# ALMA Science:
# a review of (sub)mm band science and instruments in the ALMA era


Marcella Massardi

INAF- Istituto di Radioastronomia

Italian node of European ALMA Regional Centre

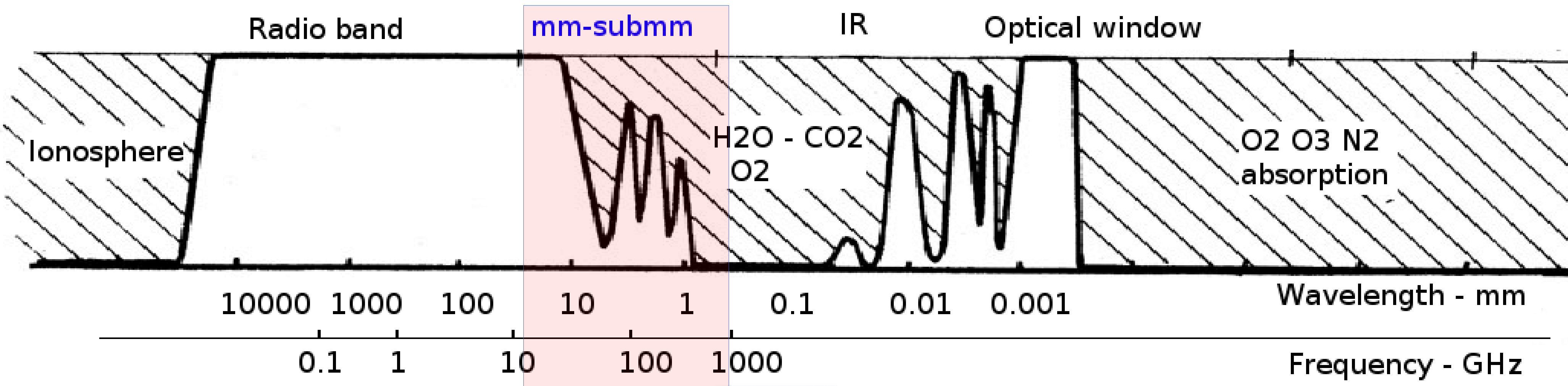

ALMA

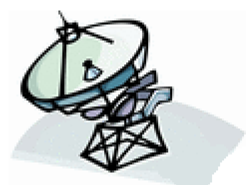
EUROPEAN ARC

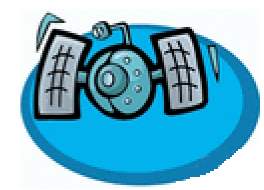
ALMA Regional Centre || Italian

SISSA – February 2014

# Outline



| | |
|---|---|
| **Signals in (sub)mm band** | What can we get out of them? |
| **The reasons for ALMA** | Pills of interferometry<br>ALMA properties<br>Writing a proposal |
| **Galactic Science** | From planets to our Galaxy |
| **Extragalactic Science** | AGNs<br>Submm galaxies<br>Galaxy clusters |

# Extragalactic science

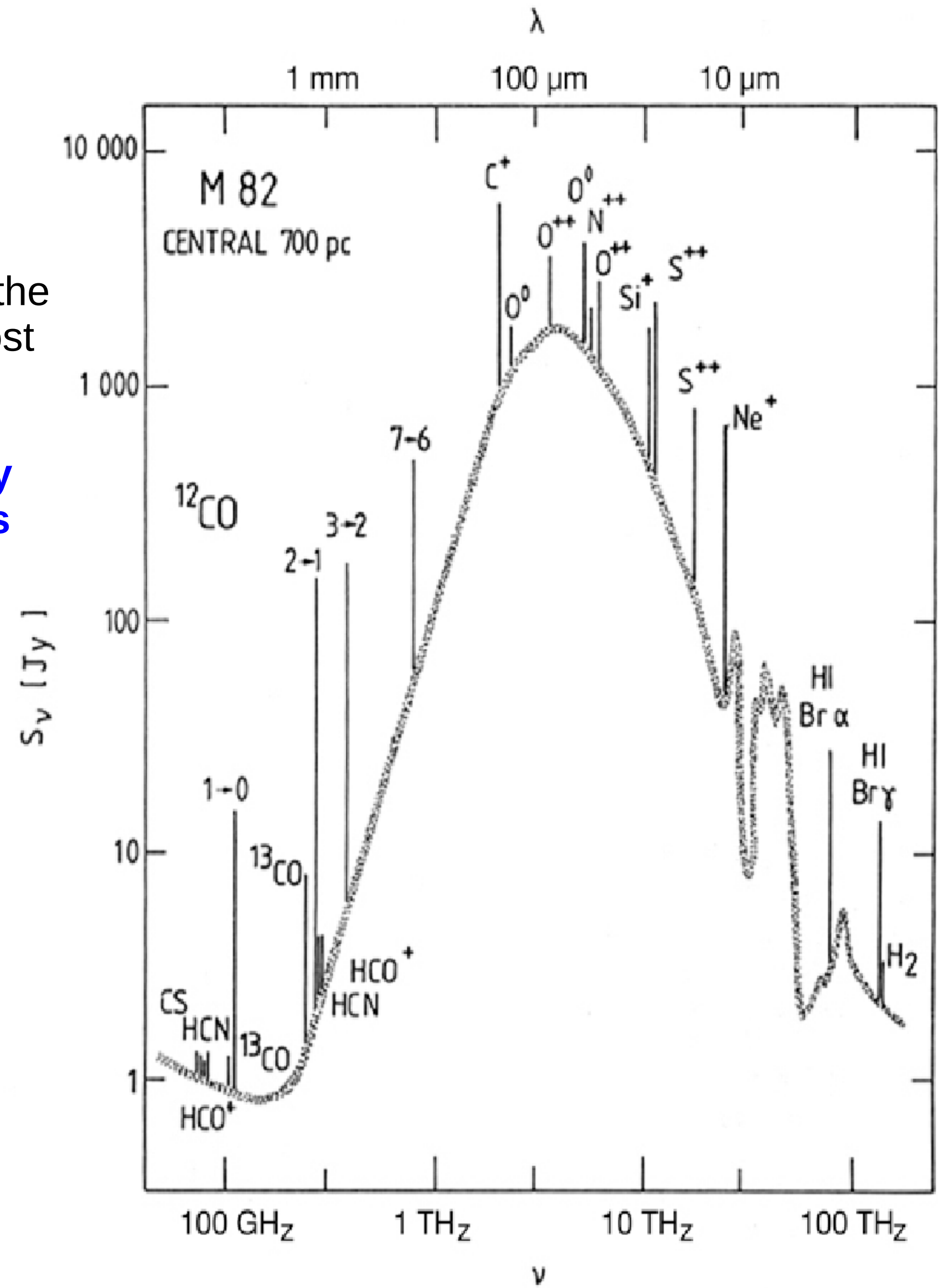
# Extragalactic science in (sub)mm

The (submm) bands encompass the RJ region of the warm dust thermal emission and the high frequency tail of the synchrotron emission (dominating the radio emission in most galaxies).

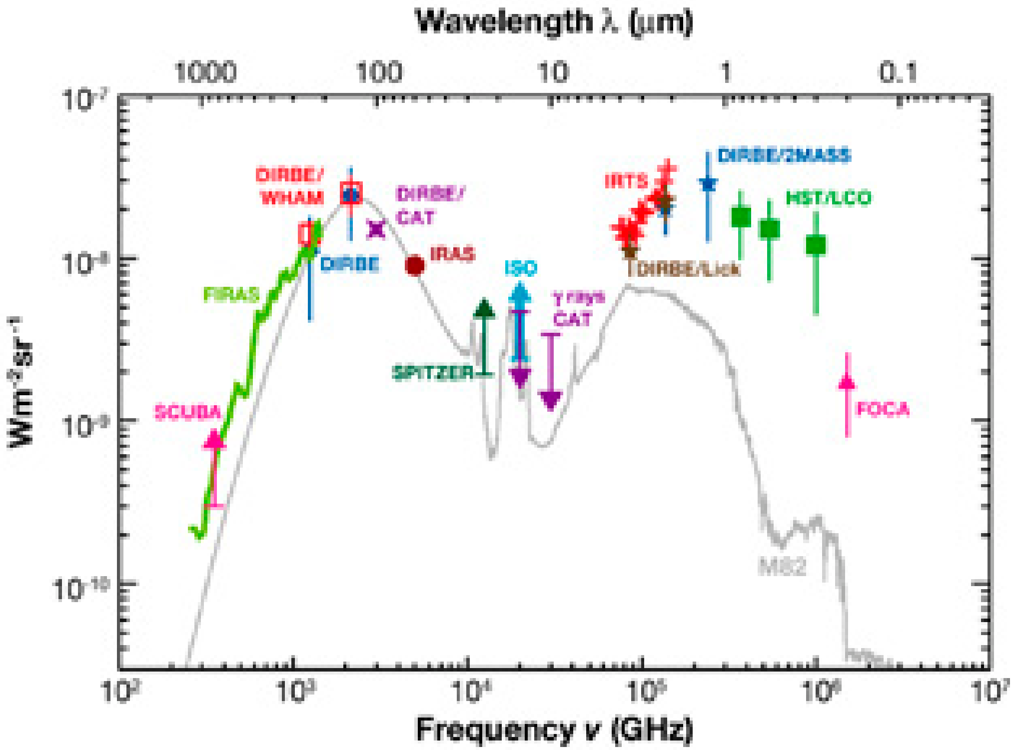
**The warm dust emitting at far–IR wavelengths is mostly heated by the UV-radiation field of young massive stars in star forming regions.**

**The far infrared luminosity is considered good tracer of star formation in galaxies.**

The spectrum of each galaxy in the submm is rich of rotational molecular transition ladders and atomic fine structure lines, which shapes and relative abundances can be used to trace physical and dynamical properties of the ISM and the mechanisms of SF and AGN activity.

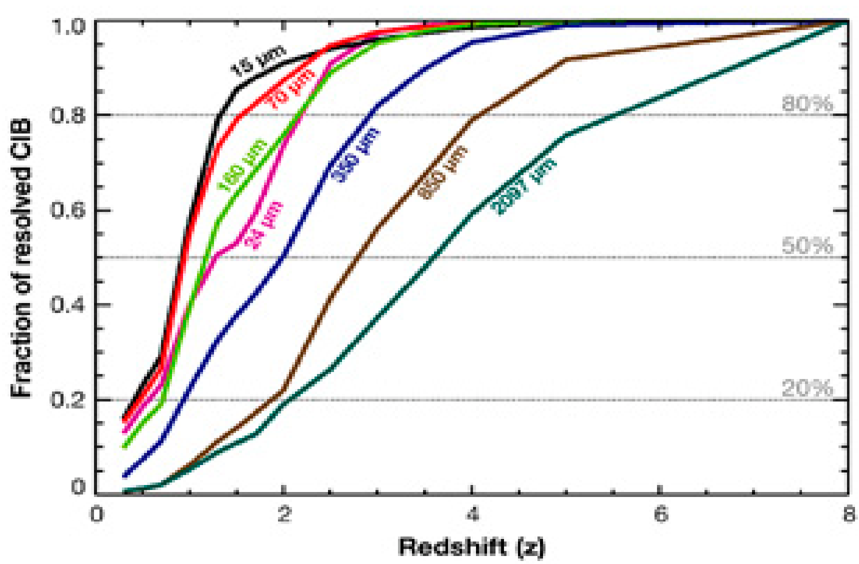


# Cosmic Infrared Background




The power in the infrared is comparable to the power in the optical.
Locally, the infrared output of galaxies is only one third of the optical output.

This implies that **infrared galaxies grow more luminous with increasing z faster than optical galaxies.**




(Lagache et al. 2005)

The fraction of resolved CIB as a function of z.
50% of the CIB is due to galaxies at
z<1 at 15 and 70 μm,
z<1.3 at 24 and 160 μm,
z<2 at 350 μm,
z<3 at 850 μm
z<3.5 at 2 mm
The CIB at longer wavelengths probes sources at higher redshifts.

# (sub)mm galaxy populations

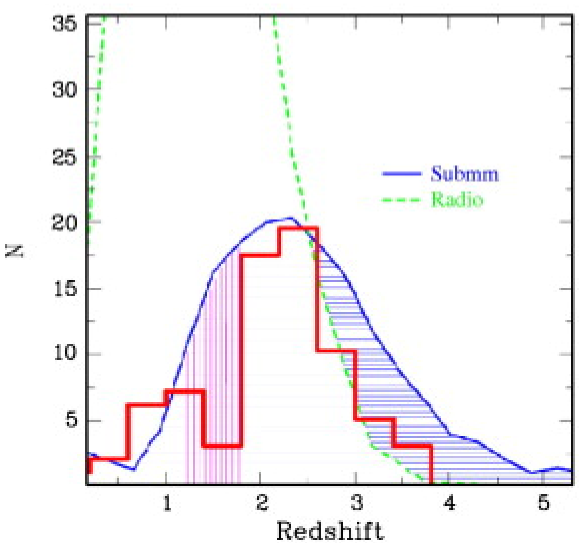
SCUBA surveys (Blain et al. 2000) identified the existence of **a population of highly dusty galaxies with high SFR.** Limits to their classification and observations were mostly due to confusion.
They were defined **SubMillimeter Galaxies (SMG)**.

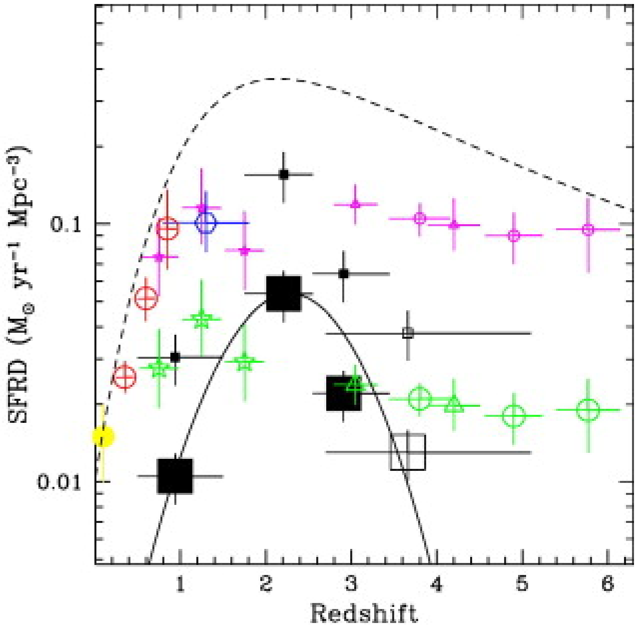
CO observations (Genzel et al. 2003, Greve et al. 2005, Tacconi et al. 2008...) measured masses and redshift for the SMGs, observing that there is a large fraction of massive galaxies at **z>2**.

**These fractions were at odd with hierarchical formation models**
**(larger galaxies are formed through the continuous merging of smaller ones)**
**and were the basics of "downsizing" (most massive galaxies form earlier and faster).**

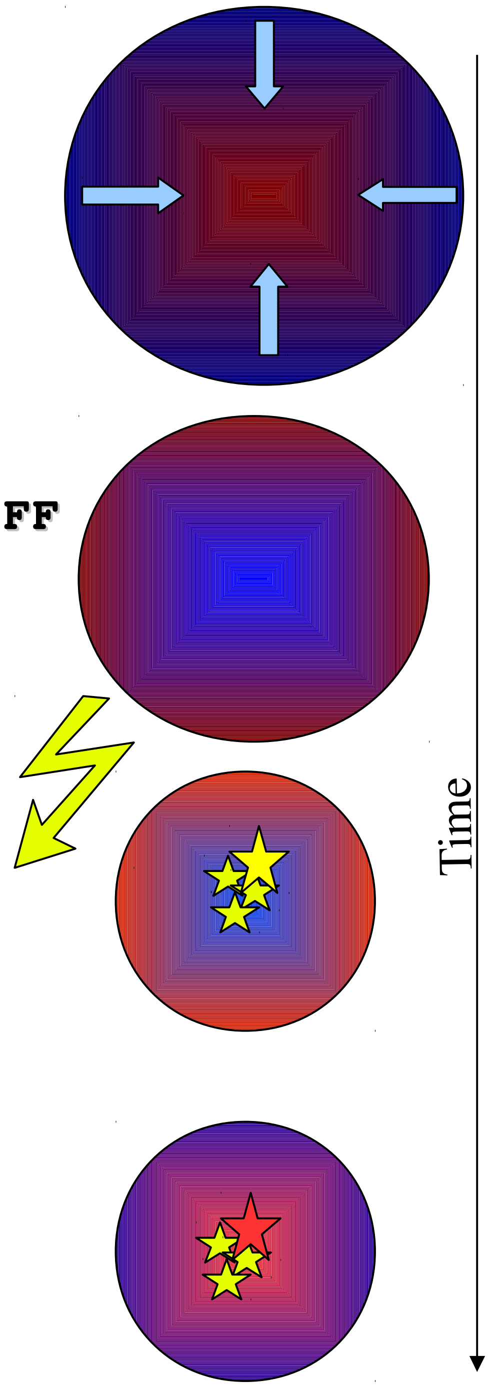
Chapman et al. (2003,2005) exploited the FIR-radio relation for SMGs to select them in radio bands and found that redshift distribution is similar to those of QSOs and that they contribute to SF history at z=2

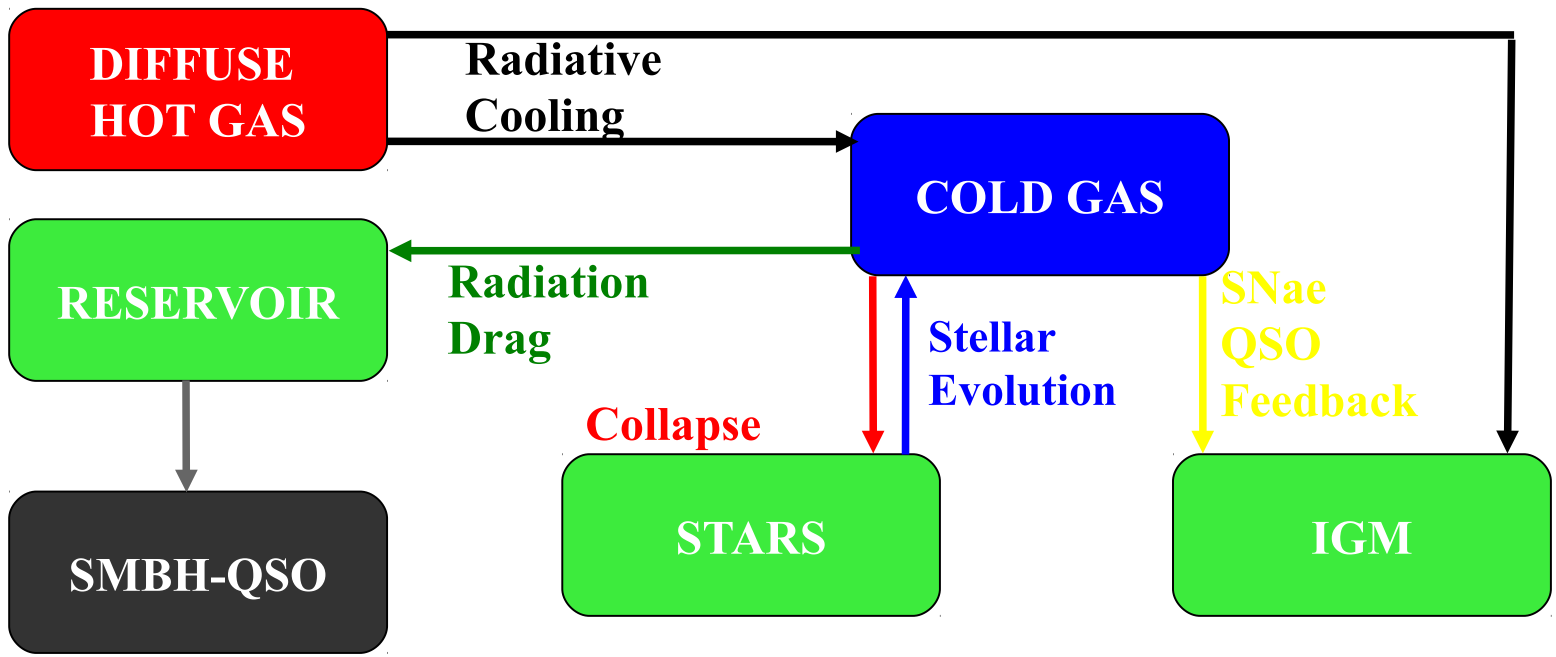
In the FIR the dust is predominantly heated by the star-formation activity rather than by the AGN also in QSO (Beelen et al. 2004).



# Example: Anti-hierarchical model




**Virial Collapse** : the gas becomes hotter and denser
**Radiative cooling** : free-free emission and SF
Radiation drag : reduces the gas angular momentum and produces a reservoir torus that feeds the central SMBH
**SNae feedback** : the gas is reheated and shocks are created, generating denser regions where SF continues
Most massive clouds have higher SFR and faster depletion time
AGN feedback: halts the collapse

Granato et al. 2004

# (sub)mm galaxy populations

**SMGs are the high redshift counterparts of local massive elliptical galaxies**
**(ULIRGs L_FIR>$10^{12}$ L_sun),**
**with AGN activity obscured by the high dust content.**

Open issues remain:
- What is the role of starburst or AGN activity in powering the dust heating and associated infrared emission?
- What is the role of merging events?
- What inject the SF events?

- Which are the properties of the dusty torus of AGN?
- How does the AGN feed the BH?
- How the AGN interact with the host galaxy?

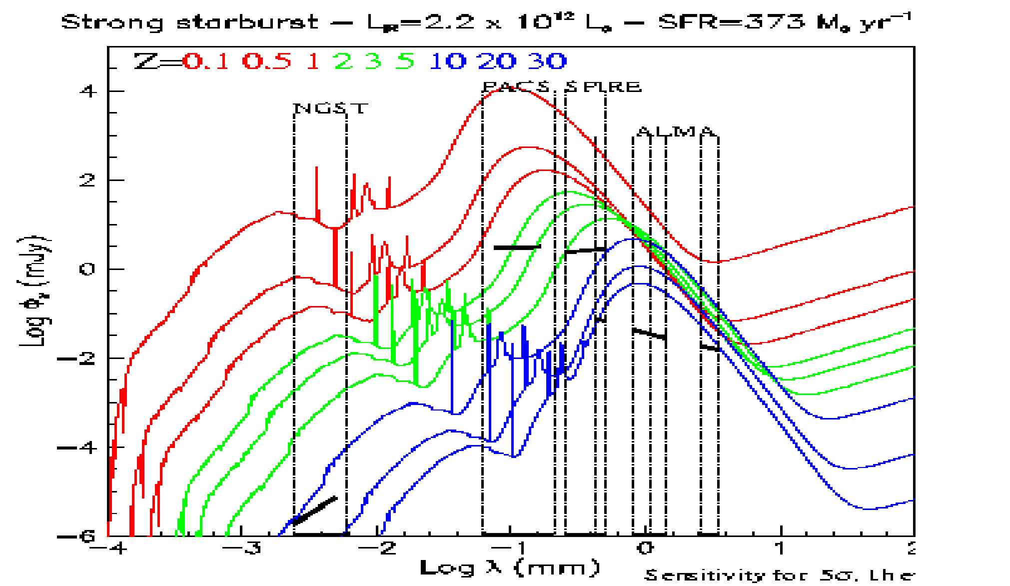
- Which is the most probable evolutionary scenario?
- They are only the tip of the iceberg, how do 'normal galaxies' evolve?

...

Answers - in the (sub)mm signals
- matching low to high-z observations

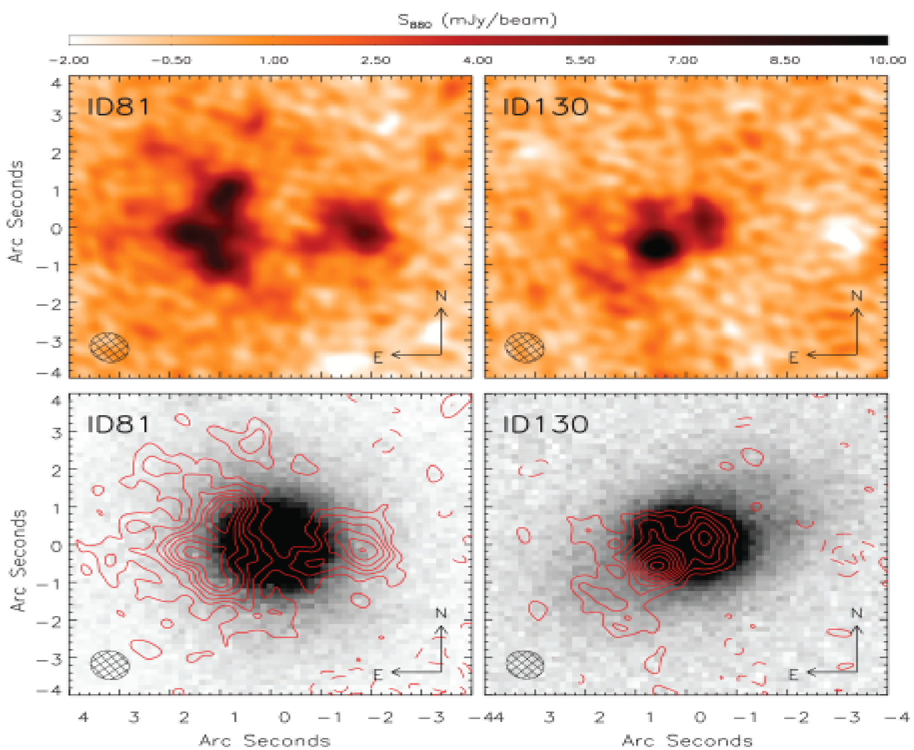
# Extragalactic science in (sub)mm

At high redshift the prominent **IR dust thermal bump** (which dominates the SED in starburst galaxies) is shifted into the submm band.

