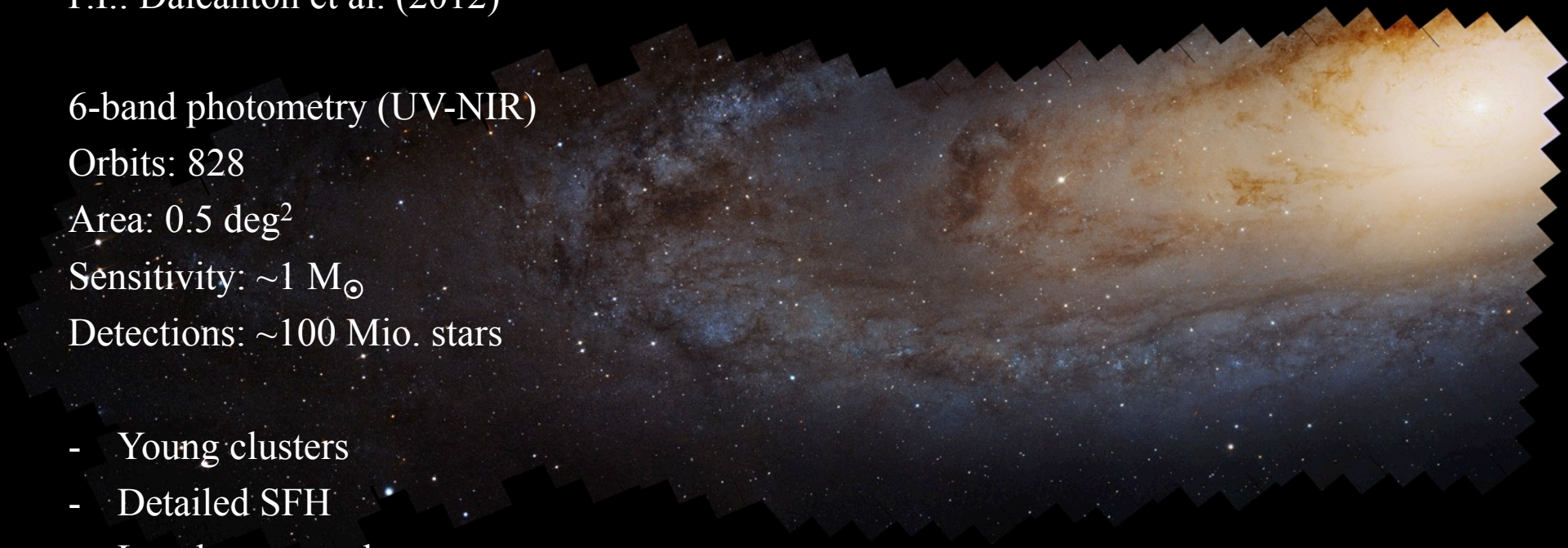
Properties of the Molecular Gas and Star Formation Process in Andromeda

Andreas Schruba (MPE)
and PHAT, CARMA M31, ALMA NGC300, Local Group L-Band Teams
especially A. Leroy, F. Walter, N. Scoville, J. Dalcanton, D. Kruijssen

The Panchromatic Hubble Andromeda Treasury

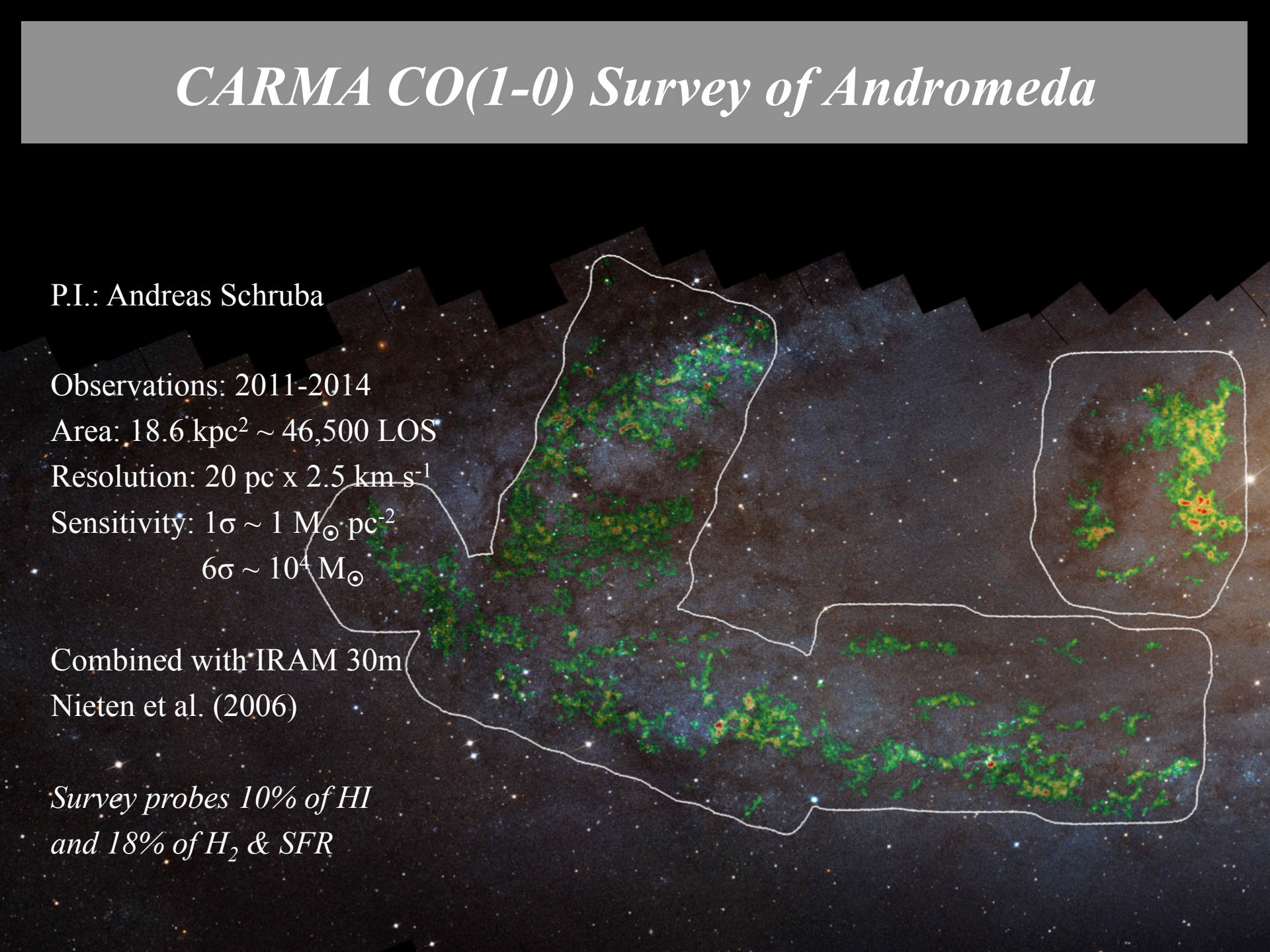
P.I.: Dalcanton et al. (2012)

6-band photometry (UV-NIR)
Orbits: 828
Area: 0.5 deg^2
Sensitivity: ~1 $M_\odot$
Detections: ~100 Mio. stars



- Young clusters
- Detailed SFH
- Local energy release
- Local extinction A_V

CARMA CO(1-0) Survey of Andromeda



P.I.: Andreas Schruba

Observations: 2011-2014

Area: 18.6 kpc^2 ~ 46,500 LOS

Resolution: 20 pc x 2.5 $km\ s^{-1}$

Sensitivity: $1\sigma \sim 1\ M_\odot\ pc^{-2}$

$6\sigma \sim 10^4\ M_\odot$

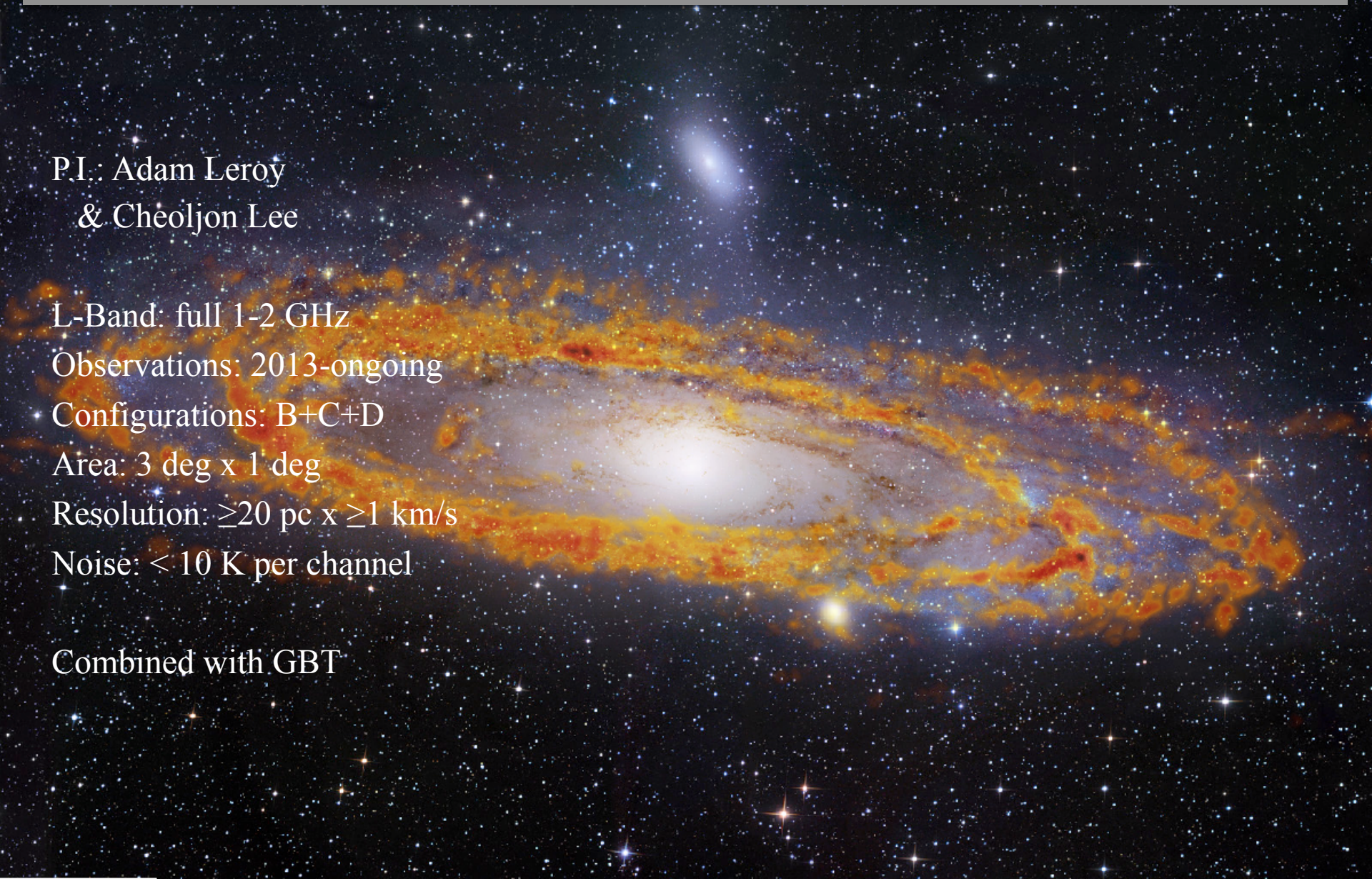
Combined with IRAM 30m

Nieten et al. (2006)

