Molecular Gas and Star Formation from Galaxy to Sub-Cloud Scale 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

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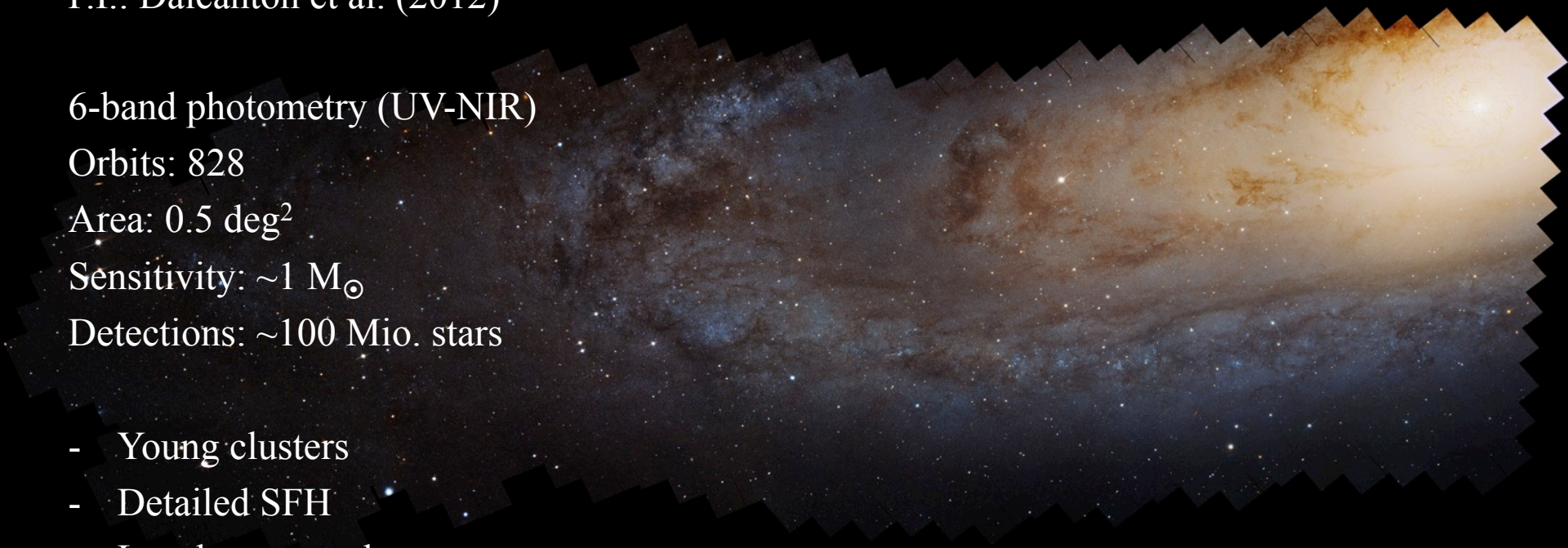
The Panchromatic Hubble Andromeda Treasury

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



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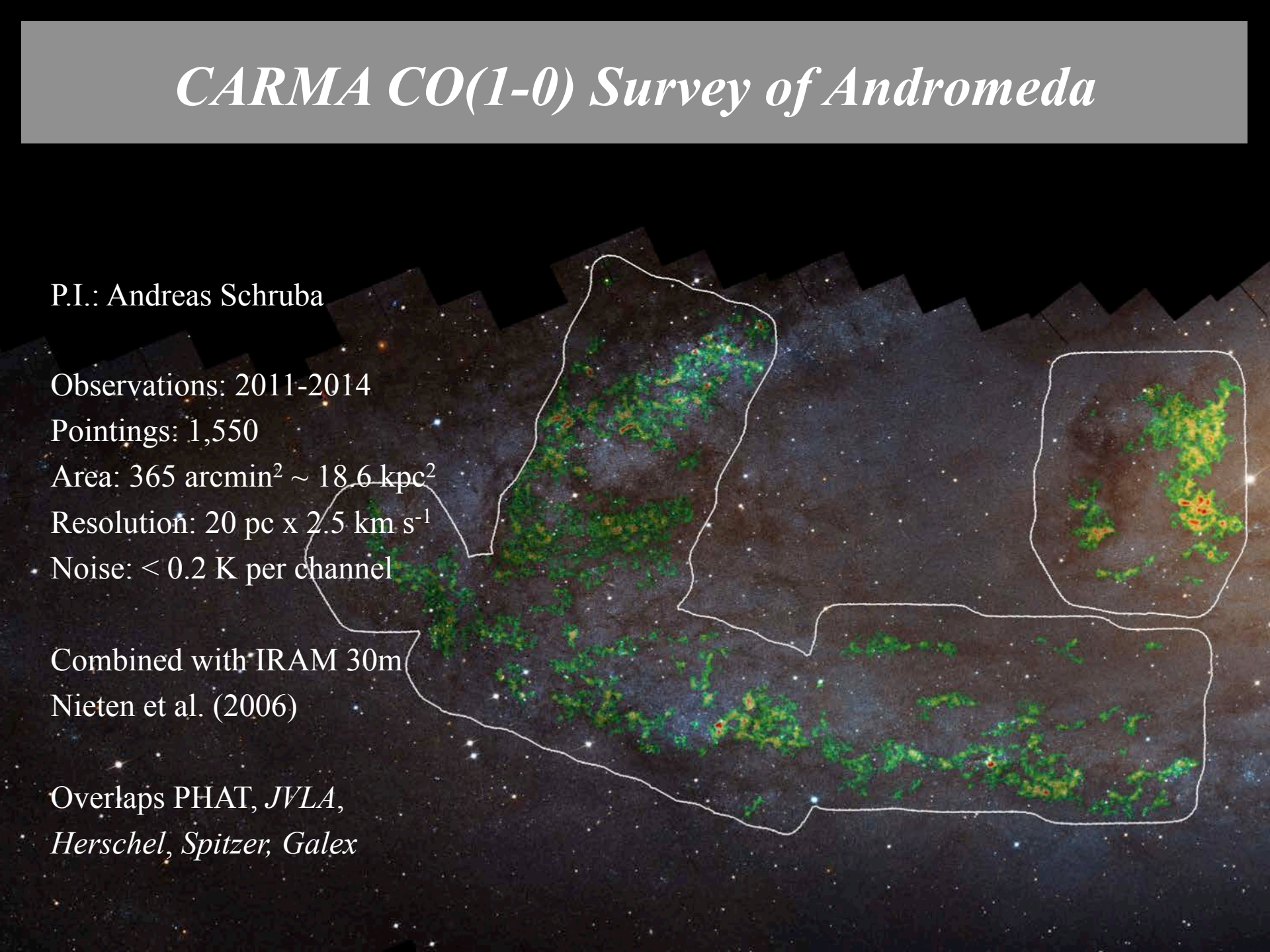
CARMA CO(1-0) Survey of Andromeda



