ALMA Science Cases beyond our Galaxy

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Contents

- ALMA's key parameters for Extragalactic Science
- (some highlighted) ALMA extragalactic science cases

ALMA, designed for extragalactic science...

- Sensitivity

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

- (spectral/spatial) Resolution

  - The ability to provide precise images at an angular/spectral resolutions of $0.''1$ and > 0.01 km/s of all sources transiting at an elevation < -20°

De Breuck (2004)

ALMA's observing capabilities for Extragalactic Science

- Sensitivity

  - detect spectral line emission from CO or [CII] in MW-like galaxies at z~3 in less than 24h

- Spectral/spatial resolution

  - ~0.5 km/s channel resolution

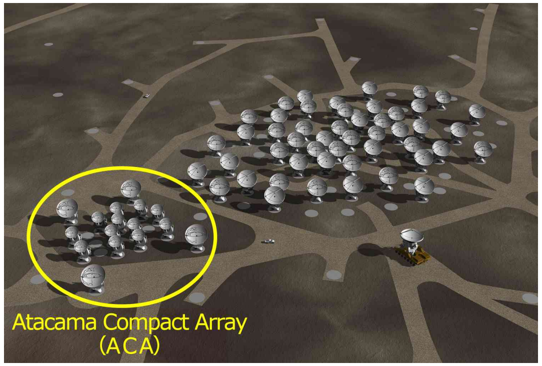
  - down to milli-arcsec resolution: ~1 pc (local Universe) to ~1 kpc (z~1.0)

- Array configuration

  - ALMA 12-m x 50 array (~150m out to ~16 km)

  - Atacama Compact Array (ACA; 7-m x 12) + TP (4 x 12m)

  → short spacing

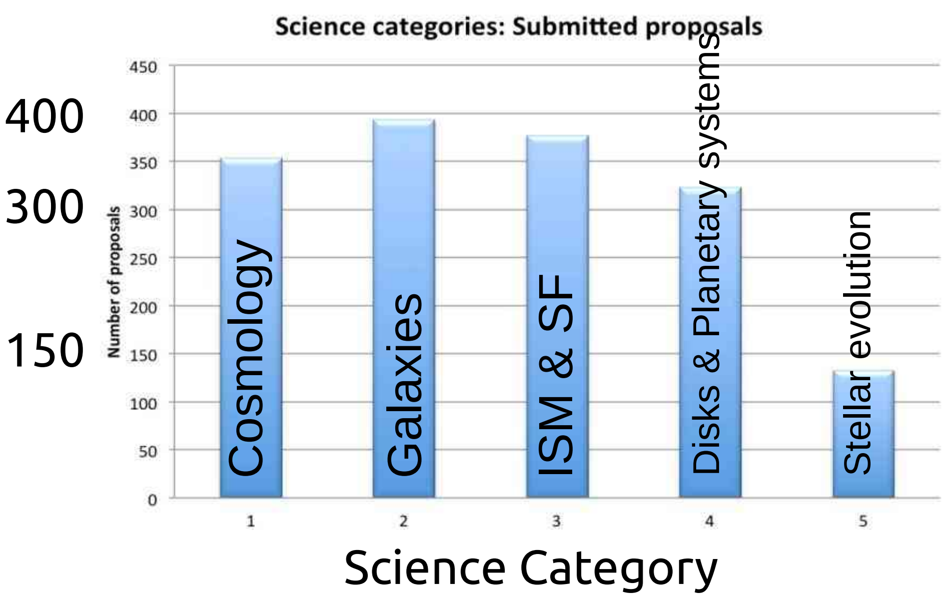


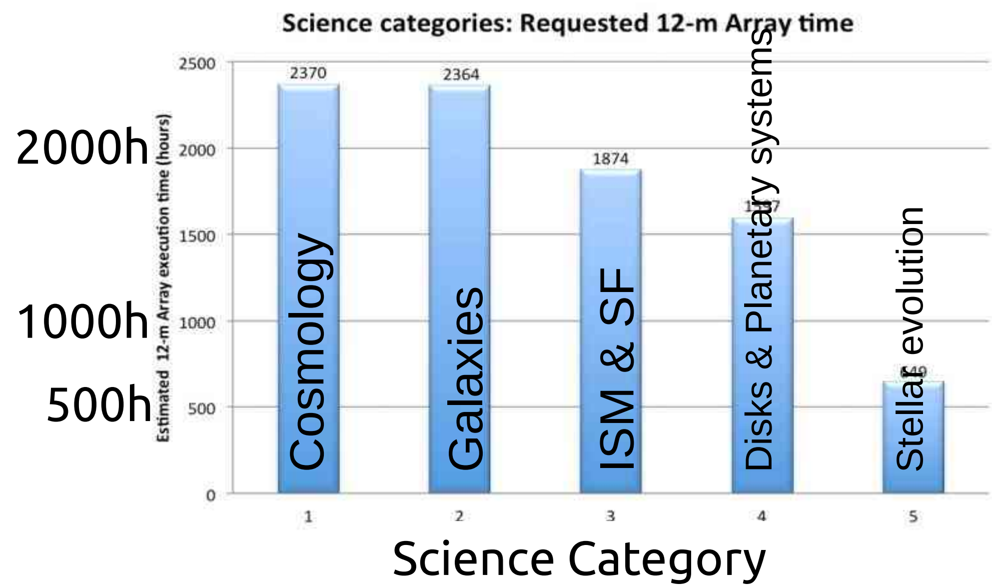
- Filed of view

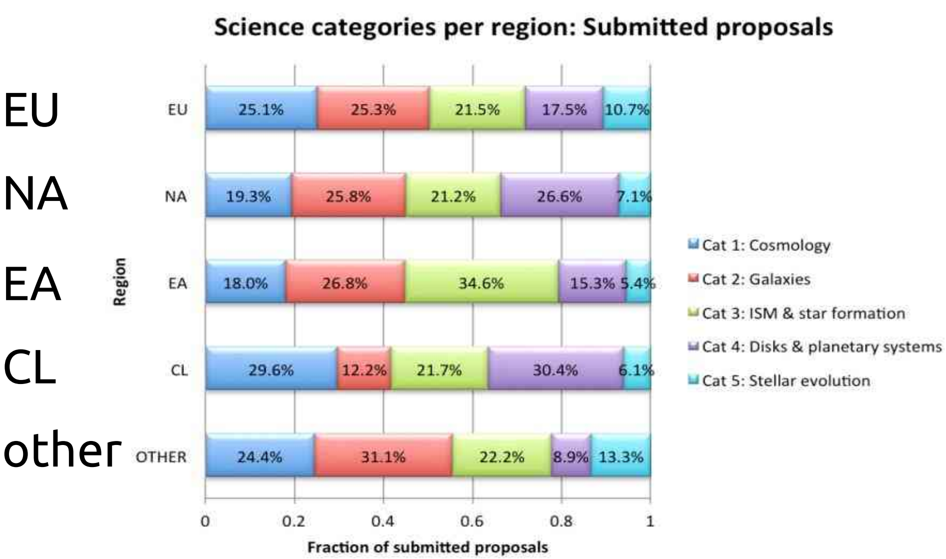
  - 21" @ 300 GHz (primary beam), scaling linearly with wavelength

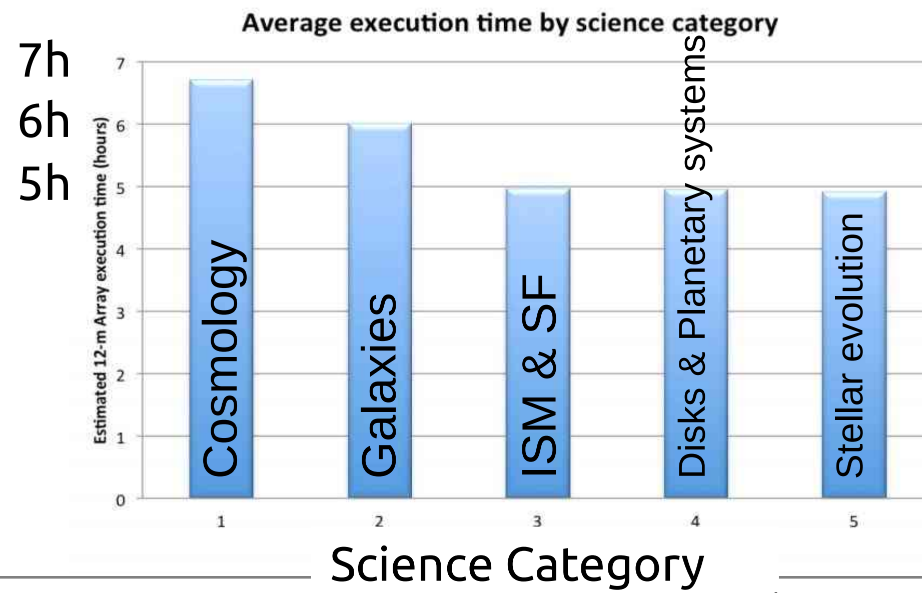
  - mosaicking required for regions larger than the primary beam

