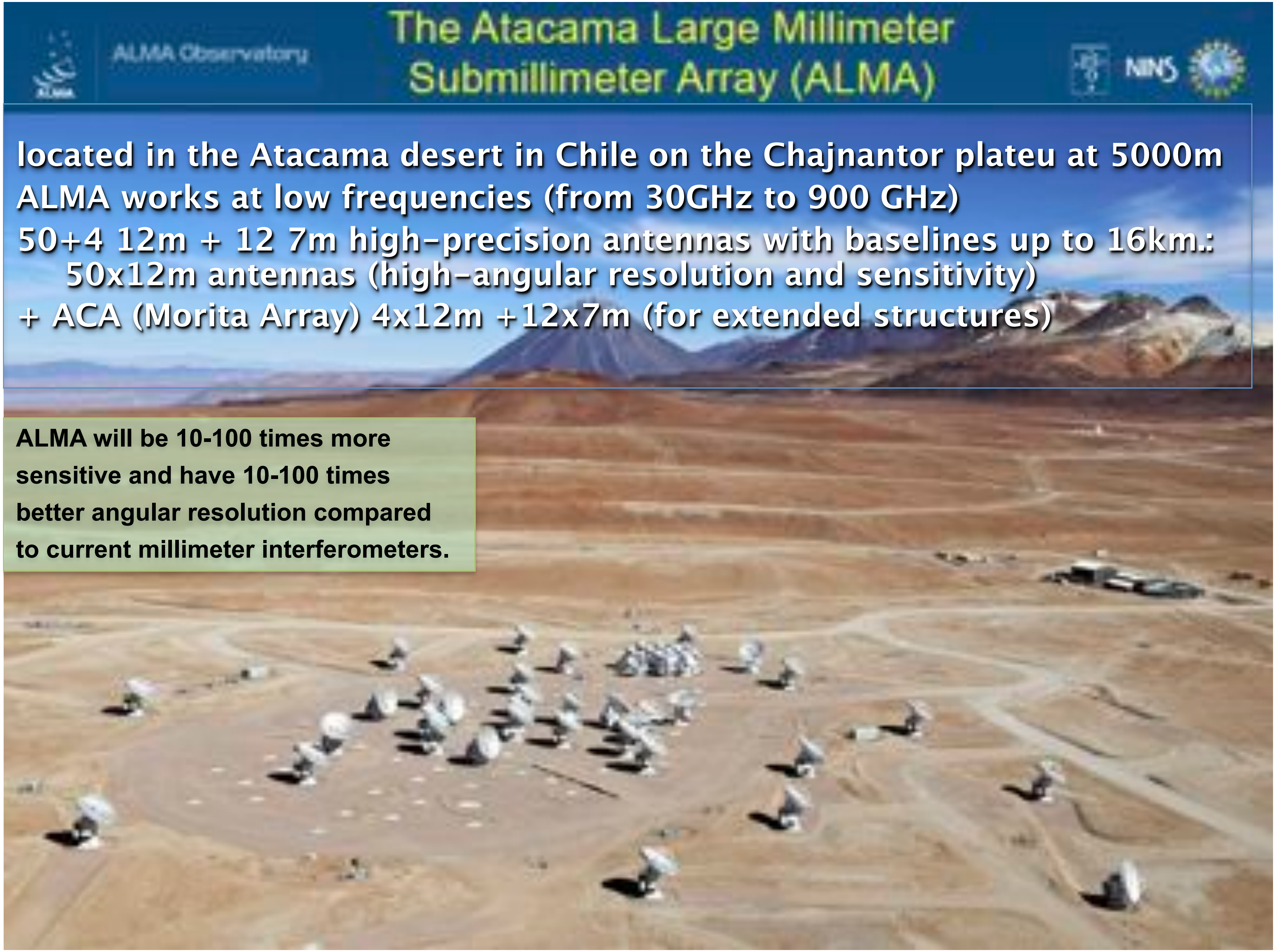
ALMA scientific capabilites and first scientific results

Paola Andreani
ESO-ALMA

Talk outline

- Review of the ALMA project and goals
- Review of the ALMA scientific capabilities
- First scientific results
  - High-redshift ‘blobs’ (+ redshift survey)
  - Clusters of galaxies
  - Outflows/AGN feedback in nearby active galaxies
  - SN1987A
  - Serendipity discoveries
- Full capabilities and future plans


ALMA Observatory
The Atacama Large Millimeter Submillimeter Array (ALMA)
NINS
located in the Atacama desert in Chile on the Chajnantor plateu at 5000m
ALMA works at low frequencies (from 30GHz to 900 GHz)
50+4 12m + 12 7m high-precision antennas with baselines up to 16km.:
50x12m antennas (high-angular resolution and sensitivity)
+ ACA (Morita Array) 4x12m +12x7m (for extended structures)
ALMA will be 10-100 times more sensitive and have 10-100 times better angular resolution compared to current millimeter interferometers.

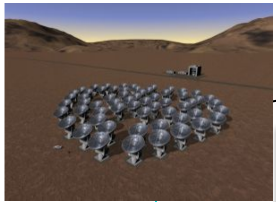
ALMA an international project

Inauguration took place on March 13th 2013

Paola Andreani, ESO

Where is ALMA?

ALMA Sites in Chile



Antenna Operations Site (AOS)

40 MB/s (peak)

Operation Support Facility (OSF)

6 MB/s (average)

Santiago Central Office (SCO)

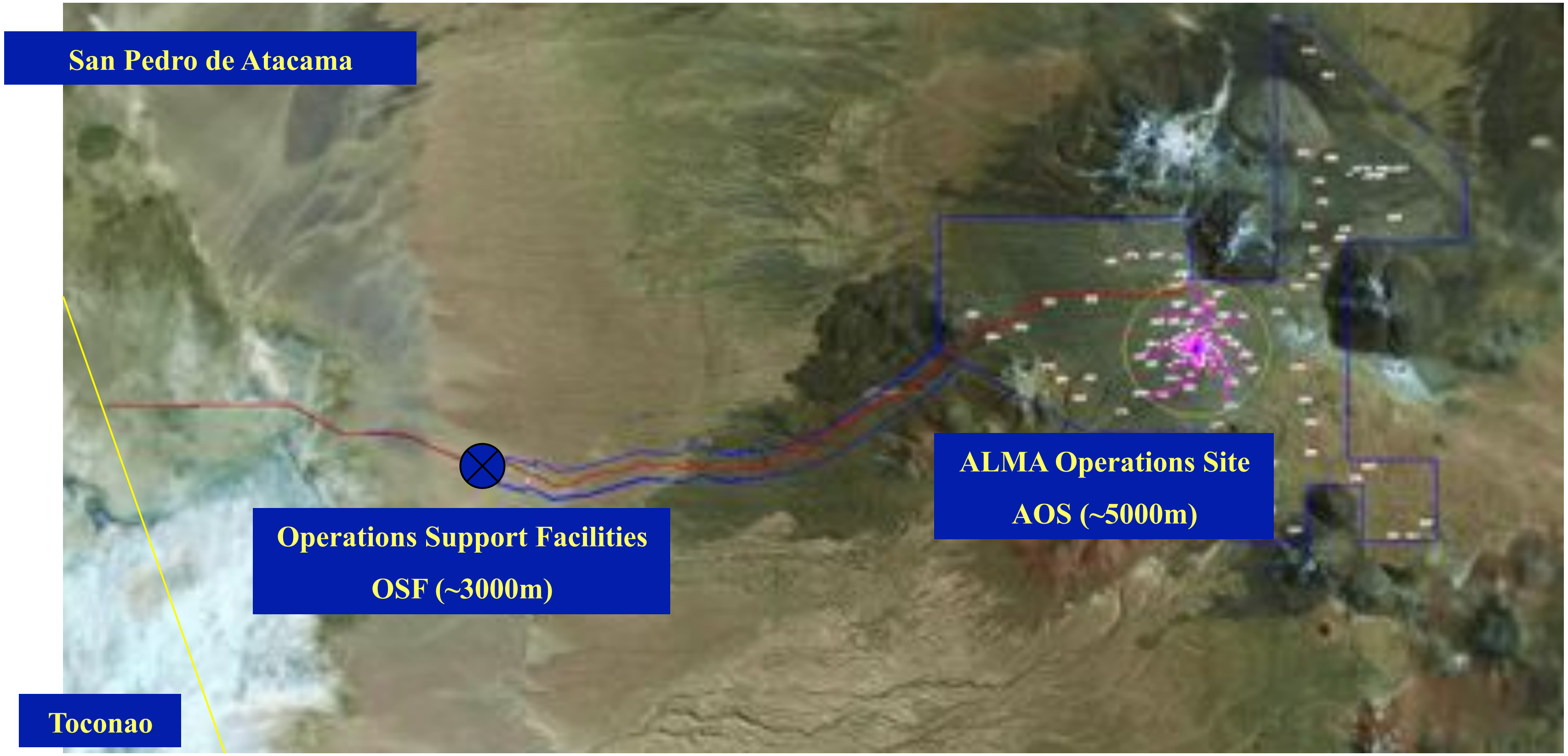
ALMA Site

Three sites in Chile

ALMA Operations Site (AOS): high, dry site, Chajnantor Plateau (5000m)

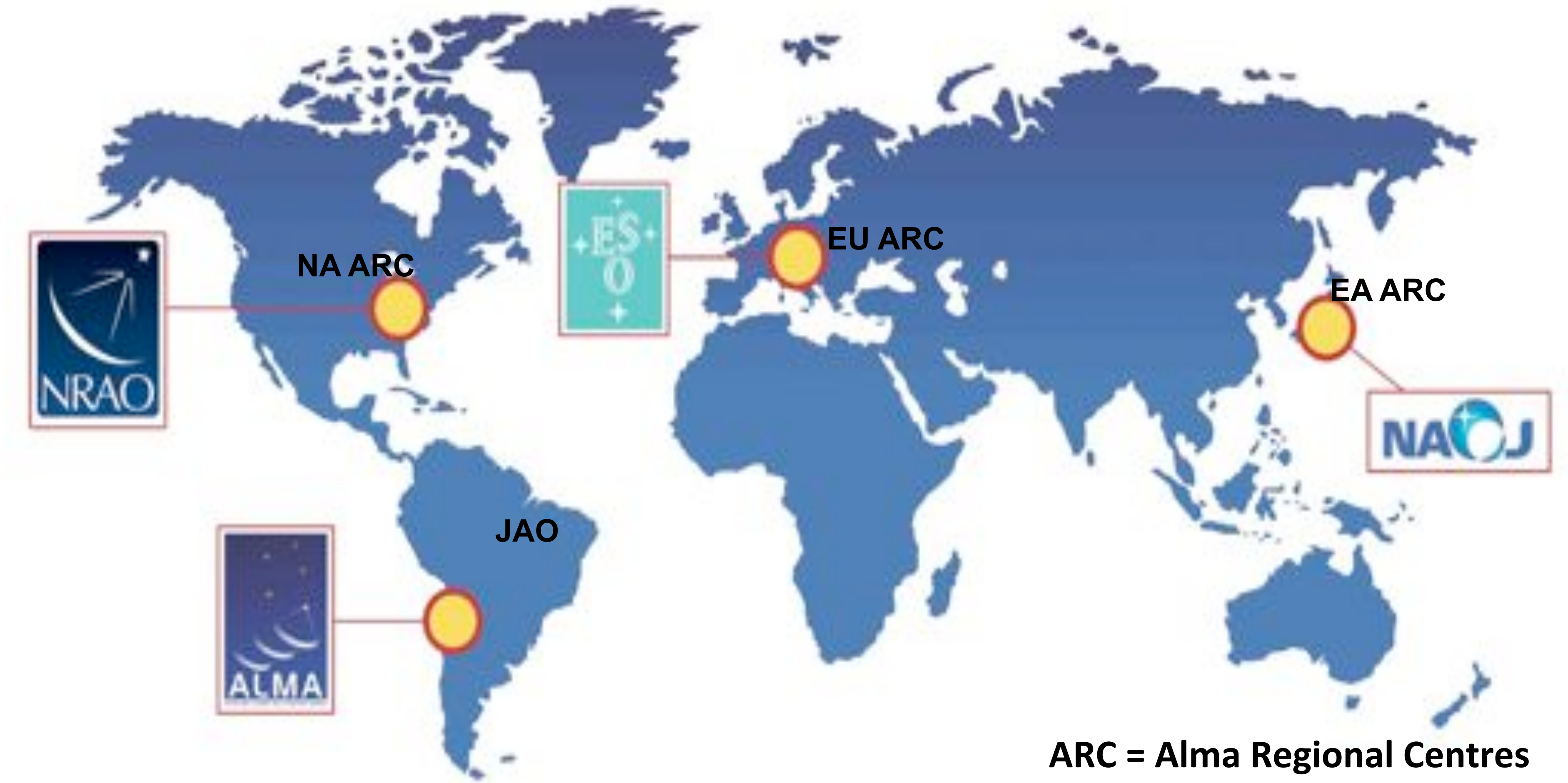
Operations Support Facility (OSF): Technical base (2900m) near San Pedro de Atacama