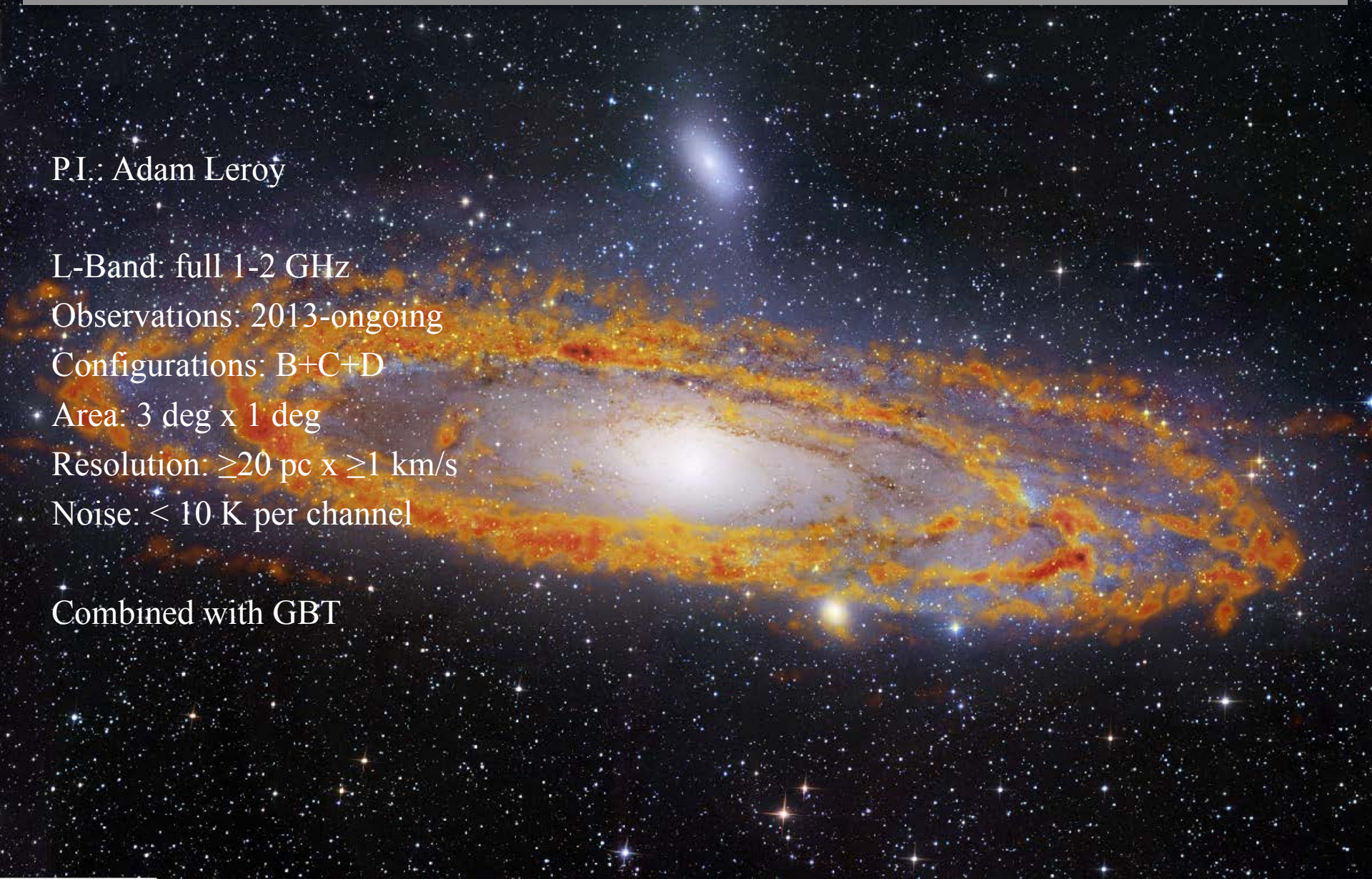
P.I.: Andreas Schruba

Observations: 2011-2014
Pointings: 1,550
Area: 365 arcmin^2 ~ 18.6 kpc^2
Resolution: 20 pc x 2.5 km s^{-1}
Noise: < 0.2 K per channel

Combined with IRAM 30m
Nieten et al. (2006)

Overlaps PHAT, *JVLA*,
Herschel, *Spitzer*, *Galex*

JVLA L-Band Survey of Andromeda



P.I.: Adam Leroy

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+ (subm); CII: Kapala, Sandstrom+ '14;
Clusters/Stars: Johnson+ '12,'15; SF History: Lewis+ '15.

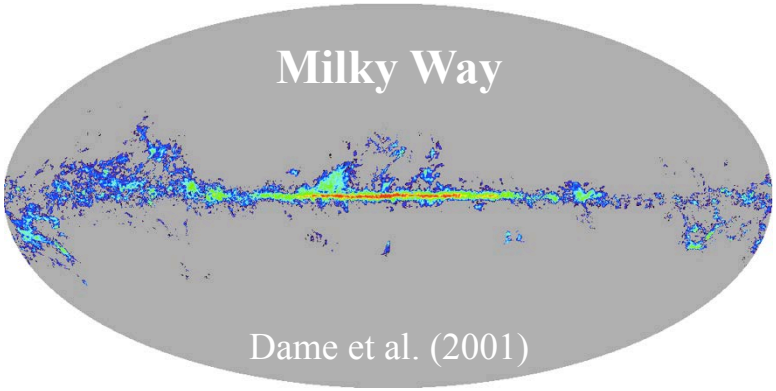
1. How do molecular clouds form? Compare HI, CO, kinematics at high resolution.

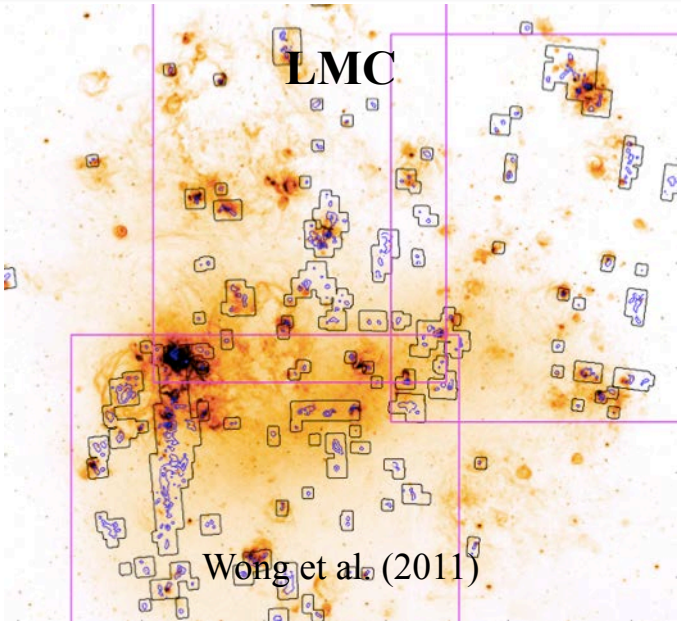
2. How to trace H_2? Overconstrain CO-to-H_2 conversion factor and DGR.

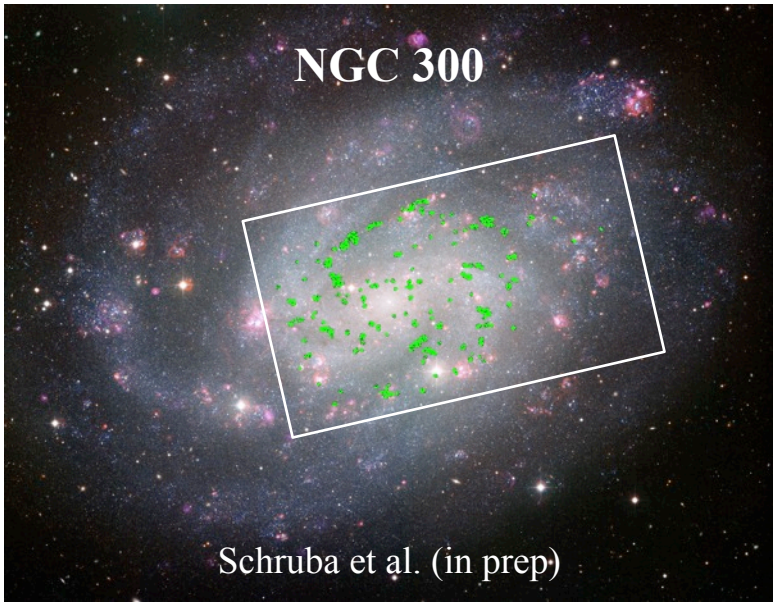
3. Multiphase cloud structure: H_2/HI but also opaque HI (*Braun '12*), A_V vs. HI and CO.

