Science with ALMA

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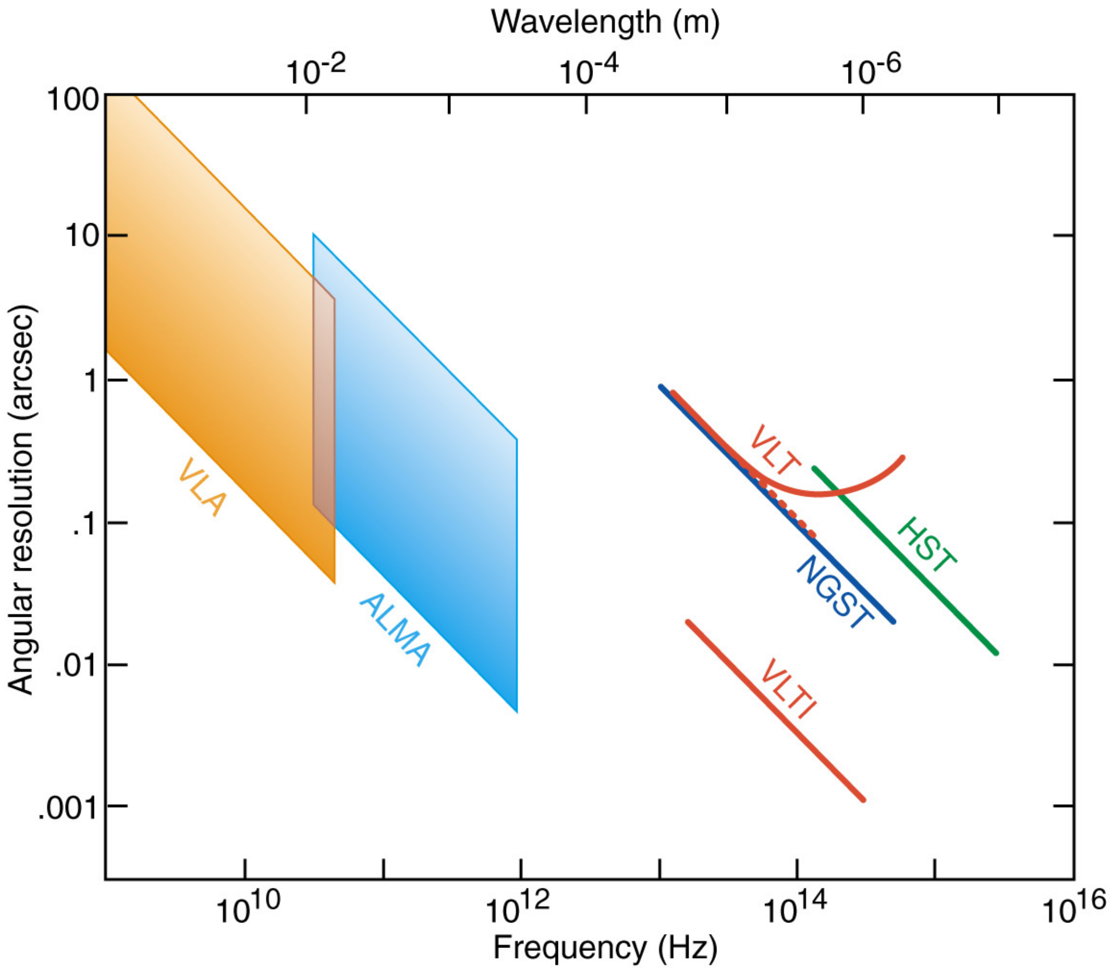
Main reference: "ALMA Science Case"- January 2001 http://iram.fr/ guillote
Other references are given

ALMA: scientific goals

- **ALMA is not a specialized telescope,**
- **but very well suited to some domains**
  - **A** High-Z universe
  - **B** Structure and evolution of galaxies
  - **C** Stellar formation and evolution
  - **D** Planetary system formation
  - **E** Solar system
  - **F** Interstellar chemistry (from galaxies to protoplanetary disks and planetology)
  - Dual Polarisation
- **One should even observe the Sun...**(if antenna surface allows...)