Santiago headquarters



Paola Andreani, ESO

ALMA Operations Centres



ARC = Alma Regional Centres
JAO = Joint ALMA Observatory

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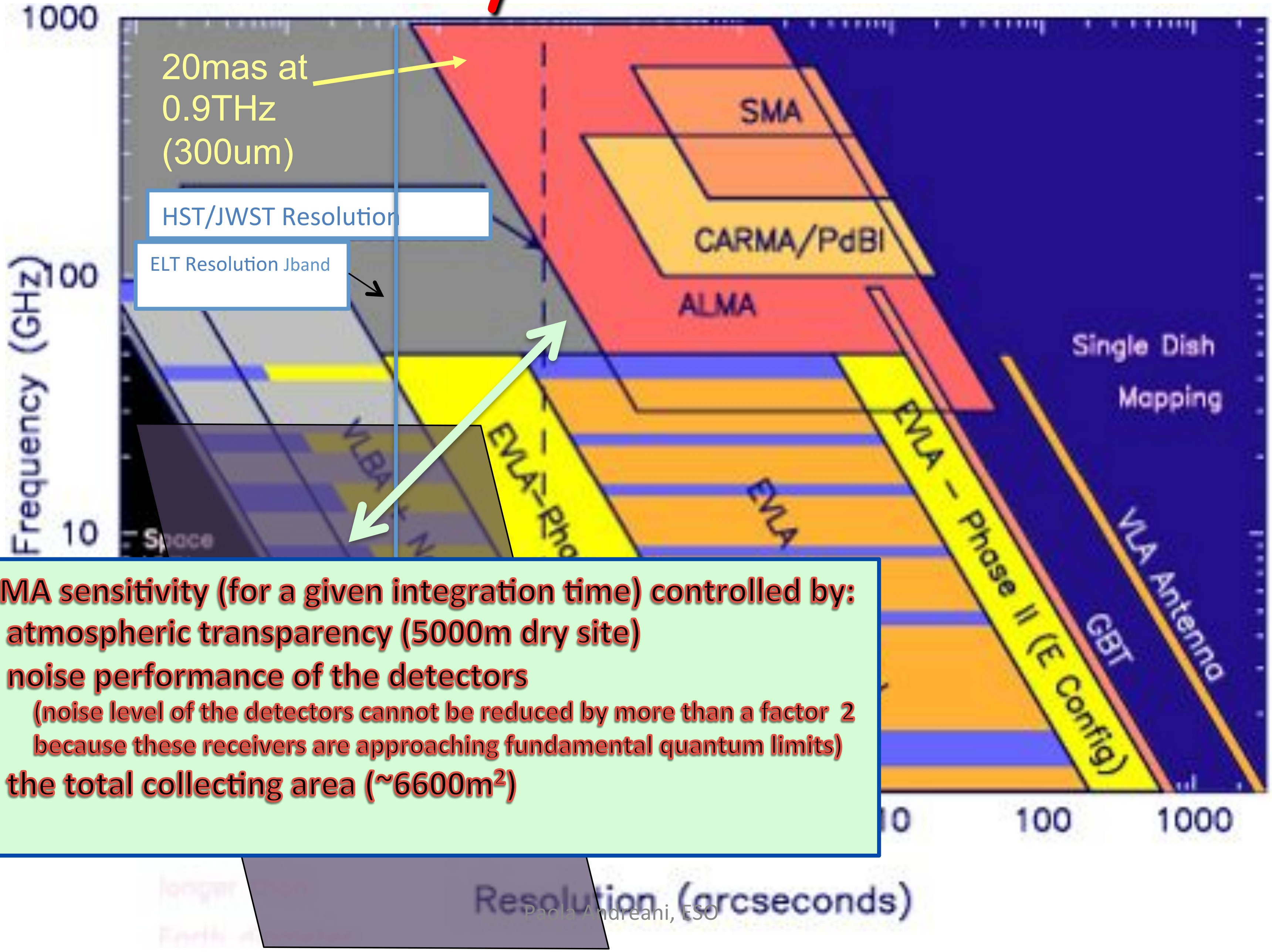
Sensitivity and Resolution



ALMA sensitivity (for a given integration time) controlled by:

- atmospheric transparency (5000m dry site)
- noise performance of the detectors
  (noise level of the detectors cannot be reduced by more than a factor 2 because these receivers are approaching fundamental quantum limits)
- the total collecting area (~6600m^2)

Highest Level Science Goals

Bilateral Agreement Annex B:

ALMA has three level-1 science requirements:

Ability

- To detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- To image the gas kinematics in a solar-mass protostellar/protoplanetary disc at a distance of 150 pc (~ distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling the study of the physical, chemical, and magnetic field structure of the disc and to detect the tidal gaps created by planets undergoing formation.
- To provide precise images at an angular resolution of 0.1” (accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness). This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

<u>These requirements drive the technical specifications of ALMA</u>

These science goals cannot be achieved by any other instrument

ALMA Science Requirements

- These require the instrument to have certain characteristics:
- High Fidelity Imaging
  - ✧ Best images with current mm arrays **0.5" angular resolution**
  - – 0.1" (comparable with that of optical telescopes)

This translates into requirements:

- ➢ high quality antennas,
- ➢ superior pointing precision.
- ➢ relative positions of the antennas determined accurately to compute the geometrical delay

•   ") in

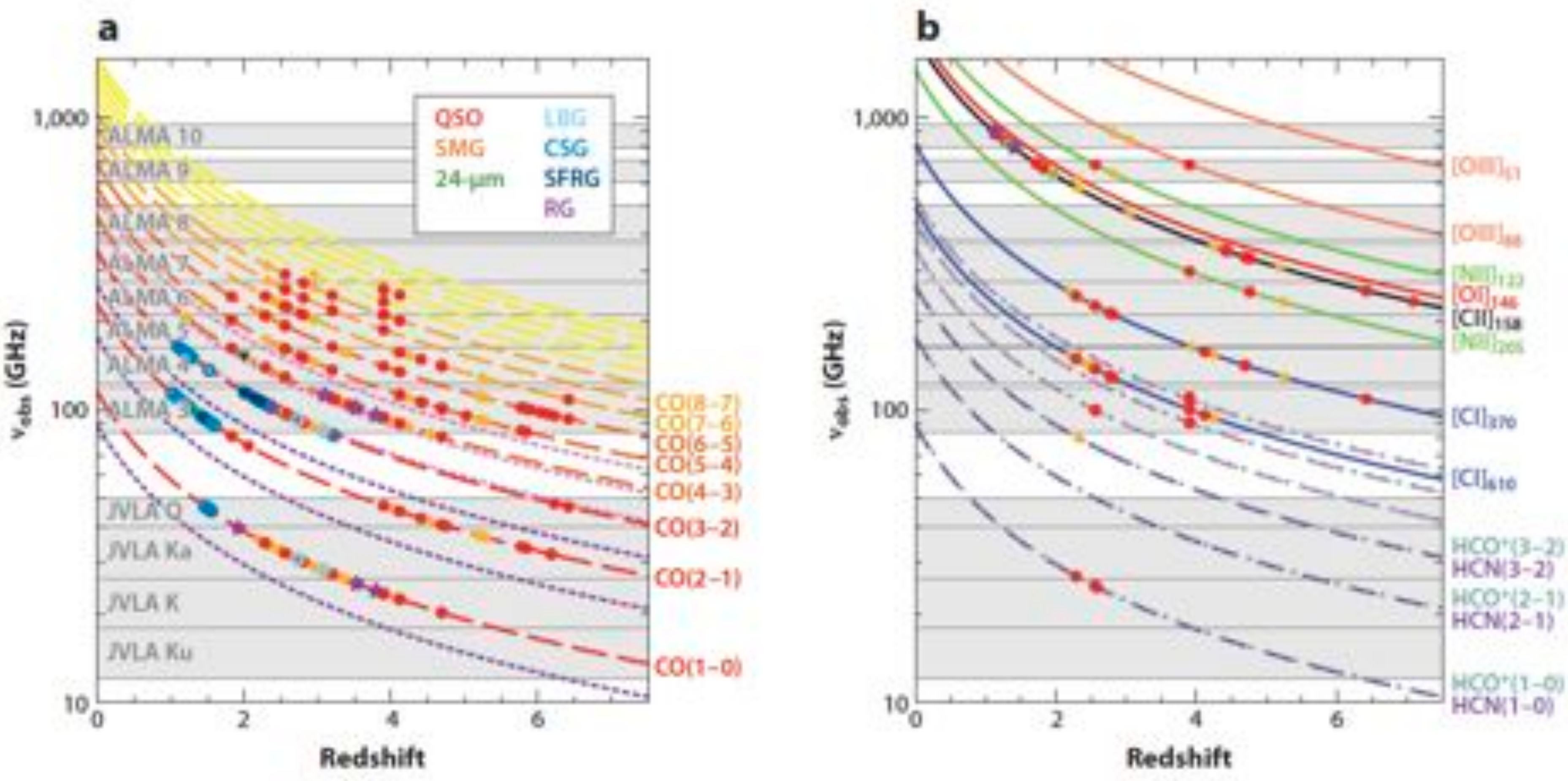
- == sufficient number of baselines (to cover adequately the uv plane (i.e., the time, frequency domain plane in which the data are sampled).

ALMA Science Requirements

- These require the instrument to have certain characteristics:
- **Routine sub-mJy Continuum / mK Spectral Sensitivity**
  - Kinematics study requires spectroscopy with velocity resolutions <0.05 km/s (~10 kHz at 3mm)
- **Wideband Frequency Coverage**
  - Unknown galaxy redshift → large instantaneous bandwidths of the receivers + rapid tuning
- **Correlator configuration**
  - to resolve thermal line widths → achieve resolution of 0.01 km/s at 100 GHz

ALMA Tuning for high-z lines

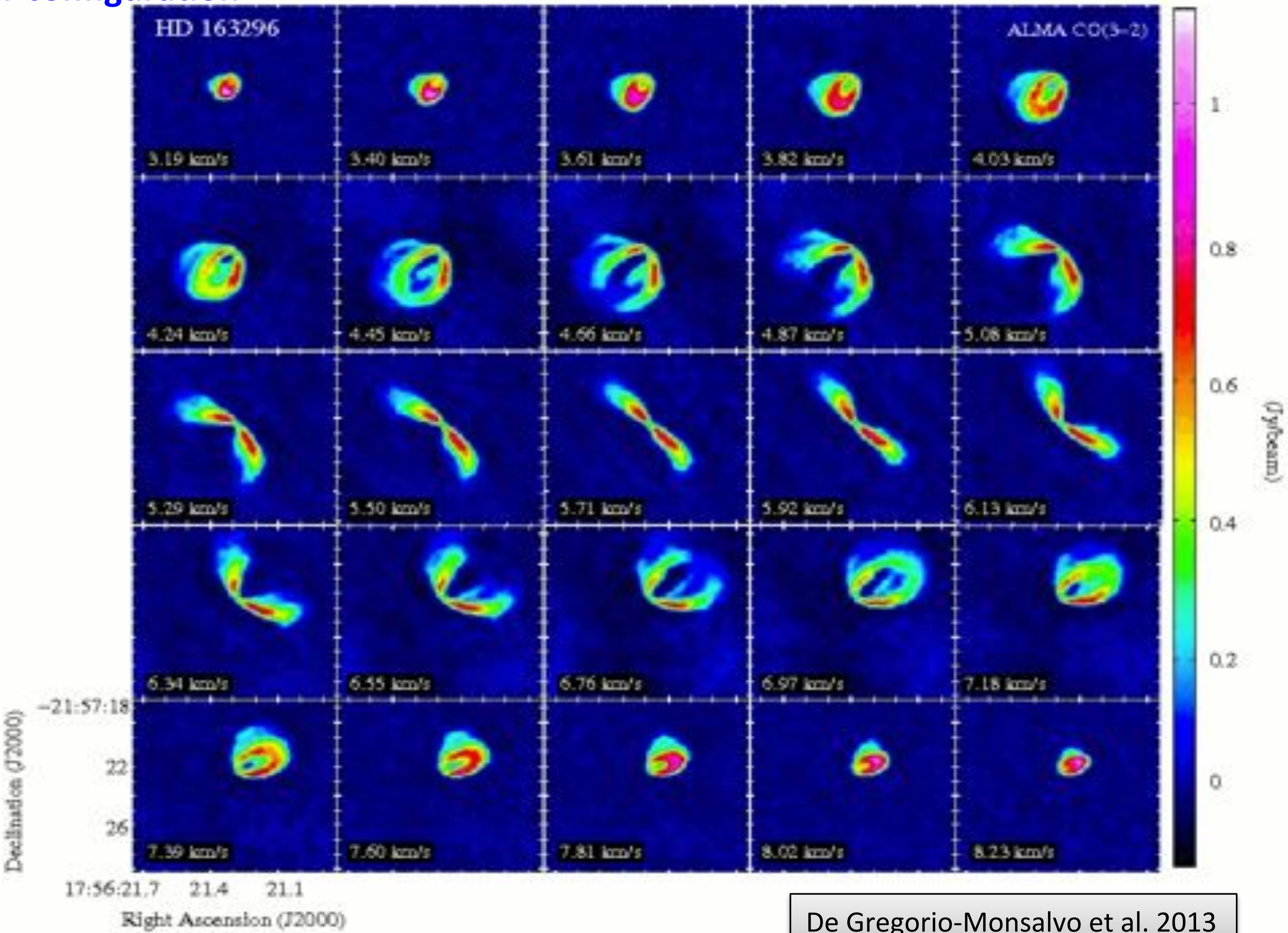
Wideband Frequency Coverage



Carilli and Walter 2013

Spectral Line Channel Maps of CO(3-2) circumstellar disc HD 163296

Correlator configuration



De Gregorio-Monsalvo et al. 2013

ALMA Science Requirements

The need of the Compact Array (ACA, Morita Array) and single dish

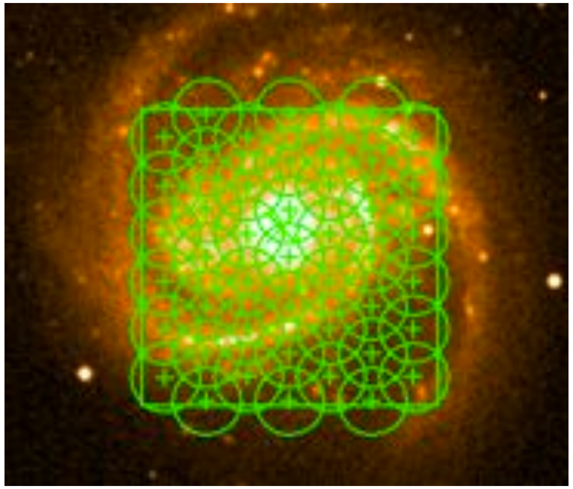
- ➢ Observations of sources > ~2/3 PB: ability to observe in total power mode (single dish)
  - ➢ Any array fails to measure interferometrically the smallest spatial frequencies < 2/3 primary beam (PB)
  - ➢ Filtering shortspacings information (the most extended structures) can introduce major artifacts in the resulting images.
- Submillimeter Receiver System + dry site
- Full Polarization Capability (dust and lines)
  - structure of the magnetic field in the larger protostellar regions and in the small protoplanetary disks
  - Hydrodynamics and magnetodynamics of star formation:
- System Flexibility (hardware/software)

ALMA Compact Array

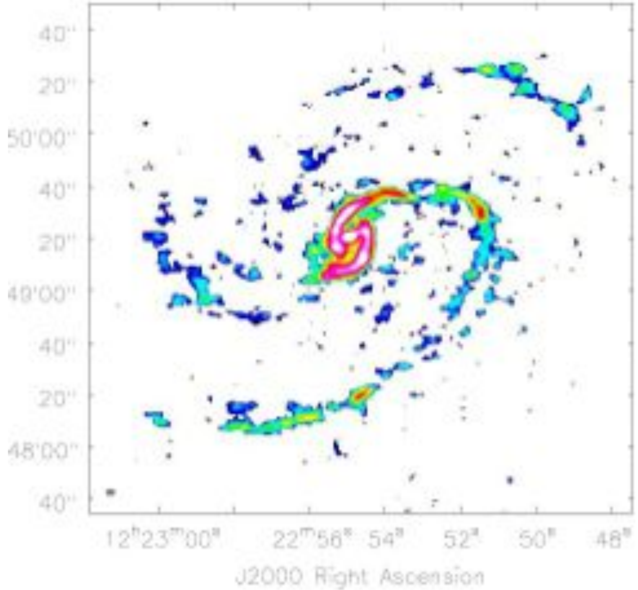
Atacama Compact Array – fills in the short spacings. 11 (out of 12) 7m dishes in place. Plus 3 (out of 4) of the 12m dishes for total power.

