Extragalactic Science with ALMA

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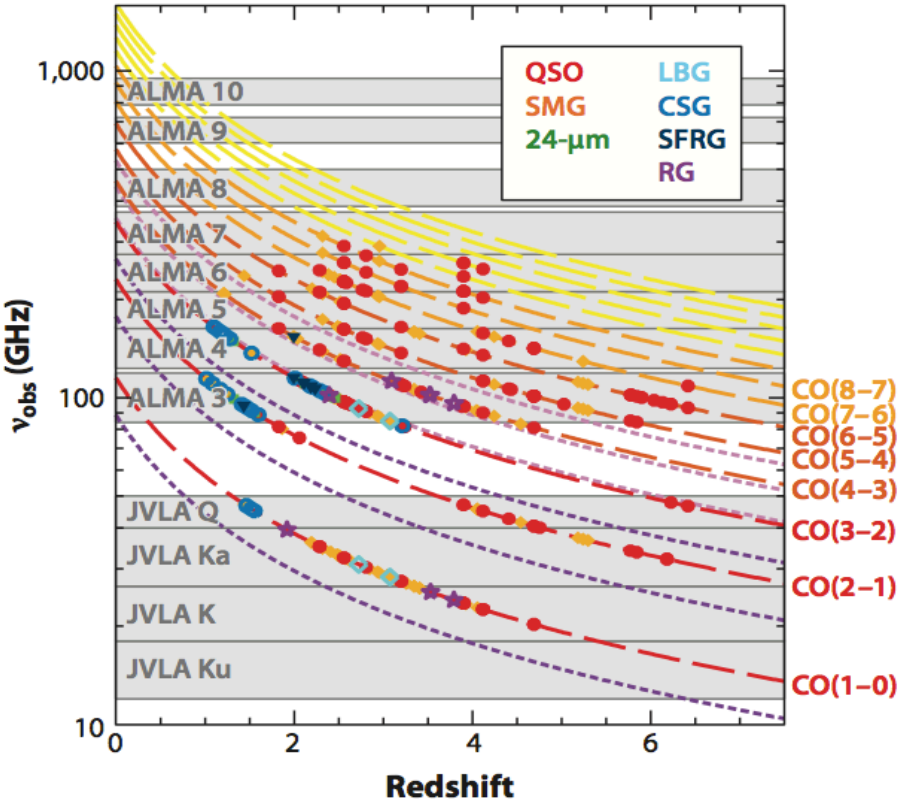
Cosmology and the high z universe

- Galaxies across the history of the universe ➛ star formation rate history
- Sub-Millimeter Galaxies ➛ gravitational lensing and mm/submm extragalactic background light
- Dusty starburst galaxies ➛ redshifts determined
- Searching for the first galaxies ➛ galaxy formation

Cosmology and the high z universe

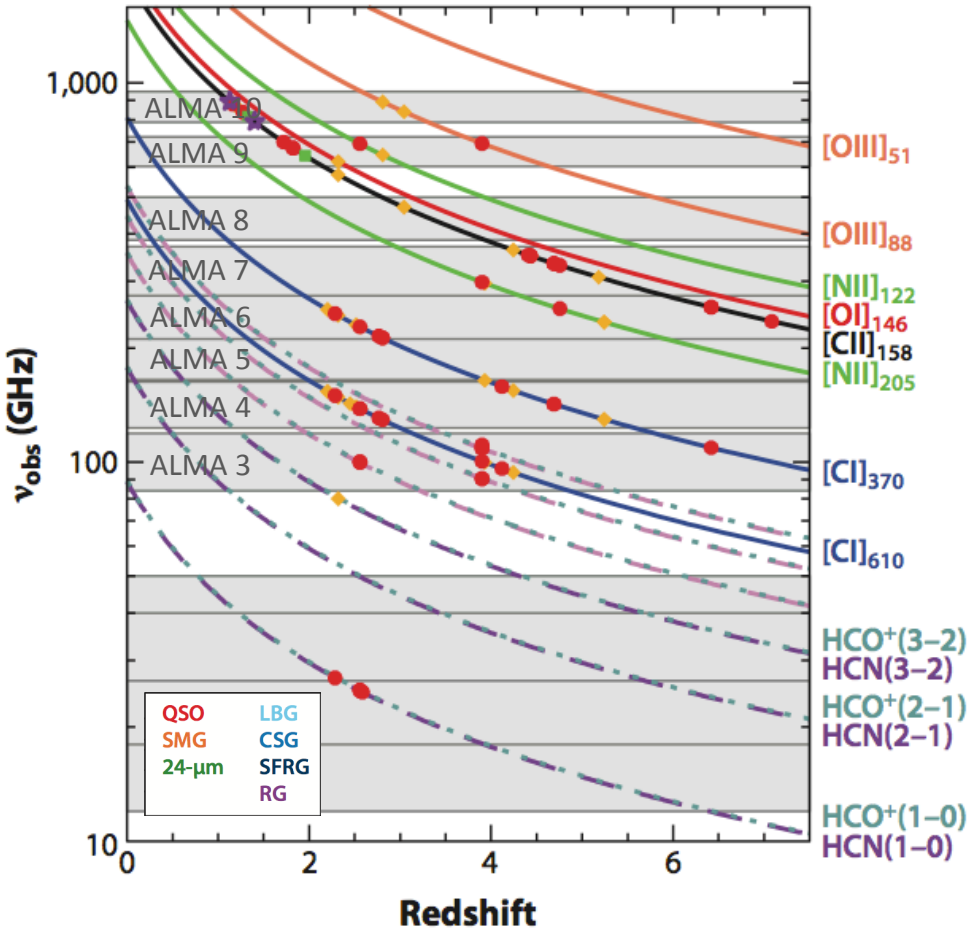


(Carilli & Walter 2013)