ALMA compared to other intruments



Spectroscopy: 25 × more sensitive at 1.3mm than PdBI
Continuum: 50 × more sensitive at 1.3mm than PdBI

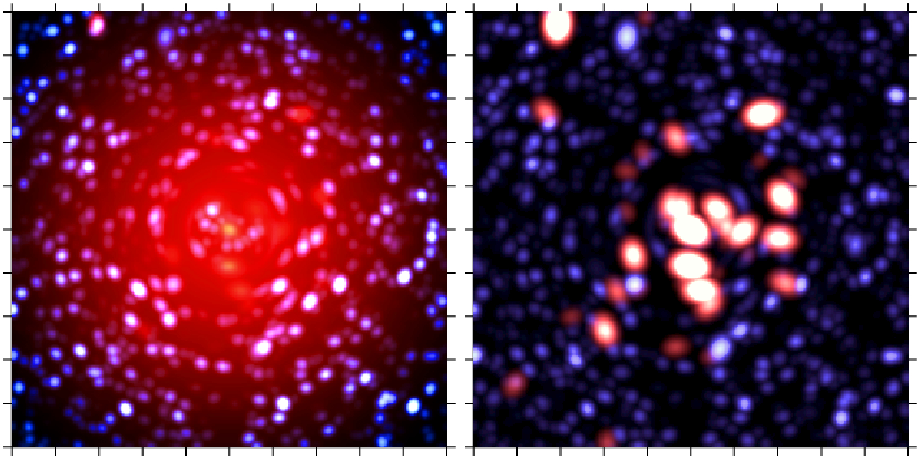
A - High-z Universe

- **Deep continuum images in very large fields in mm and/or sub-mm $\rightarrow$ no confusion, better sensitivity**
  - **Identification of high-z objects**
  - **High resolution images (gravitational lensing models)**
  - **Measurements of the kinematics (virial masses)**

- **Very large band spectrum (70-800 GHz)**
  - **Redshift determination**
  - **Search for high-z galaxies in CO lines**
  - **Search for CII (other lines...)**

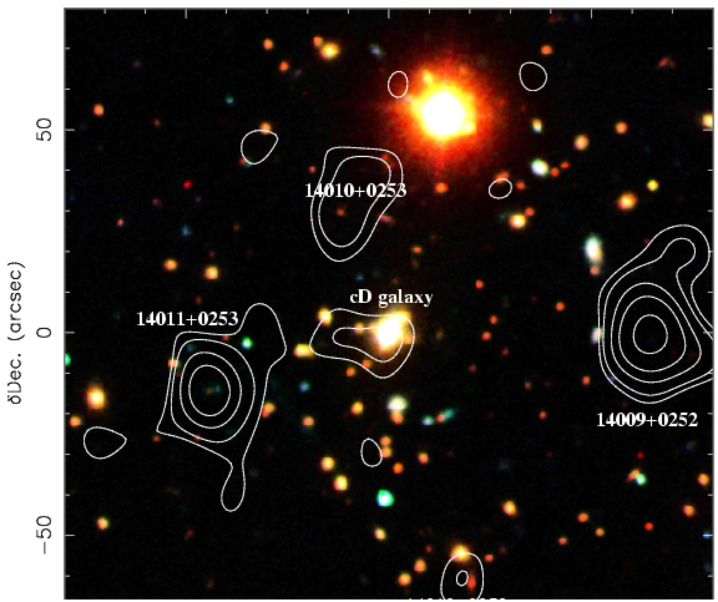
- **Cosmic background**

A cluster in mm-wave and in optical - simulations



+ LEFT: simulated appearance of a cluster of galaxies at redshift z =0.2 observed with ALMA at 0.8 mm and resolution $\sim 3''$.
+ Red is used for cluster members & emission from the Sunyaev-Zel'dovitch effect.
+ Blue is used to represent background galaxies magnified by the cluster
+ RIGHT: Simulation of the same field in the optical R band.
+ The submm image is much more sensitive to high-z galaxies. With ALMA, a survey of the whole field (100$''$ or 30 pointings at 0.8mm) should allow to detect the faintest sources (0.01mJy) in $\sim$ **70 hours /field** = 2100 hours in total !

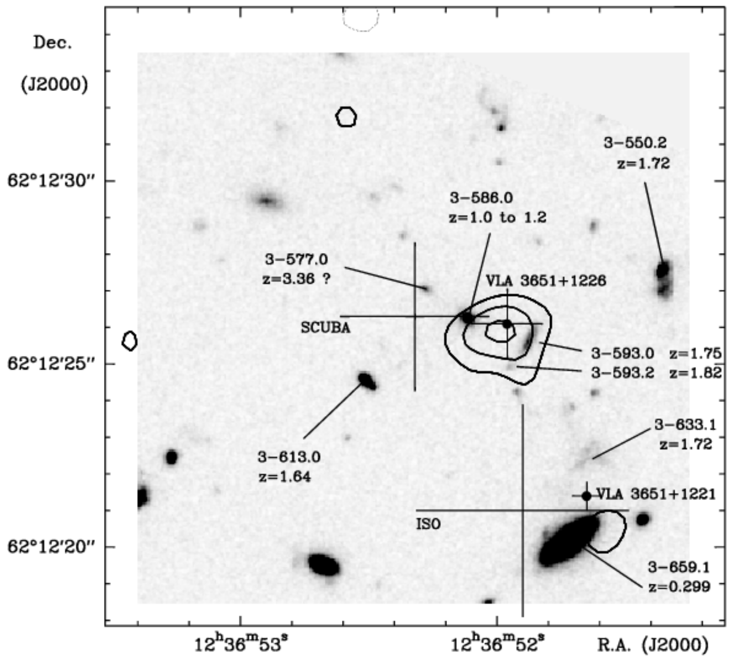
A cluster in mm-wave and in optical - observations