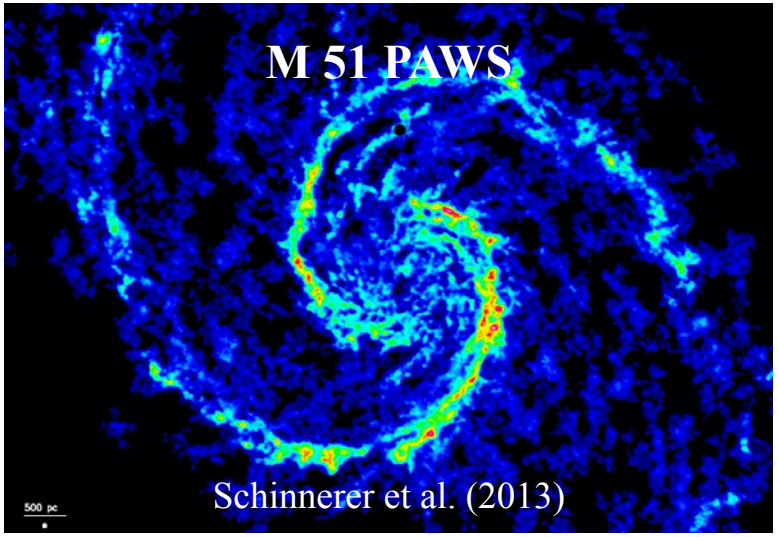
4. What are the time scales of cloud formation, star formation, and feedback?

Link to Nearby Galaxies whenever Possible

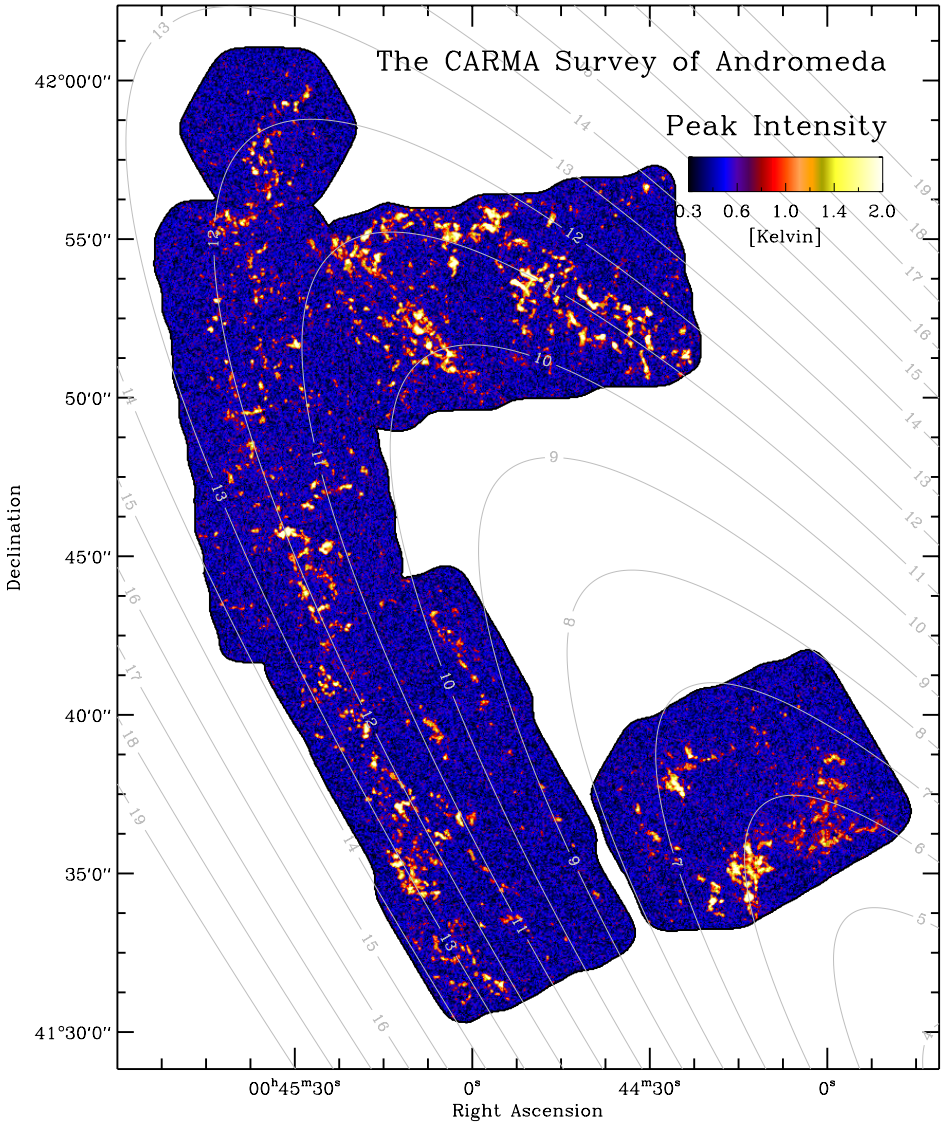








Identification of Molecular Clouds

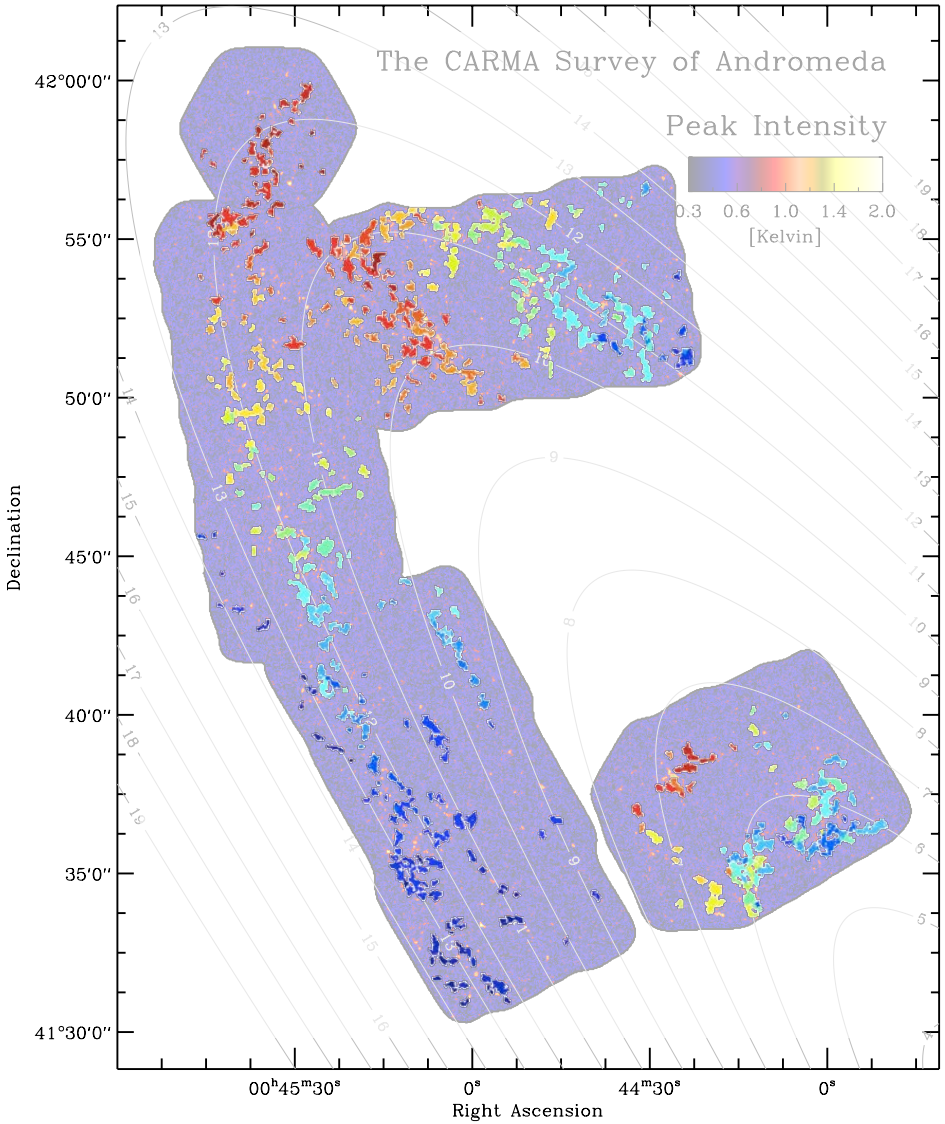


500 local maxima
identified by CPROPS package
(up from ~50 Rosolowsky+'07)

