

Galaxies: Near & Far with CCAT, ALMA, & EVLA (& Spitzer)

Mission Impossible



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NRAO – Charlottesville

NAASC CSV Liaison / ALMA

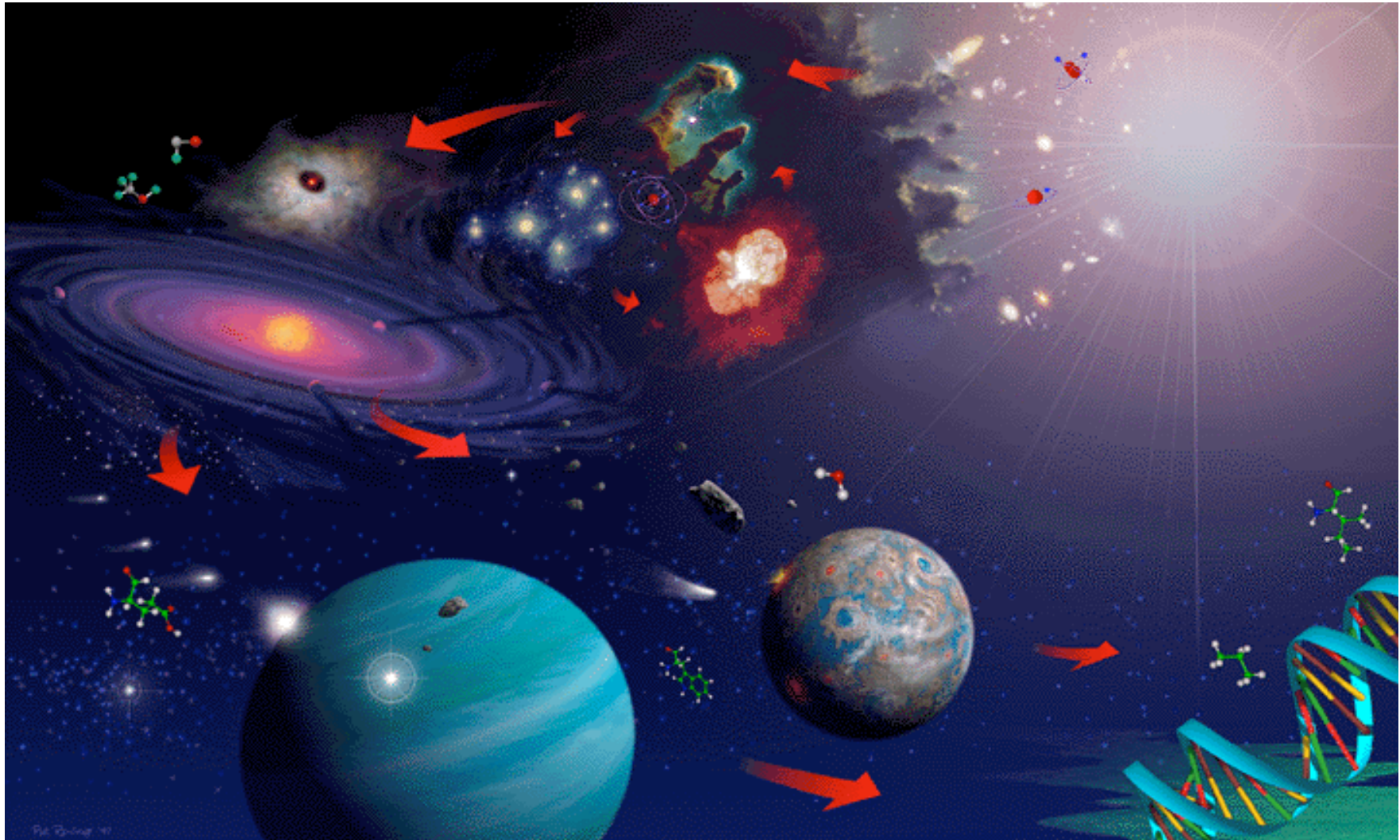
w/ thanks to Schinnerer, Koda, Leroy,
Aravena, Munoz-Mateos, Kim

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array



How do Galaxies Form?

ALMA 



Basic Questions (cm/mm/submm)

- What is the distribution of molecular gas and dust?
- What are the gas kinematics?
- How do stars form from their molecular nurseries?
- What is the relation between the ISM, star formation, AGN, feedback?

Recent Millimeter / Submm Studies

Interferometric Surveys:

- ('98-02) SONG (Regan, Helfer, Thornley, KS, Wong, Blitz, Vogel, Bock)
 - BIMA survey of CO (1—0) in 44 galaxies + NRAO 12m OTF Maps / Total Power
 - Central 3 arcminutes @ 3--6" & 10 km/s
- ('97-'99) MAIN (Scoville, Sakamoto, Baker, Joglee)
 - OVRO survey of central arcminute in 20 galaxies
- ('08-..) CARMA + Nobeyama Survey of SINGS Galaxies (Koda et al.)
 - CO (1-0) in 17 galaxies
- ('08-..) CARMA STING (Bolatto, et al. – see previous talk)
 - CO (1-0) in 27 nearby galaxies

Recent Millimeter / Submm Studies

Interferometric Surveys:

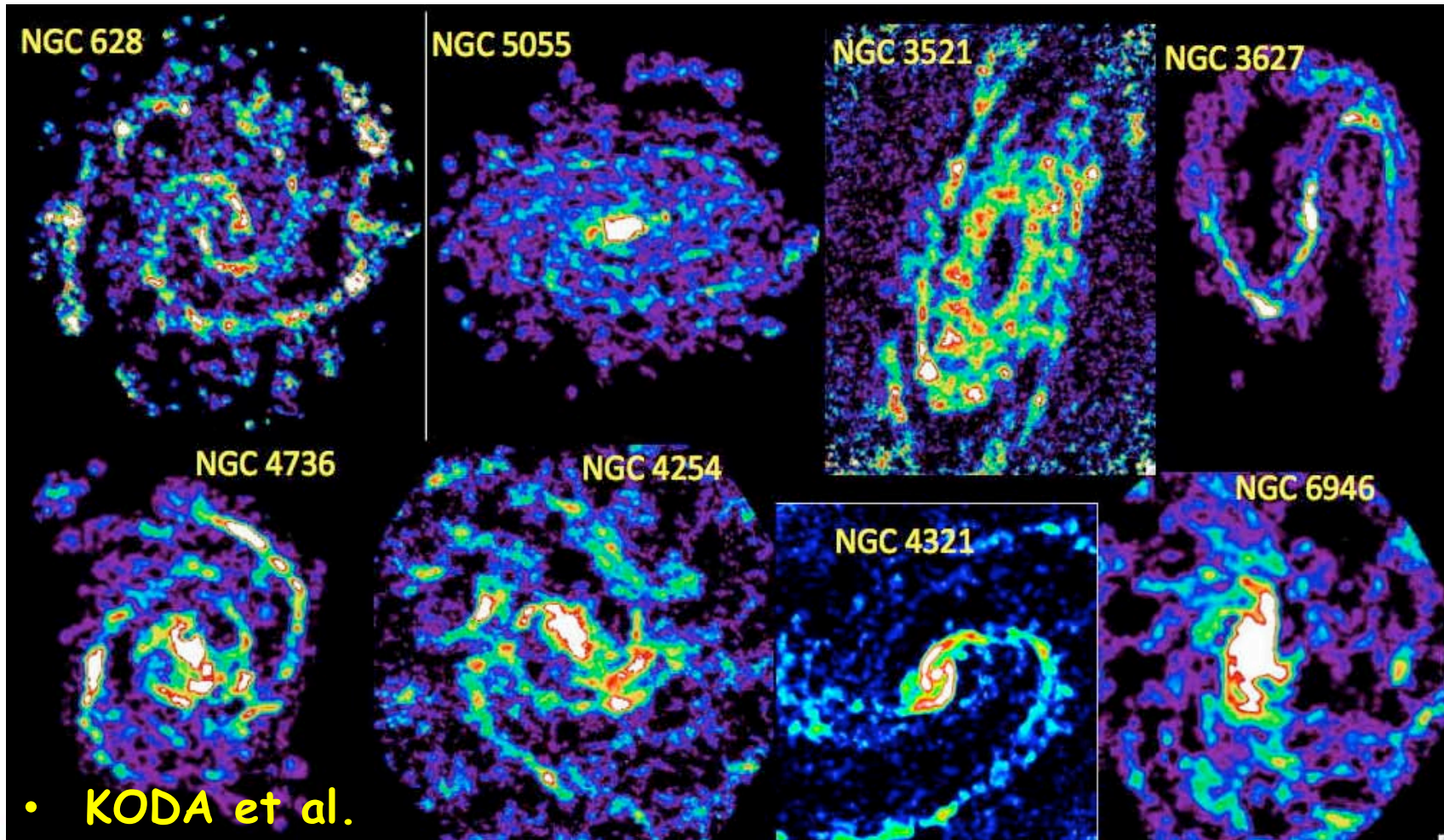
- SMA Survey of **14** LIRGs and ULIRGs (Wilson et al.)
 - ^{13}CO (2-1), CO(2-1), HCO+ (4-3), dust @ 1.3mm, 0.88mm

Single – Dish Surveys:

- ('09-..) HERACLES (Leroy, Walter, Bigiel, Usero, Sandstrom, Weiss, Brinks, de Blok, Kennicutt, Roussel, Kramer, Schuster)
 - IRAM 30m HERA survey of CO (2-1) in **18** galaxies
 - 13" resolution maps over D_{25}
- JCMT Nearby Galaxies Legacy Survey (Wilson, Israel, Sarjeant, Warren, Bendo + > 35 co-Is)
 - CO (3-2) in **~150** galaxies using HARP (12" resolution)

What have we learned so far?