A 850 μm SCUBA image of the core of the cluster A1835 (contours) superimposed on a multi-colour Hale telescope image (from Ivison etal., 2000).
+ Red cluster member galaxies are not typically submm sources
+ Counterparts to the labeled submm sources are faint optical objects
+ Today, only $\sim$ 12 identifications
+ $\sim$ 100 mm/submm detections
→ Optical and mm wide field images provide complementary information...

ALMA → submm images with finer resolution than optical ones.

Confusion: Hubble Deep Field



Map at 1.3mm (IRAM interferometer) of the region around the brightest SCUBA source (HDF 850.1), superimposed on a Hubble Deep Field BVI image (from Downes etal.,1999).

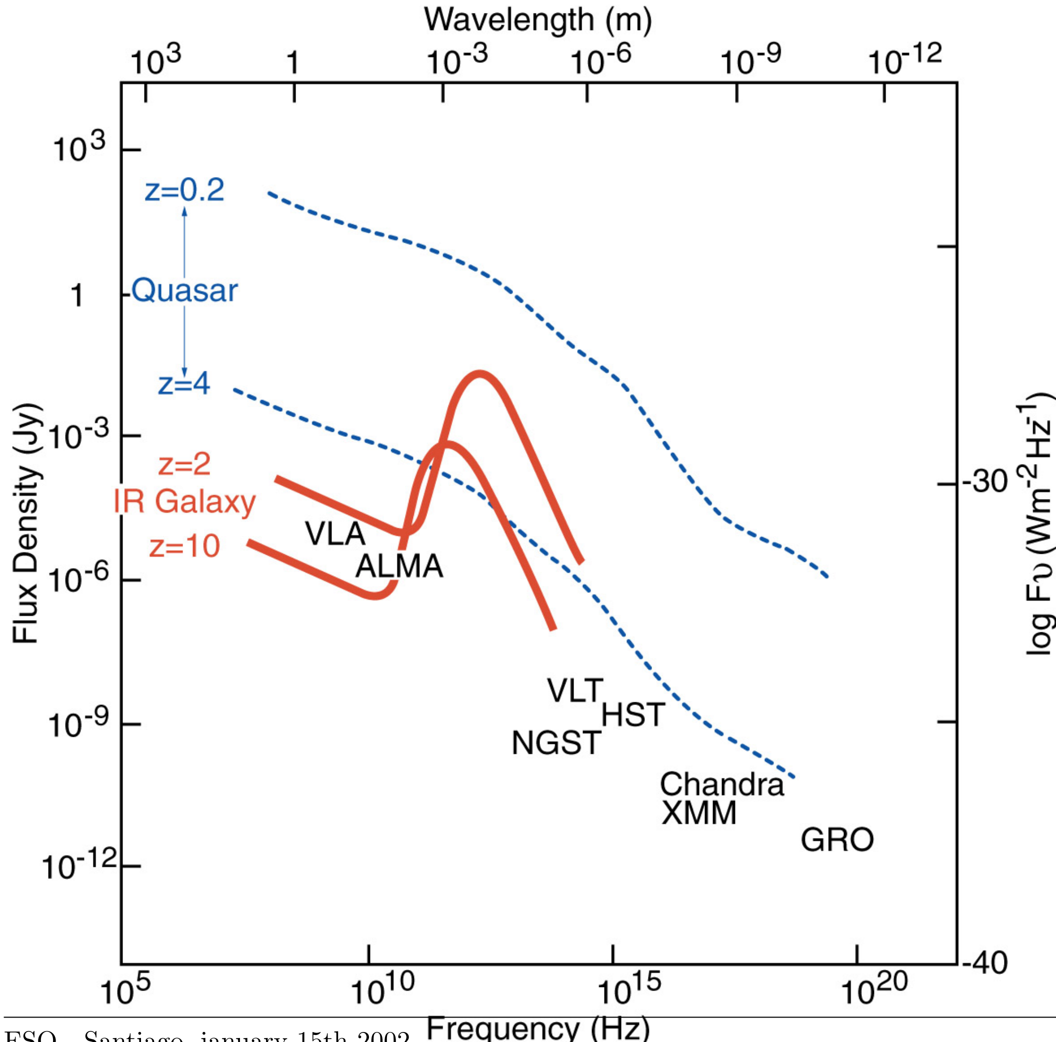
\+ The cross marked SCUBA indicates the position and 3σ uncertainty of HDF 850.1.

