A review of (sub)mm band science and instruments in the ALMA era

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ALMA
EUROPEAN ARC
ALMA Regional Centre || Italian

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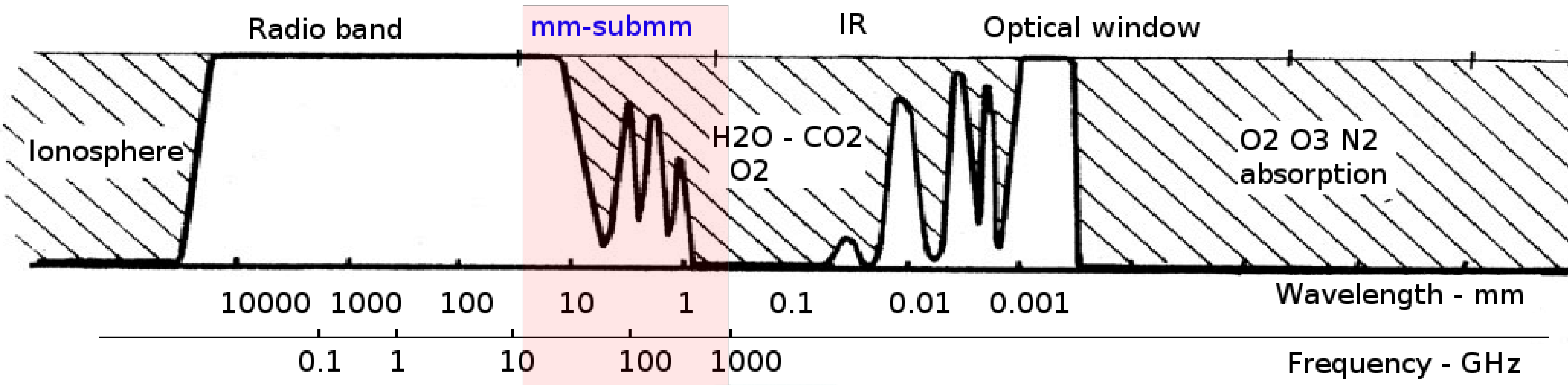
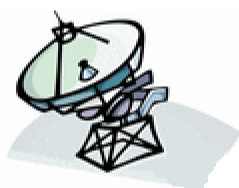
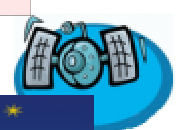
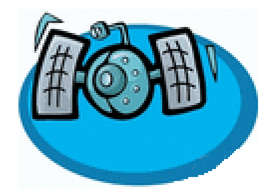
Outline









Observing instruments: **Interferometers (ALMA)**

Signals in the (sub)mm bands

Science cases parade

Observing processes: **Proposals, archives & images**

How to extract science from images: hands-on tutorial

General words: ALMA pros for science

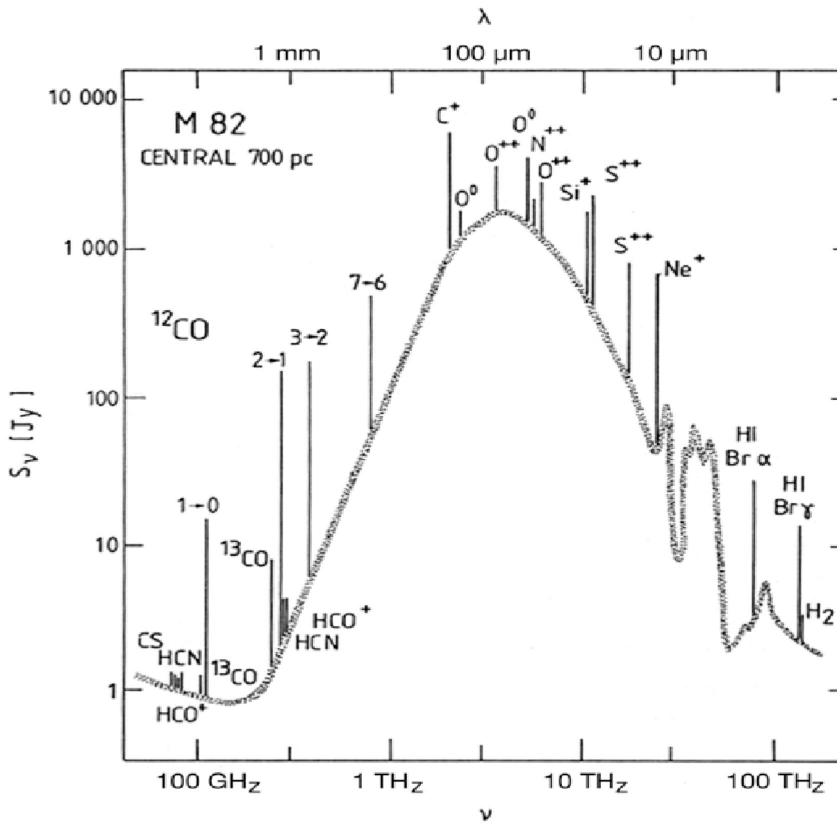
Sub(mm) is characterized by dust and rich chemistry.

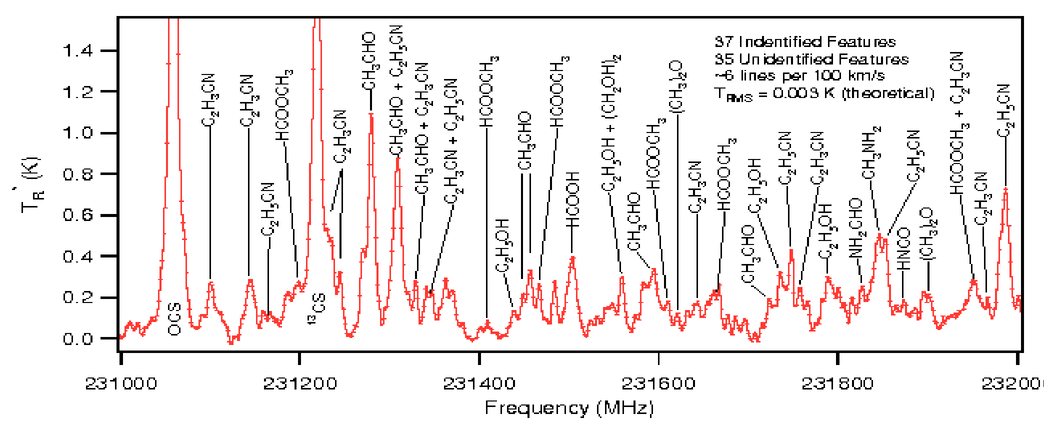
Dust and molecules are mostly (but not only) associated with forming structures.

Hence **sub(mm) helps studying structure formation.**

Higher resolution and sensitivity allows to go farther so to investigate a deeper sky region, getting more sources and more statistics on populations.

Higher spectral resolution allows to detect more narrow lines and more details from broad lines, and hence investigate chemical compositions, source dynamics and pressure and temperature structures.



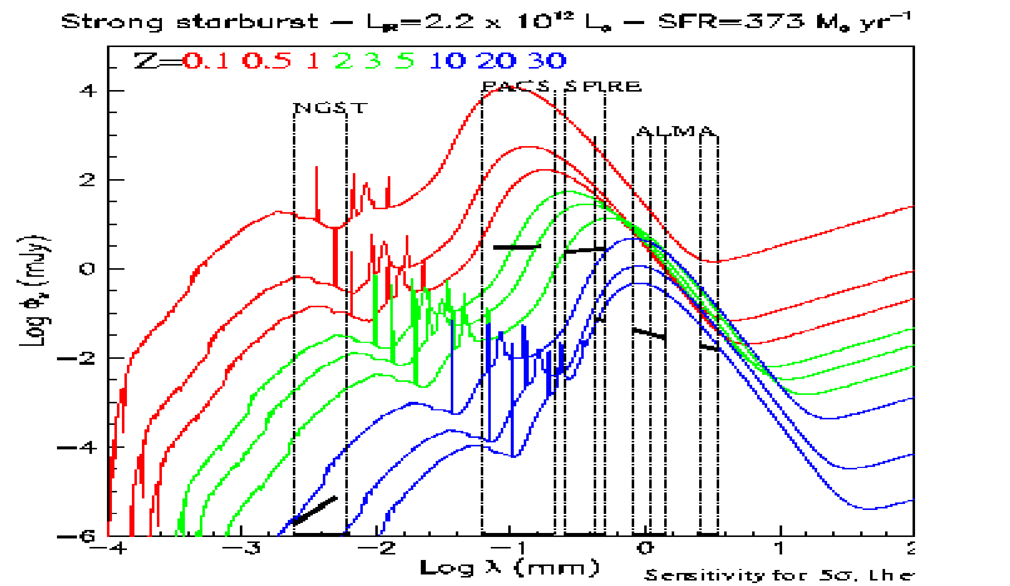


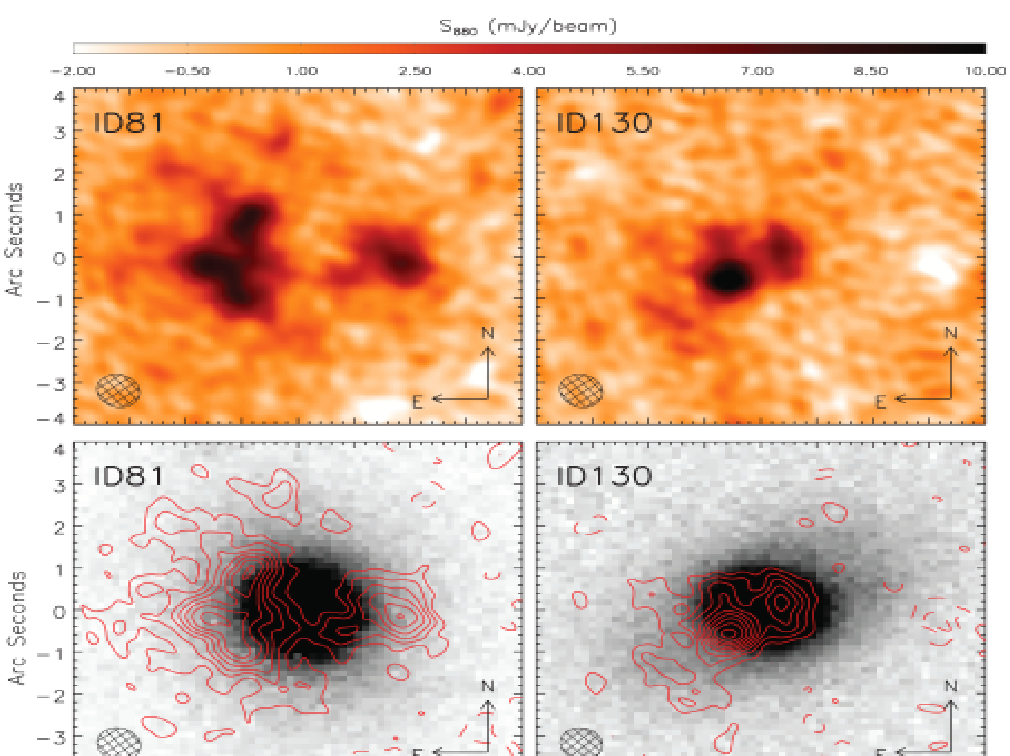
Extragalactic science in (sub)mm

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

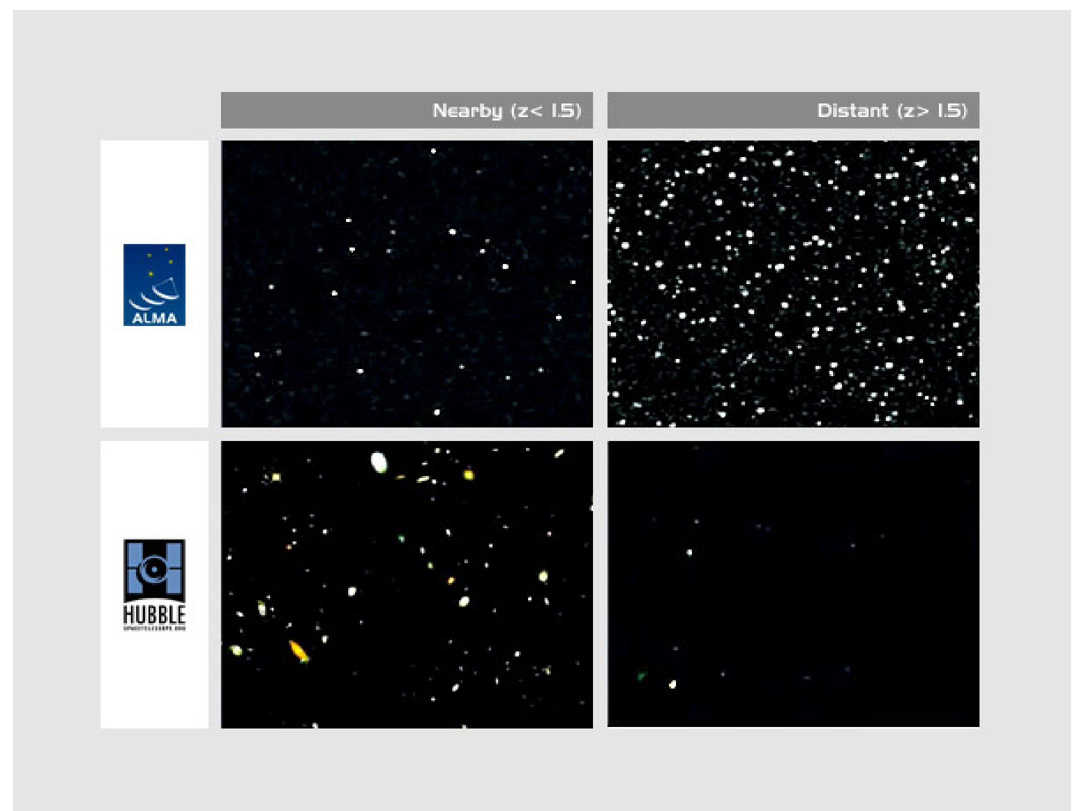
Negative k correction: for 1<z<10 galaxy flux density remain constant for $0.8<\lambda<2$mm. High-z galaxies look brighter than low-z & more high_z than low_z in deep fields.

Obscuration is not an issue as in optical bands





(Negrello et al 2010)



CO

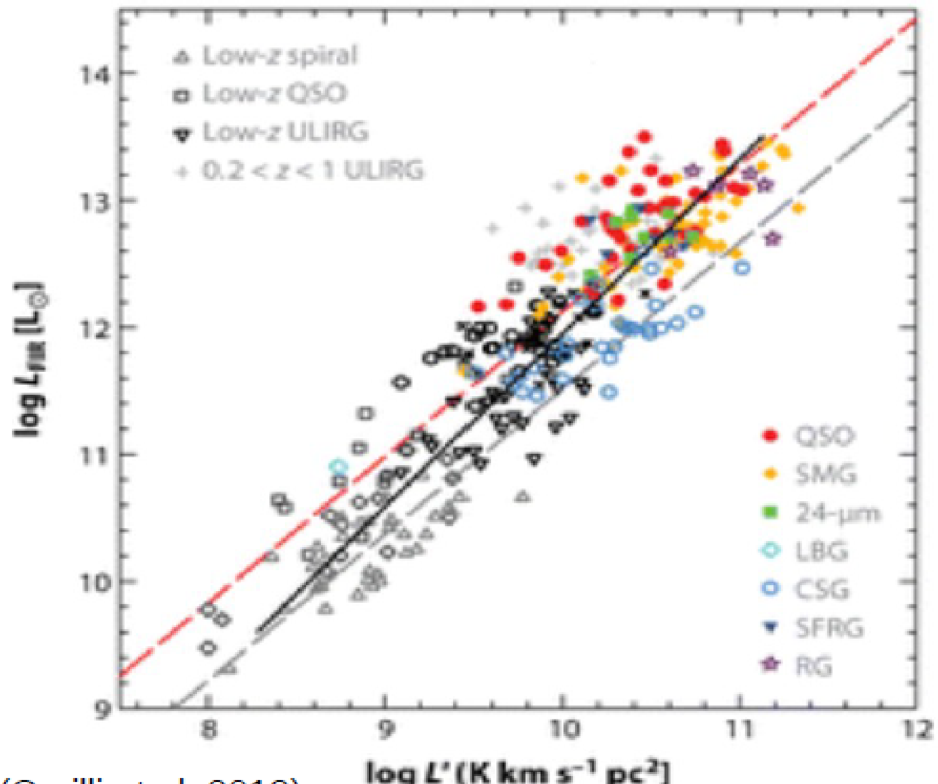
L_CO is proportional to the gas mass (via the relation with H2), L_FIR to the SFR.

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

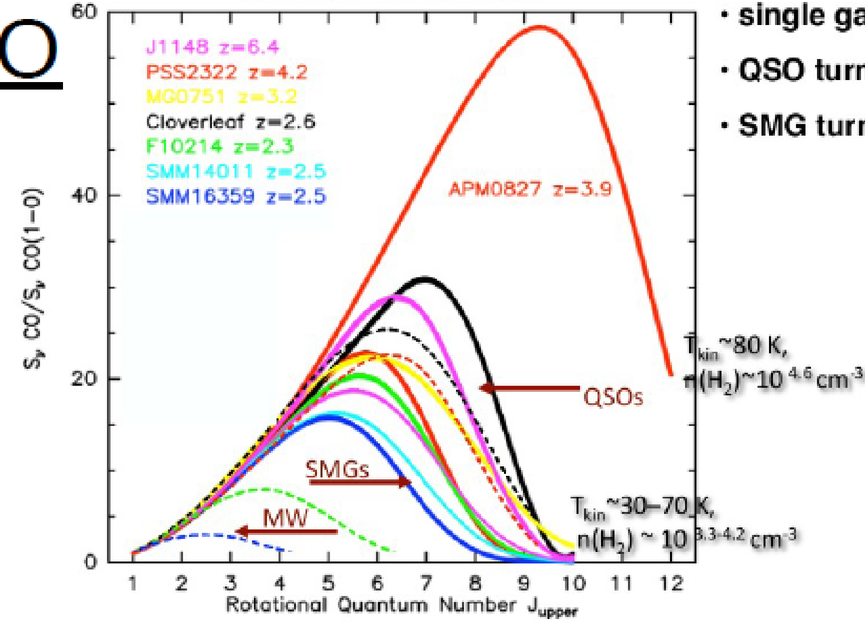
The efficiency of SF grews faster than mass, Hence massive galaxies exhaust their gas faster because of SF.

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

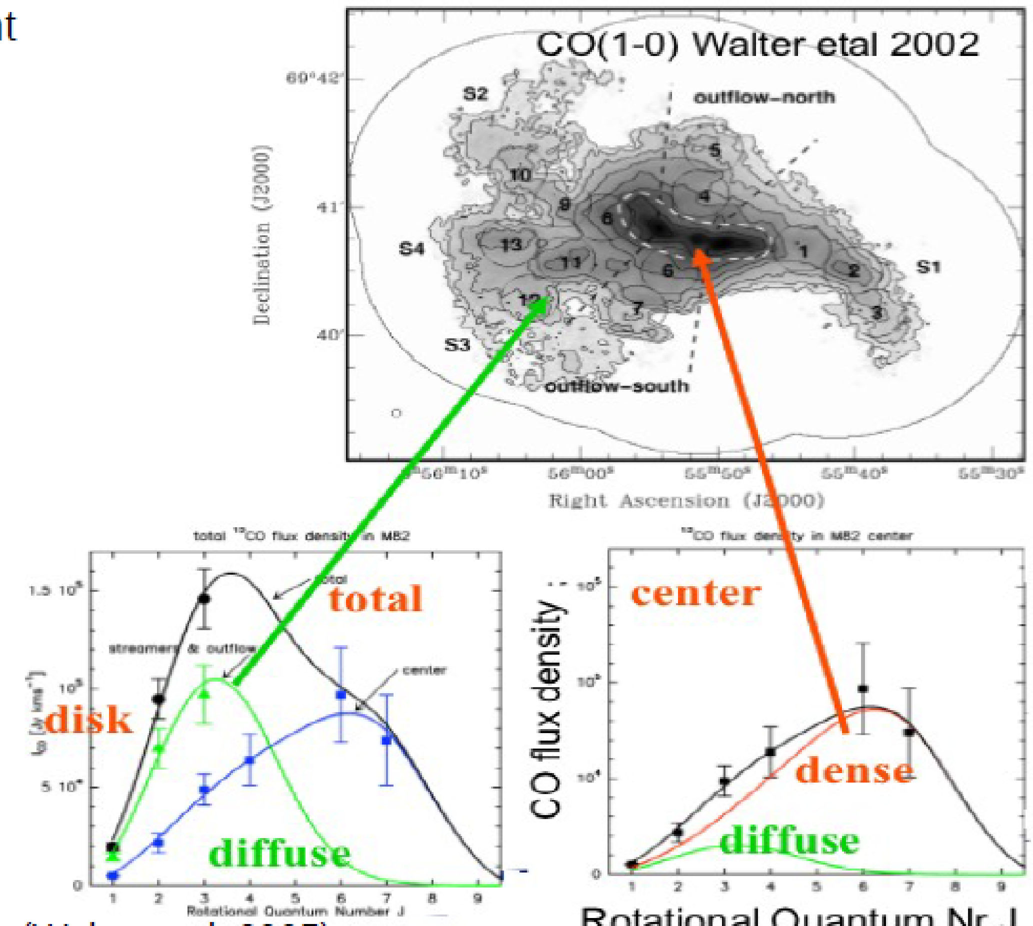
Different CO lines are sensitive to different environment (because of critical density increases with J)



(Carilli et al. 2013)