Greater Variety in Molecular Gas Distribution than in Stellar Disk!



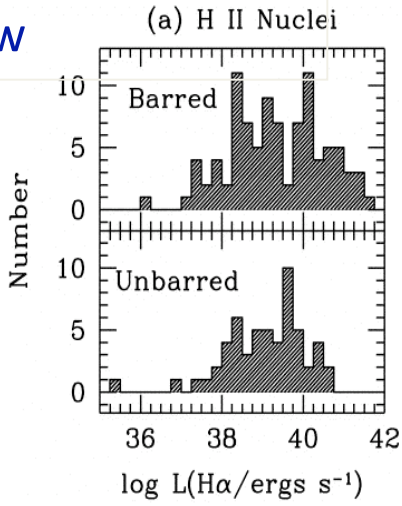
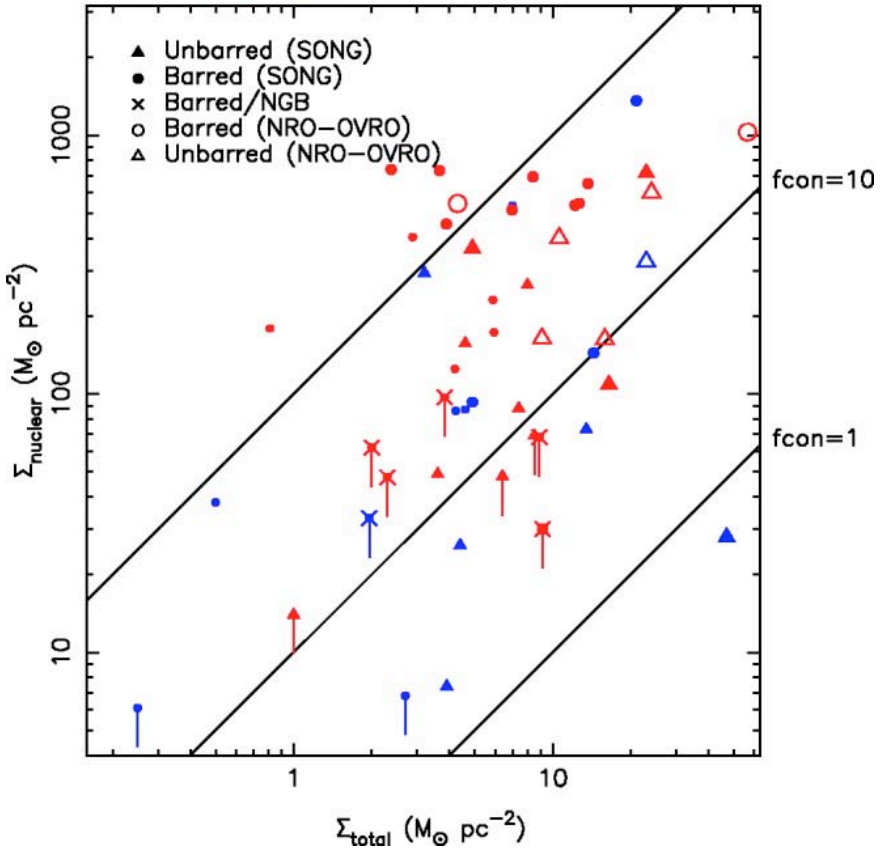
CARMA Studies are starting to push to GMC scales / cloud formation

What have we learned so far?

Bars Feeding Gas to Nuclei

- Bars have higher central concentrations of molecular gas (Sheth et al. 2005; Sakamoto et al. 1999)
- Difference pronounced in early type bars
- Late type - \boxtimes -> Early types via bar driven gas inflow

Early-type Late-type Sheth et al. (2005)



(Ho et al. 1997)

What have we learned so far?

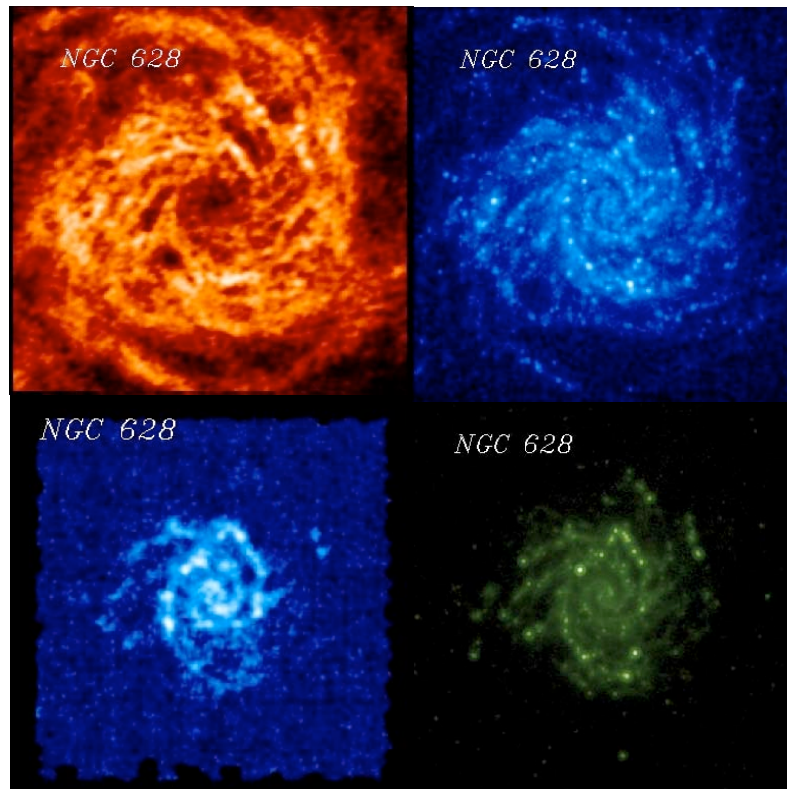


Molecular Gas and Star Formation

- Multi- λ database to understand star formation in galaxies:

THINGS

VLA Large Program
WALTER+ '08



GALEX

Nearby Galaxies Survey
GIL DE PAZ+ '07

HERACLES

IRAM Large Program
LEROY+ '09

SINGS + LVL

Spitzer Legacy Surveys
KENNICUTT+ '03, DALE+ '05



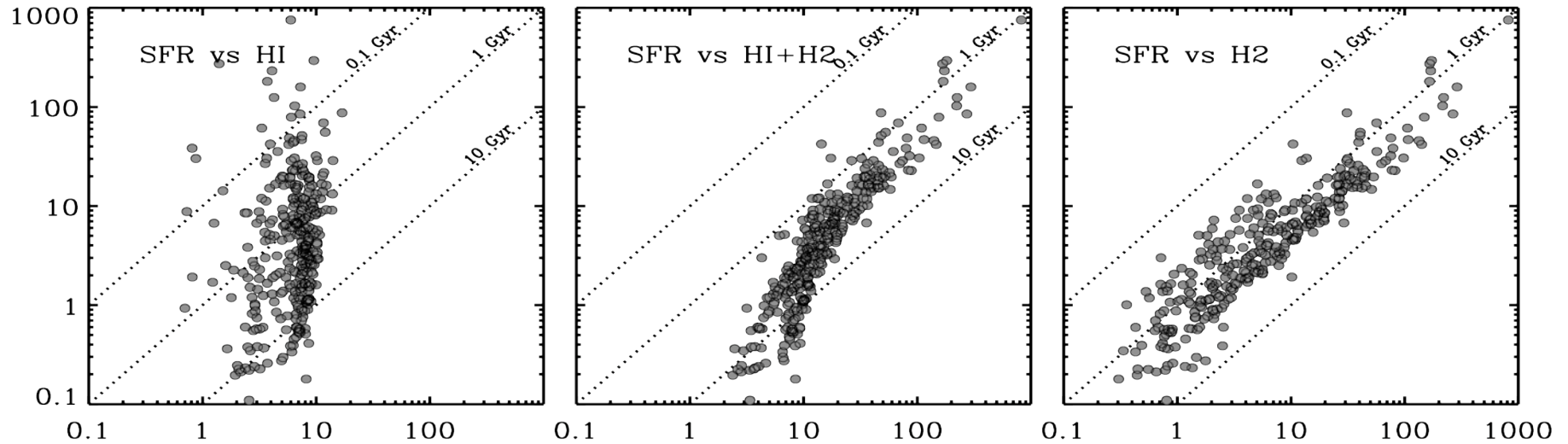
Currently: data on HI, H₂, star formation, stars,
kinematics, dust for **47** galaxies.