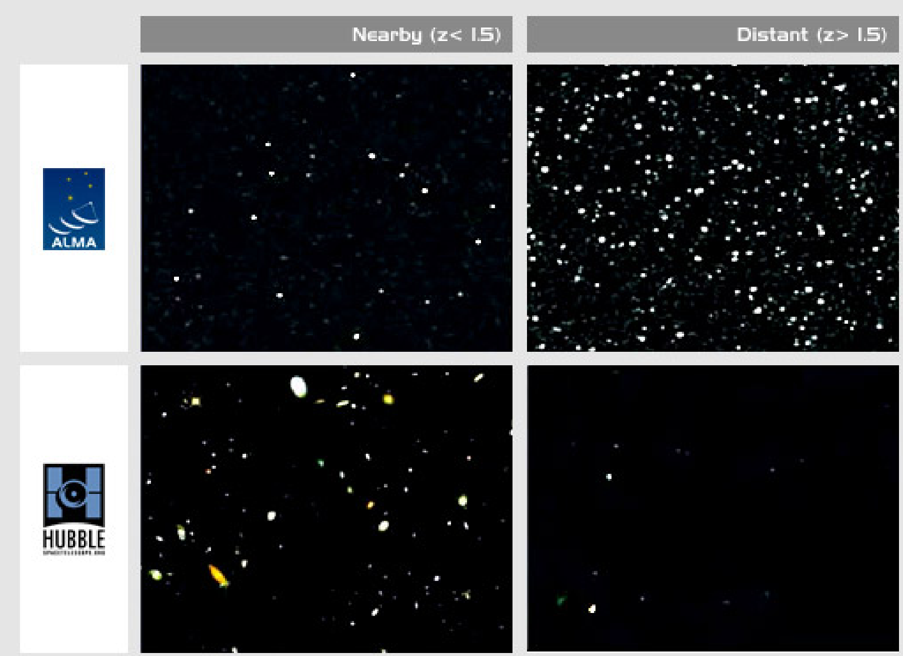



**Negative k correction**: for 1<z<10 galaxy flux density remain constant for 0.8<λ<2mm. High-z galaxies look brighter than low-z & more high_z than low_z in deep fields.

**Obscuration** is not an issue as in optical bands




(Negrello et al 2010)



# Molecular lines

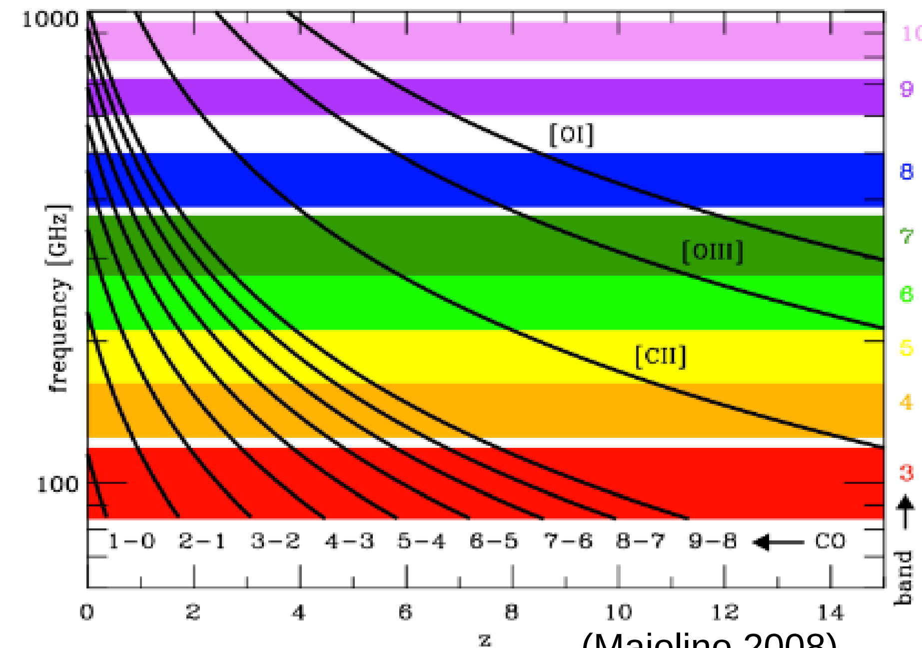
Molecular rotational transitions are diagnostics of the chemistry, physics and dynamics of the Inter Stellar Medium (ISM) from which stars form.

Some of these lines are so strong (e.g. the CO transitions) to be observable even in distant galaxies.

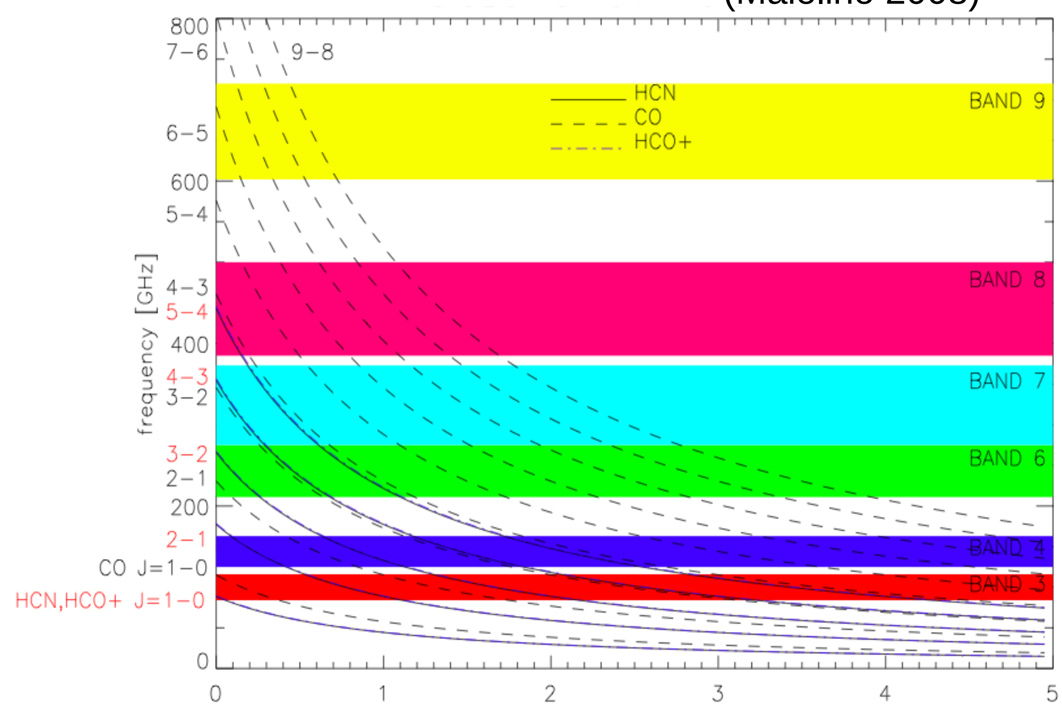
Some of the strongest lines emitted by the ISM of any galaxy, such as the [CII]158 μm and the [OI]63 μm fine structure lines (the two main coolants of the ISM), are redshifted into the (sub)mm bands at z > 2–4

HCN, HCO+ and other high density tracers are powerful tools to distinguish PDR (associated to SF regions) from XDR (associated to AGN).

In most of the ALMA band more than one line is observable for the higher redshifts.



(Maiolino 2008)



(Courtesy by Bianchi)

# CO

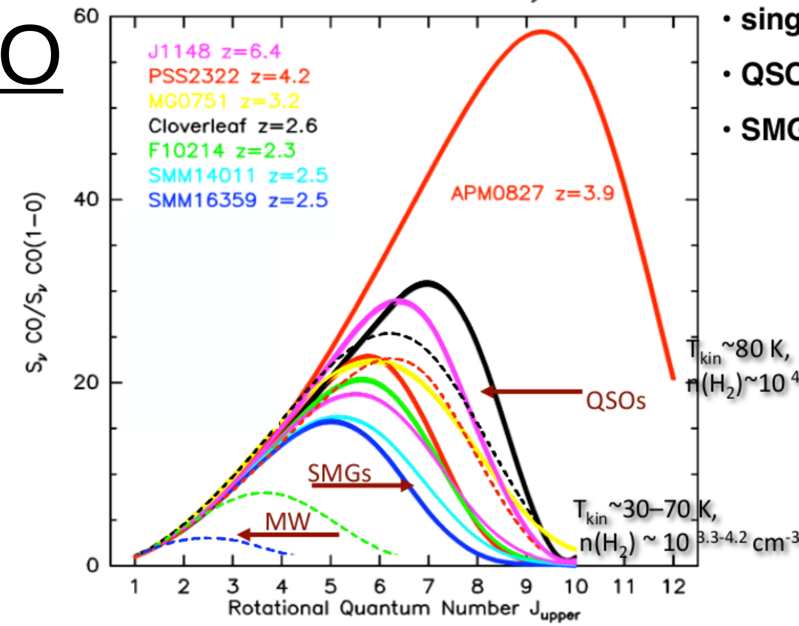
L_CO is proportional to the gas mass (via the relation with H2), L_FIR to the SFR.

$$\log L_{\rm FIR} = 1.7 \log L'_{\rm CO} - 5.0$$

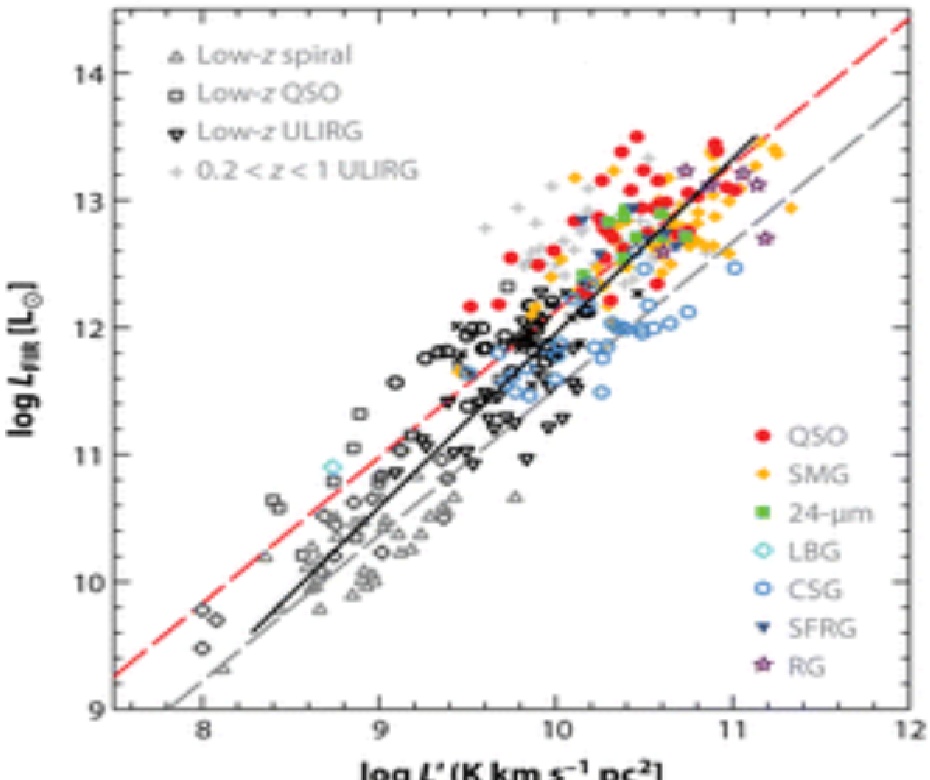
The efficiency of SF grews faster than mass, Hence massive galaxies exhaust their gas faster because of SF.

At high-z the relation is still linear, but with a different slope for SMG and QSO (i.e. different evolution?)

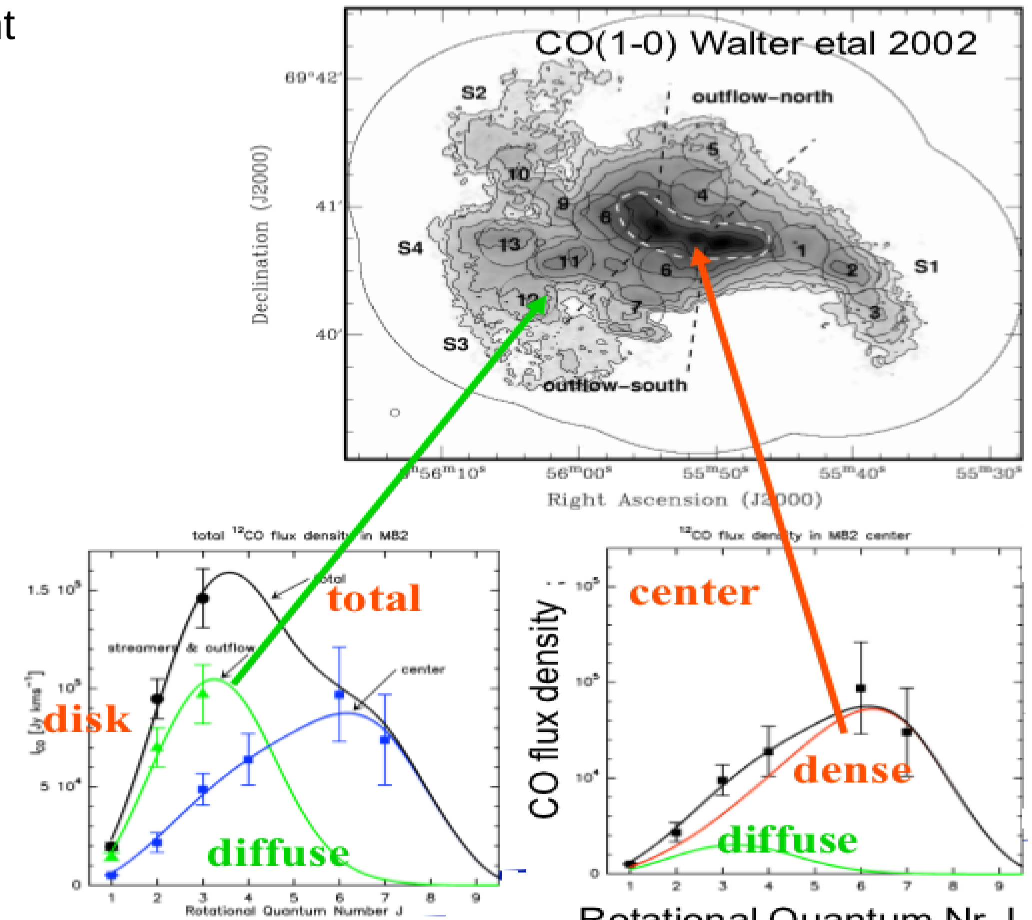
Different CO lines are sensitive to different environment (because of critical density increases with J)




- single gas component
- QSO turnover: J > 6-5
- SMG turnover: J ~ 5-4

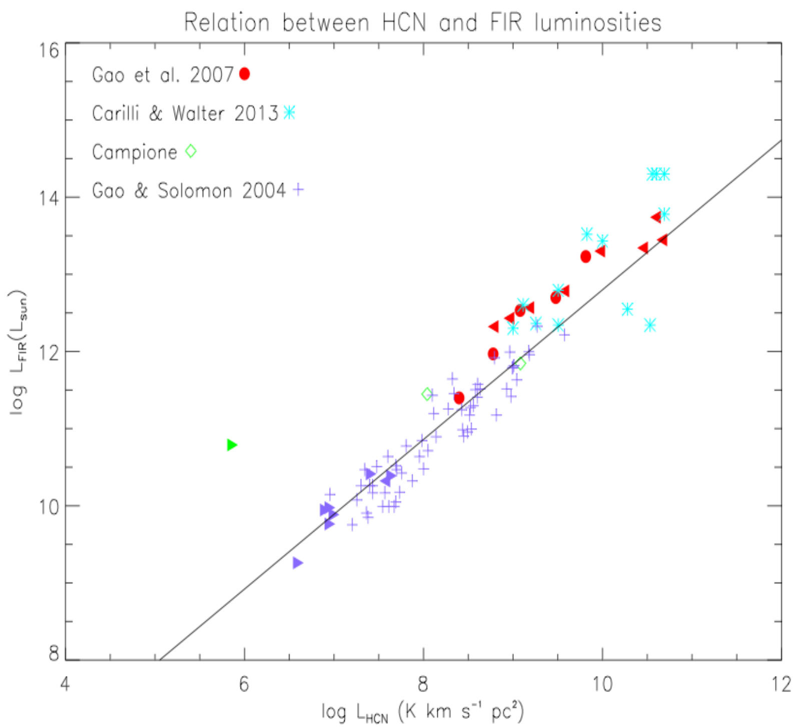



(Carilli et al. 2013)




(Weiss et al. 2005)

# HCN & HCO+

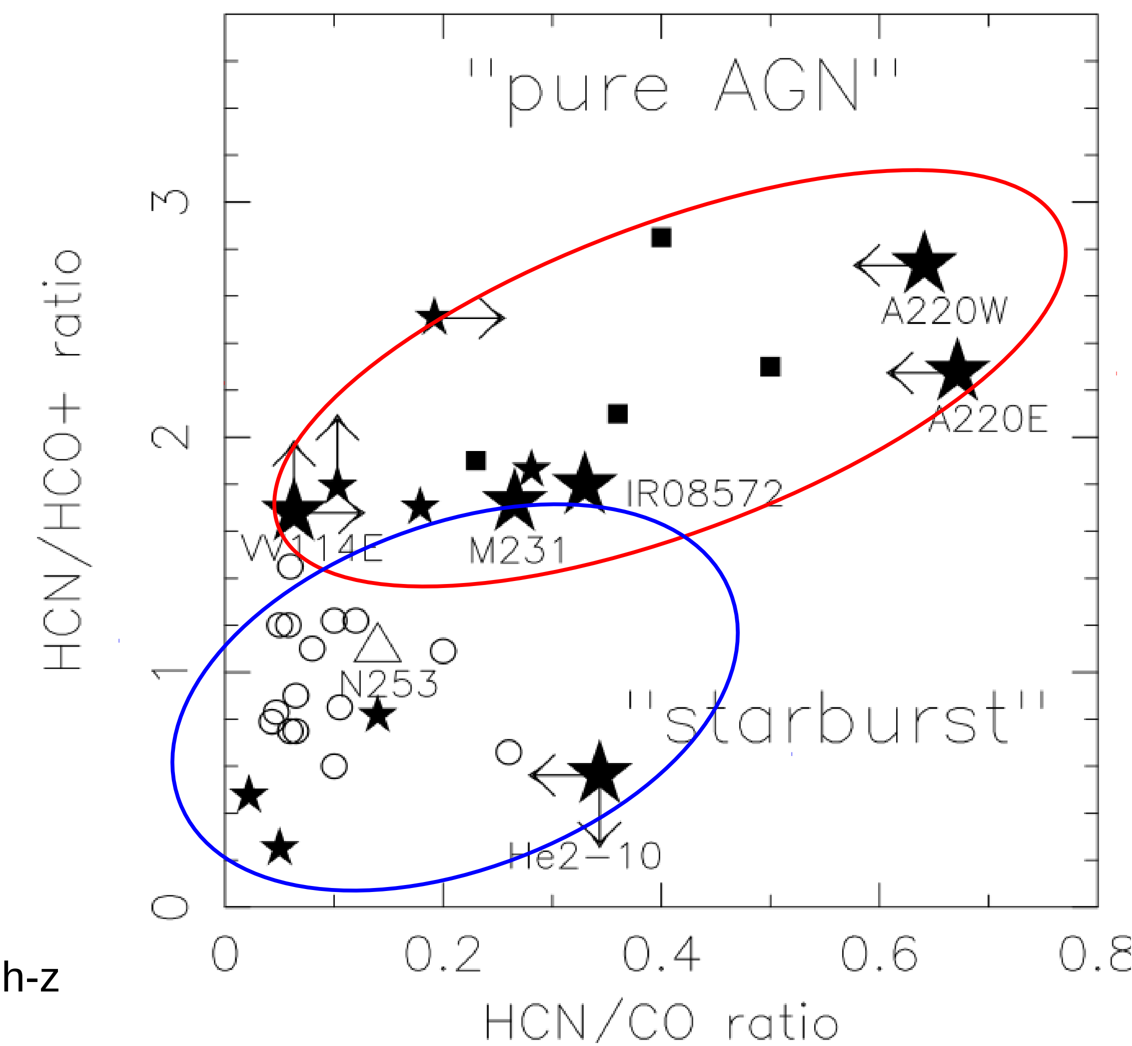



A linear relation links also Lfir and HCN.

$$logL_{IR} = 1.00(\pm 0.05) logL_{HCN} + 2.9$$

Only few observations are available so far at high-z (HCN is 10 times fainter than CO), but there are indications of lower L_HCN than predicted from low-z extrapolations, maybe on the effect of denser environment at high-z and/or higher SF efficiency.

HCN is enhanced in XDR wrt CO and HCO+, so it can discriminate AGN and starforming galaxies.




(Gao et al. 2007, Khono et al. 2005
Courtesy by Bianchi)

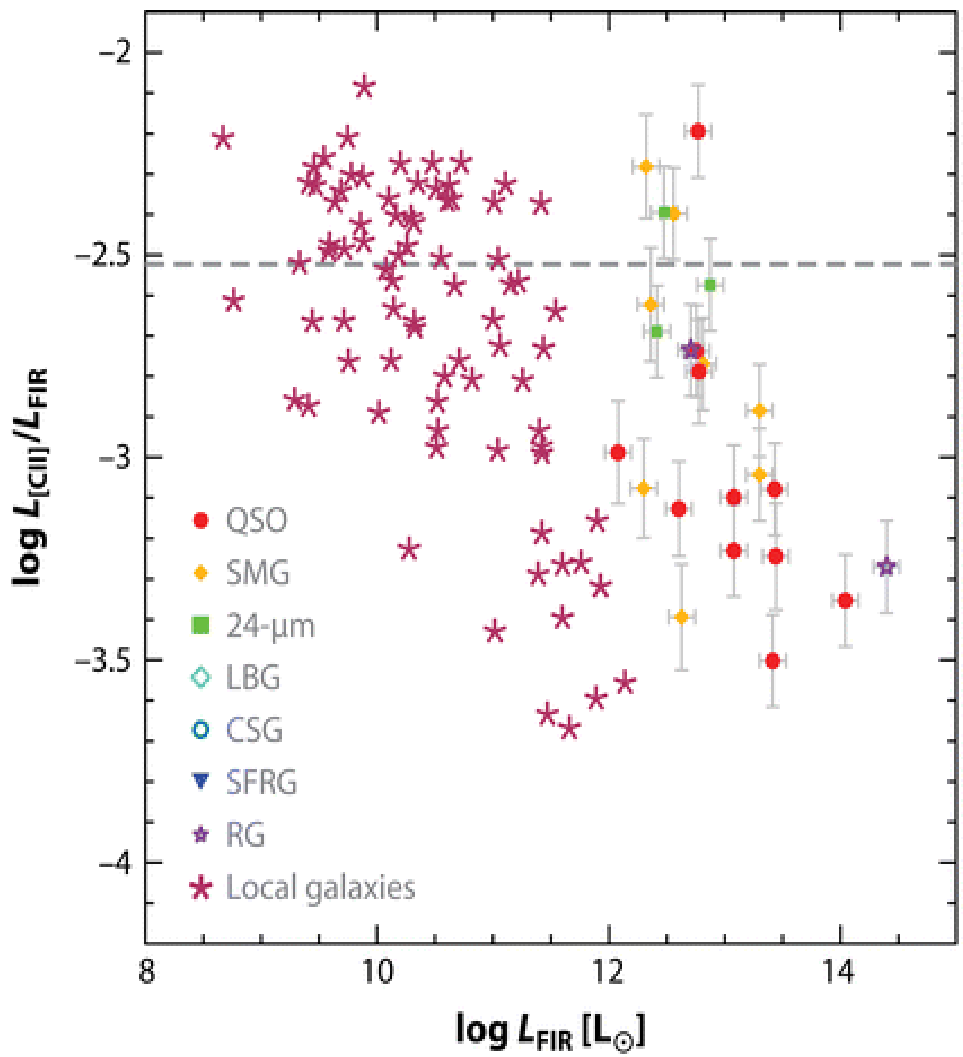
# CII & atomic lines

CII is a tracer of gas cooling.
CII appears to be suppressed in denser regions.
Also CII is related with L_FIR even if with a larger scatter.
The L_CII/L_FIR is higher at higher z for galaxies with similar properties

Hence cooling is more effective at high-z as observed in local galaxies with low metallicity.

Observations of OI, OIII and CII lines in ULIRGs at z>1 found ratios with L_FIR higher than local starbursts, indicating lower suppression of fine-structure lines than in local ULIRGs.

AGN activity (and NLR radiations) might enhance abundances of these lines.

