Dust-Enshrouded Galaxy Formation

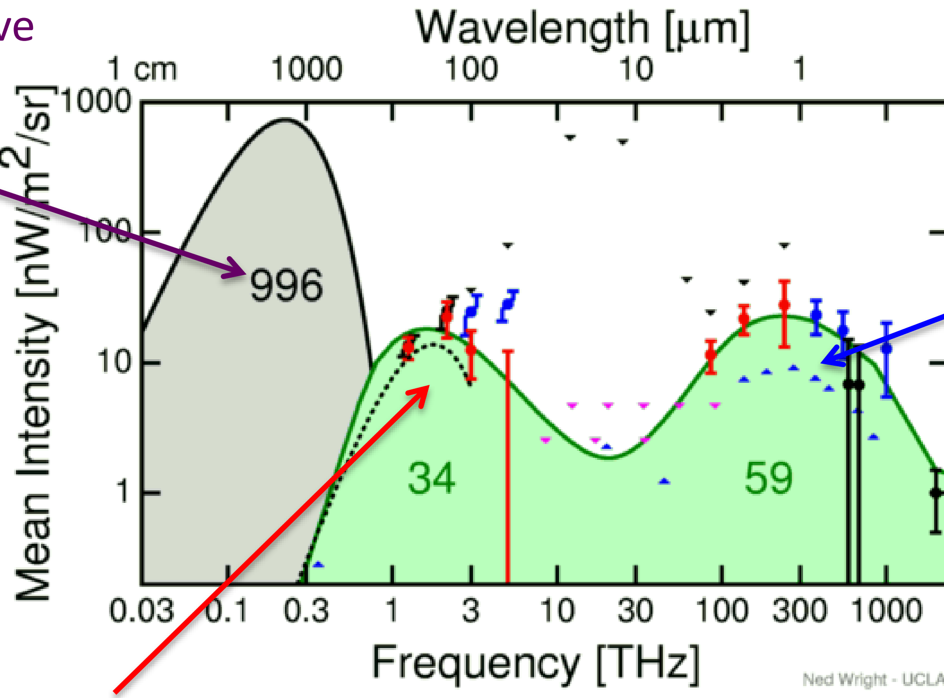
Steve Eales, Cardiff University and the Herschel ATLAS team, with particular thanks to:

Aris Amvrosiadis, Tom Bakx, Nathan Bourne, Loretta Dunne, Simon Dye, Cristina Furlanetto, Mattia Negrello, Steve Maddox, Matt Smith and Elisabetta Valiante

Why the submm/far-infrared is important

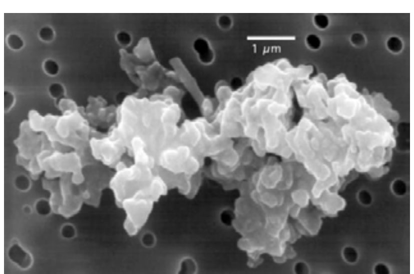
Cosmic mircrowave background

Optical background – from stars



Far-infrared submillimetre background – from interstellar dust

Dust grain



- The infrared background has roughly the same strength as the infrared background, implying that roughly half the optical light from stars and quasars emitted since the Big Bang has been absorbed by dust and reradiated in the infrared
- Birth of stars and galaxies even more hidden by dust

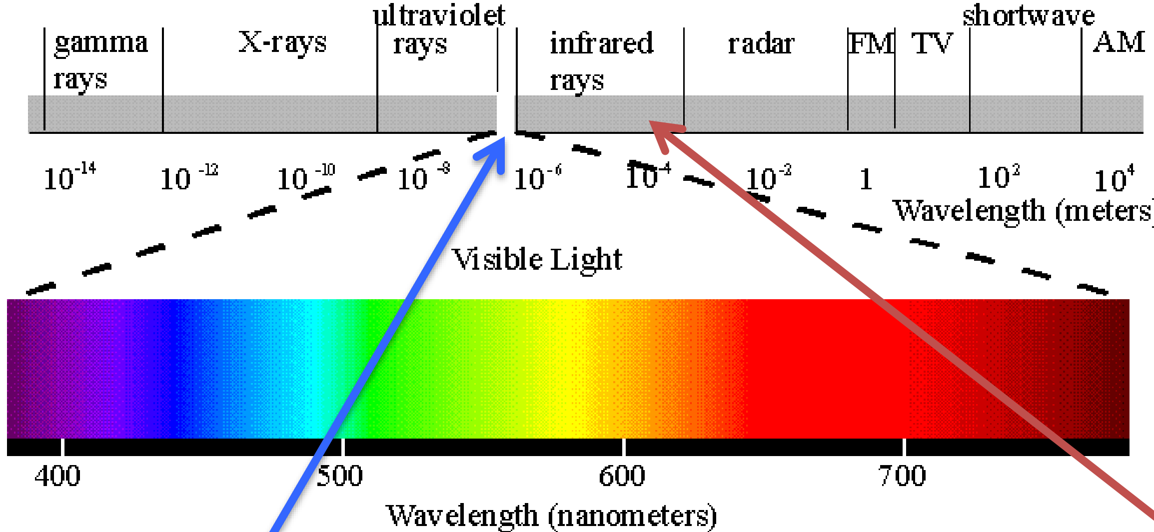
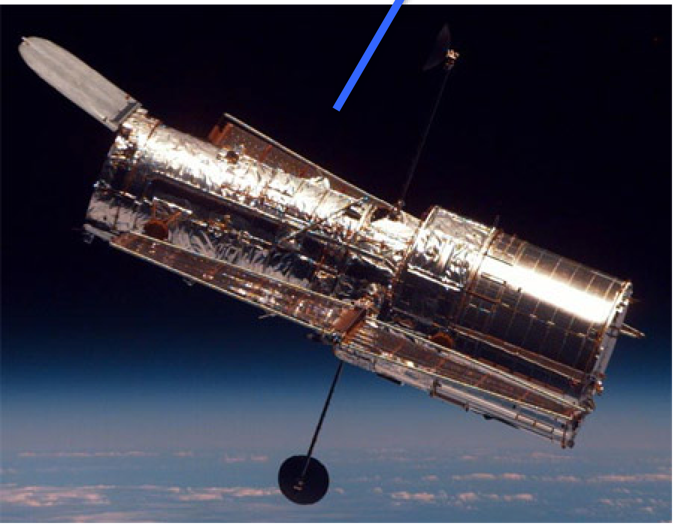