Courtesy A.
Leroy

What have we learned so far?

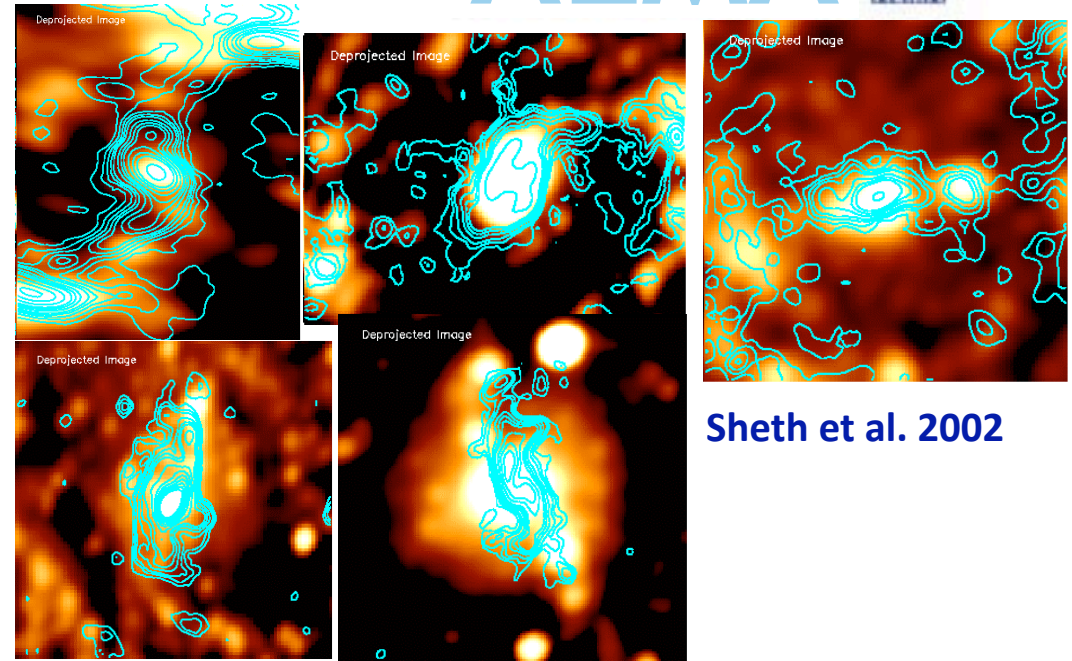
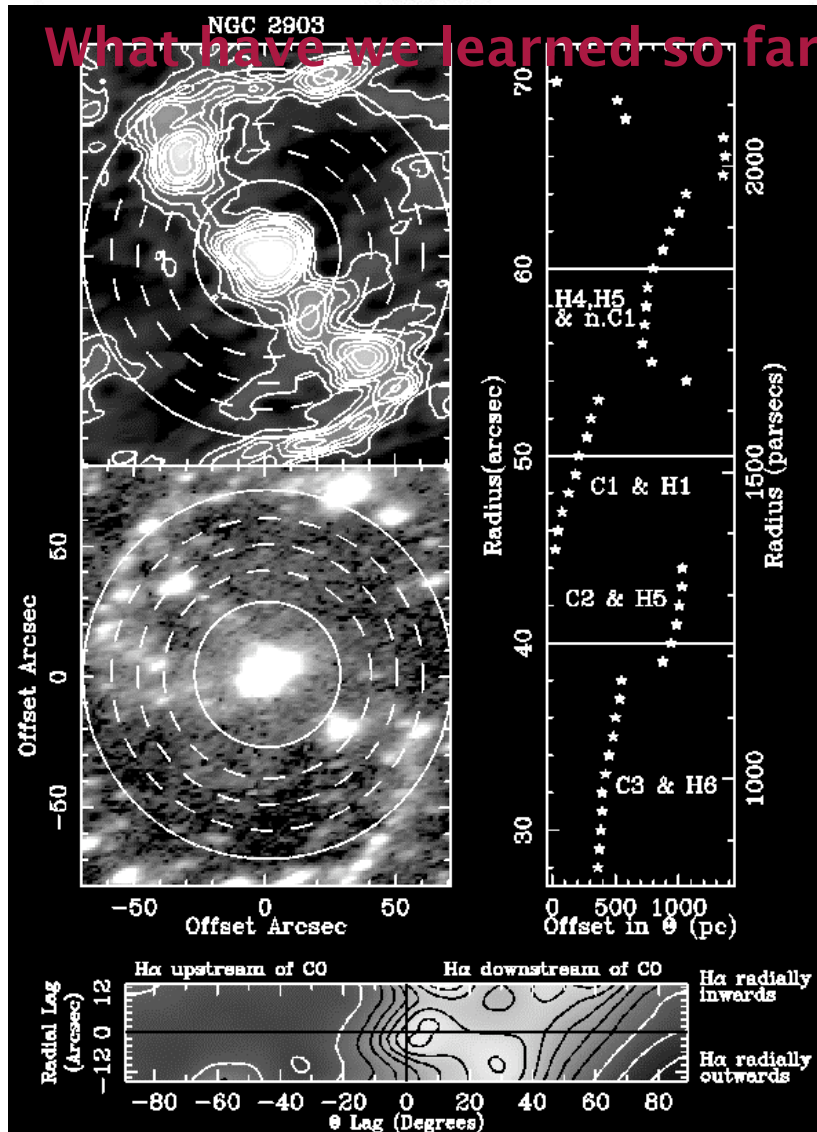
HI, H₂ and SFR Scaling

SCHRUBA+ '10



- SFR-H₂ correlation extends to where HI > H₂
- Correlation with total gas depends on regime (“threshold”).

What have we learned so far?



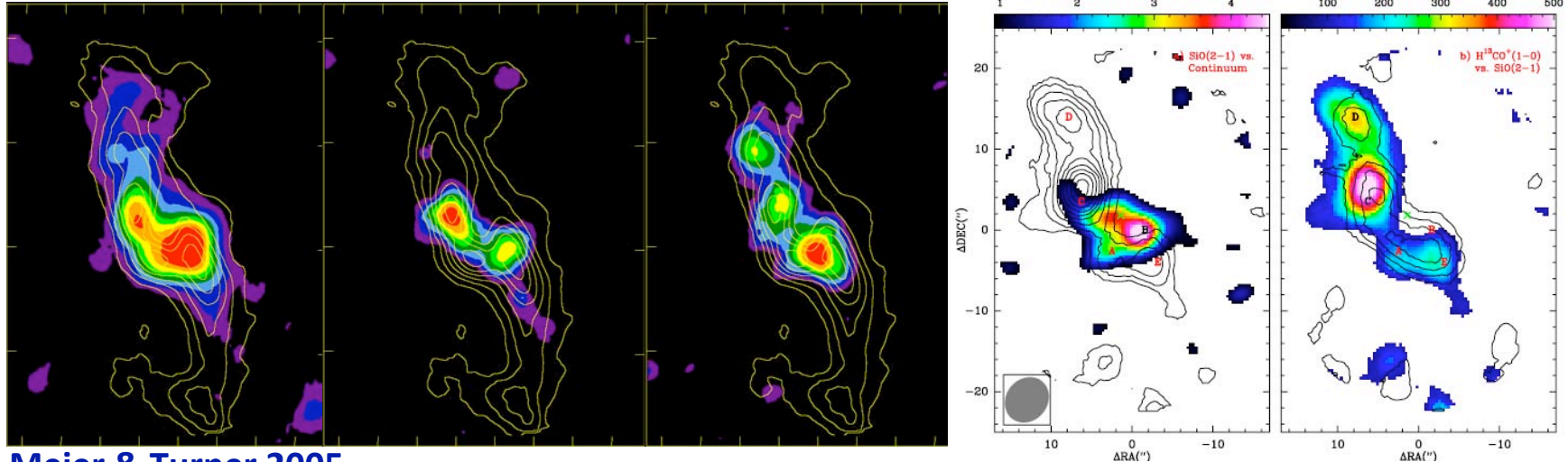
Sheth et al. 2002

- 2-phase molecular gas medium (Sheth et al. 02)
 - H α offset towards the leading side
 - Kinematics consistent w/ hydrodynamic model
 - Variations in the $^{12}\text{CO}/^{13}\text{CO}$ line ratios
 - Molecular clouds on leading side