\+ Small crosses with black dots indicate radio sources.

\+ The large cross marked ISO indicates a 15-μm source

ALMA → no confusion, thanks to resolution and sensitivity

Spectral Energy Distribution (SED) of redshifted galaxies



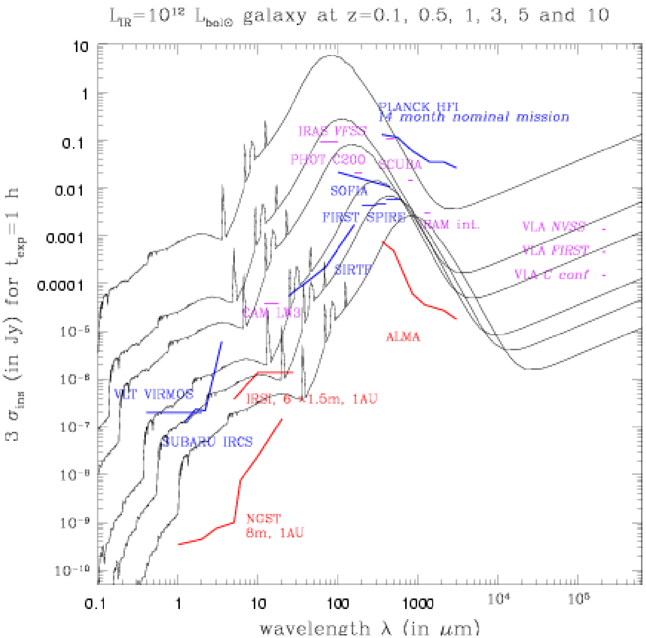
+ Broadband flux from distant galaxies is diminished in the UV and optical both due to the redshift and obscuration by internal dust

+ **However**, the same dust produces a large peak in the rest-frame far-infrared

When redshifted, this greatly enhances the millimeter and submillimeter emission.

→ **Inverse K correction**

Redshifts for z=0 to 10 (photometry)

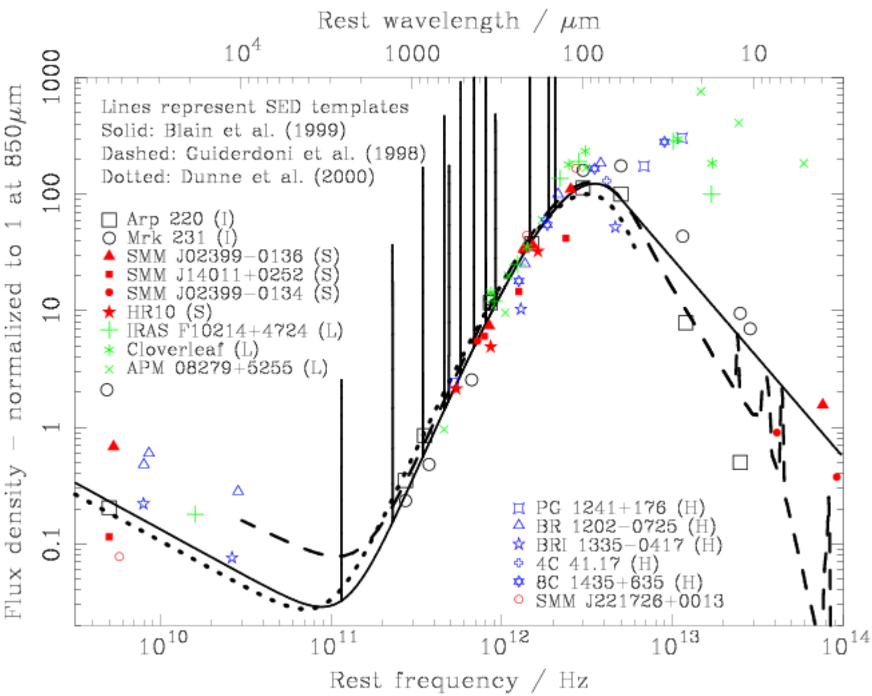


+ ALMA compared to other instruments (wavelengths)

+ Flux ratio between 100 and 300 GHz (3 - 1 mm) is enough to provide the **photometric redshift for z** $\geq 3 - 4$

ALMA → Finding the first galaxies that formed after the "dark ages".