ALMA Cycle 3 proposal results report

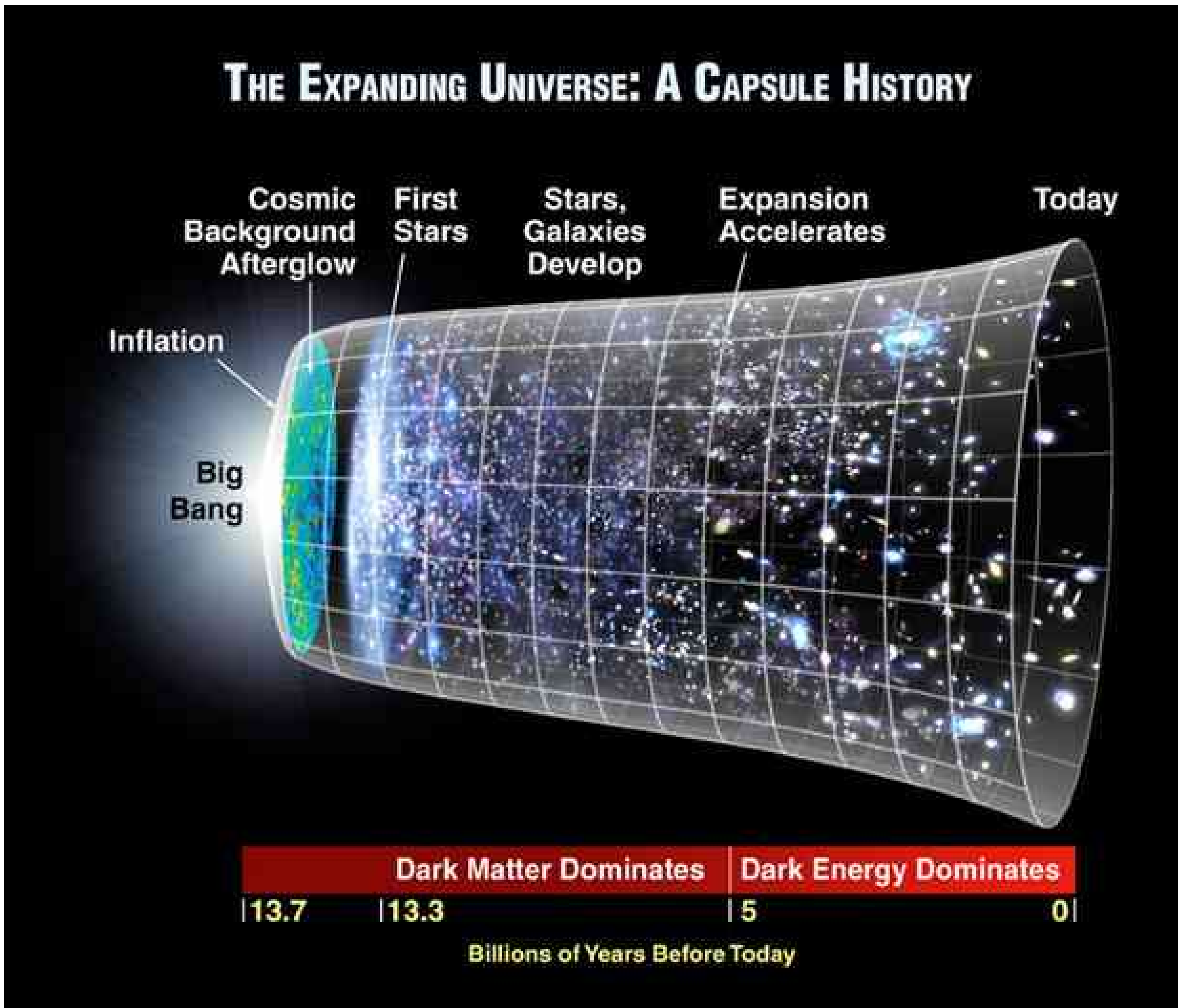


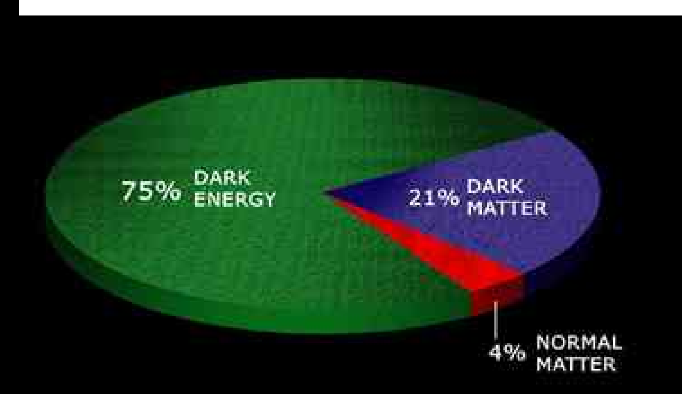






Galaxy formation & evolution:
a key towards understanding the cosmic history of the Universe





ALMA Extragalactic Science: observing perspectives

- Mapping

  - distribution and kinematics of molecular gas in galaxies

  - Giant Molecular Clouds (GMCs) in nearby galaxies

  - outflowing or infalling molecular gas (feedback or fueling?)

  → observational constraints on the role of molecular gas in star formation, and thus the evolution of galaxies

- Detection

  - (faint) source counts and cosmic H_2 contents of the Universe

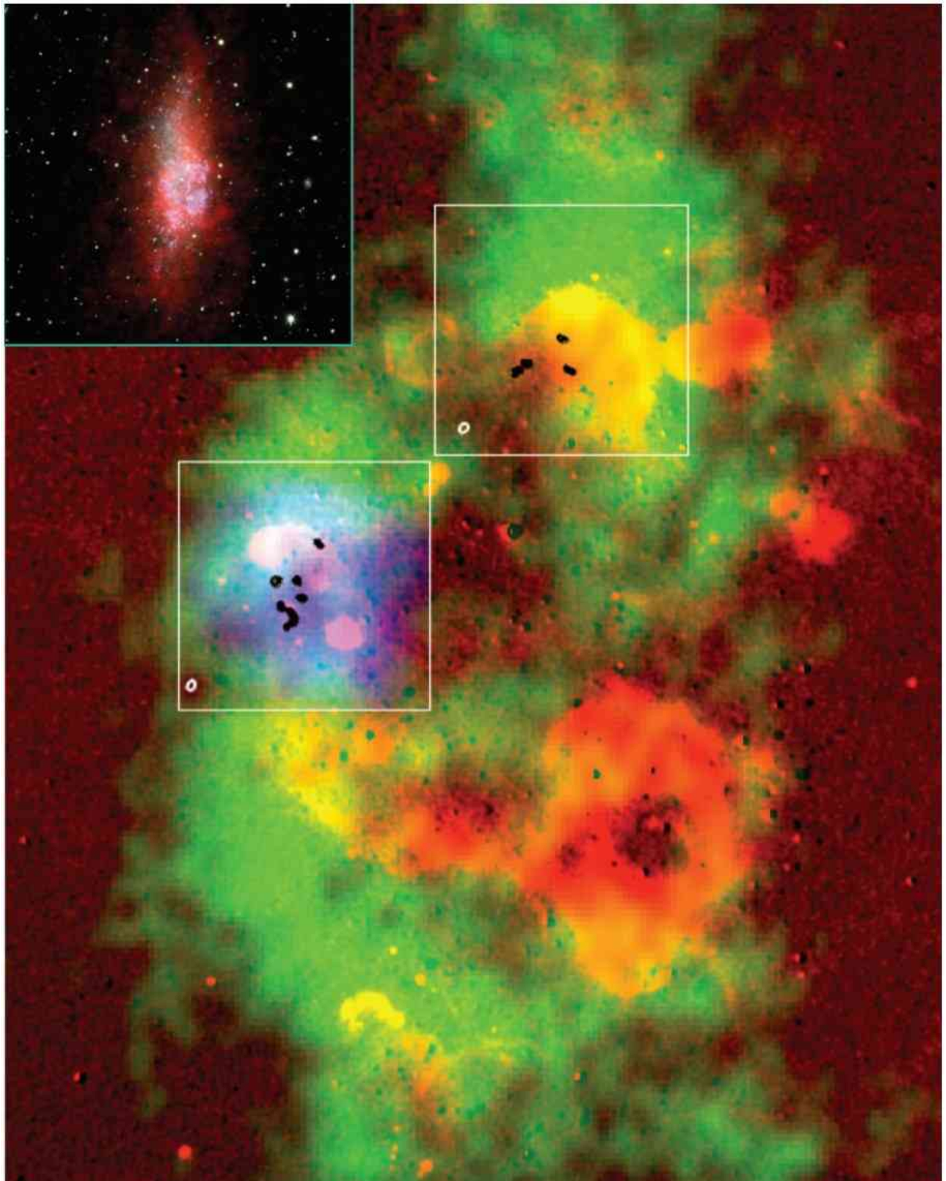
  - SFR of sub-mm galaxies in the early Universe

  - new populations?