Survey probes 10% of HI

and 18% of H_2 & SFR

JVLA L-Band Survey of Andromeda



P.I.: Adam Leroy
& Cheoljon Lee

L-Band: full 1-2 GHz
Observations: 2013-ongoing
Configurations: B+C+D
Area: 3 deg x 1 deg
Resolution: ≥20 pc x ≥1 km/s
Noise: < 10 K per channel

Combined with GBT

A Major Focus on Andromeda's ISM

Scientific Goal: Dissect the multiphase ISM of the nearest big spiral <u>at cloud scales</u>.

HI: Lee, Leroy+ (in prep); CO: Schruba+ (in prep); Dust (IR): Draine+ '14;
A_V: Dalcanton+ (ApJ subm); CII: Kapala, Sandstrom+ '14;
Clusters/Stars: Johnson+ '12,'15; SF History: Lewis+ '15.

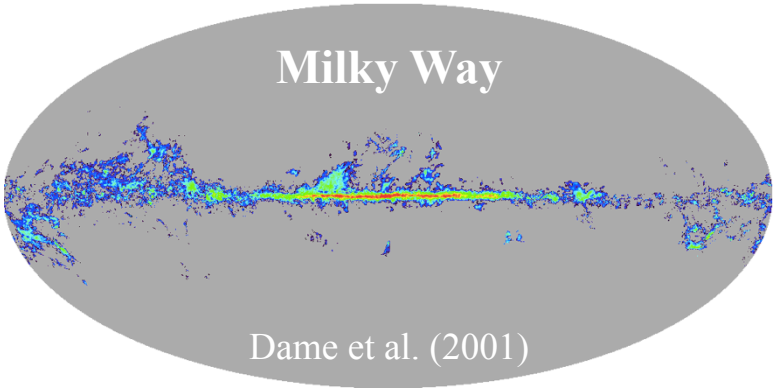
1. How do molecular clouds form? Compare HI, CO, kinematics at high resolution.

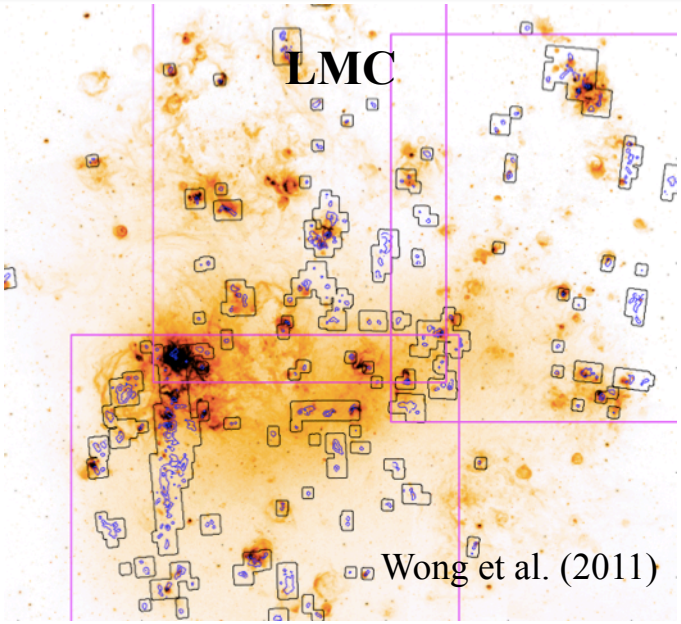
2. How to trace H_2? Overconstrain CO-to-H_2 conversion factor and DGR.

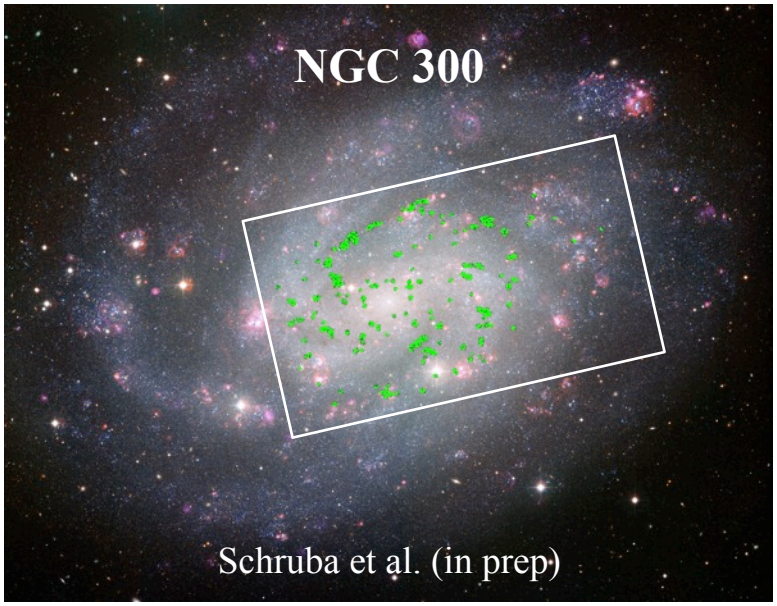
3. Multiphase cloud structure: H_2/HI complexes, opaque HI, and dynamical state.

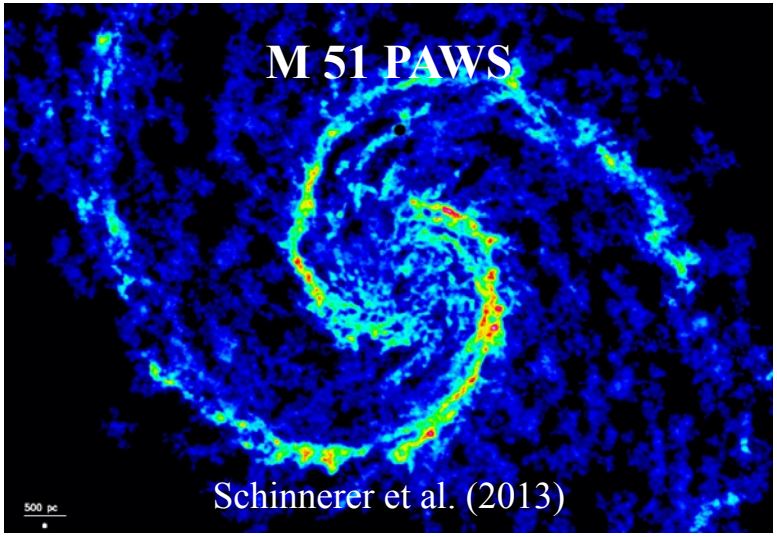
4. What are the time scales of cloud formation, star formation, and feedback?