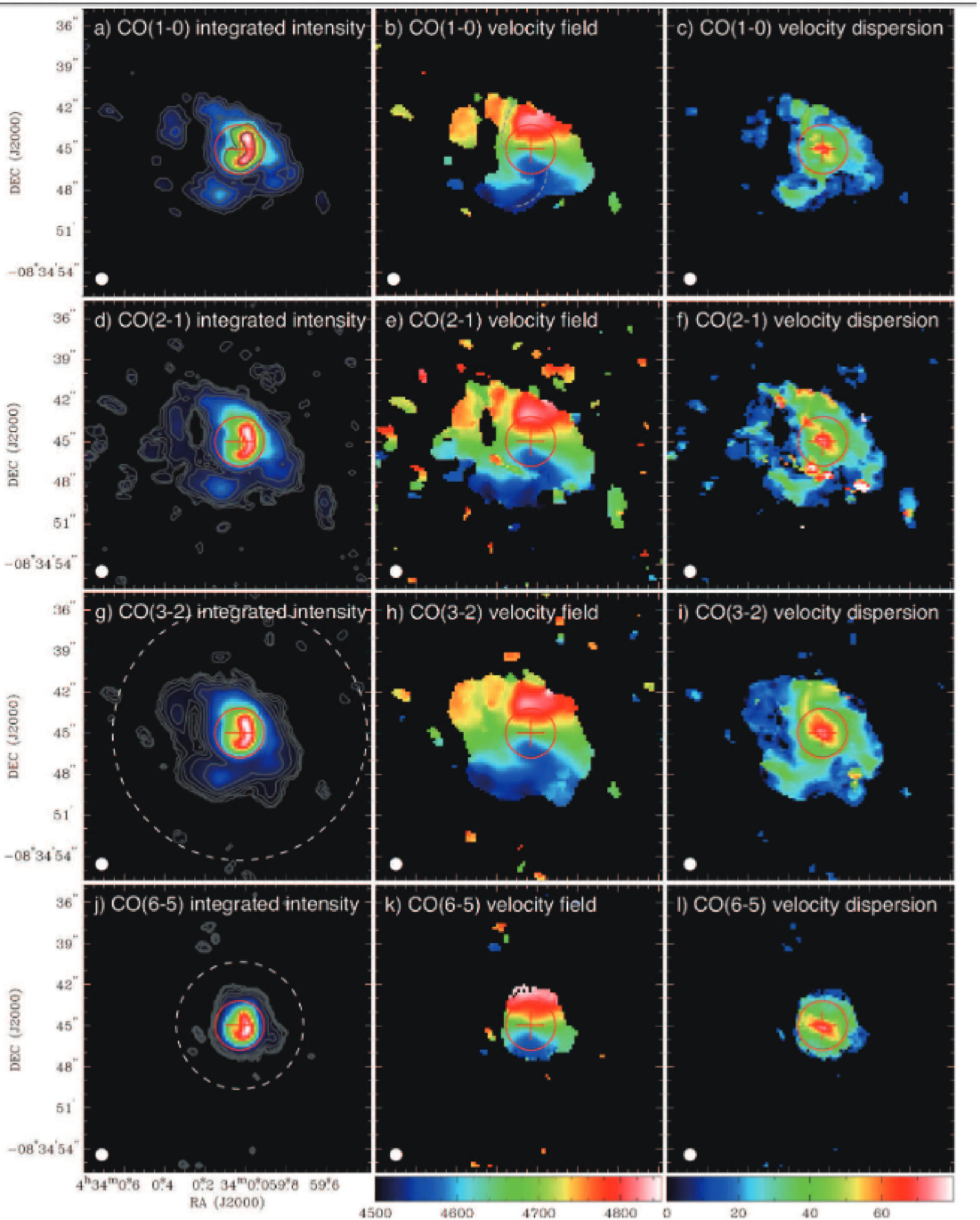


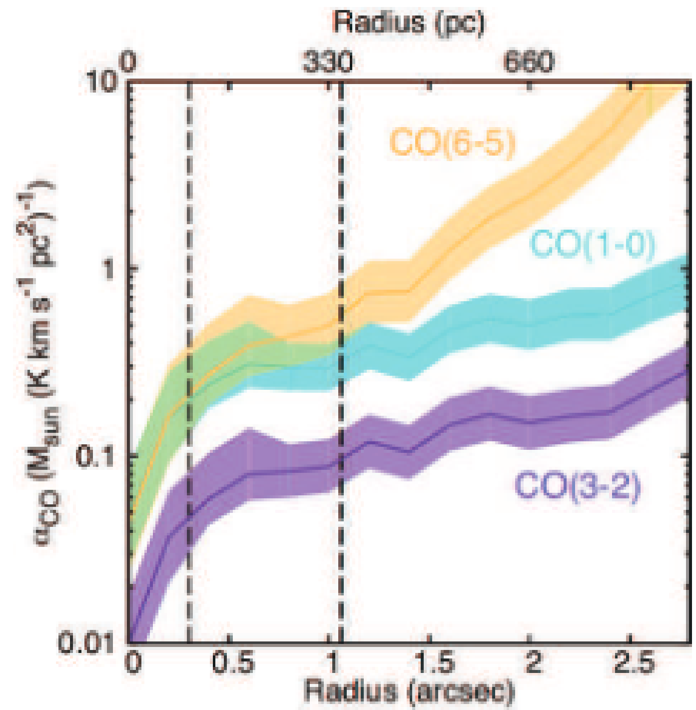
- single gas component
- QSO turnover: J > 6-5
- SMG turnover: J ~ 5-4



(Weiss et al. 2005)

Spatially resolved CO SLED in NGC1614 (Garcia-Burrillo et al 2014)





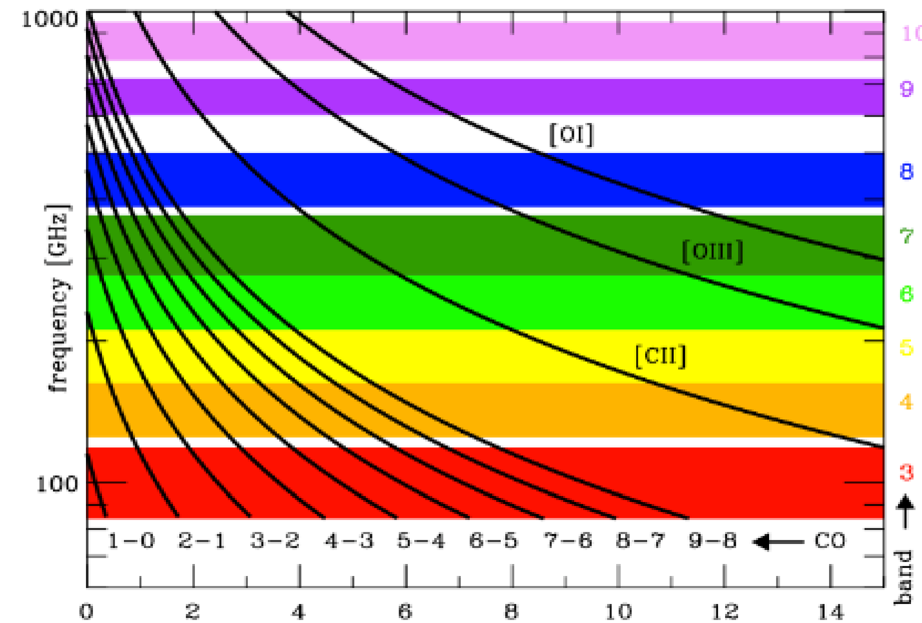
Molecular lines

CO is a tracer of H2

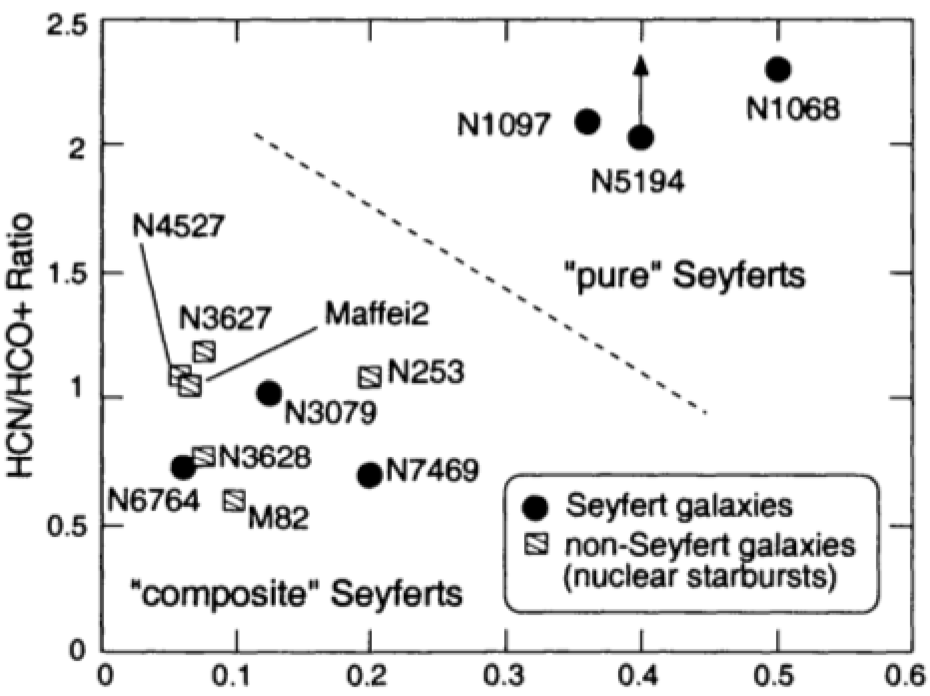
[CII]158 µm and the [OI]63 µm fine structure lines
are the two main coolants of the ISM and
are redshifted into the (sub)mm bands at z > 2–4

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

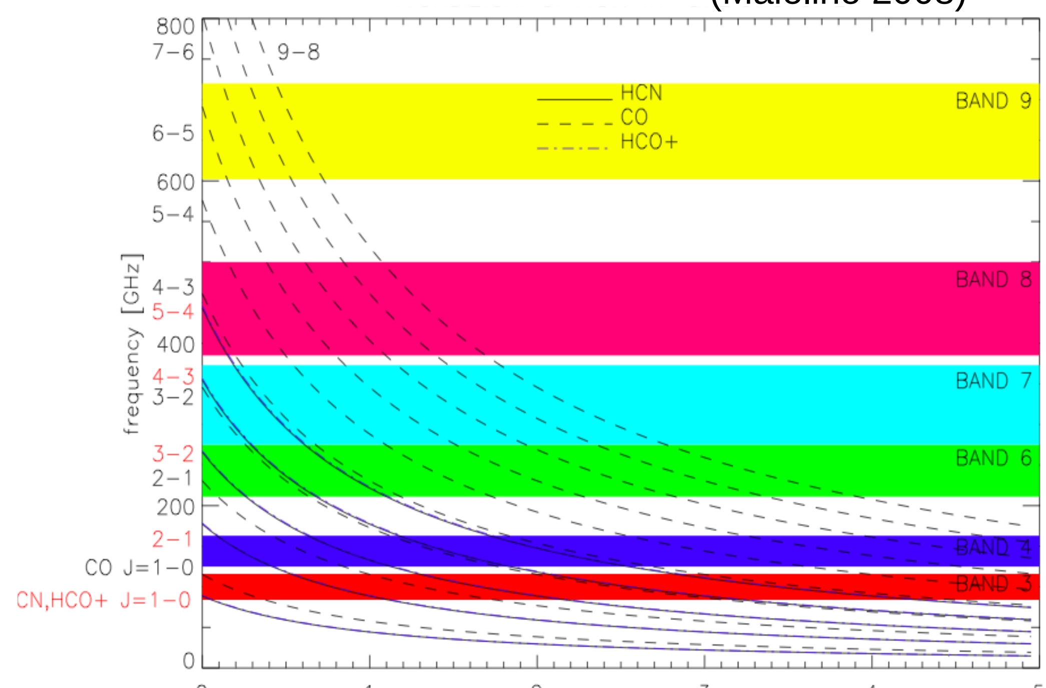
In most of the ALMA band more than one line is
observable for the higher redshifts.



(Maiolino 2008)

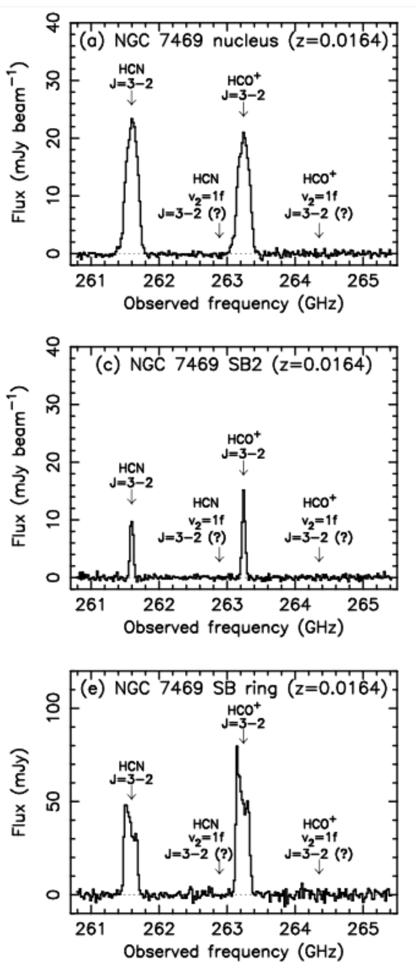


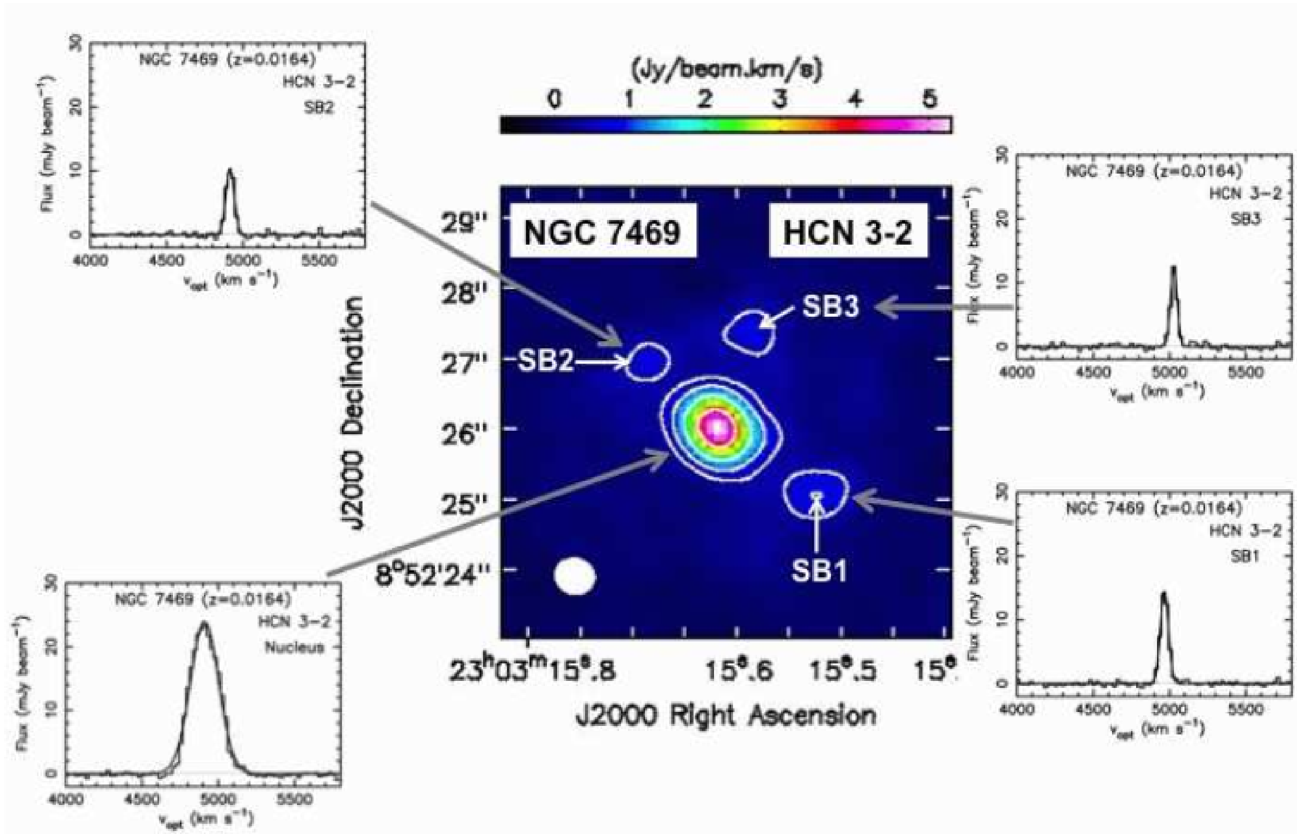
Kohno 2001

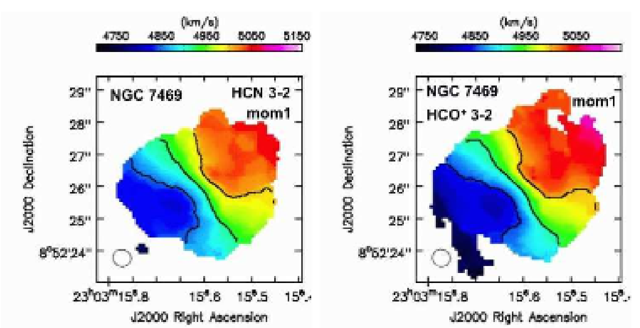


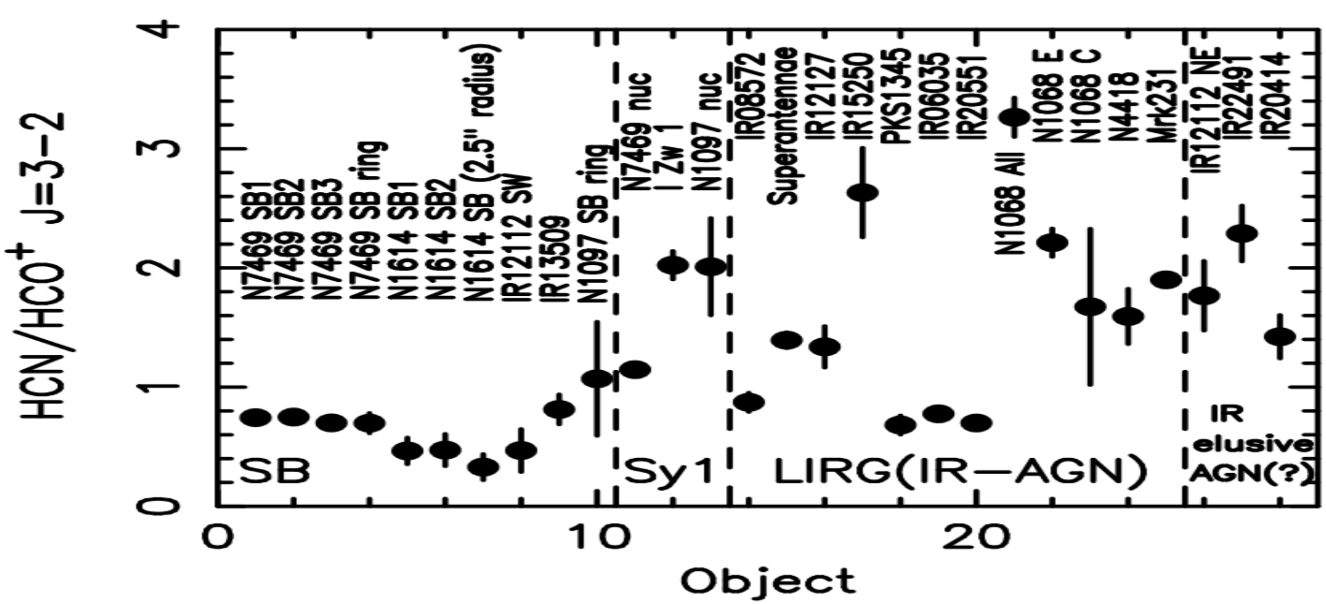
(Courtesy by Bianchi)

HCN AND HCO+(3–2) OF OPTICAL 3 Sy AND 11 LIRG @z<0.13 (Imanishi et al 2016)





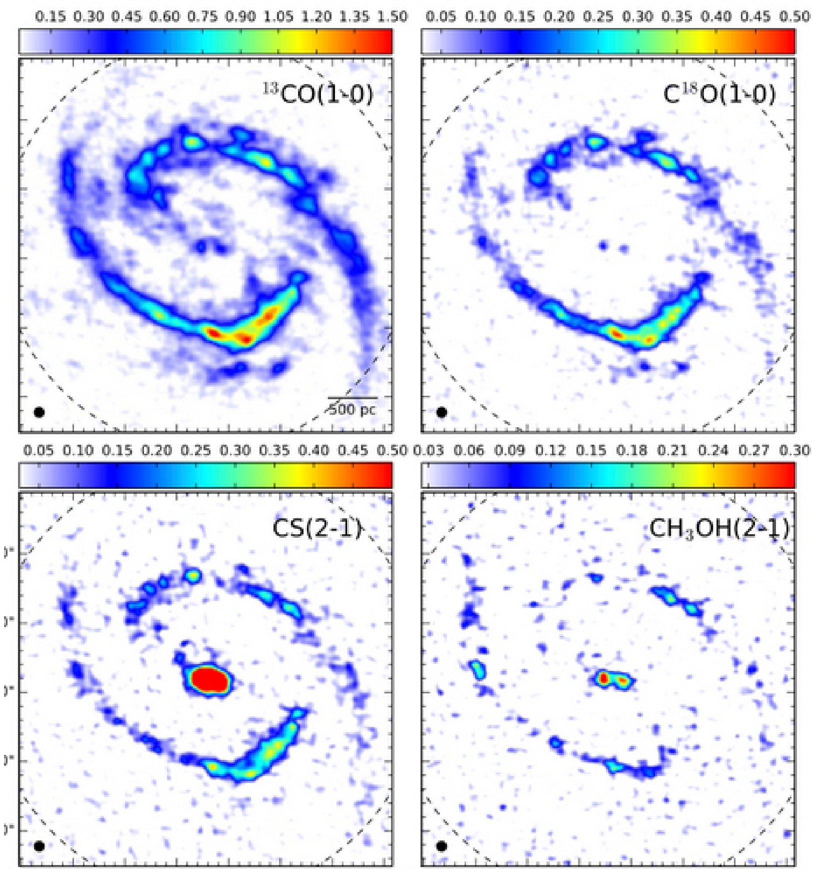


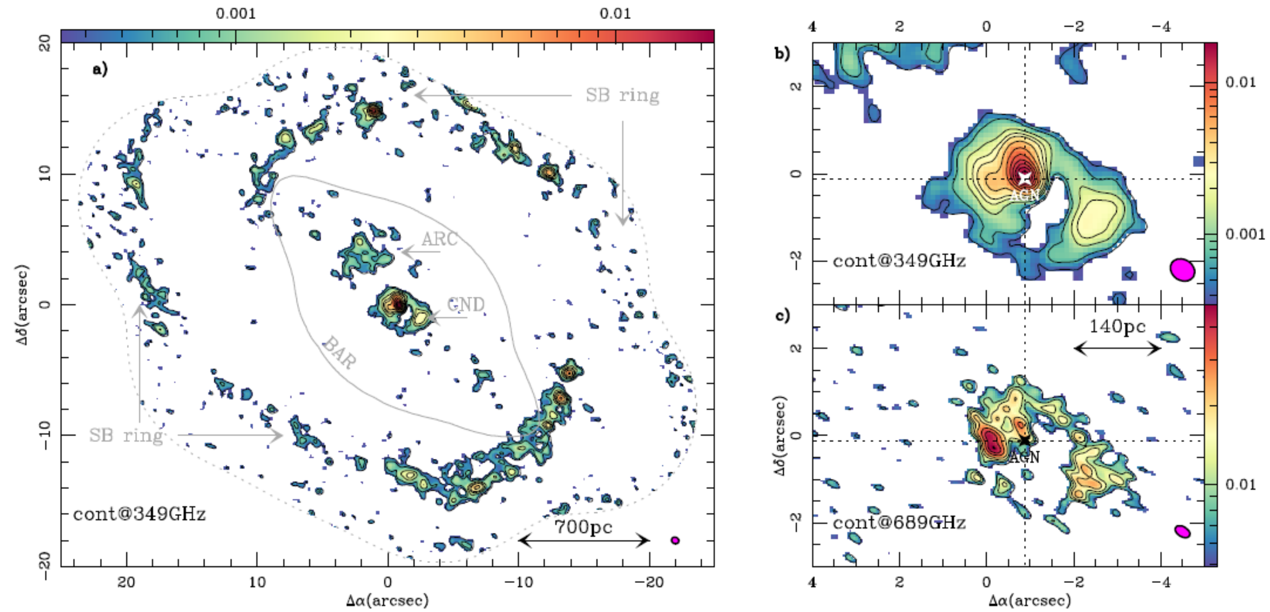


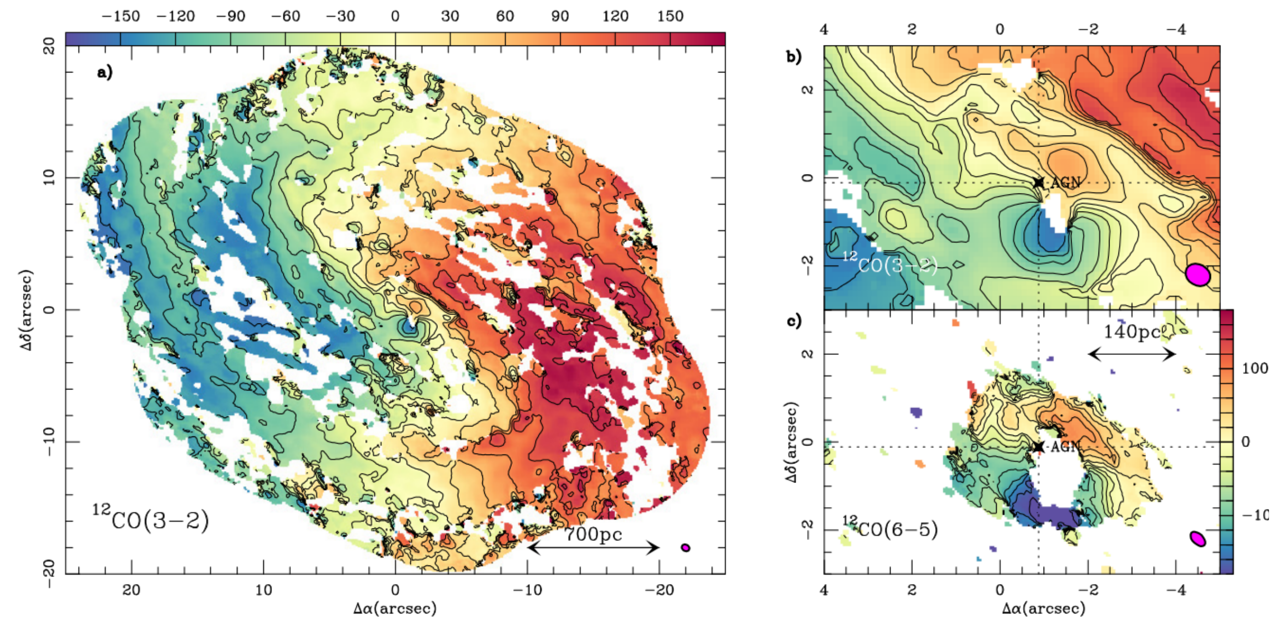
ALMA observations of NGC1068, a Sy2 @14Mpc (Garcia-Burrillo et al 2014 Tosaki et al. 2016, Imanishi et al. 2017)