  → observational cosmology and high-z Universe

inspired by several ALMA review talks including Muller's one

Dense CO clouds in the low metallicity dwarf galaxy WLM
(Rubio et al. 2015, Nature)



- In primeval and local dwarf galaxies:

  - Carbon and oxygen are low

  - the dust opacity is low

  - CO forms slowly and easily destroyed

  → challenging for the standard SF model in CO-rich clouds

- WLM, a metal-poor isolated dwarf galaxy

  - with 12+log(O/H)~7.8 (c.f. MW~8.66)

  - at 0.98 Mpc

  - showing efficient SF even with a low CO abundance (12 times higher than the MW)

- To understand SF in metal-poor galaxies:

  → ALMA $^{12}CO(1-0)$ Band 3 observations of the two unresolved regions by APEX obs.

  → 6.2 x 4.3 pc @ 5 mJy/beam + 0.5 km/s

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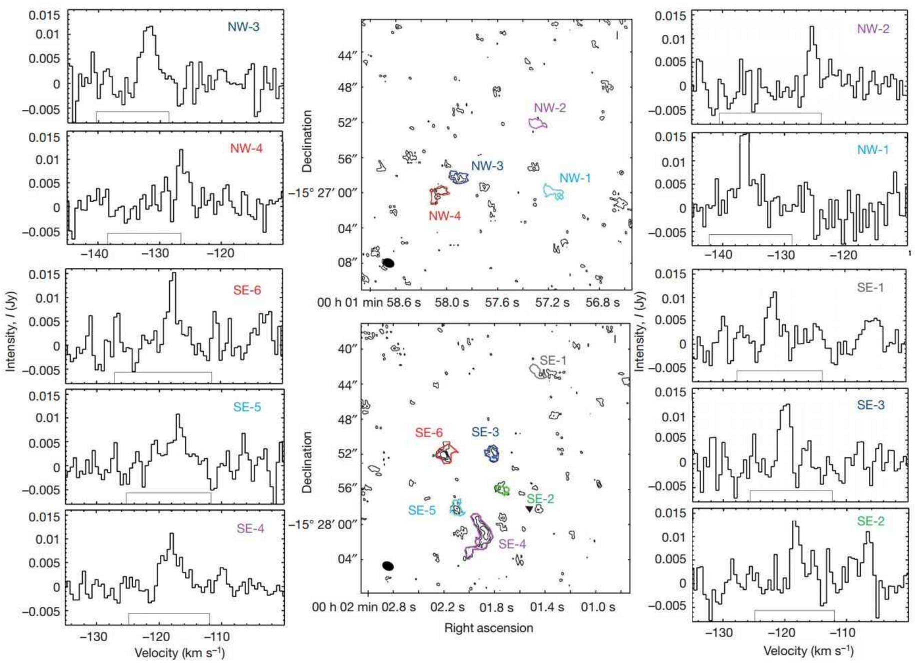
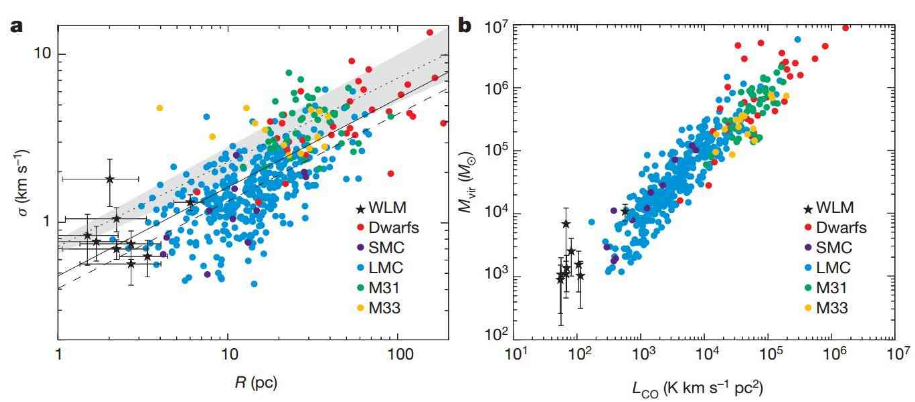




- 10 dense CO clouds detected

  → the sizes and virial masses, and thus the densities calculated

  → an average radius of 2 pc and M_{vir}~$2x10^3 M_\odot$

  → showing a gradual transition between low-density atomic gas to high-density CO

  → the clouds are tiny but have typical densities and column densities as in the MW

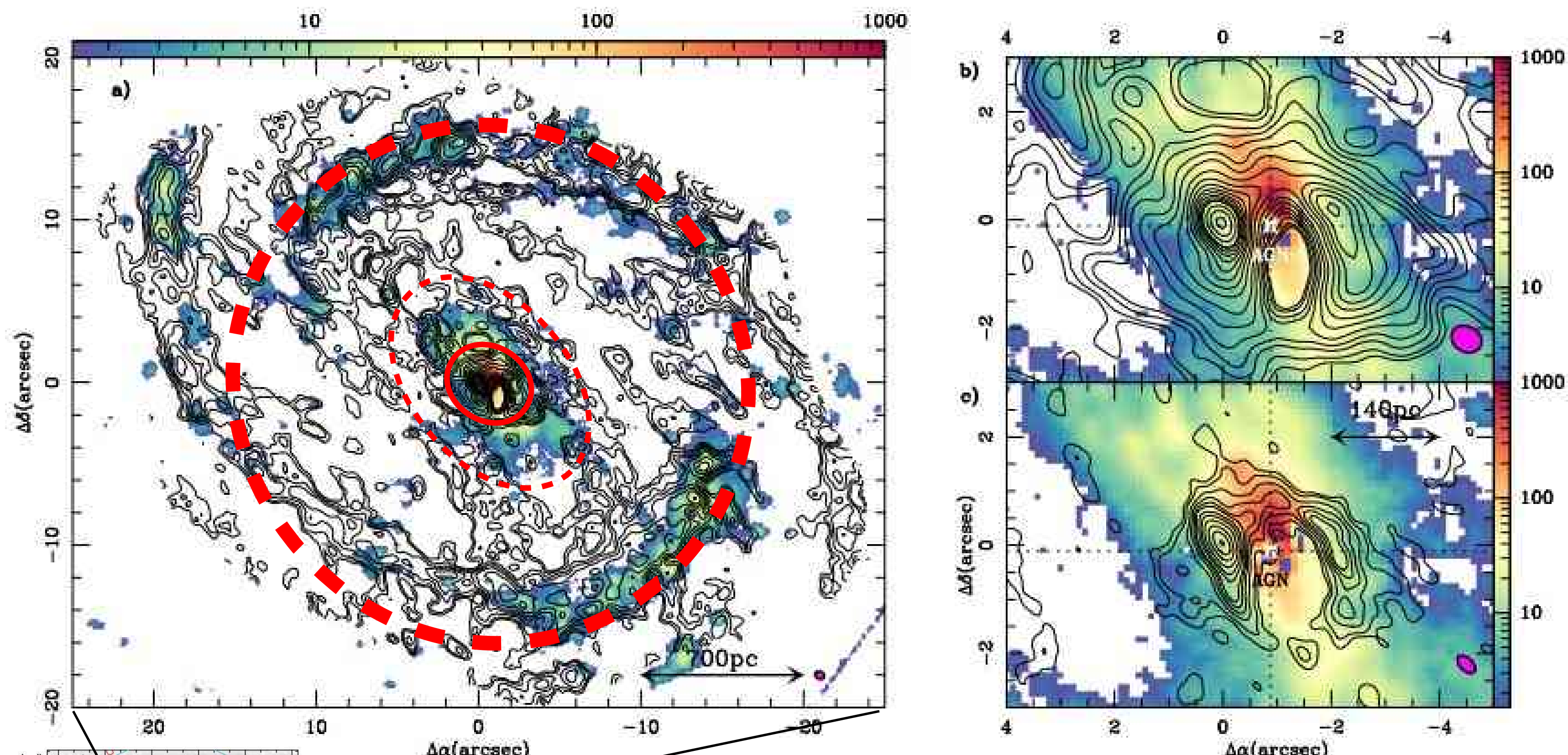
  → the lack of massive CO clouds at low metallicity which satisfy the usual correlations