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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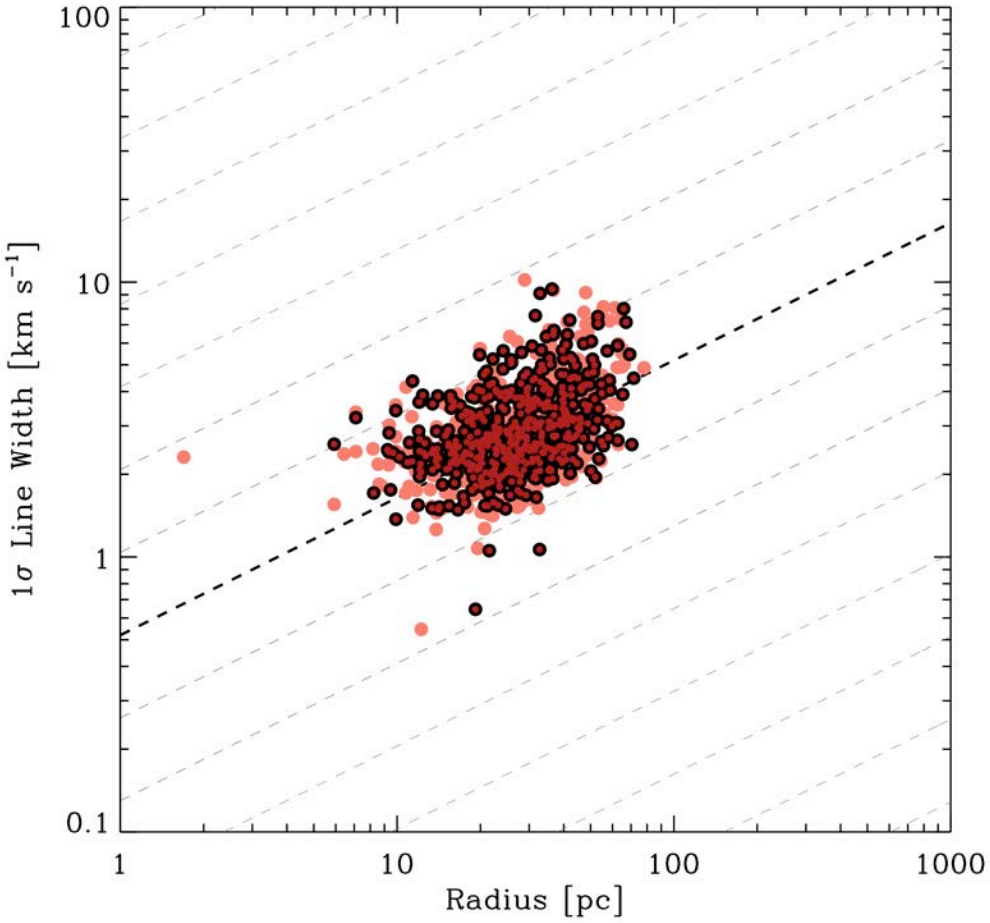
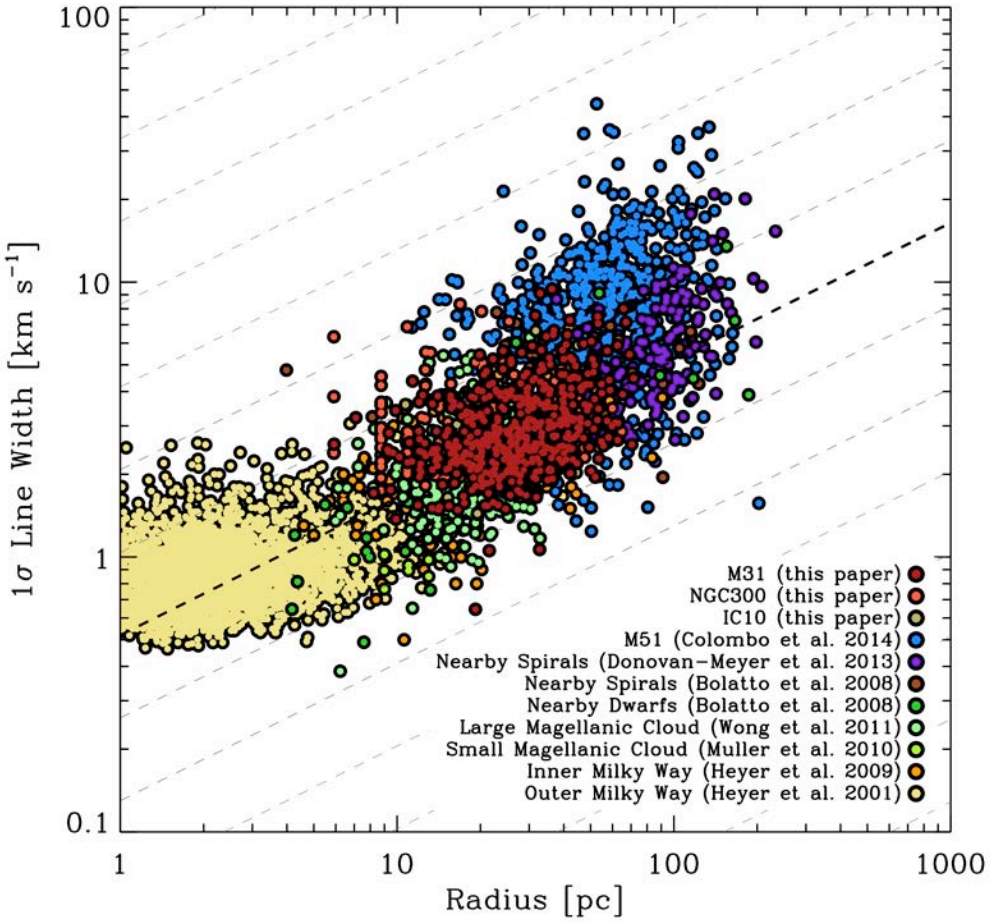
Line Width - Size Relation