Table of Contents
Visual Stimulus

Hubble Space Telescope



Herschel Space Observatory – biggest telescope in space (3.5 metres), launched May 2009, ran out of helium in 2013. Wavelength range: 70-600 μm

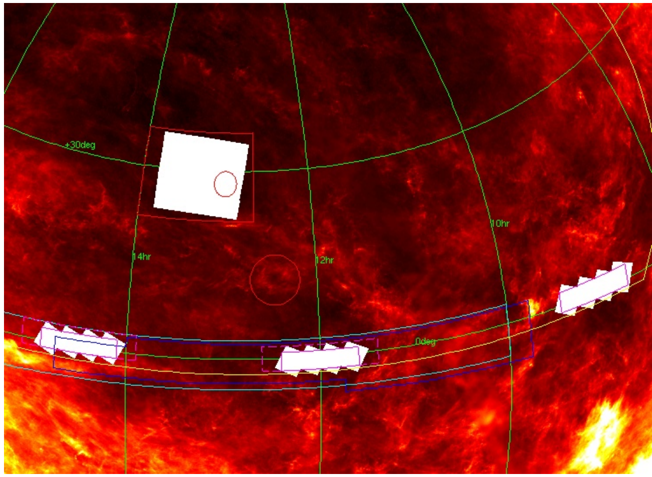
Why Carry out a Wide-Field Submm Survey with Herschel?

- In the eighties, IRAS did an all-sky survey of dust in the nearby Universe, but 90% of the dust is too cool (≈20 K) to radiate in the IRAS wavebands (Devereux and Young 1990). This dust should radiate in the Herschel bands, and we needed a wide-field Herschel survey to detect a large number of galaxies.
- Observe the sources detected by Planck with high resolution
- Prediction that bright 500-μm sources are strongly lensed
- Detection of AGNs and other rare objects
- Large-scale structure and high-redshift galaxies
- Galactic star and planet formation
- New waveband (250 – 500 μm) to explore – are there new types of objects?

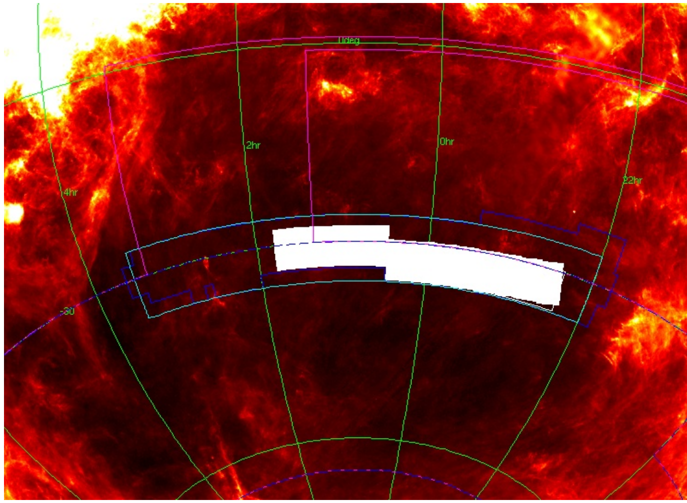
The Herschel ATLAS

- The widest area extragalactic survey with Herschel (660 deg^2) in five bands from 100 to 500 μm and in five fields
- Detected 426,372 sources
- In the equatorial fields there are 113,937 sources, 44,835 counterparts with 23,778 spectroscopic redshifts
- Images and catalogues for all fields are on h-atlas.org and the data release is described in five papers (Valiante et al. 2016, Bourne et al. 2016, Smith et al. 2017, Furlanetto et al. 2018, Maddox et al. 2018).