Gas Chemistry

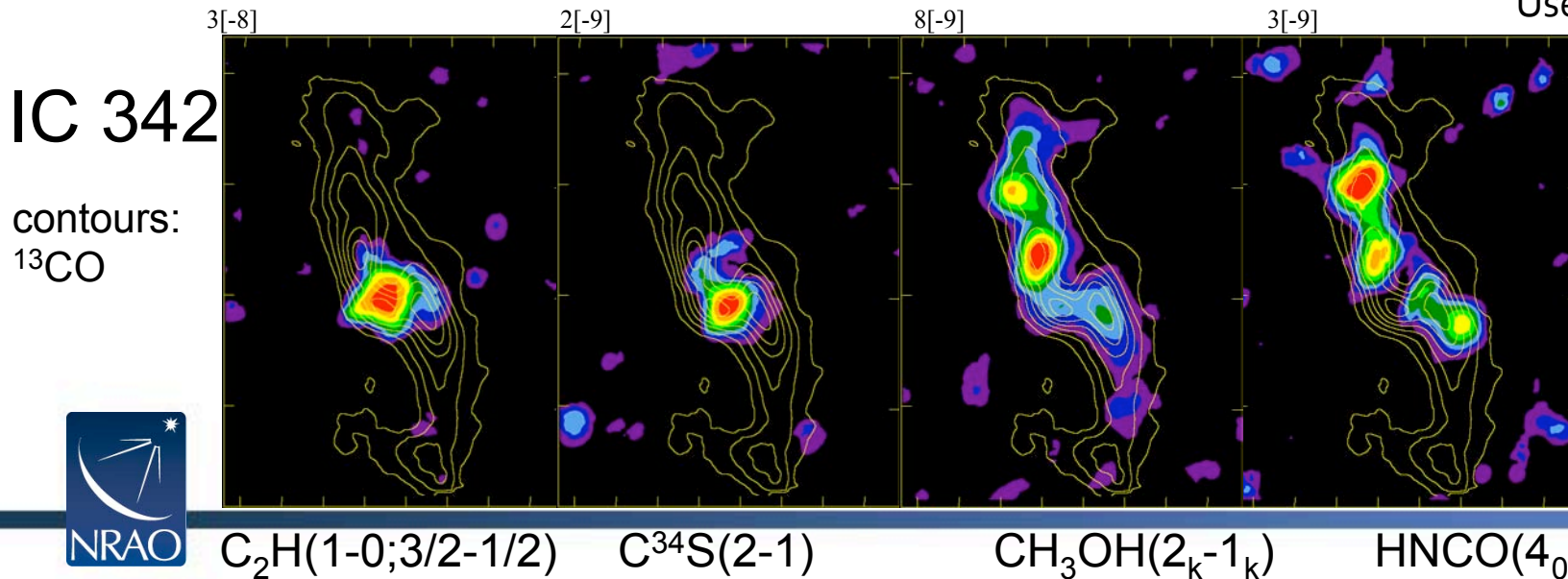


HNC(1-0) $>2[-9]$ HC₃N(10-9) 2[-9] N₂H⁺(1-0) 5[-10] SiO (2-1) H¹³CO⁺ (1-0)



Meier & Turner 2005

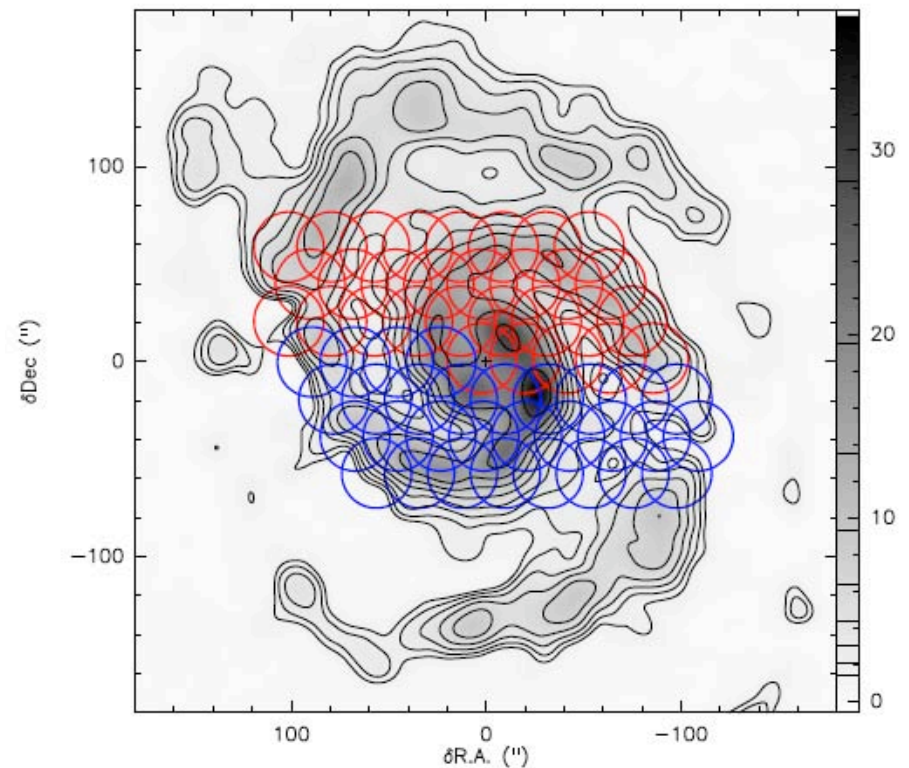
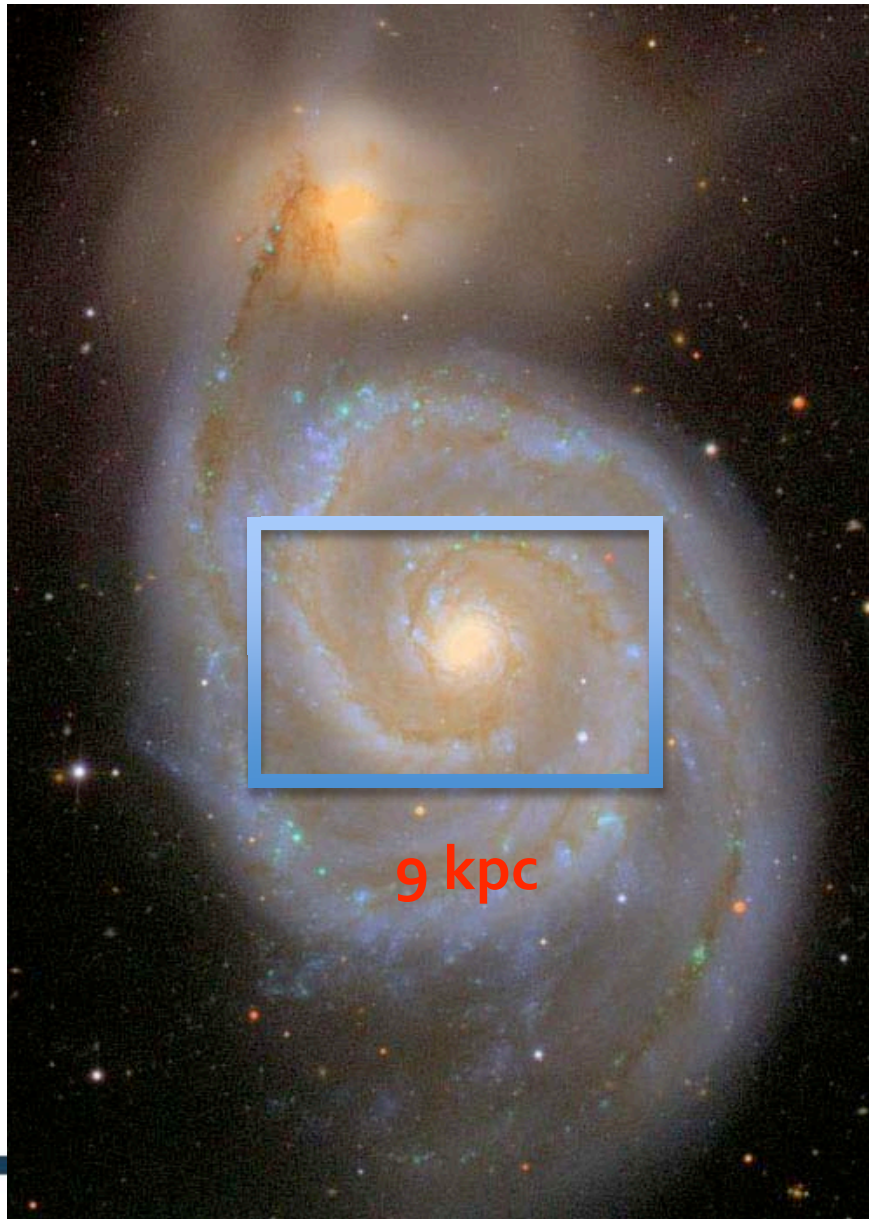
Usero et al. 2006