Redshifts for z=1 to 10 (spectroscopy)

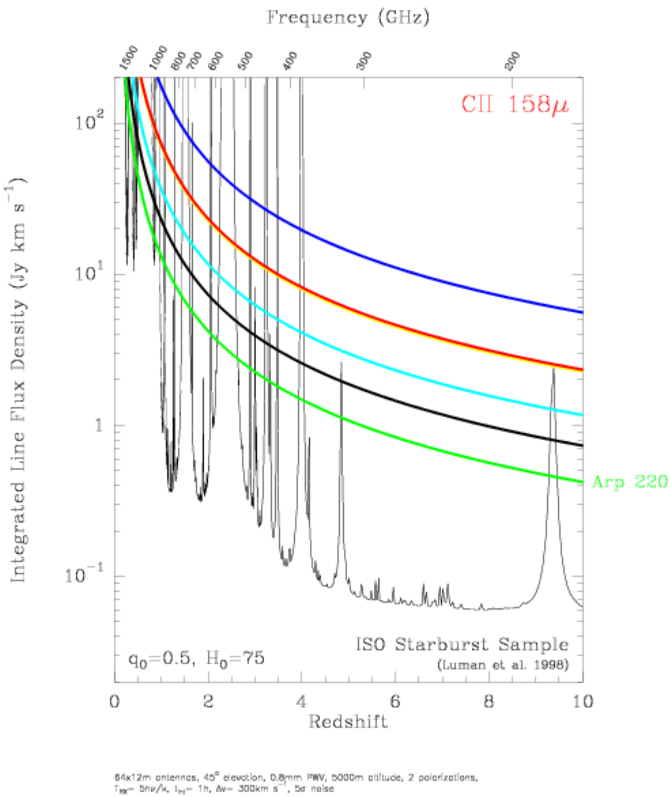


Details of SED of galaxies in the ALMA domain
+ A wide range of detectable spectral CO and atomic lines (from Blain etal., 2000)

+ Ladder is compressed by (1+z)
+ At z$\geq$ 3, two CO lines are separated by less than 28 GHz

$\rightarrow$ If $\Delta\nu = 16$ GHz, 3 adjacent tunings are enough (48 GHz) to get the **spectroscopic redshift**

High-Z objects: CII - redshift



+ The colored lines represent the integrated line flux densities one would observe for the 158 μm CII fine structure line from the sample of ULIRG observed by Luhman etal., 1998 using the ISO satellite if those galaxies were at the redshifts indicated by the abscissa

+ The thin line indicates the typical 5σ noise level of ALMA in two hours of integration, for a velocity resolution of 300 km s^{-1}, and assuming the precipitable water vapor content of the atmosphere is 0.8 mm

For z≥ 1.5, the CII line at 158 μm is in the ALMA bands, an efficient way to directly measure redshifts