Link to Nearby Galaxies whenever Possible

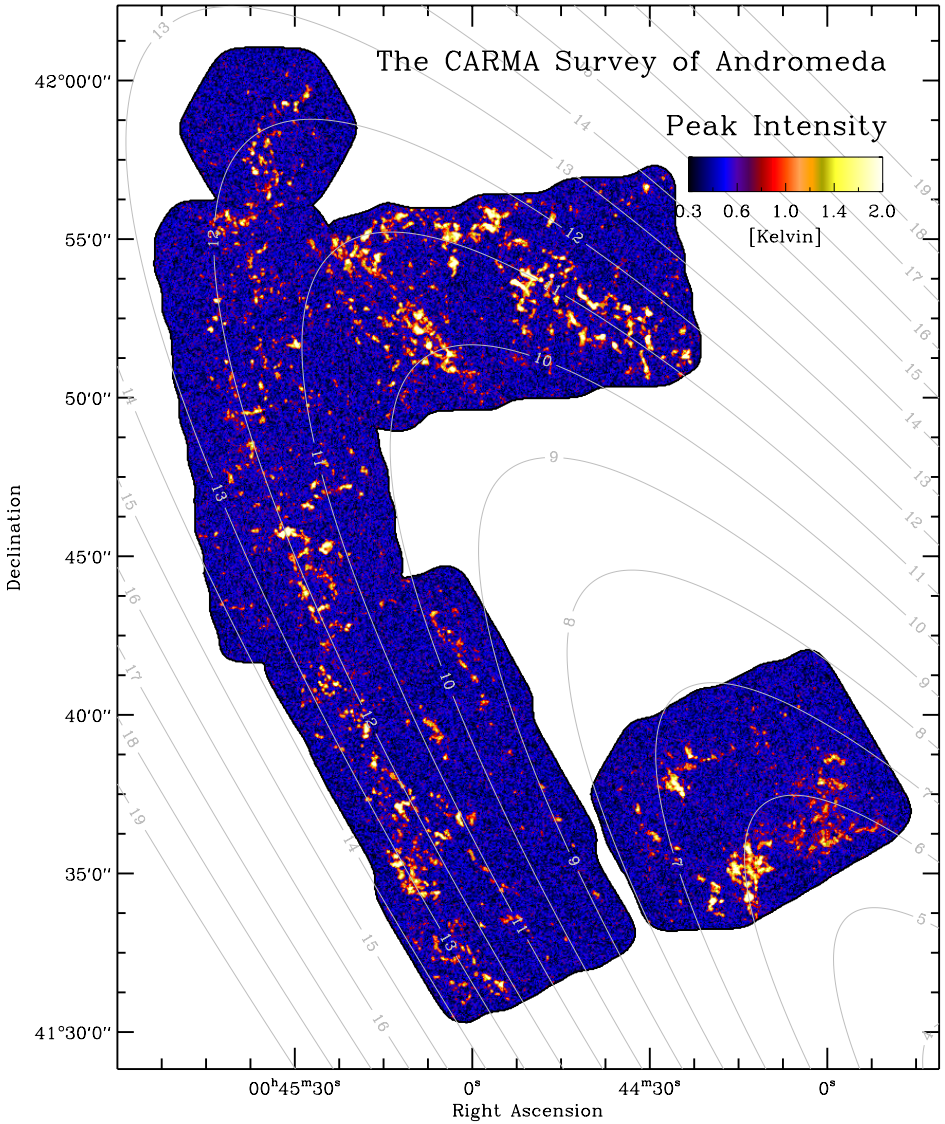








Identification of Molecular Clouds

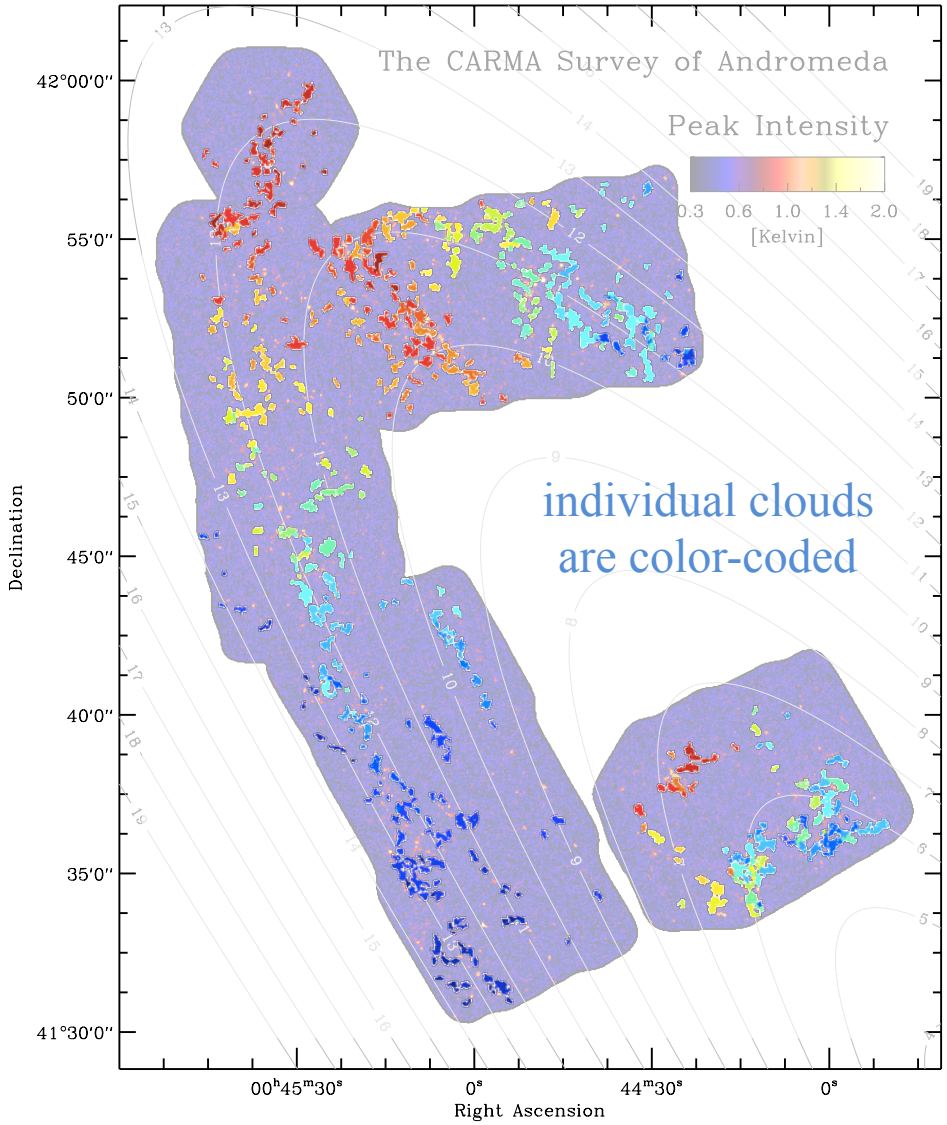


500 local maxima
identified by CPROPS package
(up from ~50 Rosolowsky+'07)

Decompose map into GMCs
but also run multi-scale
property extraction with
dendrograms
(not a large effect in M31)

Properties are aggregates
of several attempts at size
measurement, aperture
correction, etc.

Identification of Molecular Clouds



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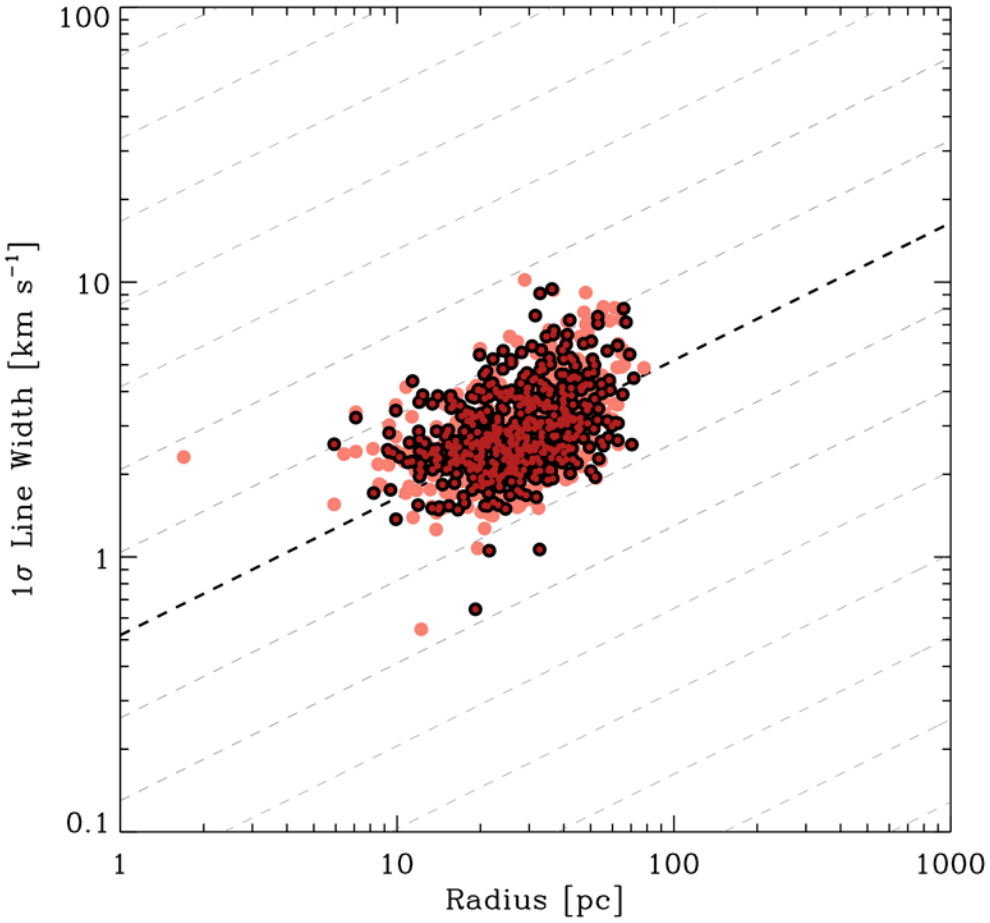
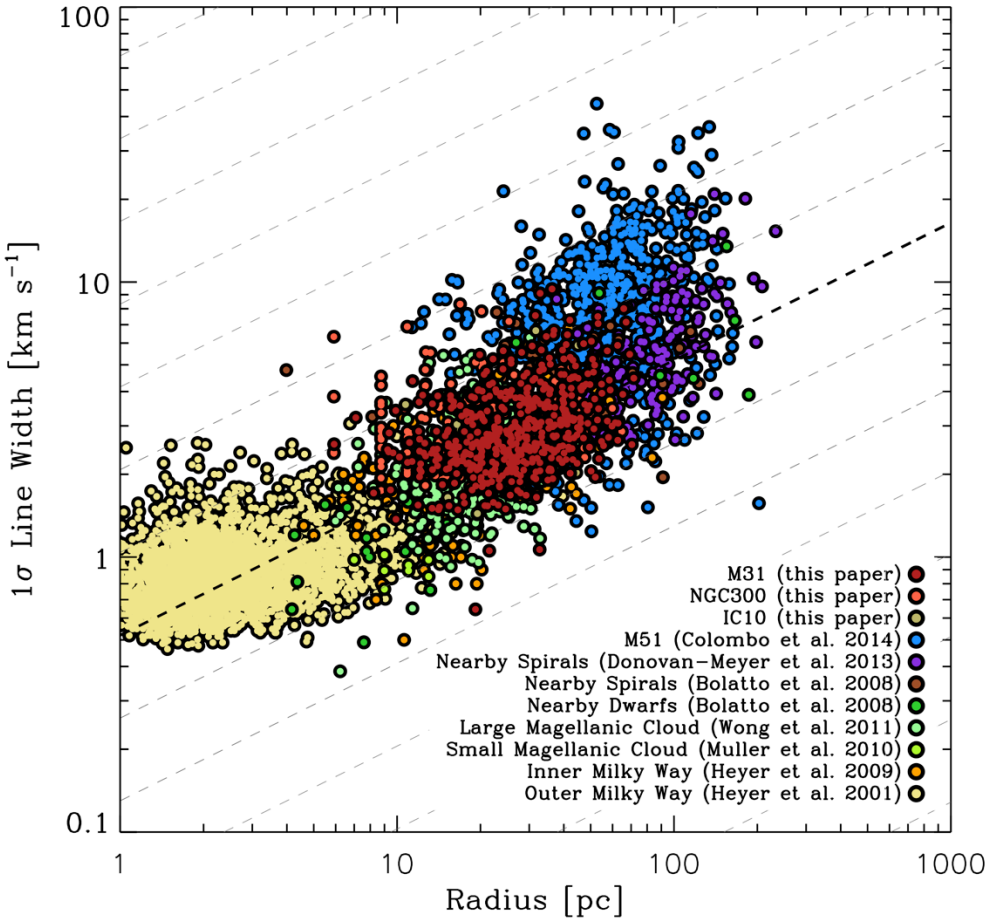
Line Width - Size Relation

Different methods (here CPROPS vs CLFIND) result in similar properties, thus …
Aggregate properties of several attempts at size measurement, aperture correction, etc.