CO emission lines: various redshifts across the Universe

- distribution & kinematics
- molecular excitation
- gas/dynamical mass
- inflow/outflow
- properties of star formation
- metallicity

Cosmology and the high z universe



(Carilli & Walter 2013)

Other molecular/atomic lines:

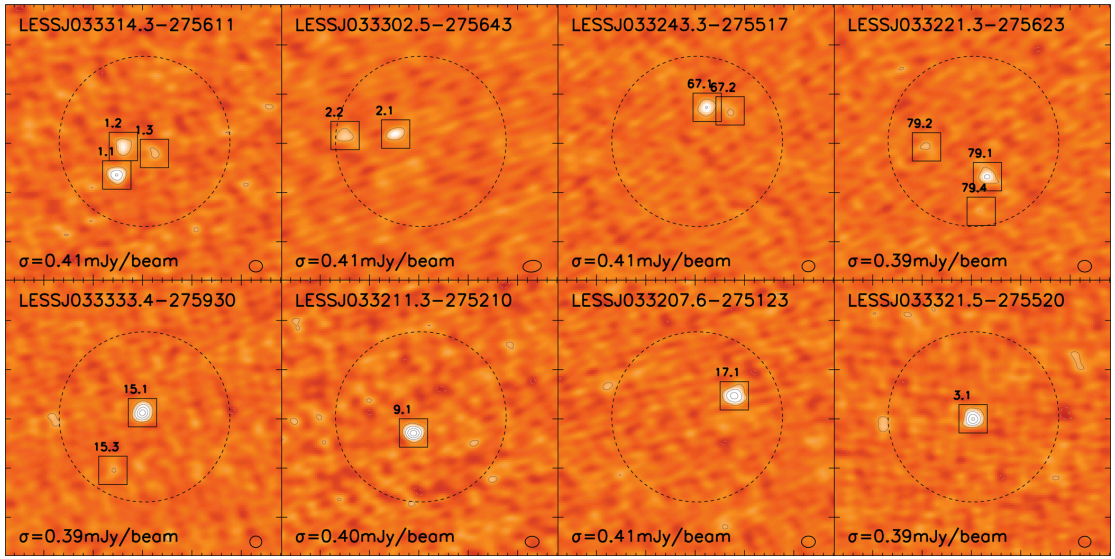
- HCN & HCO$^+$: dense gas
- SiO: shock
- CII (158 μm): coolant in the ISM & strongest fine structure line
- NII, OI, OIII: strength of the radiation field or metallicity

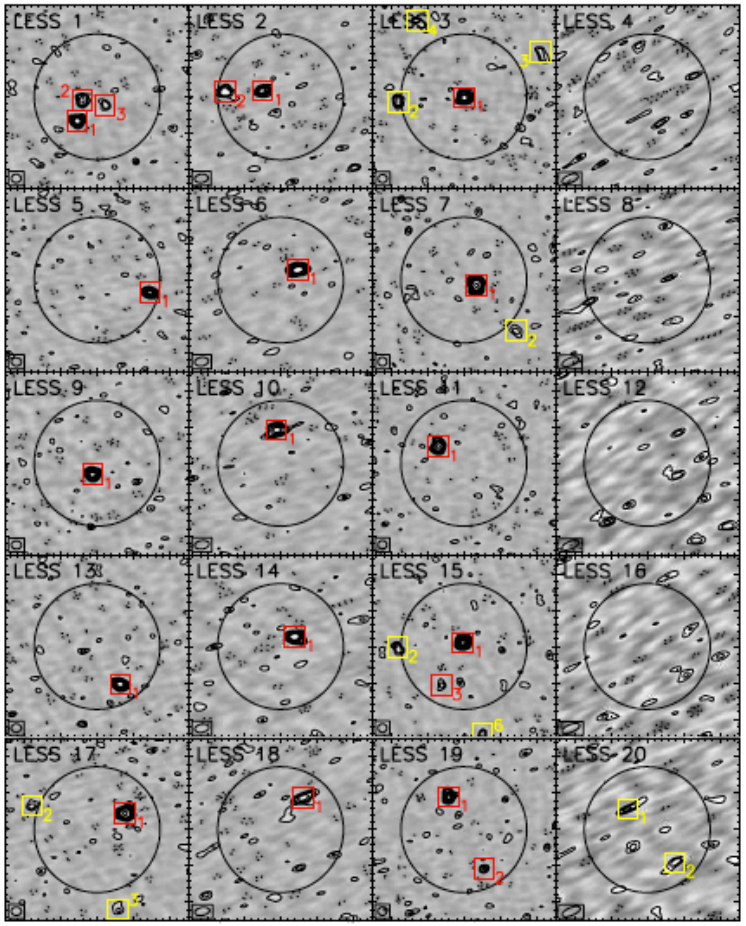
➜ very high-z galaxies, possibly the first galaxies