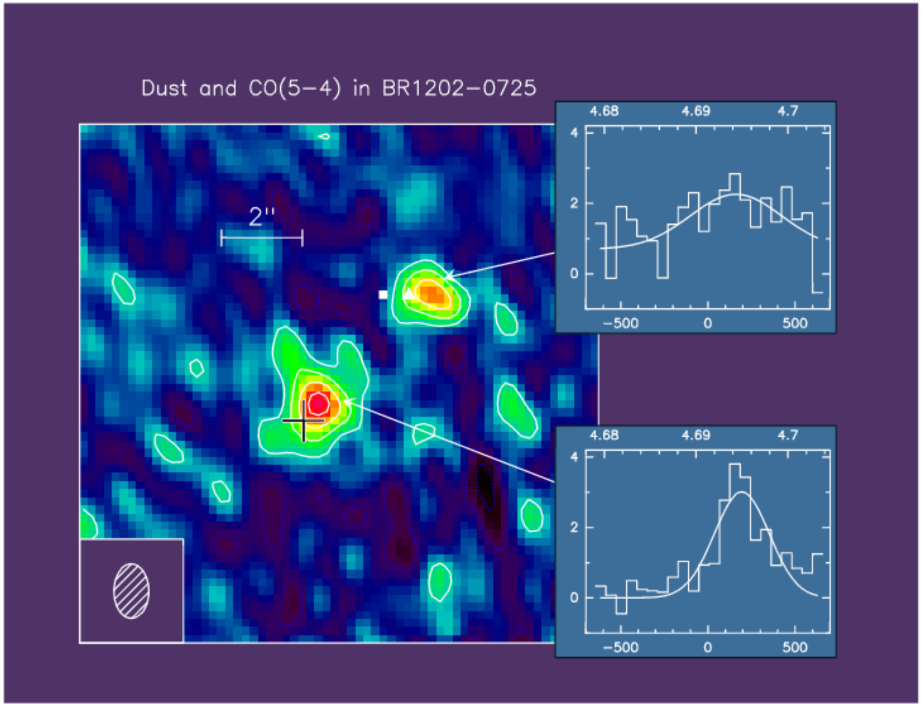
Strategy for an ALMA redshift survey

- **$4' \times 4'$ field, about twice the HDF area**

- **Step 1:** Continuum survey at 1mm to reach 0.1mJy/field, 5σ, with 140 pointings in 3 days. It should find 100-300 sources (30-100 brighter than 0.4 mJy)
- **Step 2:** Continuum + Line survey at 3mm down to 7.5μJy (5σ) in 16 pointings and 4 tunings covering 84-116 GHz (8 days).
  - 300 GHz /100 GHz flux ratio
    $\rightarrow$ **photometric redshifts distribution** for z $\geq 3 - 4$
  - For linewidth larger than 300 km/s: line sensitivity should be 0.02 Jy.Km/s
    $\rightarrow$ **CO lines detected in all sources detected in Step 1**
  - At least **ONE** CO line for sources with z $\geq$ 2, **TWO** for z$\geq$6
    $\rightarrow$ **"blind" redshift regions are 0.4-1 and 1.7 - 2.0** (previous figures)
- **Step 3:** Continuum survey at 600 GHz down to 0.4mJy: 1.5 hours /pointings. 100-300 sources means 1-2 weeks.
  $\rightarrow$ All low redshift sources (z≤ 1) detected in step 1 are detected
  $\rightarrow$ Low 650 GHz/ 300 GHz flux ratio indicates high redshift sources ($r \leq 1$ for z ≥ 5)

- **Grand total of integration time required for a "complete" ALMA sample on a $4' \times 4'$ field: 3- 4 weeks**

High-Z objects: BR1202-0725 (grav. lensing?)



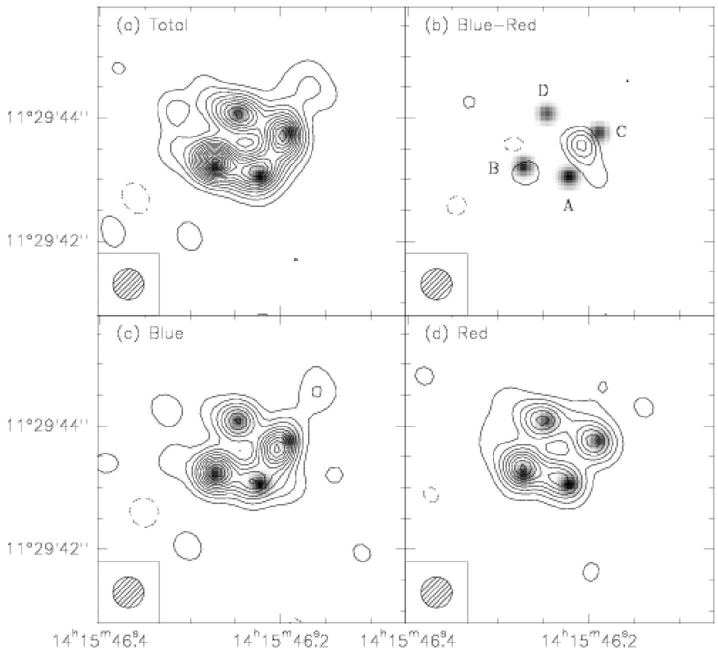
The quasar BR1202-0725 at $z = 4.69$, mapped in the dust continuum at 1.3 mm and CO(5-4) spectra of each component with the IRAM array (Omont et al., 1996)

+ A large amounts of dust and CO molecules are present already at $z = 4.7$

+ This redshift corresponds to a look-back time of 92% of the age of the Universe

+ It shows that enrichment of the interstellar medium occurred at very early epochs

Gravitational Lensing



Images of the Cloverleaf quasar, H1413+117, at $z = 2.56$, in the CO(7-6) line with the PdBI with an 0.6″ beam (Kneib etal., 1998)

+ The difference visible in panel b) indicates velocity gradient which, using an appropriate lens model, can be attributed to a circumnuclear disk of about 100 pc around the quasar

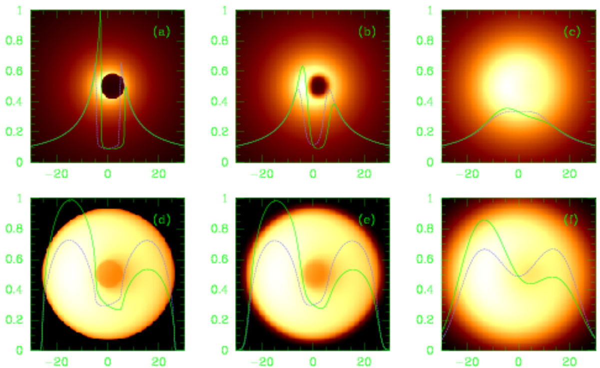
+ In all panels, the greyscale background is an HST optical image