- Band 7 (350GHz)
  CO(3-2), HCN, HCO+(4-3), CS(7-6)
- ~18-27 antennas,
- ~138min (11 pointing mosaic)
- Resolution ~ 0.6''x0.5''=35 pc

- Band 9 (690GHz)
  CO(6-5)
- ~21-27 antennas,
- ~52min (1 pointing)
- Resolution ~ 0.4''x0.2''=20 pc







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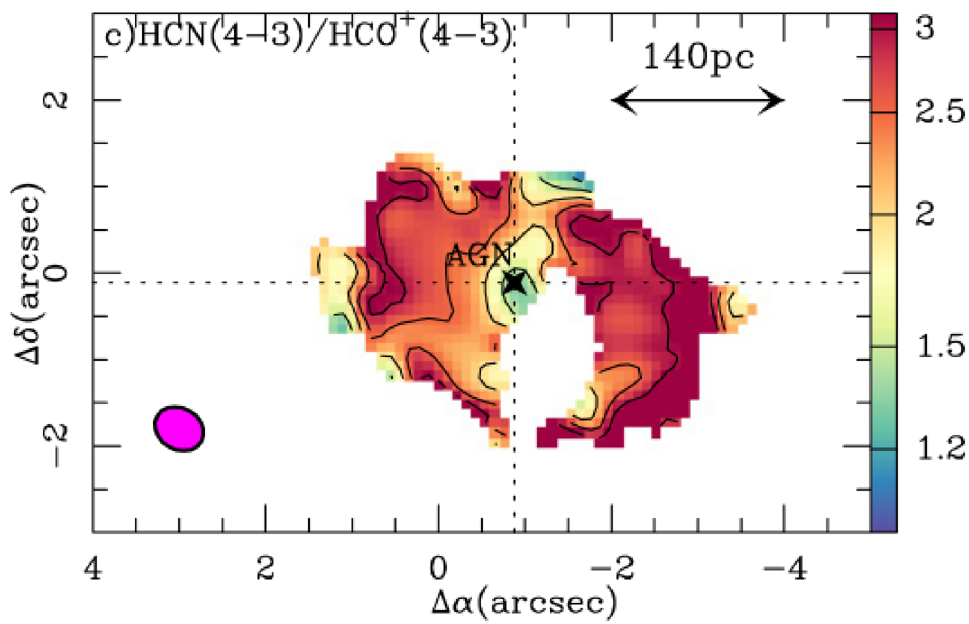
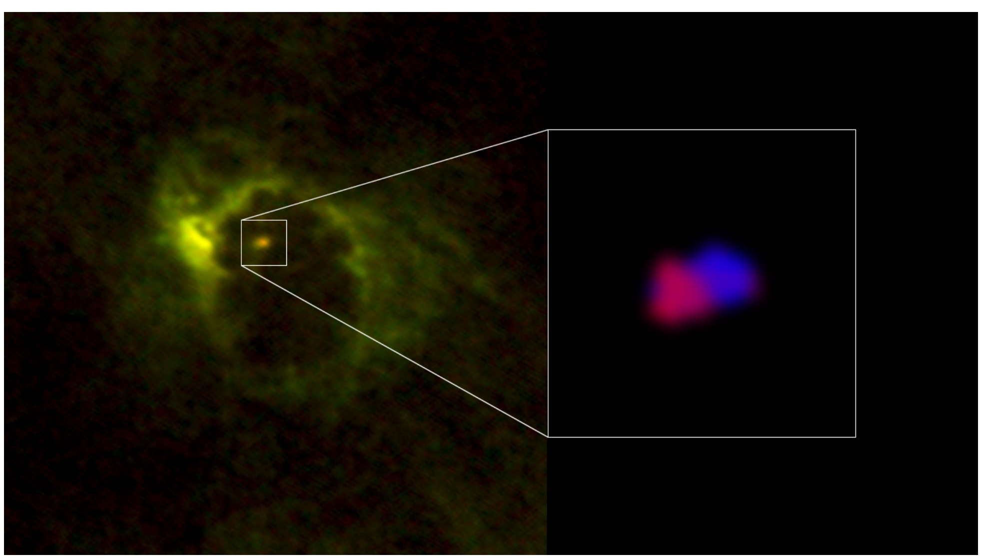
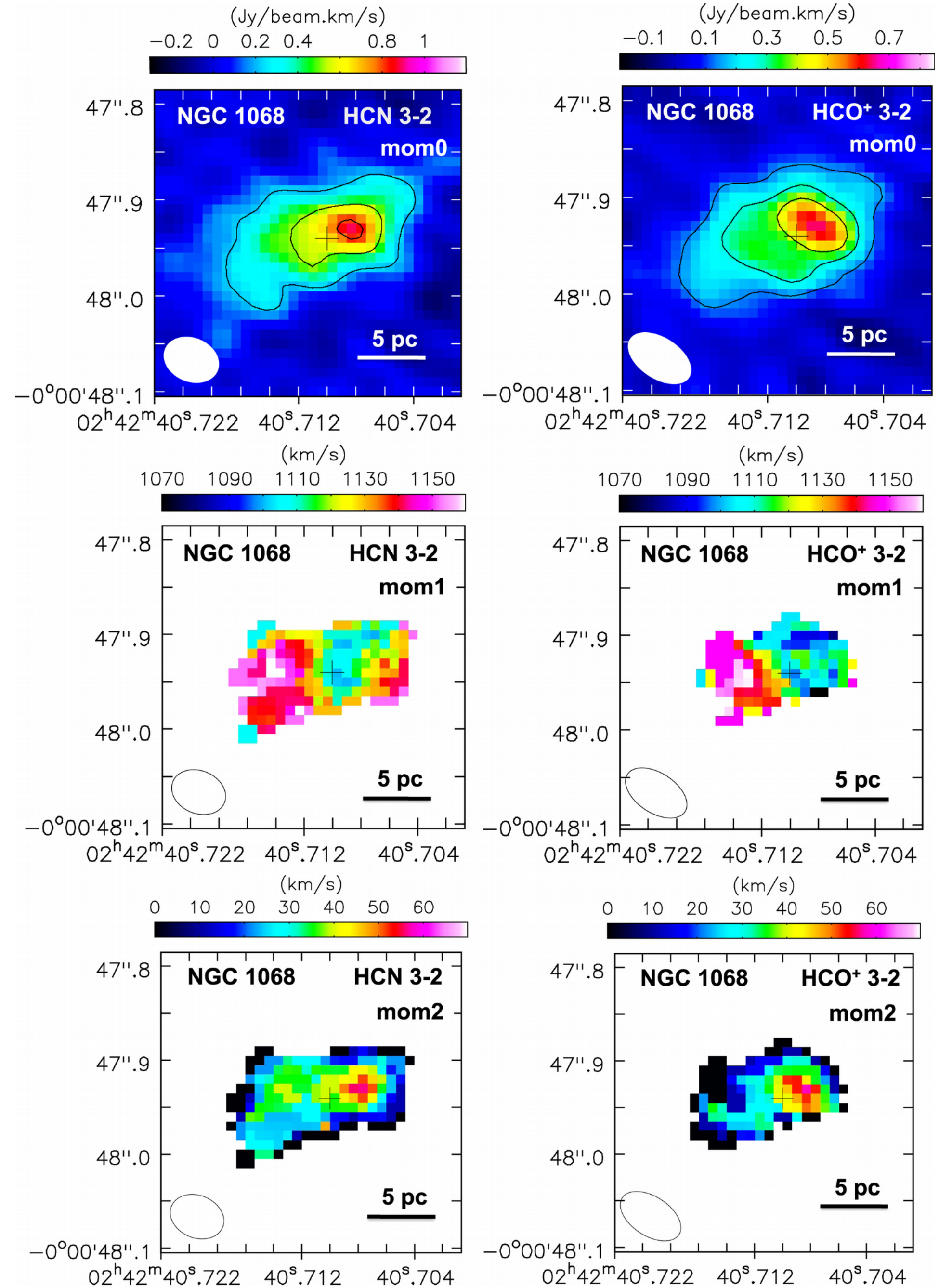
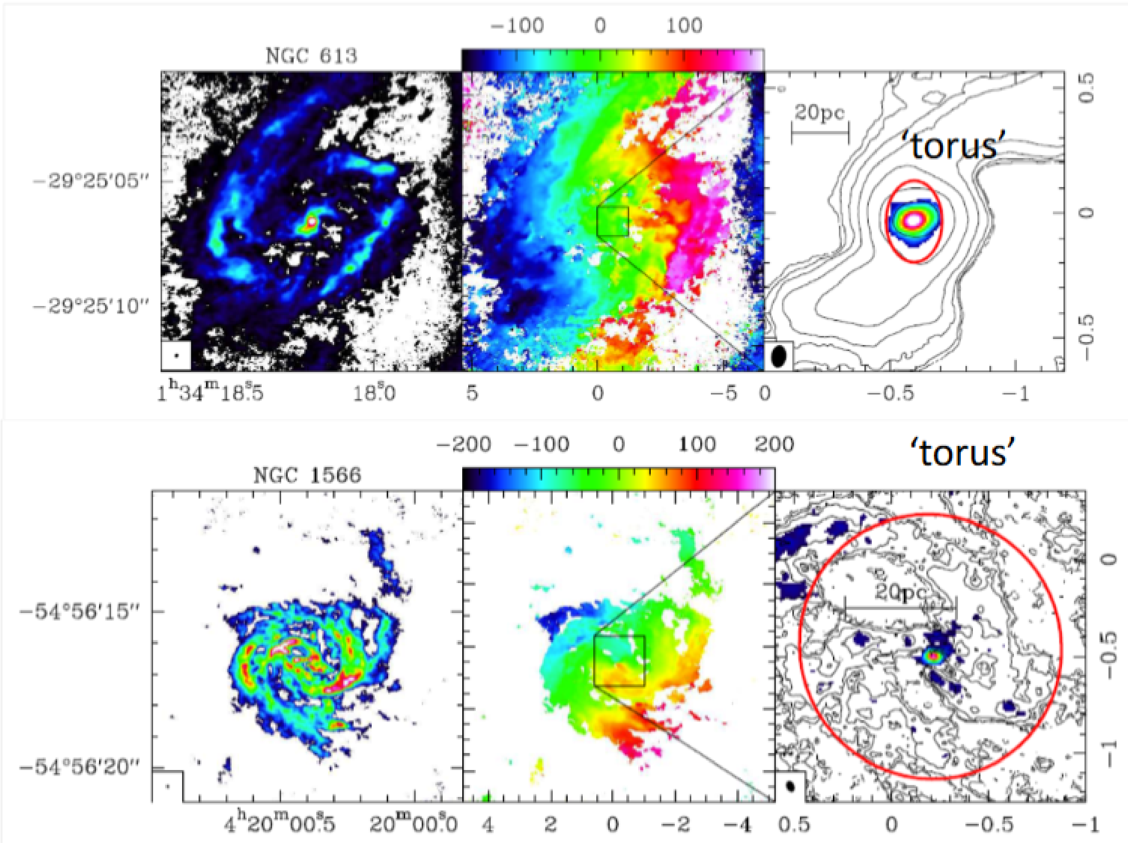






Resolving the torus and AGN fueling



Combes+19

- Systematic study of molecular tori with ALMA on nearby low luminosity AGNs. CO(3-2), resolution ~ a few pc
- Structures consistent with tori in 6/7 sources. Sizes ~ 6-30 pc, M~ few x 10^7 M_{sun}
- *Torus kinematics decoupled from larger-scale disk: different inclination and angle*
- AGN tori are asymmetric and off-centered. Two sources show a nuclear spiral supporting AGN fueling

Resolving the BH shadow in M87

$$R_{Sch} = (2\,G/c^2)\,M_{BH}$$

$$\theta_{Sch} = R_{Sch}/D$$

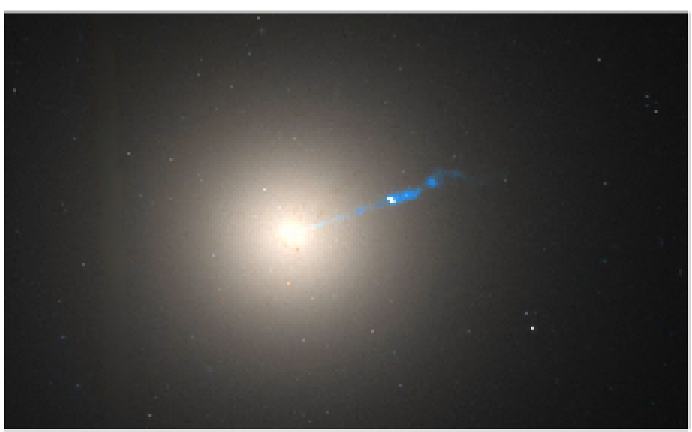
$$\approx 0.02 \text{ nano-arcsec } (M_{BH}/M_\odot)/(\text{kpc}/D)$$

- Stellar mass BHs (D~1 Kpc, M_{BH} ~10 $M_\odot$)
- Super-massive BHs (D~1 Mpc-1Gpc, M_{BH} ~10^6-10^9 $M_\odot$)

M87 :

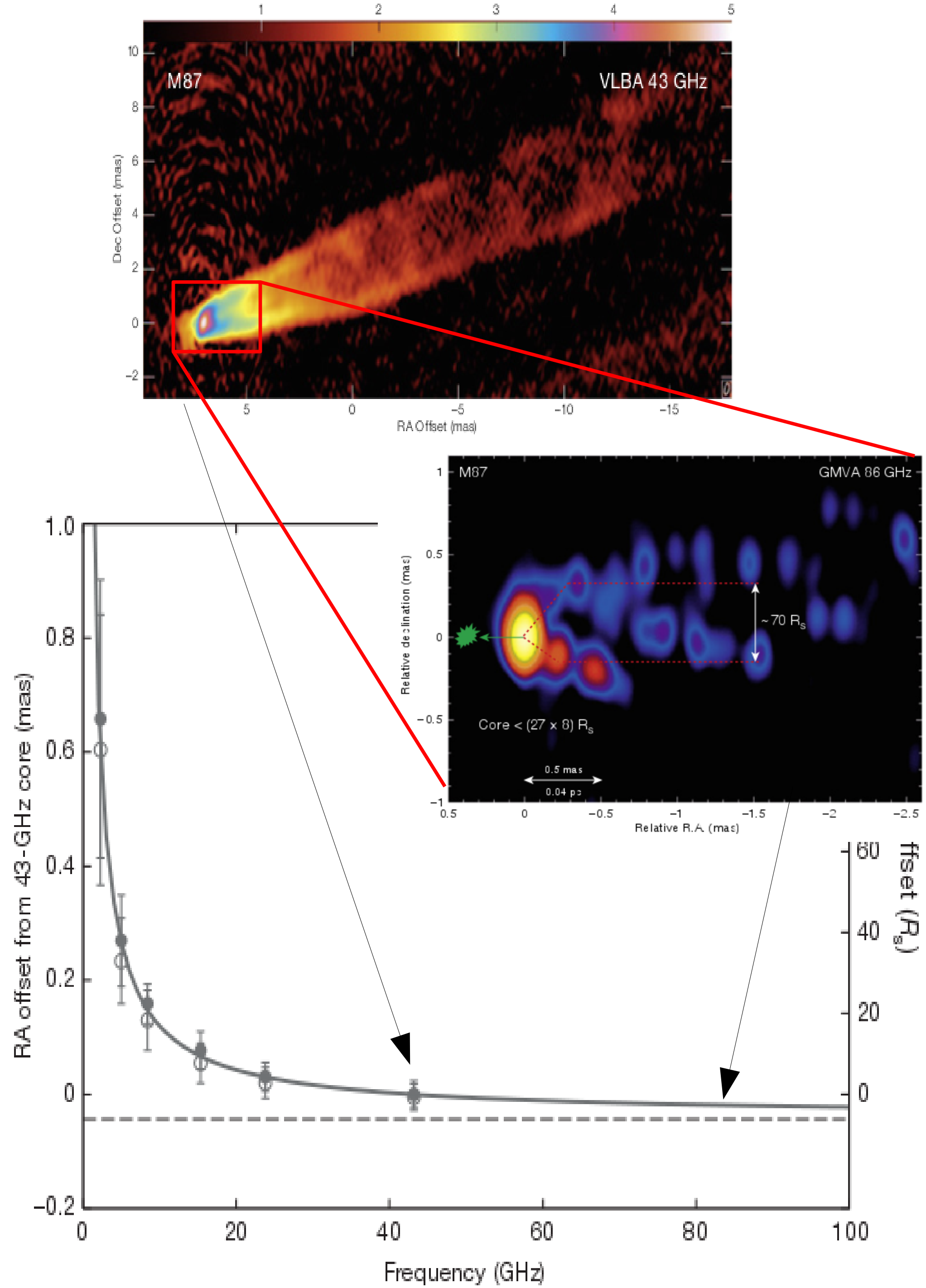
55 milions light years

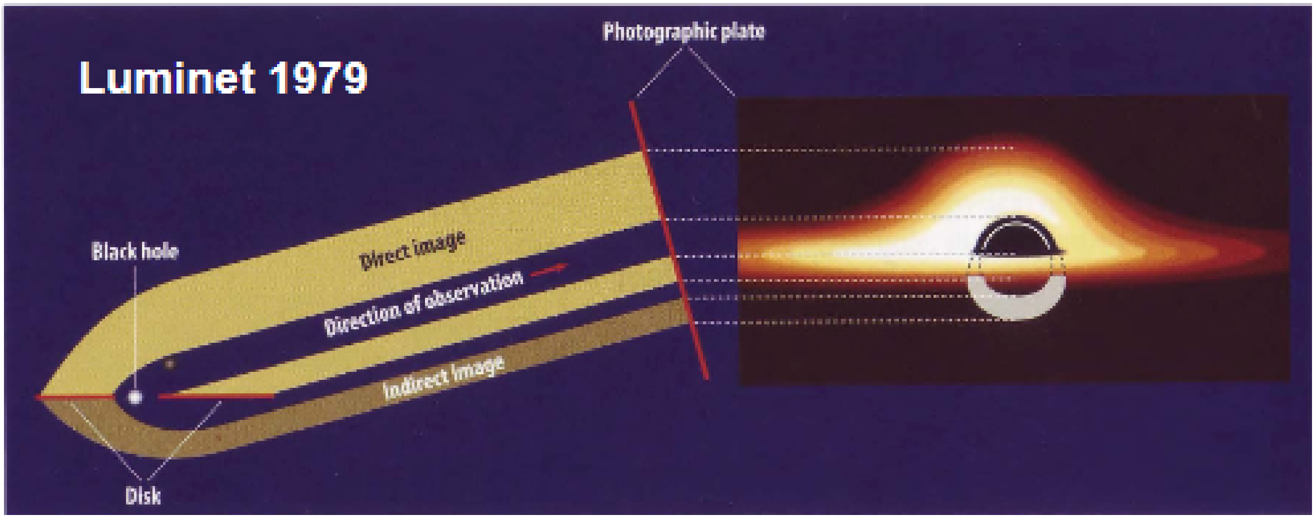
~7 billions solar masses



M87 : D~17 Mpc, M_{BH} ~6.5x10^9

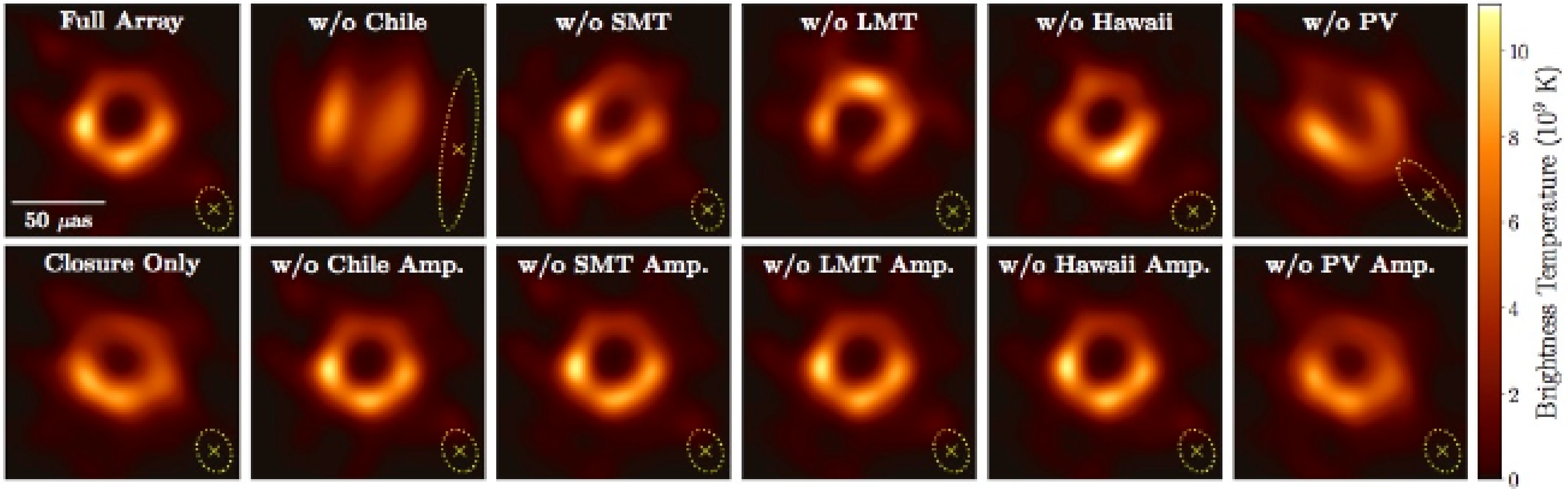
$M_\odot$ => θ_{Sch} ~ 8 micro-arcseconds