Cosmology and the high z universe

- **SMGs (Sub-Millimeter Galaxies)** by Hodge et al. (2013), Karim et al. (2013), and Swinbank et al. (2012)

ALMA Band 7 (870 μm)

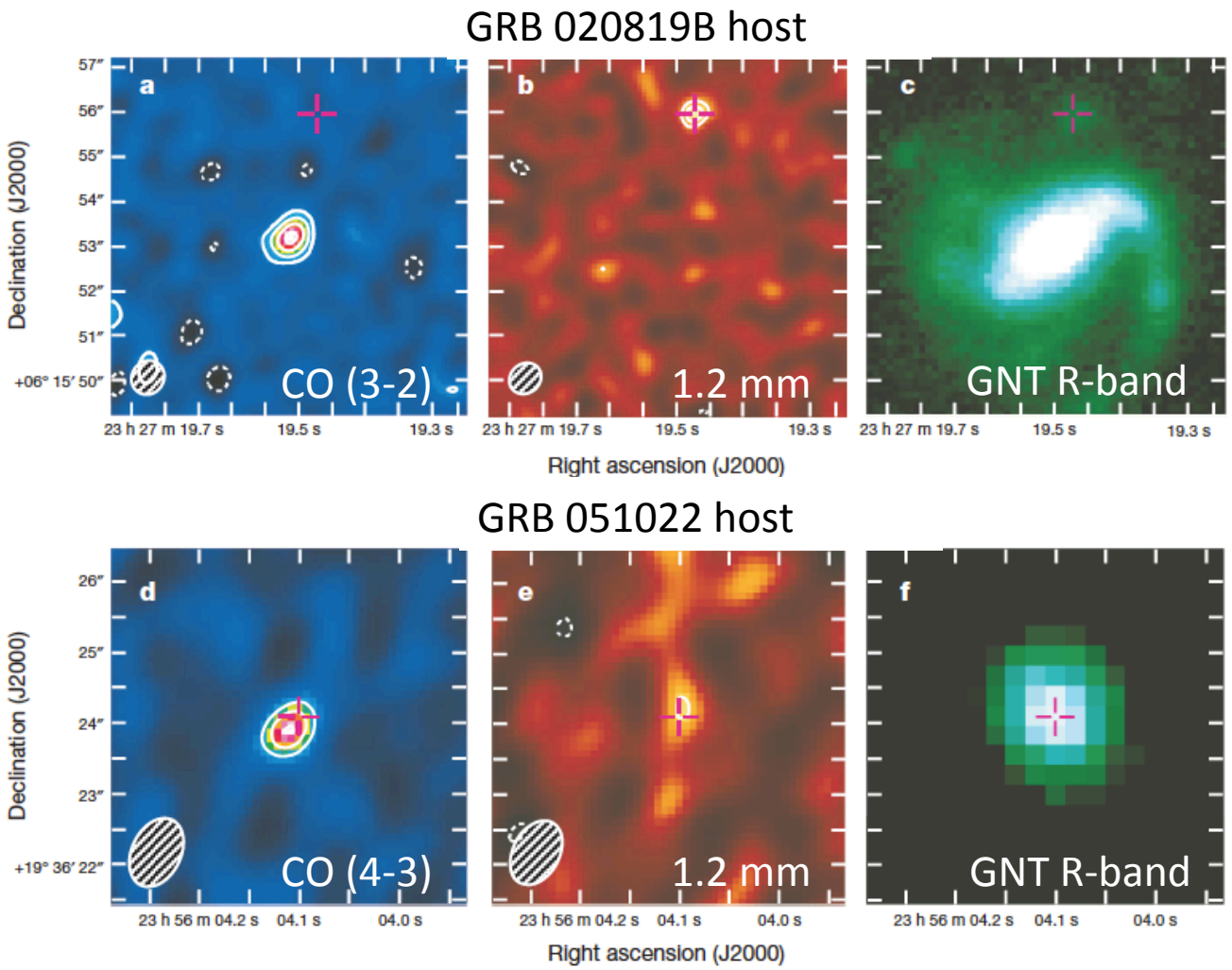




- Brightest sources in the LESS survey : multiple SMGs in the ALMA survey
- [CII] 158 μm at z=4.42 and z=4.44: dominant fine-structure cooling lines from SMGs in 2 min