M100 – 47 point mosaic

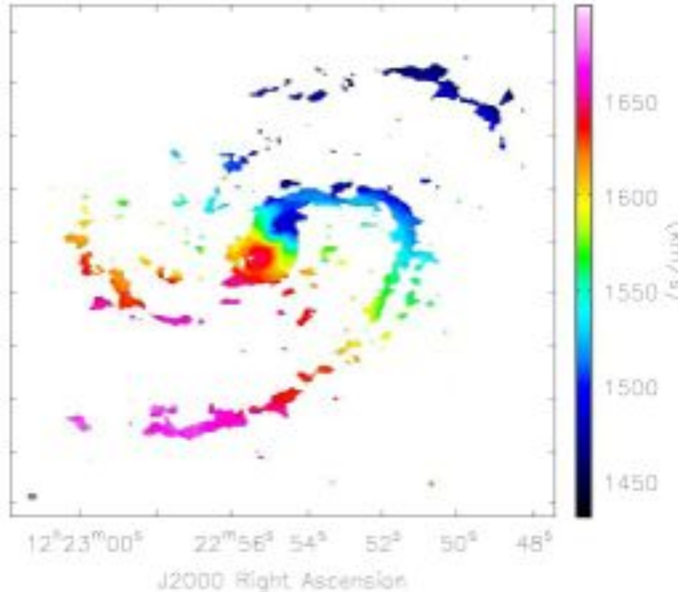
Band 3 (115 GHz) for 6 hours 13 antennae Sept 2011



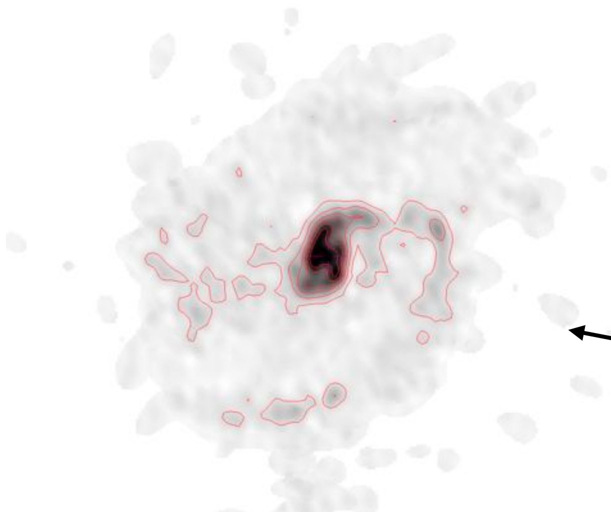
47 pt mosaic



CO(1-0) integrated intensity

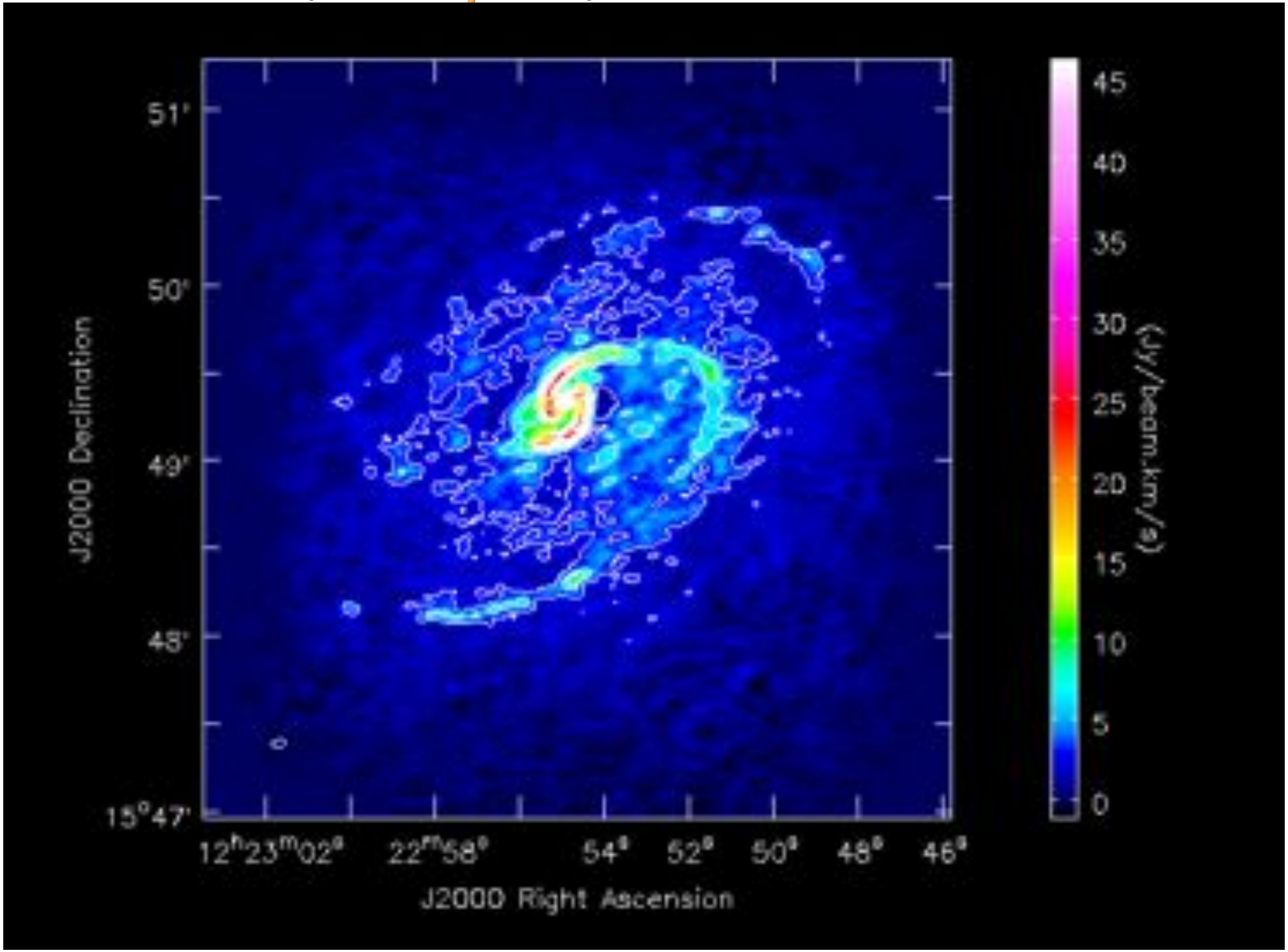


CO(1-0) velocity field

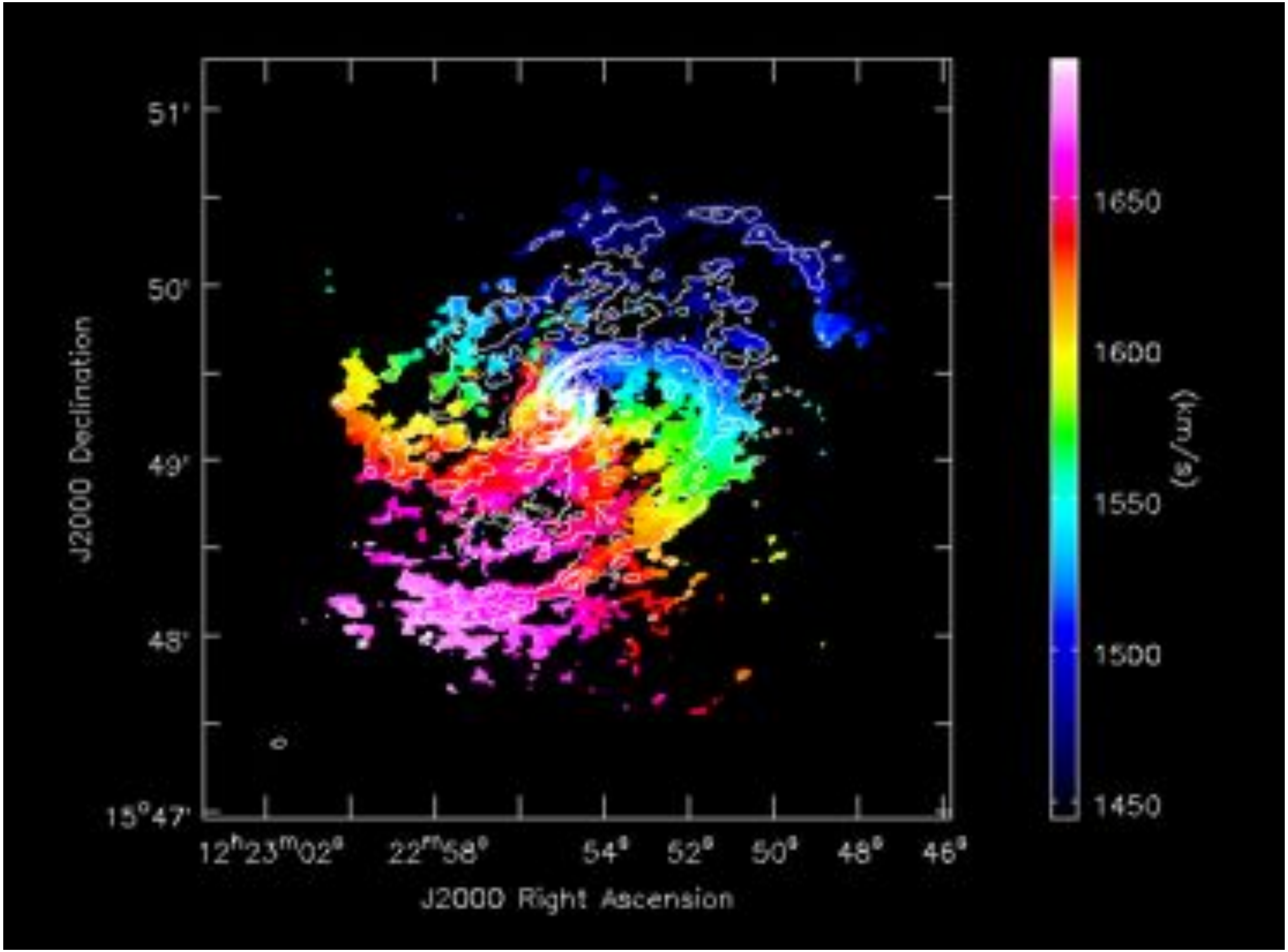


CO (1-0) integrated intensity observed with BIMA(Helfer et al, 2003) (note slightly different scale).

Combining 12m and ACA data



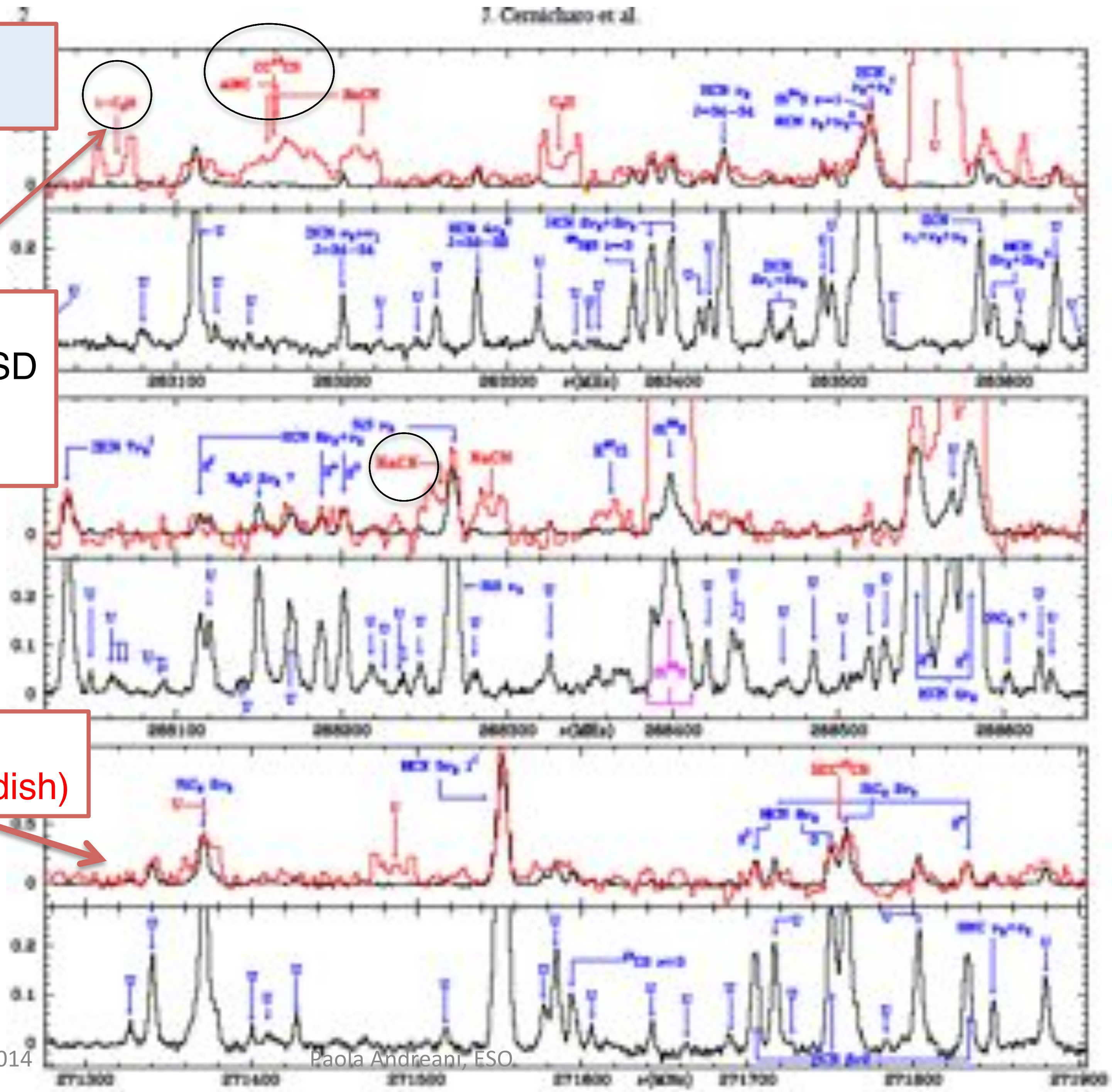
Velocity field is much more complete



ALMA spectrum of IRC+10216

Red label:
lines detected with SD and filtered by the interferometer

Comparison with 30m IRAM (single dish)



Specifications Demand Transformational Performance

- With these specifications, ALMA improves
  - Existing sensitivity, by about ***two orders of magnitude***
    - ***Best accessible site*** on Earth
    - ***High***
    - ***Eno*** m^2)
  - Resoluti
    - Not km baselines or longer may be accommodated.
  - Wavelength Coverage, by a factor of two or more
    - Take advantage of the site by covering all atmospheric windows with >50% transmission above 30 GHz
  - Bandwidth, by a factor of a few
    - Correlator processes 16 GHz or 8 GHz times two polarizations

•Sensitivity: 100x
•Spatial Resolution: up to 100x
•Wavelength Coverage: ~2x
•Bandwidth: ~2x

Scientific discovery parameter space is greatly expanded!