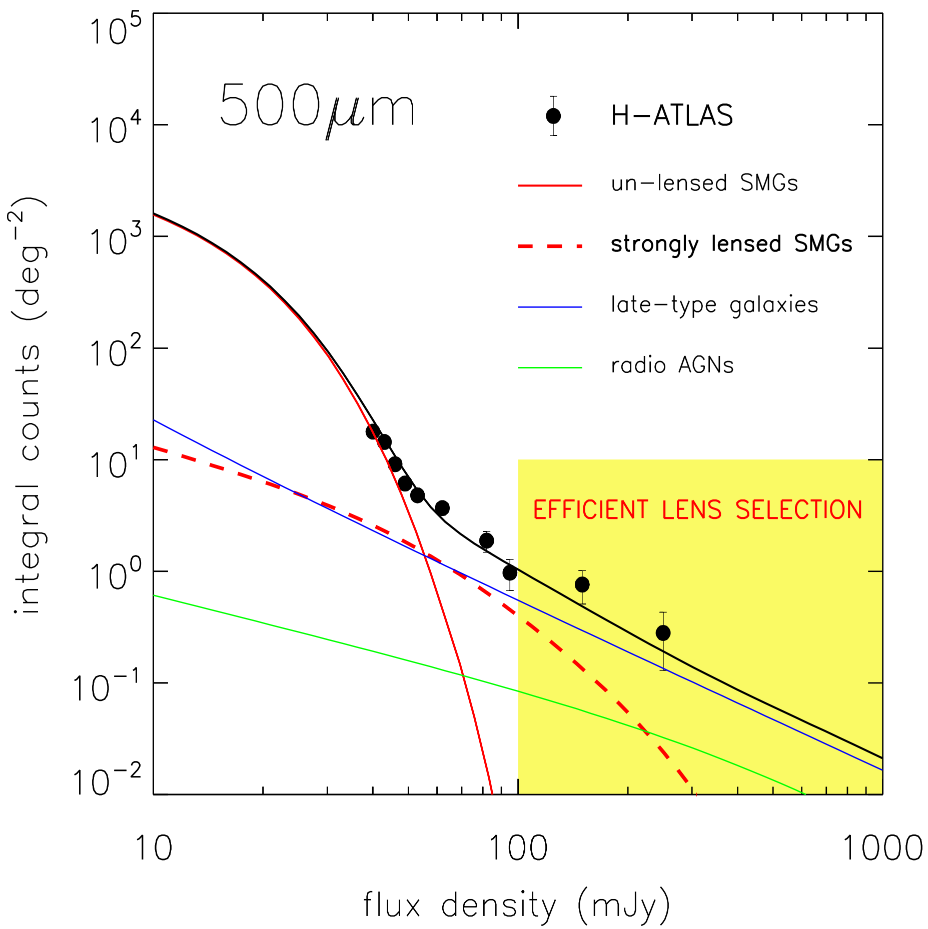
North



South

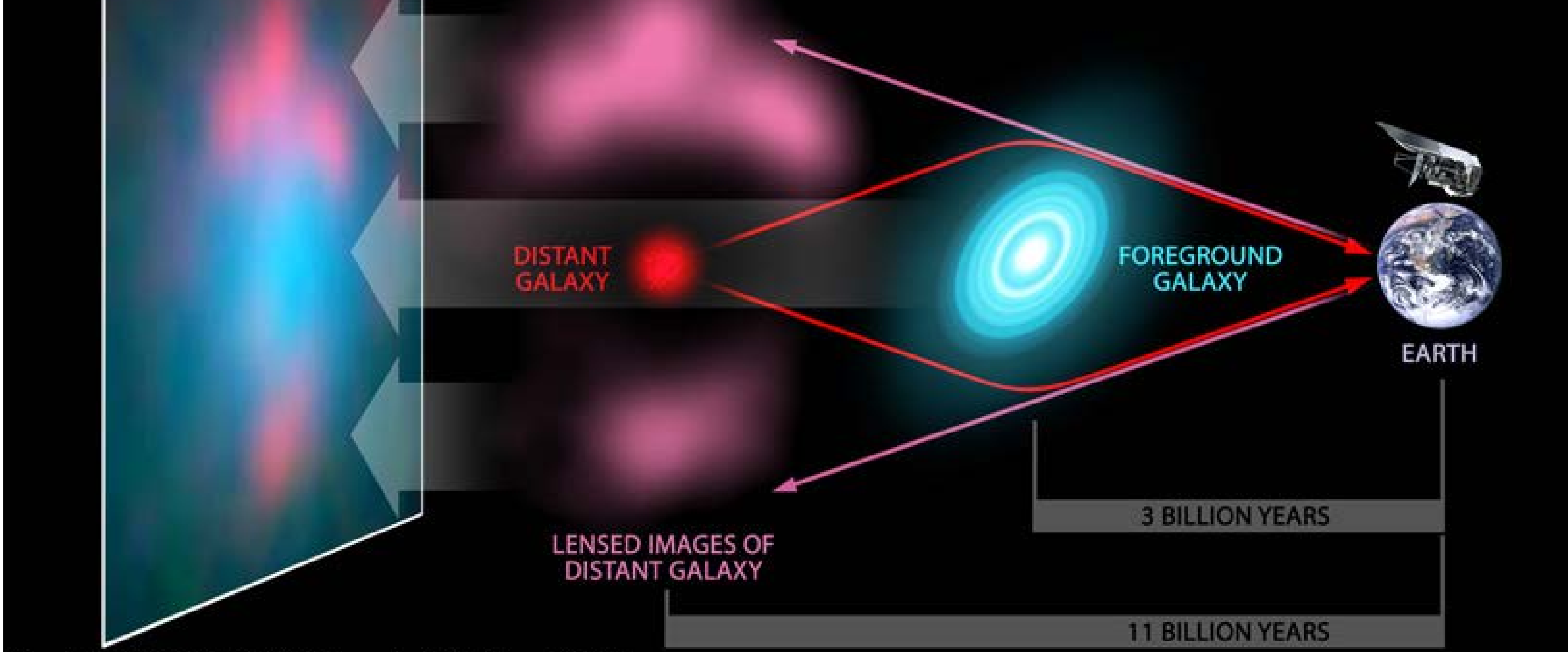


Why the submm surveys might be a good way of finding lensed systems