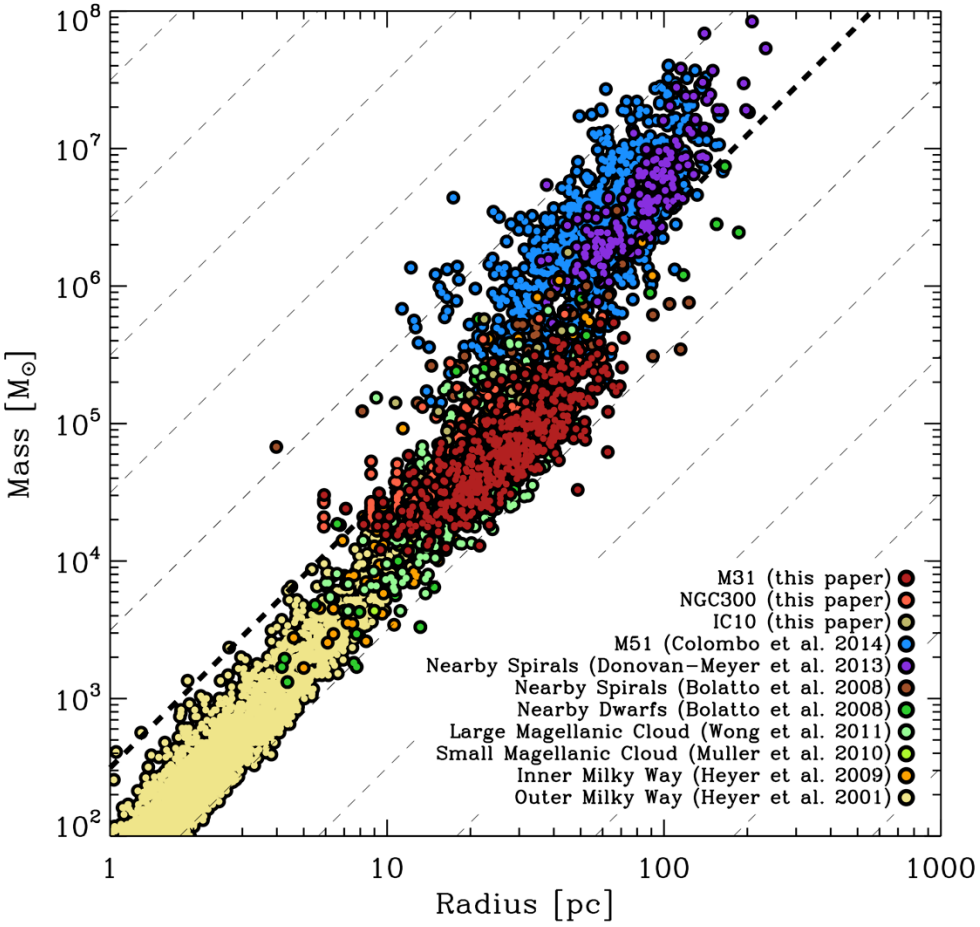
Line Width - Size Relation

Consistent for low surface density galaxies: MW, LMC, M33, M31, NGC300; but different in high surface density, strong spiral arm galaxy: eg, M51.



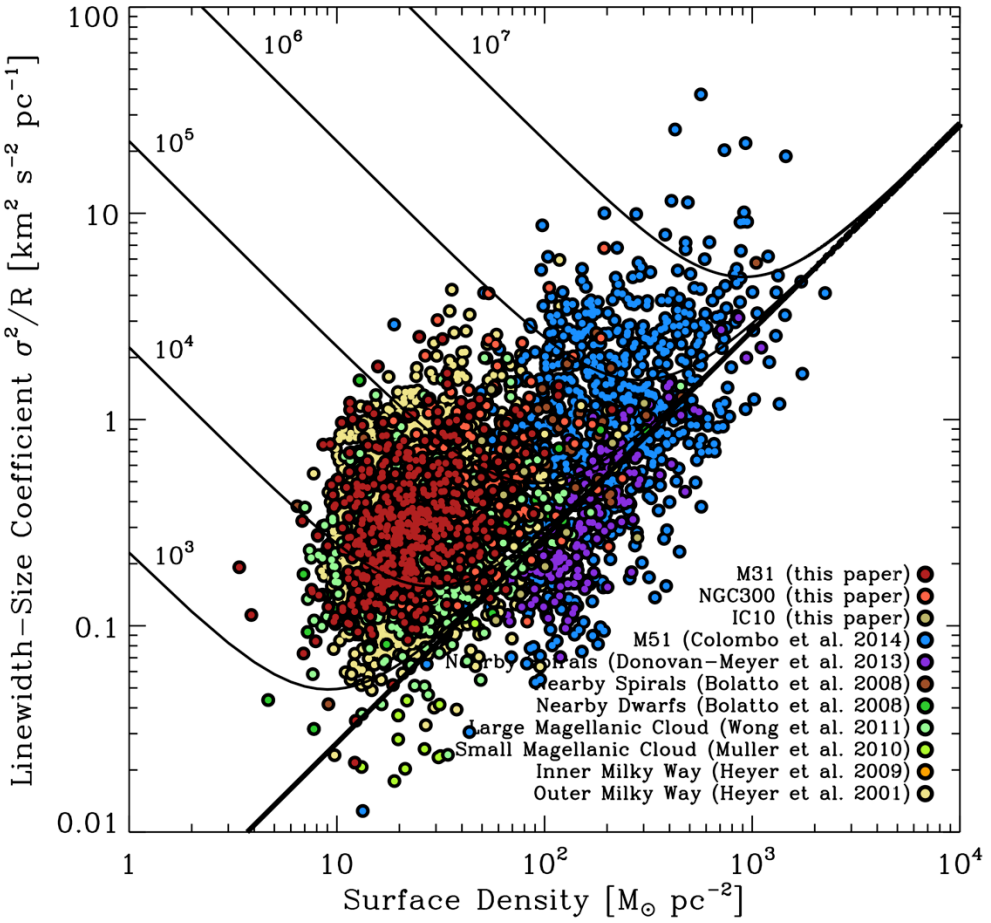
Surface Densities of Clouds

Cloud surface density ~ 25 $M_\odot$ pc^{-2} (± 0.3 dex) for MW, LMC, M33, M31, NGC300
but ~100-300 $M_\odot$ pc^{-2} in high surface density galaxies: M51, NGC4826, NGC6946



Dynamical State of Clouds

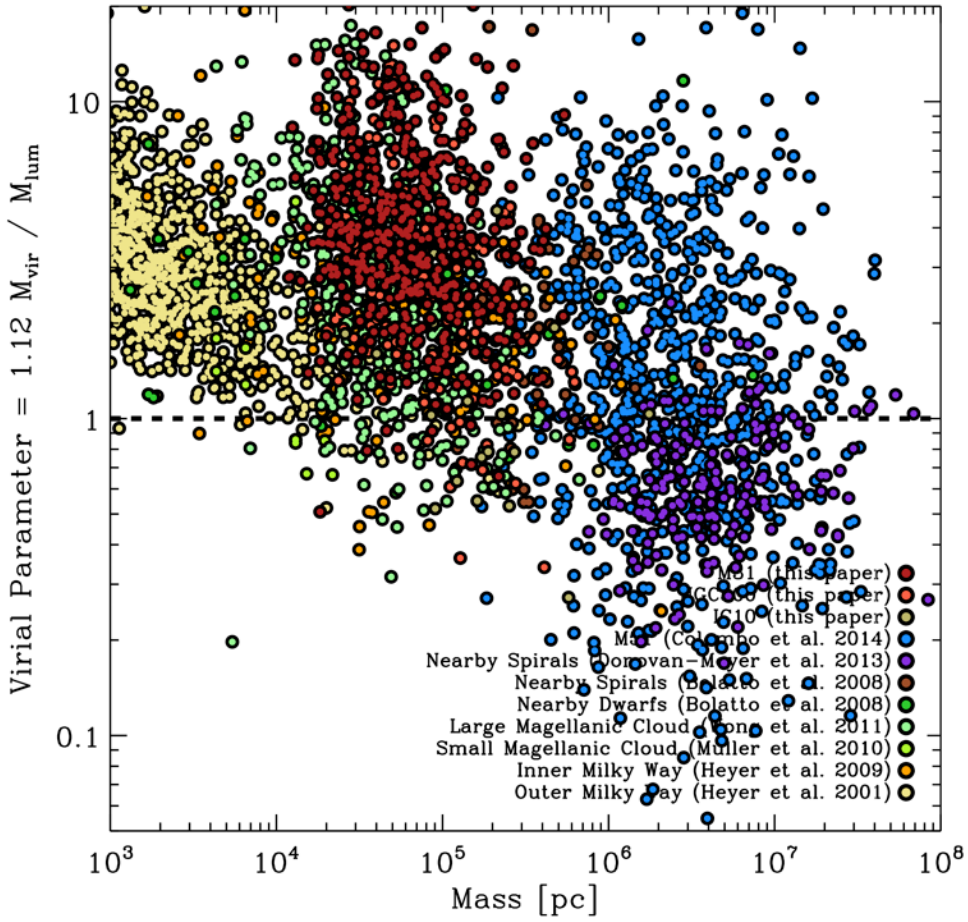
Clouds in virial equilibrium fulfill Larson relations: $\sigma^2 = (\pi G/5)\, R\, \Sigma_{GMC}$ *(diagonal line) (lower mass) clouds in MW, LMC, M33, M31, NGC300 have enhanced kinetic energy.*



Lines of constant external pressure follow *Field, Blackman, Keto '11, Keto & Myers '86*