ALMA antennae key specifications

fast switching of the antenna between target object and nearby calibrator both spatially and in frequency

monitoring of a water vapor line along a direction near to the observation by a water vapor radiometer (WVR) (observing the 183GHz atmospheric water line.)

Detect calibration sources (i.e. quasars) in a time short enough to minimize the atmospheric phase flutcuations

→ needed correction as small as possible

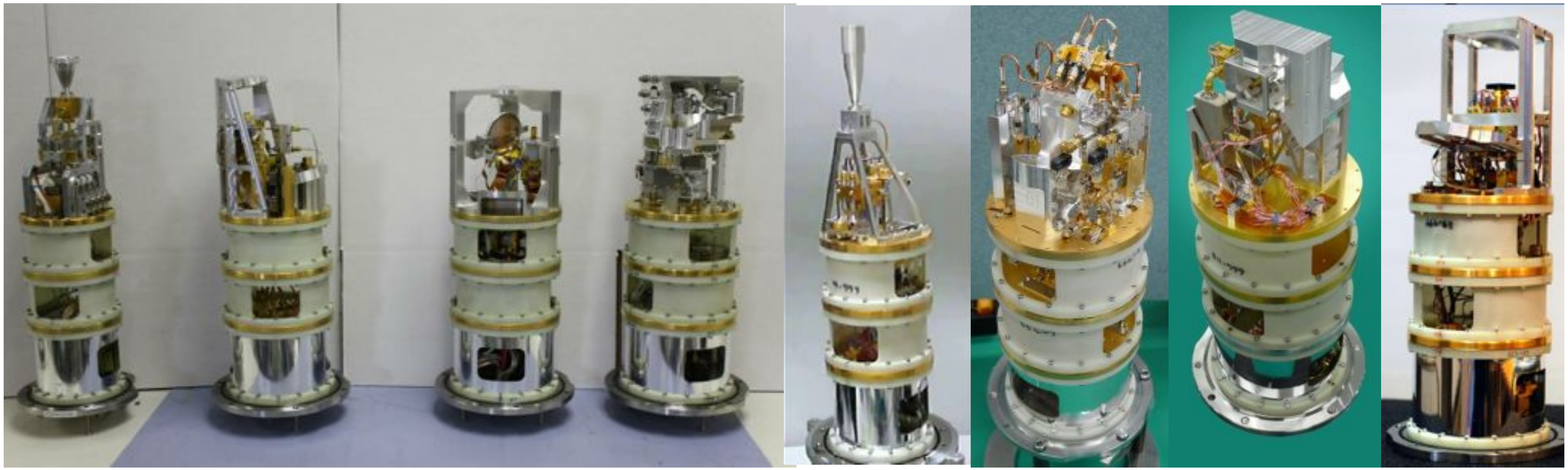
Antenna integration at the OSF and Transporter

ALMA frequency bands

ALMA Band	Frequency Range (GHz)	Receiver Noise (K) over 80% of the RF band	Temperature (K) at any RF Frequency	To be produced by	Receiver Technology
1	31 - 45	17	26	tbd	HEMT
2	67 - 90	30	47	tbd	HEMT
3	84 - 116	37	60	HIA	SIS
4	125 - 163	51	82	NAOJ	SIS
5*	162 - 211	65	105	OSO	SIS
6	211 - 275	83	136	NRAO	SIS
7	275 - 373	147	219	IRAM	SIS
8	385 - 500	196	292	NAOJ	SIS
9	602 - 720	175	261	NOVA	SIS
10	787 - 950	230	344	NAOJ	SIS

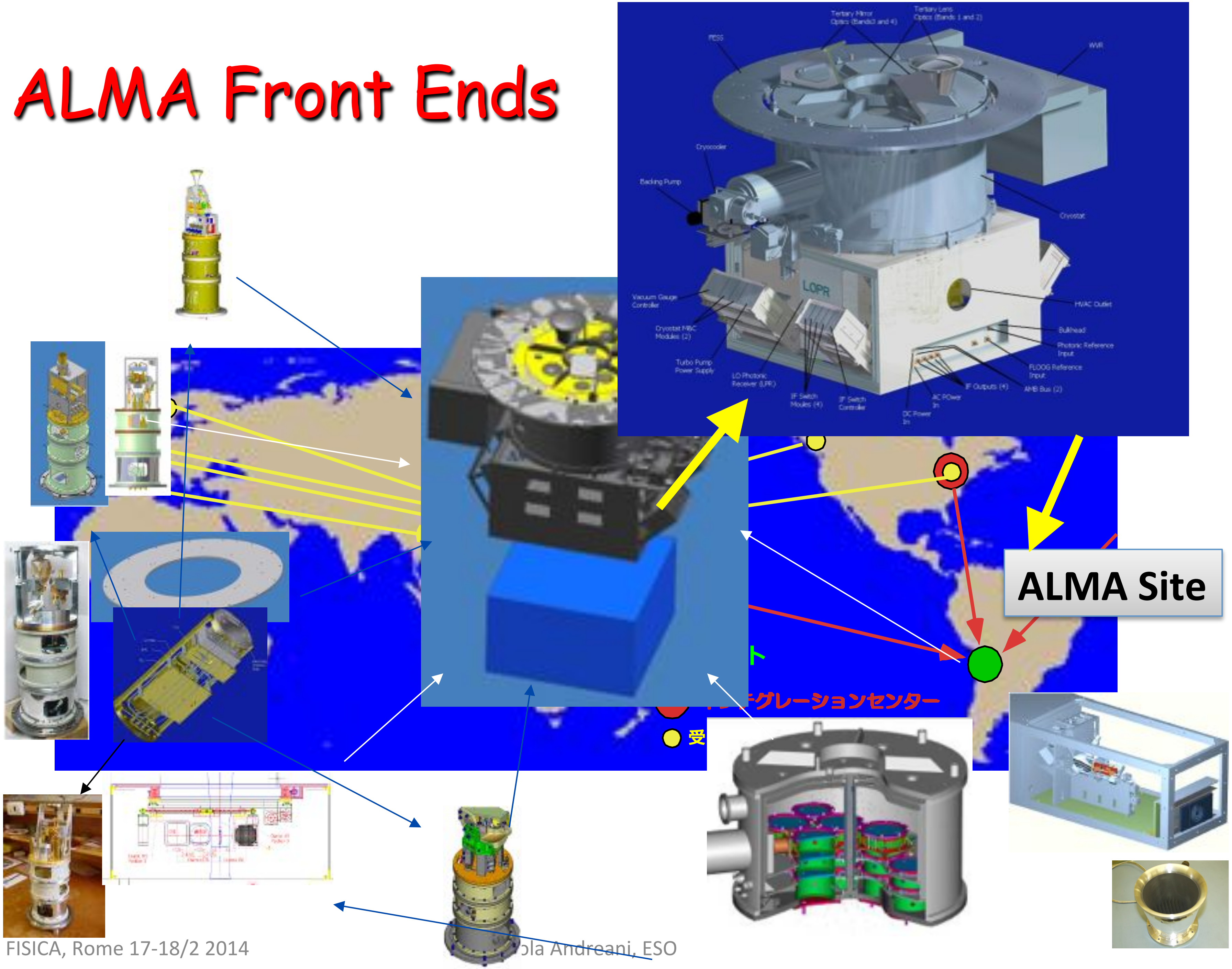
Receiver Cartridge

The ALMA receivers are built in different institutes/countries across the ALMA partnership



Band 3	Band 6	Band 7	Band 9	Band 4	Band 8	Band 10	Band 5
HIA	NRAO	IRAM	NOVA	NAOJ	NAOJ	NAOJ	GARD+

ALMA Front Ends



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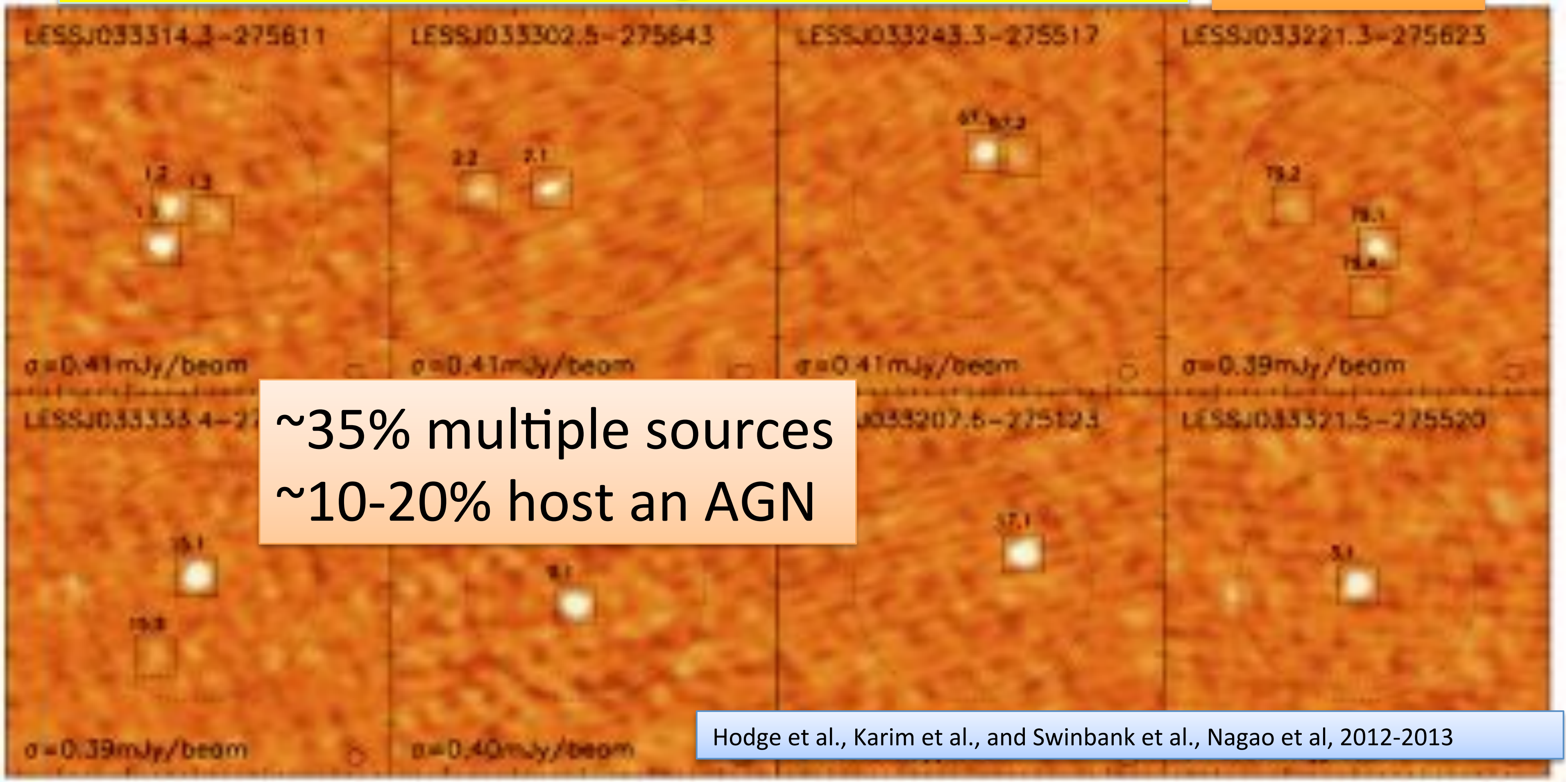
ALMA Science Verification and Early Science

- ***ALMA Early Science*** begins the transformation
  - Sensitivity: ~10% full ALMA
  - Resolution: up to ~0.4" (0.1" goal)
  - Wavelength Coverage: 3-4 of final 8 bands (7 goal)
  - Bandwidth: ~2x improvement
  - Beginning the Discovery Space Expansion

122 Submm galaxies

1.5" resolution



~35% multiple sources

~10-20% host an AGN

Hodge et al., Karim et al., and Swinbank et al., Nagao et al, 2012-2013

Bright LESS (LABOCA Extended Chandra Deep Field South Submillimeter Survey) in Band 7

the brightest sources in the original LESS sample comprise emission from multiple fainter SMGs (35%).

Serendipitously detected bright emission lines in two SMG spectra (likely [CII] 158 micron emission at z=4.42 and z=4.44).

***In Band 6 a z=4.8 LESS SMG and detected [NII] 205 micron** emission line and assessed the metallicity of the SMG from the [NII] 205 micron and [CII] 158 micron flux ratio.*

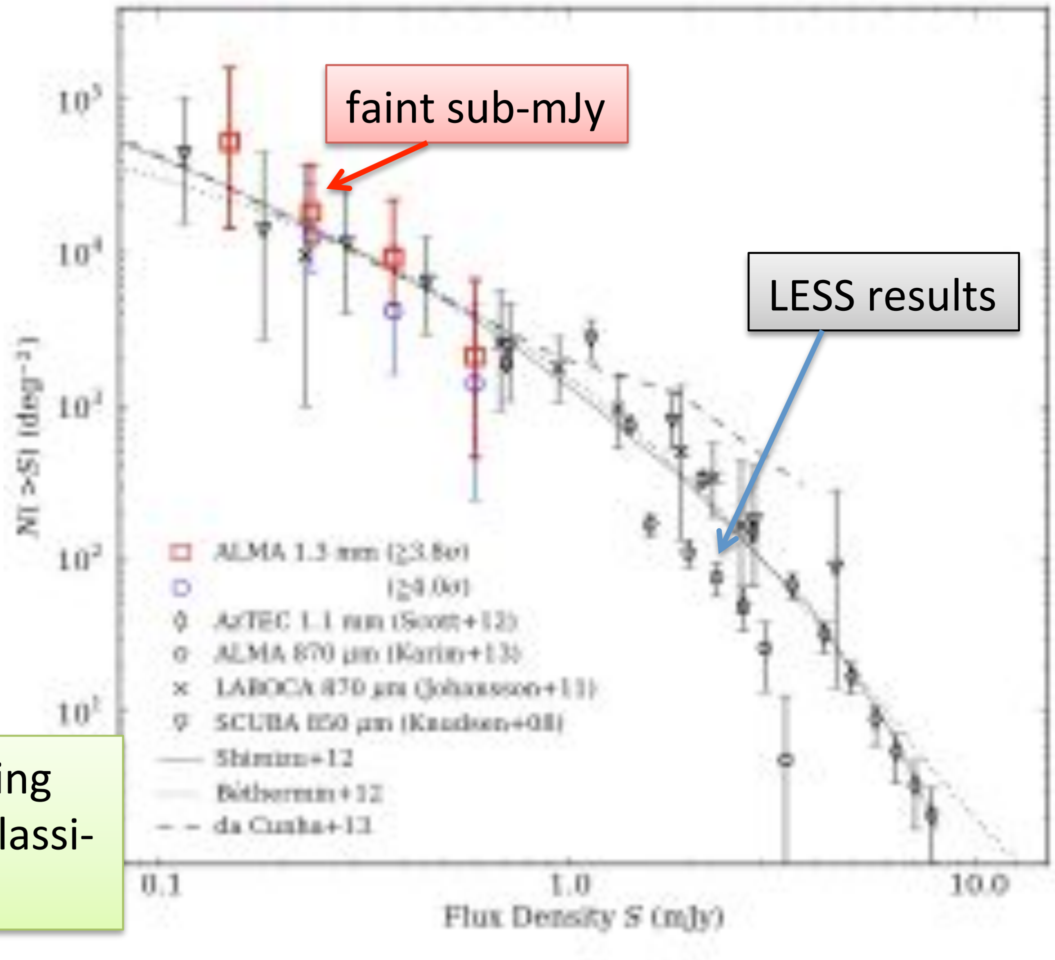
The metallicity in the SMG is consistent with solar, implying that the chemical evolution has progressed very rapidly in high-z SMGs

ALMA galaxy counts

Hatsukade et al. serendipitously detected 15 faint "sub-mJy sources" in the Band 6 data targeted for the 20 star-forming galaxies at z~1.4.