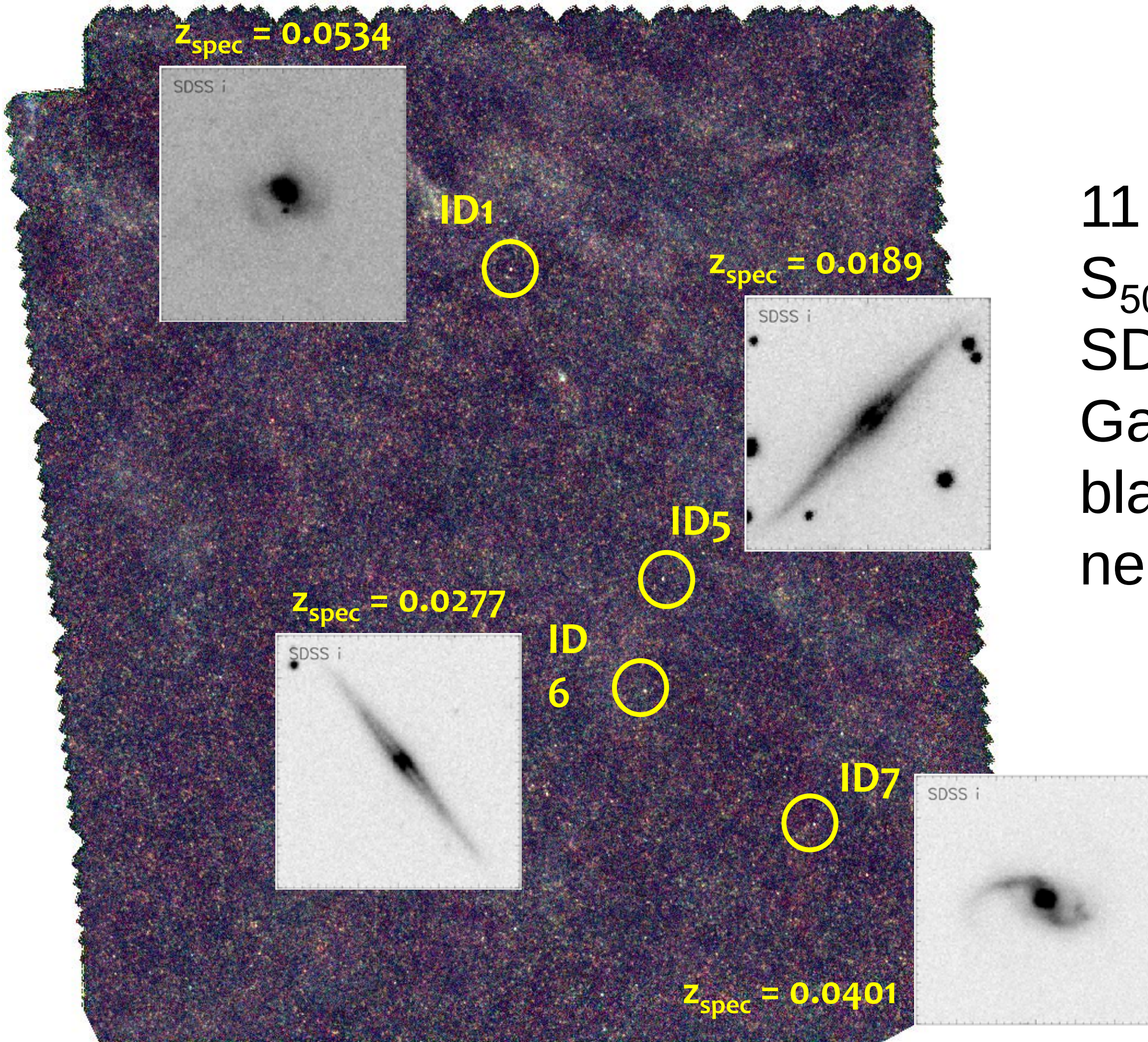
Negrello et al. 2007, 2010

Science Demonstration Phase (September to December 2010): 16 square degrees of the total 660 square degrees – approximately 6000 sources