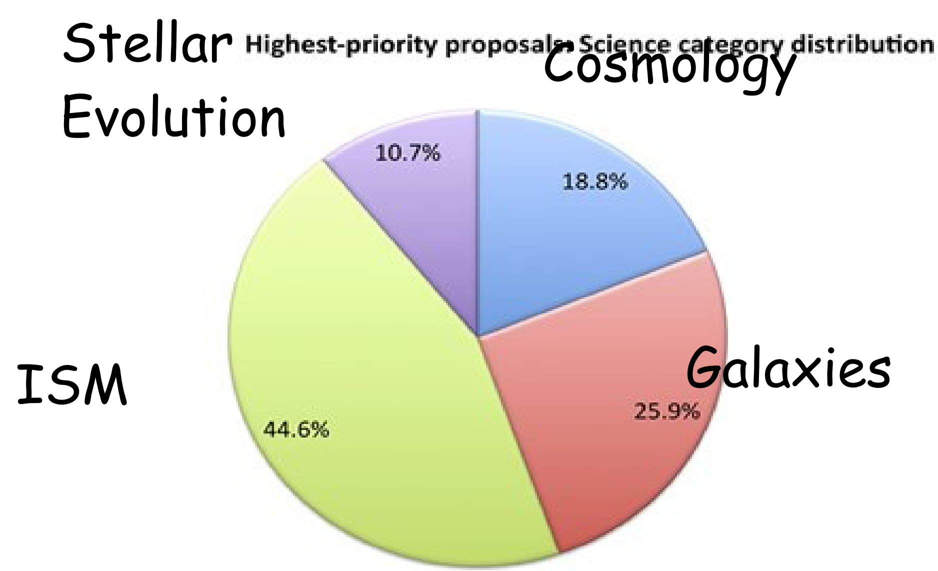



(Carilli et al. 2013)

| | Full array | Cycle 0 |
|---|---|---|
| Frequency range: | **10 bands 30-900 GHz** | **4 bands (3, 6, 7, 9)** |
| Antennas: | **50x12m** + ACA | **16x12m** (no ACA) |
| Sensitivity | **0.15 mJy in 1 min @ 230 GHz** | **0.5 mJy in 1 min @ 230 GHz** |
| Max baseline: | **150m-16km** | **2 configs: 18-125m, 36-400m** |
| Angular Resolution: | **20 mas @ 230 GHz** | **1000 mas @ 230 GHz** |
| | **70 correlator modes** | **14 correlator modes** |
| | **Mosaic** capability | **Limited mosaic** capabilities |
| | Pipeline reduction in Chile | **Reduction @ ARCs** |

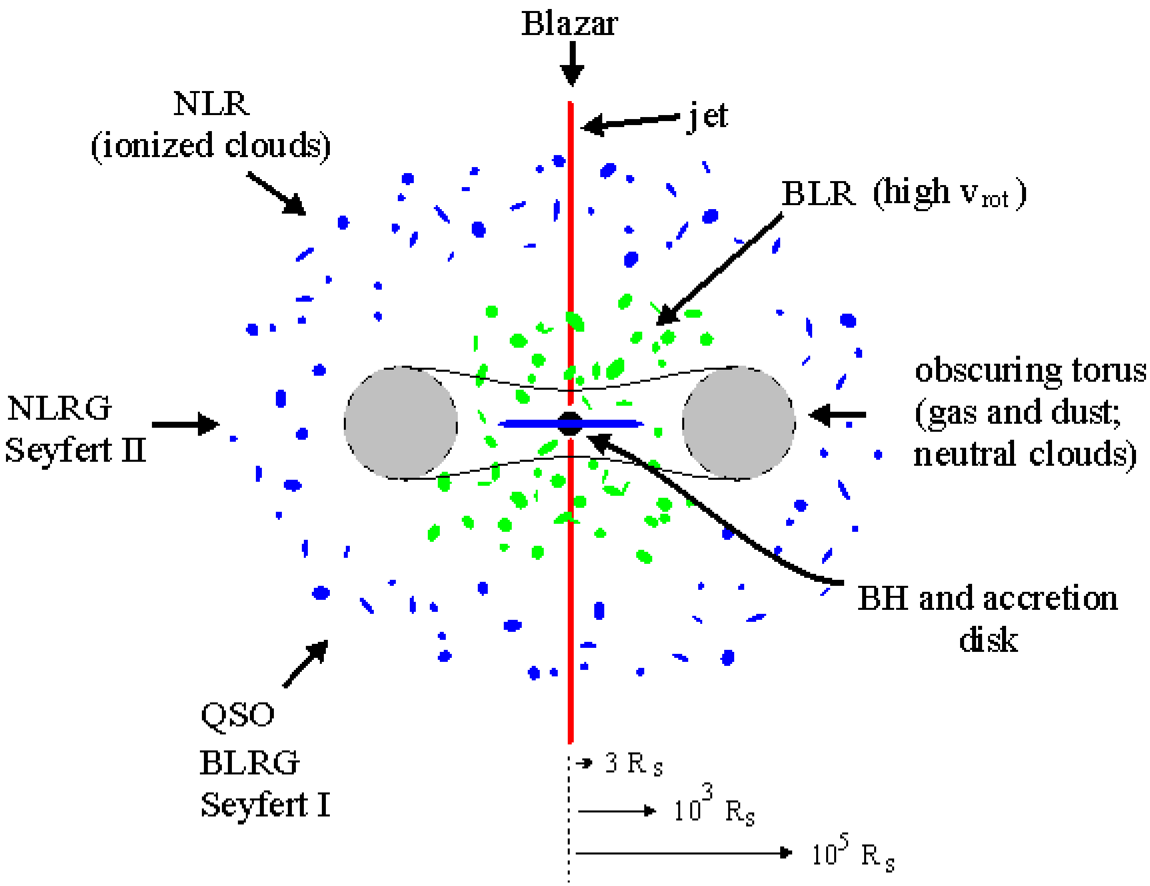
## Cycle 0:

- 111 Highest-priority + 51 filler proposals (out of 919 submissions)
- 108 (98%) Highest-priority PIs received some data



# AGN

AGNs generally heat their circumnuclear dust to temperatures much higher than starburst galaxies.
The far-IR and submm emission is dominated by star formation in the host galaxies, even in powerful QSOs.




**NOTES on SCALES**

BLR< 0.1pc
(velocities $10^{3\text{-}4}$km/s)
Torus 1-5 pc
NLR 100 pc
Jet <1Mpc

**An ALMA resolution element (10marcsec @300 Ghz) Corresponds to**
**@z=0.1 10pc**
**@z=0.5-3 40-60pc**

**In CenA (z=0.018) → 0.4pc**
**In NGC1068 (z=0.037) → 0.8pc**

# AGN Fuelling

**Fuelling is the mechanism in which matter accrete on the AGN, removing its angular momentum, feeding the BH and triggering the nuclear activity.**

Some theories consider AGN driven by mergers. However, locally there is no strict relation between presence of AGN, companions or barred structures.

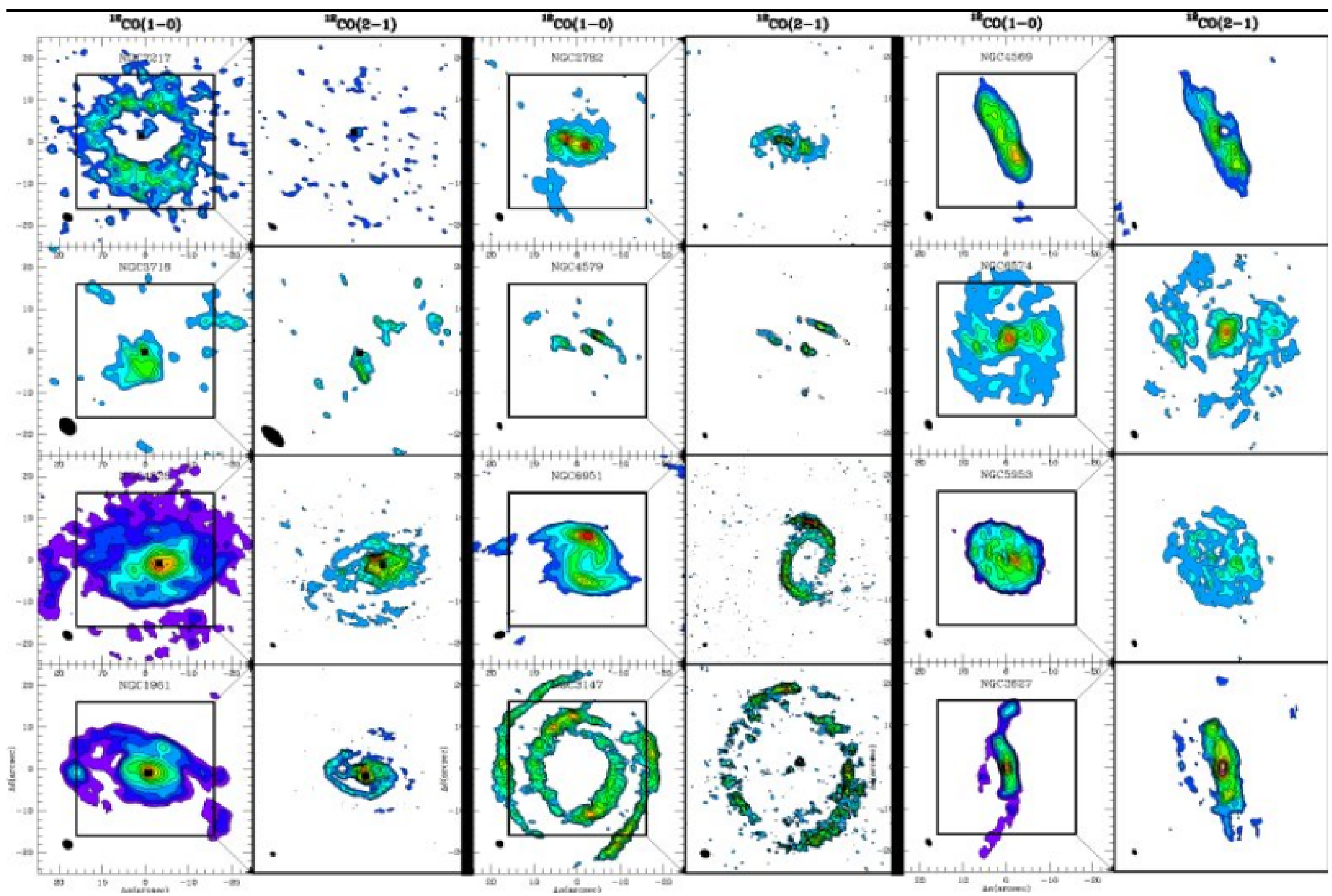
Local AGNs do not show obvious systematic signatures of nuclear fuelling from the host galaxy.

Therefore, it is important to trace the dynamics of the molecular gas in the host of these powerful QSOs, and investigate for instance whether in these systems gas funneled by bars or driven by galaxy merging is common.

The CO distribution presents several possible features (see the NUGA survey @ 50-100pc resolution). Hence AGN do not need fuelling?

For local Seyfert $10^{-3}$ m_sun/yr (one molecular cloud) can activate the nucleus for 1 Gyr.

For QSOs we need 1M_sun/yr.

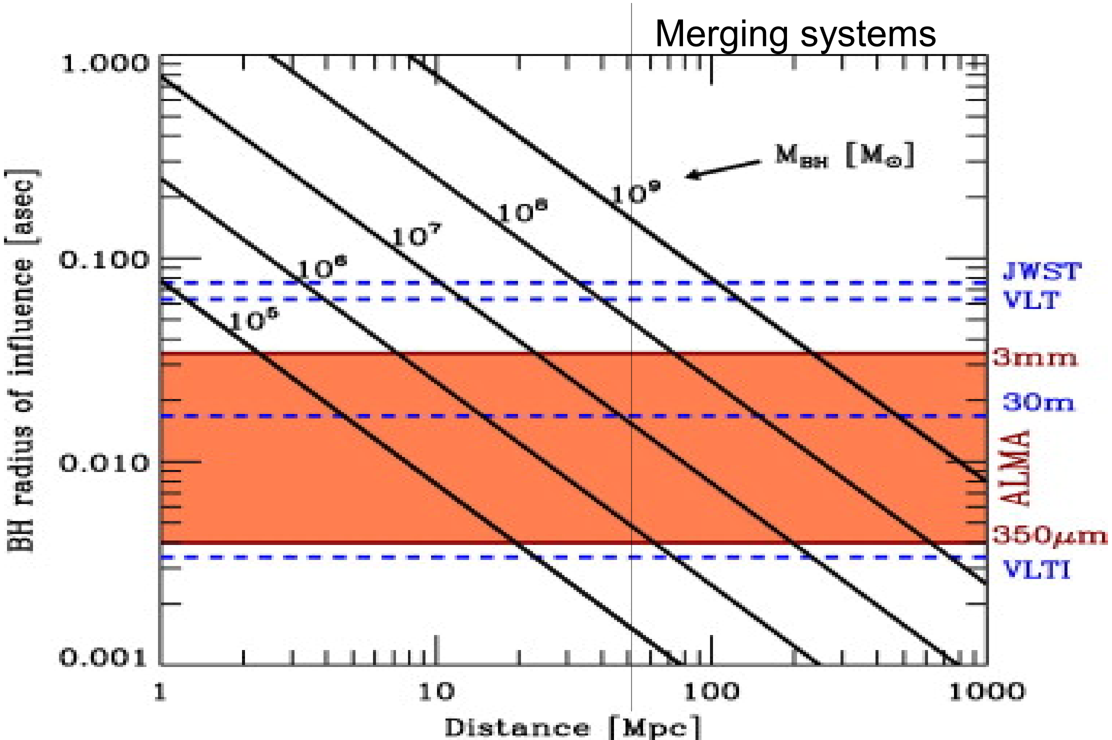


# AGN Tori

**The circumnuclear molecular medium is both responsible for the obscuration of AGNs and related to their feeding.** Models predict:

- a **uniform gas distribution in a toroidal geometry** whose thickness is supported by IR radiation pressure (e.g. Krolik, 2007).
  A strong radial temperature gradient is expected for dust and, therefore, the innermost warm dust should emit much at higher submm frequencies, than the cold dust in the outer regions.
  Motion is dominated by rotation
- **a clumpy structure originated by the outflow of the accretion disk** (Elitzur et al. 2006).
  Each individual cloud spans a wide range of temperatures and emits at all wavelengths.
  Hence, the nuclear "torus", should show the same morphology at all infrared wavelengths.
  Turbulent components and outflow should trace the dynamics

For closer AGN subpc scale observations can disentangle the models and spectroscopy can trace the tori dynamics. Resolving the gas dynamics allows to directly measure the BH masses




**NOTES on SCALES**

Torus 1-5 pc

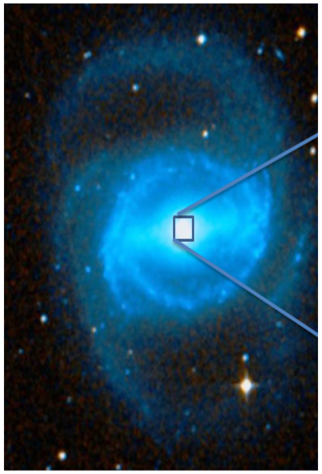
**ALMA resolution element (10marcsec @300 Ghz)**

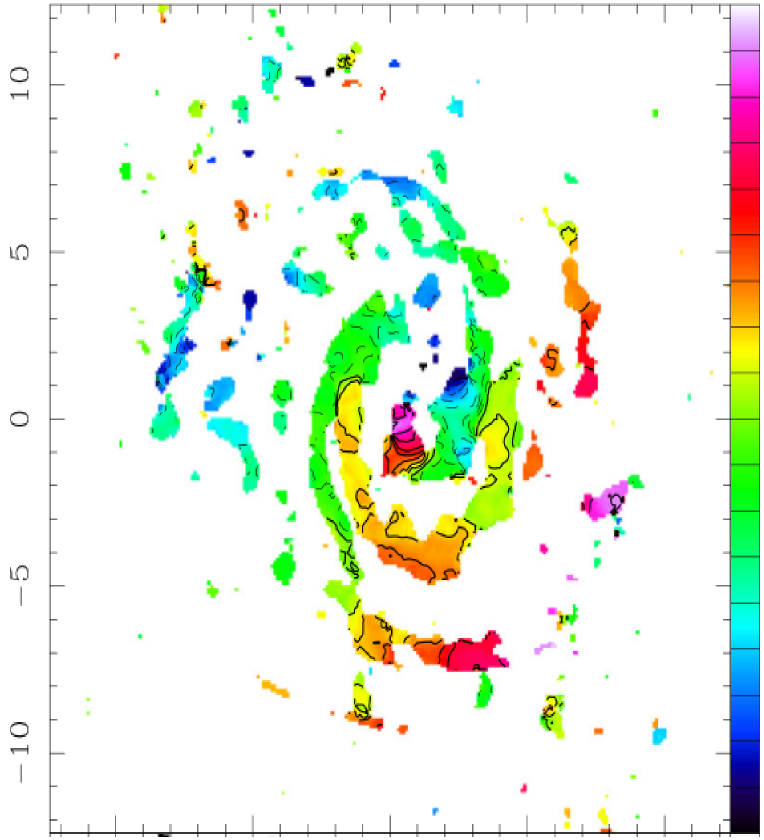
**In CenA (z=0.018) → 0.4pc**
**In NGC1068 (z=0.037) → 0.8pc**

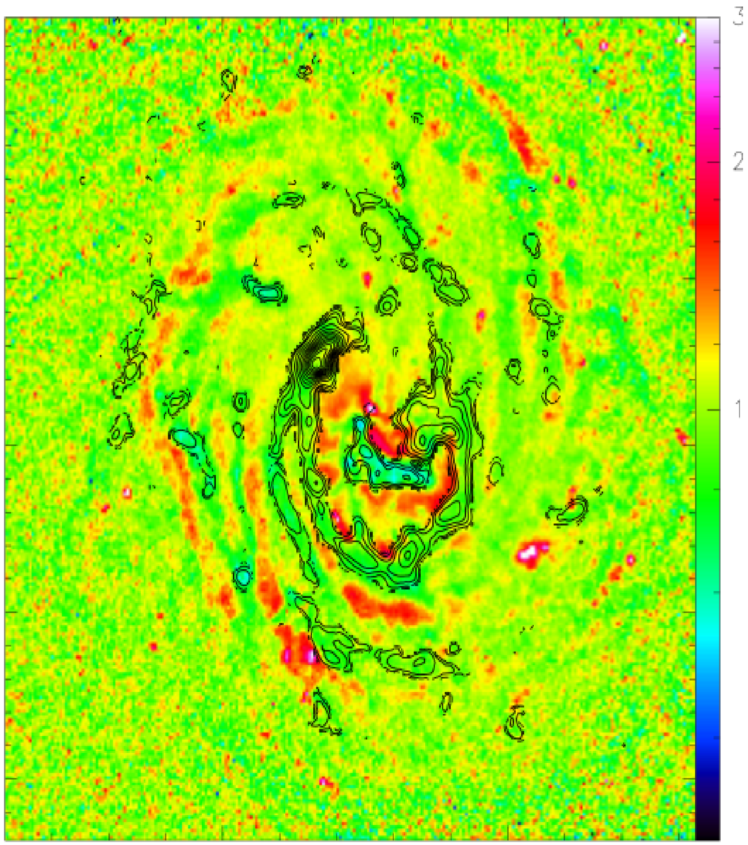
# ALMA discovers an outflow of molecular gas in a nearby spiral galaxy: NGC 1433

Combes, Garcia-Burillo, Casasola et al. 2013

PI: F. Combes






NGC1433 is a Seyfert 2, strongly barred spiral, D ~ 10 Mpc (z=0.0035)

## OBSERVATIONS

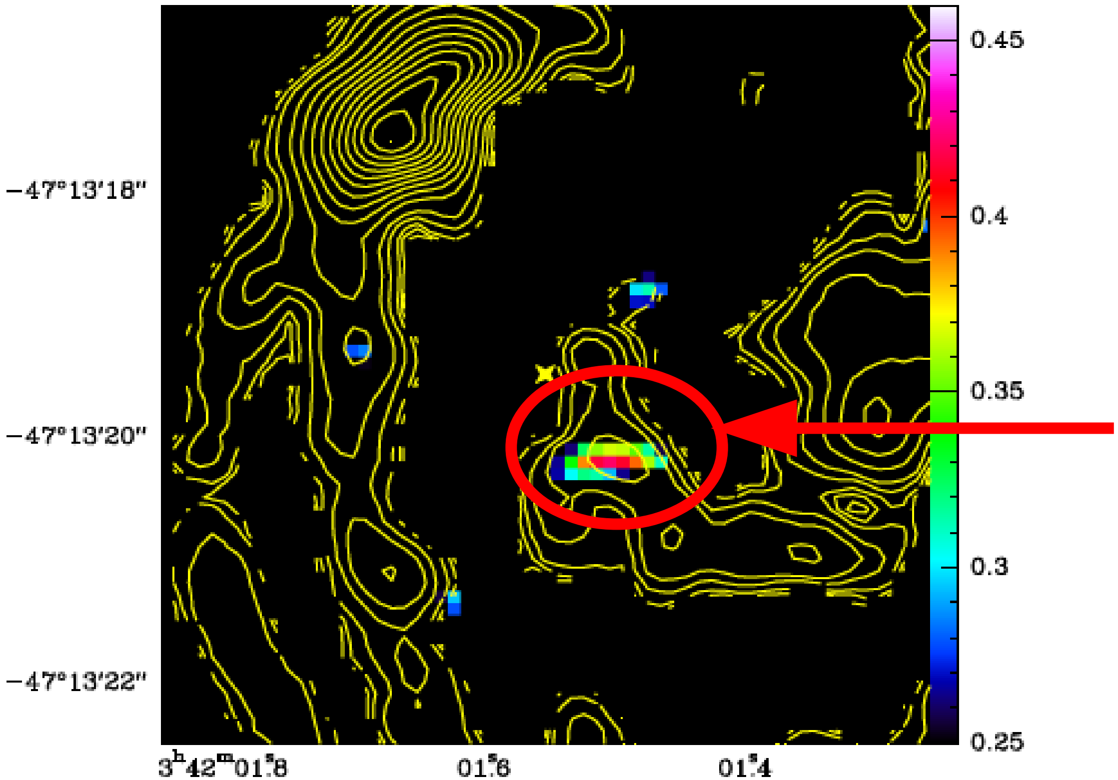
- 19 x 12m antennas
- CO(3-2) map
- (~345 GHz, Band 7)
- one pointing, 2 hrs
- FOV = 18'' ~ 850 pc
- Resolution 0.5''=24pc

The dust lanes traced by CO flow on a 200pc nuclear ring
and from there reaches the inner 20pc. There is no clear bar structure

# ALMA discovers an outflow of molecular gas in a nearby spiral galaxy: NGC 1433

Combes, Garcia-Burillo, Casasola et al. 2013

PI: F. Combes




CO(3-2) contours on the continuum map
inner 6''

**Continuum emission at 0.87 mm was detected at the very center**
**It might be due to thermal dust emission from a <u>MOLECULAR TORUS</u>**

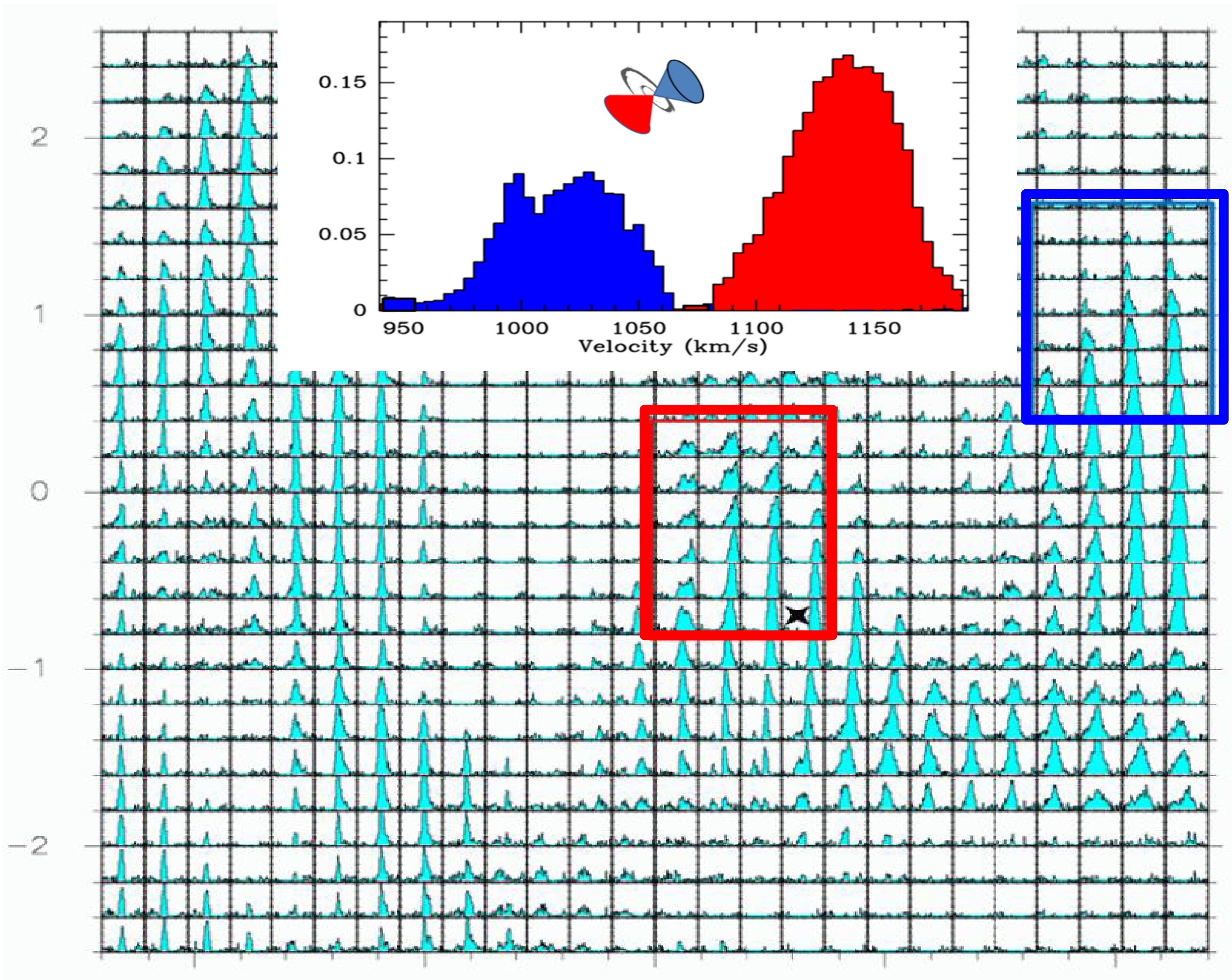
The emission is extended 1x0.5 arcsec (20pc).