Source number counts at the faintest flux range among surveys at mm wavelengths

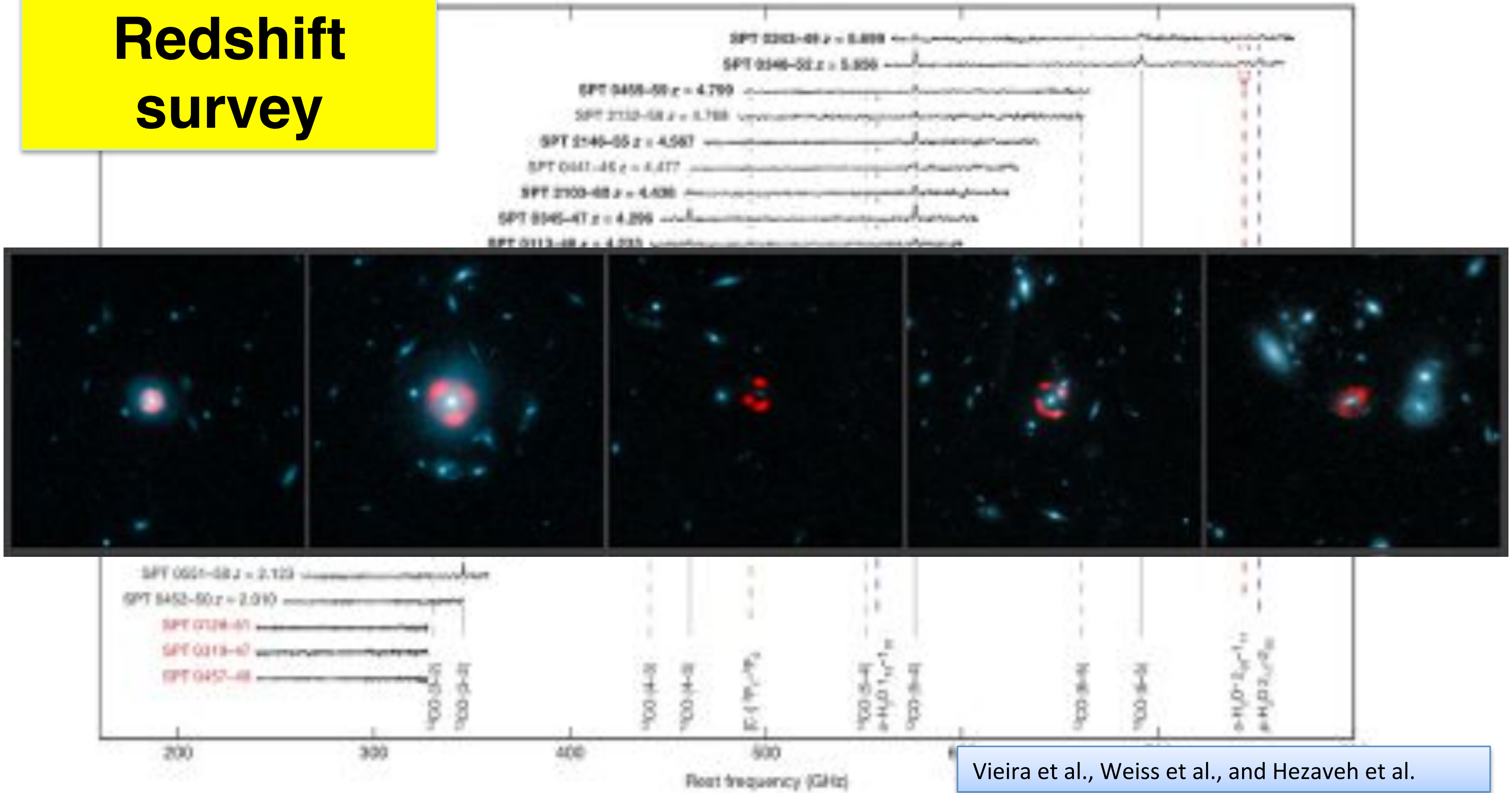
~80% of the extragalactic background light at mm /submm wavelengths come from such fainter galaxies.



sub-mJy sources are moderately star-forming galaxies with SFR <100 $M_{\odot}$/yr rather than classical SMGs with intense star formation.

ALMA Band 6 observations constrain the faint mm source number counts Hatsukade et al. 2013, ApJ, 769, 27

Redshift survey



Vieira et al., Weiss et al., and Hezaveh et al.

ALMA Bands 3 and 7: strongly gravitationally lensed sources from the South Pole Telescope (SPT) survey: sources are composed of multiple components, indicative of gravitational lensing.

Gravitational lensing model: sources amplified by factor 4 - 22, → lensed sources are ultra luminous starburst galaxies at high-z.

Blind redshift search in band 3: *line detections in 23 sources, with 44 line features in the spectra, providing secure redshifts for ~70% of the sample, with a mean redshift of z=3.5.*

A significant portion of SMGs are at high-z (z>4)

These new findings will impact our current understanding of the formation of massive galaxies at high-z.

Outflow in the starburst galaxy NGC 253

CO emitting clouds

Imaging a galaxy-scale molecular outflow

Image of an expanding molecular shells in the starburst nucleus (50-parsec resolution)

The extraplanar molecular gas:

closely tracks the Hα filaments

connects to expanding molecular shells located in the starburst region

Molecular outflow rate

Expanding molecular shells

→ mass-outflow rate / star-formation rate ~1–3

→ starburst-driven wind limits the star-formation activity and the final stellar content.

→ **The growth of large galaxies may be limited by strong wind-driven outflows**

→ **Star formation activity in the galaxy regulated by the starburst-driven wind and will therefore determine the final stellar content**

The sensitivity of the ALMA data is an order of magnitude better than previous ^{12}CO image of NGC253.

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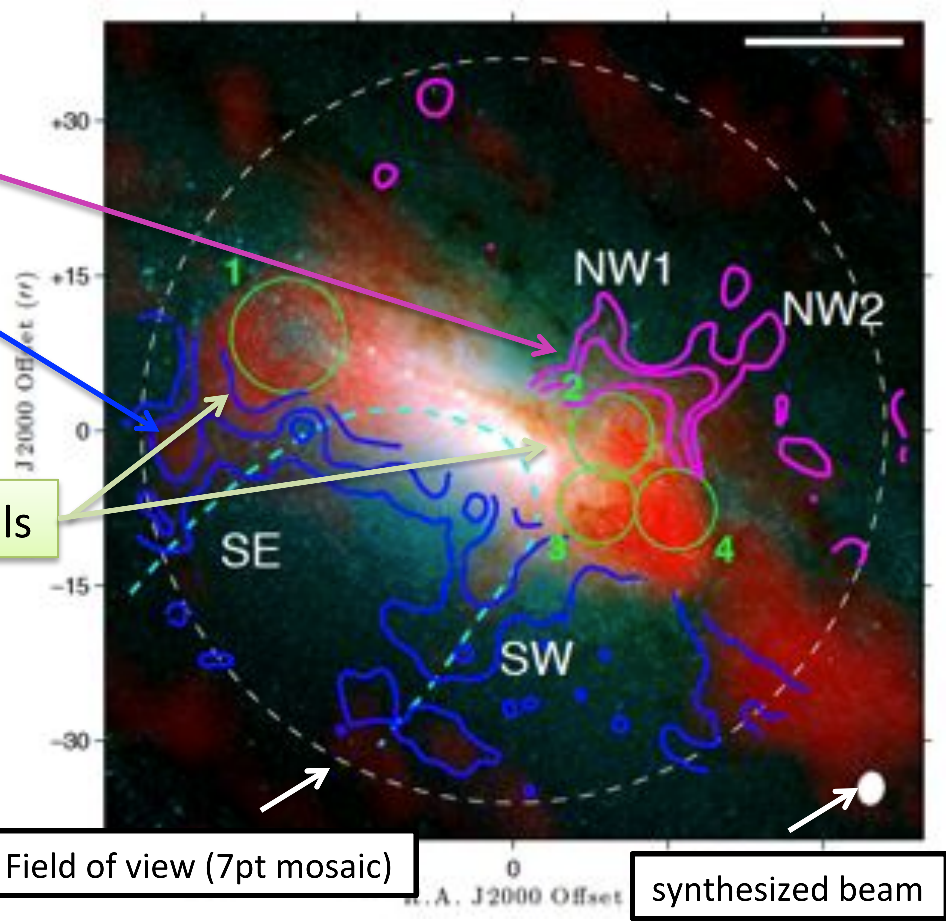
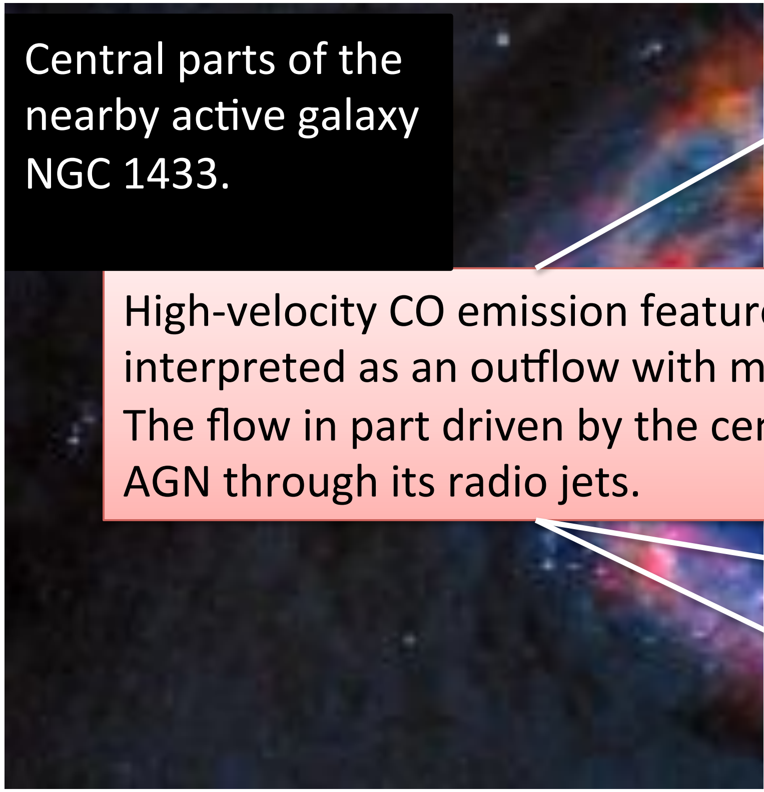
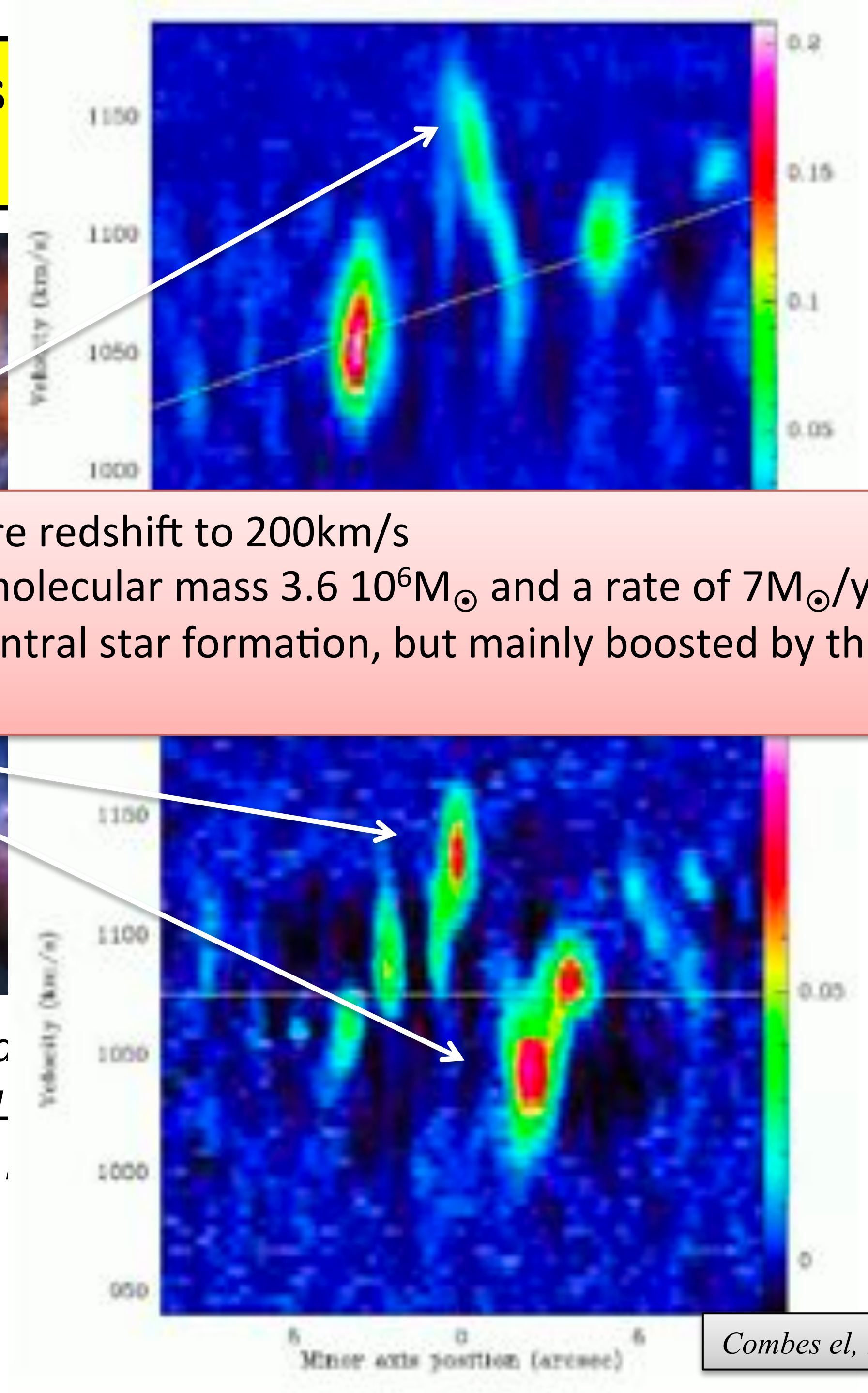


Blue and magenta contours are CO(1-0) emission at +/- 100 km/s around the nucleus of NGC 253 (Bolatto ea. 2013)

A surprising molecular gas s … N?
And an outflow: an AGN jet



Central parts of the nearby active galaxy NGC 1433.