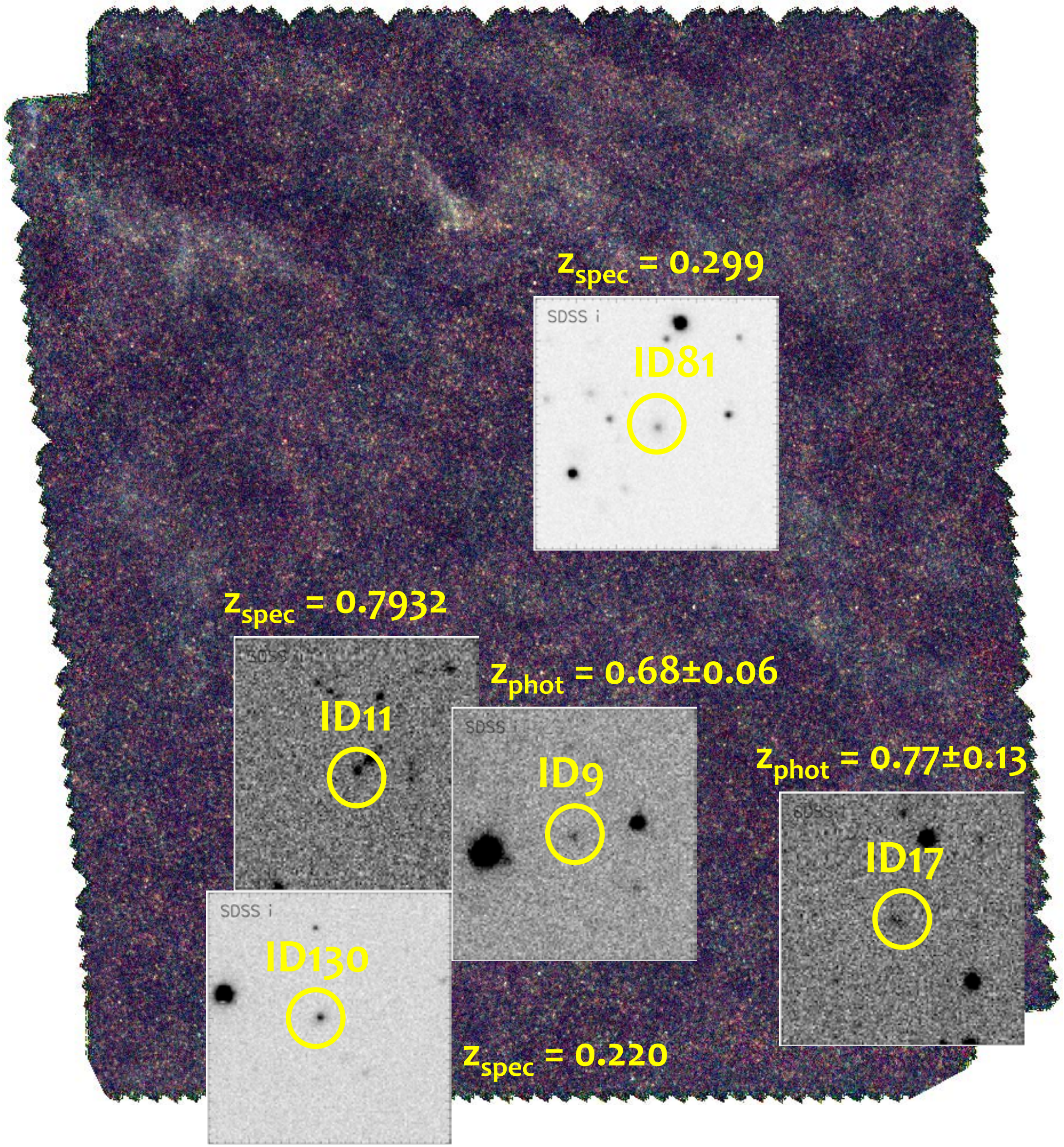
Credit: NASA/ESA/Caltech-JPL/Keck/SMA

Brightest galaxies in SDP field

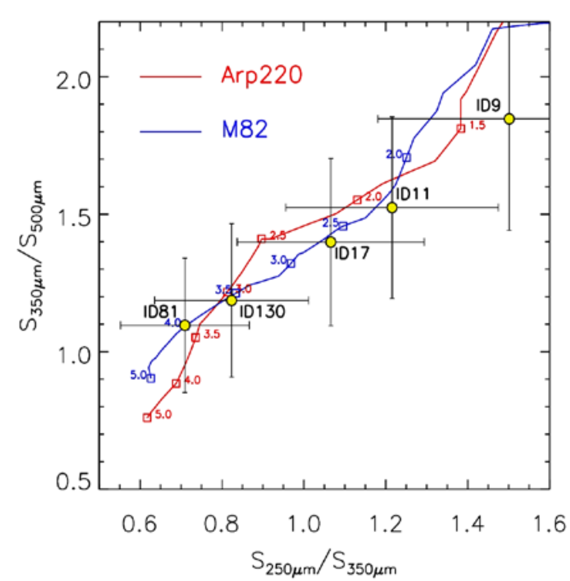


11 sources with $S_{500\mu m}$ > 100 mJy in SDP field – one Galactic source, one blazar and four nearby galaxies