Only high-resolution ALMA observations at several frequencies would be able to settle the origin of the continuum emission.

# ALMA discovers an outflow of molecular gas in a nearby spiral galaxy: NGC 1433

Combes, Garcia-Burillo, Casasola et al. 2013

PI: F. Combes




CO(3-2) spectra within 2.5'' of the center

The kinematics over the disk reveal rather regular rotation, with traces of an outflow

near the nucleus an intense high-velocity CO emission feature redshifted to 200 km/s

a blueshifted counterpart at 2" (100 pc) from the center

Flow could be mainly boosted by the AGN through its radio jets. AGN able to remove gas and stop star formation.
Outflow should be confirmed by higher-resolution ALMA observations.

**OBSERVATIONS**

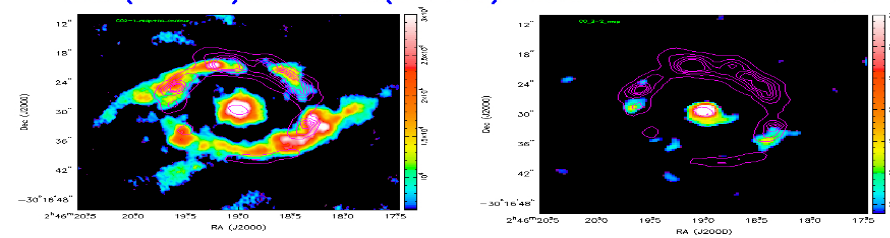
# NGC 1097

PI: Izumi

- 15 x 12m antennas
- **HCN(4-3) and HCO+ maps (~345 GHz, Band 7)**
- **one pointing, 2 hrs**
- **FOV = 18" ~ 850 pc**
- **Resolution 1.5"=50pc**

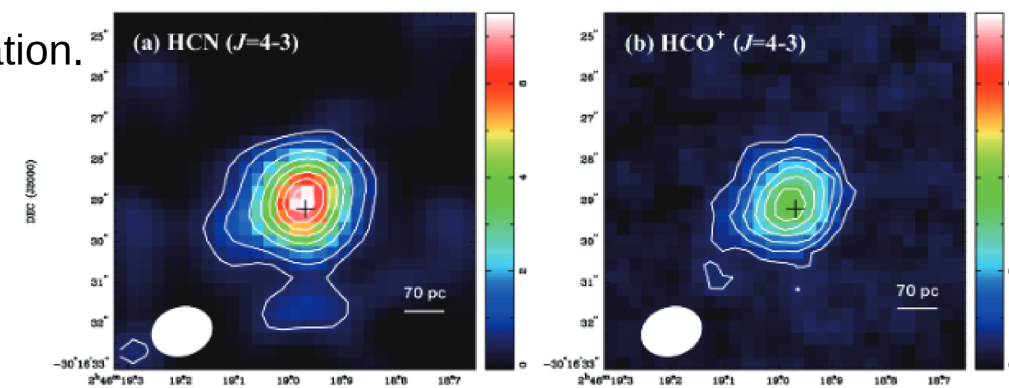
Izumi et al. 2013

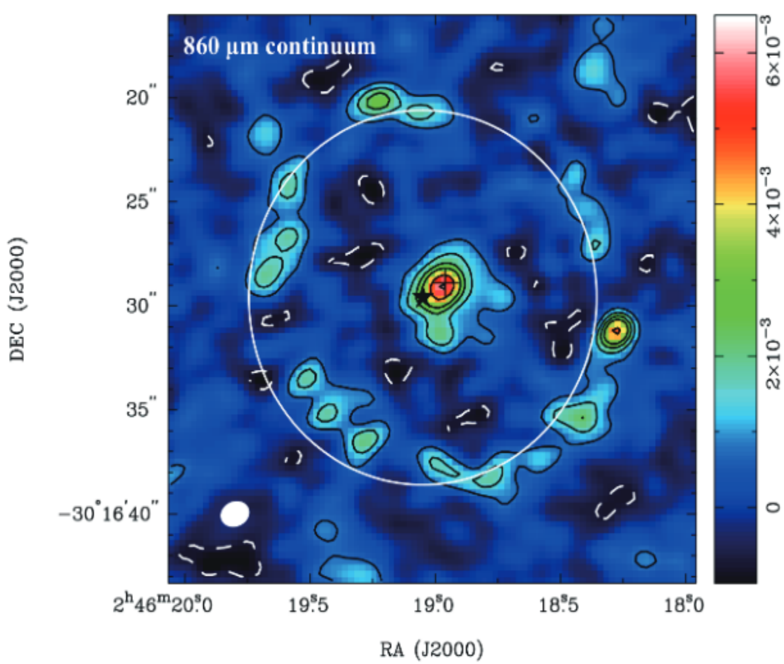
CO (J=2-1) and CO(J=3-2) overlaid with Hα contours

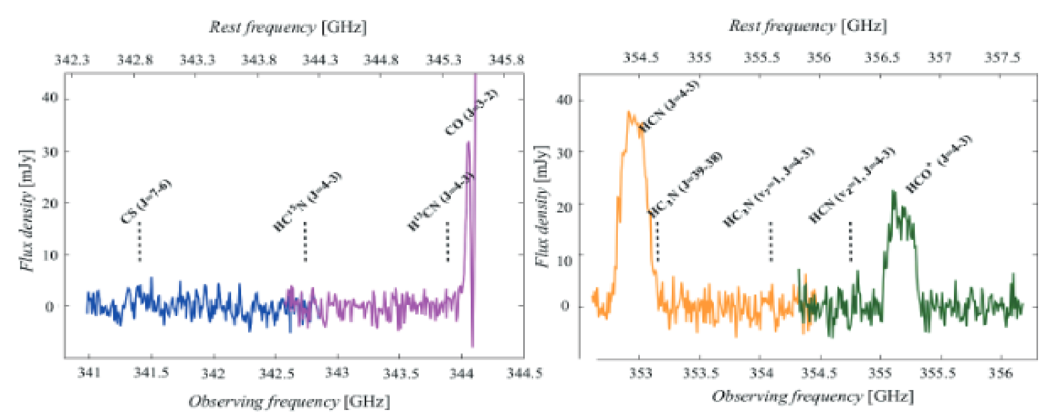



It hosts a type-1 Seyfert nucleus with a circumnuclear starburst ring with a radius of 10".

CO and continuum not only in the center but also in the starburst ring.
HCN and HCO+ only in the center with enhanced HCN emission and spectral broadening due to rotation.



# Compact Obscured Nuclei with ALMA

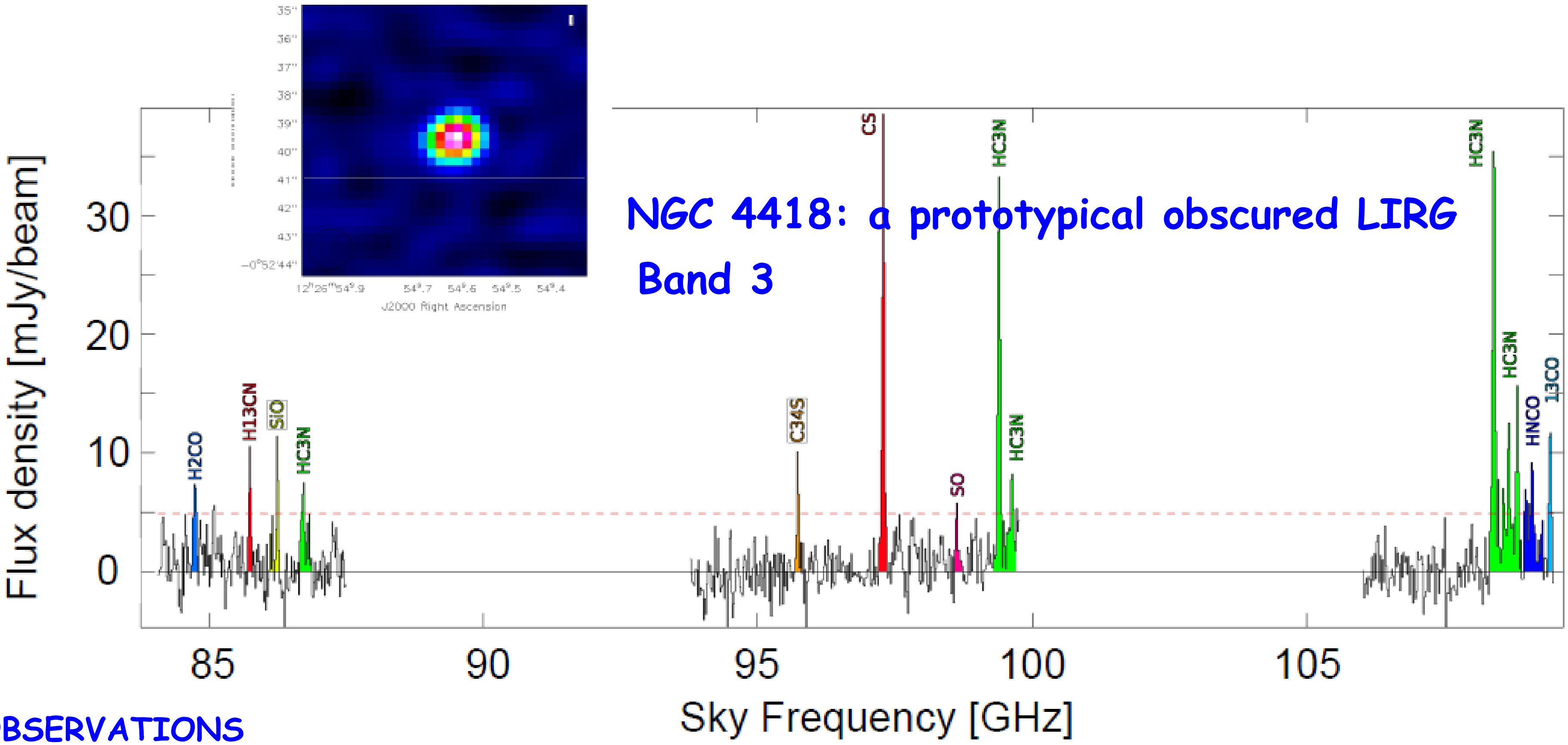
PI: F. Costagliola

PI: K. Xu

PI: S. Aalto

NGC 4418: a prototypical obscured LIRG

Band 3




OBSERVATIONS

- 16 antennas
- Lowest spectral resolution
- **In B3: in 5 min on source 14 lines within 8 GHz**
- **170 GHz wide scan in B3, B6 and B7 in < 1 hr 50 line detected**

**LIRGs are identified as an early obscured stage of AGN**

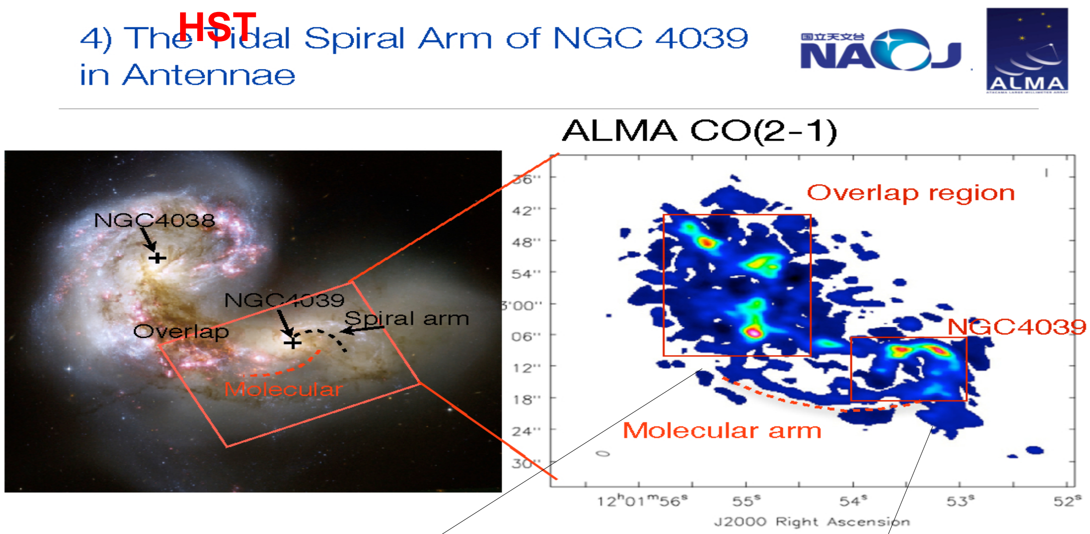
**Local objects might constitute database for physics and chemistry of gas in similar objects**

The inner regions were so far observed with VLBI, ALMA allows to investigate the radiative processes, penetrating the dust

**Unveil the power-source: starburst or AGN via molecular transitions (CO, HCN, CS...)**

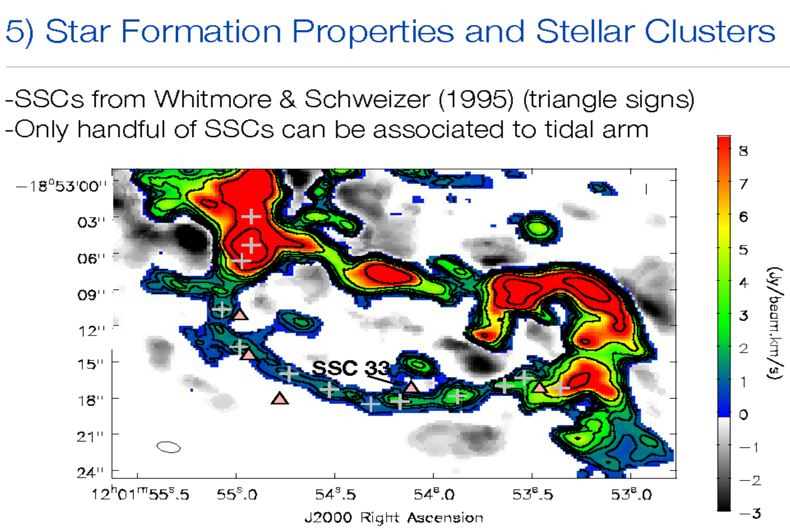
# Mapping merging systems: Antennae Galaxies

Espada et al. 2012




**OBSERVATIONS: Science Verification**

- Band 6, 14 antennas
- **Angular resolution ~1.5"**
- 13-17 pointings for NGC4038 and NGC4039
- **rms = 1.2 mJy/beam**




**Newly discovered tidal arm**: 3.4 kpc long, <200 pc wide, Δv=10-20 km/s

**~10 clumps of stellar star clusters (SSCs):** most of them unresolved, ~350 pc SSC separation, Mgas ~ 1-8 x 10$^6$M$_\odot$

**SFE ~ 10 higher** (log(SFE) ~ -8.2) than in disk galaxies and other tidal arms and bridges

**The tidal arm morphology is different to that predicted by high-resolution simulations for the Antennae Galaxies**

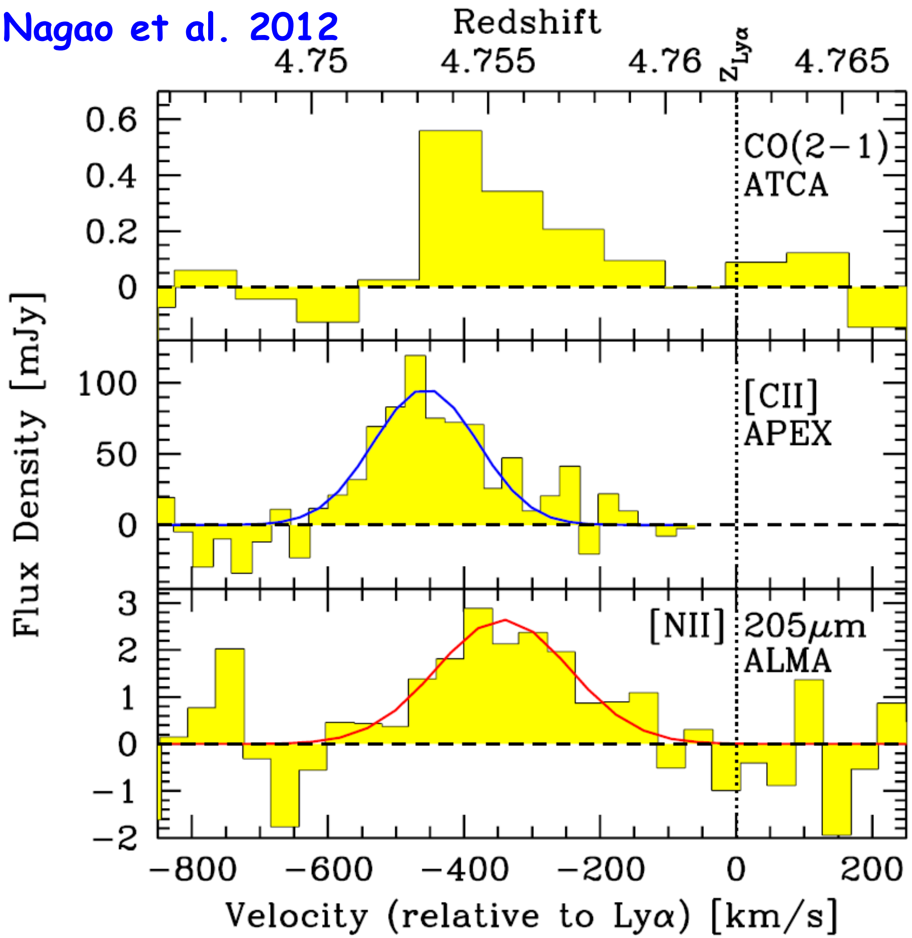
# ALMA reveals a chemically evolved SMG at z = 4.76

LESS J033229.4-275619

**PI: C. De Breuck**

**PI: R. Gilli**

Nagao et al. 2012




Band 6, 250 GHz, 18 antennas, 3.6 hrs, 1.5" res (PI: Nagao)

[NII] 205 μm detection: [NII] arises from HII regions (Nagao et al 2011)

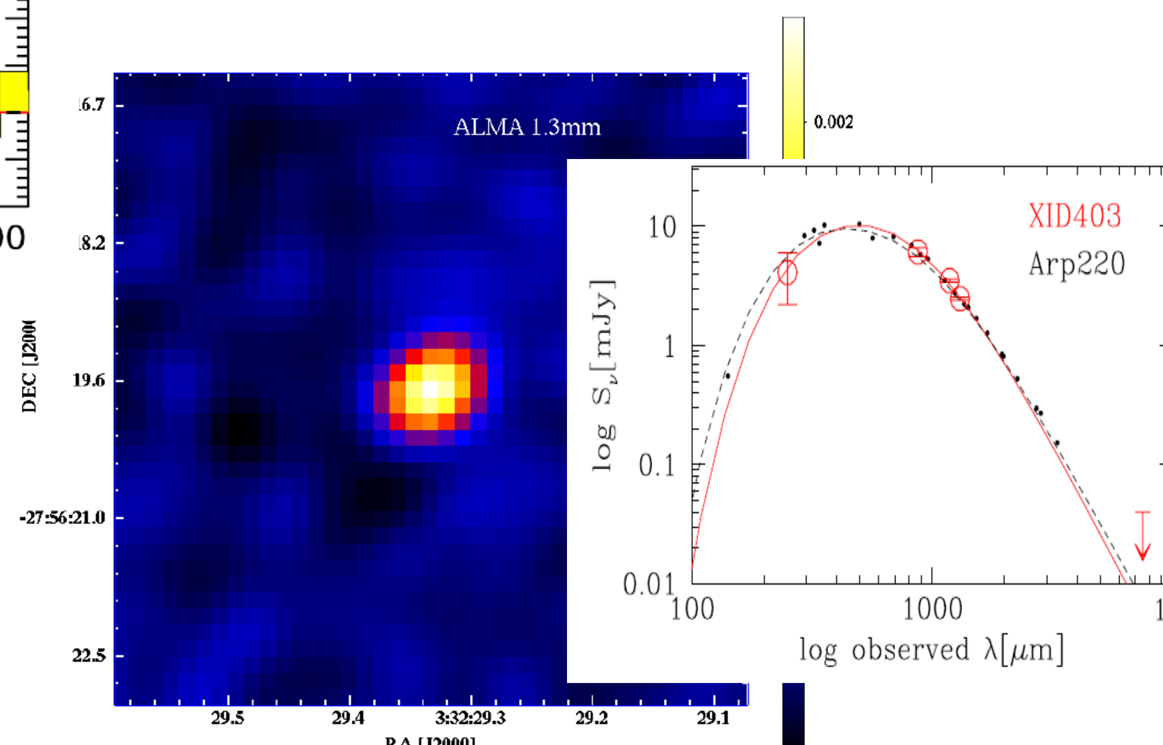
**The first measure of [NII]/[CII] in high-z galaxies**, ~0.043, similar to the nearby Universe

[NII]/[CII] metallicity indicator: as the metallicity in this SMG is consistent with solar, **the chemical evolution has progressed very rapidly**

Band 6, 1.3 mm continuum, 17 antennas, 23 min (including cal.), 0.75" res (PI: Gilli)

**First measure of the dust temperature, Tdust ~ 60 K (with ALMA + Herschel), mass and size.**

Warm and compact starburst surrounds an obscured BH. Progenitor of local compact quiescent galaxies




Gilli et al 2013 – Supported by Italian ARC

# CII at z=6

Wang et al. 2012

**OBSERVATIONS**

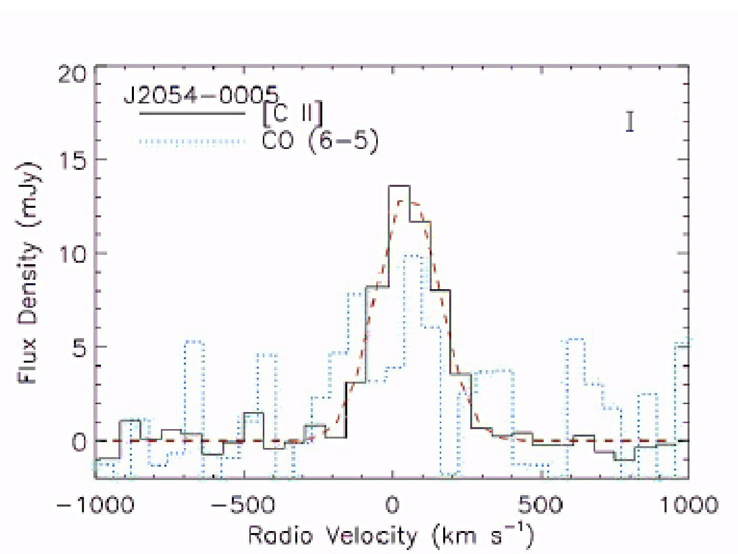
- Band 7, 17 antennas
- **Angular resolution ~0.5''**
- CII and CO6-5
- 1 hr

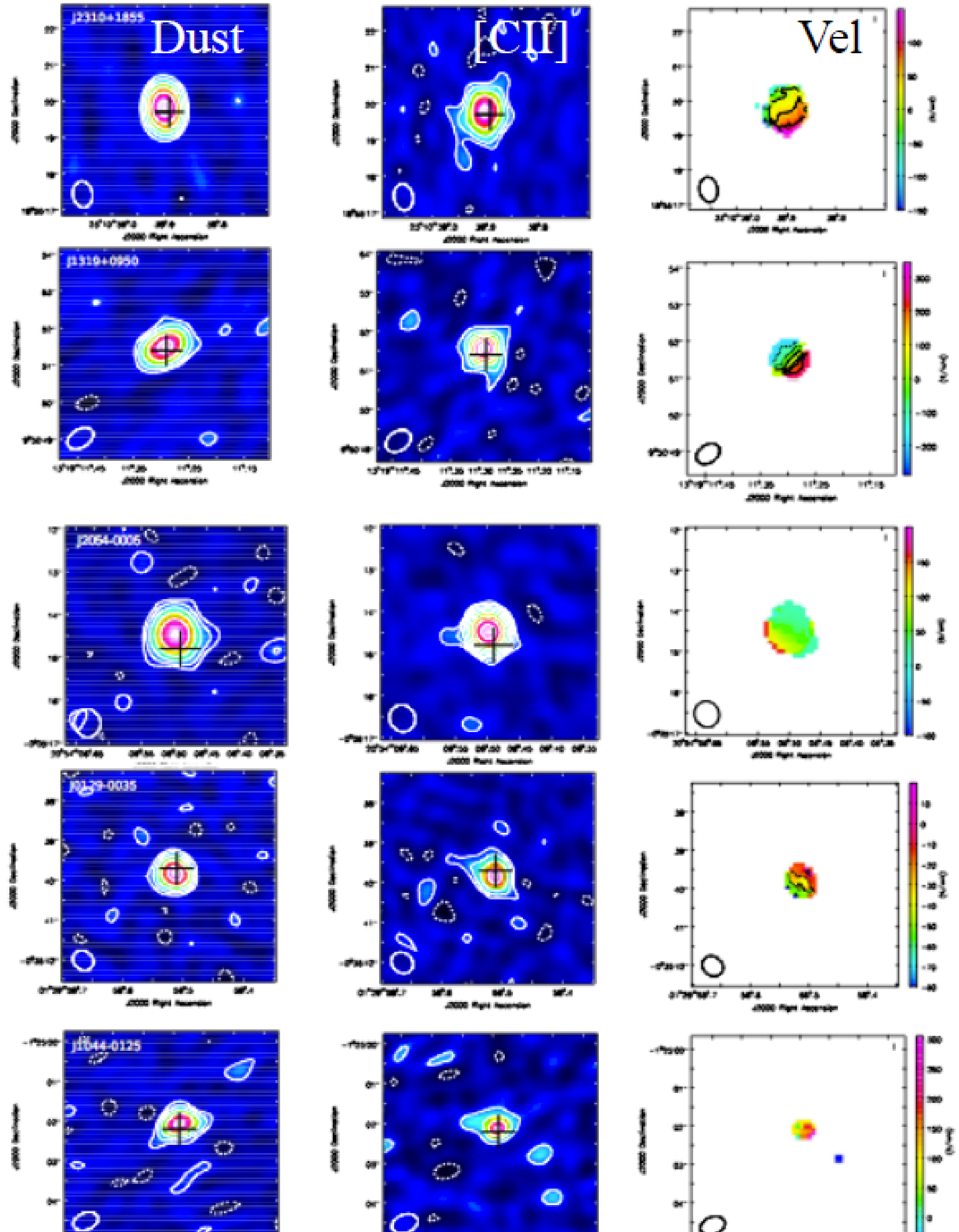
- z=6 quasar hosts

- Dust CO6-5 and CII resolved
  on sizes of 2-3kpc

- Velocity gradients

- CII and high transition CO show different
  shapes as associated to different density
  regions.