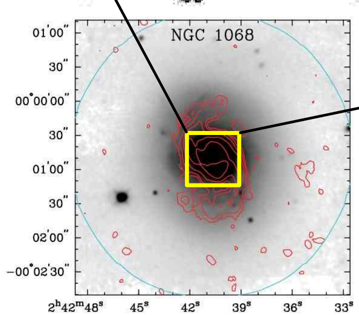
  → this explains why star clusters in dwarfs have similar densities to those in giant spirals

- Without a major impact to increase the pressure and mass, dwarfs cannot form massive clusters (e.g., NGC 1569, NGC 5253)

  → if the massive metal-poor GCs in the halo of the MW formed in dwarfs, they were triggered by such an impact

An AGN-driven outlfow in the dense molecular gas (Garicia-Burillo et al. 2014, A&A)





BIMA SONG (6") (Regan et al. 2001)

- ALMA Cycle0 band 7/9 observations of Seyfert 2 galaxy, NGC 1068 (0.3"-0.5"; ~20-35 pc at 14 Mpc)

  → distribution/kinematics of the molecular gas in the disk

  → fueling/feedback of SF and nuclear activity in NGC 1068

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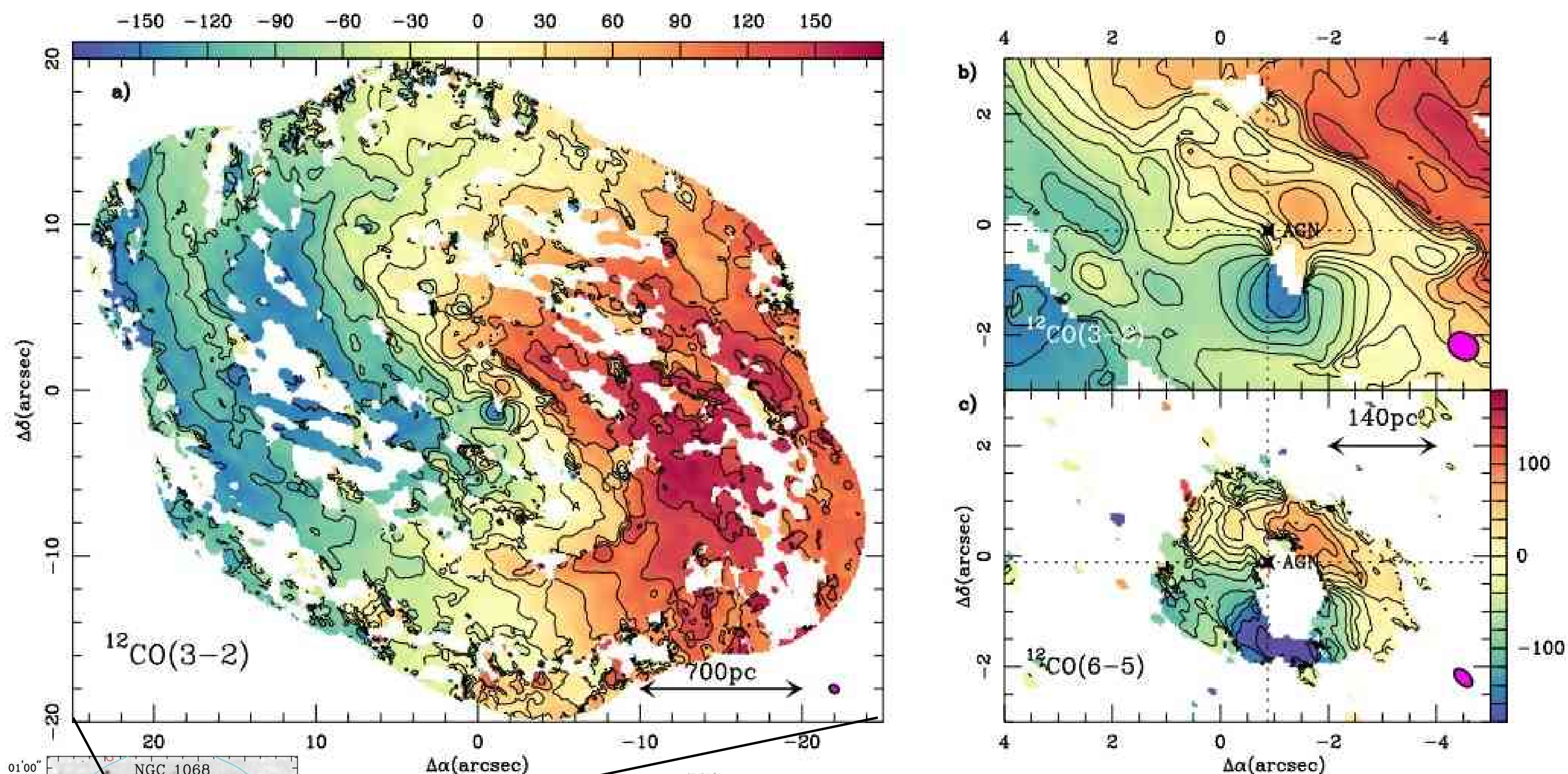

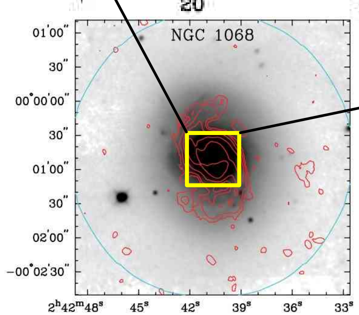

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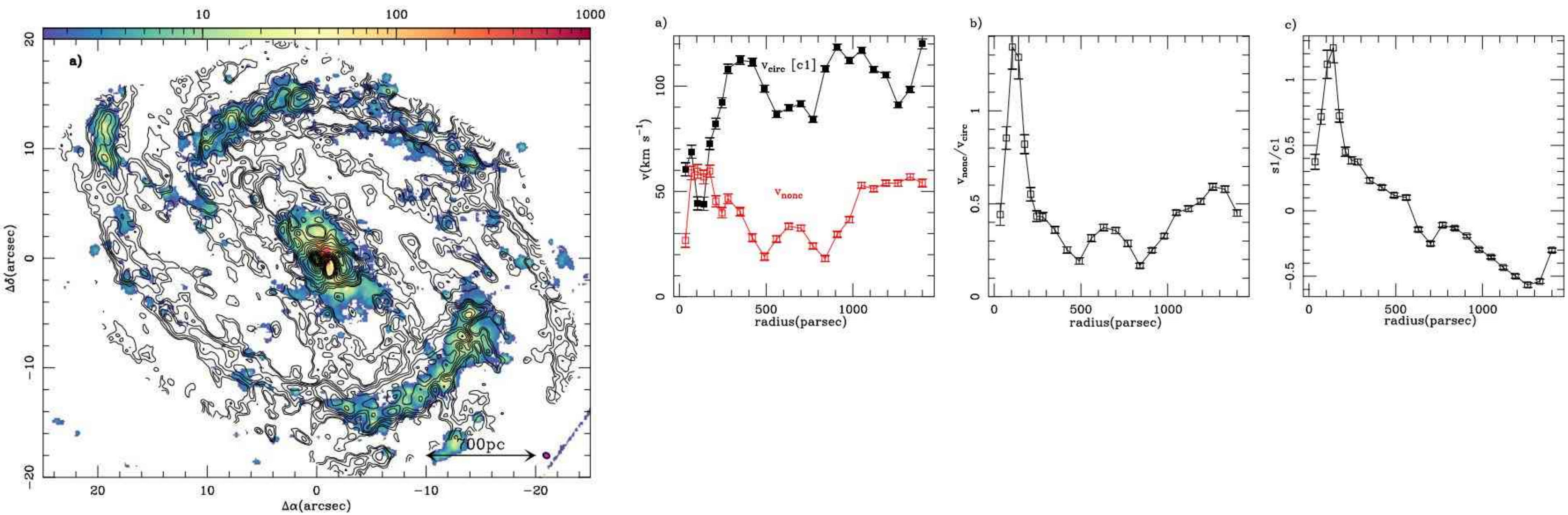