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



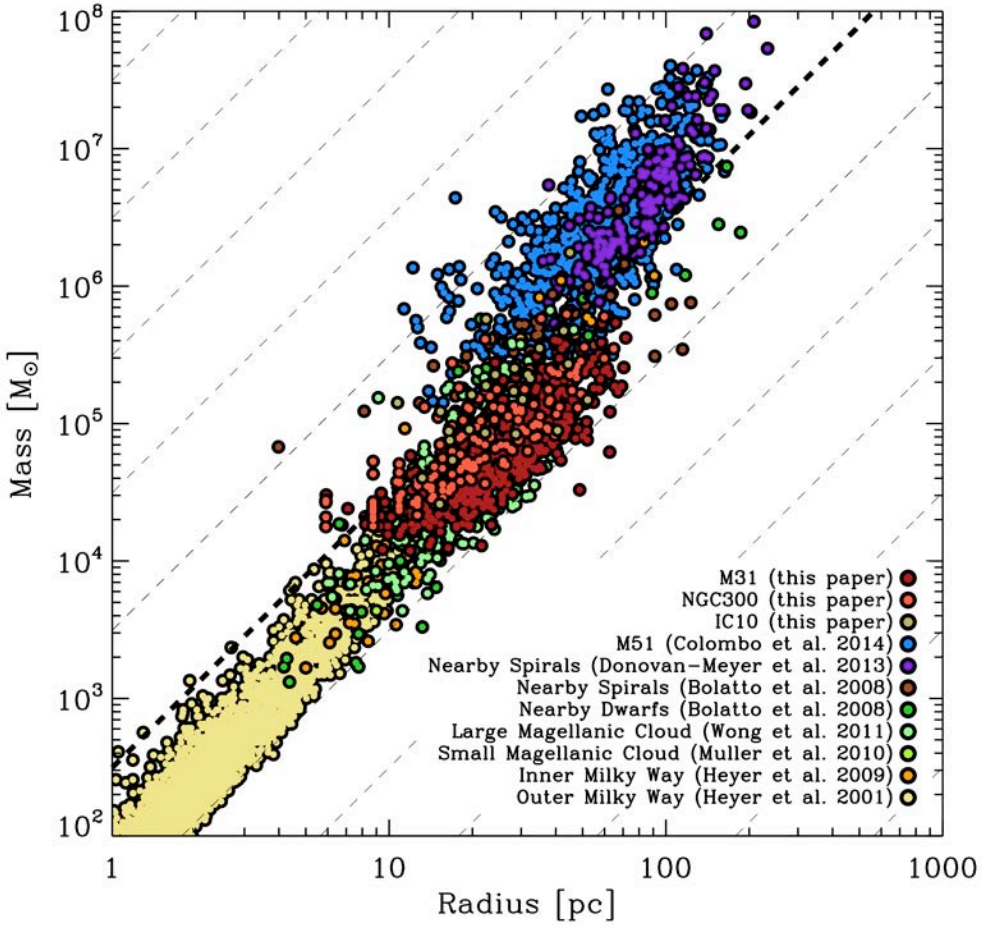
Line Width - Size Relation

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



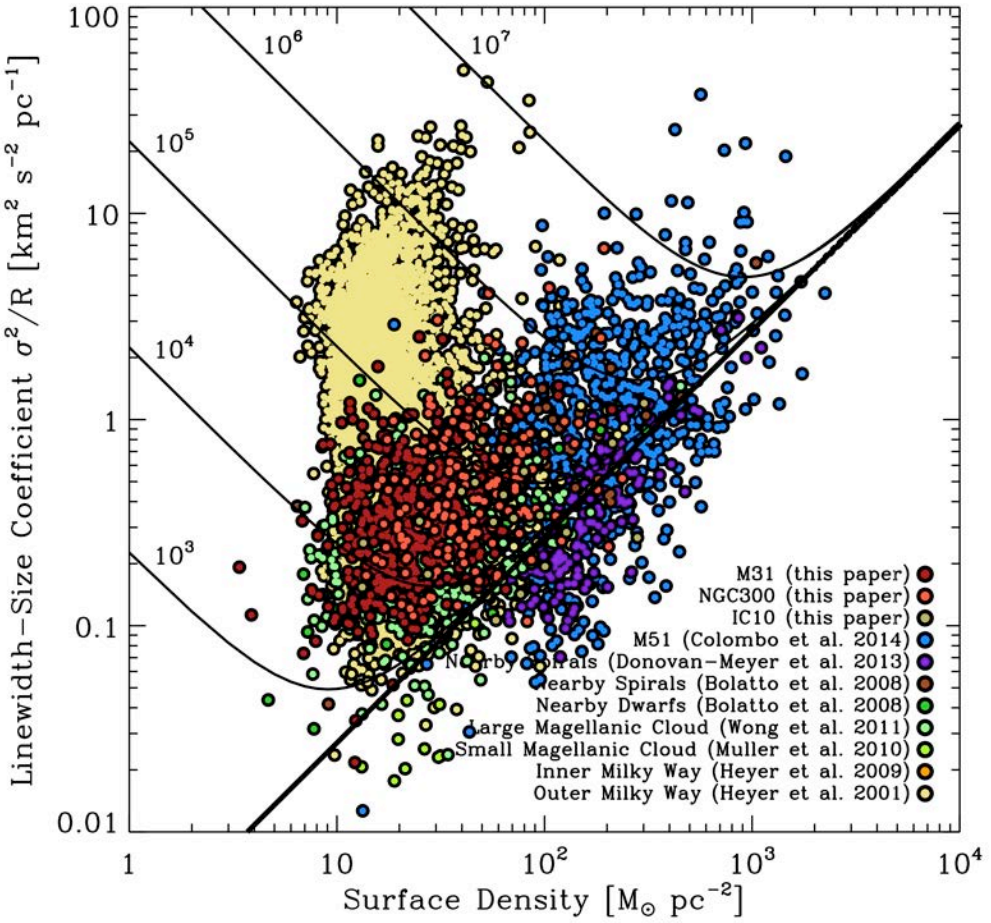
Surface Densities of Clouds

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

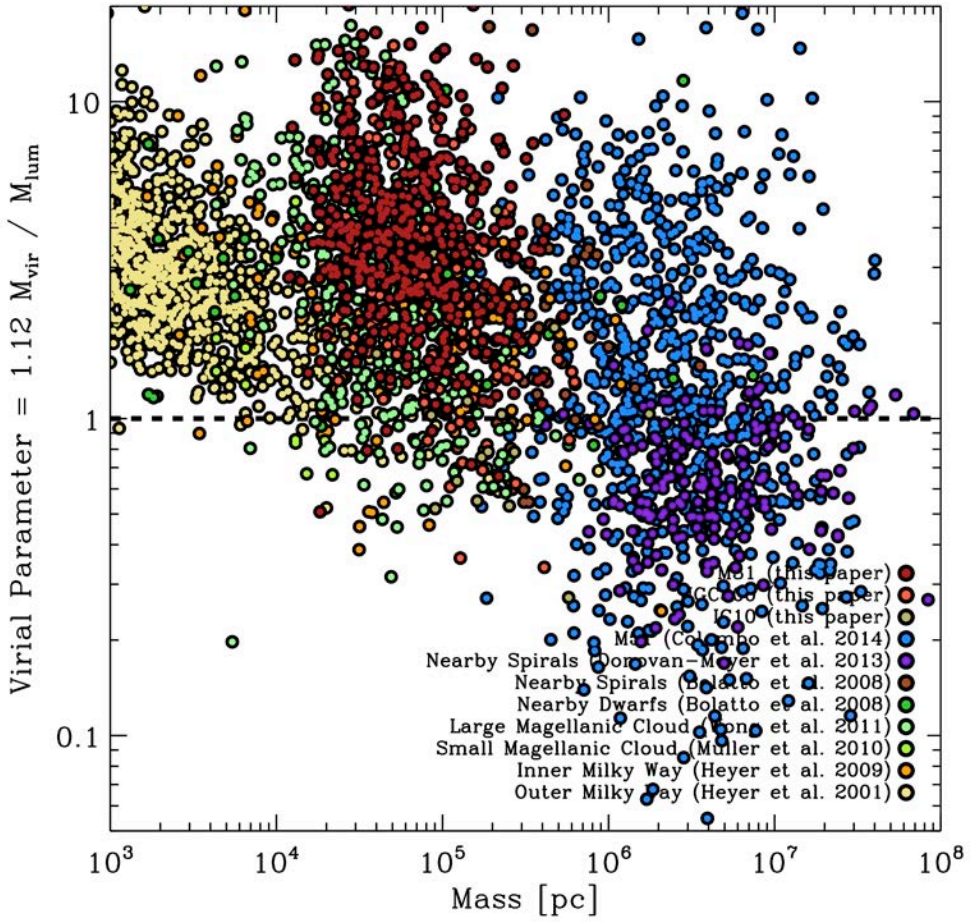
Clouds in virial equilibrium fulfill Larson relations: $\sigma^2 = (\pi G/5)\, R\, \Sigma_{GMC}$ *(diagonal line) (lower mass) clouds in MW, LMC, M33, M31, NGC300 have enhanced kinetic energy.*