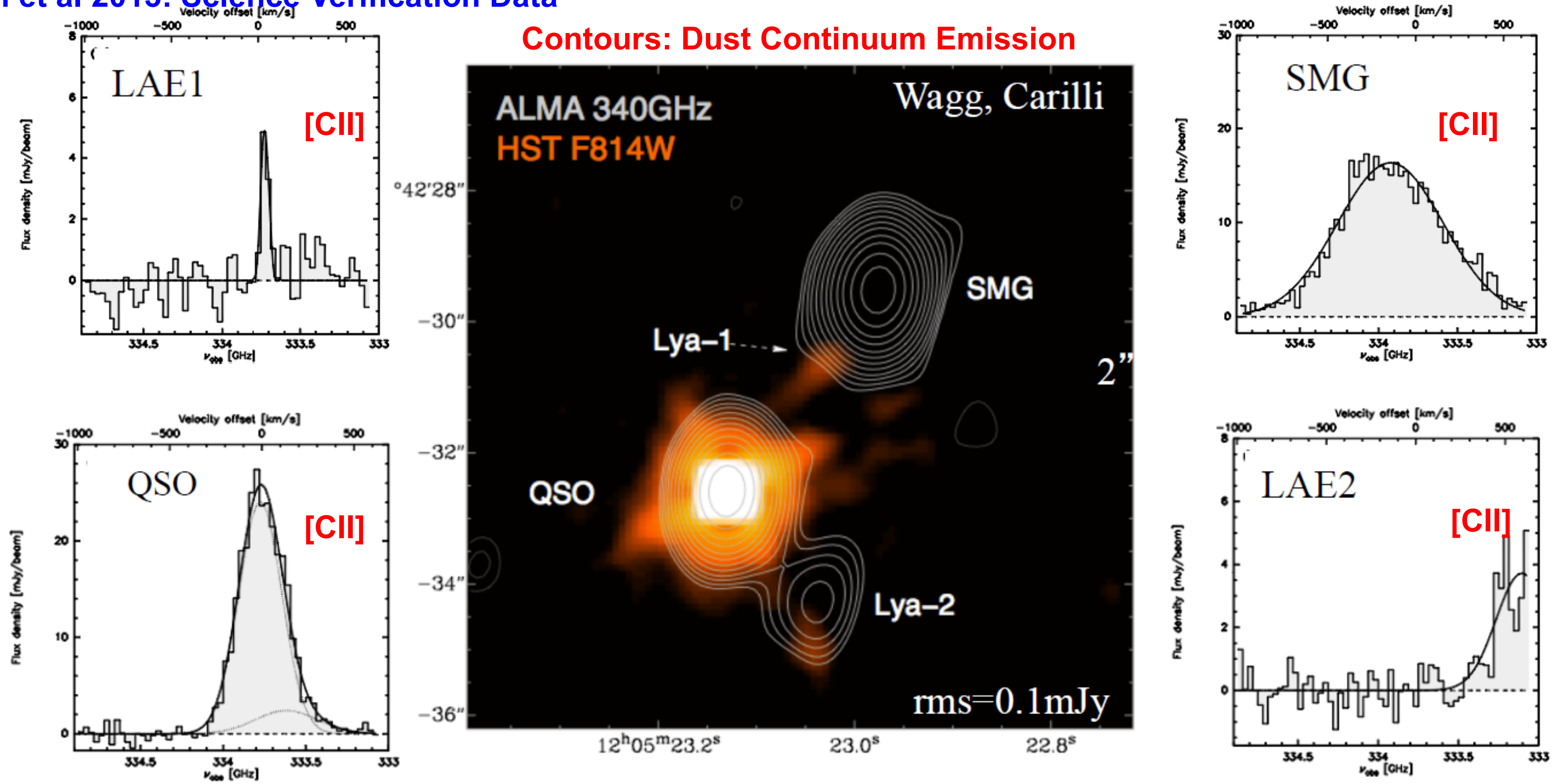


# The Anatomy of an Extreme Starburst within 1.3 Gyr of the BIG Bang Revealed by ALMA

**Carilli et al 2013: Science Verification Data**

**Contours: Dust Continuum Emission**




**OBSERVATIONS**

- **~17 antennas,**
- **~25 min on source**
- Band 7: 334 GHz
- ~1" res,
- 31 MHz/ch

BRI 1202-0725

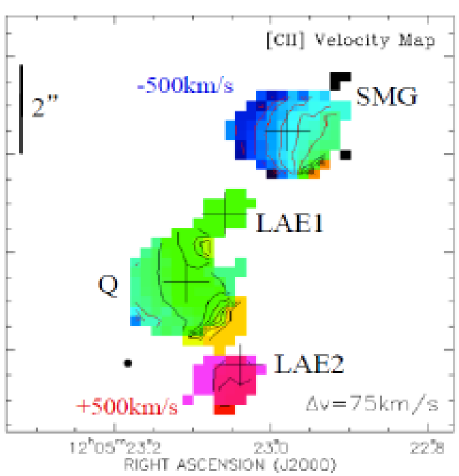
Extreme starburst/AGN group of galaxies at z = 4.7

**It has a closely separated (26 kpc in projection) FIR hyperluminous quasar and a optically obscured SMG**

Two hyperstarburst (SMG & quasar): SFR ~ $10^3$ $M_\odot$/yr

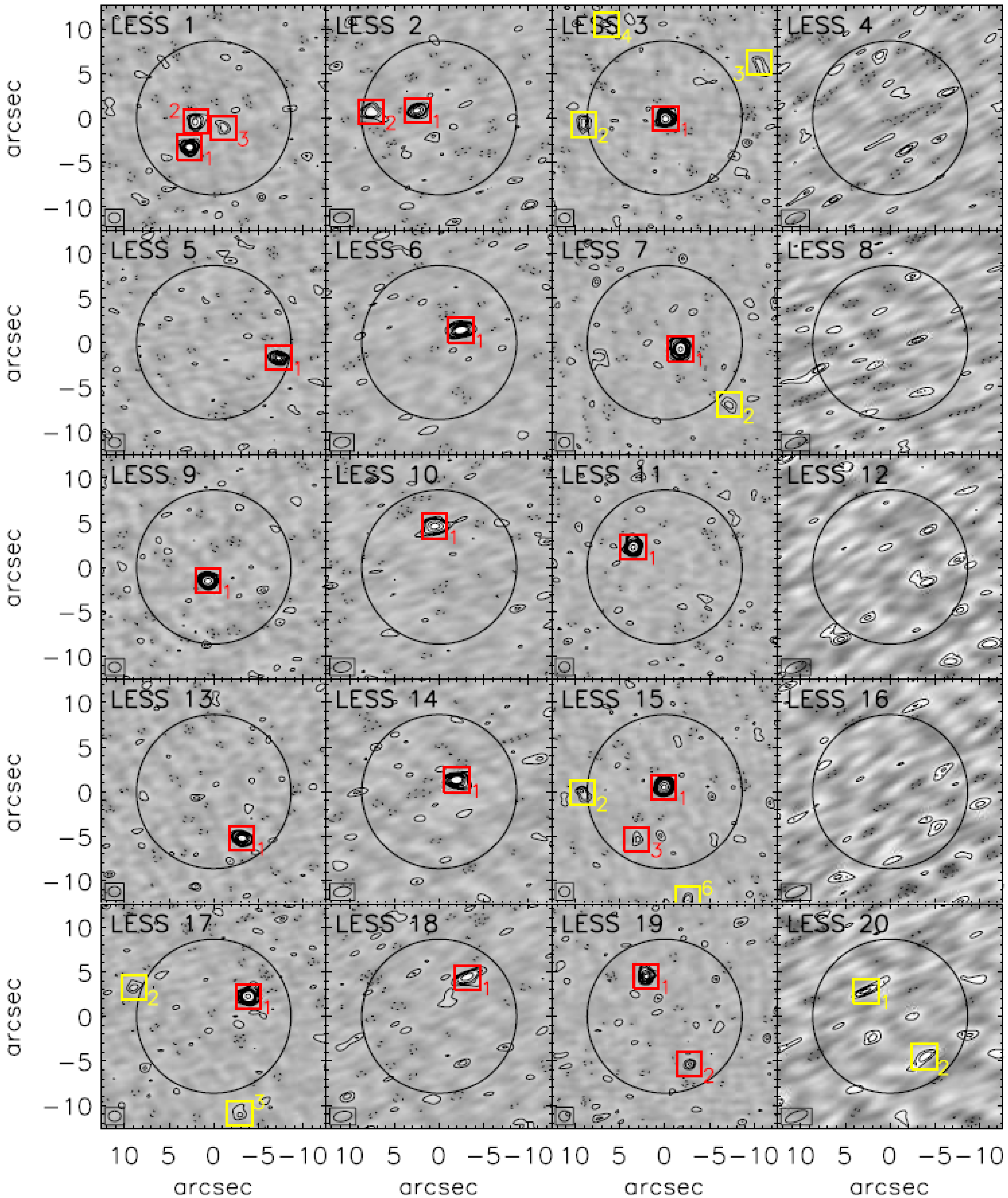
Two “normal” Lyα : SFR ≤ $10^2$ $M_\odot$/yr

**All detected in [CII], three detected in dust continuum.**
**From velocity map traces of interaction**



# An ALMA survey of submm in the Extended Chandra Deep Field South

PI: I. Smail




## OBSERVATIONS

- 870 µm (Band 7) follow-up of a LABOCA Extended Chandra Deep Field South Submm Survey (LESS)
- **122 submm sources**
- ~15 antennas, FOV = 17", **2 min/source**
- rms < 0.6 mJy/beam (**x3 deeper than LABOCA**)
- Resolution ~1.5" (**x10 better than LABOCA**)

~35% of the detected LABOCA sources are resolved in multiple SMGs

In 2 SMGs detection of [CII] 158 µm at z ~ 4.4: ALMA able to detect the dominant fine-structure cooling lines with short integration

**Selections in radio/mid-IR bands miss 45% of SMGs**

**First statistically survey of SMGs: basis for an unbiased multifrequency study of SMGs**

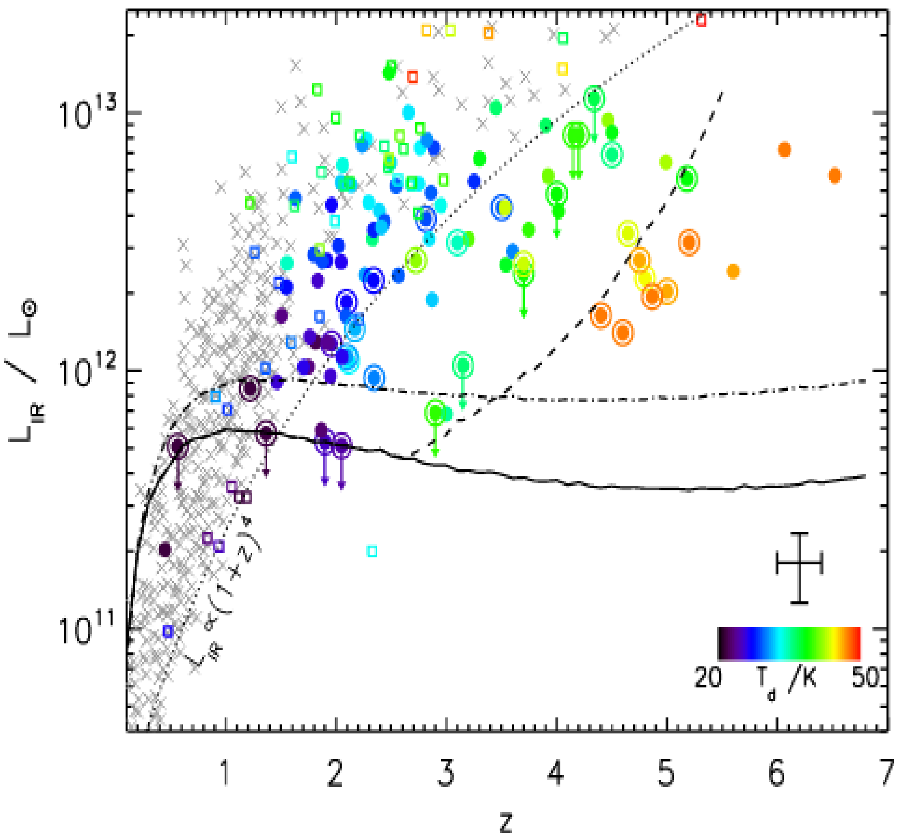
**Median redshift of z_phot=2.5±0.2 with 35±5 per cent of SMGs lying at z >3**

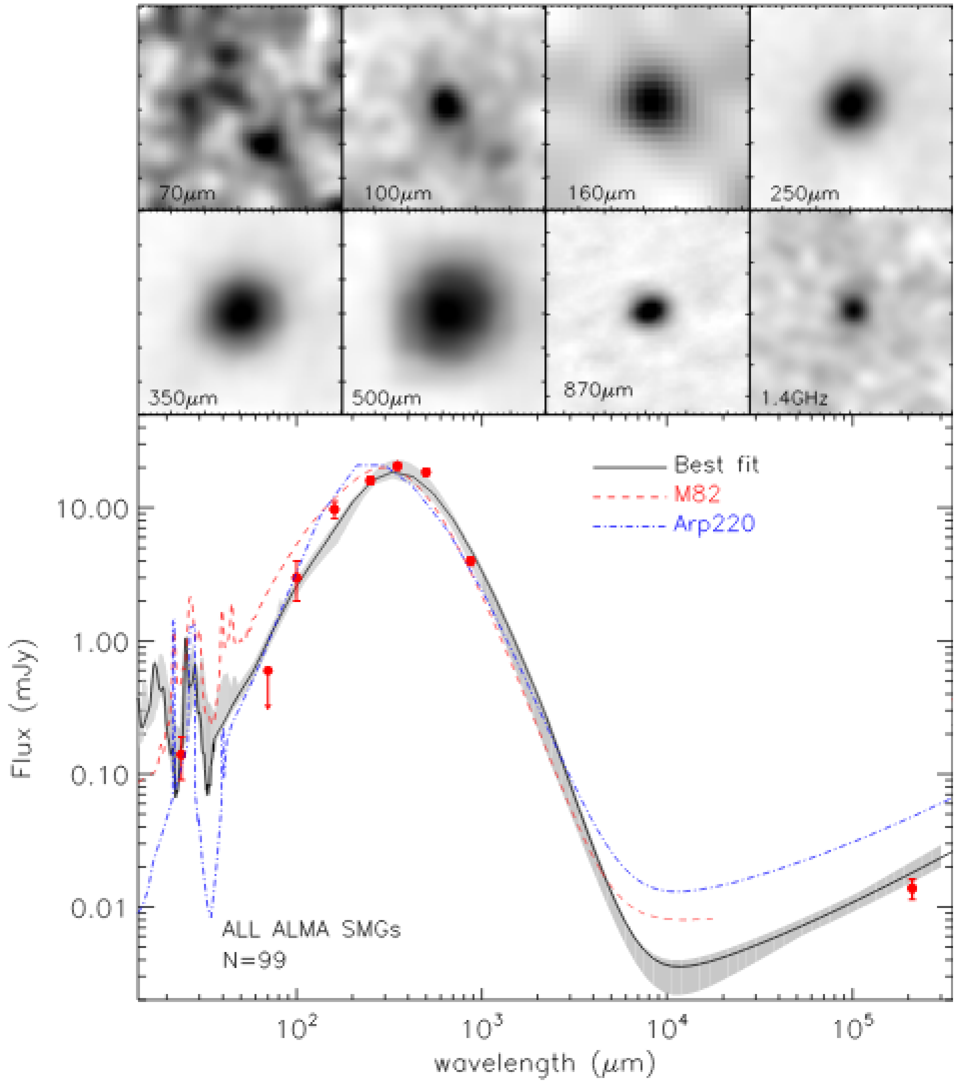
Hodge et al 2013; Karim et al. 2013; Simpson et al. 2013, Swinbank et al. 2014, and many other papers ….

# An ALMA survey of submm in the Extended Chandra Deep Field South

**PI: I. Smail**

- By fitting and averaging the SEDs, the far-infrared luminosities are
  L_FIR=(3.0±0.3)×$10^{12}$ L_sun (SFR=300±30 M_sun/yr)
- The characteristic dust temperature is Td=32±1 K
  (3–5 K lower than comparably luminous galaxies
  at z=0, reflecting the more extended
  star formation in these systems).



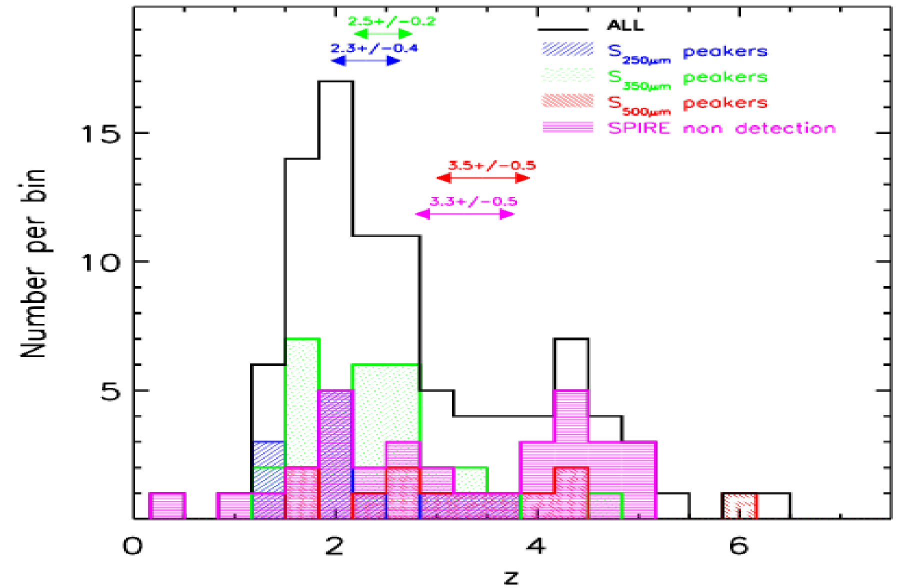



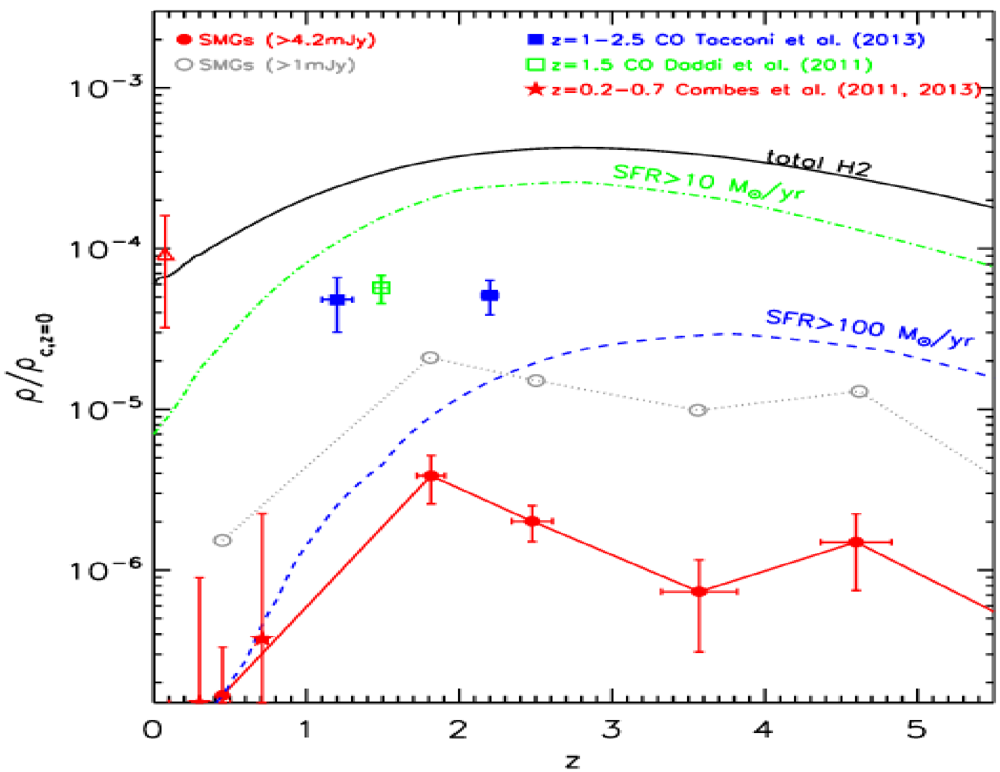

**Swinbank et al. 2014**

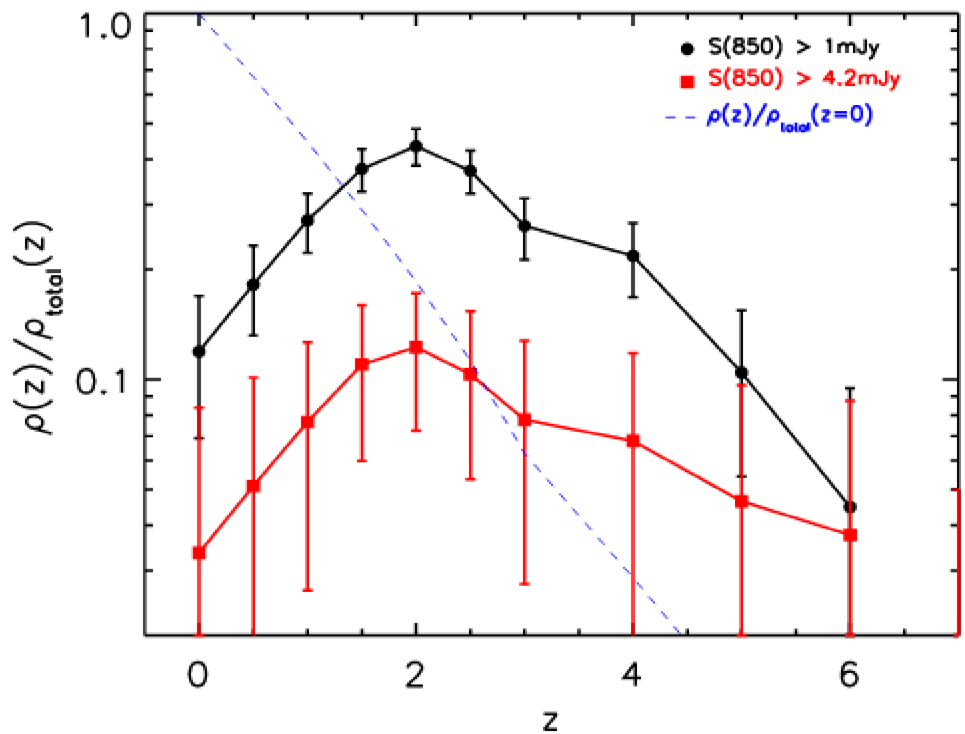
# An ALMA survey of submm in the Extended Chandra Deep Field South

**PI: I. Smail**

- The contribution of S(870μm)≥1 mJy SMGs to the cosmic star formation budget is 20% of the total over the redshift range z∼1–4.
- Adopting an appropriate gas-to-dust ratio, the typical molecular mass of the SMGs is $M(H_2)=(4.2\pm0.4)\times10^{10}$M_sun
- SMGs with S(870μm)>1mJy (L_FIR>$10^{12}$L_sun ) contain ∼10 per cent of the z∼2 volume-averaged H2 mass density