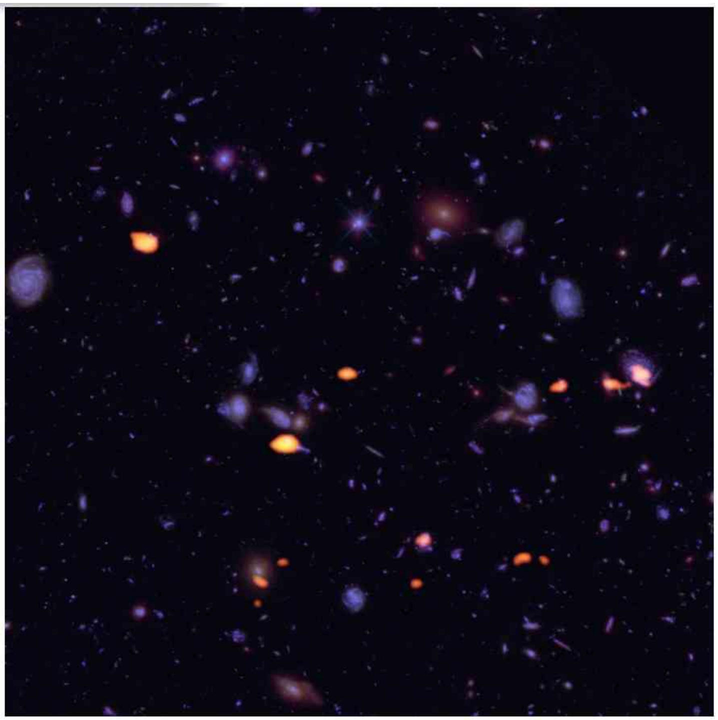
- From the kinematic analysis of maps traced by several molecular lines (CO, HCN, CS)

  → near the circumnuclear disk (CND), significant outflowing motions (driven by AGN) observed

  → the kinematics near starburst ring & bar regions is perturbed by inward motions

  → AGN-driven molecular outflow could quench SF in the inner part on short time scale but the molecular gas reservoir is replenished by gas inflow from the outer disk : self-regulated star formation

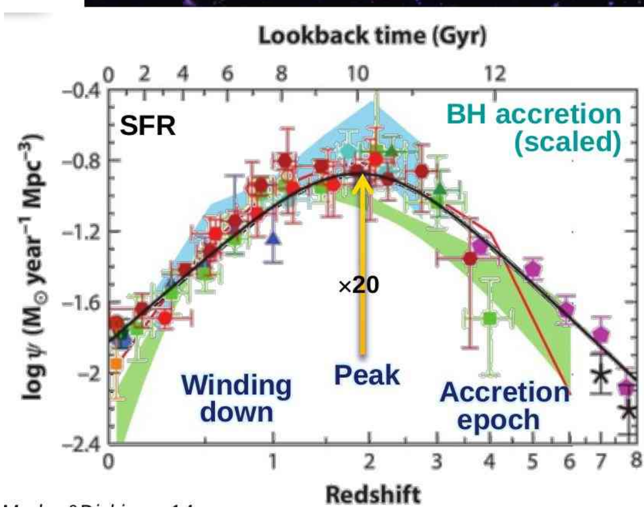
Uncovering the golden age of galaxy formation
(Decali et al. 2016, ApJ)



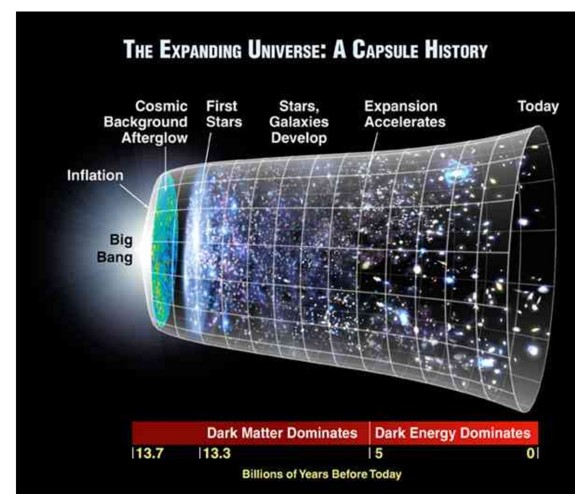
- Early results from ALMA Spectroscopic Survey in the Hubble UDF (ASPECS): 50 hrs (observed so far) + 150 hrs
- An ALMA band 3/5 blind survey for HUDF (z~4.5)

→ a rapidly rising gas content in galaxies with increasing look-back time

→ the root cause for vigorous SFR over the peak epoch of cosmic SF at z ~ 2



Madau & Dickson (2014)



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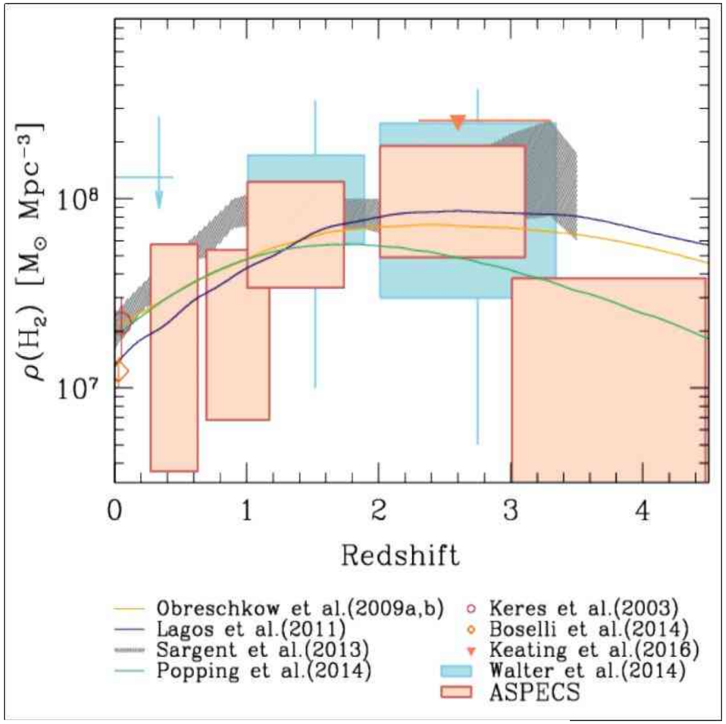


→ (first) CO luminosity function (solely from CO emission) and cosmic H2 density as a function of z out to ~4.5

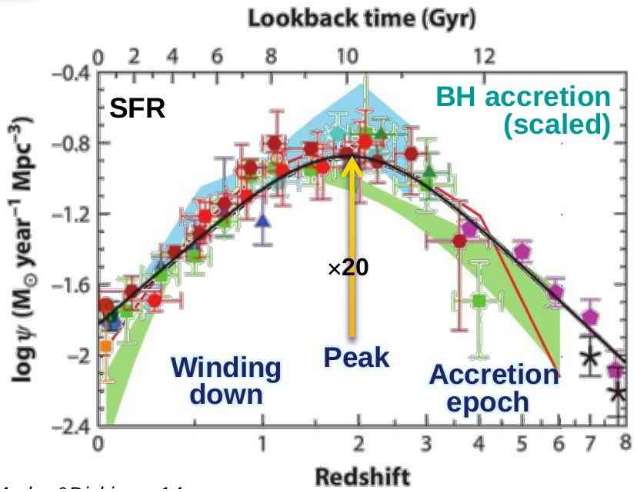
→ Clear evidence of an evolution in the CO luminosity function