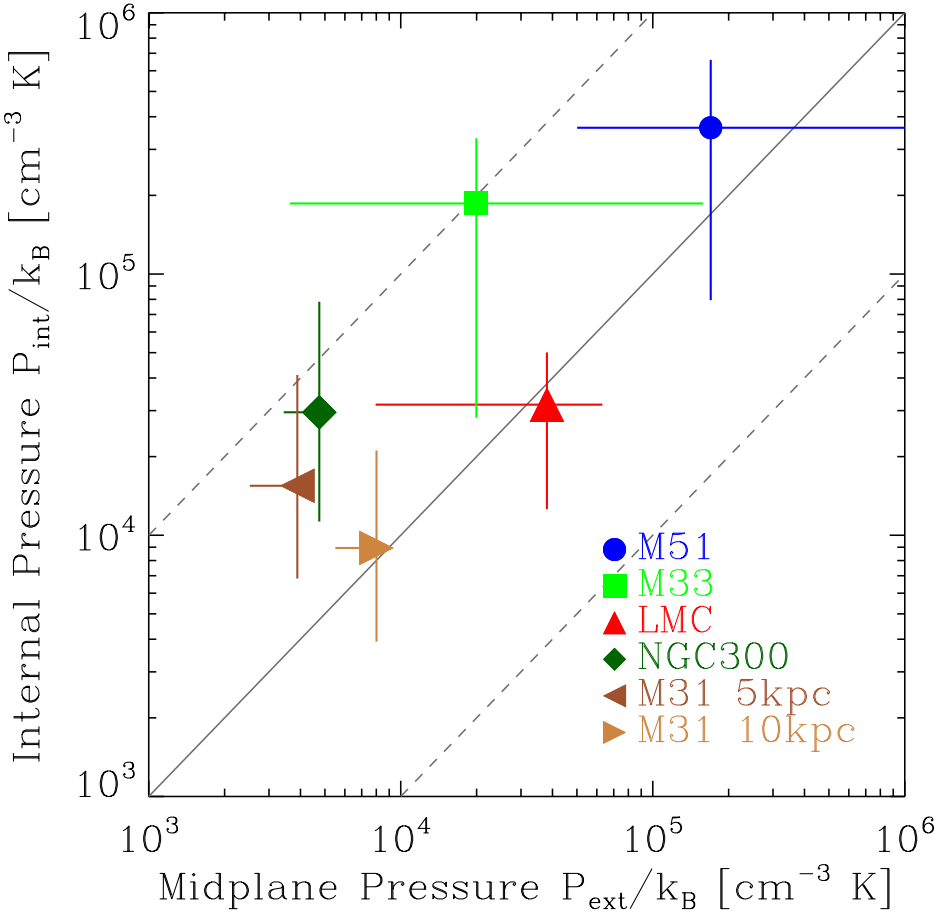
Dynamical State of Clouds

Clouds in virial equilibrium fulfill Larson relations: virial parameter ~ 1 (dashed line) (lower mass) clouds in MW, LMC, M33, M31, NGC300 have enhanced kinetic energy.



Dynamical State of Clouds

Midplane pressure of diffuse ISM but also atomic shielding layer around CO-bright cores provide sufficient support to keep (low mass/density) clouds in pressure-bound equilibrium.



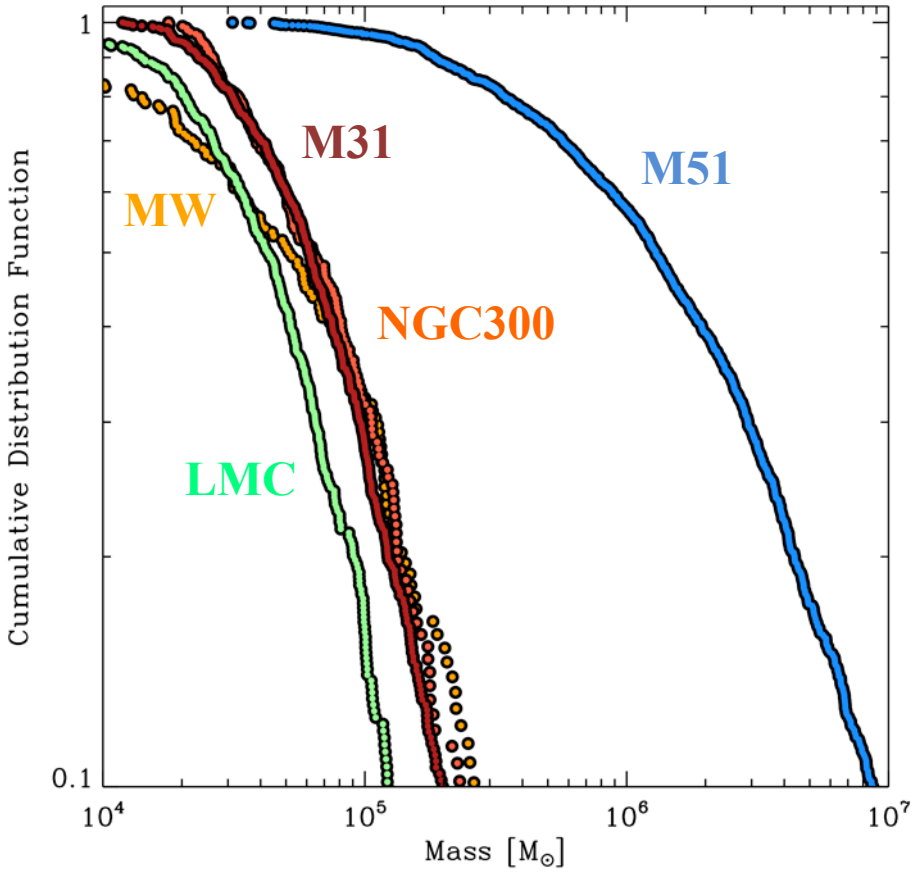
Atomic shielding layers provide 1-4x additional external pressure.

Following *Hughes et al. (2013)*

Cloud Mass Function

M31 survey probes to a few times 10^4 $M_\odot$, almost no clouds >5.10^5 $M_\odot$

Mass function of low surface density galaxies is bottom heavy and truncated at high masses; but environmental / radial dependencies (eg, M51).



Following *Rosolowsky et al. (2005), Colombo et al. (2014)*

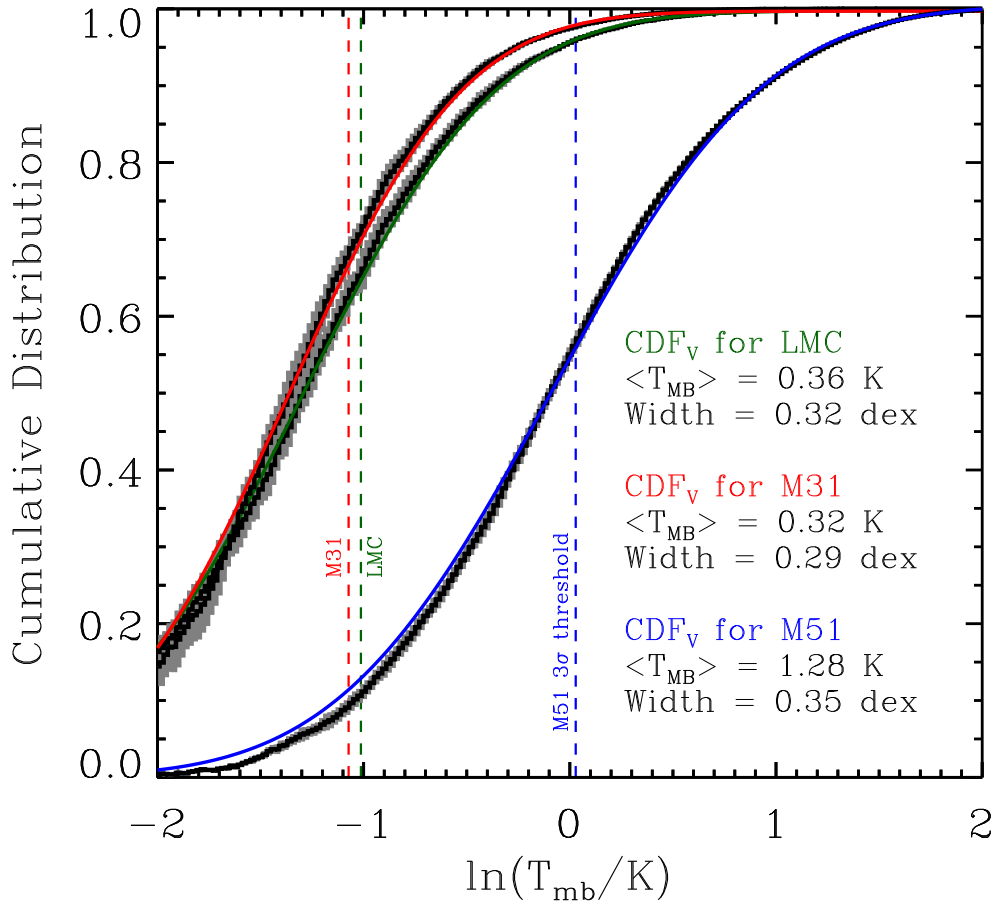
Synthesis of Cloud Properties

Property	M31 Survey Average
Velocity Dispersion at R=25pc	**~ 2.7 km/s**
Implied Mach Number	**~ 15 (T=20K)**
CO Surface Brightness	**~ 5 K km/s**
Virial Parameter*	**~ 3.5**
Surface Density*	**~ 25 $M_\odot$ pc^{-2}**
Volume Density*	**~ 2 $M_\odot$ pc^{-3} ~ 30 cm^{-3}**
Free-Fall Time* ~ Crossing Time*	**~ 7 Myr**