Cosmology and the high z universe

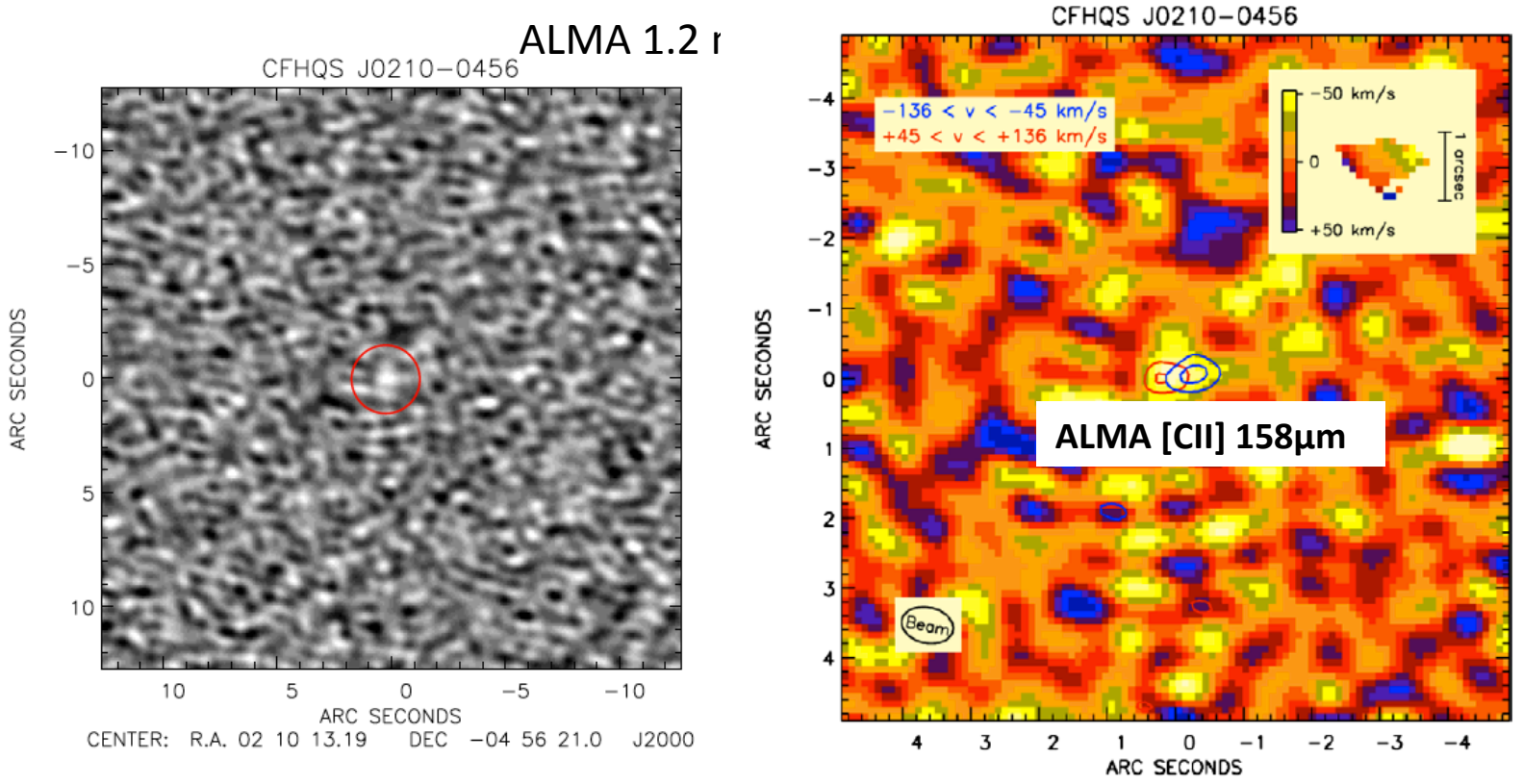
- **GRBs (Gamma-Ray Bursts)** by Hatsukade et al. (2014)



- First CO detection in GRB host galaxies
- Molecular gas: center
- dust: outskirts

Cosmology and the high z universe

- **QSOs (Quasi-Stellar Objects) at z=6.4** by Willott et al. (2013)

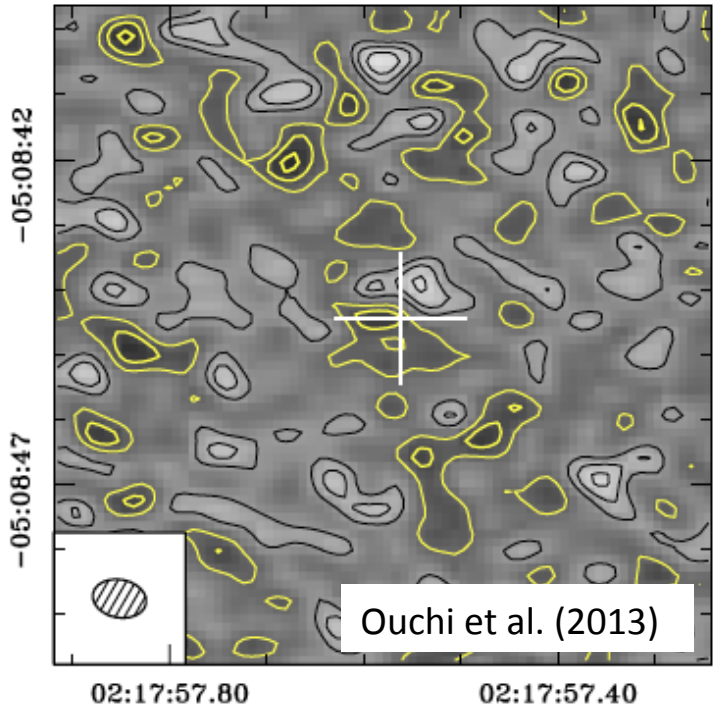


- Much lower dynamical masses of the host galaxies → stellar mass growth lags black hole accretion for high-z QSOs