→ More CO luminous galaxies at z~2

→ More gas-rich than predicted by recent semi-analytic models

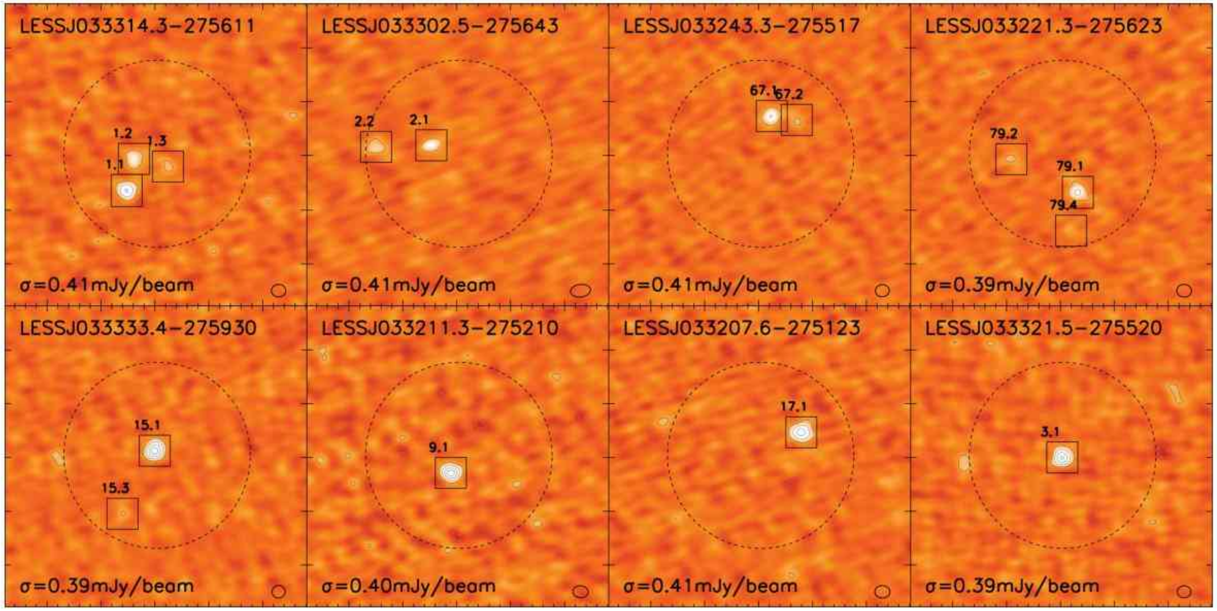
→ Cosmic H_2 with a factor 3-10 drop down from z~2 to z~0

→ The cosmic SFR partly driven by the molecular gas reservoirs at the peak of cosmic SF (z~2)



Madau & Dickson (2014)

Source counts of faint SMGs from high-resolution ALMA survey
(Karim et al. 2013, MNRAS)



- Submilimetre galaxies (SMGs: dust-obscured starbursts galaxies) placed in ULIRG/HLIRG classes
- Linked to QSO activity and the SF at high-z
- An essential element and constraint on galaxy evolution theories

← ALMA follow-up for 126 submilimetre sources detected from the APEX LESS survey for the Extended Chandra Deep Field South

← ALMA Cycle0 Band 7 receivers in the compact array configuration

← High sensitivity (~0.4 mJy/beam) & angular resolution (~1.5")

← ~120s integration time for each science field

Korea Astronomy and Space Science Institute

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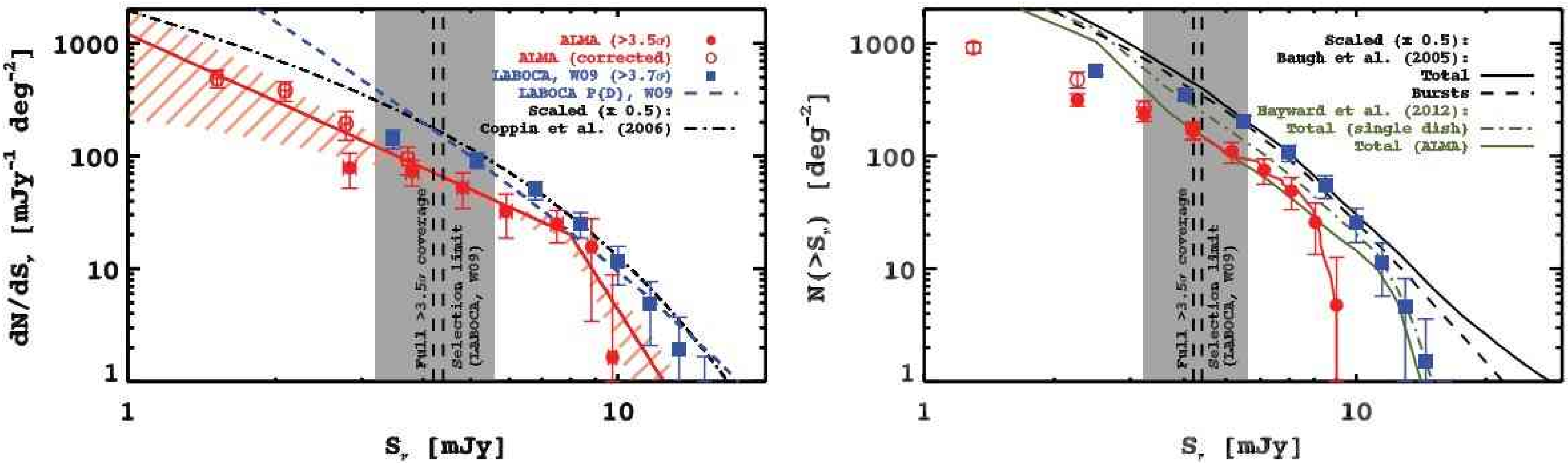


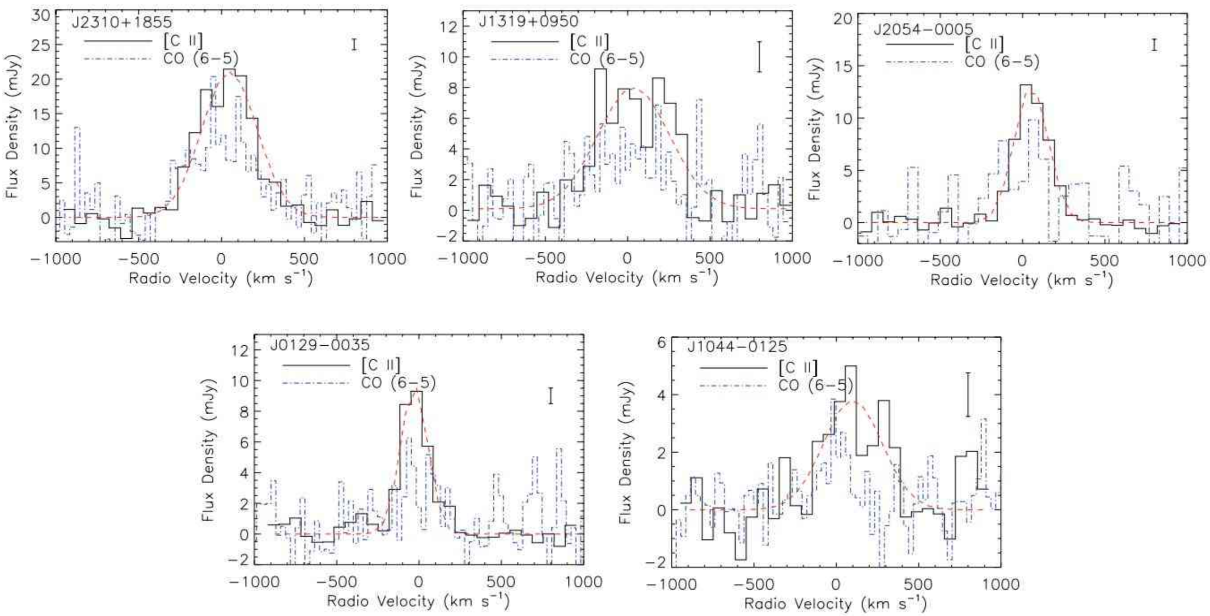
→ source number counts from the 870 μm ALMA survey for the ECDF

→ ~3x deeper and ~10x higher than the APEX single dish survey

→ in broad agreement with those from the APEX survey but showing a deficit of bright sources with > ~8 mJy:

← comprised of multiple sources: → a limit to the maximum SFR in an SMG, which in turn indicates the galaxies' space densities of < 10^{-5} Mpc^{-3} with M_{gas} > 5 x $10^{10}M_{\odot}$

SF & gas kinematics of QSO host galaxies at z~6
(Wang et al. 2013, ApJ)



- QSOs at z > 6, a unique sample for the first SMBHs and their host galaxies
- ~60 QSOs known at z ~ 6 from optical/IR surveys
- 10^9 $M_\odot$ SMBHs at z ~ 6 → fast BH accretion and SMBH-galaxy evolution within 1 Gyr after the big bang