* assuming $\alpha_{CO} = 4.35\ M_\odot\ pc^{-2}\ (K\ km\ s^{-1})^{-1}$

Pixel-wise Intensity Distribution

CO pixel intensity distribution identical in M31 & LMC but different from M51

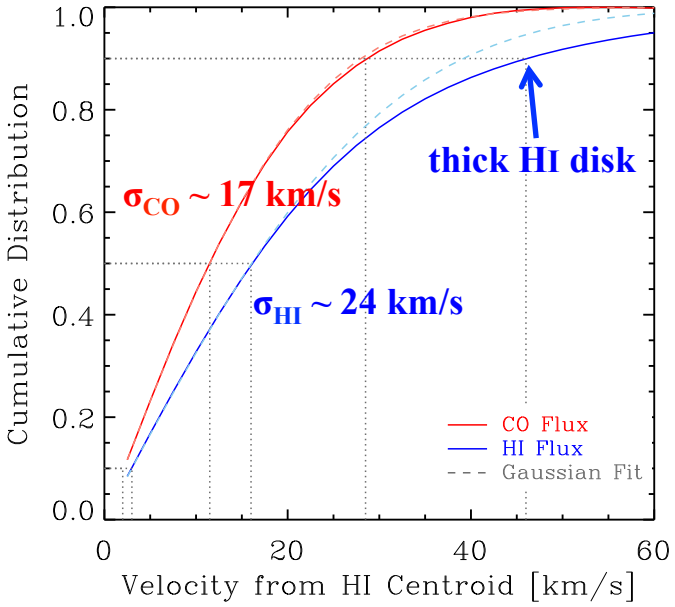


Spatial Distribution

Atomic and molecular gas well mixed with ~2x thicker HI disk (+5% HI in thick disk)

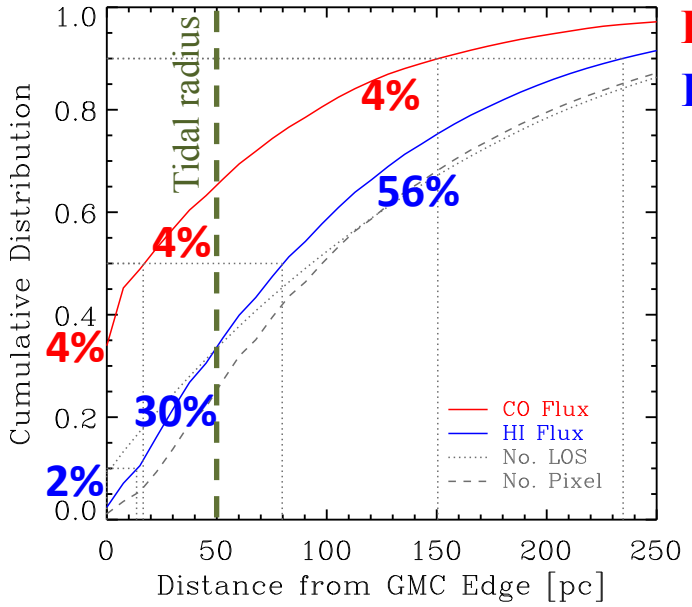
Molecular mass by 1/3 in "GMCs" M > 10^4 $M_\odot$; 1/3 in envelopes; 1/3 diffuse phase

LOS "Distribution" of HI and H_2



HI and H_2 profile around Clouds

(percentages = fraction of neutral gas mass)



H_2 (12%)

HI (88%)

=> deproject face-on: σ_{CO} ~ 4 km/s, σ_{HI}~ 8 km/s

(assuming Gaussian profile and isotropic turbulent gas motions)

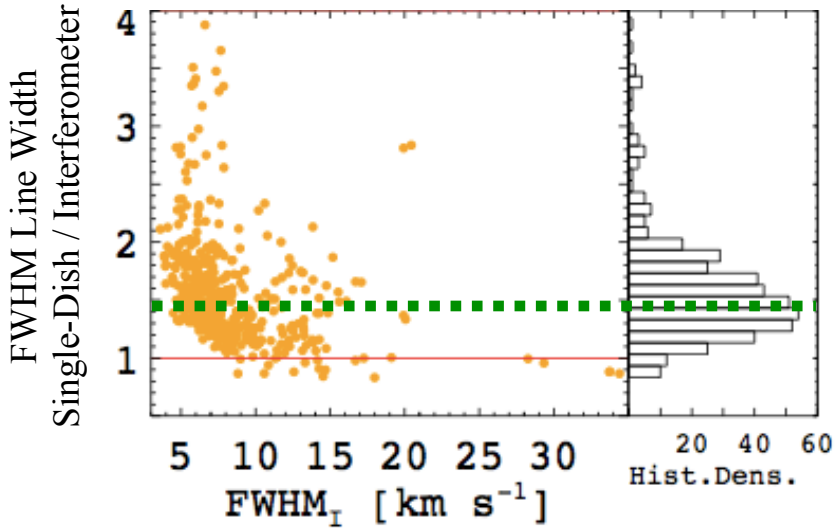
Following *Hughes et al. (2013)*, see also *Sawada, Hasegawa, Koda et al. (2012)*

Compact & Diffuse Morphologies

CO line profile at 100pc consists of narrow component (ie, clouds) & broad component (ie, diffuse molecular gas) which is widespread and filtered out by interferometer.

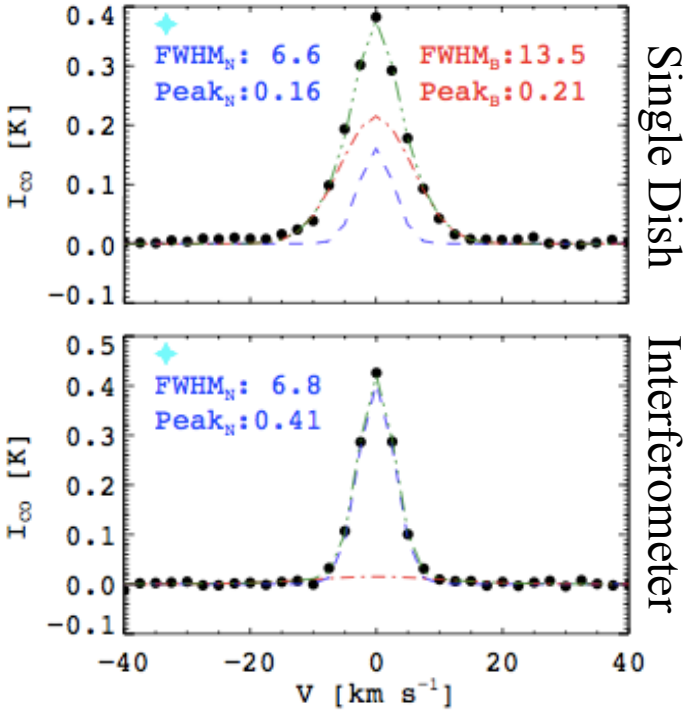
(1) Fit single Gaussian profile:

Single-dish detects 40% wider line profile.



(2) Fit two Gaussian profiles:

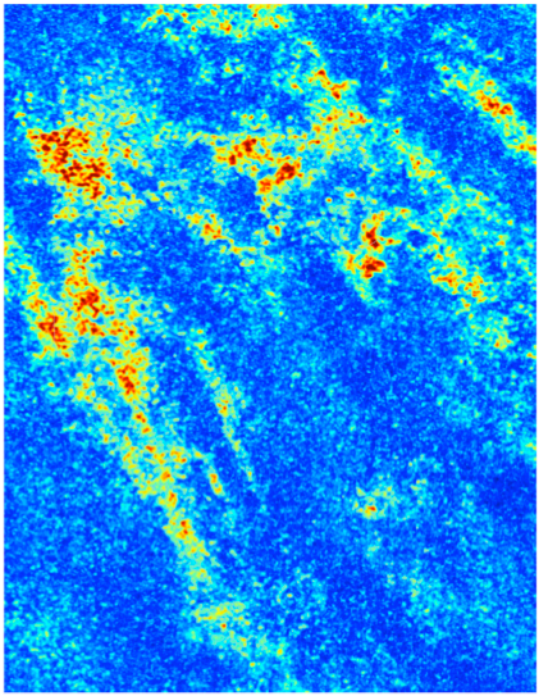
Single-dish detects broad component.

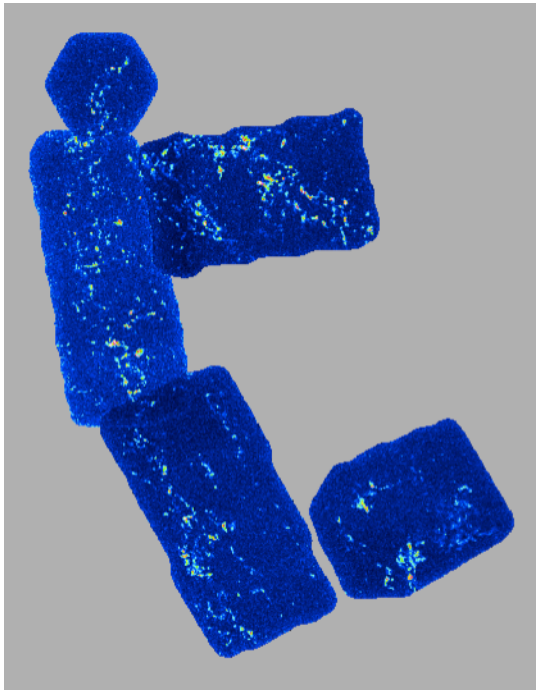


Anahi Caldu-Primo et al. (AJ subm; PhD July 2015, MPIA)

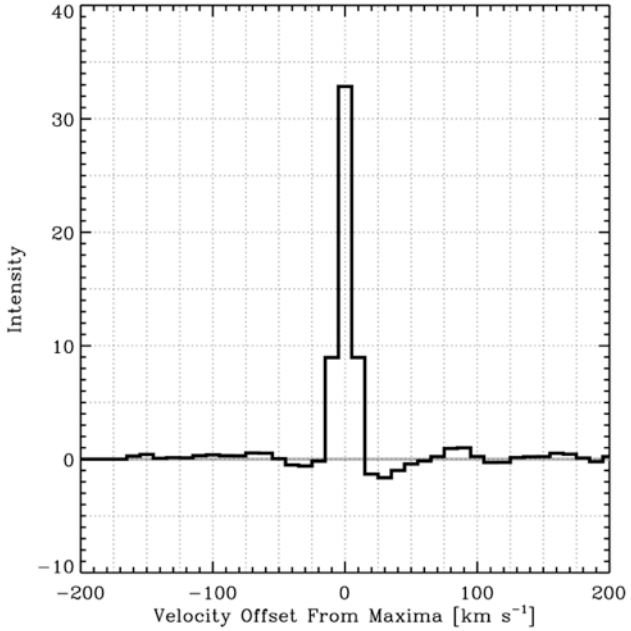
Bright HI corresponds well to CO (and A_V)

Brightness temperature T ~ 30 K broadly picks out molecular complexes well
with stacked spectrum of FWHM < 10 km s^{-1} (very narrow by extragalactic standards)
For reasonable conversion HI must be very opaque to contribute much mass.
(see also Braun+'09, '12)





Stacked spectrum of all current B+C detections at 10 km s^{-1} resolution.