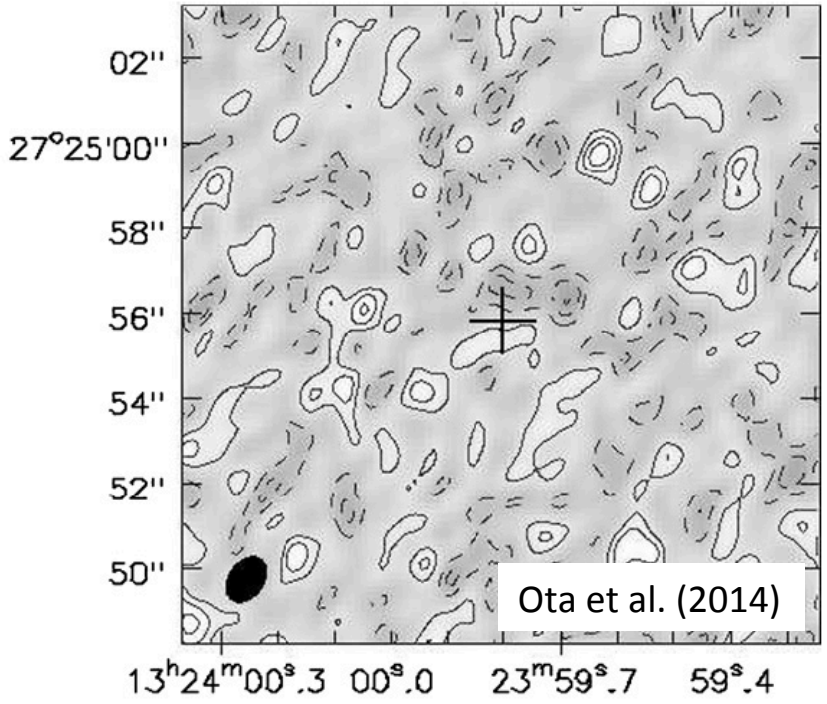
Cosmology and the high z universe

- **First Galaxies** at z=6.6-7.0 by Ouchi et al. (2013) & Ota et al. (2014)

ALMA continuum data for Himiko at 1.16 mm



ALMA continuum image of IOK-1 at 158μm



- Significantly lower gas and dust than SMGs and QSOs at similar z

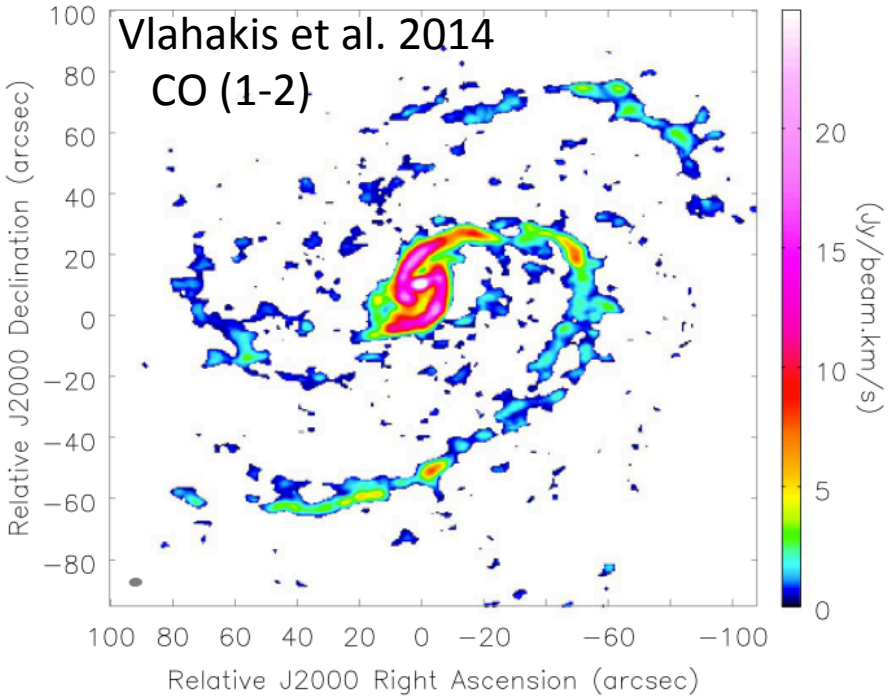
Nearby Galaxies

- Molecular gas in all types of galaxies on pc & kpc scales ➛ relationship between star formation & ISM properties
- Small scale structure ➛ mechanisms of starbursts/AGNs in galaxies and the feedback process (outflows, bubbles, & winds)
- Merging galaxies ➛ star formation & the ISM
- Individual molecular clouds in nearby galaxies ➛ understanding the star formation processes and constraining the H2/CO conversion factor