(1) dust continuum: an efficient way to search for SF activity at high z

(2) CO: molecular gas of the requisite fuel for SF

(3) [C II] 158 μm line emission at sub-mm: PDRs + ISM phase & dynamics

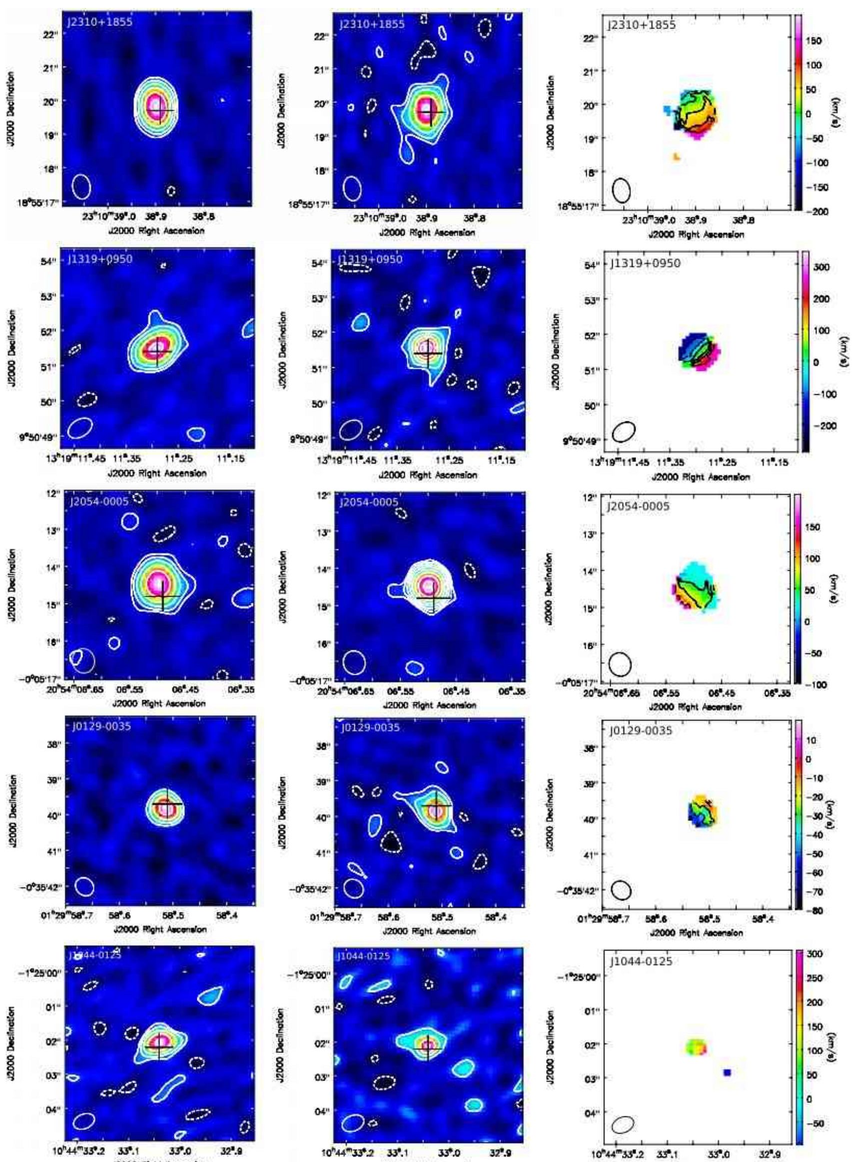
→ the co-evolution of the first SMBHs and their host galaxies

- ALMA Cycle0 Band 6/7 observations of 5 QSOs at z~6 (50-90 min/target)

→ 0.4-0.7 mJy/beam @ 0".7 (~4 kpc @ z~6) + 16-18 km/s

SF & gas kinematics of QSO host galaxies at z~6
(Wang et al. 2013, ApJ)

Dust continuum *Mom0 : [CII]* *Mom1 : [CII]*



→ Dust continuum+[C II] line detected from the host galaxies of 5 QSOs at z ~ 6

→ Indicates active SF in the central few kpc region

→ [C II] / FIR comparable to typical ones in local ULIRGs and other FIR-luminous QSOs at high z

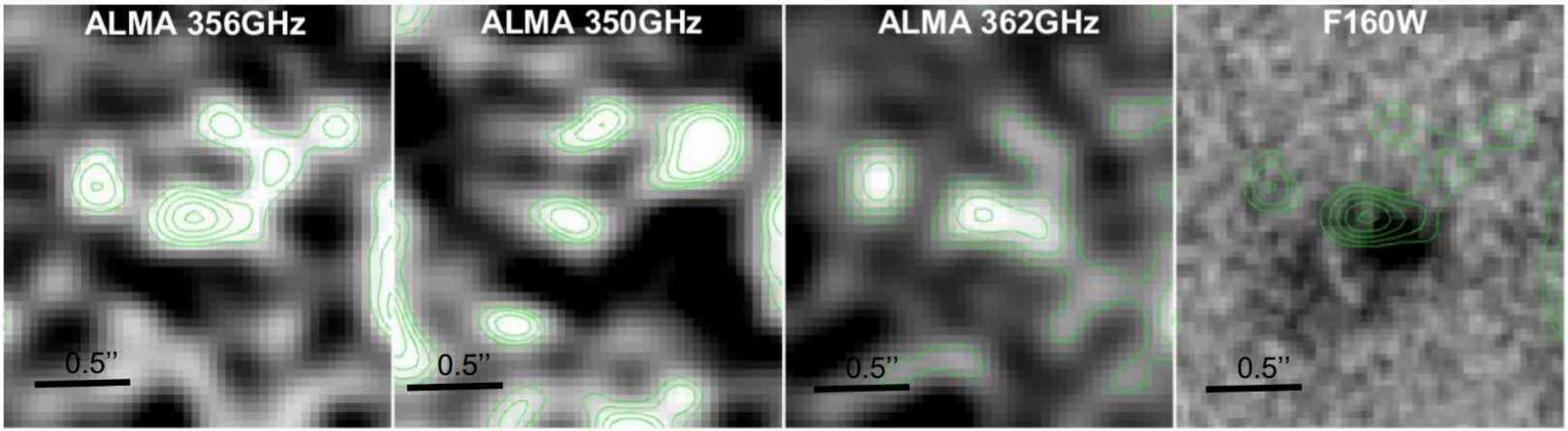
→ the dynamical masses within the [C II]-emitting region measured

→ M_{SMBH}/M_{dyn} are an order of mag. higher than those of local normal galaxies

→ study an early phase of SMBH-galaxy evolution

→ ALMA [C II] emission line observations are ideal for the study of star-forming activity + gas dynamics in the nuclear region of the starburst QSO host galaxies at high z

Dust in the reionization era: A z=8.38 gravitationally-lense galaxy (Laporte et al. 2017, ApJ)



- Measuring dust and stellar masses of the star-forming galaxies at 6 < z < 10 when HI was photo-ionized is important to trace the early SF and chemical enrichment
- Timing the dust content in such infant systems produced by the first SNe would measure the extent/duration of previous SF
- ALMA's detection capability focused on z~6 (biased?) ultra-luminous sources can be further pushed out to z~10 and beyond by targeting gravitationally-lensed systems

  → 2.5 hrs of ALMA Band 7 observations of a gravitationally-lensed galaxy at z~8.38 in the HUDF (July 2016)

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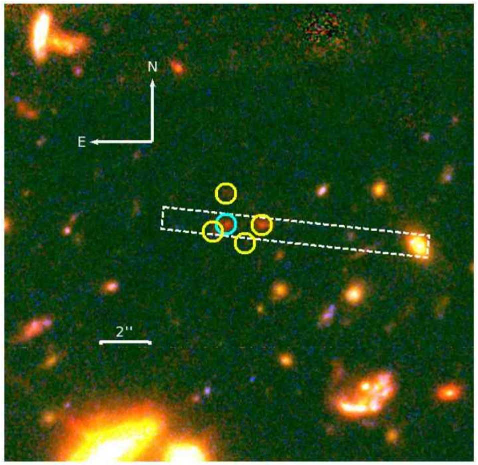
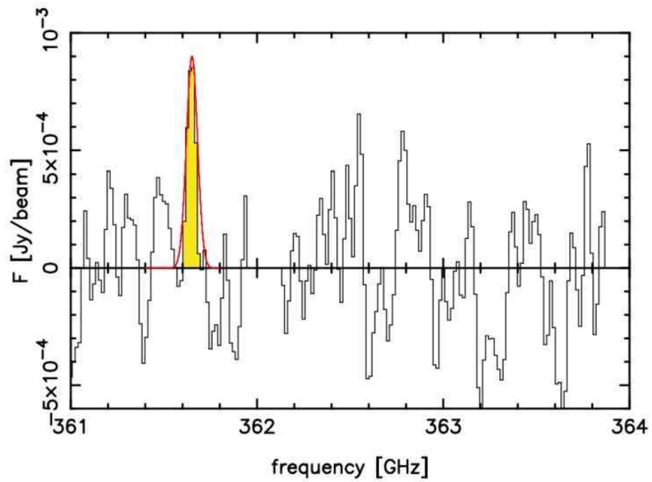




- VLT spectroscopic confirmation of z~8.38
- ALMA [O III] 88 μm spectrum
- A slightly narrow line width of 43 km/s may indicate its formation outside the body