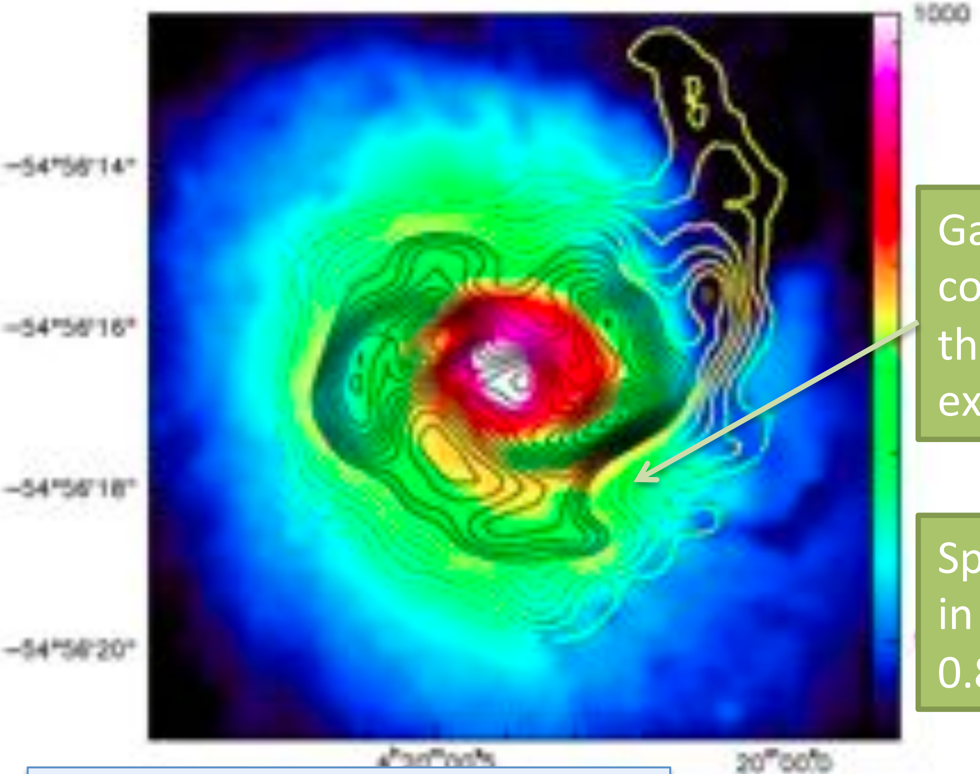
High-velocity CO emission feature redshift to 200km/s
interpreted as an outflow with molecular mass 3.6 $10^6 M_\odot$ and a rate of $7 M_\odot$/yr.
The flow in part driven by the central star formation, but mainly boosted by the AGN through its radio jets.

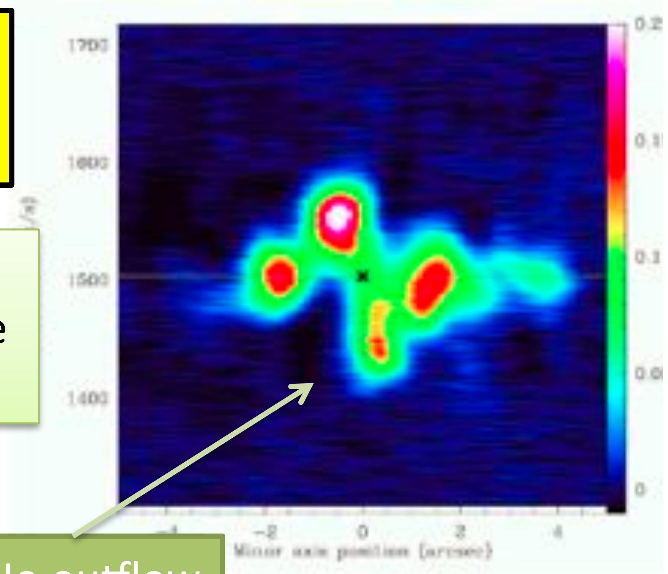
Central dust lane (dim blue backgrounc
Coloured structures near the centre: AL … ected outflow.
No HCO+ HCC → no high density gas

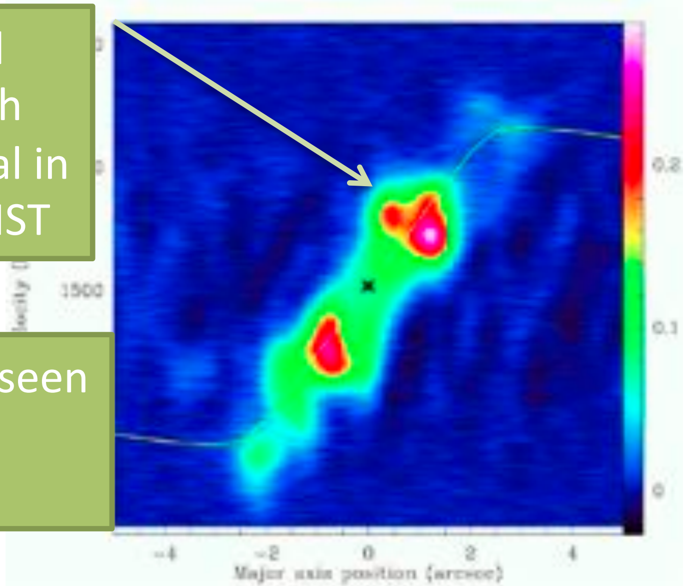
Combes el, 2013

Nuclear fueling and feedback in the Seyfert 1 NGC 1566 CO(3-2)

Dynamics inside central 1 kpc: molecular trailing spiral structure of ~ 100pc size fueling the nucleus driving the gas inwards inside the Lindblad resonance of the nuclear bar







No outflow

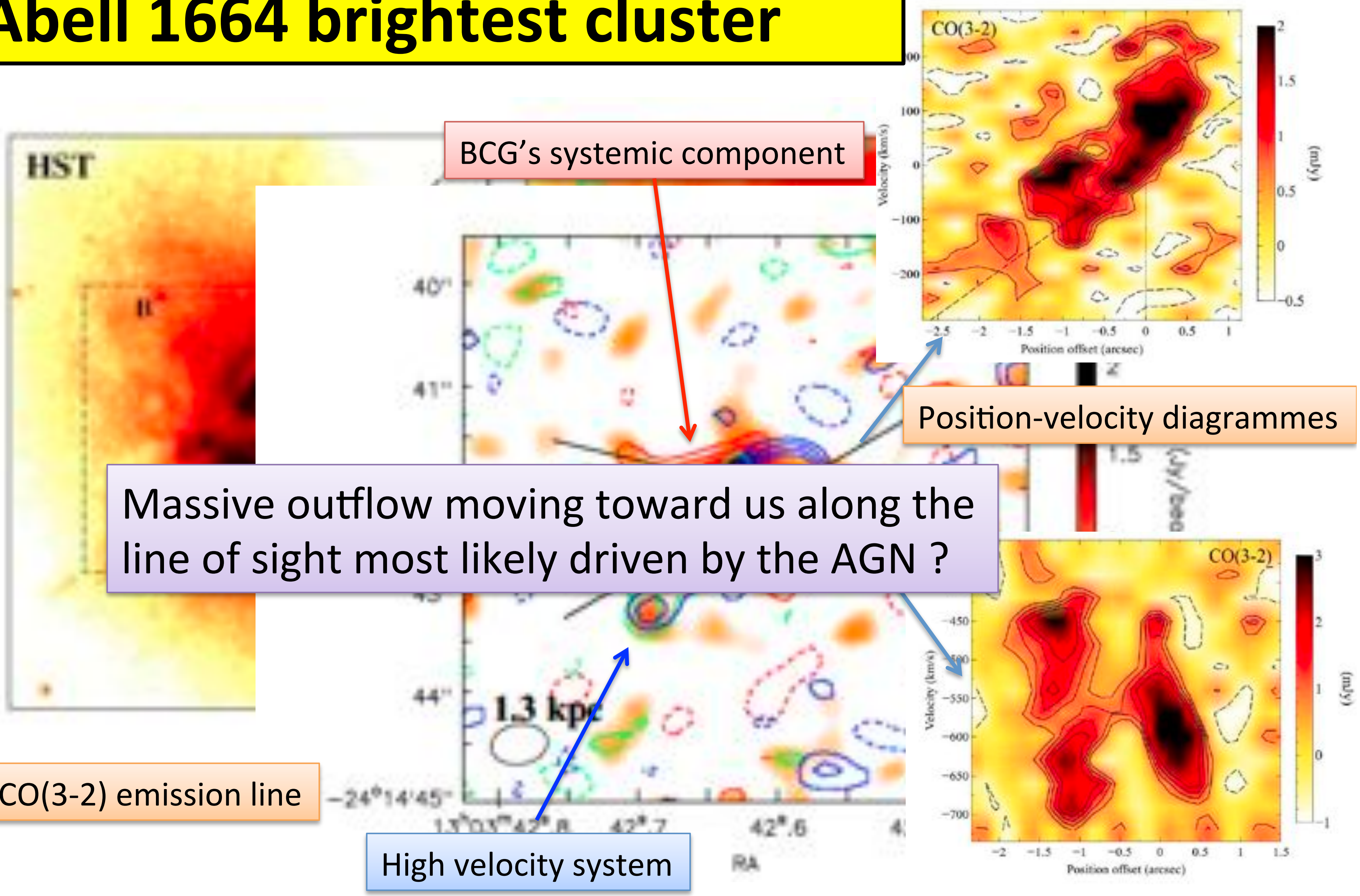
Gaseous spiral correlated with the dusty spiral in extinction in HST

Spiral feature seen in emission at 0.87mm

ALMA FOV:=0.9kpc resol=25pc

Combes el, 2014

Abell 1664 brightest cluster



BCG's systemic component

Position-velocity diagrammes

Massive outflow moving toward us along the line of sight most likely driven by the AGN ?

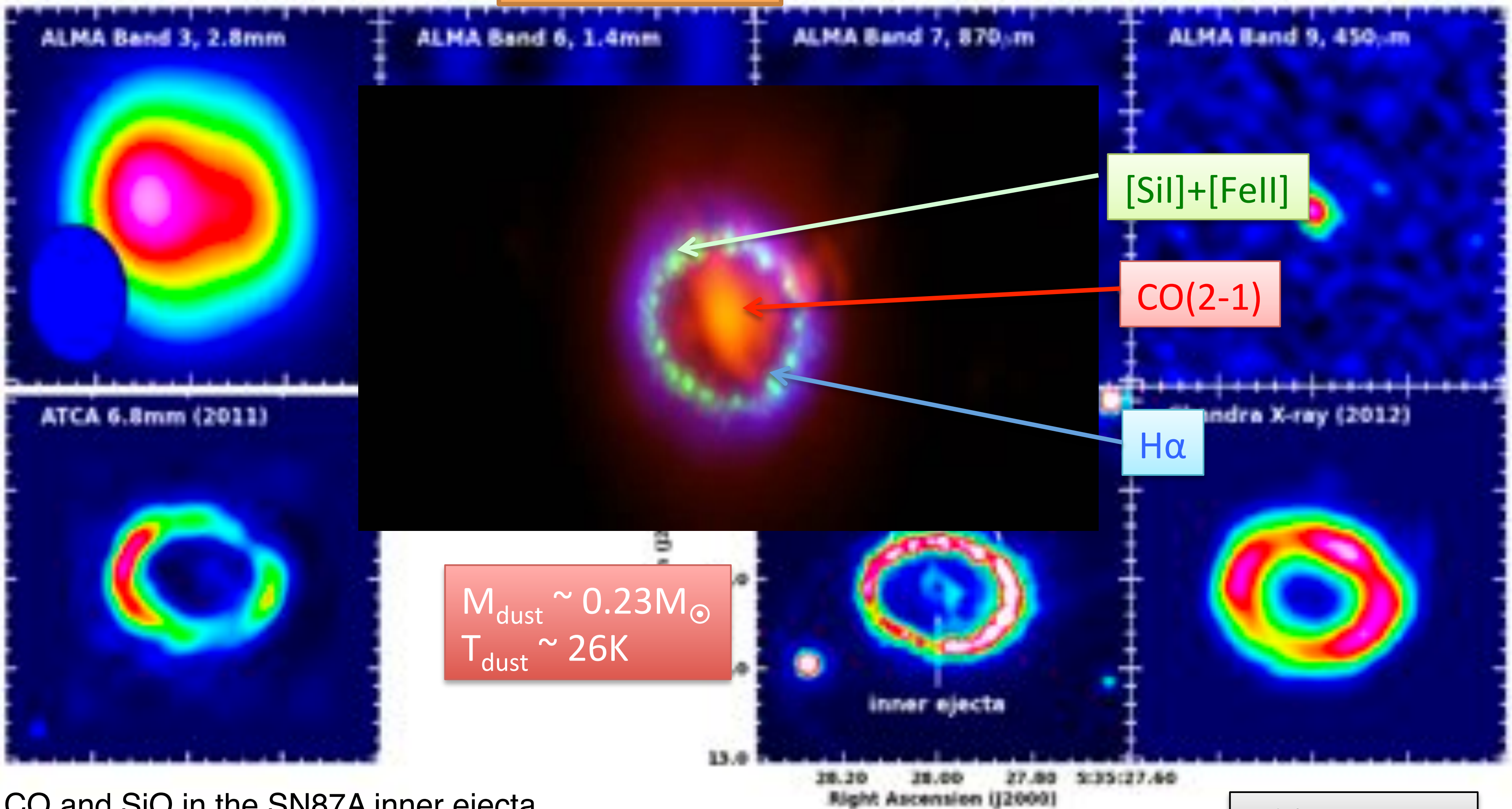
CO(3-2) emission line

High velocity system

Russell + 2013

ALMA Opens a Powerful New Window into Supernova Ejecta

SN 1987A



Indebetouw + 2014

CO and SiO in the SN87A inner ejecta.