+ High-resolution CO spectral-line observations with ALMA will allow the velocity structure within each image to be resolved, and thus the internal structure and dynamics in the lensed galaxy to be imaged in detail

B - Structure and evolution of Galaxies

- **High sensitivity and resolution mapping**
  - **"standard" galaxies up to z=0.5-1**
  - **Individual molecular clouds for the closer ones**
  - **Initial mass function**
  - **Measurements of the kinematics (virial masses)**
  - **Starburst in galaxies**
- **Active Galactic Nucleus (Black Hole)**
- **Chemistry**

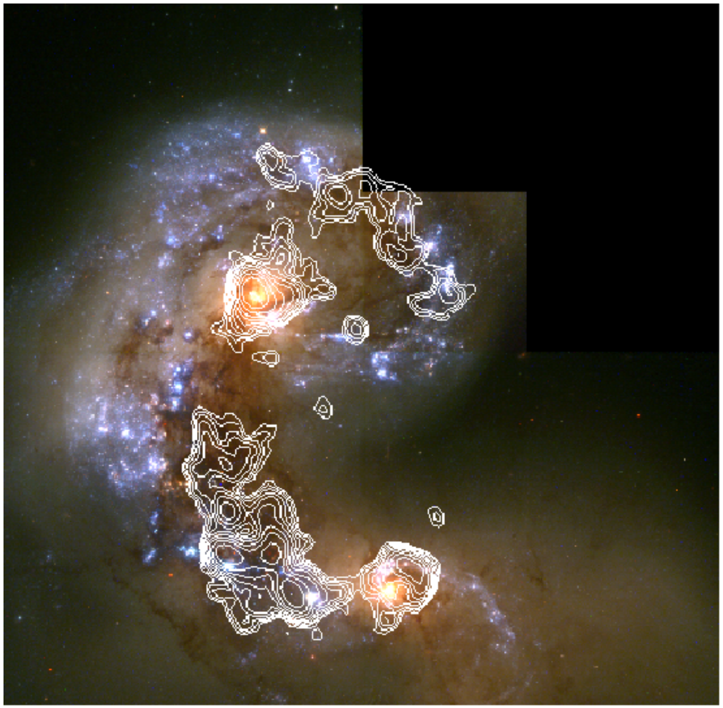
Central Engine of the Galaxy (ALMA in VLBI)



Gravitational shadow: optically thin emission region surrounding a black hole with the characteristics of SgrA at the galactic center (from Falcke et al., 2000)
+ Rotating: a-c, Non rotating models: d-f. Emitting gas in free-fall with emissivity $\propto r^{-2}$ (top) or Keplerian shells (bottom) with a uniform density and $i = 45^o$
+ Figs a&d: GR ray tracing calculations
+ Figs b&e: as seen by an idealized **VLBI array** at 0.6 mm (taking into account the interstellar scattering)
+ Figs c&f: idem for 1.3mm
+ Curves show the x and y intensities. x axis gives the distance to the black hole.