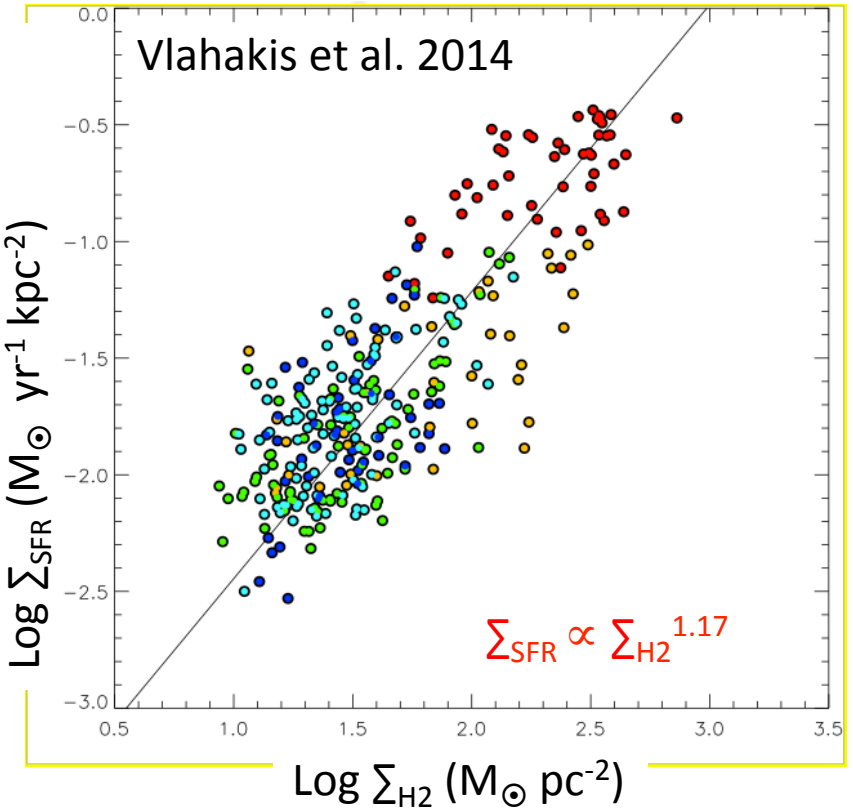
Nearby Galaxies

- Relationship between star formation & gas (SF law or K-S law)

M 100 (NGC 4321)

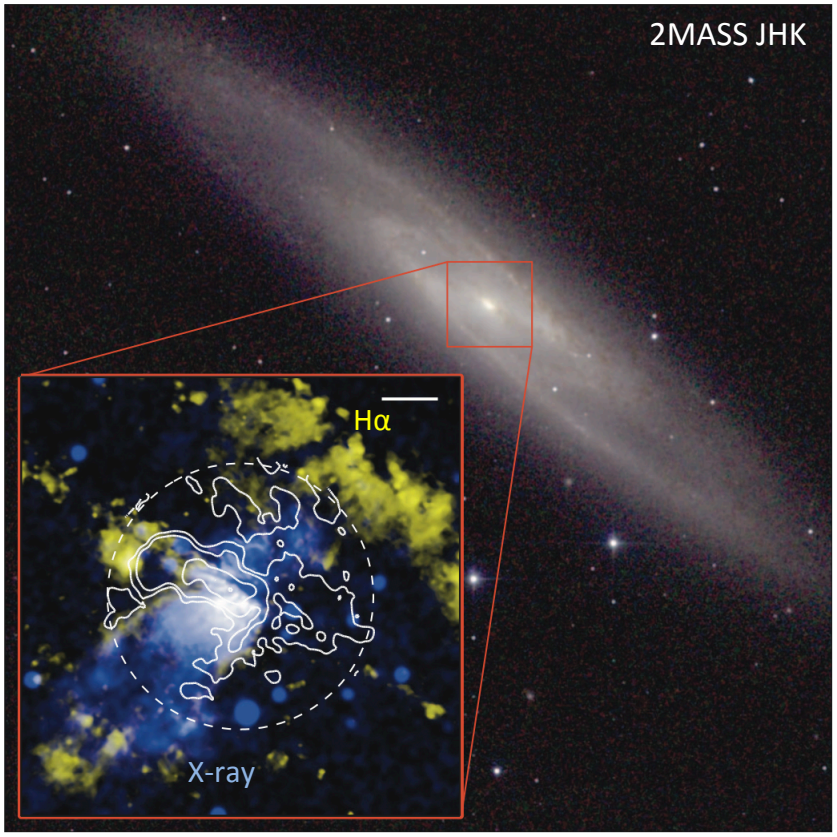


ALMA Band 3 for 6 hours, 2011

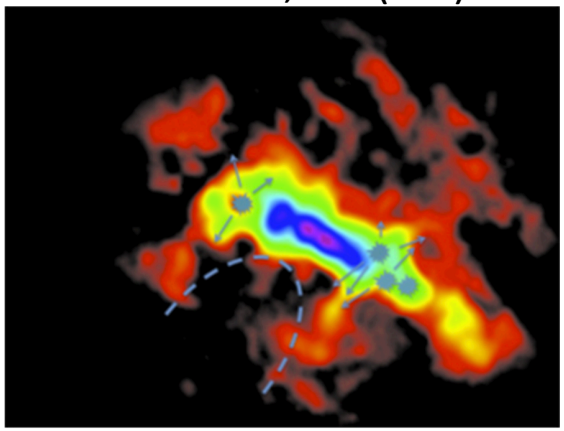


Nearby Galaxies

- Starburst-driven outflow in NGC 253 (Bolatto et al. 2013)