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

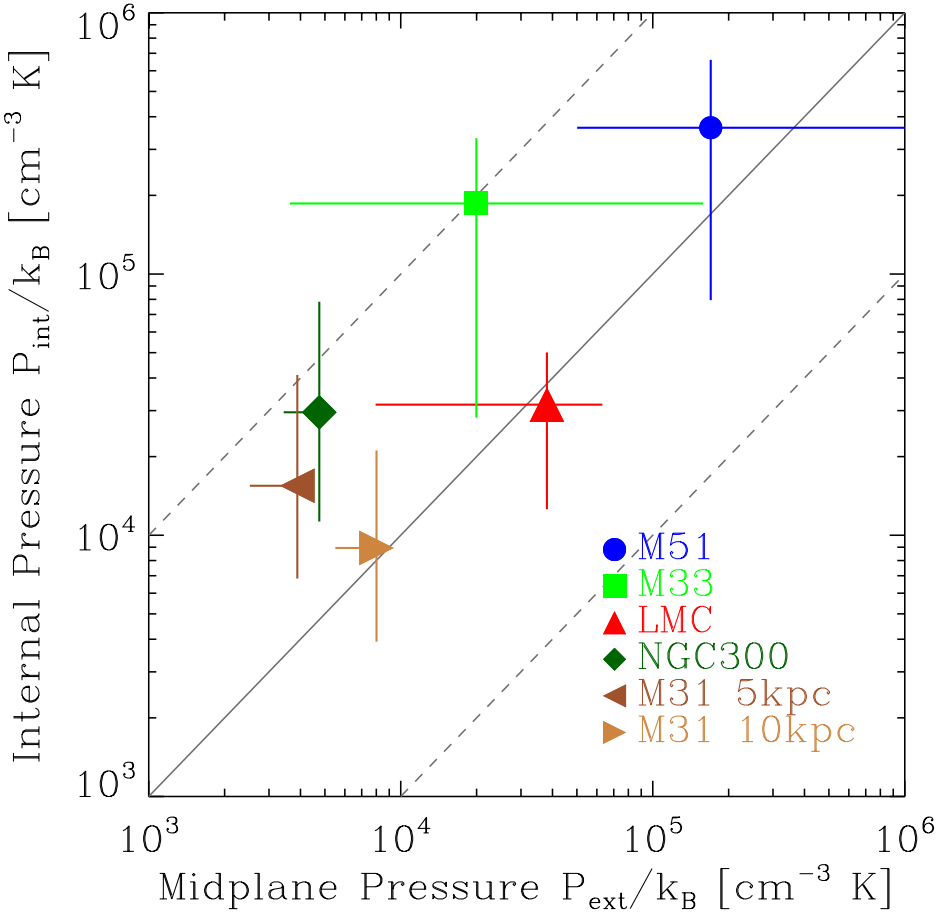
Dynamical State of Clouds

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.



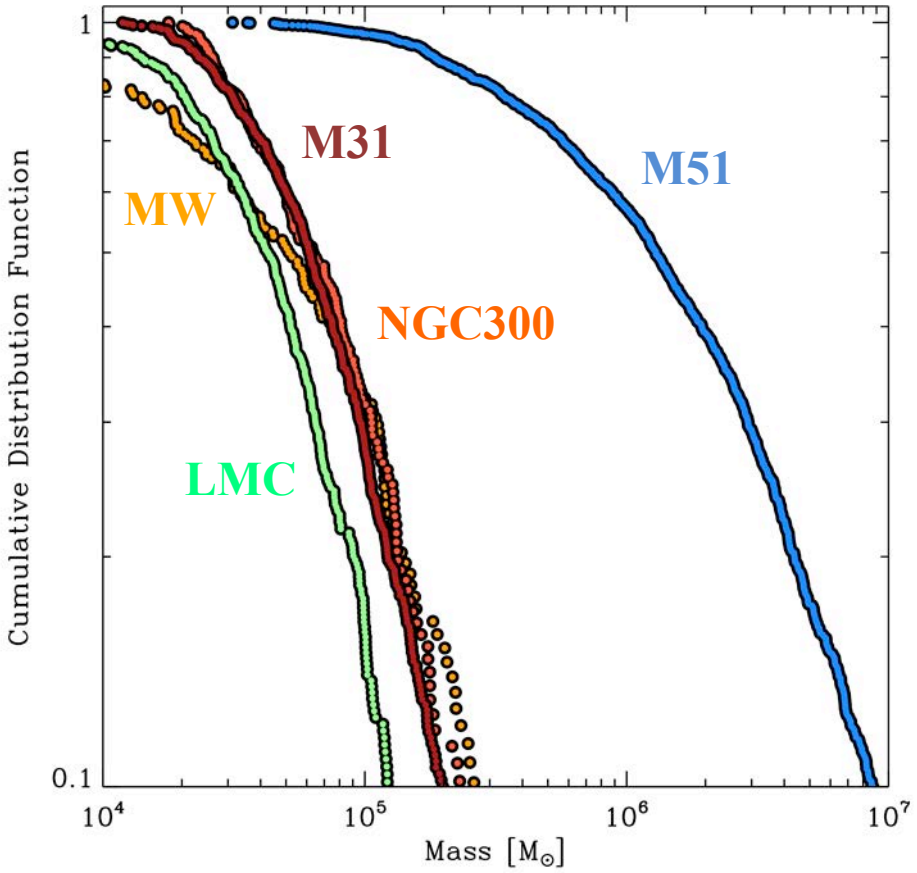
Atomic shielding layers provide 1-4x additional external pressure.