PAWS – PdBI Arcsecond Whirlpool Survey



PI Schinnerer,
data acquisitions finished
in June 2010

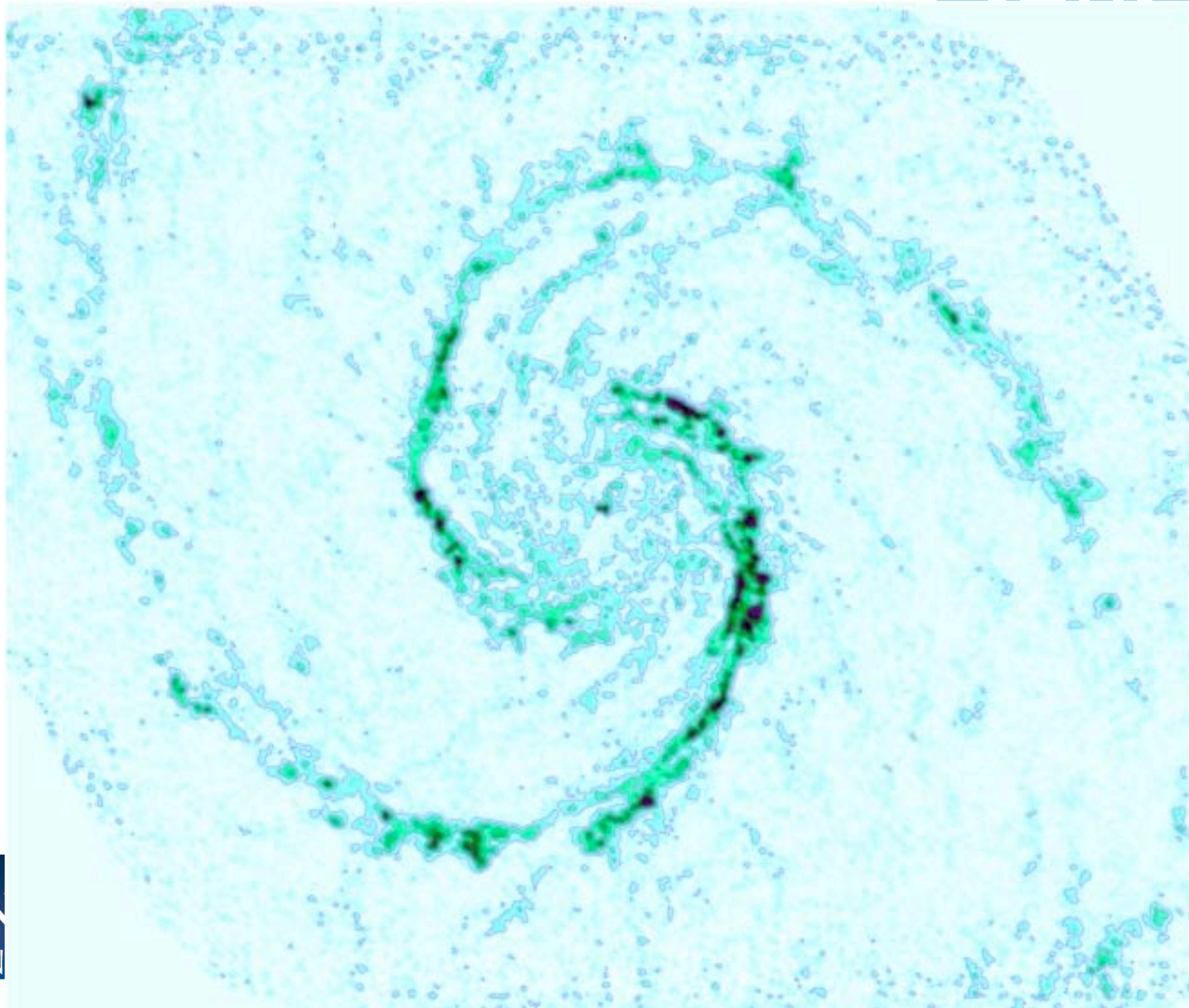


$5\sigma = 1 \text{ GMC}$

$1.2 \times 10^5 M_{\text{sun}}$ at 45 pc resolution

PAWS – $^{12}\text{CO}(1-0)$ map

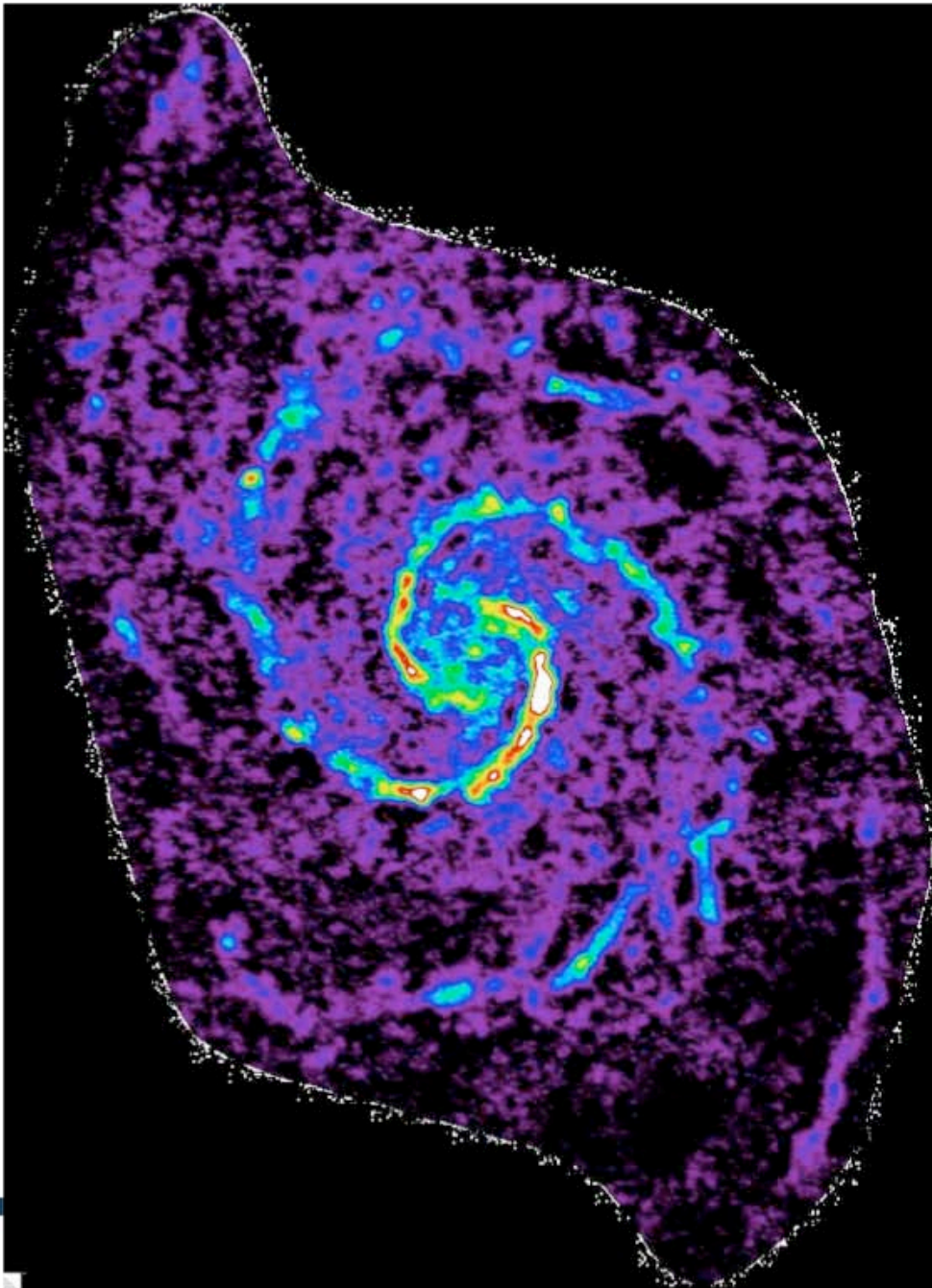
ALMA



CO(I-0)
Nobeyama
+CARMA map

PI: Jin Koda,
Jennifer Donovan Meyer, Fumi
Egusa, Rieko Momose,
Masayuki Fukuhara, Misty La
Vigne