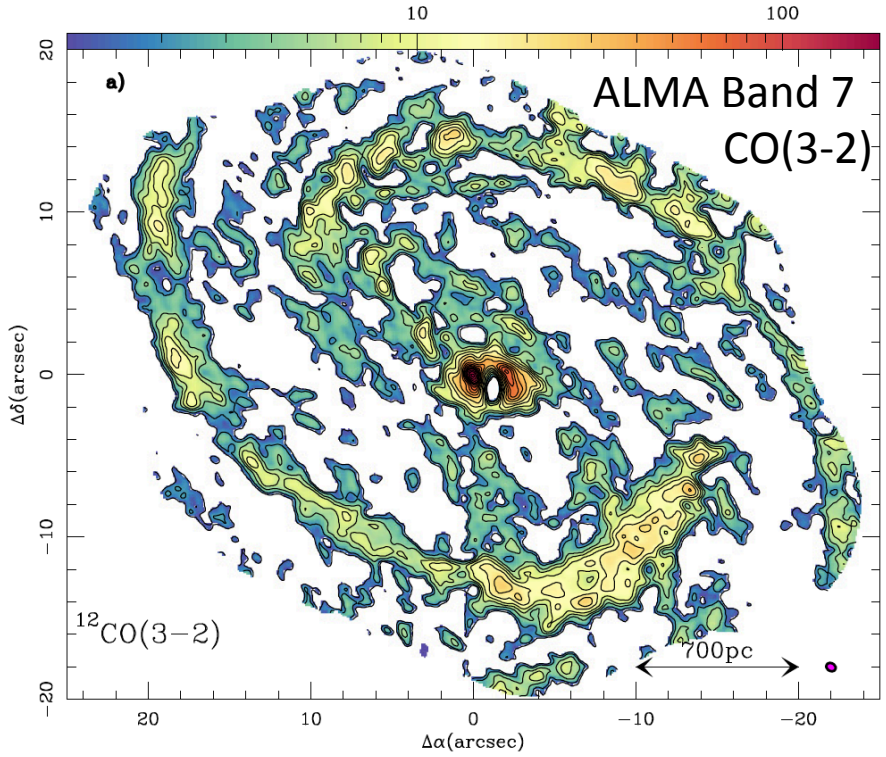
ALMA Band 3, CO (1-0)

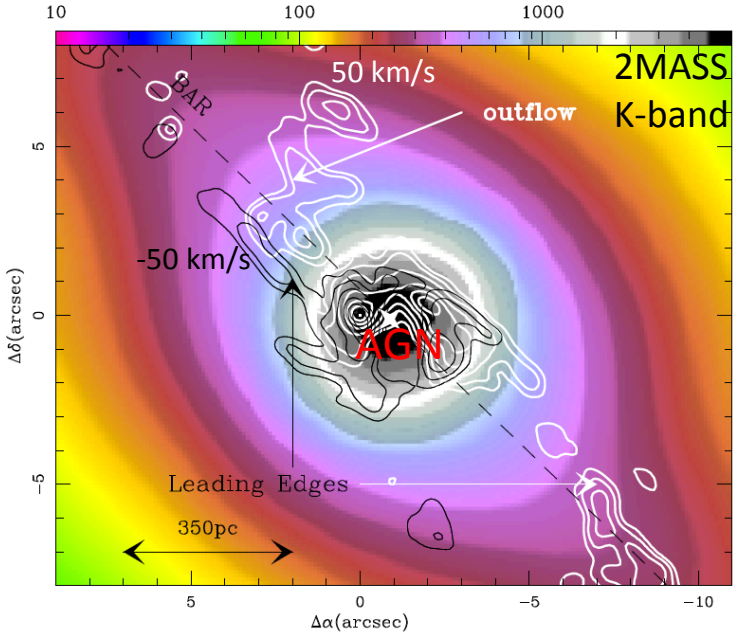


Molecular outflow rate ~3–9 $M_{\odot}$/yr
→ mass-outflow rate/SFR ~ 1–3
: starburst-driven wind regulates the star formation activity

Nearby Galaxies

- AGN-driven outflow in NGC 1068 (Garcia-Burillo et al. 2014)