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)*

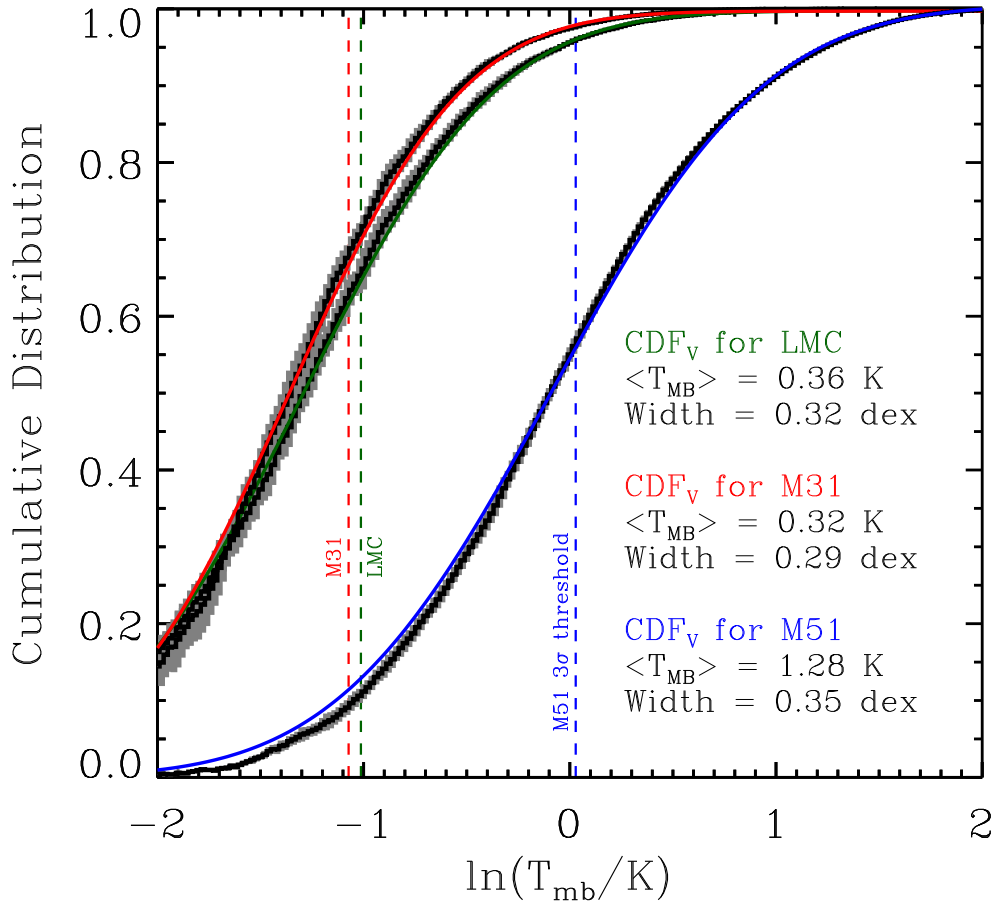
Synthesis of Cloud Properties

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

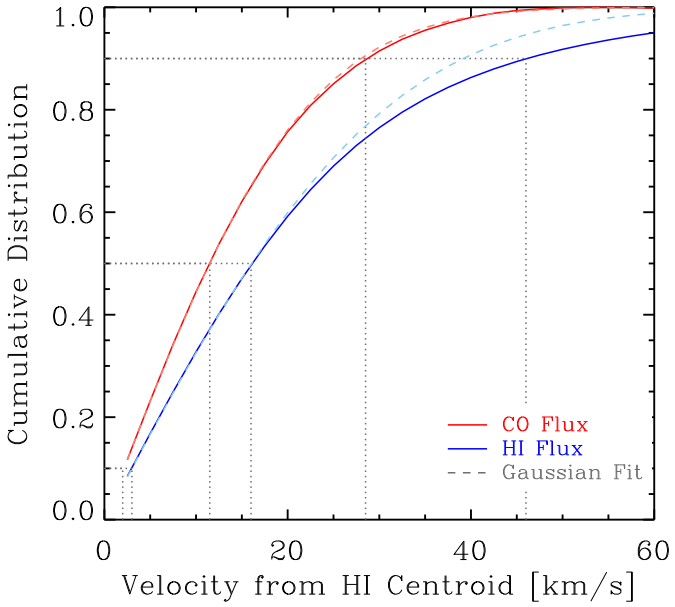


Spatial Distribution

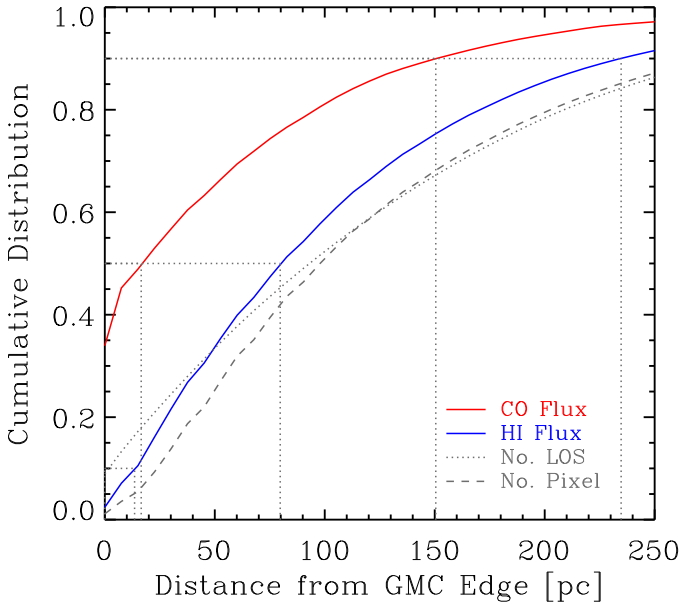
Atomic and molecular gas well mixed with (nearly) similar disk thickness

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

"Vertical Distribution" of HI and H_2



HI and H_2 profile around Clouds



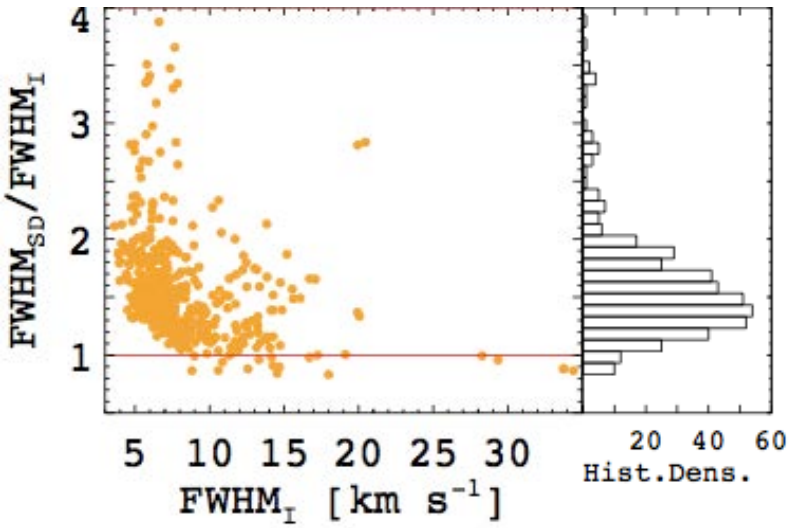
Following *Hughes et al. (2013)*, see also *Sawada, Hasegawa, Koda et al. (2012)*

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:

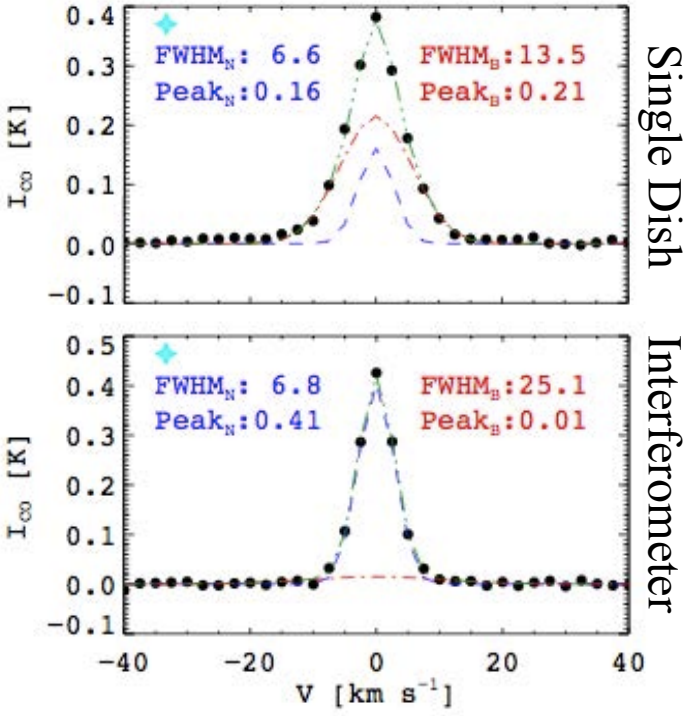
Single-dish detects 40% wider line profile.



FWHM Line Width
Single-Dish / Interferometer

(2) Fit two Gaussian profiles:

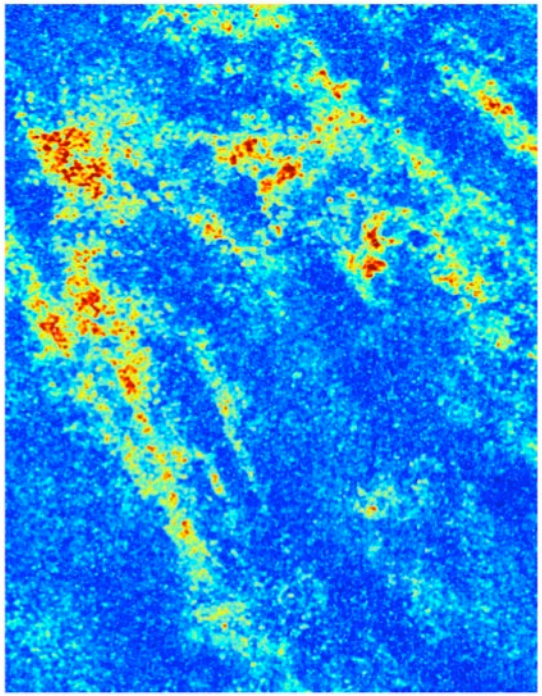
Single-dish detects broad component.

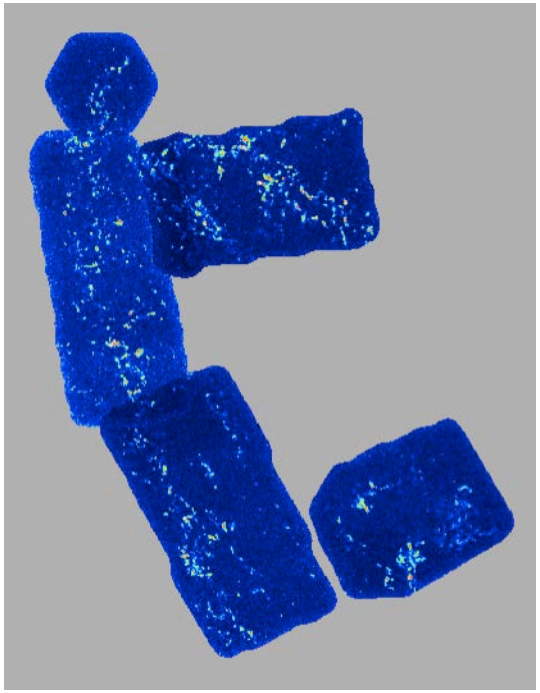


Anahi Caldu-Primo et al. (to be subm; PhD thesis)