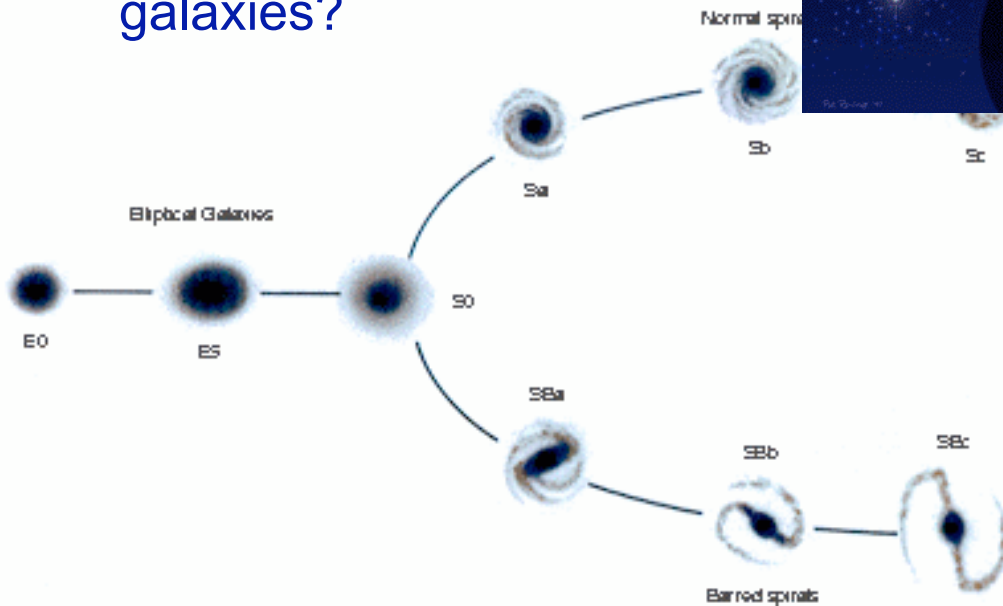
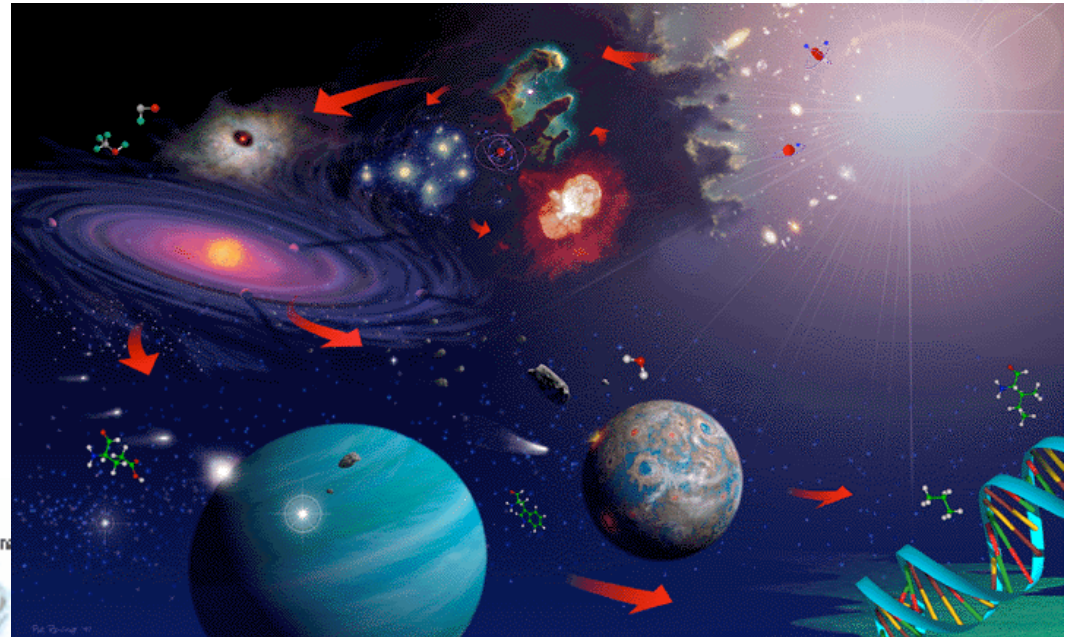
- A Rosetta Stone but we
need more Rosetta Stones!



How do Galaxies Form?

CCAT, ALMA, EVLA – gas and dust & star formation

- What about the stellar endoskeleton and evolutionary history of galaxies?



Nearby Galaxies at other wavelengths!



The Spitzer Survey of Stellar Structure in Galaxies (S⁴G)

29 original co-Is (now > 45 members)



Sheth et al. 2010

Representative sample of spiral, elliptical and dwarf galaxies
Galaxies with

$$v_{\text{rad}} < 3000 \text{ km/s (d < 40 Mpc)}$$

$$m_{\text{B}} < 15.5,$$

$$D_{25} > 1.0'$$

$$|b| > 30^\circ$$

2,331 galaxies (1,733 new targets) @ 3.6 μm and 4.5 μm

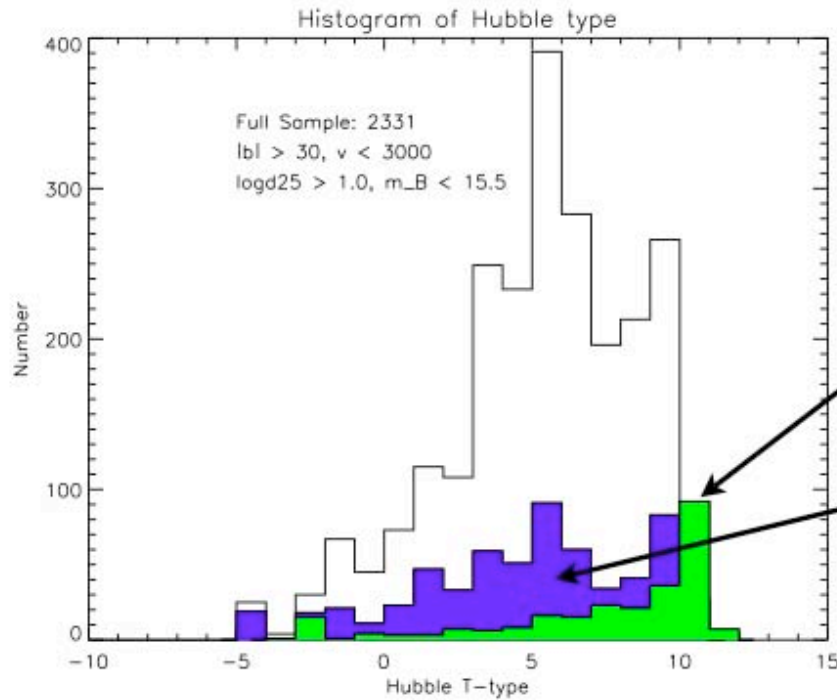
Mosaicked or mapped to 1.5 x D_{25} w/ 240s per pixel ->

Image all galaxies to $\Sigma_* \ll 1 M_\odot \text{ pc}^{-2}\text{m}$

637.2 hrs (1/2 of the data are taken so far)

Create the ultimate survey of the distribution of stellar structures, their masses and properties in the nearby Universe.





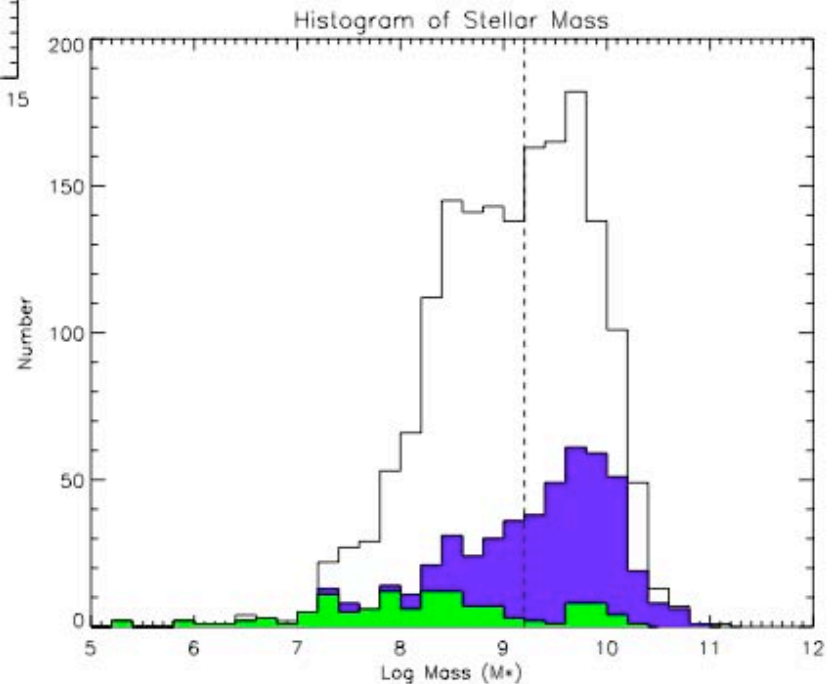
Local Galaxy Volume (3 Mpc) survey (258 galaxies)

SINGS + GO + GTO (339 galaxies)

★ S⁴G is needed to explore the full mass and T-type space.

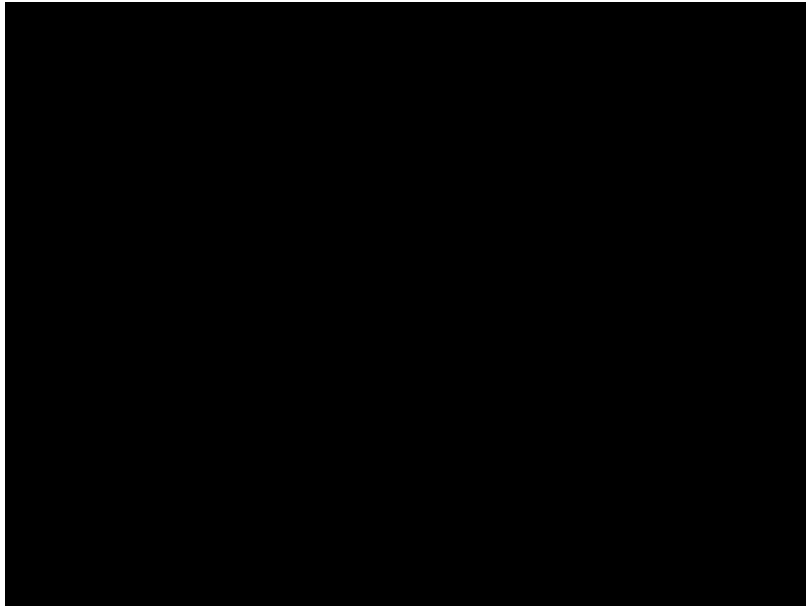


Sheth et al. 2010





Science Goals for the S⁴G Legacy Survey



Sheth et al. 2010; Buta et al. 2010

- Formation of disks, bulges, bars, rings
- Outer disk structures, debris, tidal tails,
- Thick vs. thin disks (over 800 edge-on disks)
- Detailed structure of bulges
- **Structural properties of each component**
- **A mass and structure inventory of the Local Universe (~ 2014)!**
- Old disks in dwarfs (87 DDOs)
- Merger history / evolution history
- Tully-Fisher & FP in the MIR

We need an equally large & homogenous database with CCAT, ALMA, EVLA!