Abundant Si isotopes, ^{28}Si and ^{29}Si imaged over partial velocity extents.

C/O clumps contain at least 0. 01 $M_\odot$ of ^{12}CO (x10 measured in the first few years after the explosion)

^{12}CO and dust have continued to form over the past 25 years.

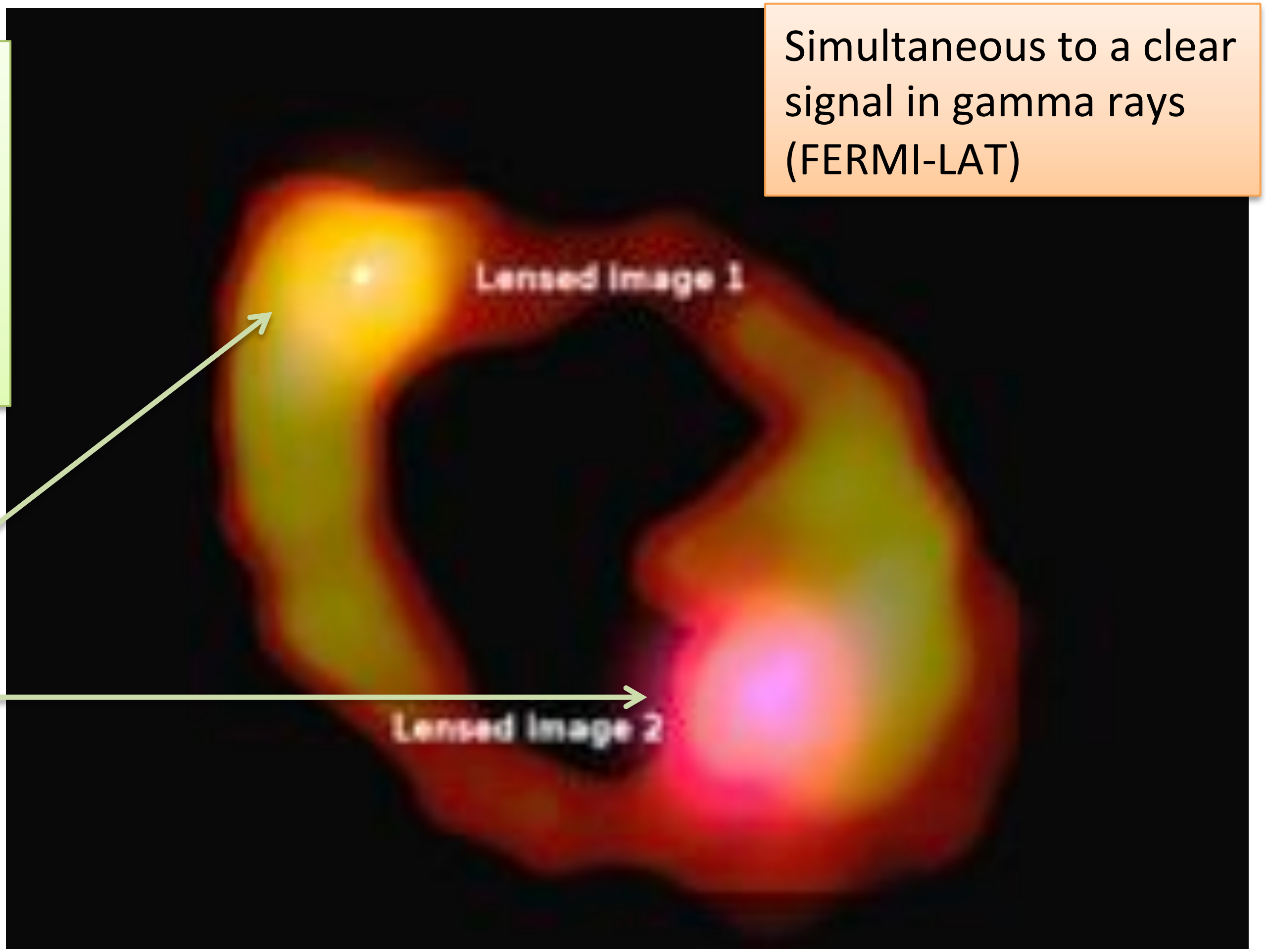
ALMA views the full velocity range of emission, unobscured by dust.

Gravitational lenses of PKS 1830-211

Chromatic behaviour not due to micro/milli-lensing (too tight variability timescale)

Time variation of the flux (Band 3, 6 and 7) of the 2 images due to fresh new matter entering into the jet base of the black hole **(core-shift effect)**

Simultaneous to a clear signal in gamma rays (FERMI-LAT)



accretion of material into the SMBH triggers the injection of plasma into the jet

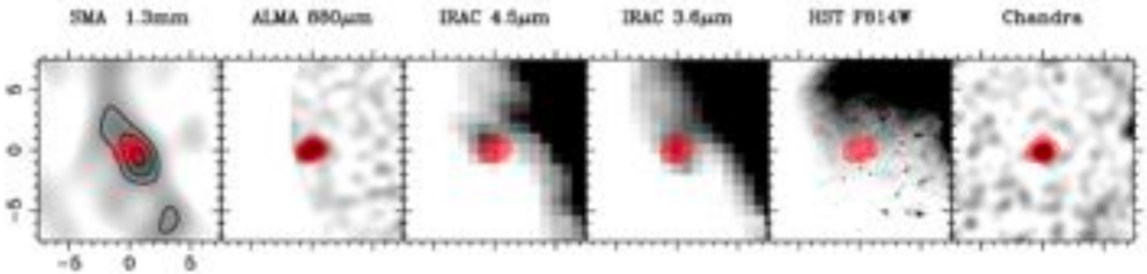
Ivan Martí-Vidal et al. 2013

Serendipitous detection of a dusty starburst galaxy ALMA J0107

coincides with a hard X-ray source, likely a buried AGN

Prospect for blind searches:
a complete census of background high-z CO emitters in Band 3 and [CII] emitters in Band 6/7.

~1000 pointings in Band 3 additional detection of a >1 Jy km s−1 CO source at redshift z > 1
A CO emitter at this flux level routinely detected at 100 GHz in a few minutes with the full ALMA.



we expect 0. 011 sources with > 1 Jy km/s per ALMA FOV (2800 arcsec2) and bandwidth (7.5 GHz)

Tamura el, 2014

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  - Serendipity discoveries
- Full capabilities

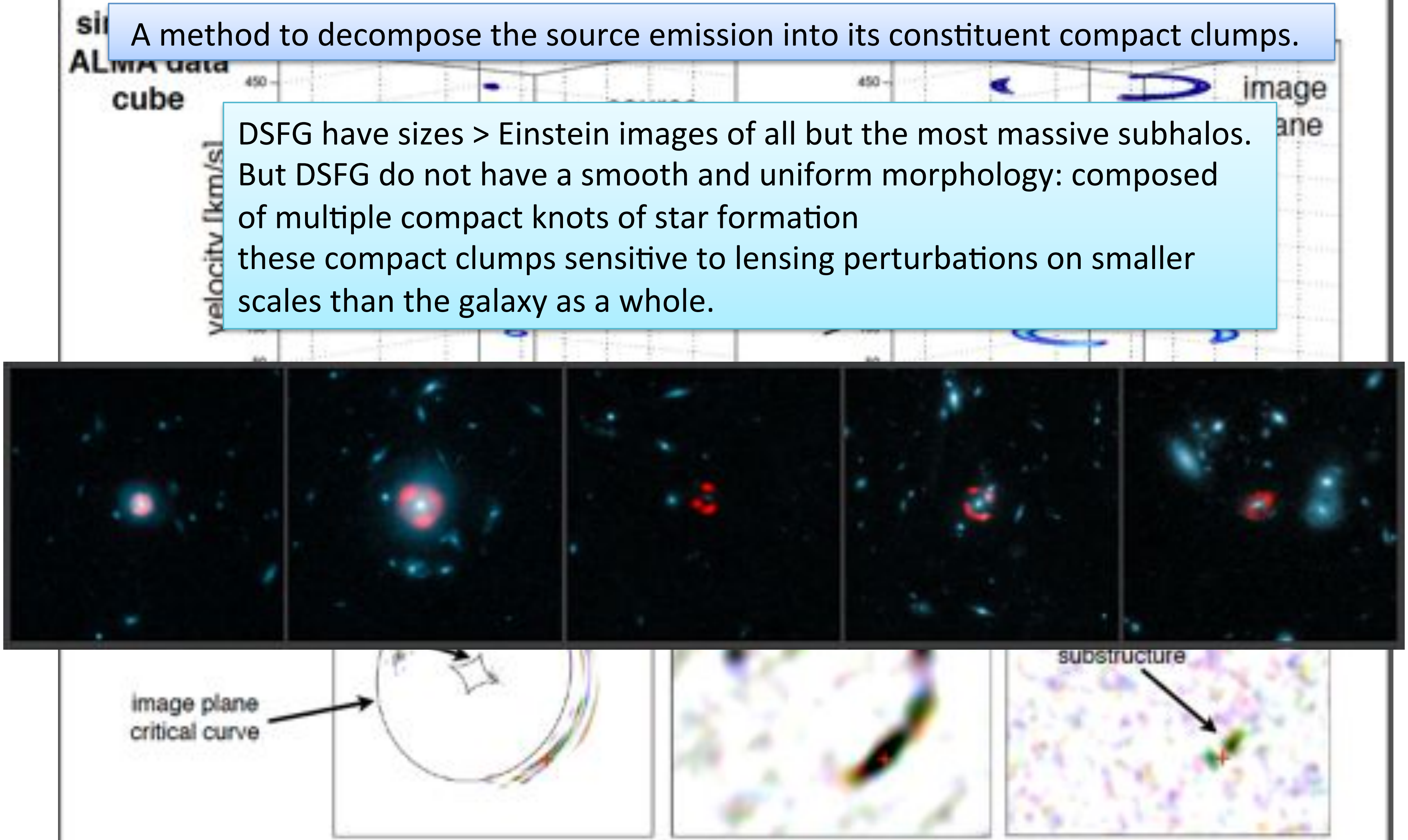
4x sensitivity
16x resolving power

Full capabilities

Detecting dark matter substructure at z~1

A method to decompose the source emission into its constituent compact clumps.

DSFG have sizes > Einstein images of all but the most massive subhalos.
But DSFG do not have a smooth and uniform morphology: composed of multiple compact knots of star formation
these compact clumps sensitive to lensing perturbations on smaller scales than the galaxy as a whole.



Hezaveh et al., 2013

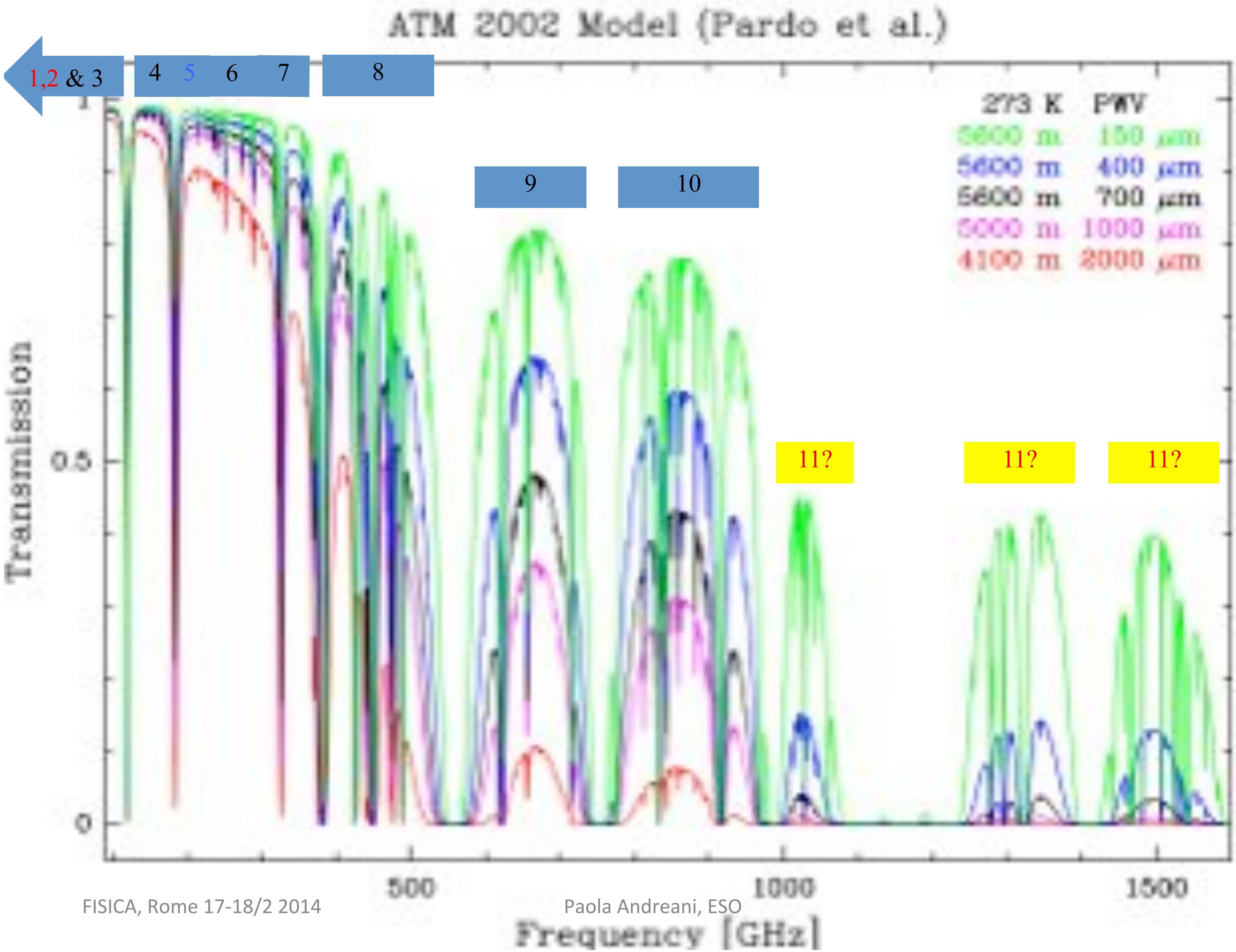
ALMA Future Development

ALMA beyond ALMA

- ALMA will allow transformational science thanks to the sensitivity, angular resolution, spectral coverage and image fidelity, but...