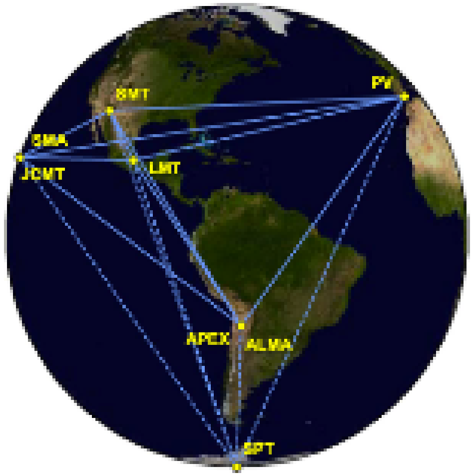




See mmVLBI in action for M87

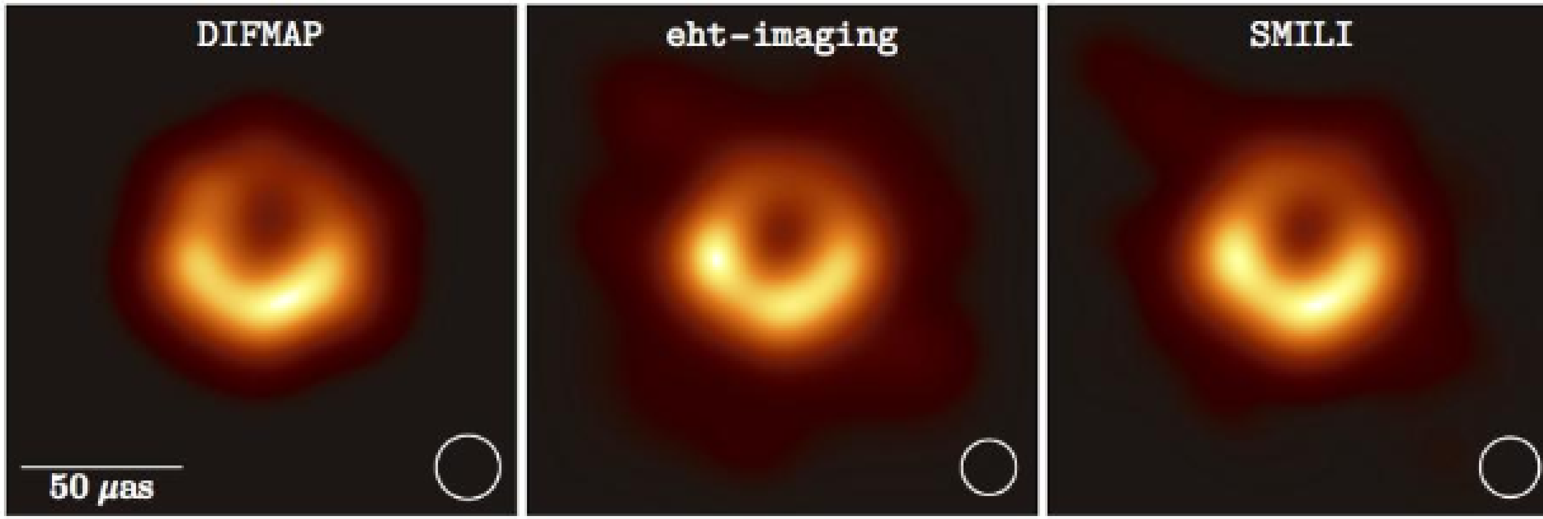
The ALMA/APEX component is crucial



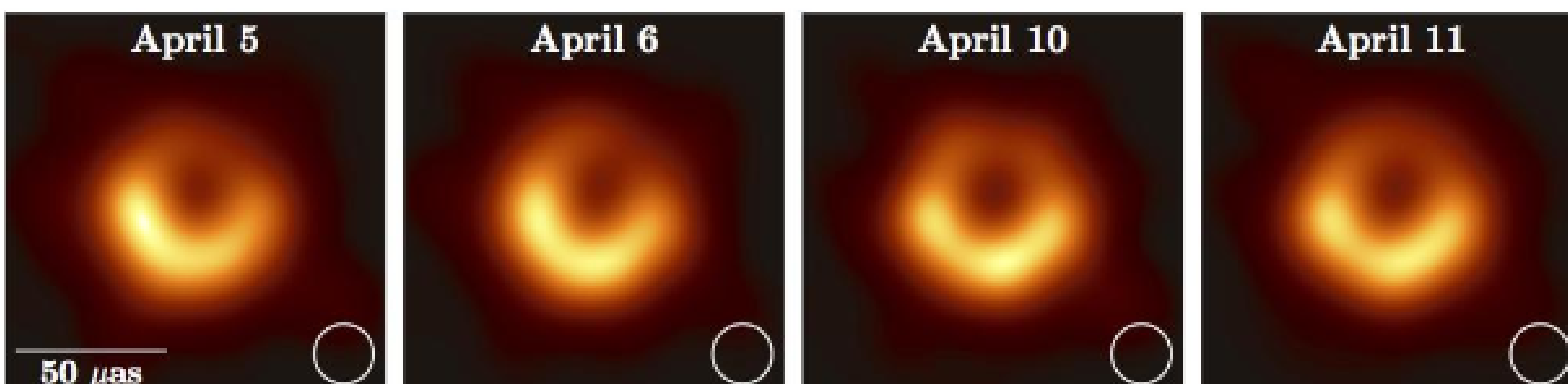


Credit: EHT collaboration, Paper IV, 2019

> 3 different imaging softwares find the **same structure**
for M87* black hole shadow on April 11

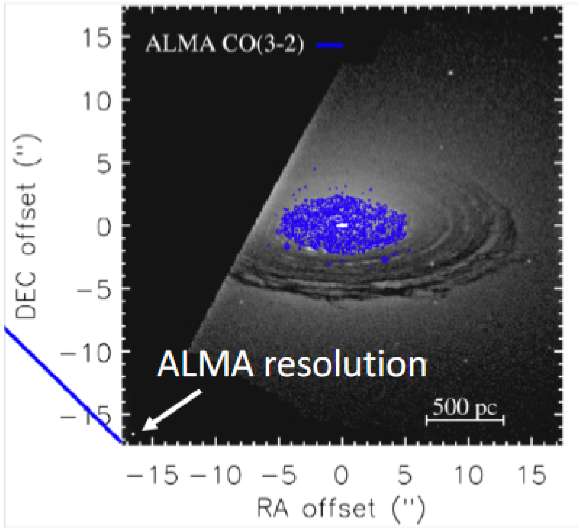


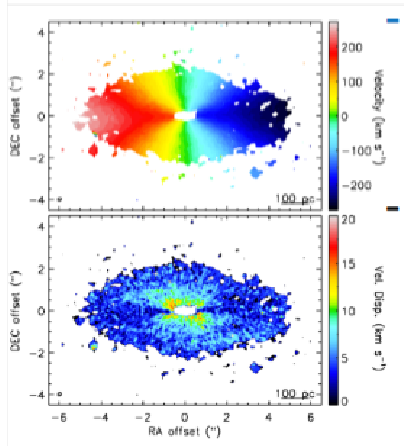
Fiducial images for each observing day: the ring structure stays the same but the brightness distribution is slightly changing



ALMA-based SMBH masses

CO(3-2) obs of lenticular galaxy

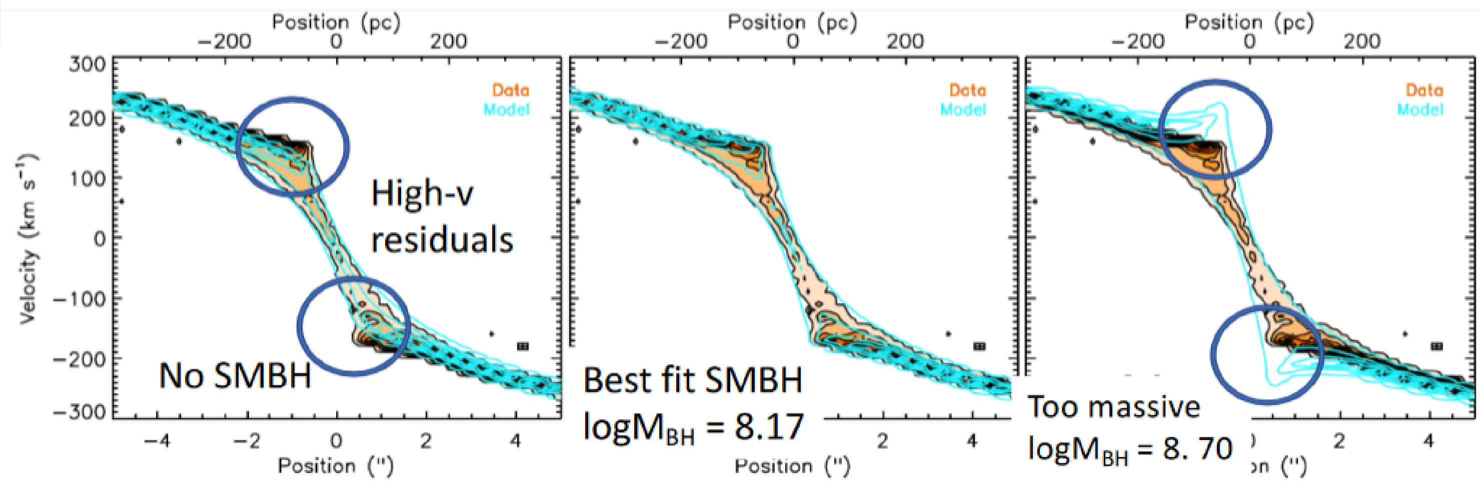




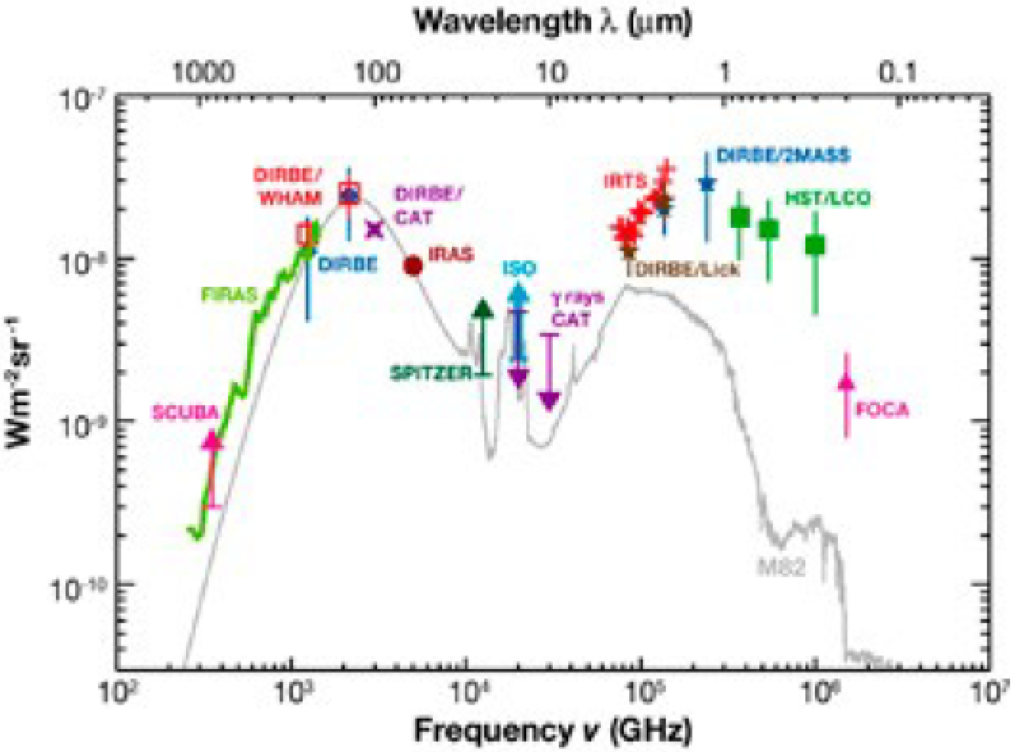
- Davis2014: CO-based M_{BH} estimates only need to resolve x2 the formal SMBH sphere of influence ($r_{SOI} \sim GM_{BH}/\sigma_*^2$)
- Kinematic signature of SMBH = rotational velocities higher than expected from luminous matter (stars), can be detected up to $2r_{SOI}$ but need good model of stars and dynamically cold + unperturbed CO disks

Davis 2014, Onishi+17, Davis+17,18

Molecular gas disk with radius = 400 pc and inner hole with r= 40 pc (sphere of influence of SMBH is ~15 pc)

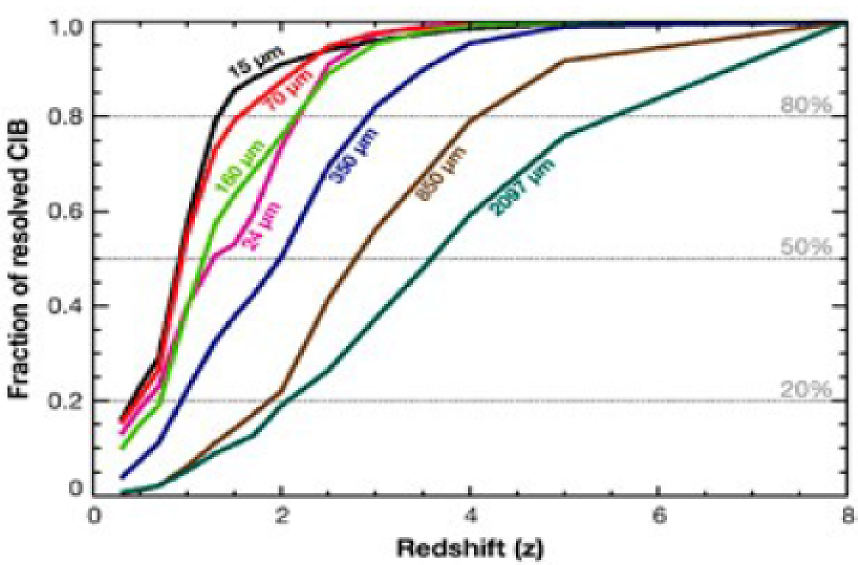


Cosmic Infrared Background



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

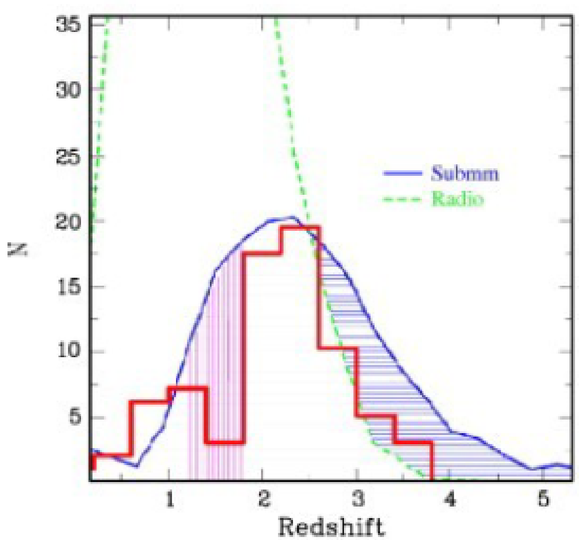
SCUBA surveys (Blain et al. 2000) identified the existence of **a population of highly dusty galaxies with high SFR.** Limits to their classification and observations were mostly due to confusion.
They were defined **SubMillimeter Galaxies (SMG)**.

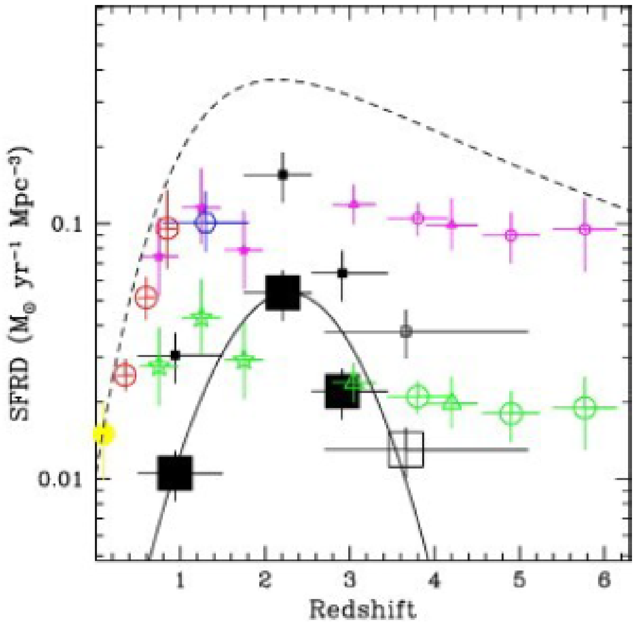
CO observations (Genzel et al. 2003, Greve et al. 2005, Tacconi et al. 2008...) measured masses and redshift for the SMGs, observing that there is a large fraction of massive galaxies at **z>2**.

These fractions were at odds 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).



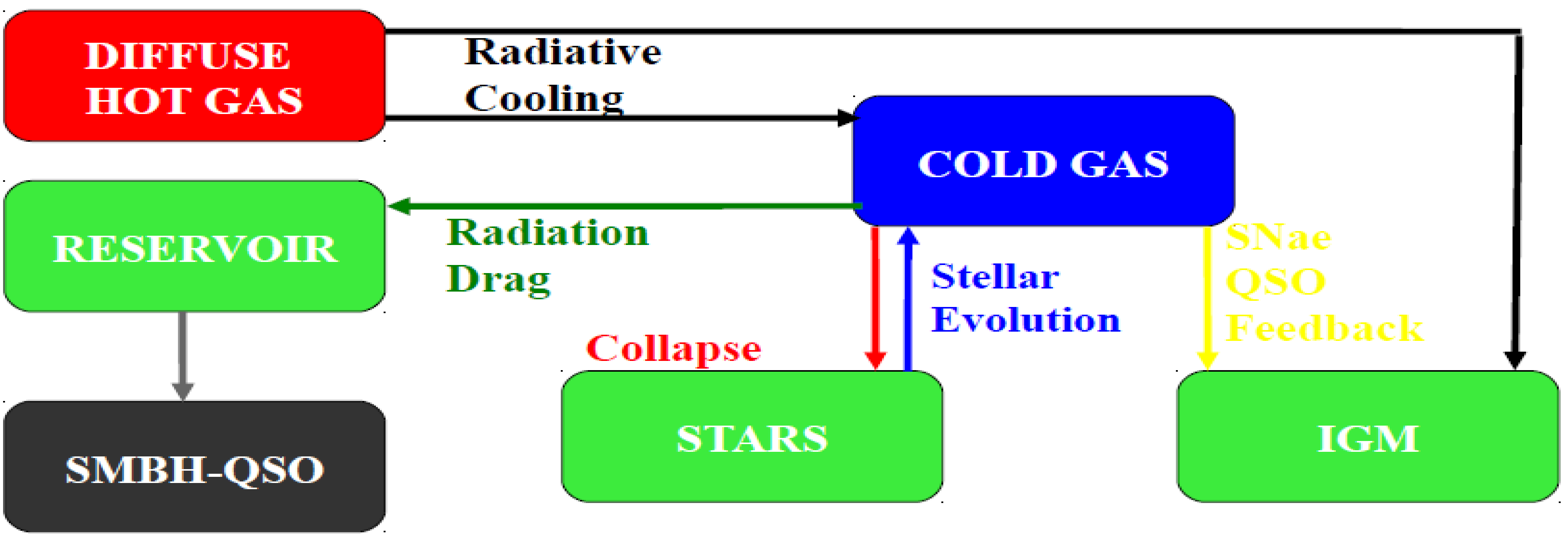


(sub)mm galaxy populations

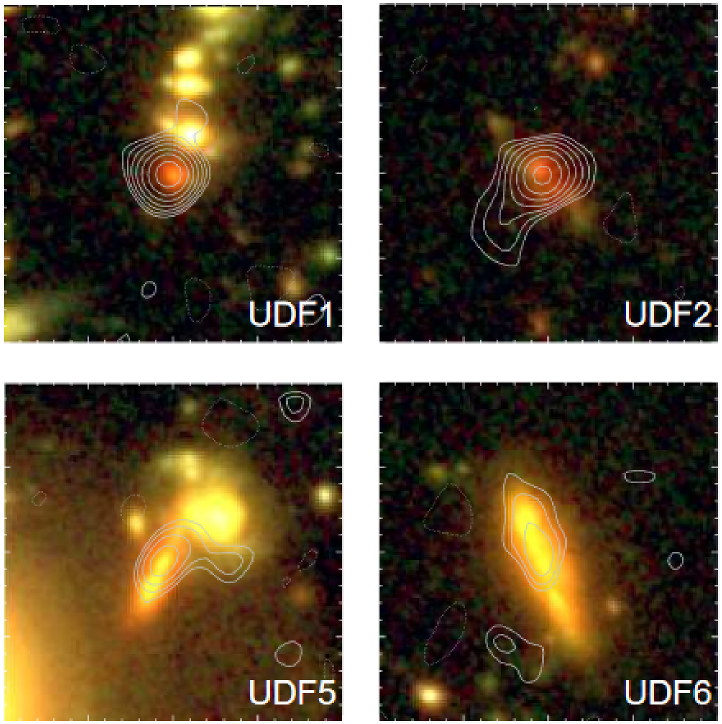
SMGs are the high redshift counterparts of local massive elliptical galaxies
(ULIRGs L_FIR>10^{12} L_sun),
with AGN activity obscured by the high dust content.

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?



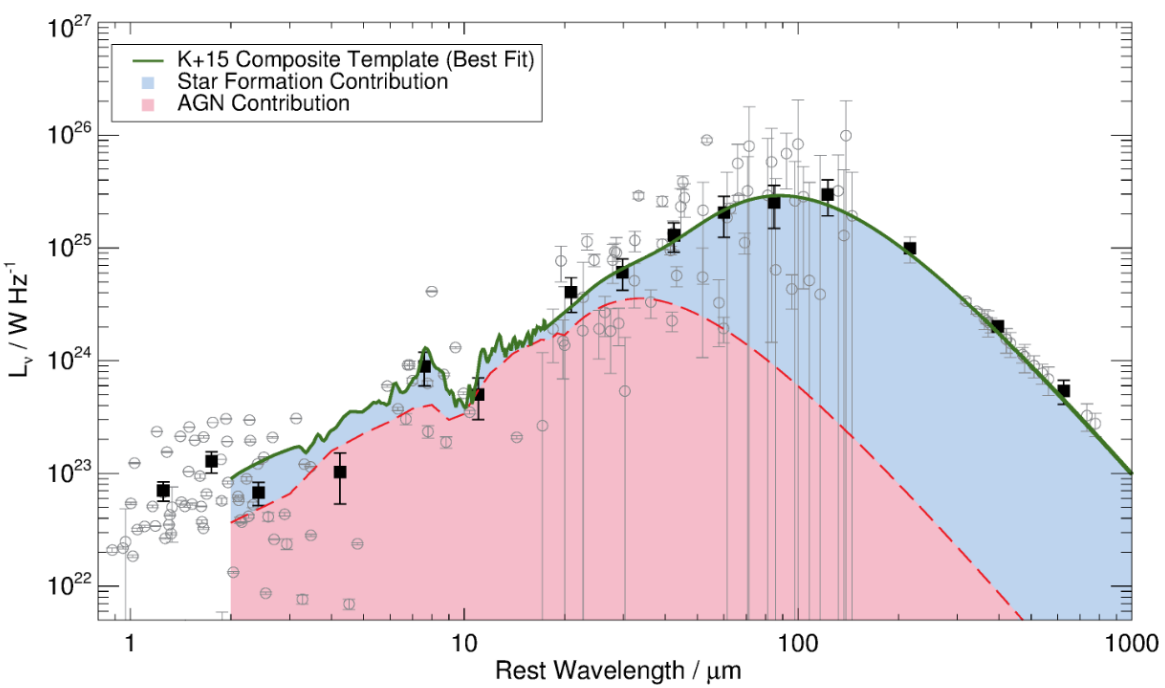
An ALMA survey of submm in the HUDFS (Dunlop et al. 2016)