CCAT Wish List: (~2x 1000 hr proposals):

CCAT ~ 7x resolution of Herschel, 3–4 times more sensitive?

- ~1000 galaxies fully imaged (to $> 1.5 D_{25}$) at all submm bands on scales of ~ 100 pc
 - Dust distribution across a galaxy
 - Outer disks & cold dust, gas/dust distribution, heating and cooling budget of the ISM
 - Dust / submm emission and stellar structure (Benson talk)

- **CCAT (SW-CAM)** will ideal for this
 - 1 hr /galaxy? (all but 200 μm band)

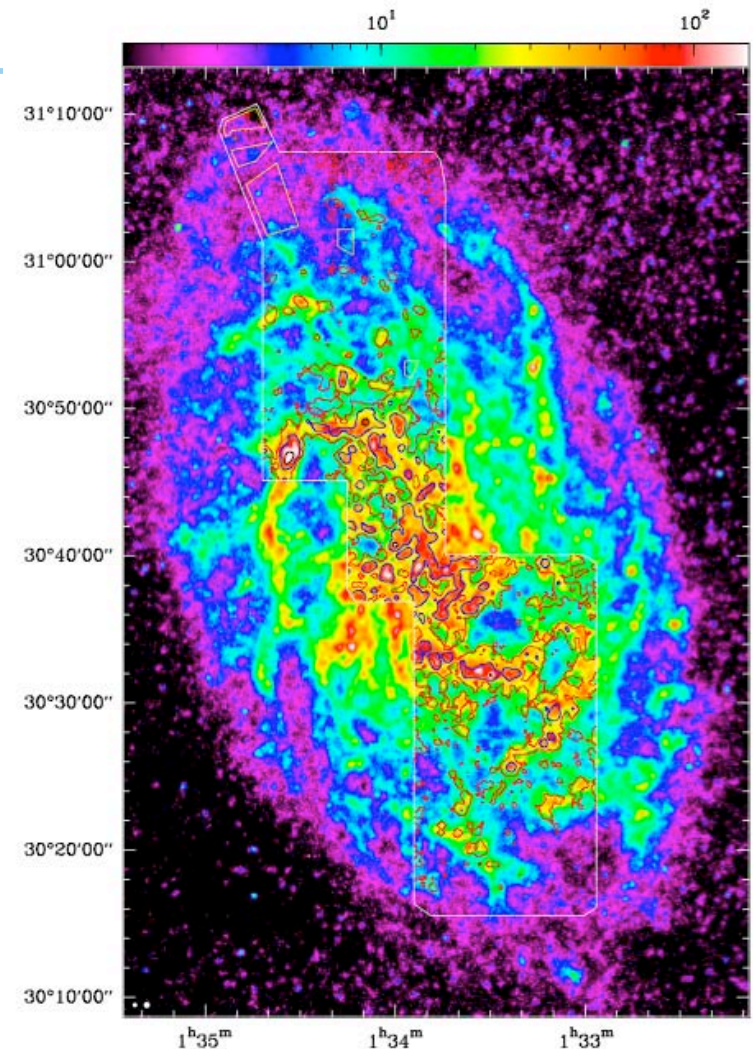
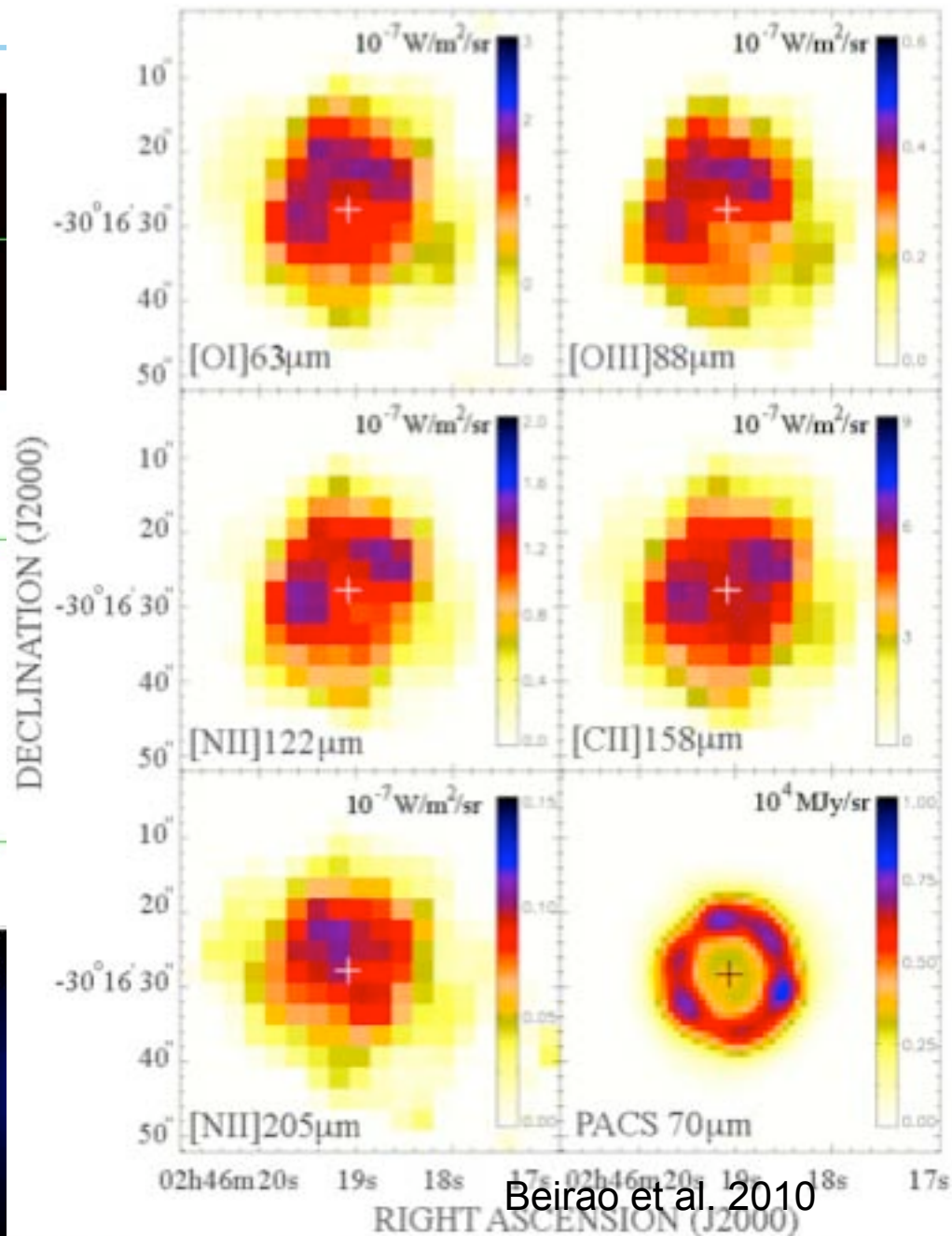
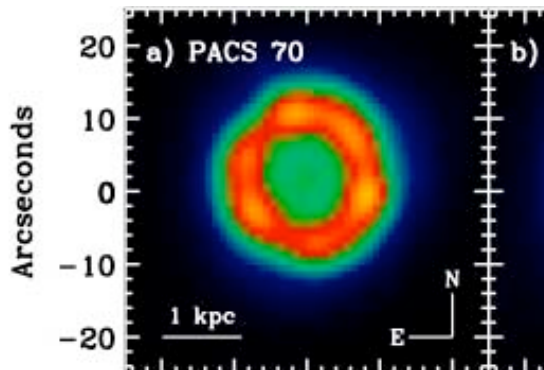


Fig. 3. SPIRE 250 μm emission with the IRAM CO(2–1) emission at 25'' resolution superposed as contours and with the polygons to the up-

CCAT Wish List: (~2x 1000 hr proposals):

- ~ few 100 galaxies in submm line emission @ high resolution (e.g., CII, NII, high-J CO lines)
 - Gas distribution / excitation / kinematics / chemistry as a function of galaxy host properties!
- Need long-slit, array or FP to resolve and map galaxies (MOS – Jonas overview)

Sandstrom et al. 2010



Beirao et al. 2010
Fig. 2. Spectral maps of the lines observed with PACS at the nuclear



EVLA / SKA Pre-Cursors Wish List (Super THINGS):

- EVLA already in Early Science mode!
- Several thousand hour proposals with EVLA and MeerKAT could get us ~500-1000 galaxies
 - **MeerKAT MHONGOOSE (30 galaxies ultra-deep with 5000 hrs)**
 - MeerKAT first light in 2015
 - THINGS ~500 hrs for 34 galaxies in HI / Little THINGS ~ 400 hrs for 20
 - LVHIS, WALLABY, THINGS, Little THINGS, ANGST, FIGGS, WHISP
- Line emission surveys of molecules with EVLA
 - Radio recombination lines H92a, H230a

ALMA Wish List

(KS, Koda, Regan, Schinnerer, Egusa, others welcome...):

- **Early Science** (CfP ~ scheduled for Dec / likely first quarter of 2011)
 - UV coverage will be limited, mosaicking unlikely
 - Cannot do a large survey of nearby galaxies nor complete disks of galaxies.
- **Full Science** possible to do thousands of galaxies but time required may be prohibitively large (> 1 hr per galaxy)!