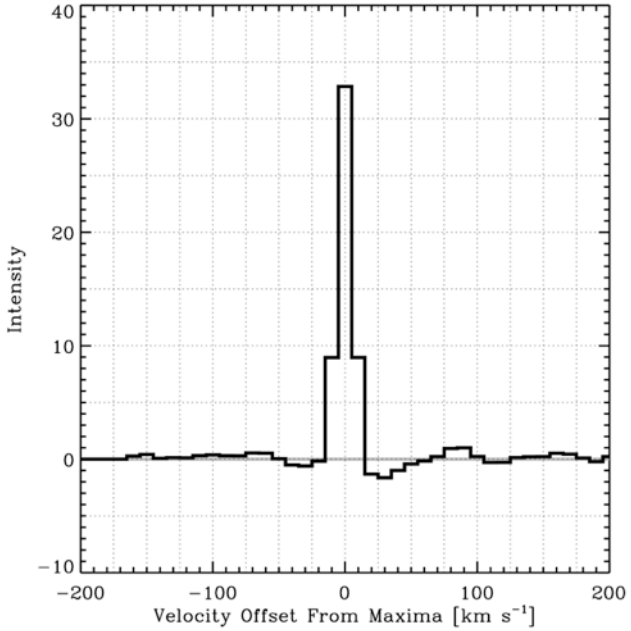
Bright HI corresponds well to CO (and A_V)

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.

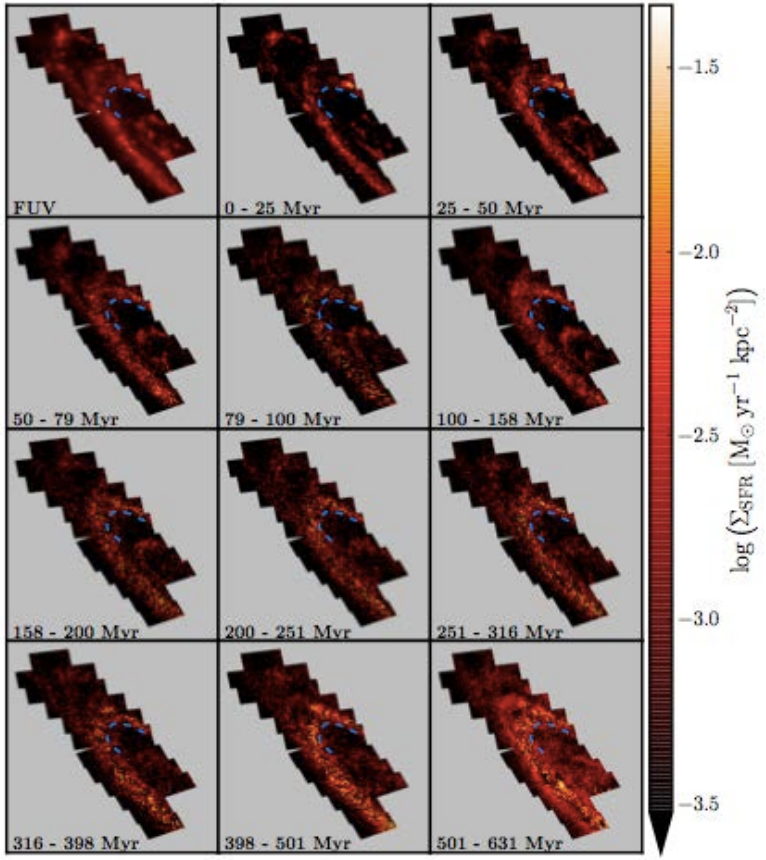


Cheoljong Lee et al. (in prep; PhD thesis)

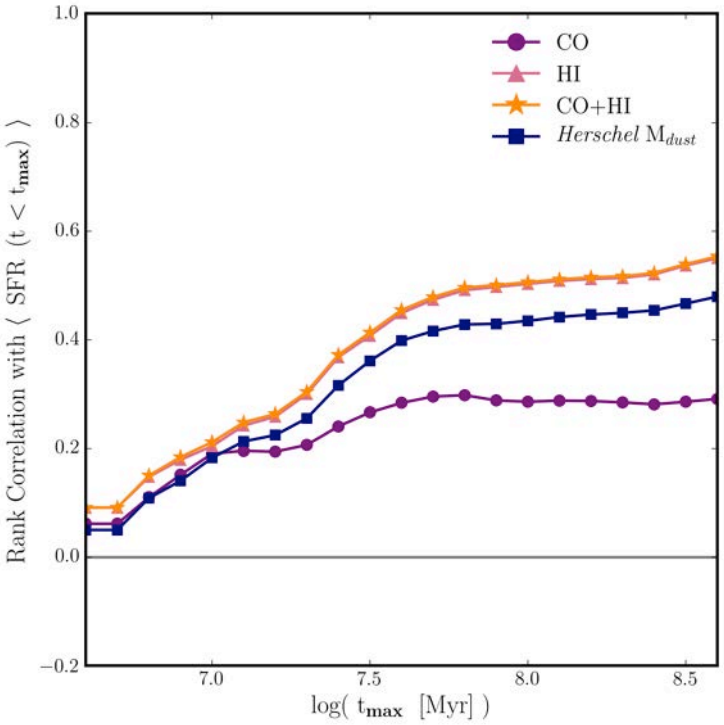
Clouds and Recent Star Formation

ISM on 100 pc-scale weakly correlated with most-recent SFH (10 Myr) on 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

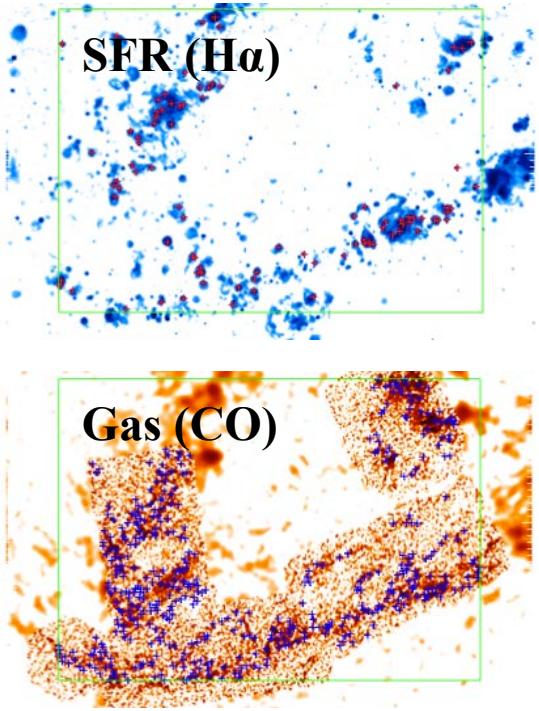


Alexia Lewis et al. (2015; in prep; PhD thesis)

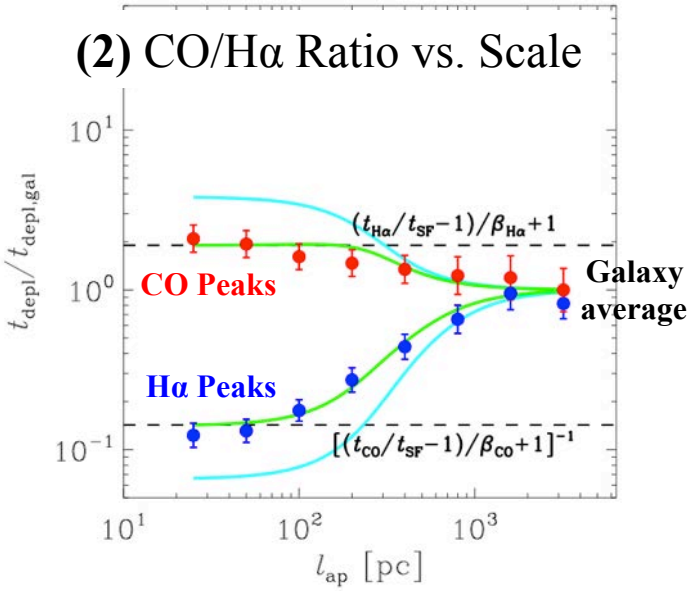
Cloud Lifetime and Duration on Star Formation

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.

(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).