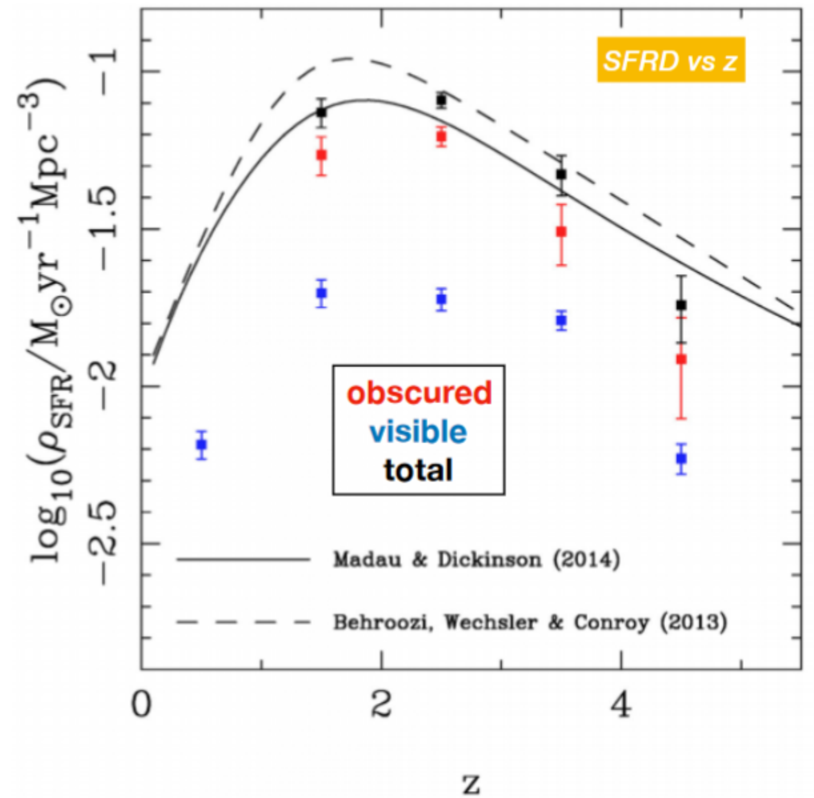


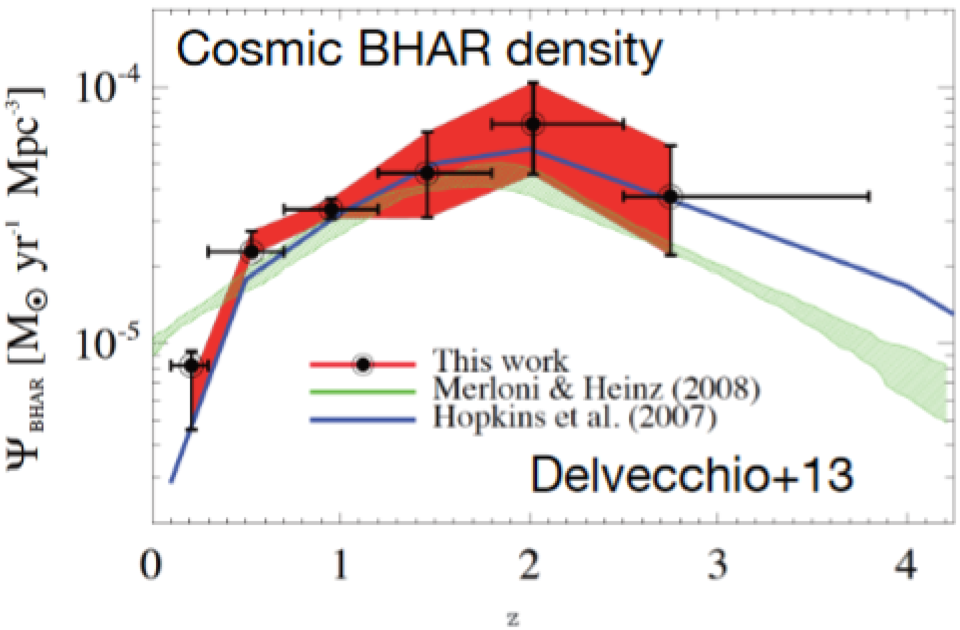
- 1.3mm (Band 6) survey of 4.5sqarcmin
- **16 submm sources**
- rms < 35 uJy/beam
- Resolution ~0.7''

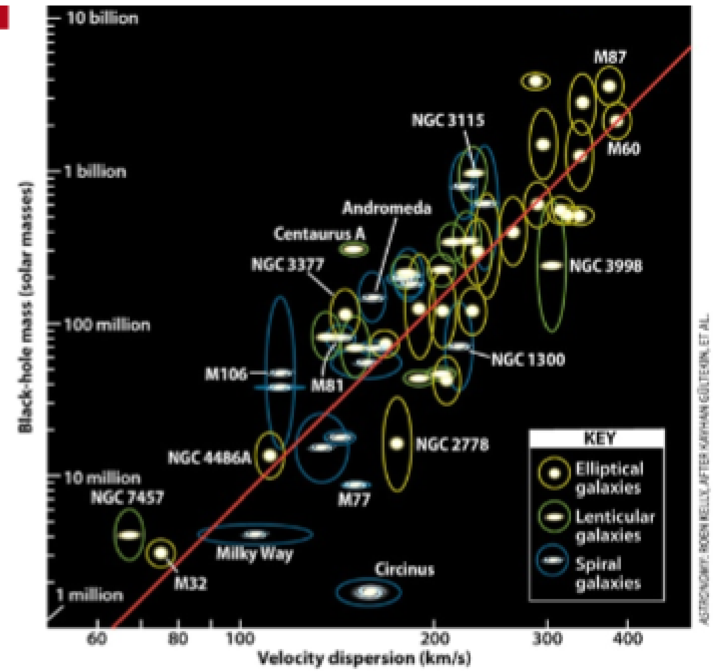
About 85% of SF at z=2 is enshrouded in dust, with 65% occurring in high-mass galaxies (>10^10Msun).

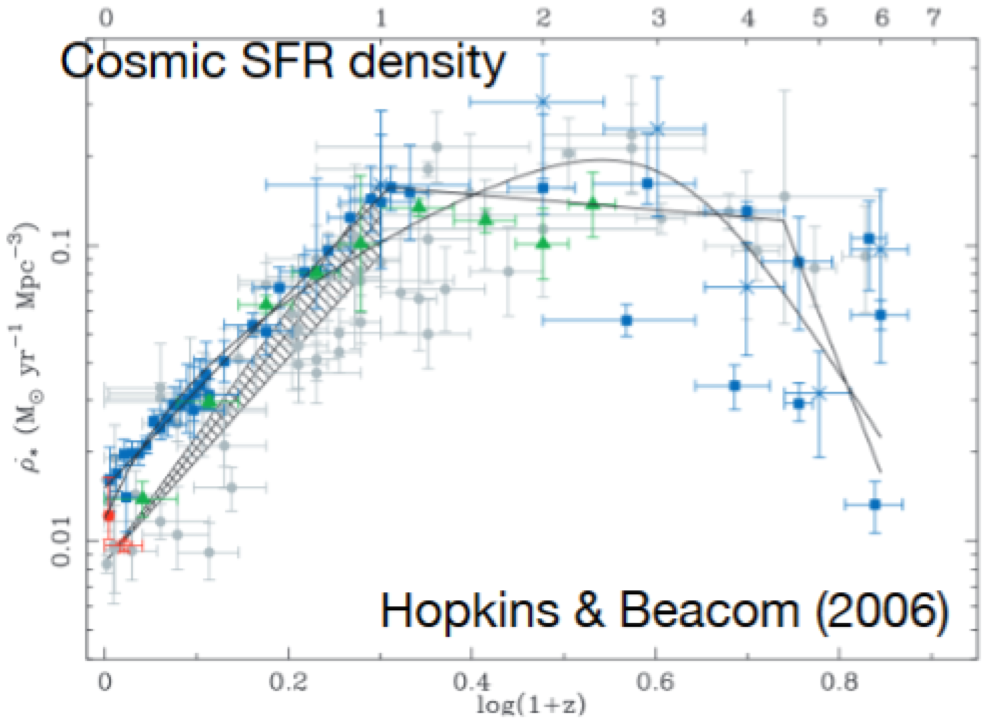
Obscured/unobscured SF=200
SF peaks at z=2







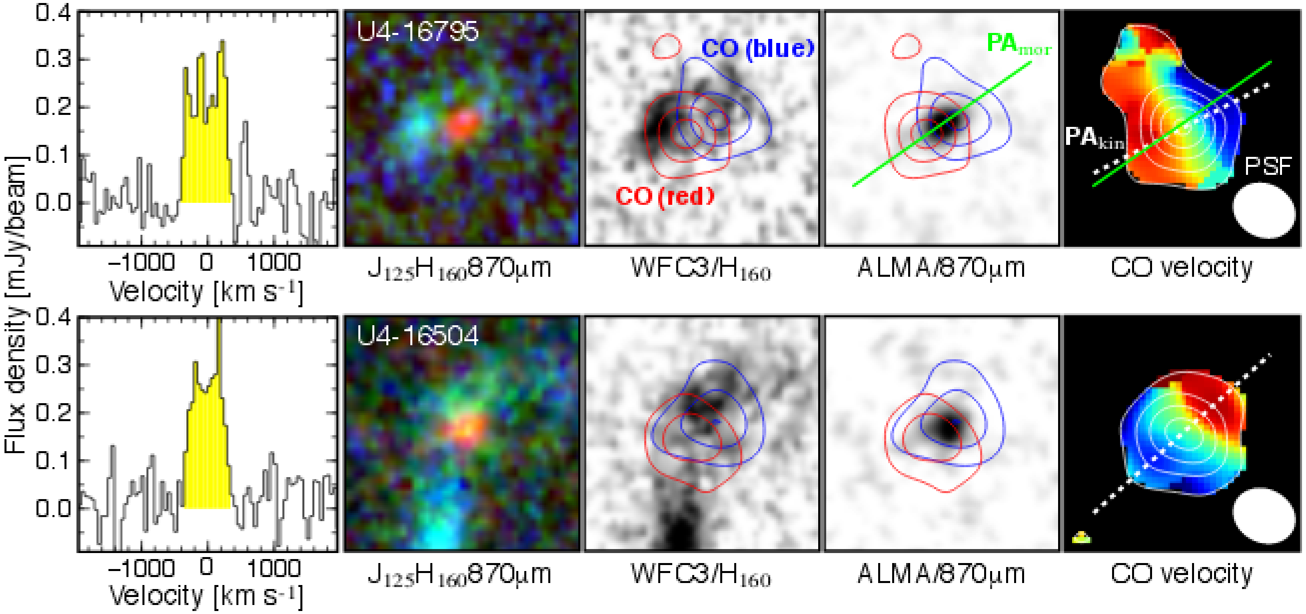




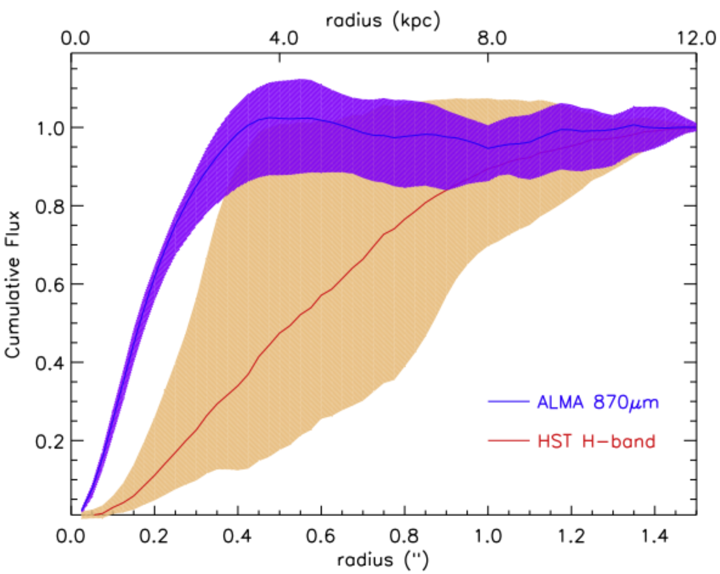
Black hole accretion and mass accretion follow a similar cosmic evolution; mass of galaxies and mass of central BH correlate

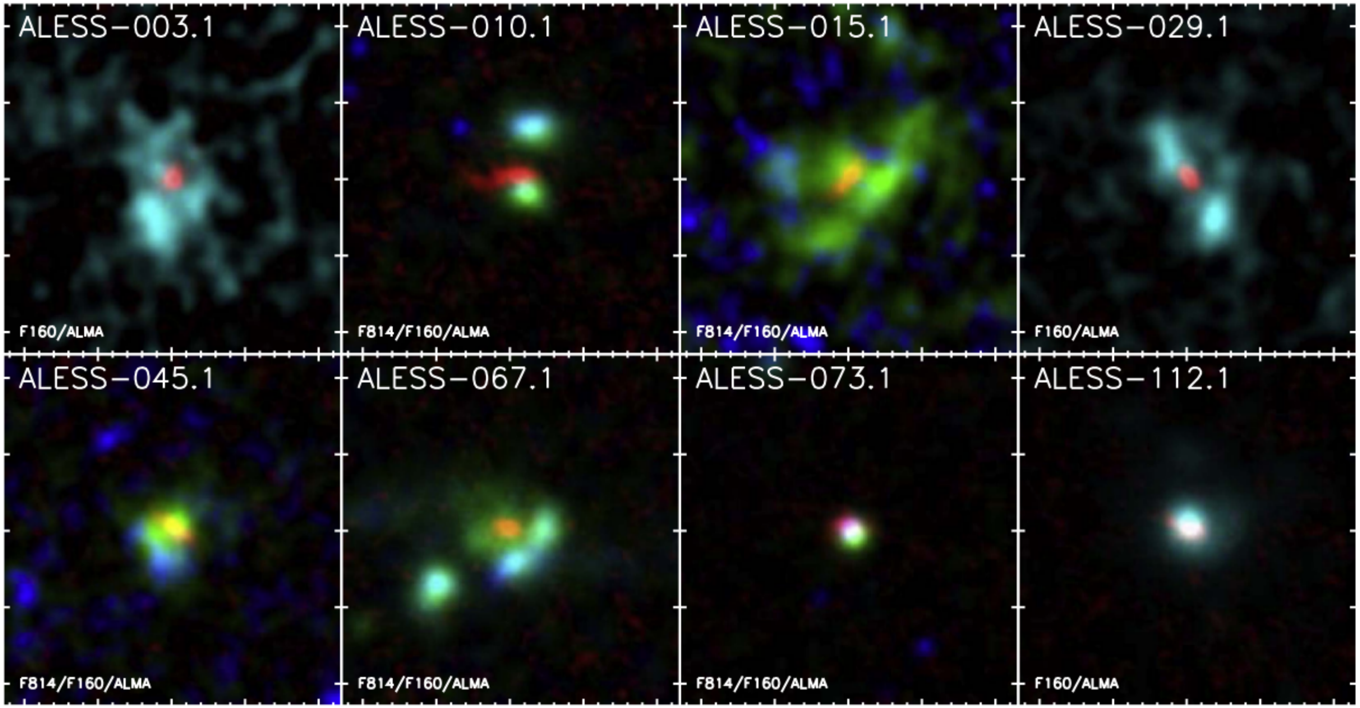
Black holes and galaxies grow together, influencing each other, feeding from the same cold gas

Evidences for co-evolution



Rotating gas disc in the inner region (<1kpc) of DSFG at z=2.5





Profile for stellar emission and dust emission

(sub)mm galaxy populations

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SMGs are the high redshift counterparts of local massive elliptical galaxies
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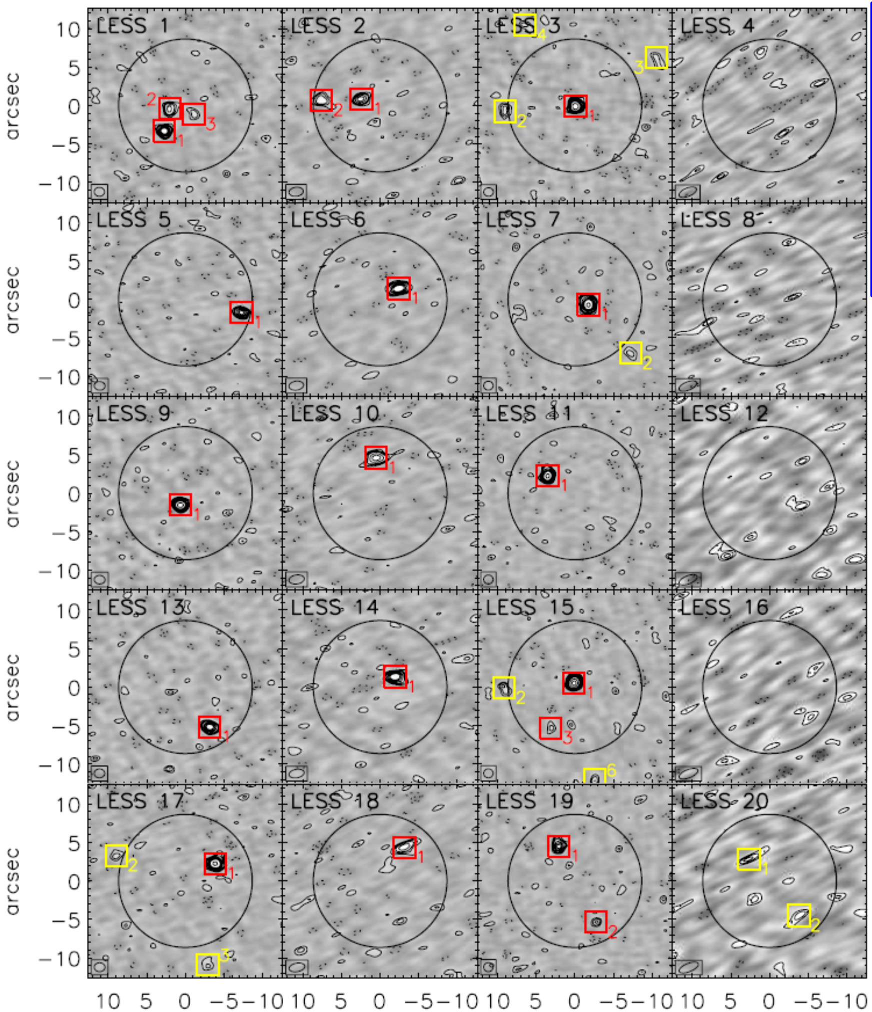
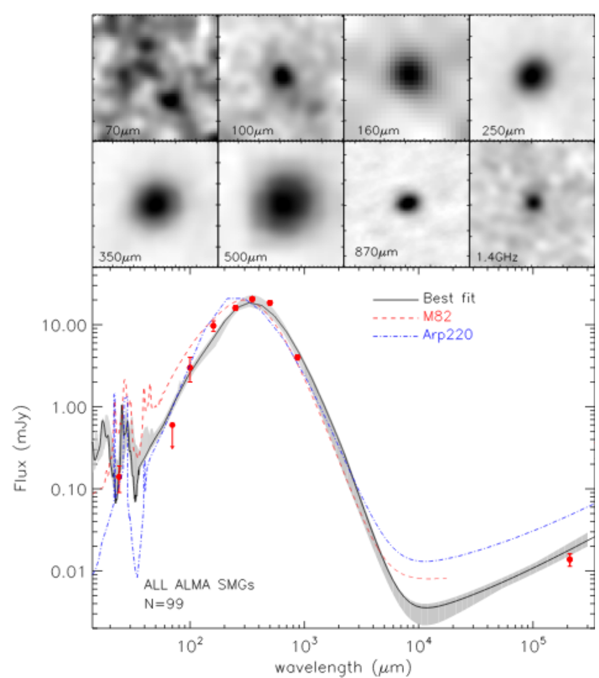
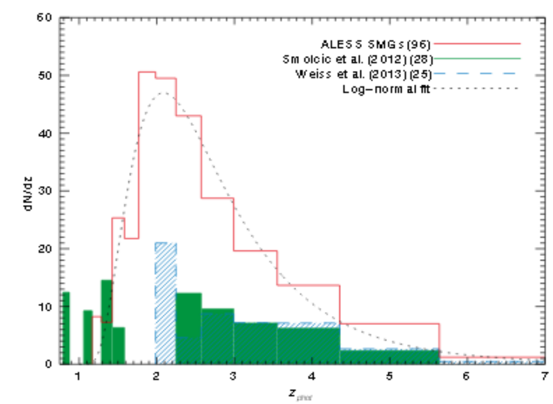
An ALMA survey of submm in the Extended Chandra Deep Field South
Smail et al. 2015, Hodge et al 2013; Karim et al. 2013; Simpson et al. 2013, Swinbank et al. 2014….)



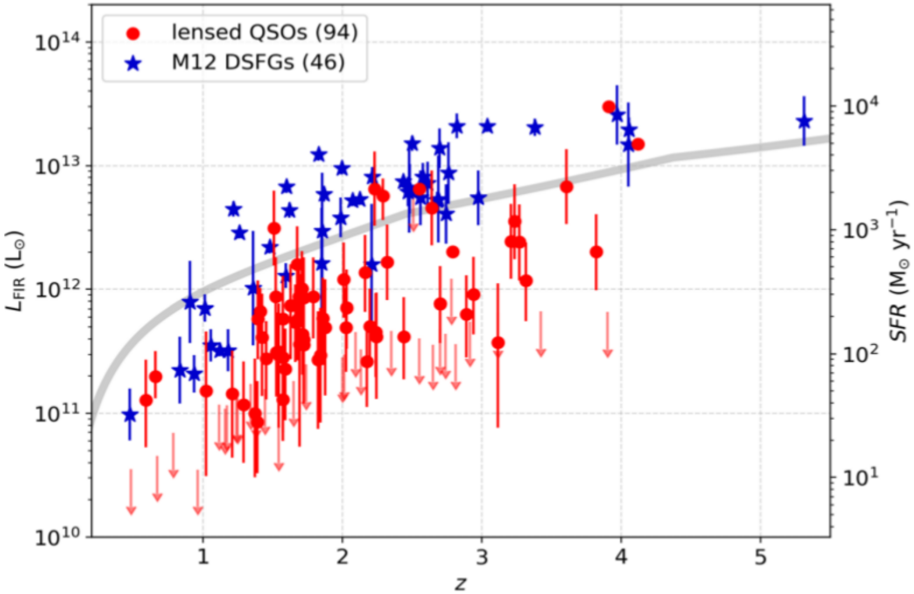
- 870 **μm** (Band 7) follow-up of a LABOCA Extended Chandra Deep Field South Submm Survey (LESS)
- **122 submm sources**
- ~15 antennas, FOV = 17", **2 min/source**
- rms < 0.6 mJy/beam (**x3 deeper than LABOCA**)
- Resolution ~1.5" (**x10 better than LABOCA**)



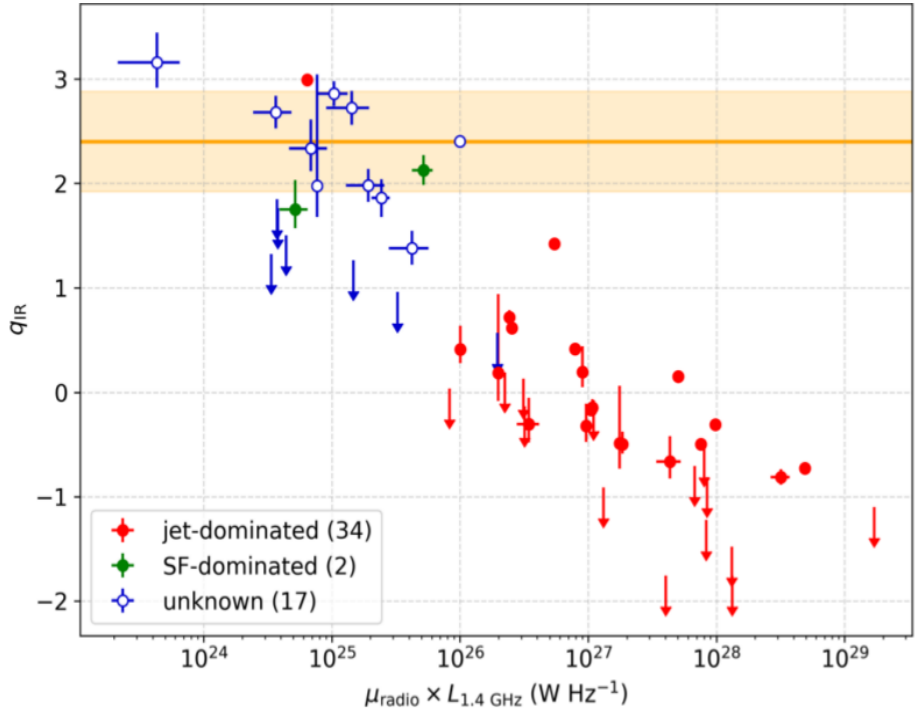


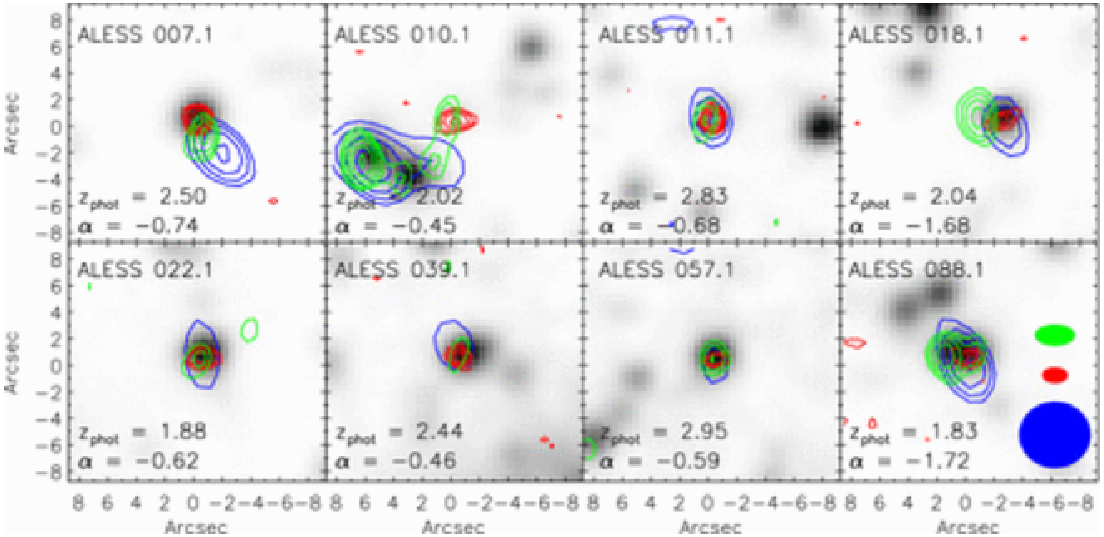
Evidences for co-evolution

$q_{IR} = \log(L_{IR}) - \log(L_{1.4GHz})$



-Gravitational lensed QSO FIRRC behaves like dusty galaxies but with smaller SFRs and LFIR