Some possible topics we are considering:

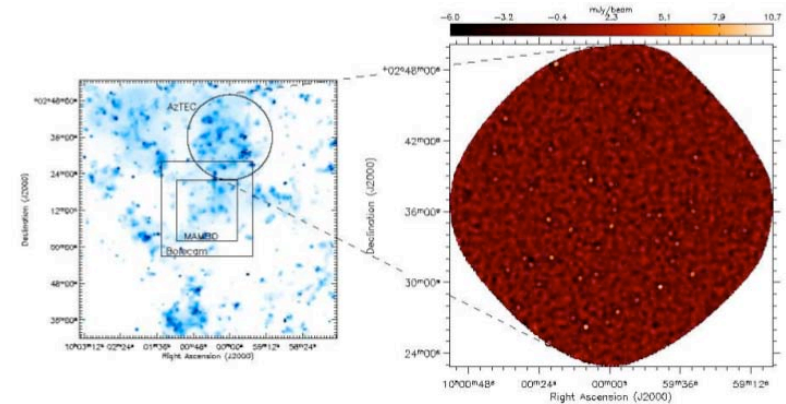
- Centers vs. Disks / GMC population across all environment
- X-factor changes / quantitative analysis
- Star formation / gas efficiency / triggering and inhibition
- Resolved CO ladder -> feedback



Gas kinematics – bars, spiral arms, bulges, AGN feeding

High-z Galaxies

CCAT will be an ideal machine for high-redshift surveys which can then be followed up with ALMA & EVLA!



COSMOS ES Survey example:

- 0.7" / Band 7 (0.8mm) of individual sources in the COSMOS field
 - Early Science ~ 50 sources in 2.6 hrs at 10 sigma ($1\sigma = 0.5$ mJy)

- 2.5" / Band 3 (3mm) blind redshift survey of typical SMGs
 - Early Science ~ 50 minutes per galaxy / FS (~ 10 minutes)
 - CCAT line identification with wideband spectrometers an ideal complement

Take-Home Points (Nearby Galaxies)

- No more than a few 100 galaxies in HI, CO, atomic & molecular lines, dust exist!
- While thousands of galaxy images exist in broad optical bands
 - Only a few hundred avail in UV, Ha, NIR, Fabry-perot or IFUs
 - Homogenous data at these wavelengths now becoming available

Summary

- Time will be ripe for an ambitious CCAT Survey of nearby galaxies
 - Good synergy with on-going large programs + possible large programs in the future (S4G, MeerKAT, ASKAP, EVLA, MEGARA, TYPHOON)
 - ALMA – ideal for detailed study of clouds / gas kinematics in selected objects.
- Please see the NAASC ALMA POSTER
- NAASC / NRAO - ALMA personnel here: Sheth, Corder, Kimball, Mangum, Kent, Wiklind, Hardy, Pilleaux, Donoso
- Watch for NRAO e-NEWS / AAS special session + splinter session
- **ALMA COMMUNITY DAYS announcement – organize & Invite us! 😊**



- Current status: 8 antennae on the high site observing!
- Already the most powerful mm-interferometer in the world!
- Call for proposals for Early Science likely in the first quarter of 2011

The Atacama Large Millimeter Array (ALMA) Quick Reference



Bands:	3	4	5	6	7	8	9	10
Frequency (GHz)	84-116	125-163	163-211	211-275	275-373	385-500	602-720	787-950
Wavelength (mm)	3.57-2.59	2.40-1.84	1.84-1.42	1.42-1.09	1.09-0.80	0.78-0.60	0.50-0.42	0.38-0.32

	Early Science	ALMA Inauguration
Antennas	≥ 16 x 12m	≥ 50 (12m & 7m)
Bands	≥ 3 bands (Bands 3,6,7,9 likely)	Bands 3,6,7,9 (+ 4,8 & 10 on some)
Maximum Bandwidth	16 GHz (2 polarizations × 8 GHz)	
Correlator Configurations	≥ 5	0.01 - 40 km/sec, 71 configurations
Maximum Angular Resolution	0.02" $\left(\frac{\lambda}{1 \text{ mm}} \right) \left(\frac{10 \text{ km}}{\text{max baseline}} \right)$	
Maximum Baseline	At least 250m (may reach 1km)	15.3 km
Continuum Sensitivity (60 sec, Bands 3–9)	~0.2 — 4.2 mJy	~0.05 — 1 mJy
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3–9)	~30 — 250 mJy	~ 7 — 62 mJy

Sensitivity Calculator: <http://science.nrao.edu/alma/tools.shtml>



The North American ALMA Science Center (NAASC)

- Your one-stop shop for all your ALMA needs!
- <http://science.nrao.edu/Alma>
- ALMA Primer
- ALMA Observing Tool
- CASA Simulator
- The Helpdesk



The screenshot shows the NRAO website interface. At the top, the NRAO logo and tagline "Enabling forefront research into the Universe at radio wavelengths" are visible. A navigation menu includes "Home", "About NRAO", "Science", "Research Facilities", "Observing", and "Opportunities". The "Research Facilities" menu is expanded to show "ALMA/NAASC", "EVLA", "GB", "VLBA", and "NTC". The main content area is titled "ALMA: An Overview" and features a photograph of the ALMA observatory site with several large radio dishes. To the right of the main content, there are sections for "Events" and "Latest News".

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ALMA/NAASC EVLA GB VLBA NTC

Research Facilities > ALMA/NAASC > About ALMA/NAASC

About ALMA

- Early Science
- HelpDesk
- Proposal Preparation (Phase I)
- Observing Preparation (Phase II)
- Post-Observation: Data Processing
- Schedules
- Software & Tools
- Data Archive
- Financial Support
- Scientific Visitor Info
- People
- Publications
- ALMA Project Status, News, and Multimedia

ALMA: An Overview



Image credit: ALMA (ESO / NAOJ / NRAO) photo by Nick Whyborn, 3 June 2010.

The Atacama Large Millimeter Array (ALMA) is composed of at least 66 high-precision antennae, and is located on the Chajnantor plain of the Chilean Andes. The ALMA site offers the exceptionally dry and clear sky required to operate at millimeter and submillimeter wavelength. The quality of the observing site, combined with the unprecedented combination of sensitivity, angular resolution, spectral resolution and image fidelity made possible with ALMA, will enable astronomers to carry out transformational research in a wide variety of astronomical areas. The wavelengths covered by ALMA range from 0.3 mm to 3.6 mm (frequency coverage of 84 GHz to 950 GHz) - this range is essential for probing the first stars and galaxies, directly imaging the disks in which planets are formed, and probing the energy output from active supermassive black holes in extremely luminous starburst galaxies. The specific **level one science goals** are:

- The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of $z = 3$, in less than 24 hours of observation.

Events

- Call for Expression of Interest in the Scientific Use of the ALMA Vertex Prototype Antenna Deadline**
Jul 1, 2010 | 5:00 PM
- NRAO Proposal Deadline**
Oct 1, 2010 | 5:00 PM
- ALMA: Extending the Limits of Astrophysical Spectroscopy**
Jan 15 - 17, 2011
Victoria, British Columbia

Latest News

- Download the presentations from the "Preparing for ALMA" Special Session at the May 2010 AAS meeting
- ALMA Attains Phase Closure
- ALMA Construction Update
- New Astrochemistry Center

ALMA ES Preparation Events

- Jan AAS Meeting (Seattle, WA):
 - ALMA Special Session (Tuesday)
 - ALMA Splinter Session Tutorial (Wednesday)
 - NRAO Booth – Hands-on demos
- Jan 14-18, Astrophysical Spectroscopy –Workshop + Tutorial (Victoria, CA)
- Feb, Apr (& May*?) 1—2 day in-house tutorials in Charlottesville
- Mar 11 (tentative) - 1-day tutorial in Santa Fe following New Horizons
- Jun AAS Meeting Splinter Session (Boston, MA)

- **ALMA Community Day – Community-sponsored event supported by NAASC Staff members.**