A new method for finding gravitational lenses?

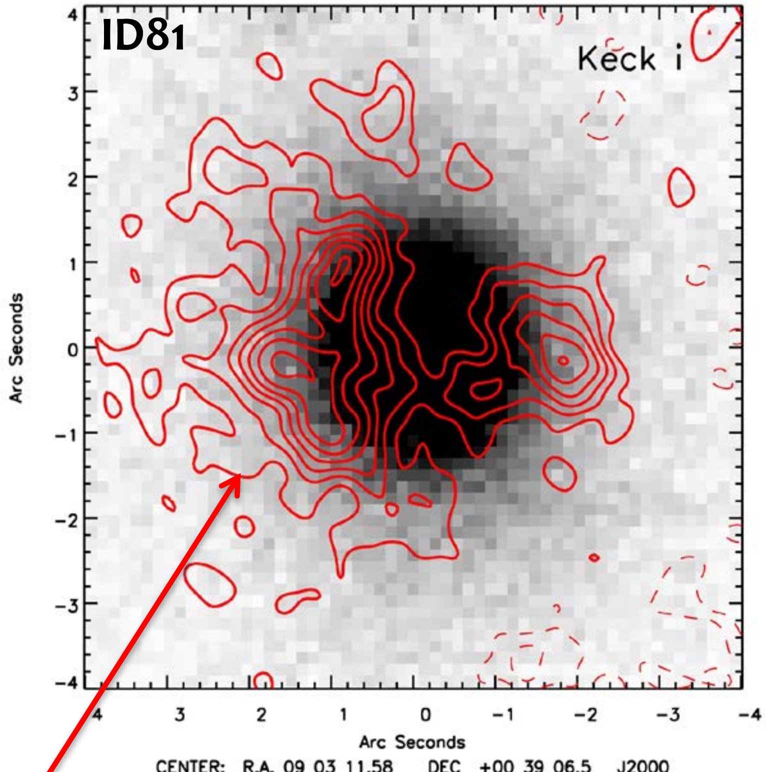


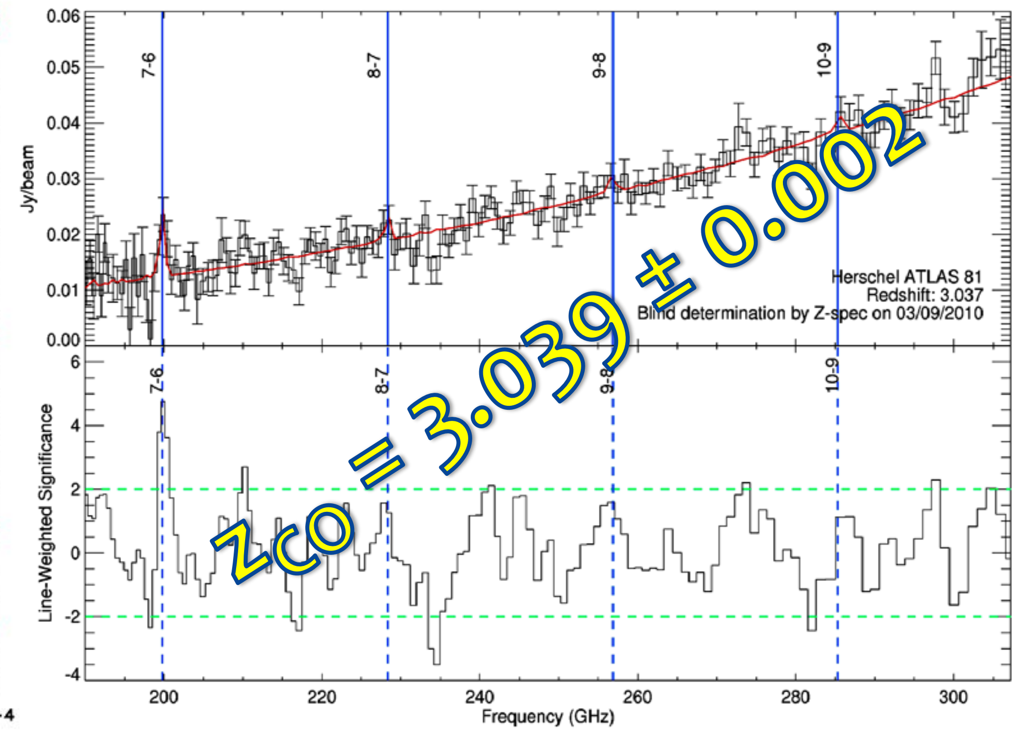
- Find the brightest sources at 500 μm
- Eliminate the blazars and those associated with nearby spirals