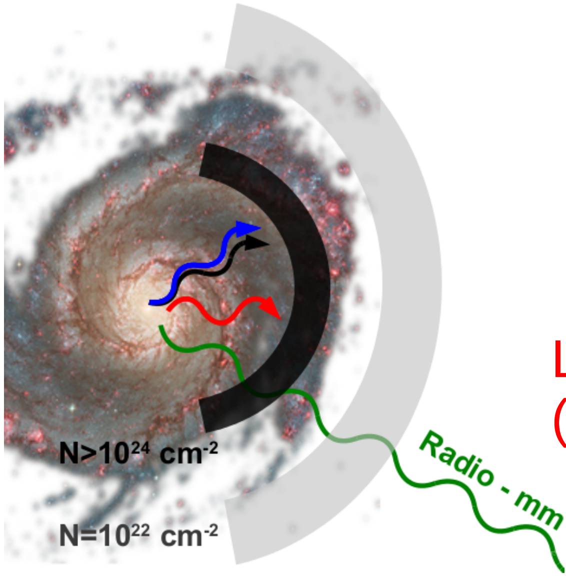




-Radio and submm trace the Same nuclear regions

VLA 1.4
ALMA 100
GMRT 0.61

Observations in highly obscured galactic cores

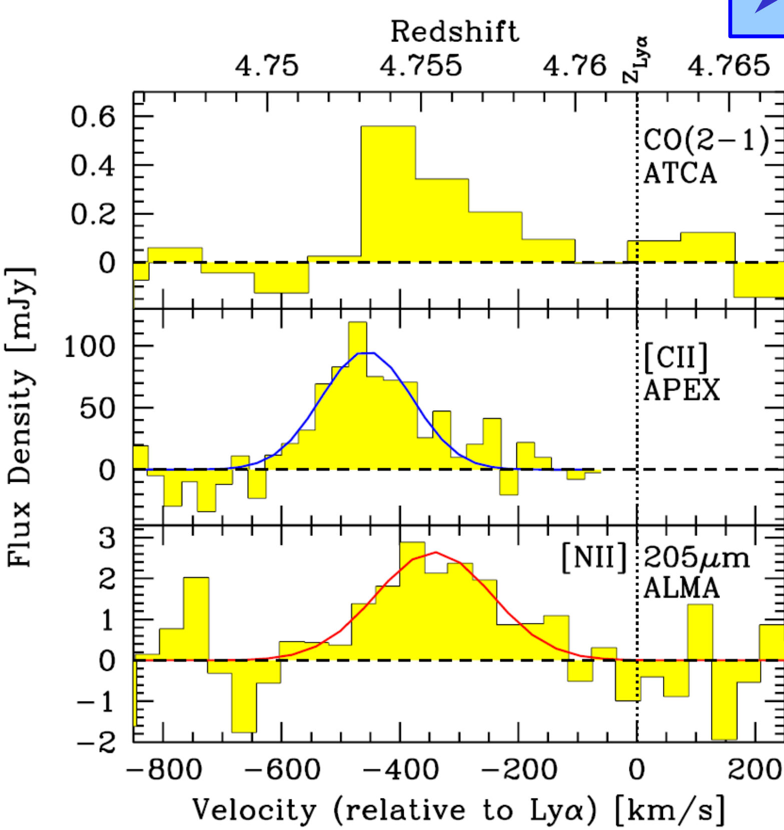


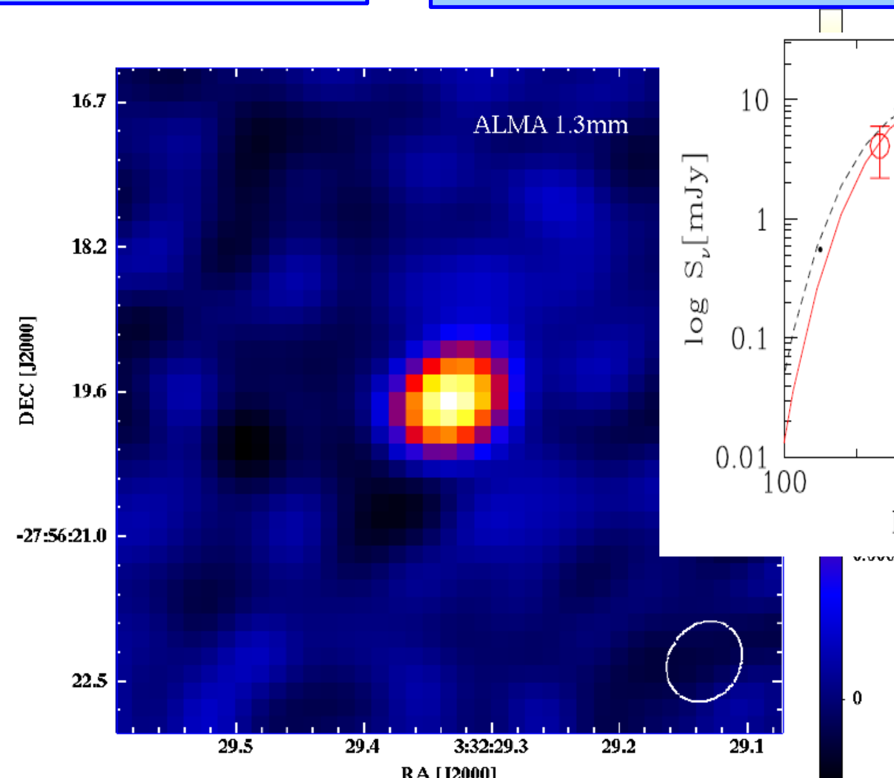
In highly obscured systems, only radio and mm-wave radiation can penetrate large columns of dust and gas and is the only tracer of the obscured regions of compact luminous infrared galaxies

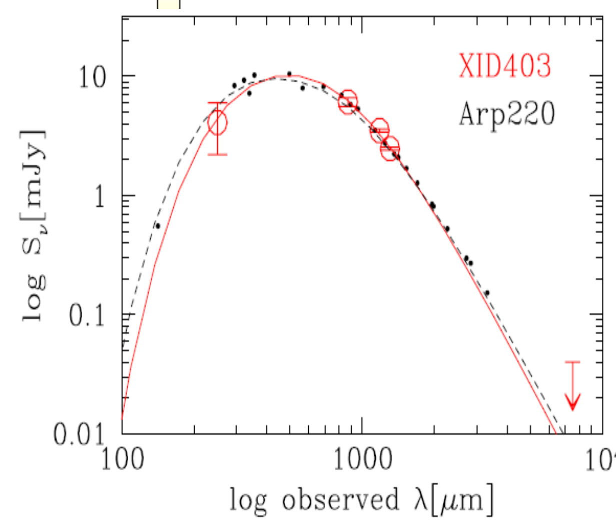
LESS J033229.4-275619: an obscured SMG at z = 4.76
(Gilli et al. 2013, Nagao et al. 2013, De Breuck et al. 2014)

- Band 6 - line
- 18 antennas,
- 3.6 hrs,
- 1.5" res

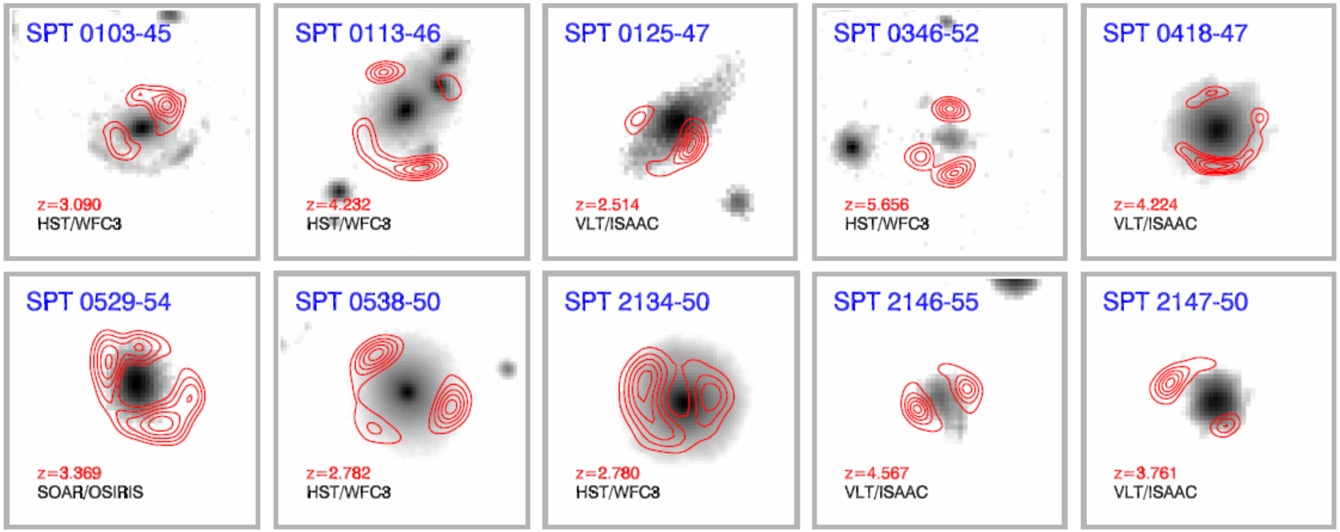
- Band 6 -continuum
- 17 antennas,
- 23 min,
- 0.75" res



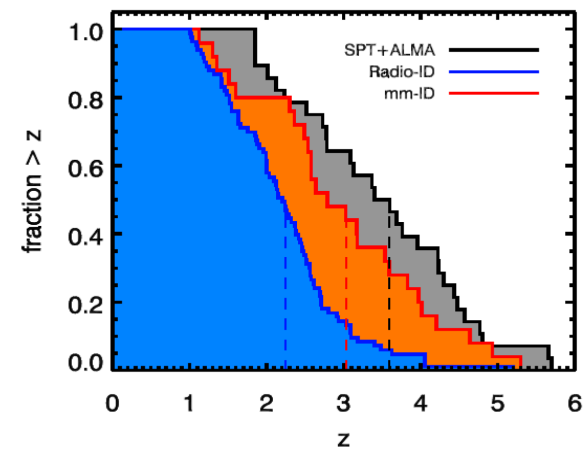


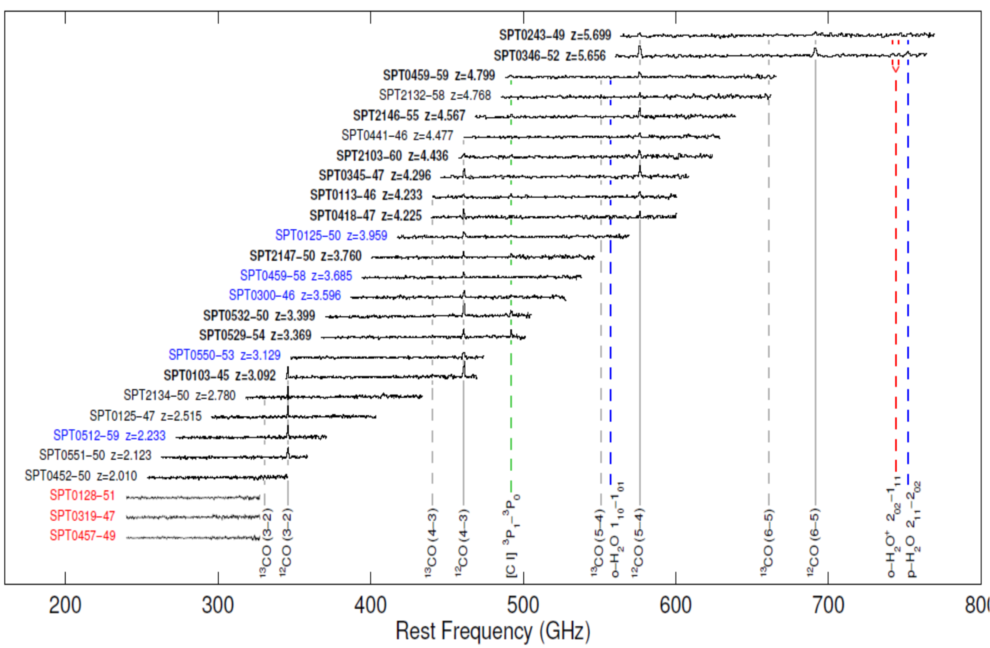


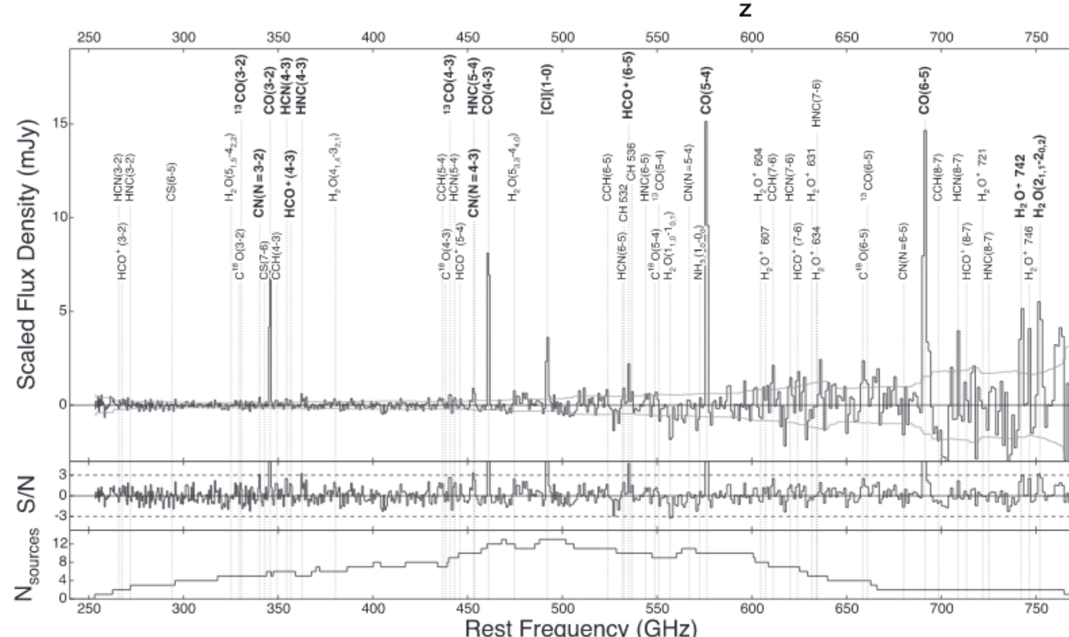
ALMA Observations of SPT Discovered, Strongly Lensed, Dusty, star-forming Galaxies(Hezaveh et al. 2013, Vieira et al. 2013, Spilker et al. 2014)



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







Bold = unambiguous redshift from ALMA

black = single lines with ALMA, confirmed with C+ or CO(1-0) with APEX or ATCA

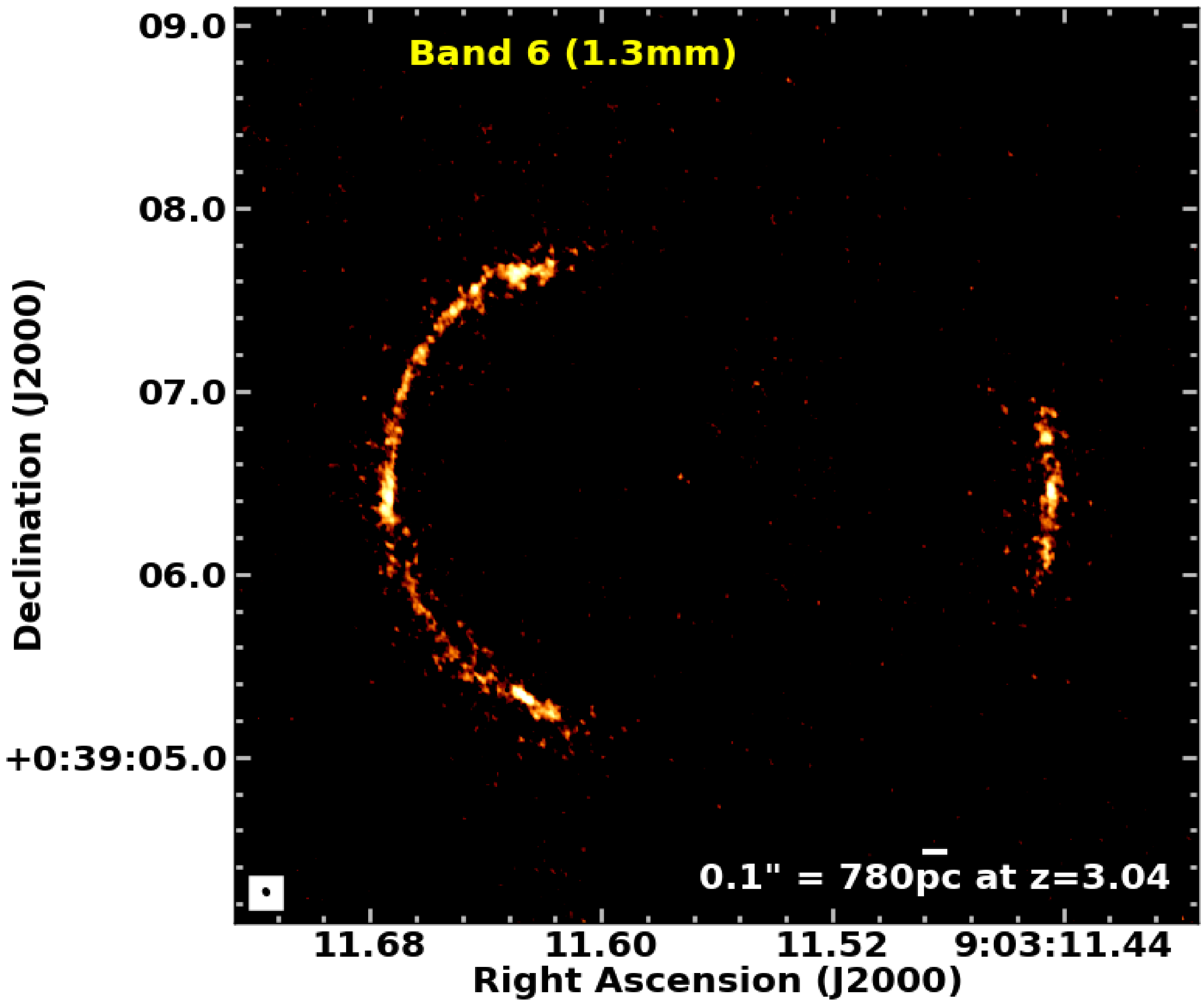
blue = single line detected with redshift, most likely redshift from photo-z

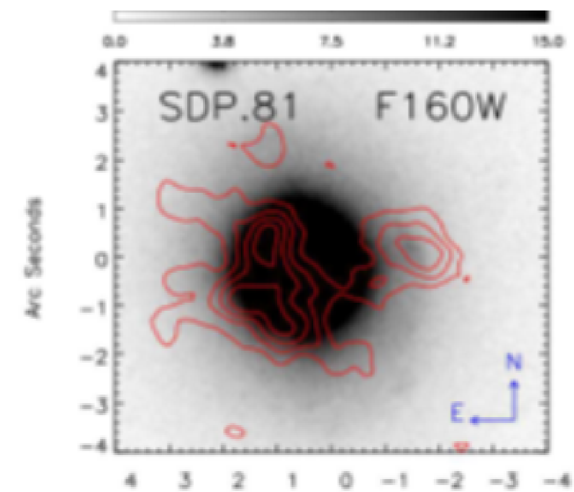
red = no line detected

Sdp.81 (ALMA Partnership 2015)

Lensed submm galaxy at z=3.042 lensed by an elliptical galaxy at z=0.299

Resolution 60 x 54 mas, 39 x 30 mas and 31 x 23 mas in Bands 4, 6, and 7
(20-80x better than SMA and PdBI) corresponding to few tenth of pc in source plane