ALMA in VLBI array will allow to study AGN in details

Opt. and submm views of a star forming galaxy

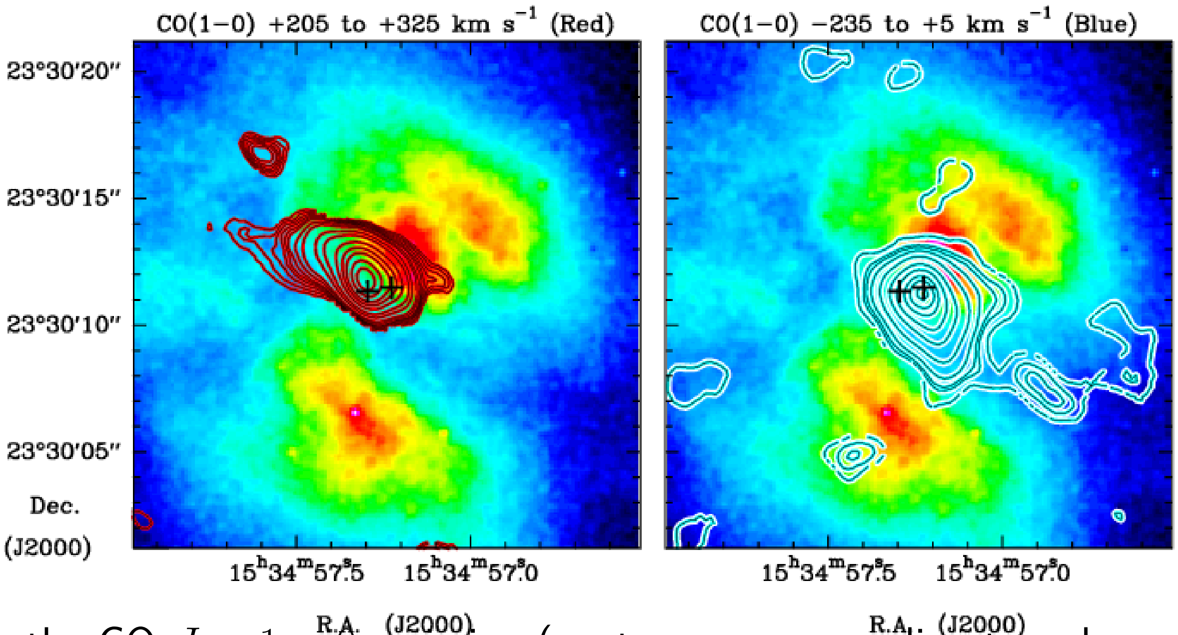


The complementarity of observations made using optical and submillimeter-wave radiation

+ The Antennae are a well known pair of interacting low-redshift galaxies (Wilson et al., 2000, Mirabel et al., 1998)

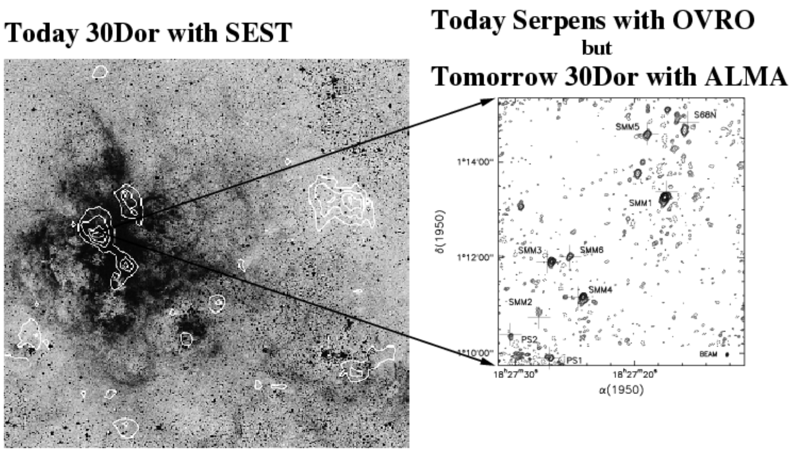
+ Comparing the appearance of the CO emission (contours) with the HST image allows to accurately account for the starlight absorbed by dust and reradiated at long wavelengths

Starburst: ARP220



Arp 220 in the CO $J = 1 - 0$ emission (contours corresponding to red- and blue-shifted gas) superposed on a false-color presentation of the HST V-band image (Downes et al., 1998). The crosses indicate the radio nuclei at centimeter wavelengths. ALMA will allow to determine the masses and kinematics of optically obscured galactic nuclei and image the distributions of a variety of molecules. In Arp 220, it will be possible to resolve single molecular clouds and study their physics and chemistry using tracers such as higher rot. CO, HCN or [C I] fine structure lines. In nearby galaxies: $1'' - 2'' \sim 15 - 30$ pc

Star-forming regions in external galaxies



A comparison the Serpens (star-forming region Serpens, at 300 pc) and 30 Doradus, in the LMC (adapted from Testi et al., 1997)

In nearby galaxies, the identification of gravitationally bound individual molecular clouds will give insight into the H_2/CO conversion ratio through virial analysis.

ALMA will allow to map in detail the main dynamical components of spiral galaxies: spiral arms, bars, and also the nuclear embedded bars and resonant rings that will constrain theoretical scenarios

Stellar Physics in External Galaxies

- **Stellar Physics in the Magellanic Clouds (D=0.05 Mpc):**
  – Resolve out molecular clouds
  – Detect envelopes similar to that of IRC+10216
  – Detect and Image molecular outflows similar to that of L1551
- **Molecular clouds:**
  – At 0.05 Mpc, 10 pc $\sim$ 30″
- **IRC+10216:**
  – At 120 pc, CO envelope $\sim 60''$ or ~ 7500 AU $= 0.036$ pc
  – At 0.05 Mpc, CO envelope $\sim 0.12''$
  $\rightarrow$ A single object per beam (resolution $\sim$ 0.03″ at 1.3mm on long baselines)
- **L1551:**
  – At 150 pc, CO flow $\sim 20'$ or $\sim 20 \cdot 10^4$ AU $= 1$ pc
  – At 0.05 Mpc, CO flow $\sim 3''$ in the flow direction !