GRAVITATIONAL LENS CANDIDATES ID81

CSO/Z-spec blind redshift determination for **ID81** (March 09 2010) from observations of the **CO ladder**



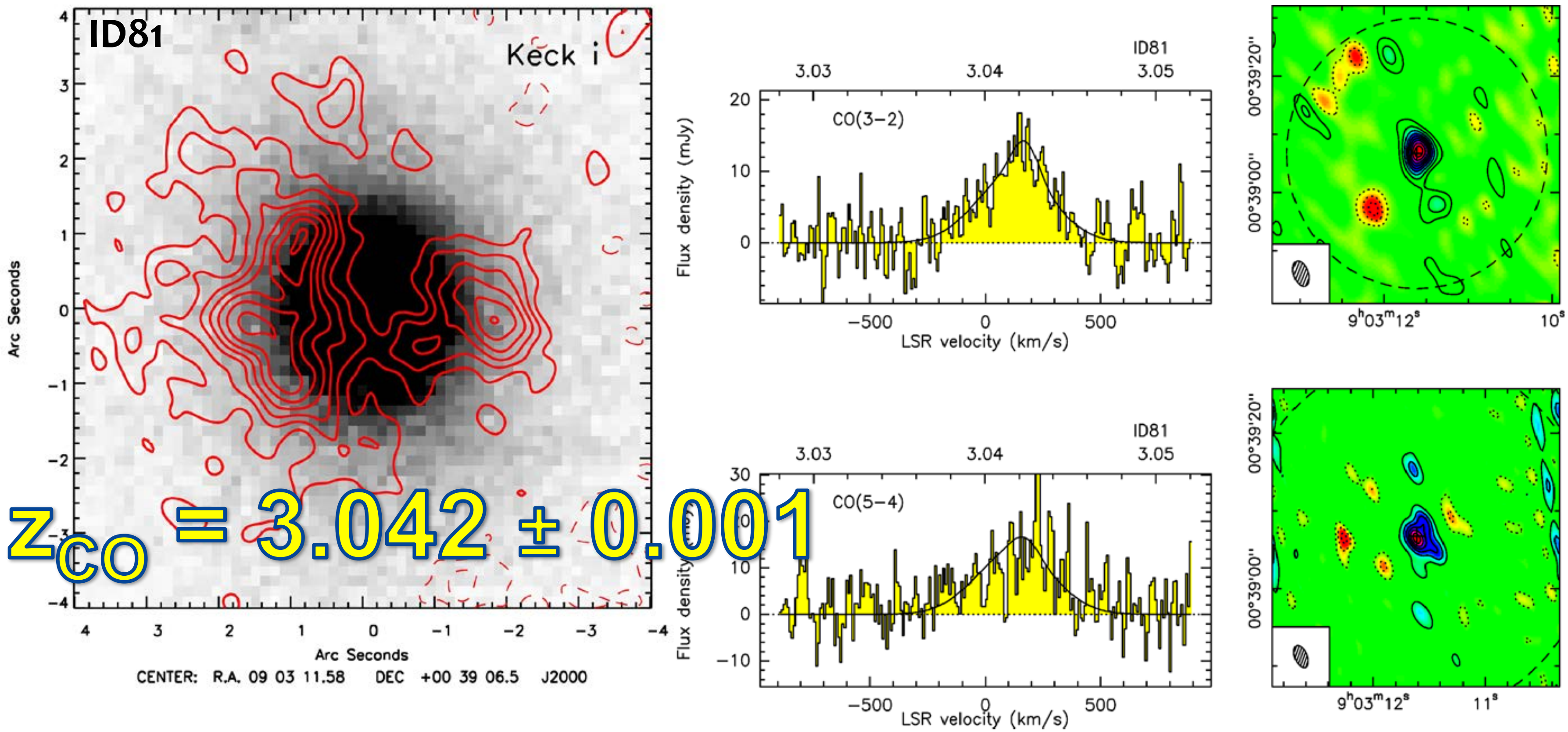


Submm map with the SMA

Credit: The Zspec team

Gravitational Lens candidates ID81

Redshift confirmed by **follow-ups** with P**dB Interferometer** (March 23 2010) and **GBT/Zpectrometer** (March 25 2010)