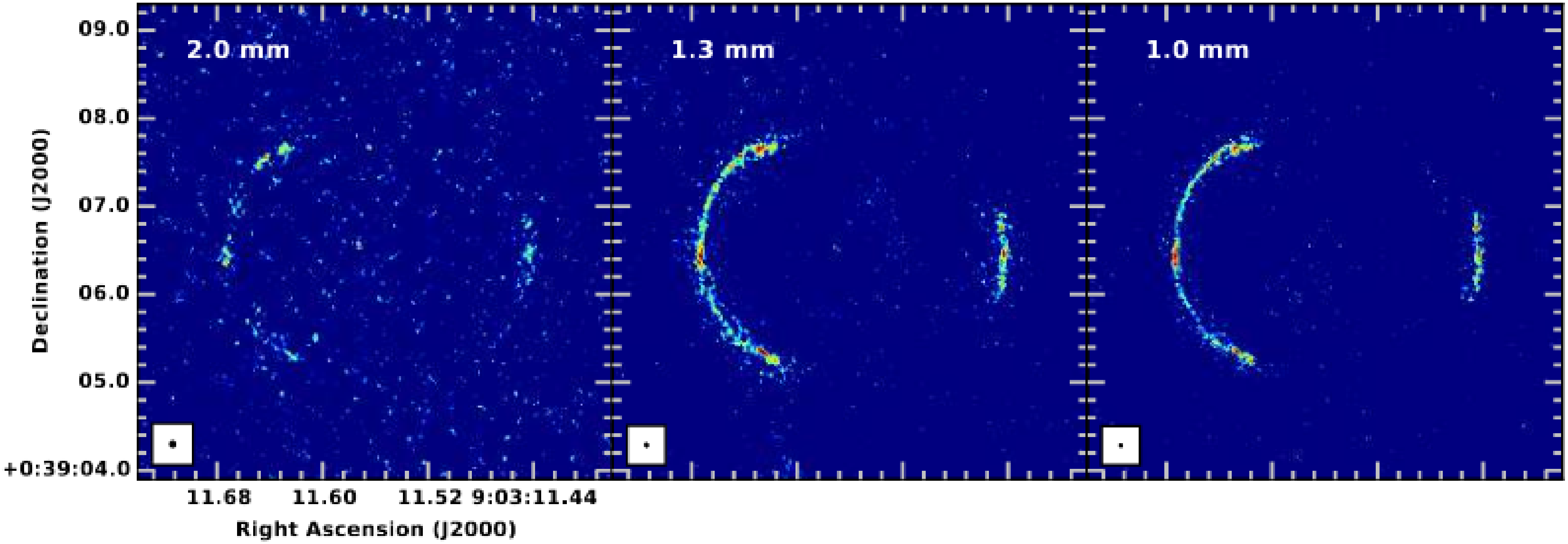




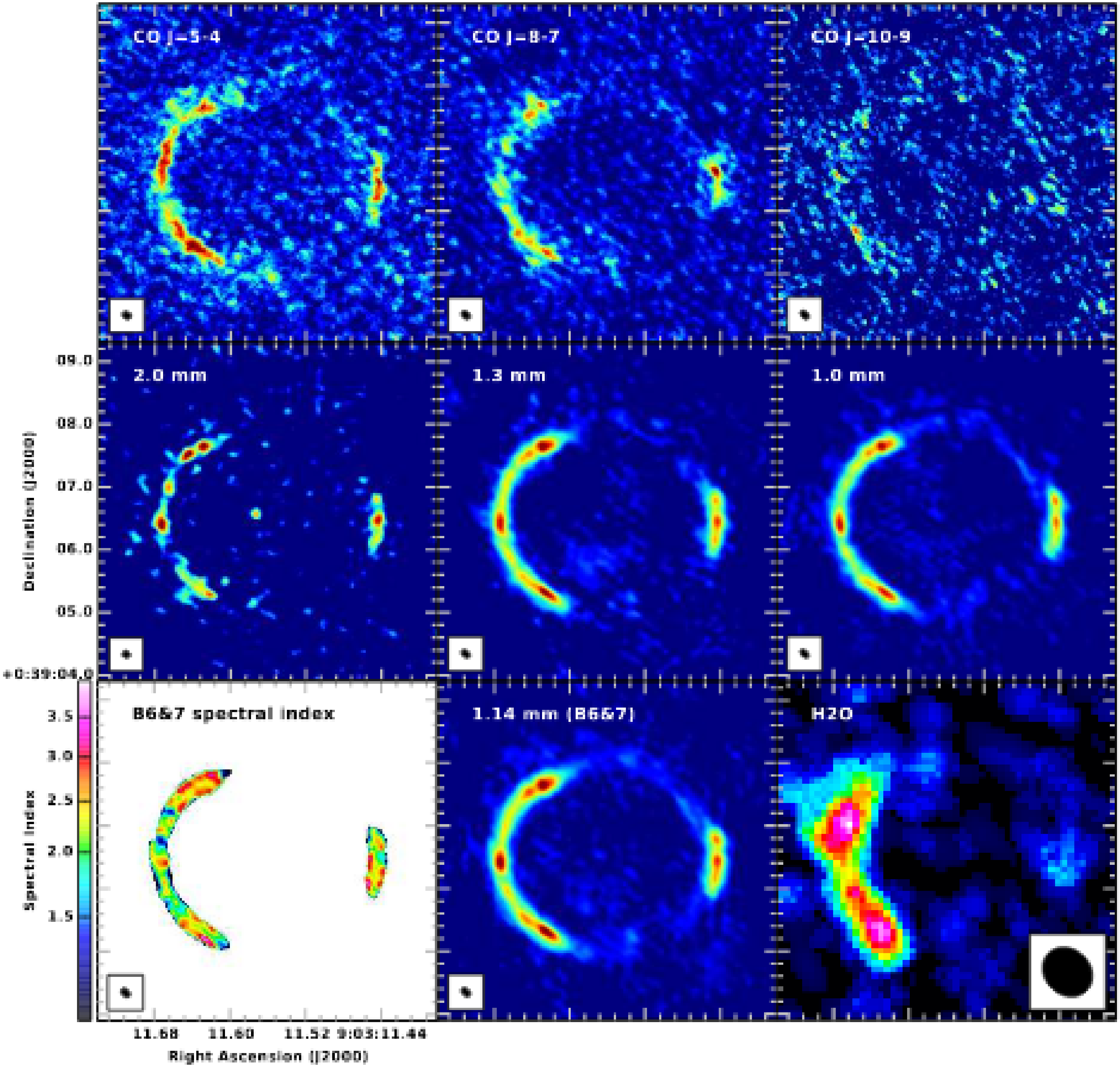
- Science Verification
- ~22-35 antennas,
- ~9-12hrs/band
- Band 4,6,7 (CO5-4. H2O, CO8-7, CO10-9)

Sdp.81 (ALMA Partnership 2015)

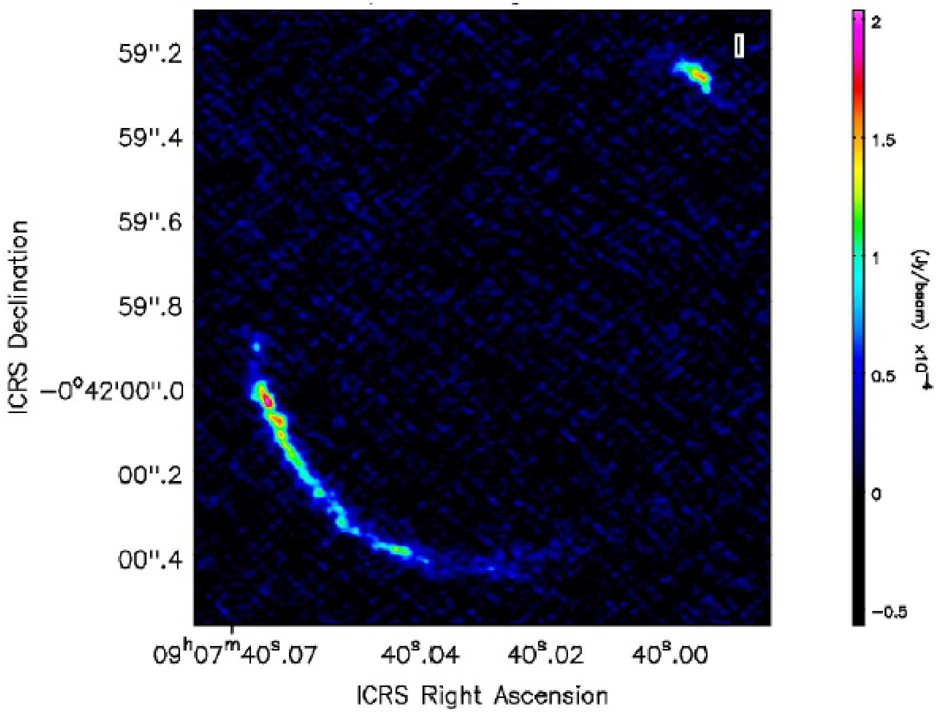
Continuum emission

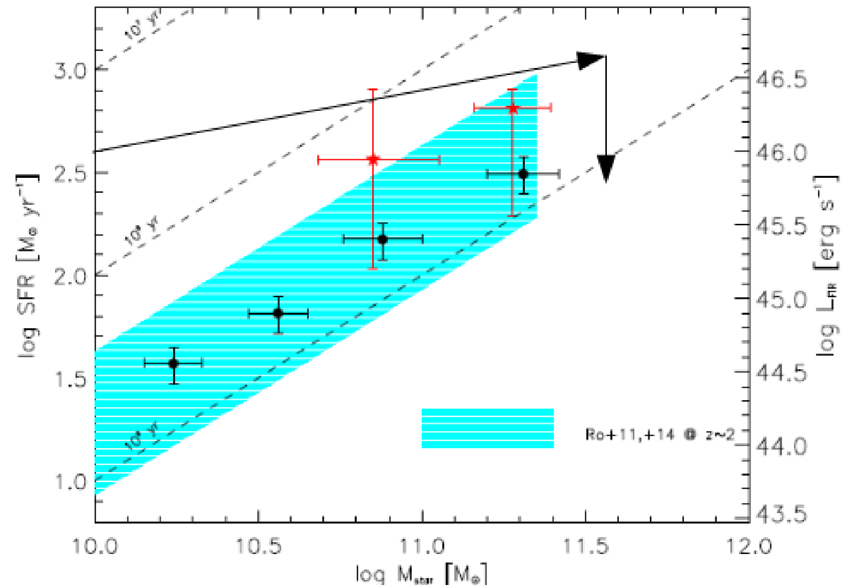


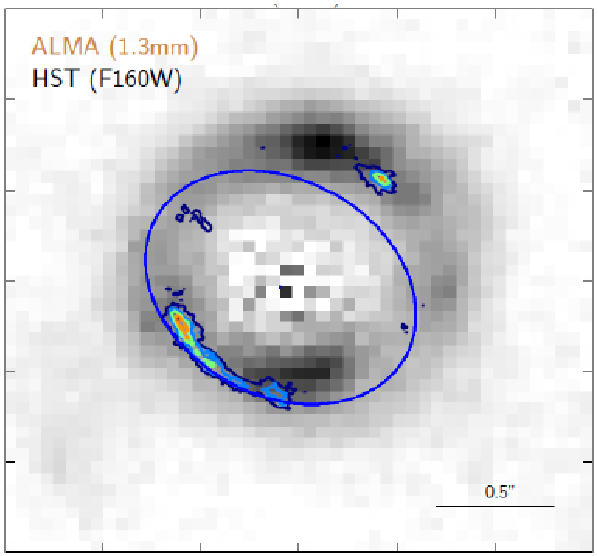
Sdp.81 (ALMA Partnership 2015)

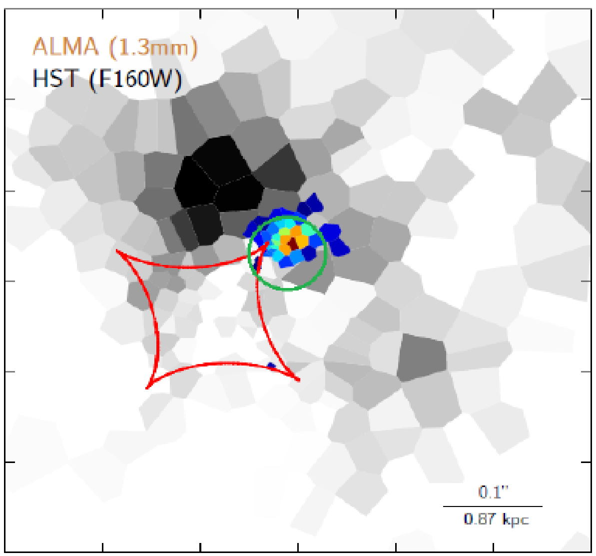


Sdp.9 (Massardi et al. 2017)









	$\mu_{3\sigma}$	$\mu_{5\sigma}$	$A_{3\sigma}$ kpc^2	$A_{5\sigma}$ kpc^2	$r_{3\sigma}$ kpc	$r_{5\sigma}$ kpc
HST 1.6μm	7.80±0.44	8.32±0.49	20.43±1.8	11.45±1.6	2.550±0.117	1.909±0.144
ALMA 1.3 mm	17.39±3.86	18.73±4.43	0.82±0.34	0.44±0.16	0.510±0.098	0.375±0.064

General words & ALMA pros

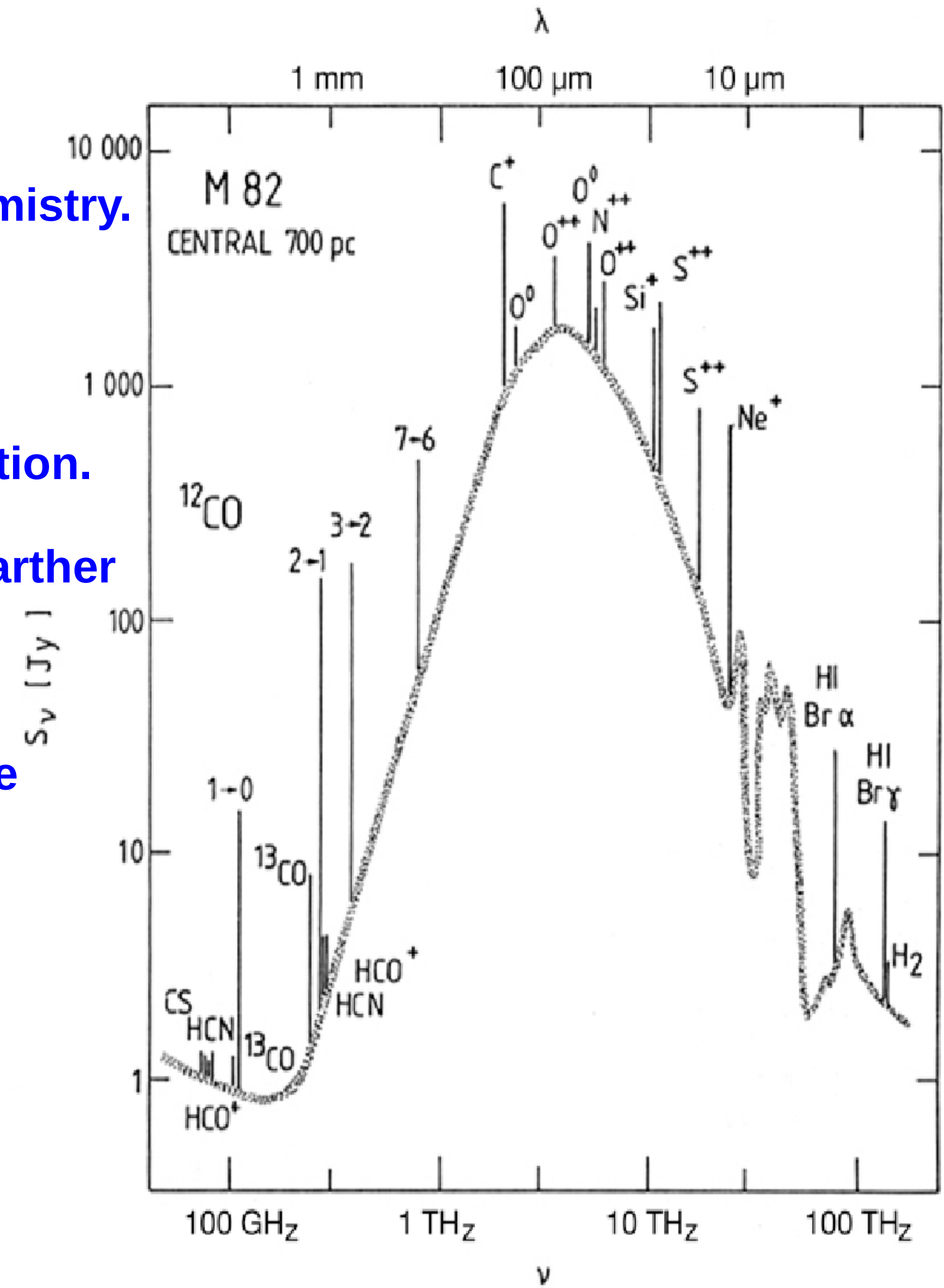
Sub(mm) is characterized by dust and rich chemistry.

Dust and moleculae are mostly (but not only) associated with forming structures.

Hence **sub(mm) helps studying structure formation.**

Higher resolution and sensitivity allows to go farther so to investigate a deeper sky region, getting more sources and more statistics on populations.

Higher spectral resolution allows to detect more narrow lines and more details from broad lines, and hence investigate chemical compositions, source dynamics and pressure and temperature structures.



A project lifetime: phase 2 Observing process

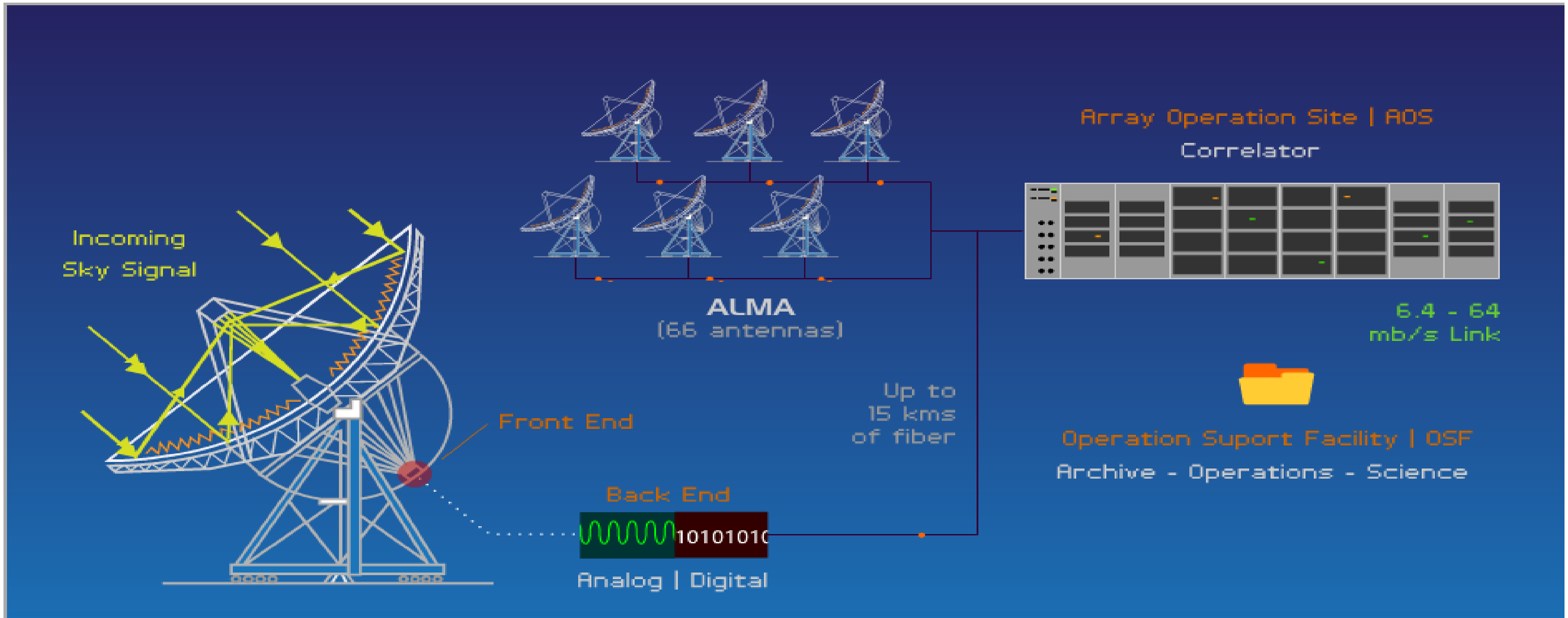
PHASE II – Observing process

Scheduling Block — Each SG is converted into a **Scheduling Block, an observational unit including targets in the same sky region and their Calibrators to be observed with the same instrumental setup.** They are the minimum set of instructions to perform an observation.

Observations — **Projects are dynamically scheduled according to telescope configuration, weather, ranking, project status...**

Quality assessment — **QA0 and 1 = telescope conditions**
QA2 = Check for PI sensitivity requests performed by ARC staff

Data archival and delivery — **1 yr of proprietary period before data are public through the archive**



Early Science Cycles

Early Science observations are conducted on a best effort basis
to allows community to observe with incomplete, but already superior array,
with priority given to the completion of the full ALMA capabilities

Initial ALMA Early Science cycles:

	Cycle 0 Sep. 2011 – Jan. 2013	Cycle 1 Jan. 2013 - May. 2014	Cycle 2 Jun. 2014 – Oct. 2015	Cicle 3 Oct 2015 - Oct 2016
Telescope				
Hours dedicated to Science	**800**	**800**	**2000**	**2100**
Antennas	**> 12x12-m**	**> 32x12m +9x7m+2TP**	**> 34x12m +9x7m+2TP**	**> 36x12m +10x7m+2TP**
Receiver bands	3, 6, 7, 9	3, 6, 7, 9	**+4, 8**	**+10**
Wavelengths [mm]	3, 1.3, 0.8, 0.45	3, 1.3, 0.8 0.45	+2, 0.7	
Baselines	up to 400 m	**up to 1000 m**	**up to 1500m**	**up to 10km**
Polarisation	single-dual	single dual	**full**	**full**
Proposal outcome				
Submitted	917	1133	1381	1578
Highest priority	112	198	354	402
Filler	51	93	159	236
Success rate	12% (18%)	17% (25%)	26% (37%)	25% (40%)

Pressure factors (highest priority projects)

- Cycle 1: Europe: 9.1 (global ALMA: 5.8)
- Cycle 2: Europe: 4.9 (global ALMA: 3.9)
- Cycle 3: Europe: 6.2 (global ALMA: 3.9)

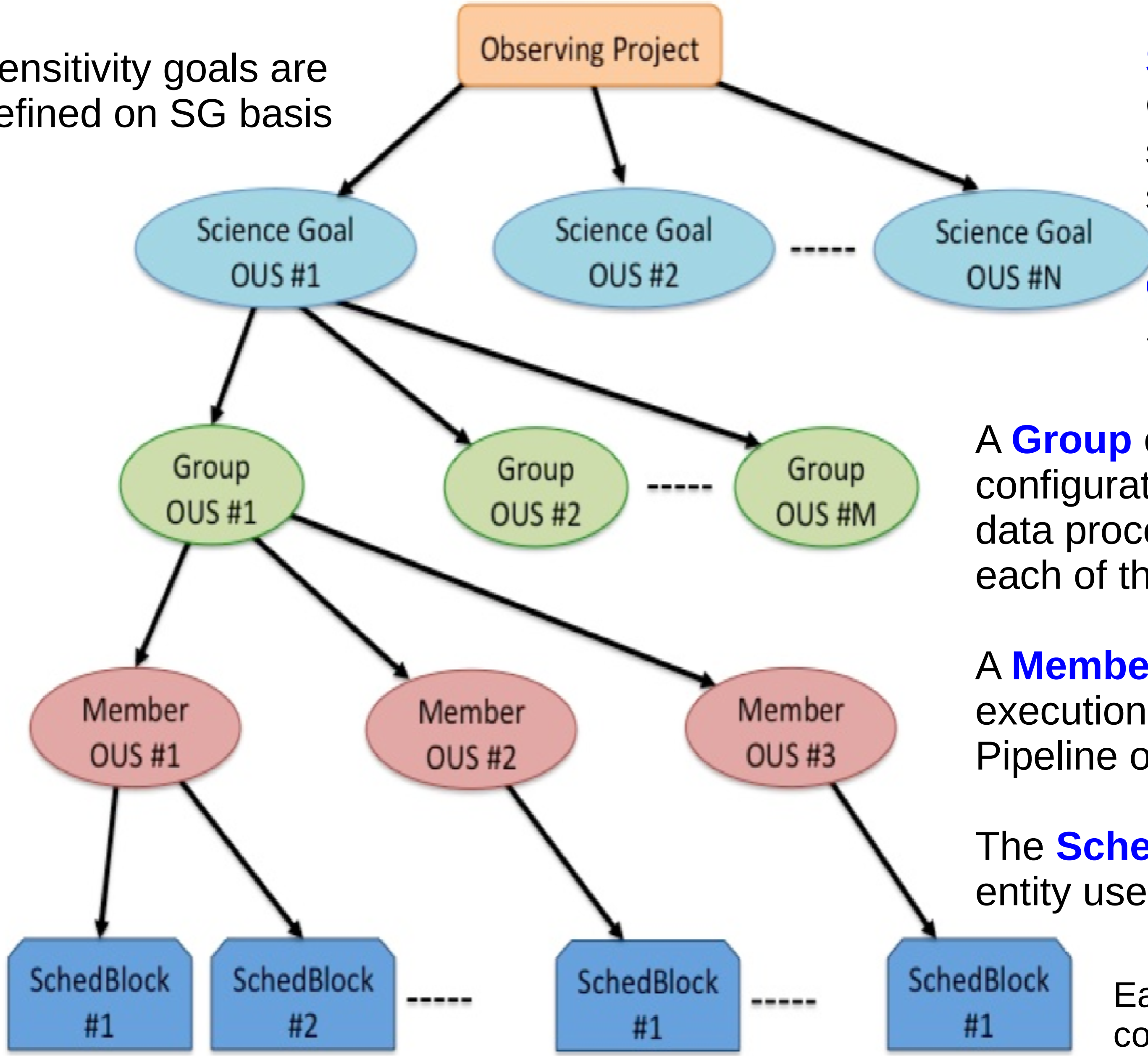
Reasons to use archived data

- Check if data are already available for a target
- Check the feasibility of a project looking for similar targets
- Retrieving information on a large sample of objects (e.g. statistics of populations, stacking, …)
- Retrieving information on a single object but with different configuration (e.g. multifrequency studies) or in different epochs (e.g. variability studies)
- Extracting unpublished information from existing data (e.g. finding additional spectral lines, targets in the same region/time of other observations,)
- **For ALMA in particular avoid the stress of competition and oversubscription**

	Proposal submission	**Archive mining**
Time to get data	✗	+
Amount of data	✗	+
Data homogeneity	+	✗
Adherence to idea	+	✗

Data structure

Sensitivity goals are defined on SG basis



Science goal:
Group of sources in the same sky region that share the same spectral setup

OUS= Observing Unit Set
Smallest unit for data processing

A **Group** can contain several configurations to be combined in data processing (e.g. several arrays), each of them is a Member.