→ By fitting a simple modified black body SED to the ALMA continuum, a total FIR luminosity (7.1 – 18.2 x 10^{10} $M_{\odot}$) and a dust mass (1.8 – 10.4 x 10^{6} $M_{\odot}$) are derived

→ Consistent with those derived from a multi-band SED library fitting which provides:

(1) SFR~20 $M_{\odot}$/yr; (2) M_{*}~2 x 10^{9} $M_{\odot}$; (3) M_{dust}~5.5 x 10^{6} $M_{\odot}$

→ Recent studies indicate significant SF began at z~10 – 12, about 200 Myr before the lensed galaxy

→ 0.2% of newly-born stars are type II SNe which is expected to produce 0.5 $M_{\odot}$ over 200 Myr
→ the dust mass produced from SNe II ~ 4 x 10^{6} $M_{\odot}$

→ tracing the early star formation / chemical enrichment out to z ~ 10 if combined with JWST

Summary

- ALMA's superb observing capabilities with 8 receiver bands (two under development) from 9.5 – 32 mm (950 – 84 GHz) allow for detailed imaging of continuum or molecular line emission from

  : 1 – 100 pc scale molecular clouds and substructures in nearby galaxies or

  : 0.1 – 1 kpc scale gas+dust discs in high-redshift sources

  : within 24 hrs, at the maximum (in general)

- Ideal for either

  (1) MAPPING and /or RESOLVING

  : the distribution and/or kinematics of molecular gas in nearby galaxies

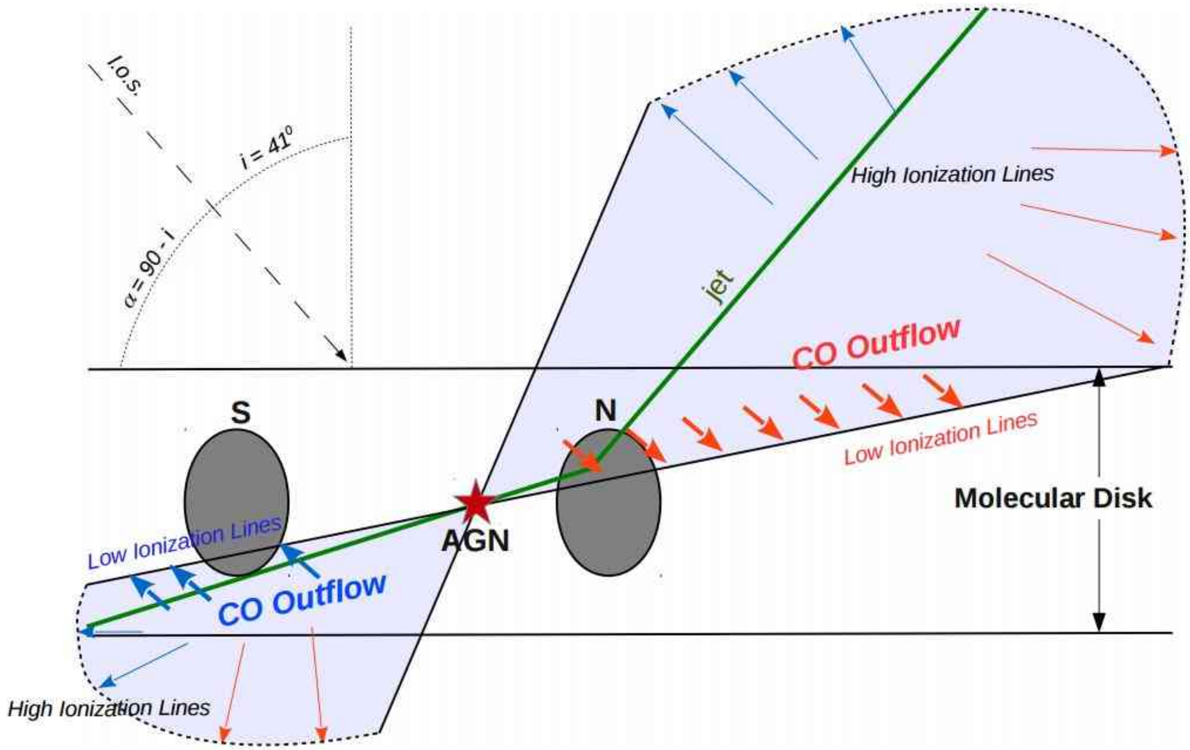
  : outflowing/infalling molecular gas in the central region of galaxies

  or (2) DETECTING

  : faint sub-mm sources & dust content in the early Universe

Thank you!

ALMA Extragalactic Science: Mapping (an AGN-driven outflow in the dense molecular gas Garcia-Burillo et al. 2014)

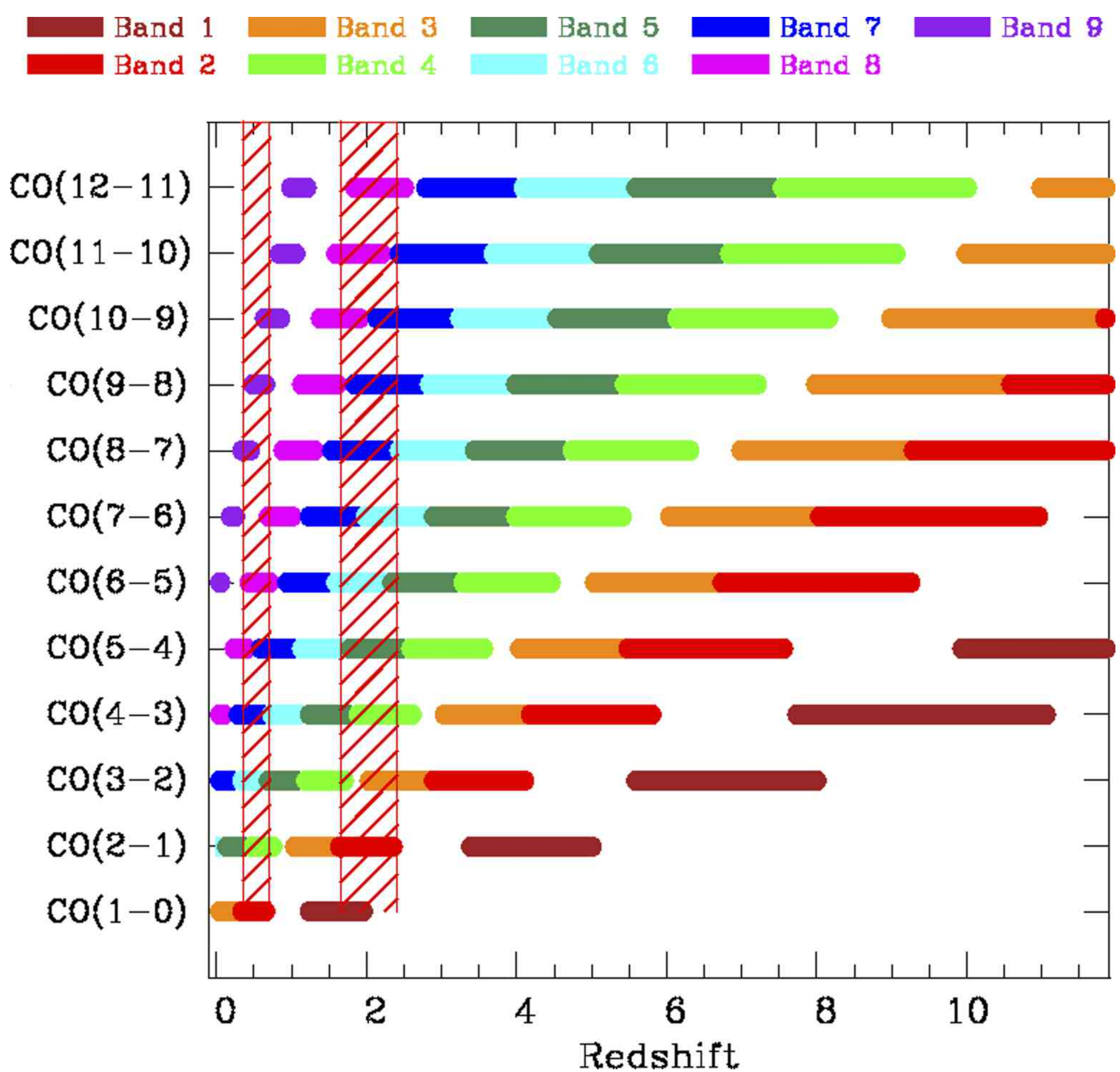


→ The molecular outflow launched when the ionization cone of the narrow line region sweeps the nuclear disk

→ The outflow rate far higher than the SFR: AGN-driven

→

CO ladder coverage for ALMA bands



Fuller et al. (2016)