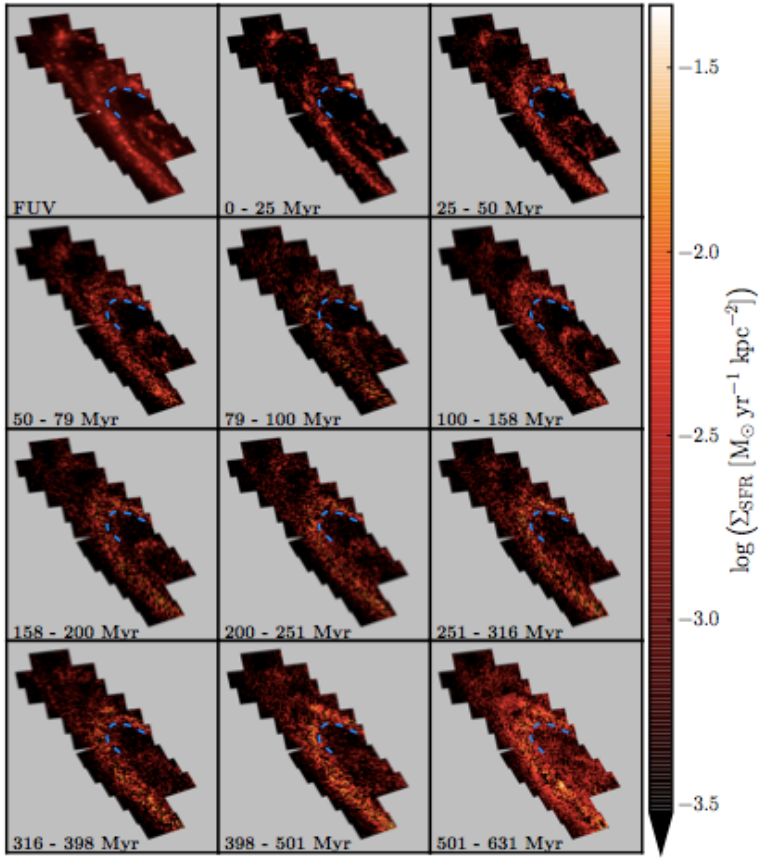


Cheoljong Lee et al. (in prep; PhD thesis work, UVA)

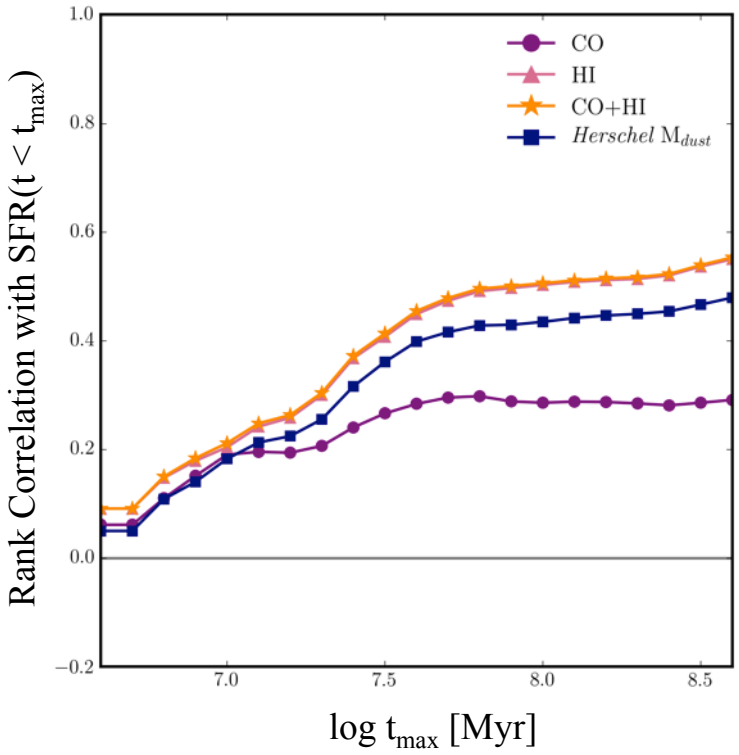
Clouds and Star Formation History

ISM on 100 pc-scale weakly correlated with most-recent SFH (10 Myr) but increased correlation over longer times (100 Myr): ISM morphology evolves on short timescale.

Optical CMD ⇨ Recent SF History



Spatial Correlation of SFH & ISM at 100pc in 5- & 10-kpc rings

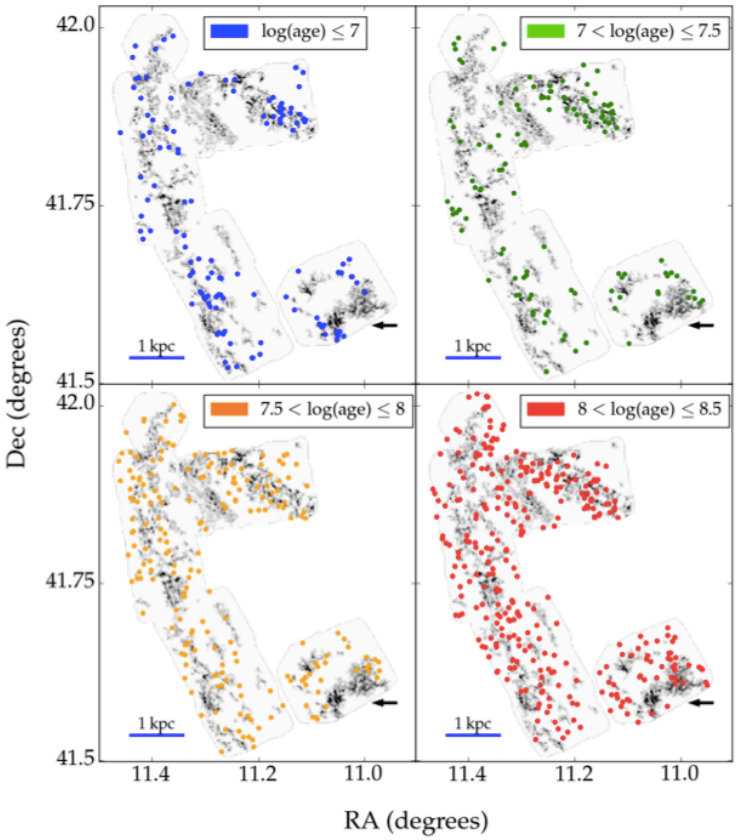


Alexia Lewis et al. (2015; in prep; PhD thesis work, UW)

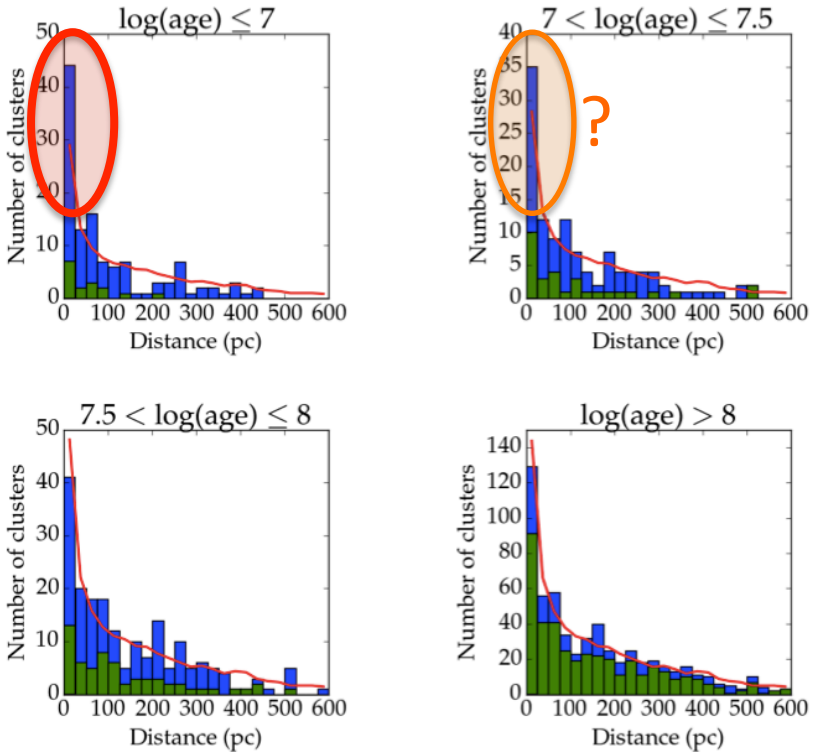
Clouds and Stellar Clusters

Enhanced spatial correlation of young stellar clusters (<20Myr) on spatial scales ~25pc.