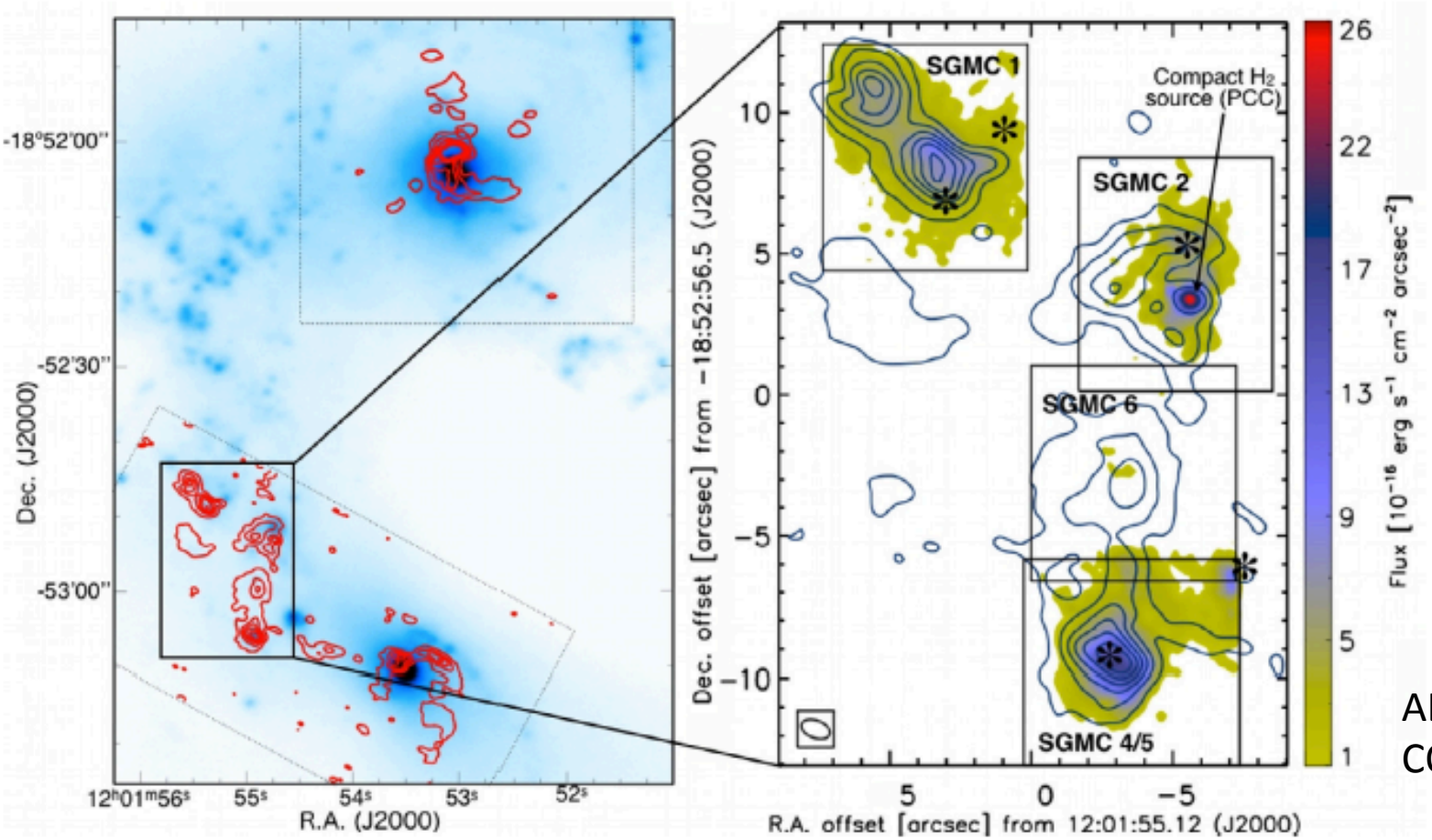




- CO(3-2): starburst ring & bar region
- Dense gas tracers HCO^+, HCN, CS: near the circum-nuclear disk (CND)
- Outflow rate (dM/dt) in the CND $\sim 63 M_\odot/yr$

Nearby Galaxies

- The Antennae galaxy merger NGC4038/4039 (Herrera et al. 2012)



ALMA Band7
CO(3-2)

- Distribution of CO and H_2 are well matched in the overlap region

ALMA Cycle 4

Early Science Primer **https://science.nrao.edu/facilities/alma/didyouknow**

- Resolve molecular clouds in a nearby, star-forming galaxy:
  - HCN mosaic of the full (4kpc) M83 bar with 30pc resolution **(2.5hr)**
  - Map 6pc clouds of CO(3-2) gas across central 400pc of M83 **(2hr)**
- Study black holes and their environments:
  - Measure BH mass of NGC4526 using CO(2-1) kinematics **(1h)**
  - Infer gas properties in the host galaxy of z=2.8 QSO **(18min)**
- Detect the ISM in high redshift galaxies:
  - Dust emission from ULIRGs (10^{12} Lsun) out to z=10 **(24min)**
  - Major [CII] cooling line in a lensed MW at z=4.2 **(34min)**
- Trace the formation of galaxy clusters, cosmic structure:
  - Survey clustering in a sample of 23 Lyα blobs at z=3.1 **(1h)**
  - Characterize merger shock in cluster gas with SZ effect **(3h)**