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's observing capabilities for Extragalactic Science

- **Sensitivity**
  - detect spectral line emission from CO or [CII] in MW-like galaxies at $z \sim 3$ in less than 24h

- **Spectral/spatial resolution**
  - $\sim 0.5$ km/s channel resolution
  - down to milli-arcsec resolution: $\sim 1$ pc (local Universe) to $\sim 1$ kpc ($z \sim 1.0$)

- **Field of view**
  - $21''$ @ 300 GHz (primary beam), scaling linearly with wavelength
  - mosaicking required for regions larger than the primary beam

- **Array configuration**
  - ALMA 12-m x 50 array ($\sim 150m$ out to $\sim 16$ km)
  - Atacama Compact Array (ACA; 7-m x 12) + TP (4 x 12m)
  → short spacing
ALMA Cycle 3 proposal results report

**Science categories: Submitted proposals**

- **Cosmology**: 400 proposals
- **Galaxies**: 300 proposals
- **ISM & SF**: 350 proposals
- **Disks & Planetary systems**: 450 proposals
- **Stellar evolution**: 400 proposals

**Science categories: Requested 12-m Array time**

- **Cosmology**: 2000h
- **Galaxies**: 1000h
- **ISM & SF**: 1500h
- **Disks & Planetary systems**: 1000h
- **Stellar evolution**: 500h

**Science categories per region: Submitted proposals**

- **EU**
  -Cat 1: Cosmology: 25.1%
  -Cat 2: Galaxies: 25.3%
  -Cat 3: ISM & SF: 21.5%
  -Cat 4: Disks & Planetary systems: 17.5%
  -Cat 5: Stellar evolution: 10.7%

- **NA**
  -Cat 1: Cosmology: 19.3%
  -Cat 2: Galaxies: 25.8%
  -Cat 3: ISM & SF: 21.2%
  -Cat 4: Disks & Planetary systems: 26.6%
  -Cat 5: Stellar evolution: 7.1%

- **EA**
  -Cat 1: Cosmology: 18.0%
  -Cat 2: Galaxies: 26.8%
  -Cat 3: ISM & SF: 34.6%
  -Cat 4: Disks & Planetary systems: 15.3%
  -Cat 5: Stellar evolution: 5.4%

- **CL**
  -Cat 1: Cosmology: 29.6%
  -Cat 2: Galaxies: 12.2%
  -Cat 3: ISM & SF: 21.7%
  -Cat 4: Disks & Planetary systems: 30.4%
  -Cat 5: Stellar evolution: 6.1%

- **Other**
  -Cat 1: Cosmology: 24.4%
  -Cat 2: Galaxies: 31.1%
  -Cat 3: ISM & SF: 22.2%
  -Cat 4: Disks & Planetary systems: 8.9%
  -Cat 5: Stellar evolution: 13.3%

**Average execution time by science category**

- **Cosmology**: 7h
- **Galaxies**: 6h
- **ISM & SF**: 7h
- **Disks & Planetary systems**: 5h
- **Stellar evolution**: 7h
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 formation and evolution of galaxies

- Detection
  - (faint) source counts and cosmic H2 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 $12+\log(O/H)\approx 7.8$ (c.f. MW$\approx 8.66$)
  - 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.
  → $6.2 \times 4.3$ pc @ 5 mJy/beam + 0.5 km/s
Dense CO clouds in the low metallicity dwarf galaxy WLM
(Rubio et al. 2015, Nature)

- 10 dense CO clouds detected
  → the sizes and virial masses, and thus the densities calculated
  → an average radius of 2 pc and $M_{\text{vir}} \sim 2 \times 10^3 M_\odot$
  → 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 outflow in the dense molecular gas (Garicia-Burillo et al. 2014, A&A)

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

- 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 ($z \sim 4.5$)
  → 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 $z \sim 2$

Madau & Dickson (2014)
Uncovering the golden age of galaxy formation

→ (first) CO luminosity function (solely from CO emission) and cosmic H$_2$ density as a function of $z$ out to $\sim 4.5$

→ Clear evidence of an evolution in the CO luminosity function

→ More CO luminous galaxies at $z \sim 2$

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

→ Cosmic H$_2$ with a factor 3-10 drop down from $z \sim 2$ to $z \sim 0$

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

Madau & Dickson (2014)
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
Source counts of faint SMGs from high-resolution ALMA survey
(Karim et al. 2013, MNRAS)

→ 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 $M_{\text{gas}} > 5 \times 10^{10} M_\odot$. 
QSOs at $z > 6$, a unique sample for the first SMBHs and their host galaxies

~60 QSOs known at $z \sim 6$ from optical/IR surveys

$10^9$ M SMBHs at $z \sim 6 \rightarrow$ 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 $z \sim 6$ (50-90 min/target)

→ 0.4-0.7 mJy/beam @ 0”.7 ($\sim$4 kpc @ $z \sim 6$) + 16-18 km/s
Dust continuum+
\[\text{[C II]}\] line detected from the host galaxies of 5 QSOs at \(z \sim 6\)

→ Indicates active SF in the central few kpc region

→ \[\text{[C II]}\] / FIR comparable to typical ones in local ULIRGs and other FIR-luminous QSOs at high \(z\)

→ the dynamical masses within the \[\text{[C II]}\]-emitting region measured

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

→ study an early phase of SMBH-galaxy evolution

→ ALMA \[\text{[C II]}\] 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 \(z\)
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 $z \sim 6$ (biased?) ultra-luminous sources can be further pushed out to $z \sim 10$ and beyond by targeting gravitationally-lensed systems.

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

- VLT spectroscopic confirmation of $z \sim 8.38$
- ALMA [O III] 88 $\mu$m 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 ($7.1 - 18.2 \times 10^{10} M_\odot$) and a dust mass ($1.8 - 10.4 \times 10^6 M_\odot$) are derived

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

1. SFR $\sim 20 M_\odot$/yr;
2. $M_\star \sim 2 \times 10^9 M_\odot$;
3. $M_{\text{dust}} \sim 5.5 \times 10^6 M_\odot$

→ Recent studies indicate significant SF began at $z \sim 10 - 12$, 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 $\sim 4 \times 10^6 M_\odot$

→ tracing the early star formation / chemical enrichment out to $z \sim 10$ 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
  2. DETECTING:
     - faint sub-mm sources & dust content in the early Universe

Thank you!
CO ladder coverage for ALMA bands

Fuller et al. (2016)
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
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 $<-20^\circ$.

*De Breuck (2004)*