A **Member** can contain multiple executions of a Scheduling Block. Pipeline operates at this level.

The **Scheduling Block** is the smallest entity used for observing

Each repetition of a Scheduling Block constitutes an **Execution Block**

Data Quality Assessment

The goal of ALMA Quality Assurance (QA) is to deliver to the PI a reliable final data product that has reached the desired control parameters outlined in the science goals, that is calibrated to the desired accuracy and free of calibration or imaging artifacts i.e. ALMA performs **science-goal-oriented service data analysis**

ALMA QA happens on 4 levels:
QA0: near-real time verification of weather and hardware issues carried out on each execution block immediately after the observation.

QA1: verification of longer-term observatory health issues like absolute pointing and flux calibration.

QA2: offline calibration and imaging (using CASA) of a completely observed MOUS. Performed by expert analysts distributed at the JAO and the ARCs with the help of a semi-automatic CASA pipeline. **Results are archived and given to the PI.**

QA3: (optional) PIs may request rereduction, problem fixes, possibly reobservation

Data format

ALMA Science Data Model (ASDM) **Final archived product from each observation**

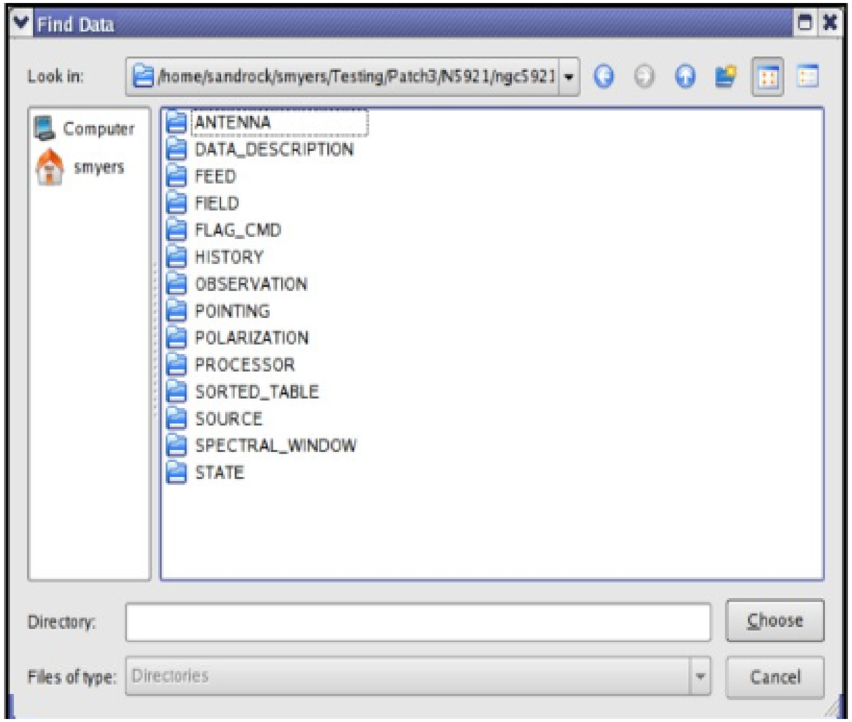
Each has an unique hexadecimal name
(eg uid://A002/X2fed6/X3f).
Each contains the meta-data (headers, descriptions of the observation setup, etc), and the binary data (the raw data)

The first step of any data processing is importing the ASDM in the format suitable for the software used

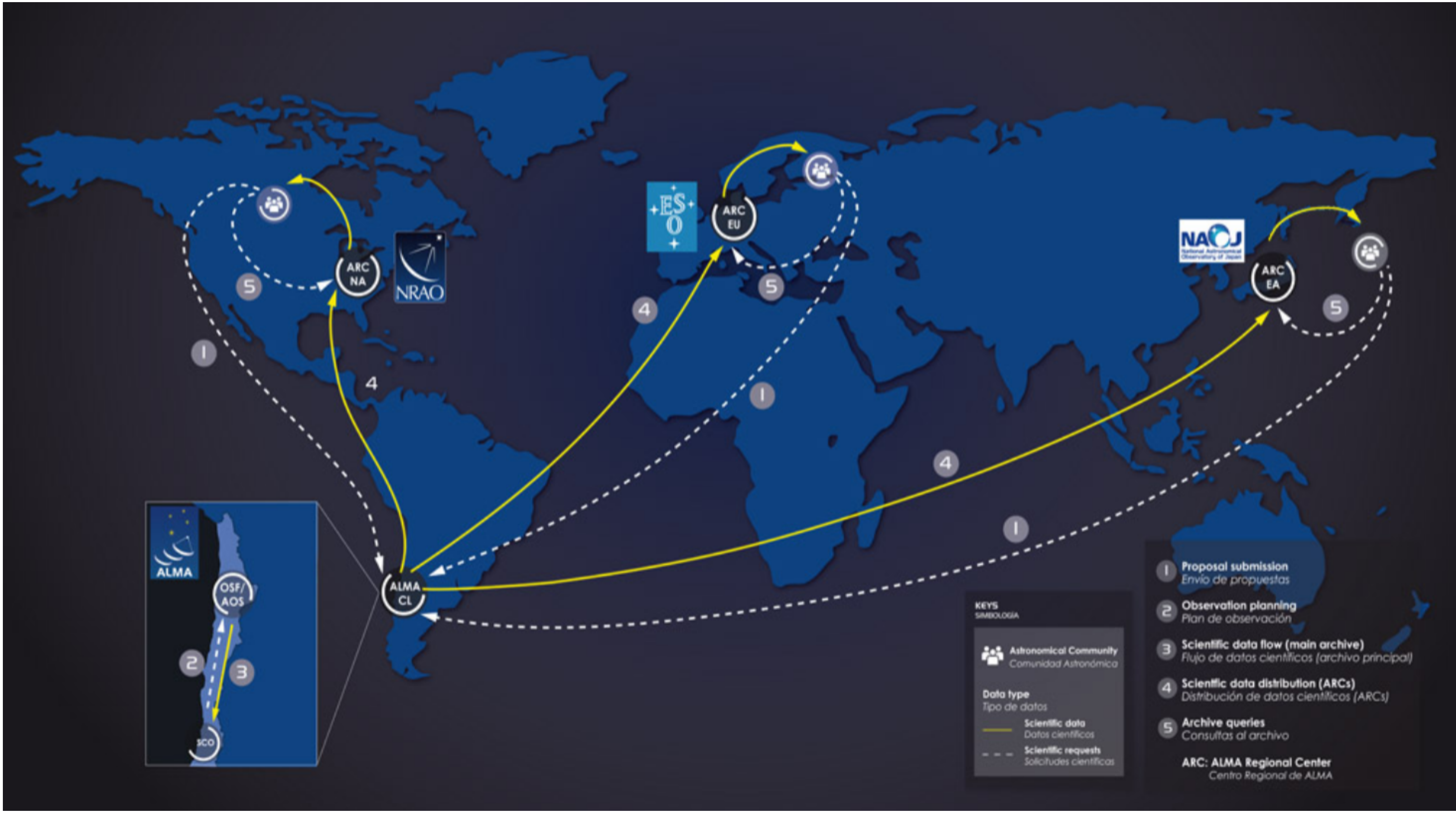
Measurement Set (MS)

Data format used in CASA

Constituted by several tables referring each other and collecting most (not all!) the information in the ASDM



ALMA data flow



Data is collected, reduced and archived.
All the “almost” raw data is archived.

Each ARC hosts an archive mirror.

The ALMA Archive - Tutorial

What is in the archive?

For each project the main deliverables are

Raw Data (in CASA readable MS), Calibration Scripts and Tables

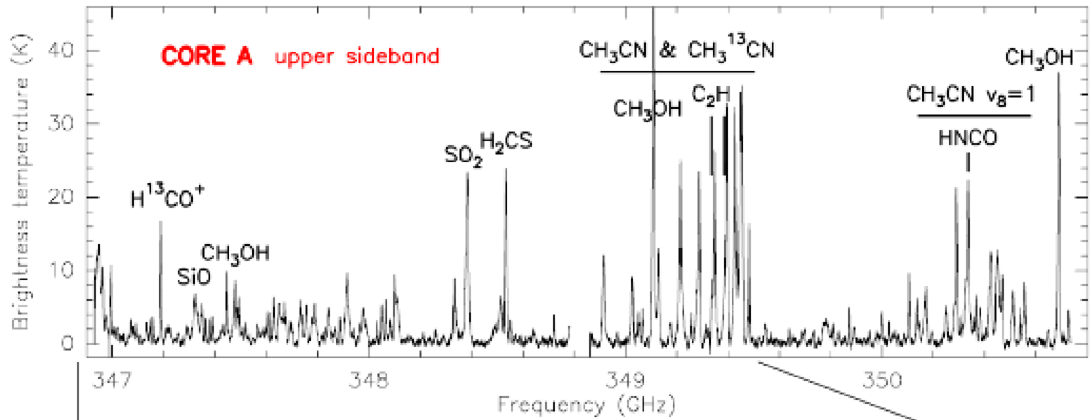
Users need to run CASA to generate the Calibrated Data.
The resulting calibrated data is considered science-ready.

Some Imaging Products are delivered too, as result of QA2 processing
(in Early Science provided on a best effort basis, not necessarily science-ready)
a) for Line Observations:
- continuum-subtracted (where needed) image cubes at the requested resolution
- a continuum image for all line-free channels (where possible)
b) for Continuum Observations:
- continuum image combining all SPWs

The main purpose is to measure the rms and verify the achievement of PI requests.

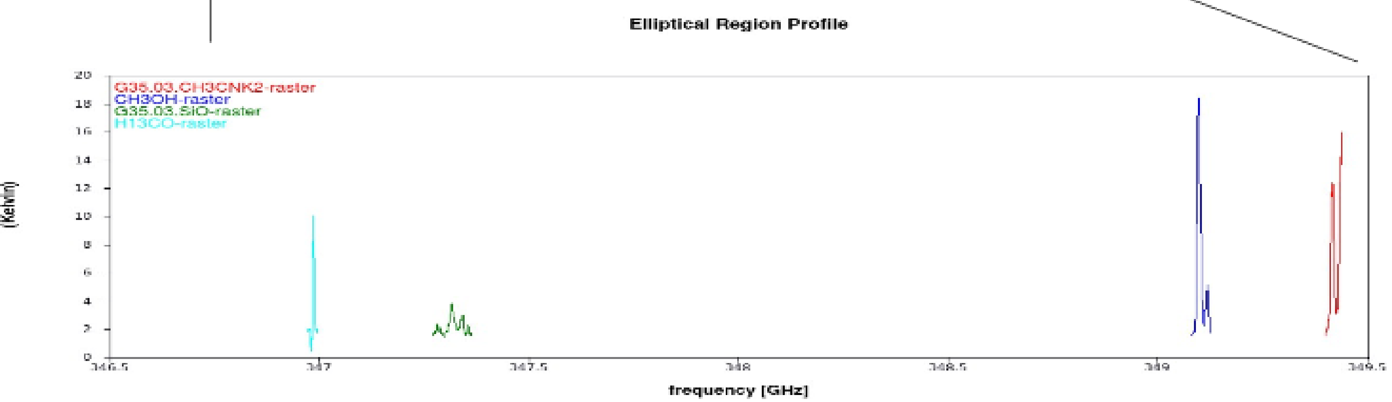
Images in the archive are provided as starting point on the way to obtain the final images and a valuable basis for archive researchers (i.e. they are not considered science-ready!!!)

What is in the archive?

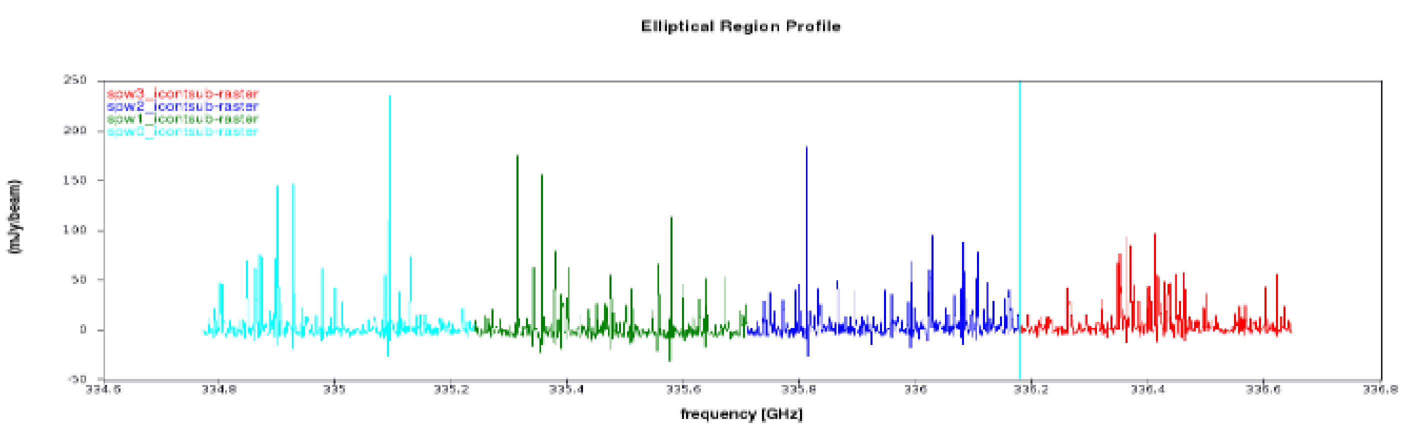


Images in the archive might cover only a fraction of the spectrum available

Spectrum observed
(and available in the raw data)



Imaged data for QA2



Different data and PI requests on different sources generate different products
In the archived images
but raw data contain the full spectral windows

What is in the packages?

When untarred, the Product Package standard directory structure contains

Untarred products only

```
|-- project_id/
| |-- sg_ouss_id/
| | |-- group_ouss_id/
| | | |-- member_ouss_id/
| | | | |-- README ......................important summary of the contents
| | | | |-- product/ .......................all the imaging products as result of QA2
| | | | |-- calibration/ ...................calibration and flagging tables
| | | | |-- qa/ ............................diagnostic plots generated during QA2
| | | | |-- script/ ........................the scripts necessary to regenerate the products
| | | | |-- log/ ...........................CASA log files from QA2 calibration and imaging
```

Untarred ASDM (raw data)

```
| | | | |-- raw/ ...........................for calibration move it in the products folder at the
                                             right level  (follow the README)
```

Untarred ASDM (Raw data)

Untarred products

In publications with ALMA data!

Acknoweledgement Statement:

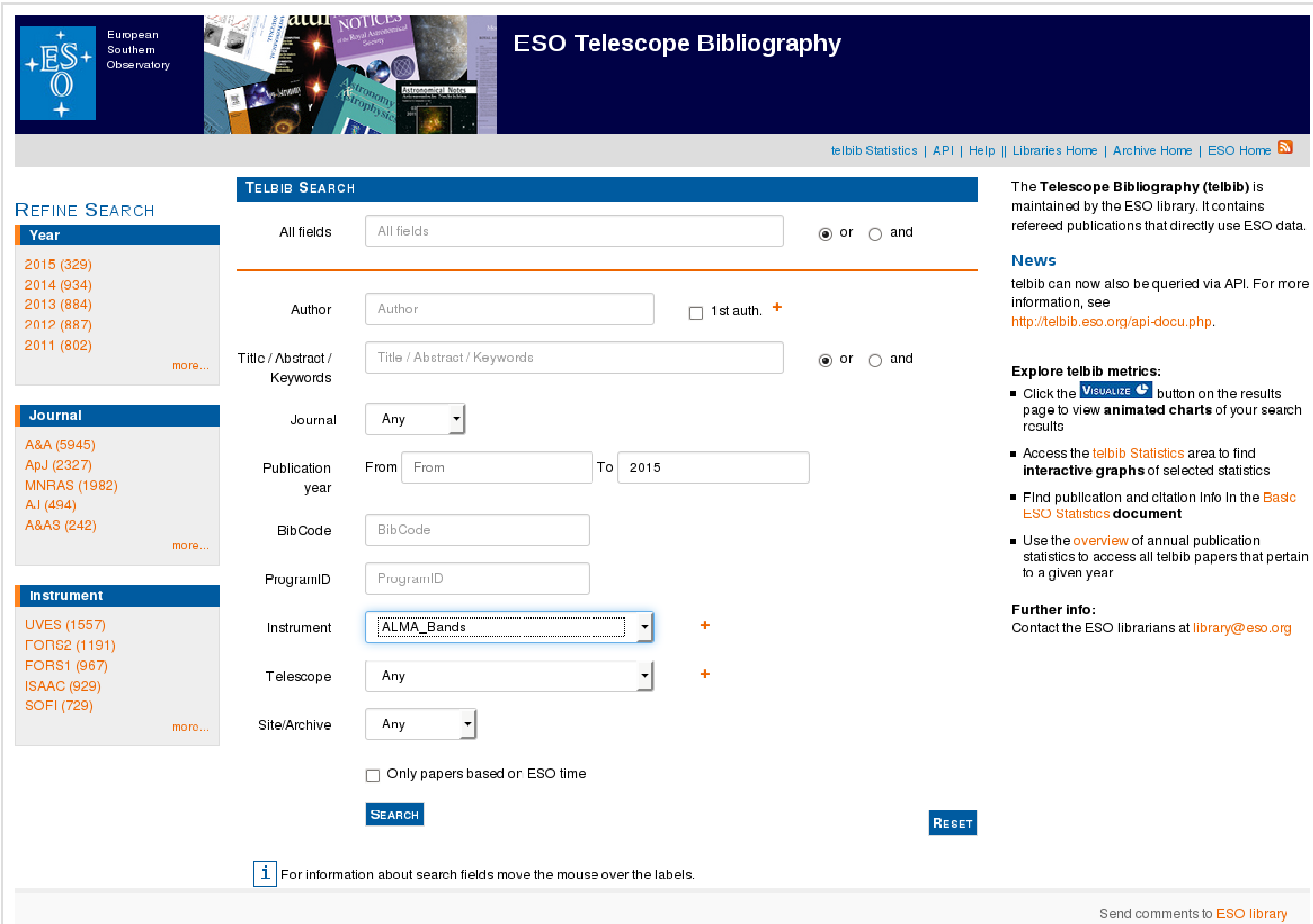
“This paper makes use of the following ALMA data: ADS/JAO.ALMA#2011.0.01234.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.”

(Can be found in the SP, on the ‘ALMA-Data’ page)

•

The ESO telbib

http://telbib.eso.org/



The ESO telbib

European Southern Observatory

ESO Telescope Bibliography

telbib Statistics | API | Help || Libraries Home | Archive Home | ESO Home

Refine Search

Year

- 2015 (40)
- 2014 (97)
- 2013 (65)
- 2012 (20)

Journal

- ApJ (121)
- A&A (54)
- MNRAS (16)
- Nature (11)
- PASJ (6)

more...

Instrument

- ALMA_Bands (222)
- LABOCA (14)
- XSHOOTER (6)
- FORS2 (5)
- SHFI (5)

more...

New Search | Edit Search | Visualize | Export

Results **1 - 25** of **222** found for (instrument:ALMA_Bands)

« Previous Next »

Year ▼	Author	Title	Instruments	Access to data	Fulltext ADS
2015	Sakai, Yusuke et al.	An ALMA Imaging Study of Methyl Formate (HCOOCH3) in Torsionally Excited States toward Orion KL	***ALMA_Bands***	2011.0.00009.SV	2015ApJ...803...97S
2015	Brouillet, N. et al.	Antifreeze in the hot core of Orion. First detection of ethylene glycol in Orion-KL	***ALMA_Bands***	2011.0.00009.SV	2015A&A...576A.129B
2015	Saito, Toshiki et al.	ALMA Multi-line Observations of the IR-bright Merger VV 114	***ALMA_Bands***	2011.0.00467.S	2015ApJ...803...60S
2015	Olofsson, H. et al.	ALMA view of the circumstellar environment of the post-common-envelope-evolution binary system HD 101584	***ALMA_Bands***	2012.1.00248.S	2015A&A...576L..15O
2015	Sakai, Takeshi et al.	ALMA Observations of the IRDC Clump G34.43+00.24 MM3: DNC/HNC Ratio	***ALMA_Bands***	2011.0.00656.S	2015ApJ...803...70S
2015	Gullberg, B. et al.	The nature of the [C II] emission in dusty star-forming galaxies from the SPT survey	***ALMA_Bands***	2011.0.00957.S, 2011.0.00958.S, 2012.1.00844.S	2015MNRAS.449.2883G
2015	Rathborne, J. M. et al.	A Cluster in the Making: ALMA Reveals the Initial Conditions for High-mass Cluster Formation	***ALMA_Bands***	2011.0.00217.S	2015ApJ...802..125R

What to do after download?

```
[massardi@arcbl02 member.uid___A001_X120_X102]$ cd script/
[massardi@arcbl02 script]$ casapy-setup 42.2.30986-pipe-1-64b
[massardi@arcbl02 script]$ casapy --pipeline
...

CASA <2>: execfile('scriptForPI.py')
```

1) Untar the packages

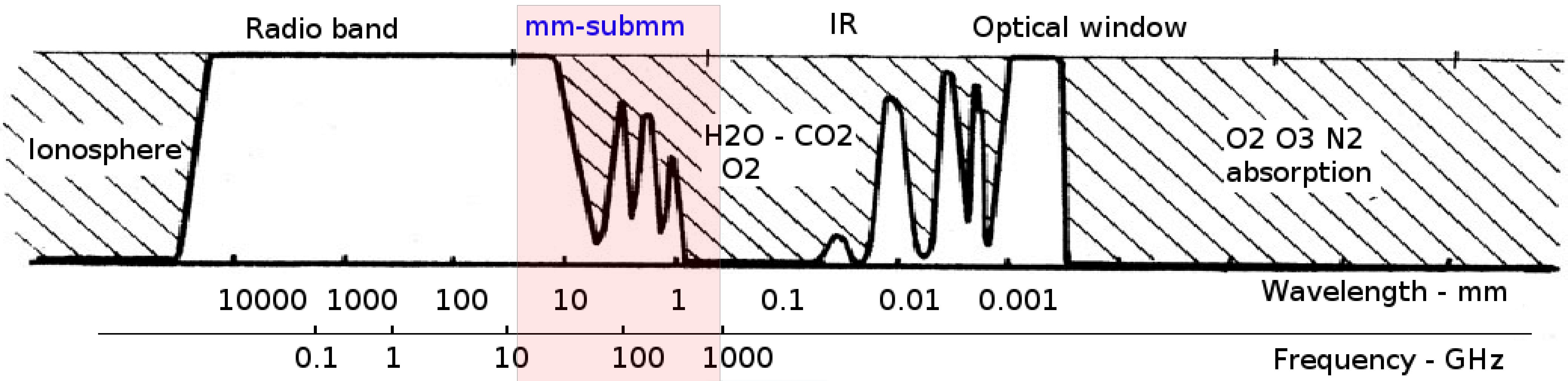
2) Look at weblog and/or QA reports

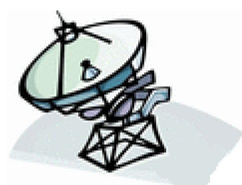
3) Read the README file and follow the instructions: typically

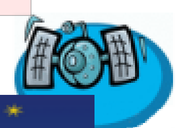
  - Launch the correct CASA (with pipeline) version in the script folder
  - Run the “Script_for_PI” to generate the calibrated MS
  - Run the “Script_for_Imaging” to regenerate the images

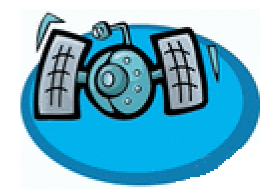
4) Edit the scripts where needed according to your purposes

Outline









Signals in the (sub)mm bands

Observing instruments: **Interferometers (ALMA)**

Science cases parade and proposals

Observing processes: **archives & images**
(with hands-on tutorial)