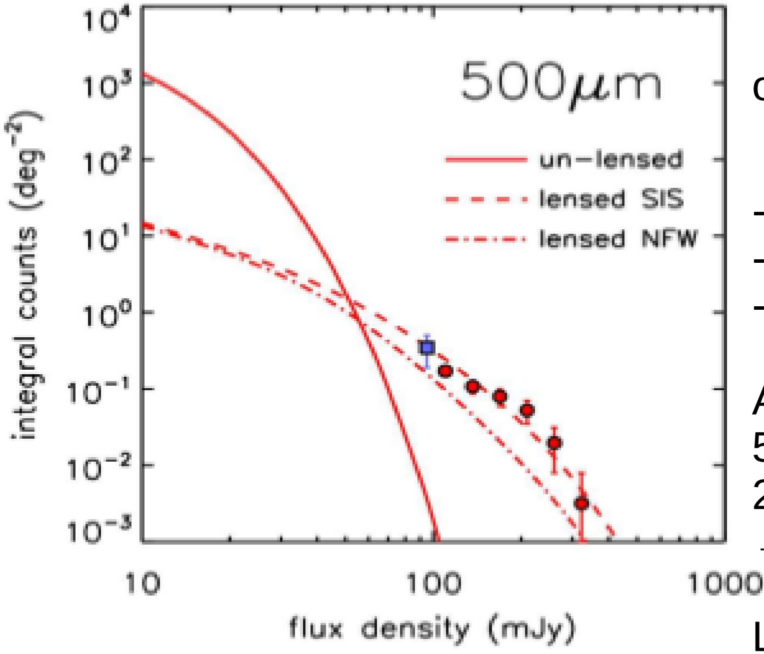



Swinbank et al. 2014

# Lensed galaxies

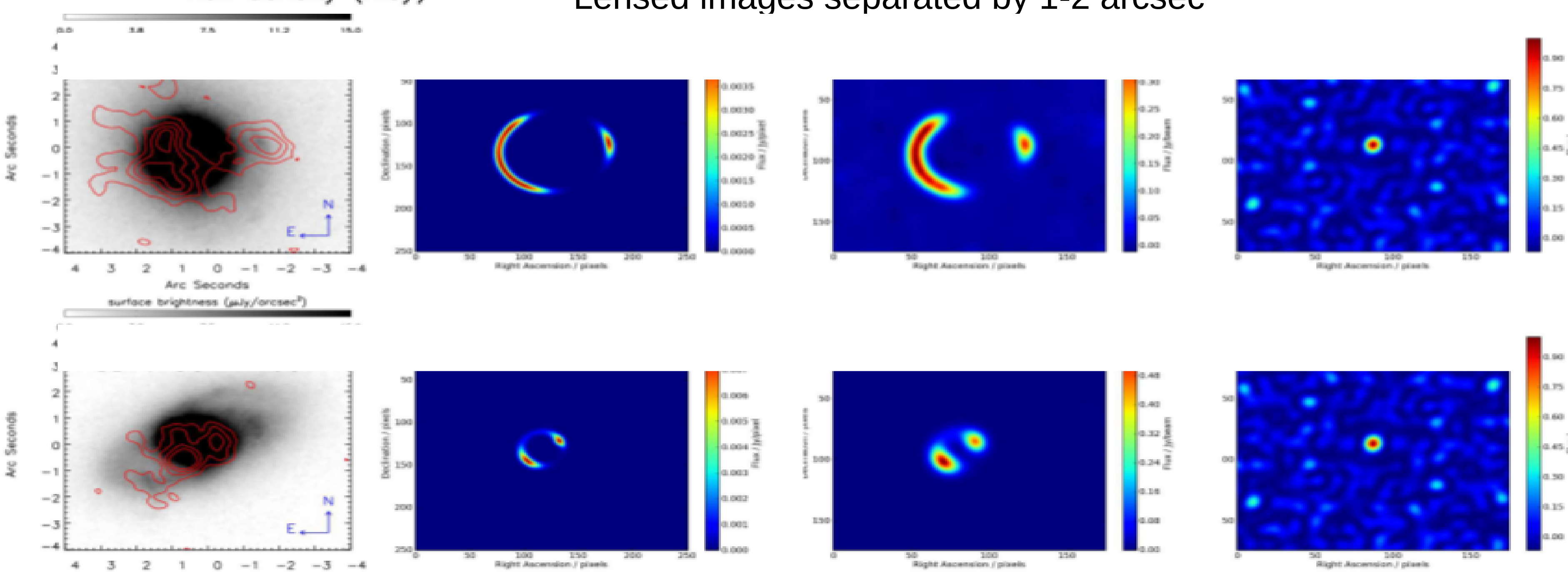



Gravitational lensing: magnifies (in flux and size) the observability of “normal” galaxies

Observing high-z lensed :
-to constrain model of galaxy formation
-to measure galx evolution up to high-z
-to investigate high-z gal physical properties

All z=1 dust-obscured star forming gal in submm above 100mJy at 500micron are boosted by lensing (by a factor 10) (Negrello et al. 2010).
→ in H-ATLAS SDP 5 lensed in 135sqdeg (all survey 400sqdeg)

Lensed images separated by 1-2 arcsec



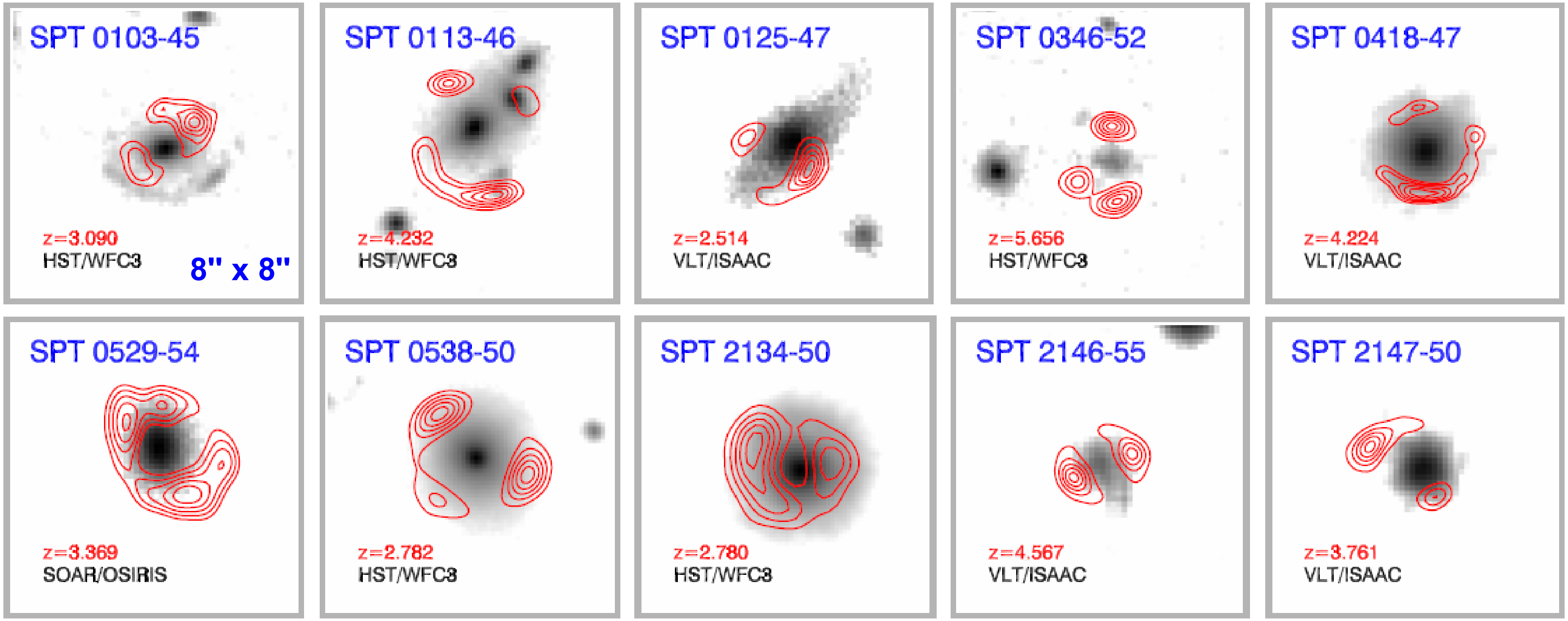

SMA 345 GHz    model of lensed    ALMA Cycle 0: 20 min in ext config

# ALMA Observations of SPT Discovered, Strongly Lensed, Dusty, star-forming Galaxies

Hezaveh et al 2013; Vieira et al 2013; Weiss et al. 2013

PI: D. Marrone

NIR Images + ALMA (Band 7) 870 μm Contours




## OBSERVATIONS

- ~15 antennas,
- ~4 hrs (~80 sec/source)
- Band 3 (spectroscopy)
- Band 7 (imaging)
- Resolution ~ 1.5''

Catalog of z > 1 strongly gravitationally lensed sources sampled from the South Pole Telescope (SPT) survey

47 SMGs detected with SPT, F(1.4 mm) > 20 mJy

**Multiple images**, separated by 1-3": **consistent with strong lensing**

Magnification Factors: 4-22

Lensed sources = ultra luminous starburst galaxies at high z

**ALMA allows to image lensed galaxies obscured in NIR/optic where the lens dominates the emission**

# ALMA Observations of SPT Discovered, Strongly Lensed, Dusty, star-forming Galaxies

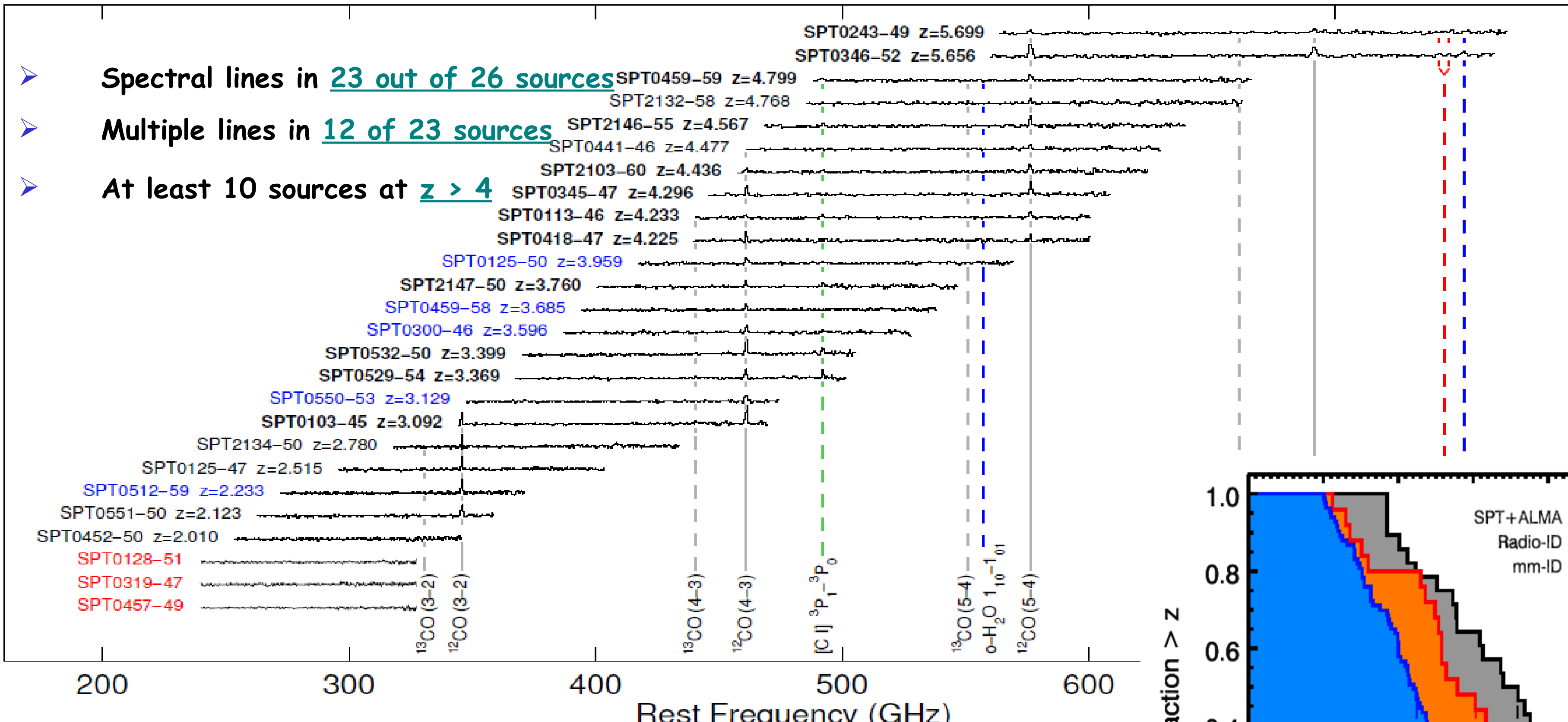
Hezaveh et al 2013; Vieira et al 2013; Weiss et al. 2013

PI: D. Marrone

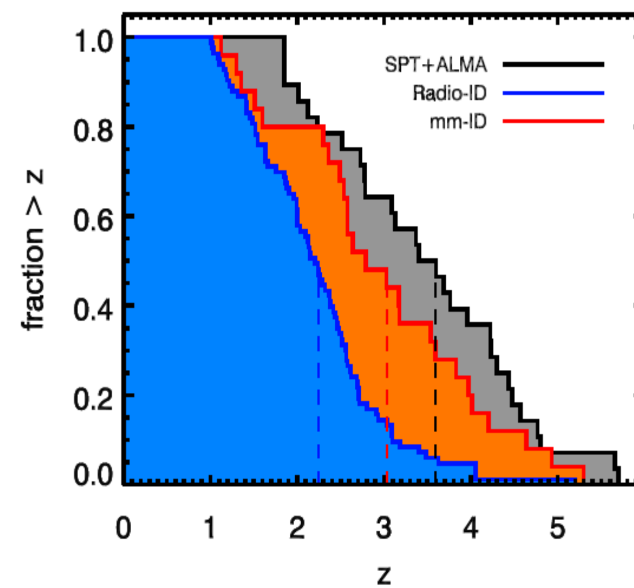
## First spectroscopic redshift survey with ALMA

ALMA Cycle 0 Band 3
100 GHz compact configuration
26 sources
5 tunings in the 3 mm band
10 minutes per source

- Spectral lines in 23 out of 26 sources
- Multiple lines in 12 of 23 sources
- At least 10 sources at z > 4




**Bold** = unambiguous redshift from ALMA
black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA
blue = single line detected with redshift, most likely redshift from photo-z
red = no line detected



# Galaxy clusters

Studies of galaxy clusters include:
- analysis of the interaction between AGN and the ICM environment
- the Sunyaev-Zel'dovich effect

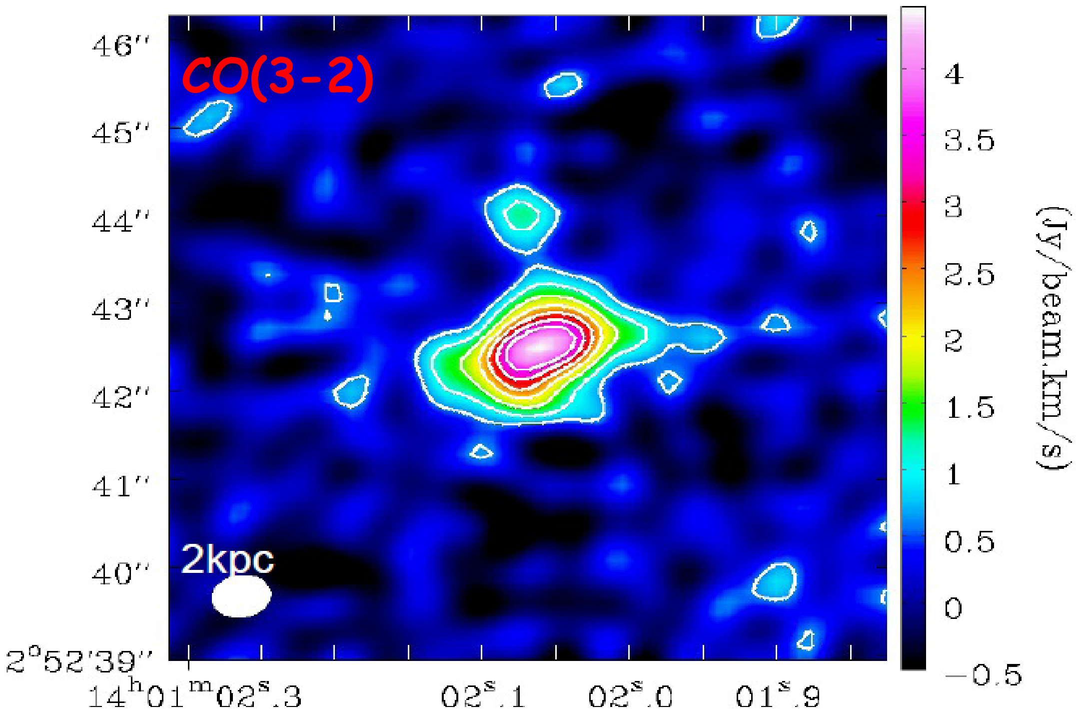
The major limit arise from the extreme resolution wrt cluster sizes
But ACA comes to help.

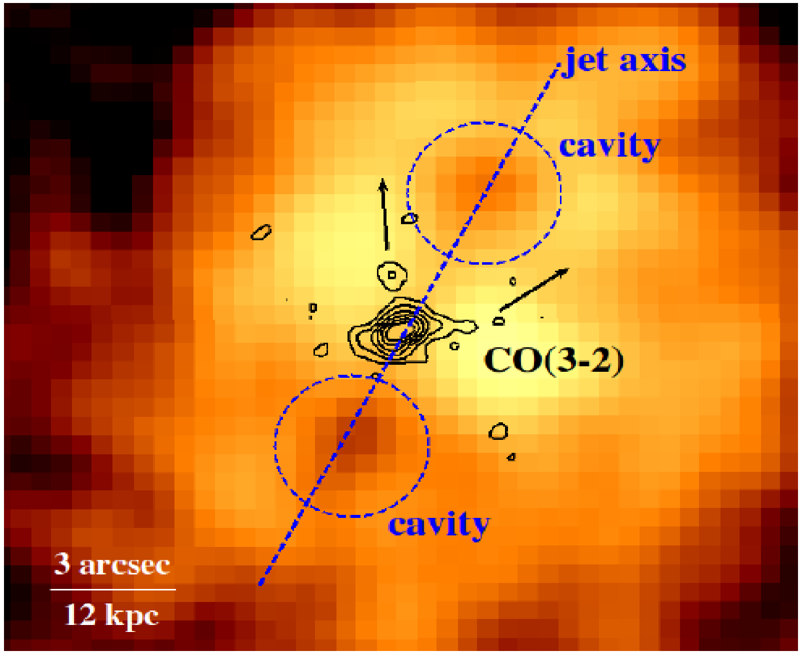
# Molecular Gas in the Cores of Galaxy Clusters

PI: B. McNamara

McNamara et al. submitted
Russell et al. 2013

## Abell 1835, a prototypical cool core cluster at z=0.25




Chandra X-ray

**OBSERVATIONS**

- Band 3: *CO*(1-0) and Band 7: *CO* (3-2)
- *Angular resolution: 0.5-1.5''*
- 1 hr on source,
- rms: 0.6-1.6 mJy

ALMA obs explore at high resolution the relationships between molecular gas, star forming, and radio AGN feedback

5 x $10^{10}$ $M_\odot$ of molecular gas within 10 kpc of the BCG in a possibly face-on disk

Gas filaments drawn up or falling back around radio bubbles

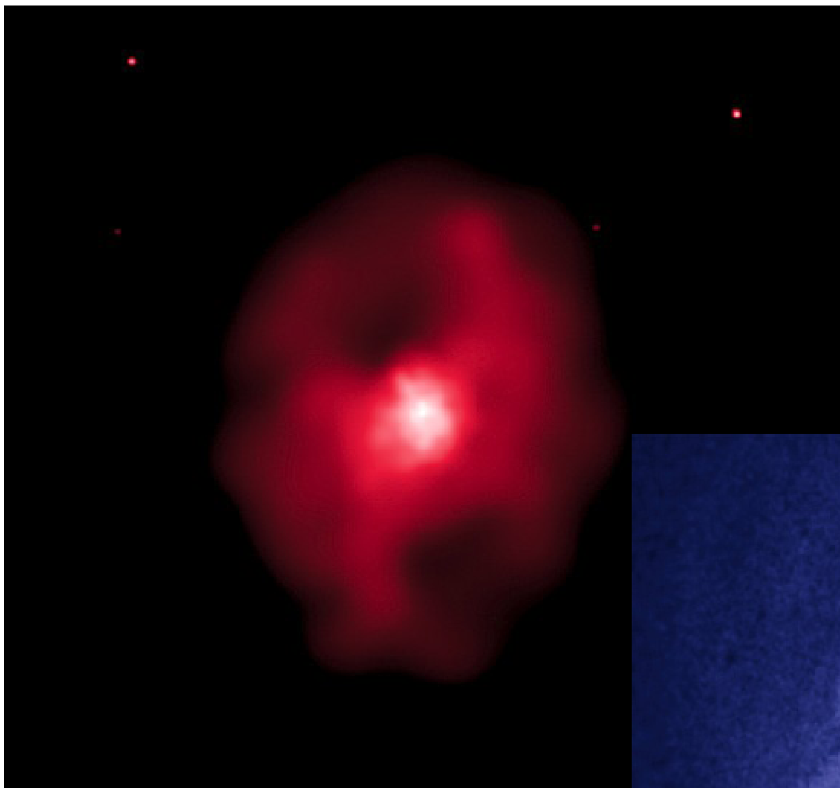
**The radio AGN heats ICM surrounding BCGs and sweeps molecular gas away from their centers**

PI: B. McNamara

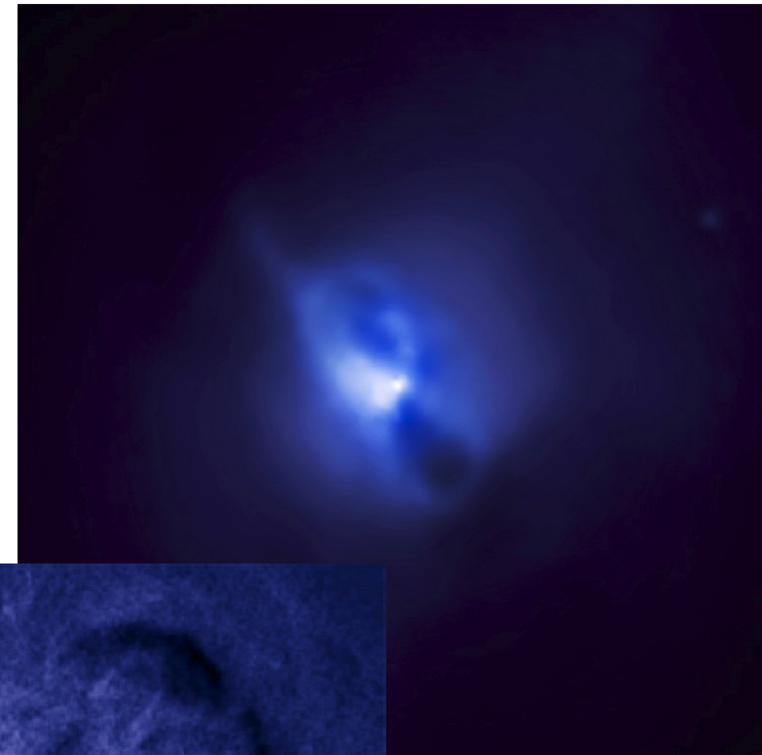
# Molecular Gas in the Cores of Galaxy Clusters

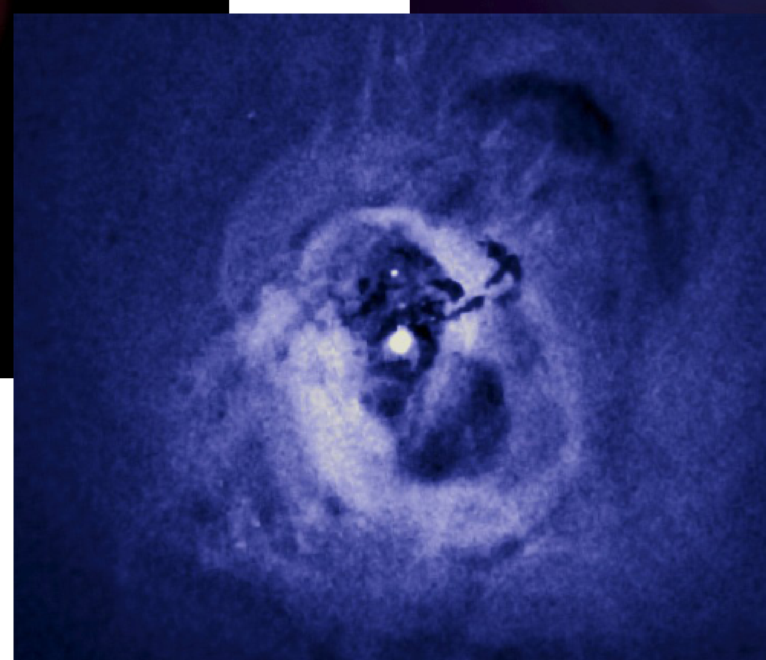
## Cavity heating

MS0735, McNamara et al. 2005



Hydra A, Kirkpatrick et al. 2009





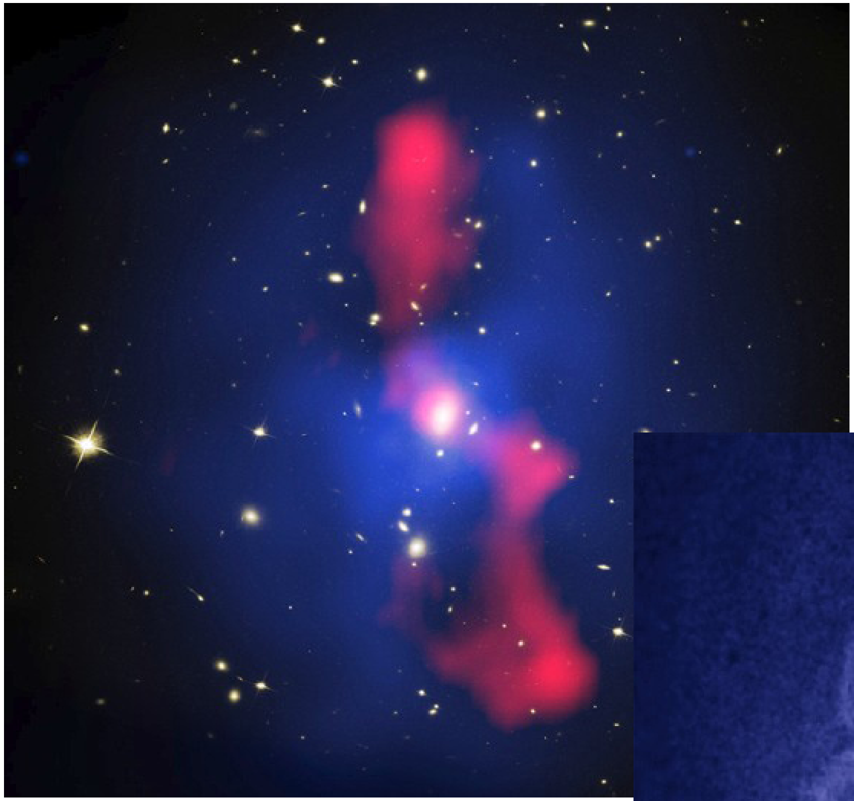
Perseus
Fabian et al. 2008

PI: B. McNamara

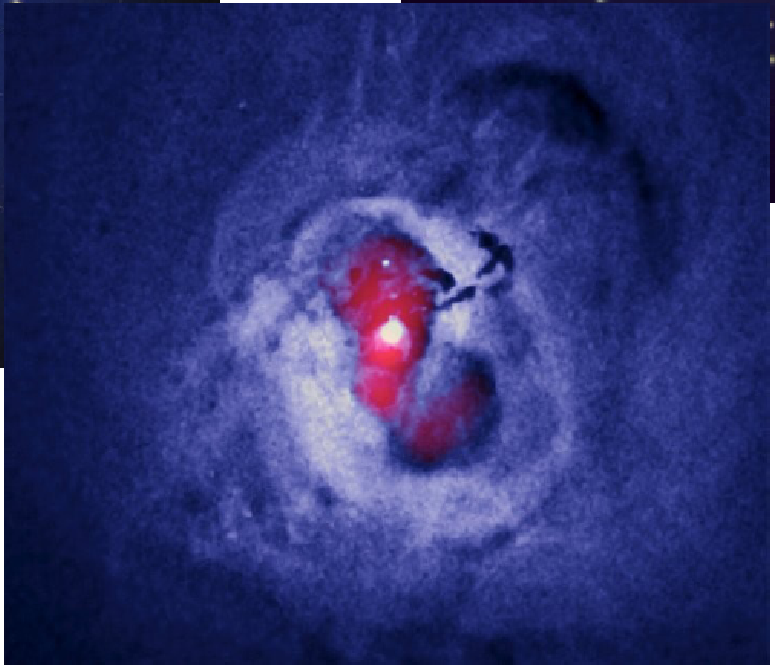
# Molecular Gas in the Cores of Galaxy Clusters