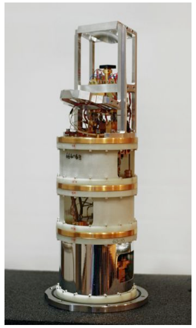
- The baseline ALMA project will only achieve a fraction of the full potential of the site and instrument

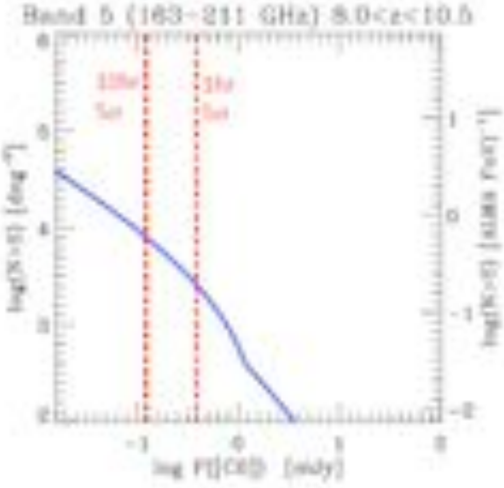
- Incomplete Receiver Complement
- Limited Wide Field Capabilities
- Limited Correlator and Data Rate Capabilities
- Extended baselines (30-50km), VLBI (200-10000km)
- Advanced Calibration, Software, Science Tools....

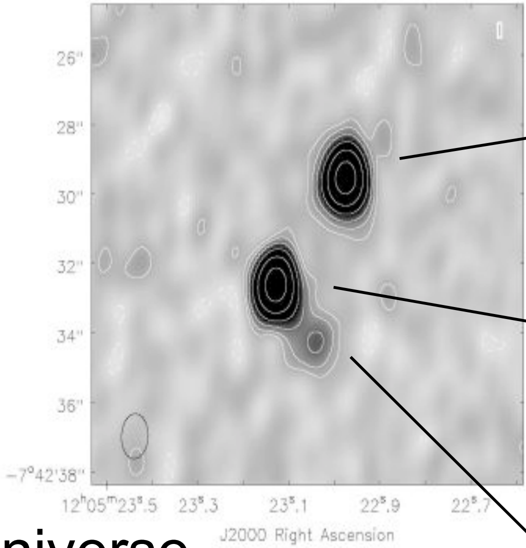

ATM 2002 Model (Pardo et al.)
1,2 & 3
4 5 6 7
8
9
10
11?
11?
11?
273 K PWV
5600 m 150 µm
5600 m 400 µm
5600 m 700 µm
5000 m 1000 µm
4100 m 2000 µm
Transmission
0.5
0
500
1000
1500
Frequency [GHz]

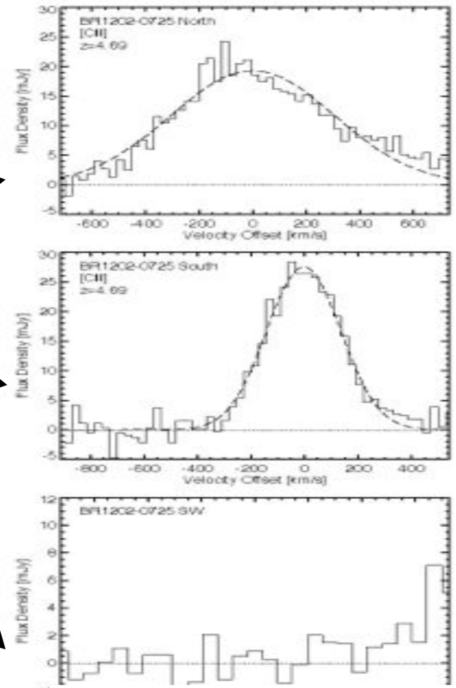
Band 5 Science

- [CII] in z~(8-10) and high-ex CO at high-z



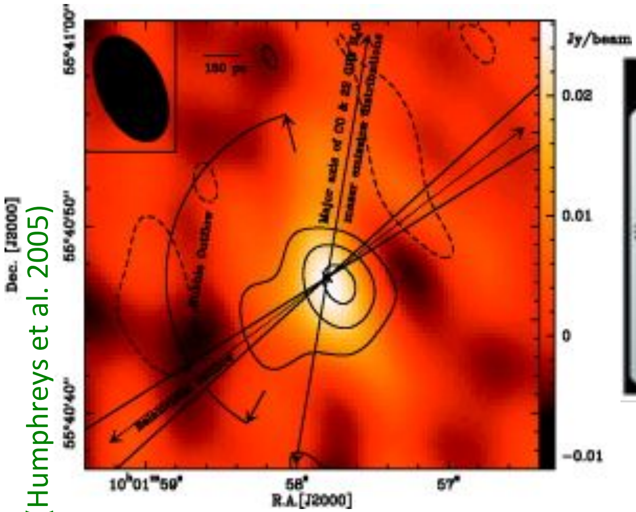




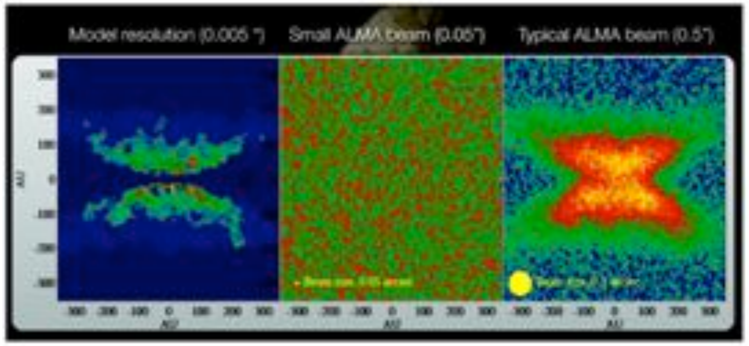


(Wagg et al. 2012)

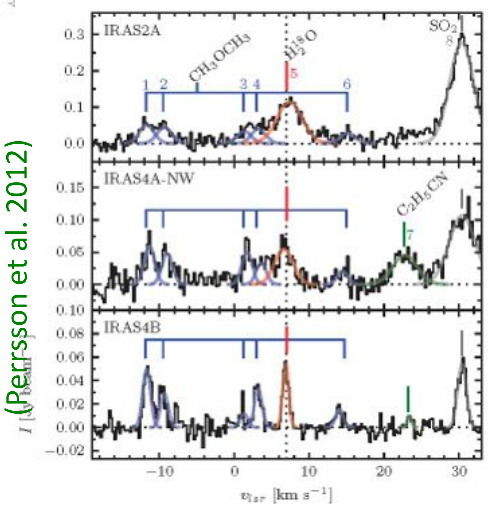
- Water in the local Universe



(Humphreys et al. 2005)

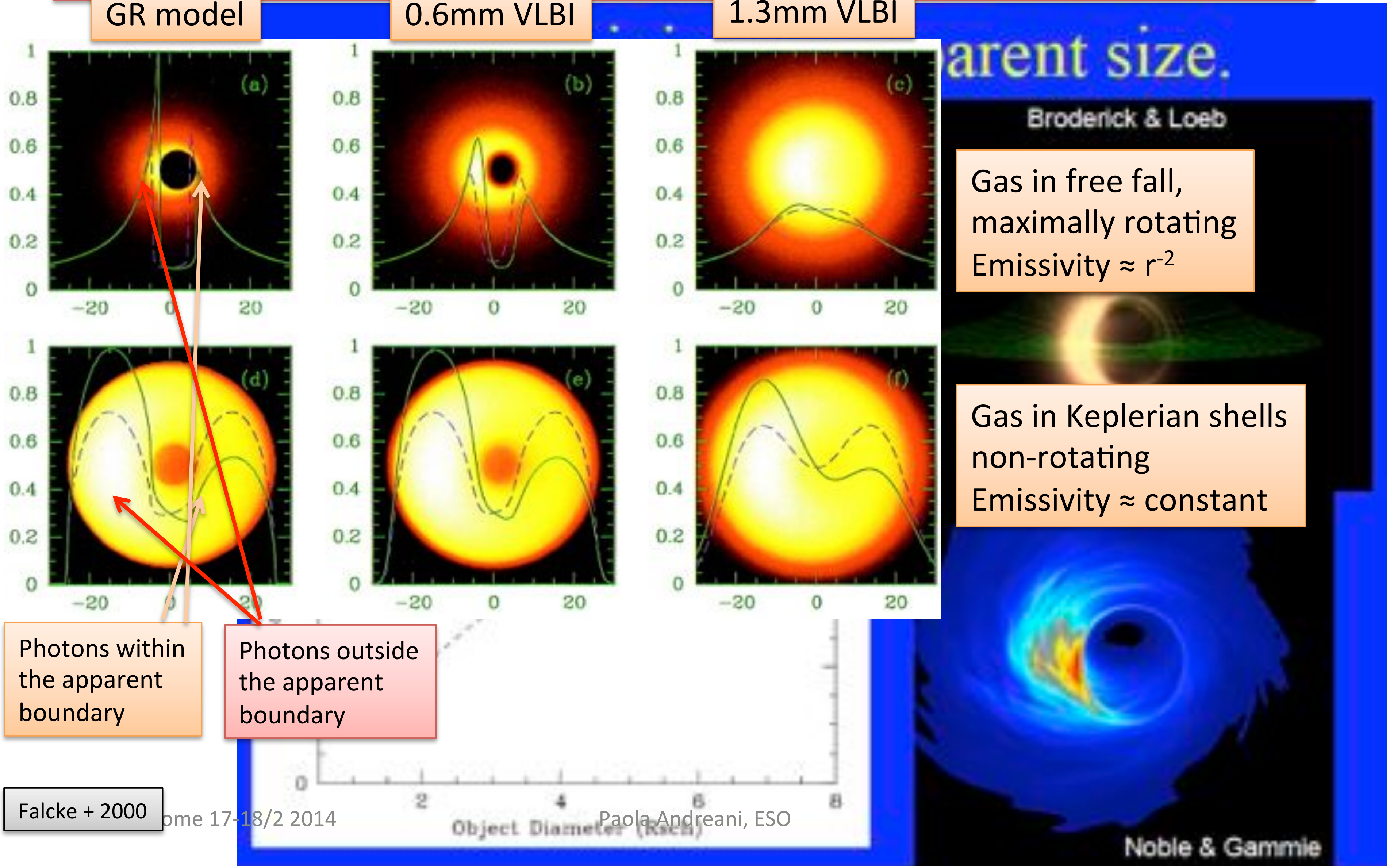


(Brinch 2010)



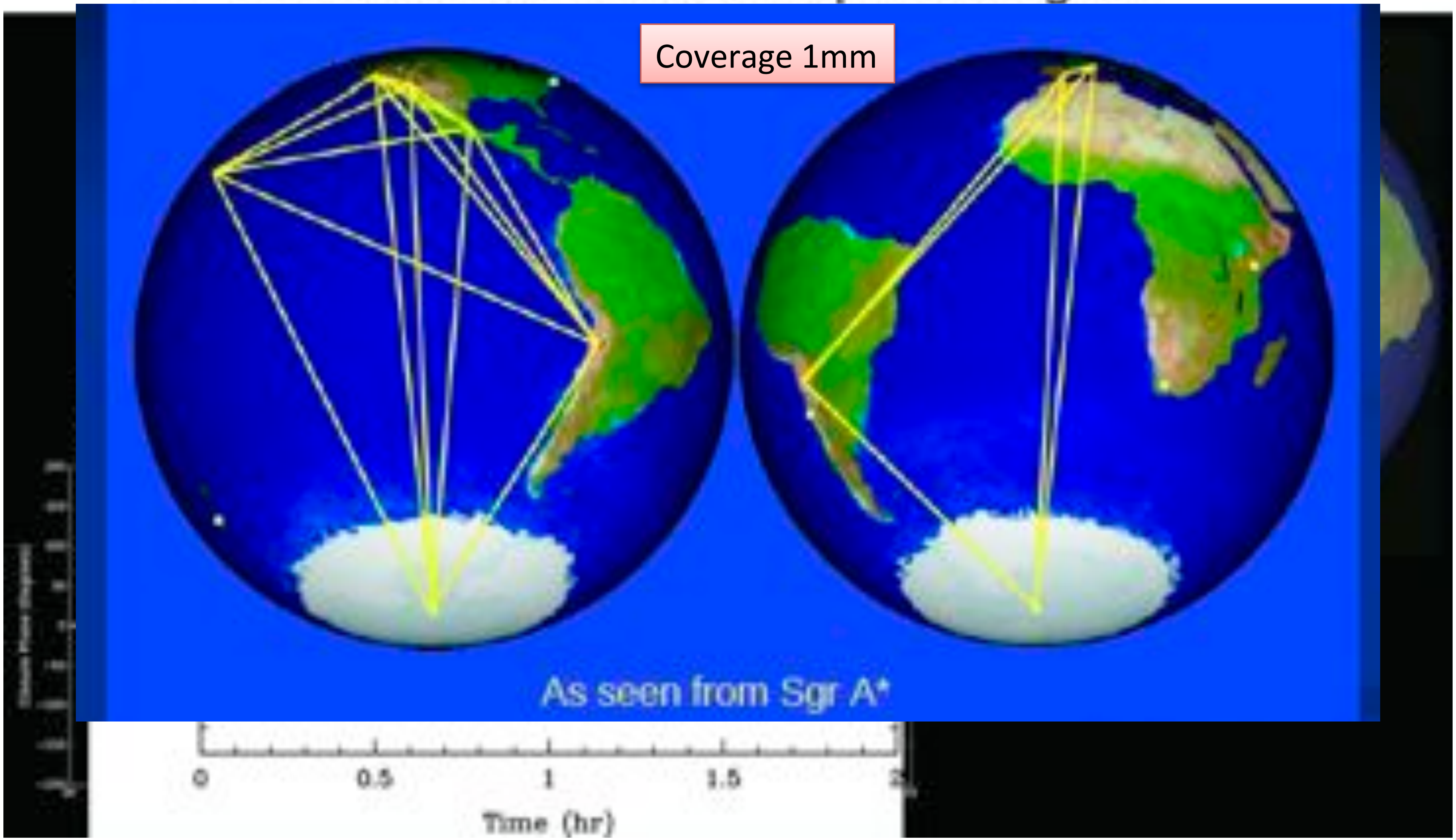
(Persson et al. 2012)

The shadow of a Black Hole



Phasing ALMA for VLBI

- The Even Horizon Telescope and Sgr A*



Summary

- ALMA Early Science is just the beginning
  - Cycle 2 – Dec 5th – additional capabilities and time
- It is already producing transformational science (some examples have been shown)
- ALMA is slowly reaching its full capabilities
  - Full Science Operations in 1-2yrs
- ALMA is a long lifetime observatory with a healthy Development Plan


Thank You !