Location of clusters in recent age bins



Spatial correlation enhanced in youngest age bins *(random sample = red lines)*



Lori Beerman et al. (to be subm; PhD thesis work, UW)

Clouds and Current Star Formation Activity

Classify clouds as 'quiescent' (no IR, Hα), 'embedded' (only IR), 'exposed" (Hα, cluster)

... and associate timescales for each evolutionary state using cluster ages

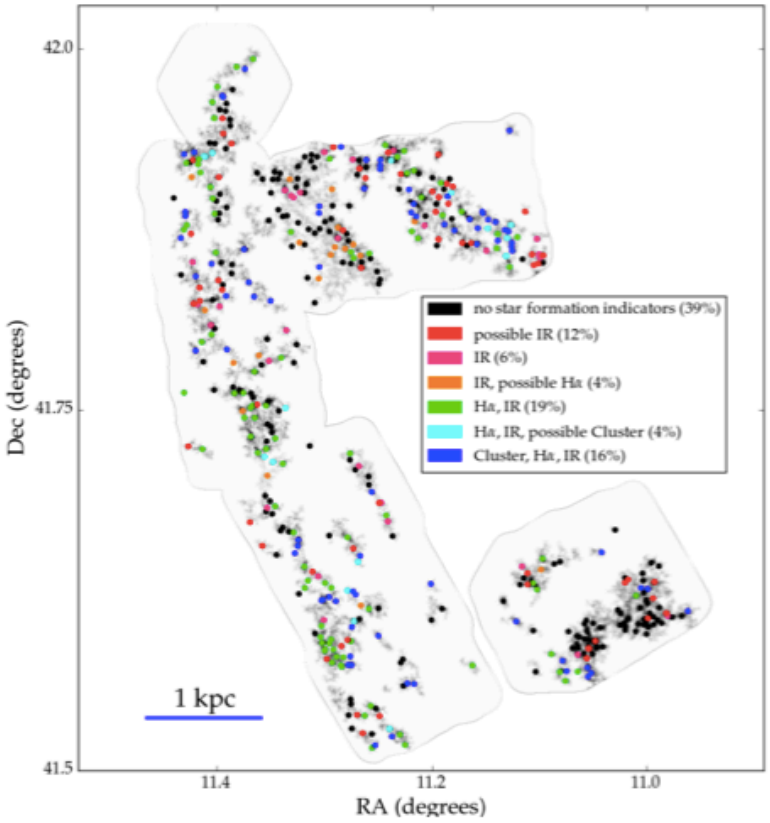


Table 2. M31 Cloud Classifications and Timescales

Classification[a]	Percentage[b]	Timescale[c]
No Star Formation Indicators		
Definite only	39%	6 Myr
Definite + Possible	51%	15 Myr
IR Emission		
Definite only	6%	1 Myr
Definite + Possible	22%	4 Myr
Hα and IR Emission		
Definite only	19%	3 Myr
Definite + Possible	27%	7 Myr
Young Cluster, Hα and IR Emission		
Definite only	16%	3 Myr
Definite + Possible	20%	4 Myr

Total cloud lifetime ~13-30 Myr
with 60% showing signs of star formation

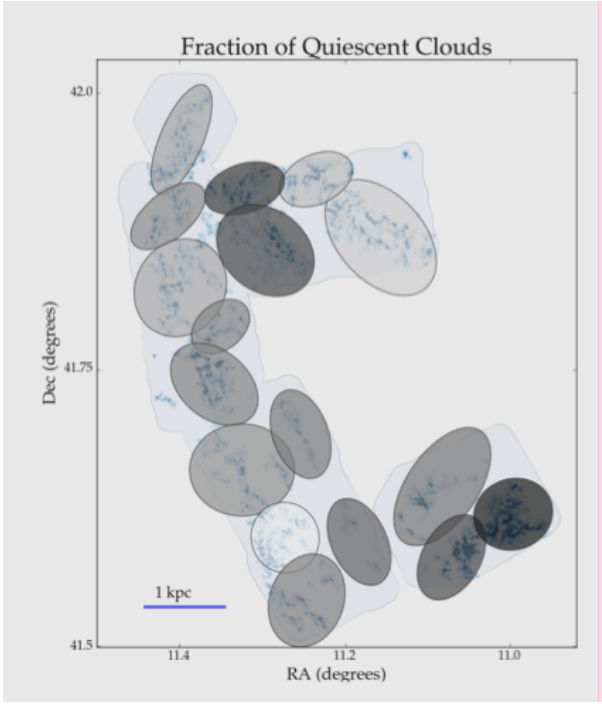
Following *Kawamura et al. (2009)*

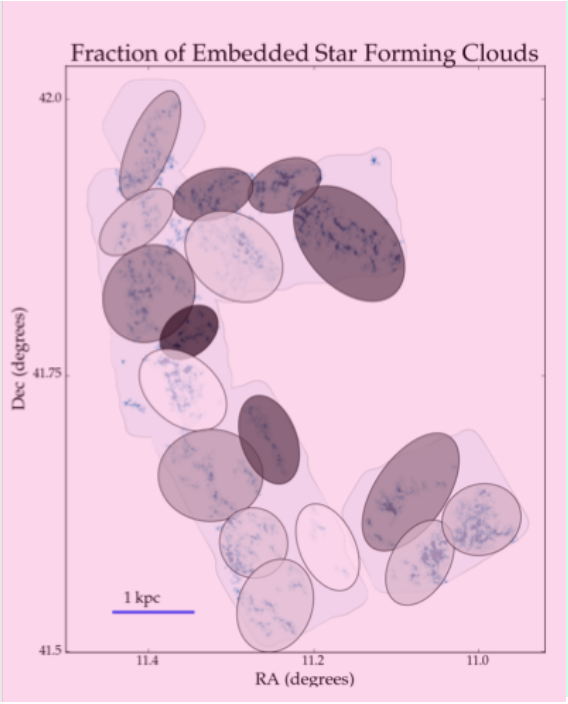
Lori Beerman et al. (to be subm; PhD thesis work, UW)

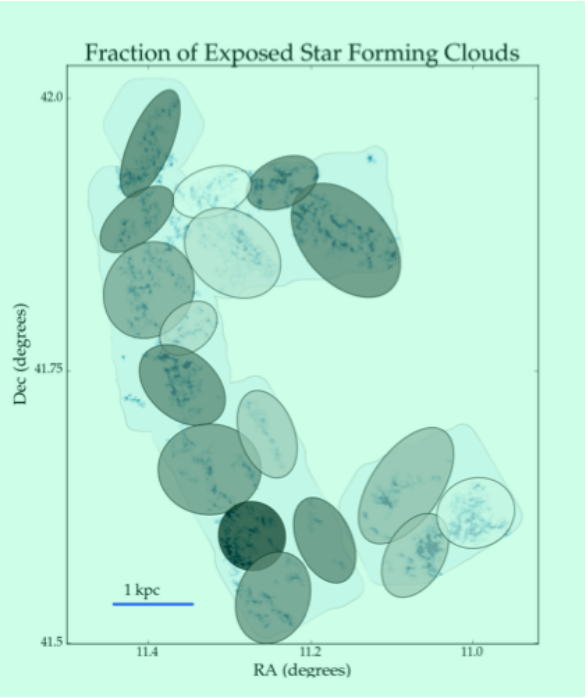
Clouds and Current Star Formation Activity

Classify clouds as 'quiescent' (no IR, Hα), 'embedded' (only IR), 'exposed" (Hα, cluster)

... first evidence of correlated cloud / star formation evolution on scales of 0.5-1 kpc (?)







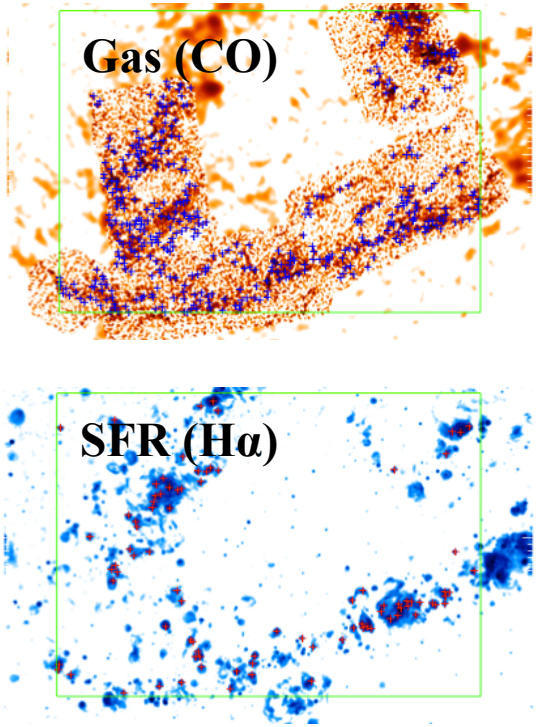
Lori Beerman et al. (to be subm; PhD thesis work, UW)

Cloud Lifetime and Duration on Star Formation

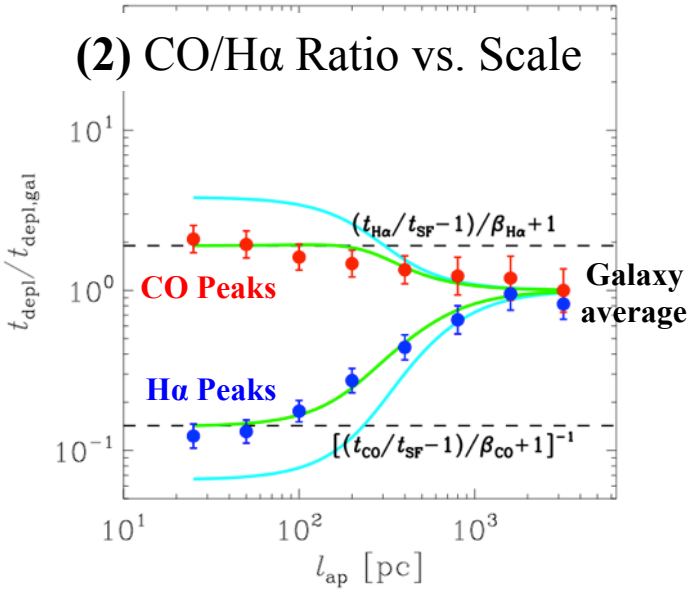
Utilize the "Uncertainty Principle of Star Formation" (Kruijssen & Longmore 2014): The scale-dependent bias in gas/SFR ratio reflects the cloud lifetime and SF duration.

Talk later today

(1) Apertures on CO & Hα peaks



(2) CO/Hα Ratio vs. Scale



(3) For $t_{H\alpha}$ = 6 Myr get …

$t_{CO} = 25^{+20}_{-6}$ Myr

$t_{SF} = 2.6^{+1.1}_{-0.5}$ Myr

SFE ~ t_{CO} / f_{cloud} t_{depl} ~ 0.08

$\lambda_{indep} = 268^{+54}_{-77}$ pc

Kruijssen & Schruba et al. (in prep)

Conclusions from Andromeda Project

Scientific Goal: Dissect the multiphase ISM of the nearest big spiral: M31.

1. New large CARMA survey covering the ring + radial extension (Schruba+; in prep.)

2. Large cloud population (500+ clouds) characterized in many ways:
Resembles clouds in other low-surface-density galaxies (MW, LMC, M33, NGC300) in surface brightness, mass distribution. Clouds are in pressure-bound equilibrium.

3. New high resolution HI map show high brightness regions along star-forming ring.
Narrow HI a good way to predict CO but not the major mass component in clouds (Lee). Diffuse molecular gas well-mixed with atomic gas.

4. HST PHAT survey traces SFH (Lewis), clusters (Beerman), dust/extinction (Lee).
Weak correlation of recent SFH and ISM: clouds & ISM structures short lived (Kruijssen).