## Cavity heating

MS0735, McNamara et al. 2005

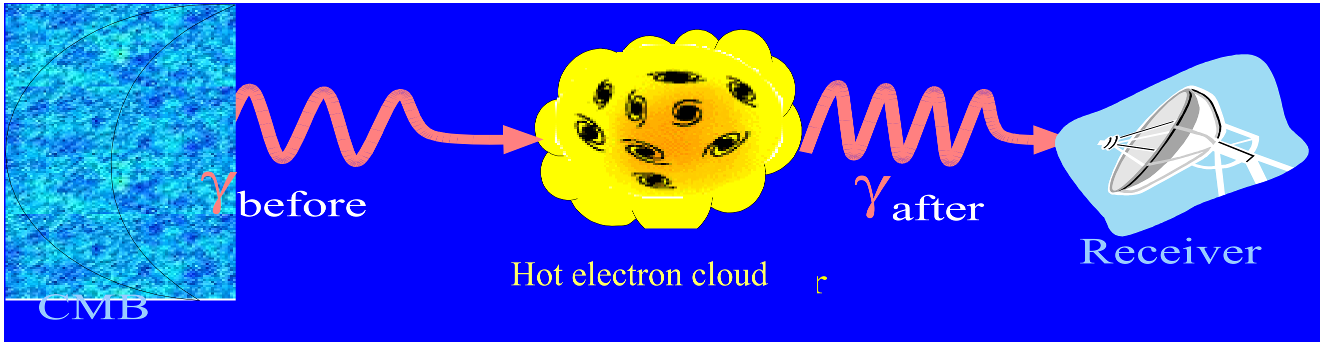


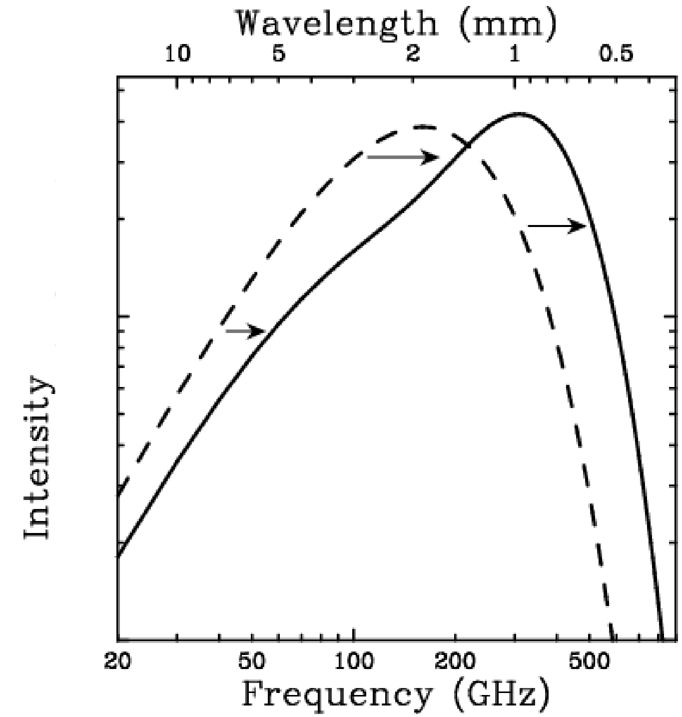
Hydra A, Kirkpatrick et al. 2009



Perseus
Fabian et al. 2008

# The Sunyaev-Zel'dovich effect



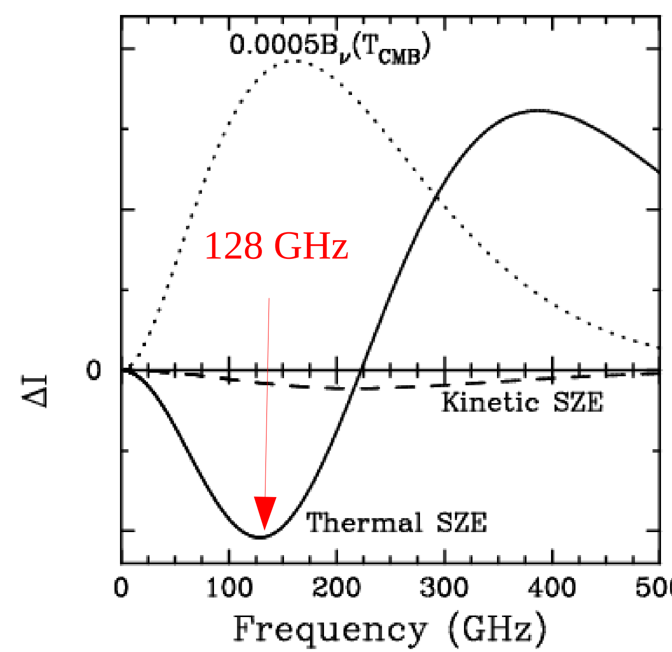

The **Thermal SZ effect** is the spectral distortion of the CMB radiation due to Inverse Compton Scattering of CMB photons with electrons in hot clouds.

$$\Delta I(\nu) = \frac{2(k_B T_{CMB})^3}{(h_p c)^3} \frac{x^4 e^x}{(e^x - 1)^2} \left[ x \frac{e^x + 1}{e^x - 1} - 4 \right] y = I_0 f(x) y$$

$$y = \int \frac{k_B T_e}{m_e c^2} \sigma_T n_e dl$$

Comptonization parameter

$$x = (h_p \nu)/(k_B T_{CMB})$$




The **Kinetic SZ effect** is a Doppler effect due to

- the cloud proper velocity.

$$\Delta I(\nu) = \pm \frac{v_e}{c} \tau I_0 \left[ \frac{x^4 e^x}{(e^x - 1)^2} \right]$$

$$\tau = \int n_e \sigma_T dl$$

(Carlstrom et al. 2002)

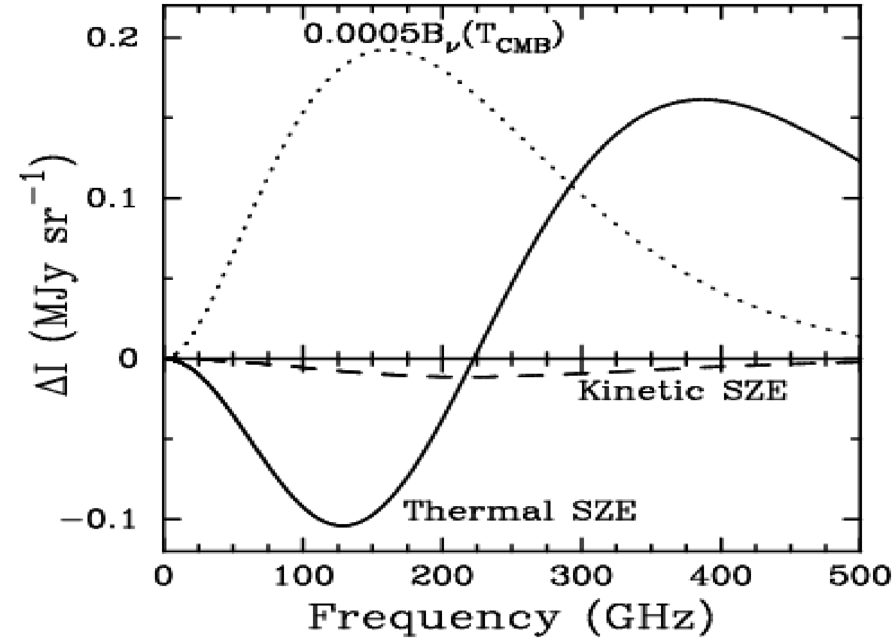
# The SZ in galaxy clusters

- Most massive virialized object
- Permeated by completely ionized gas
  - $T_e > 10^7$-$10^8$ K
  - $n_e > 10^{-3}$ cm$^{-3}$
  - $v_e > 1000$ km/s

**y > $10^{-4}$**

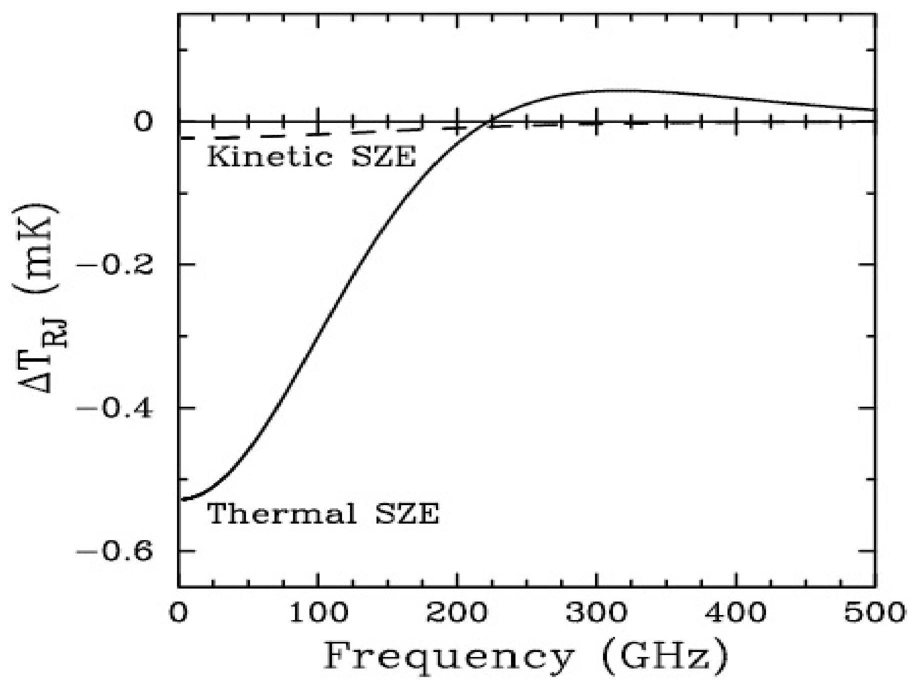
**$\Delta T_T >$ -1 mK** @ radio frequencies

**$\Delta T_K > 0.08\, \Delta T_T$**



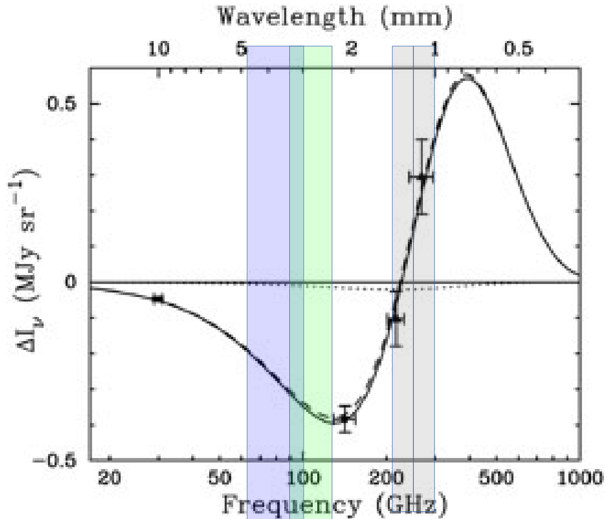

The SZ effect is a powerful tool:

- To study **high redshift** structures:
  - $\sigma_8$, $\Omega_m$
  - evolution of potential wells, merging
- To study the **cluster properties**:
  - gas density, temperature and mass
- To study **ICM**
- To estimate **cosmological parameters** (by comparing SZ with X-ray emission):
  - high redshift structure distances
  - H0, q, baryonic mass fraction




Carlstrom & al. 2002

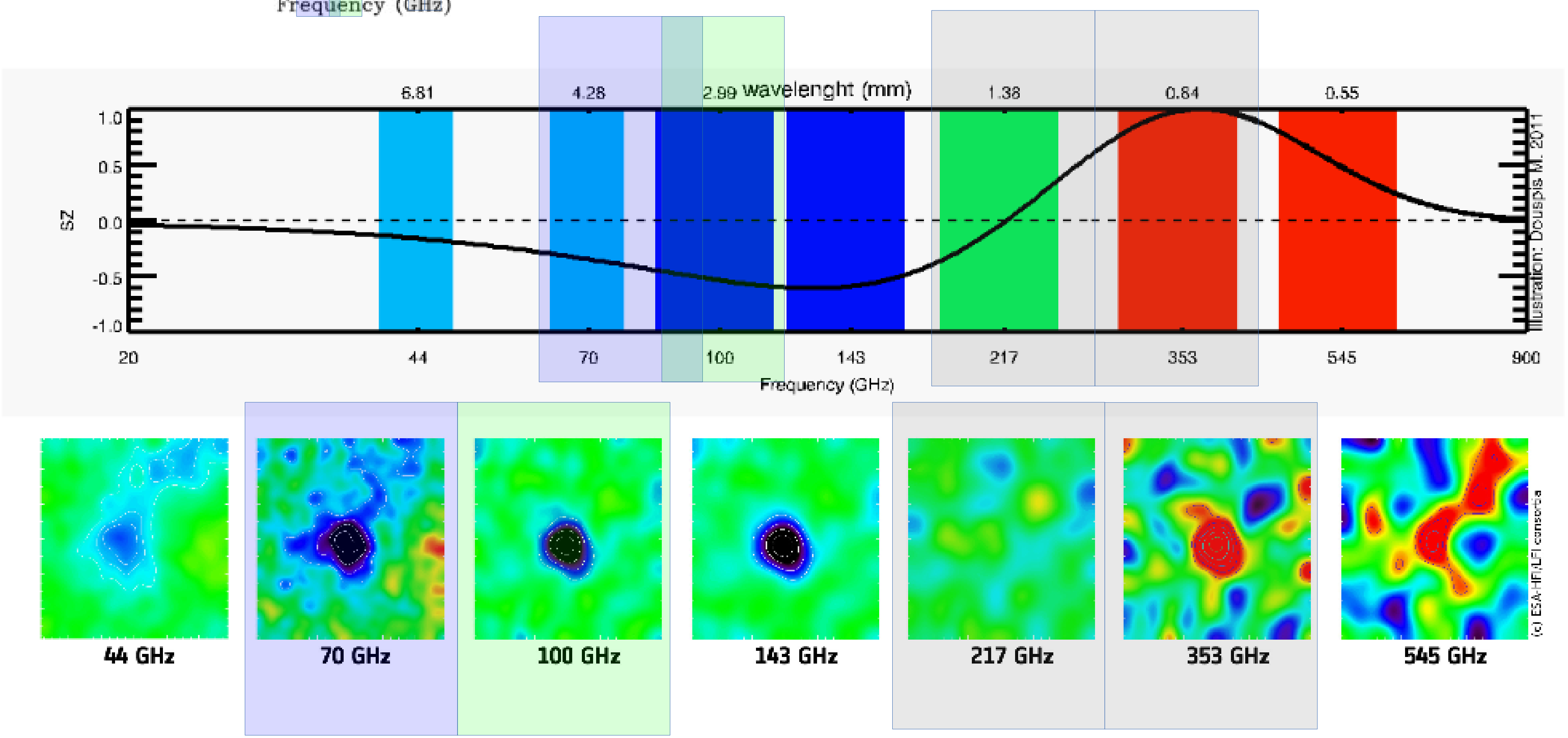
# Multifrequency observations



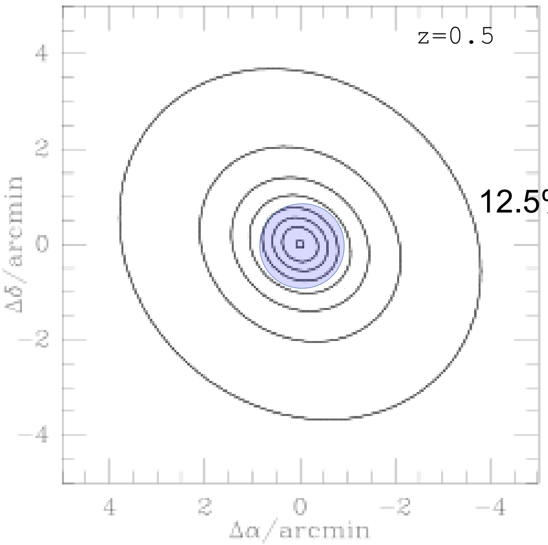

Examples of multifrequency observations (overlapped ALMA B2,3,6,7)

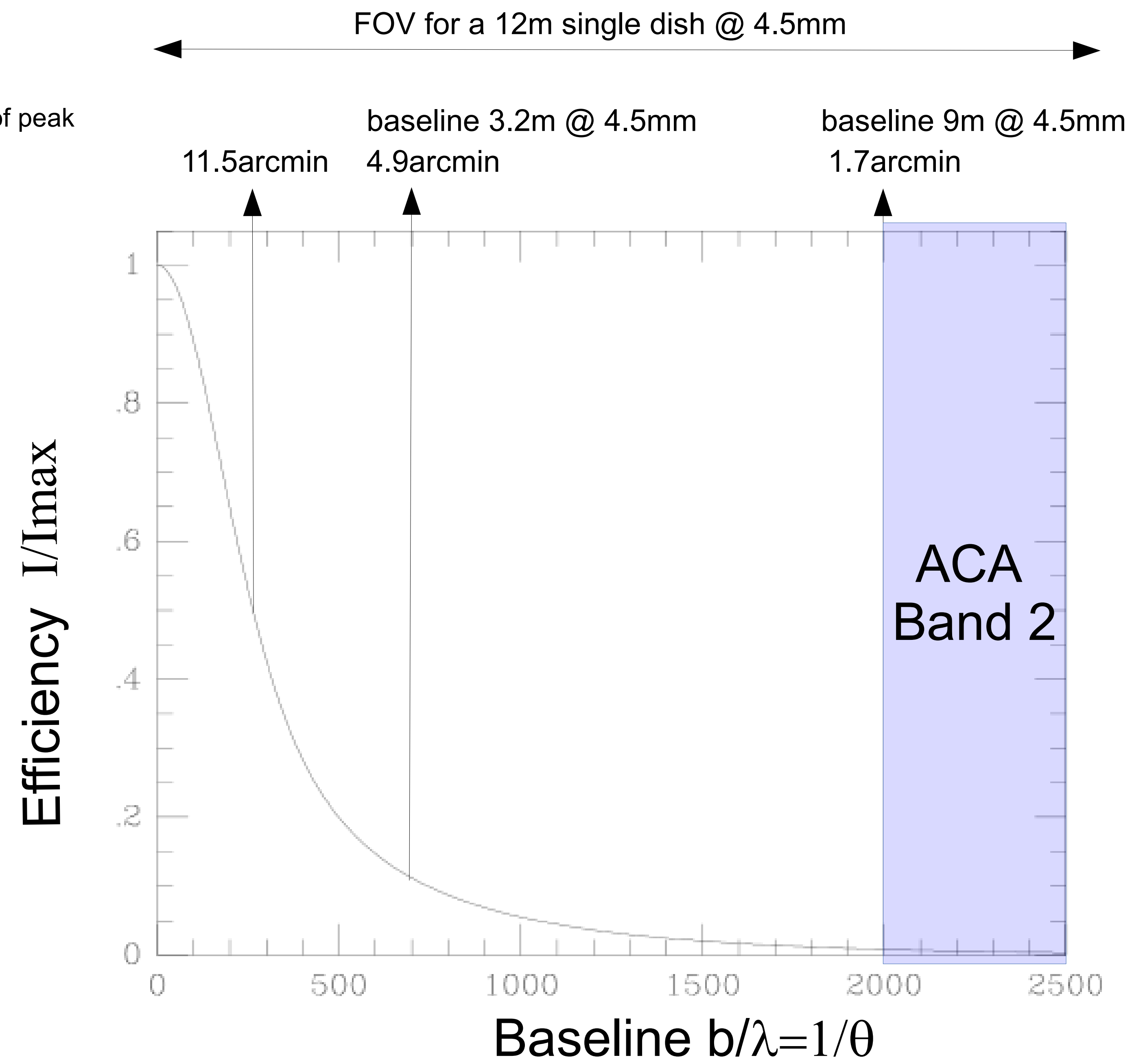
A2163: BIMA+SuZIE (ground based)

A2139: Planck satellite



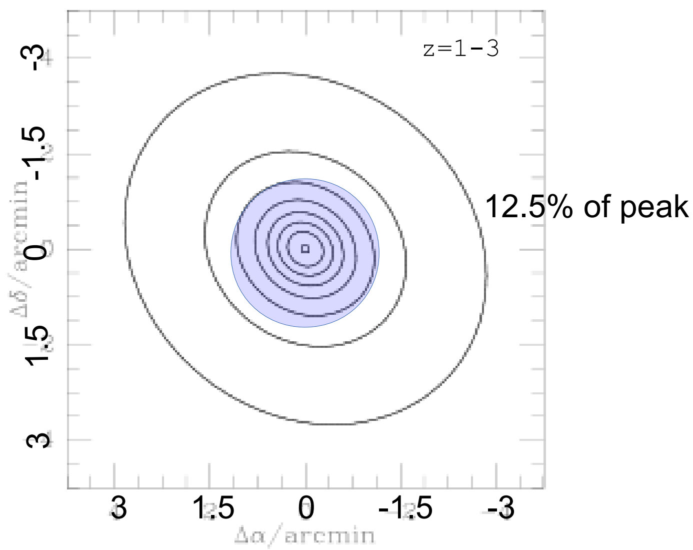
# The resolution issue

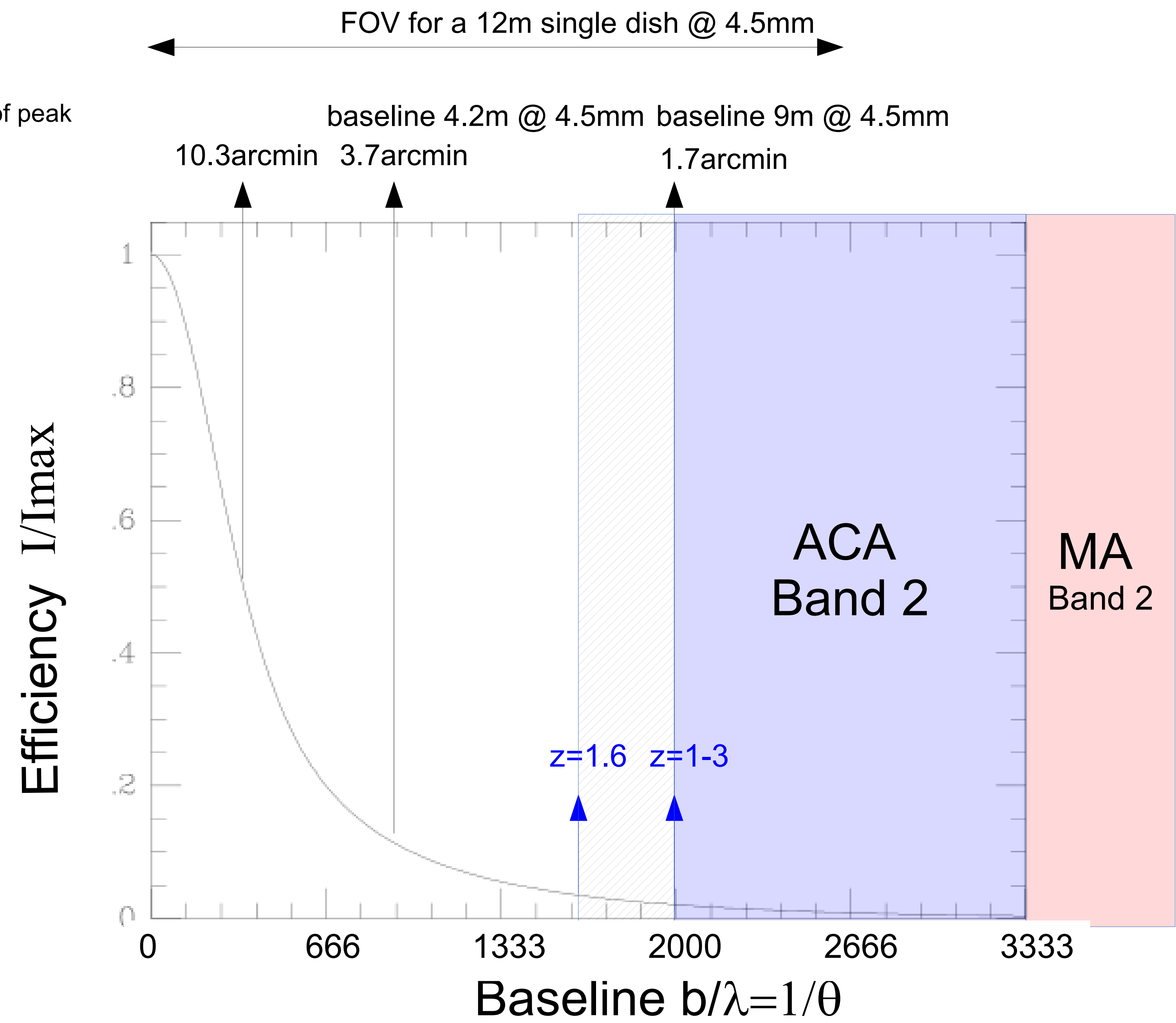



Birkinshaw & al. 1999

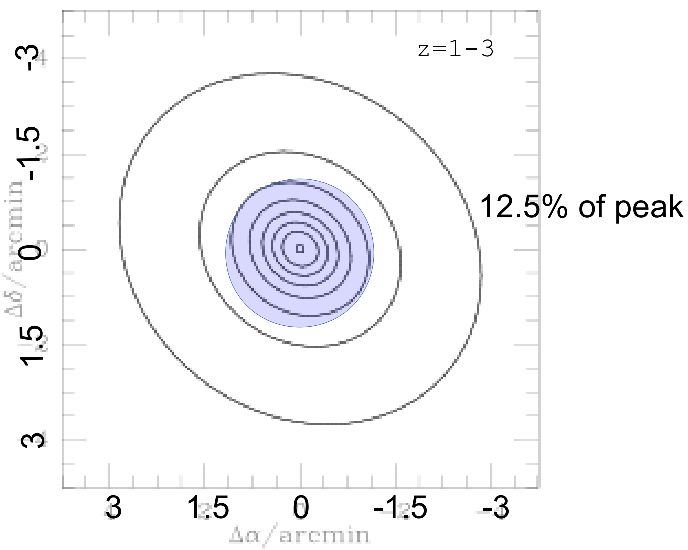
# The resolution issue

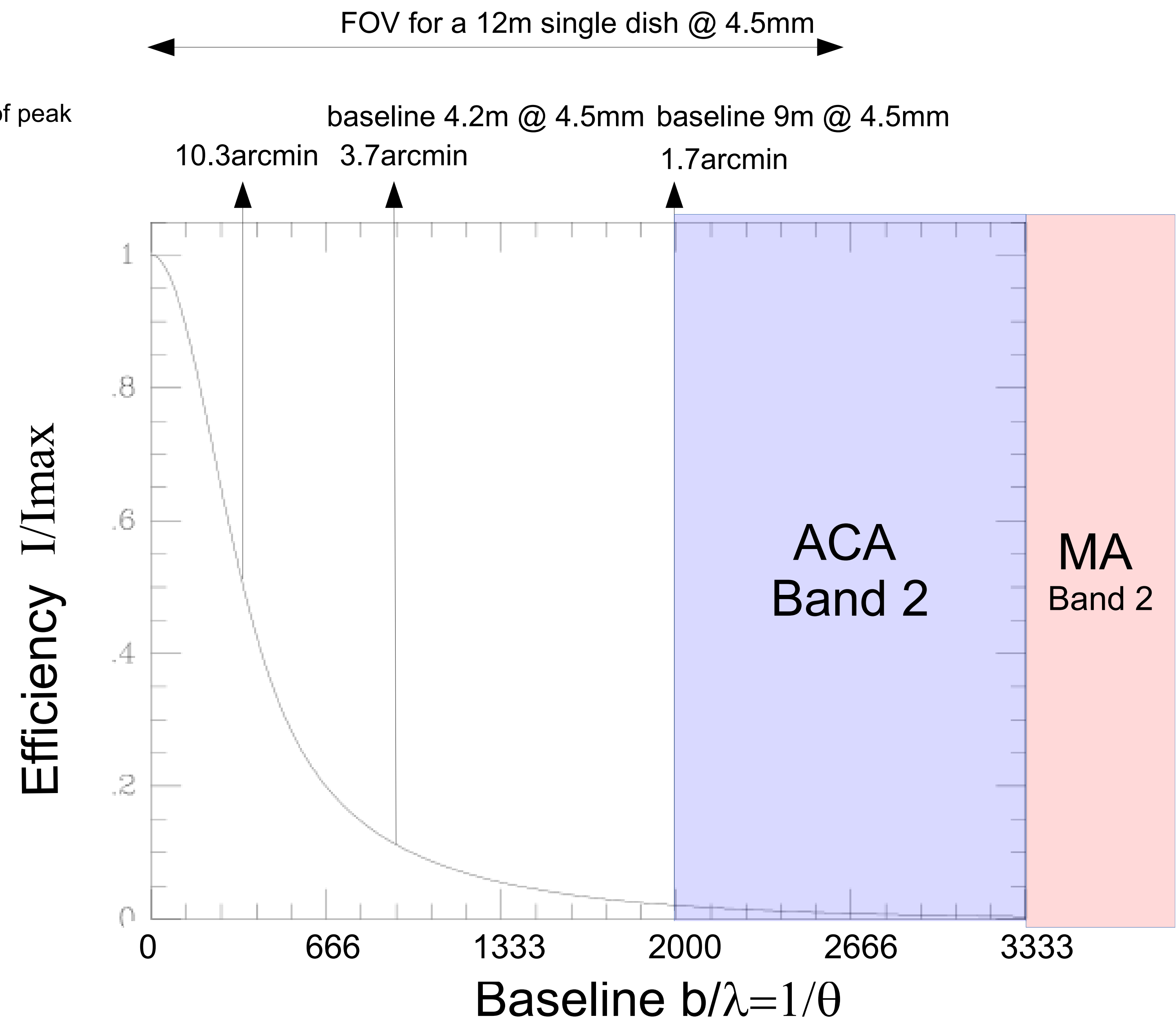



Birkinshaw & al. 1999

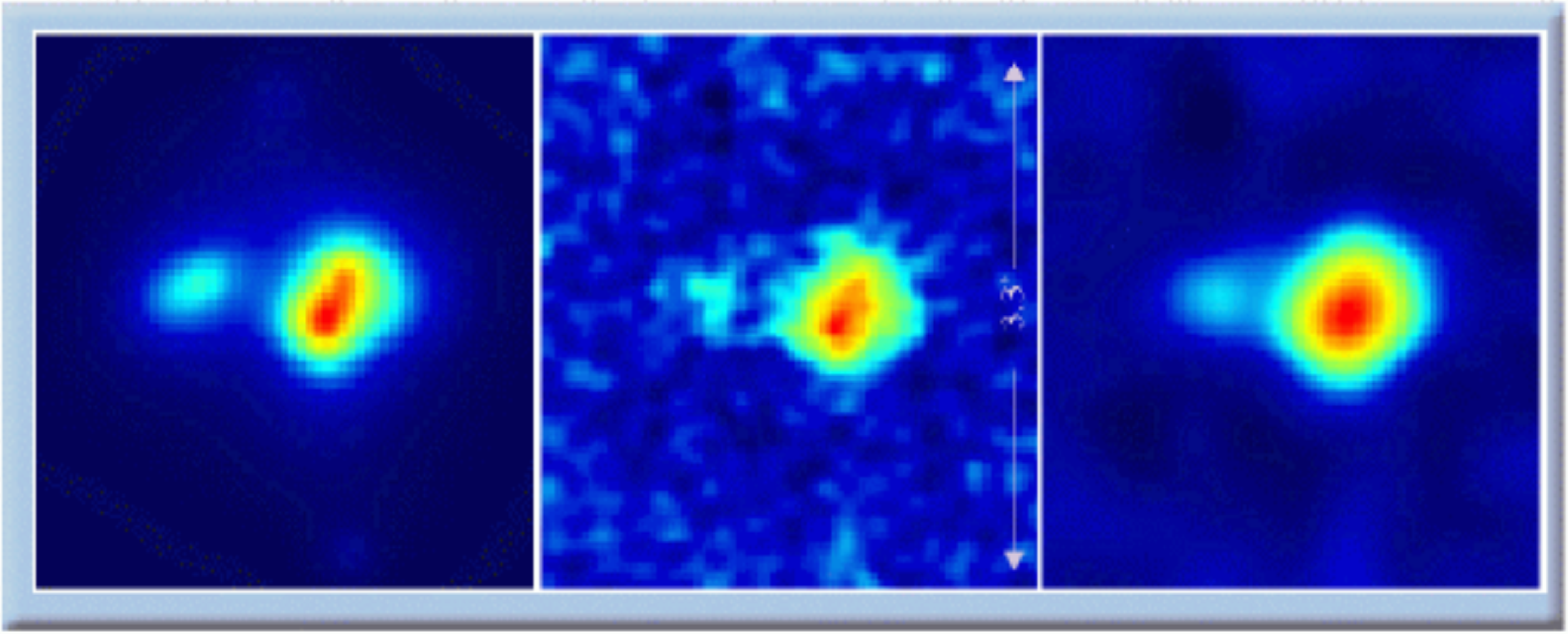
# The resolution issue




Birkinshaw & al. 1999

# The ALMA simulation




The left panel shows a hydrodynamical model of a $2.5 \times 10^{14}$ solar mass cluster at redshift 1. The center panel is a 4-hour ALMA image of the cluster at 35 GHz in compact configuration. The rightmost panel shows the same image, smoothed to a resolution of 22 arcsec.

# The SZ effect in galaxy clusters with ALMA

High redshift clusters show complex structure different in SZ and in X-ray.
It might have consequences for cosmological results.
**We need high resolution mapping and sensitivity to investigate cluster properties and cosmology.**

ALMA reaches same flux density level in
3*ATCA time (only ACA array)
0.8*ATCA time (ACA+TP antennas)

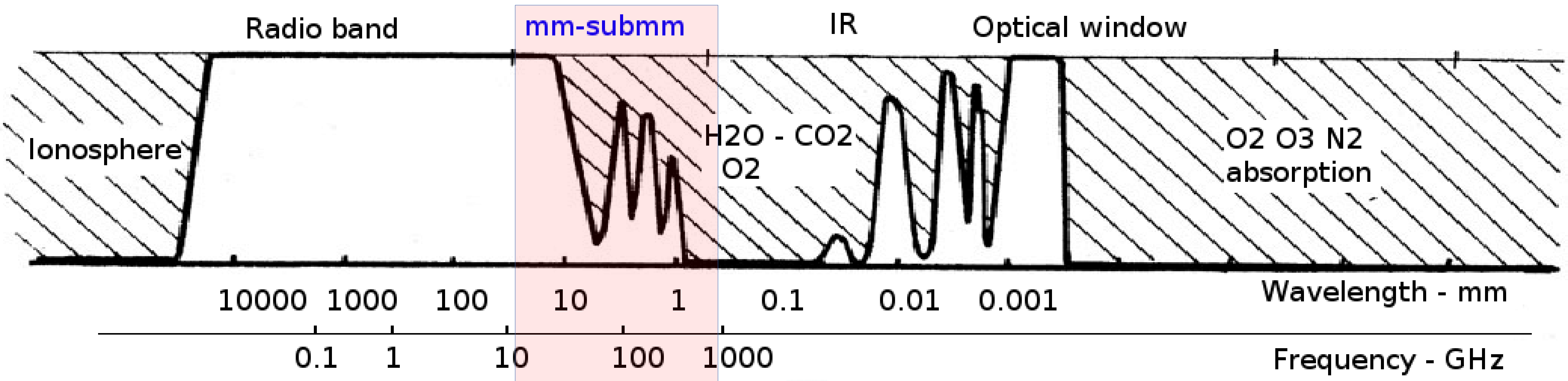
But SZ signal at 70 GHz is 12 times stronger than at 18 GHz!!!
**Only ACA reaches the same S/N as 27h ATCA at 18 GHz**
**in 34 min at 70 GHz*!!!!!!**

+ simultaneous single dish
+ reduced radio source contamination
+ simultaneous higher resolution from main array
  good for point source subtraction

*(similar FOV and beam)

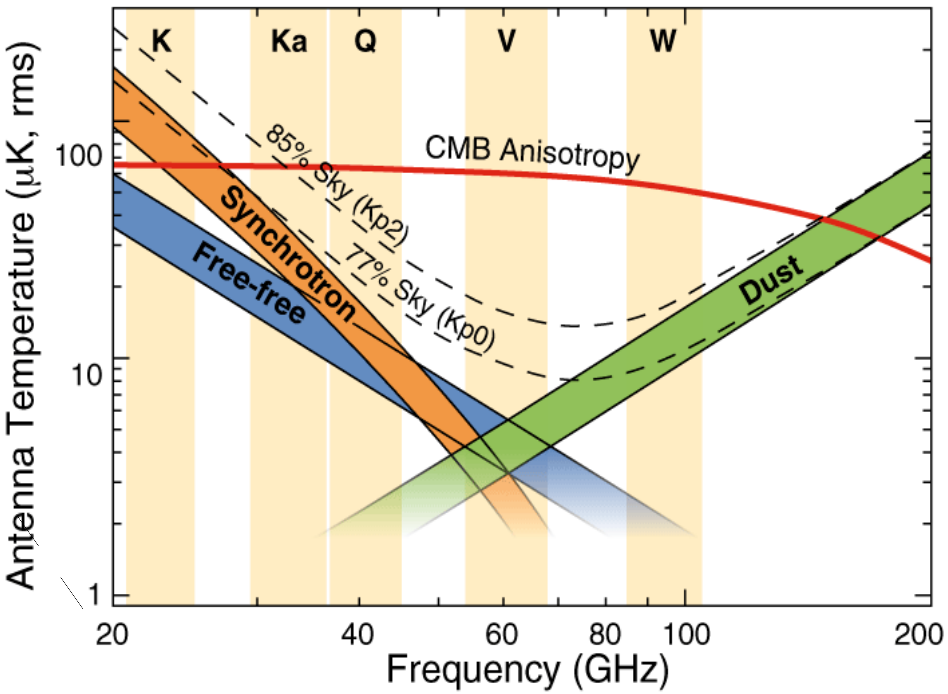
# Summary

# The signals




**The (sub)mm band ranges between 30-1000 GHz**

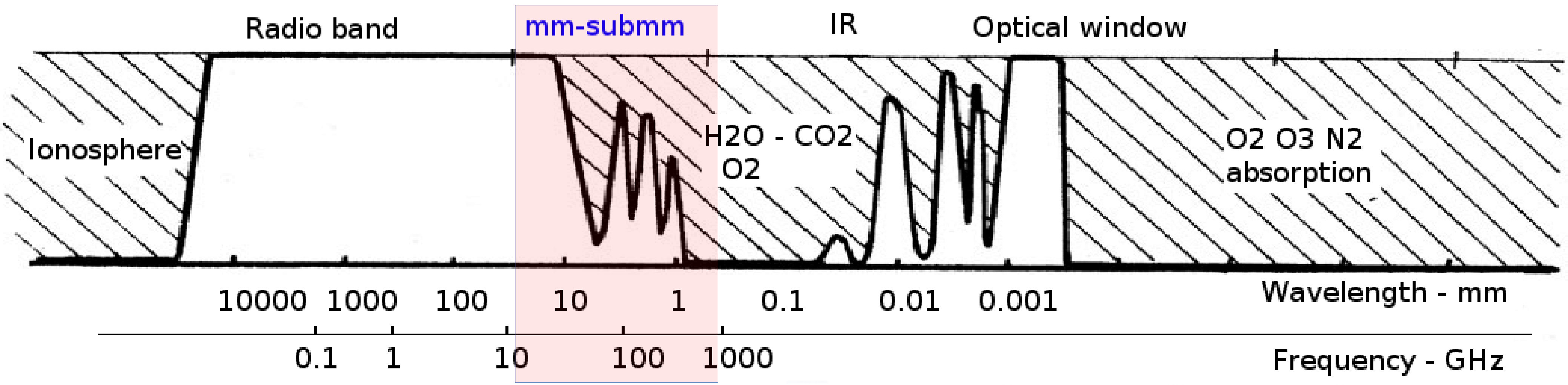
**(Sub)mm signals:** **synchrotron, dust emission, molecular lines, CMB**



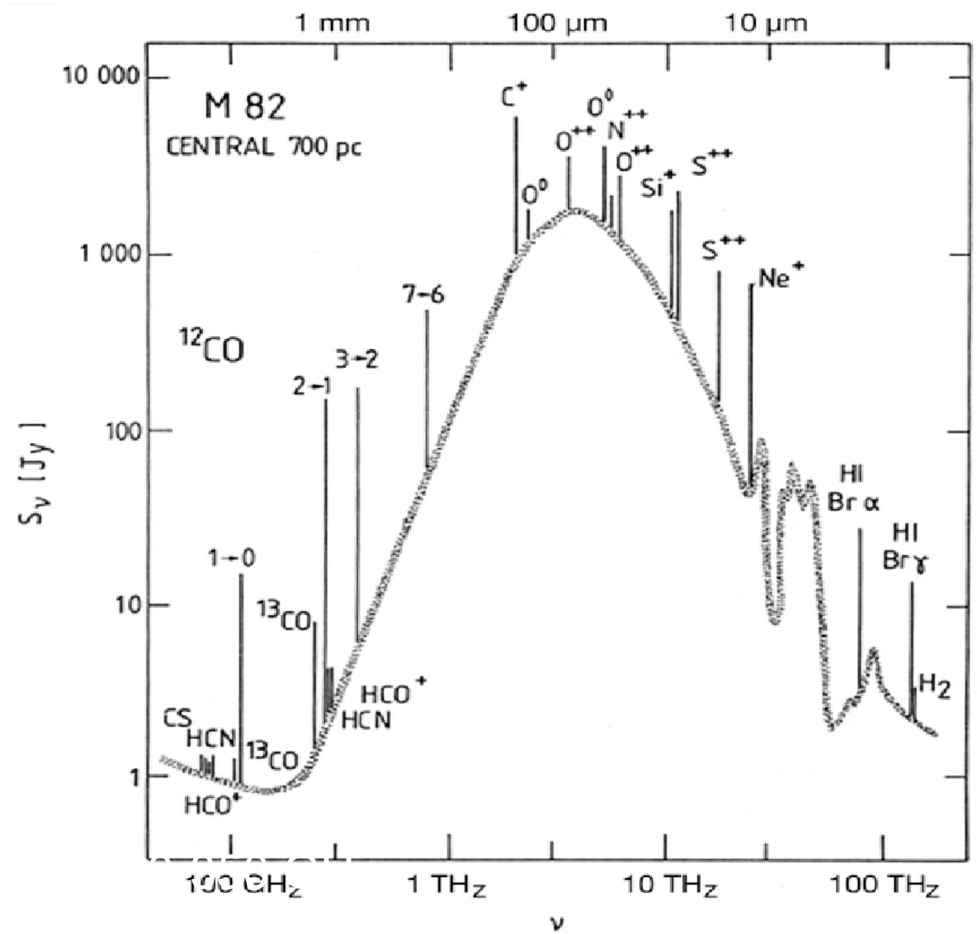

**The warm dust emitting at far–IR wavelengths is mostly heated by the UV-radiation field of young massive stars in star forming regions.**

**The far infrared luminosity is considered good tracer of star formation in galaxies.**

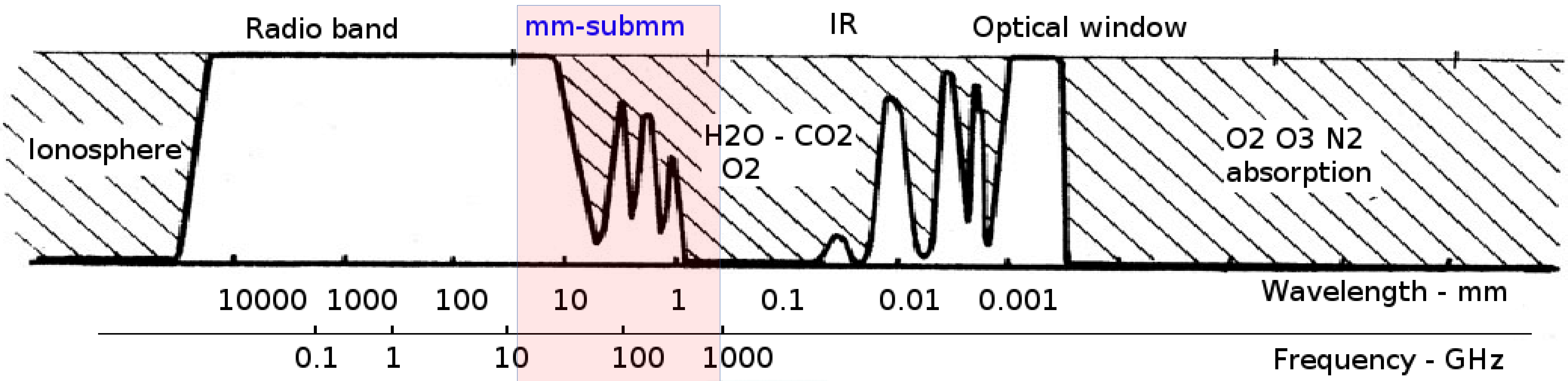
# The signals

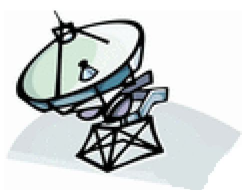


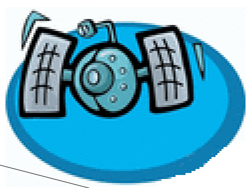

The spectrum of each molecular cloud in the submm is rich of rotational molecular transition ladders and atomic fine structure lines, which shapes and relative abundances can be used to trace physical and dynamical properties of the ISM and the mechanisms of SF and AGN activity In the local and high-z Universe.



# The instruments



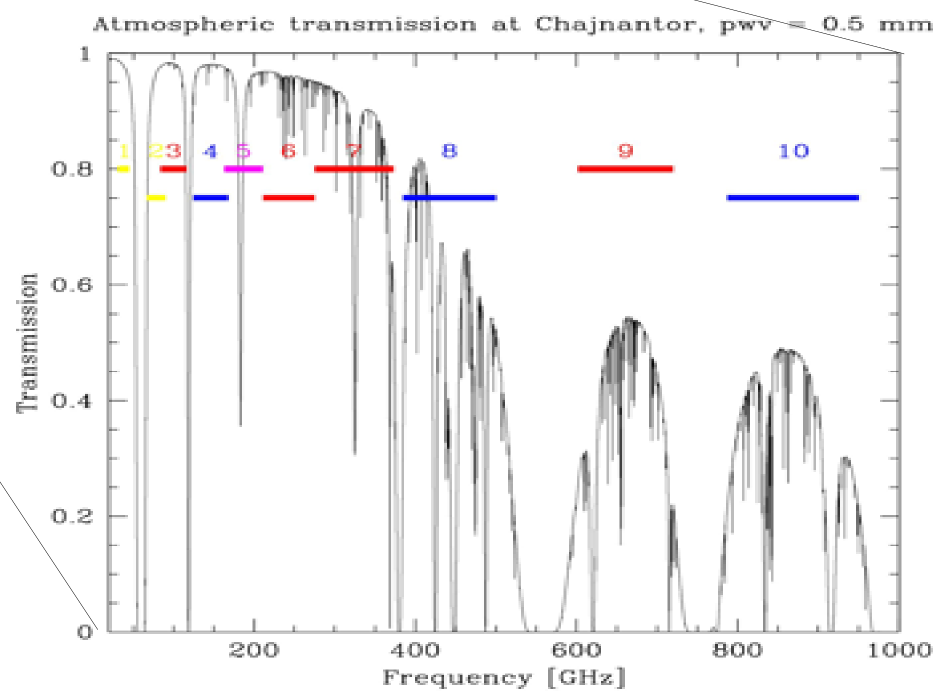





Requirements: Excellent weather
Accurate antennas
Sensitive receivers

**ALMA is a 50x12m + 12x7m+ 4x12m array operating in 10 bands between 30 and 1000 GHz in extremely dry site, reconfigurable to cover baselines up to 16km (and in the future mm-VLBI)**

**Reaches encompassed sensitivity and resolution thanks to the instrumental properties**



# Why should I go (sub)mm?

# Why shouldn't I go (sub)mm?

# Enjoy the new ALMA era!

(I acknowledge contributions from the Italian ALMA Regional Center members:
Jan Brand, Elisabetta Liuzzo, Arturo Mignano, Rosita Paladino,
Viviana Casasola, Jeremie Boissier)