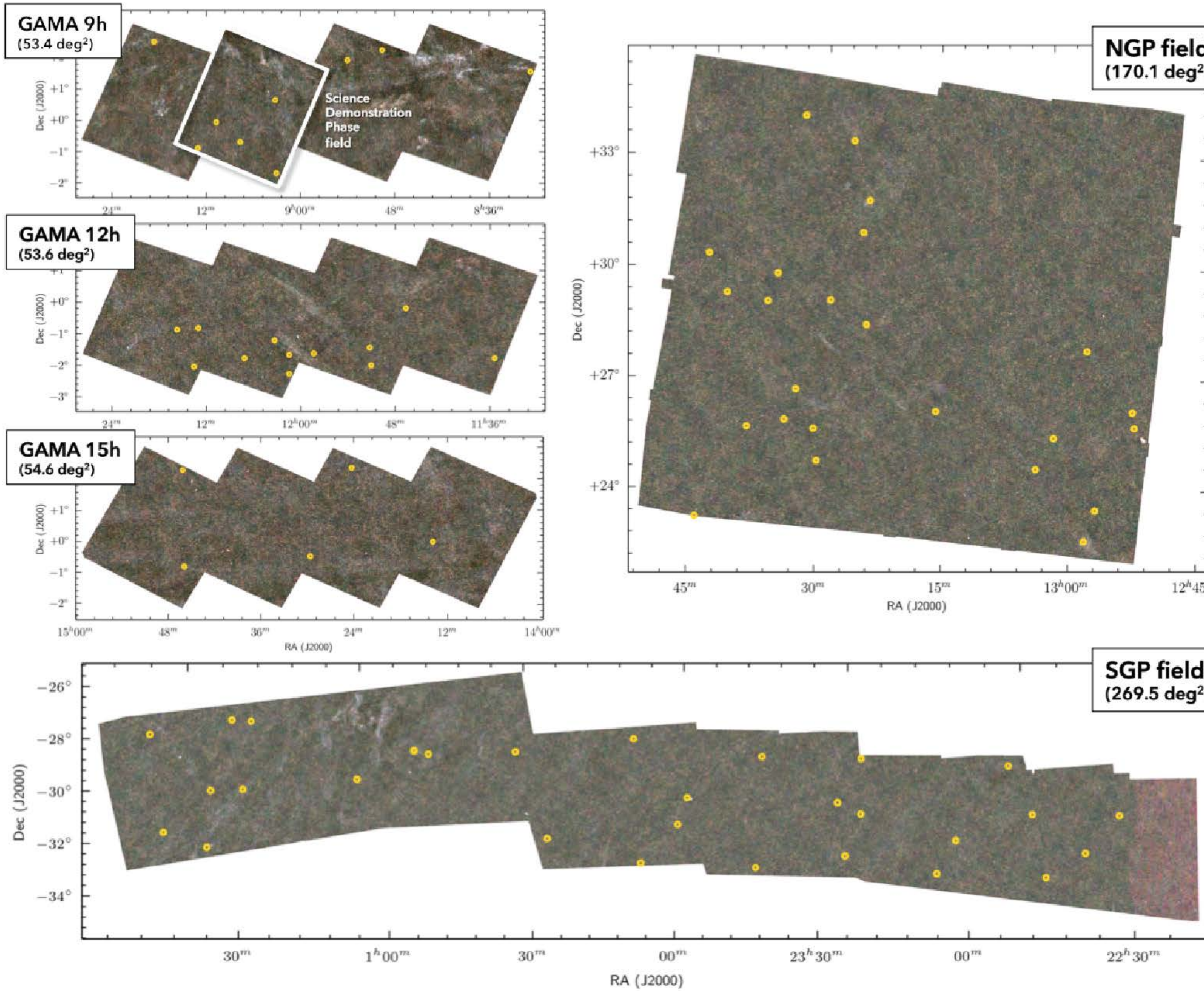


$z_{CO} = 3.042 \pm 0.001$

Credit: R. Neri, P. Cox, A. Beelen, H. Dannerbauer, F. Bertoldi

Why are the lensed sources found in submm surveys so important?

- Very clean selection technique because the lensed system is based on the brightness of the lensed source and the lens emits hardly any submm emission (most other techniques rely on the simultaneous detection of the lens and source or recognising the morphology of a lensed source)
- With ALMA it is possible to study these sources with superb resolution (aided by the magnification provided by the lensing)
- The Herschel wide-field surveys contain thousands of these systems



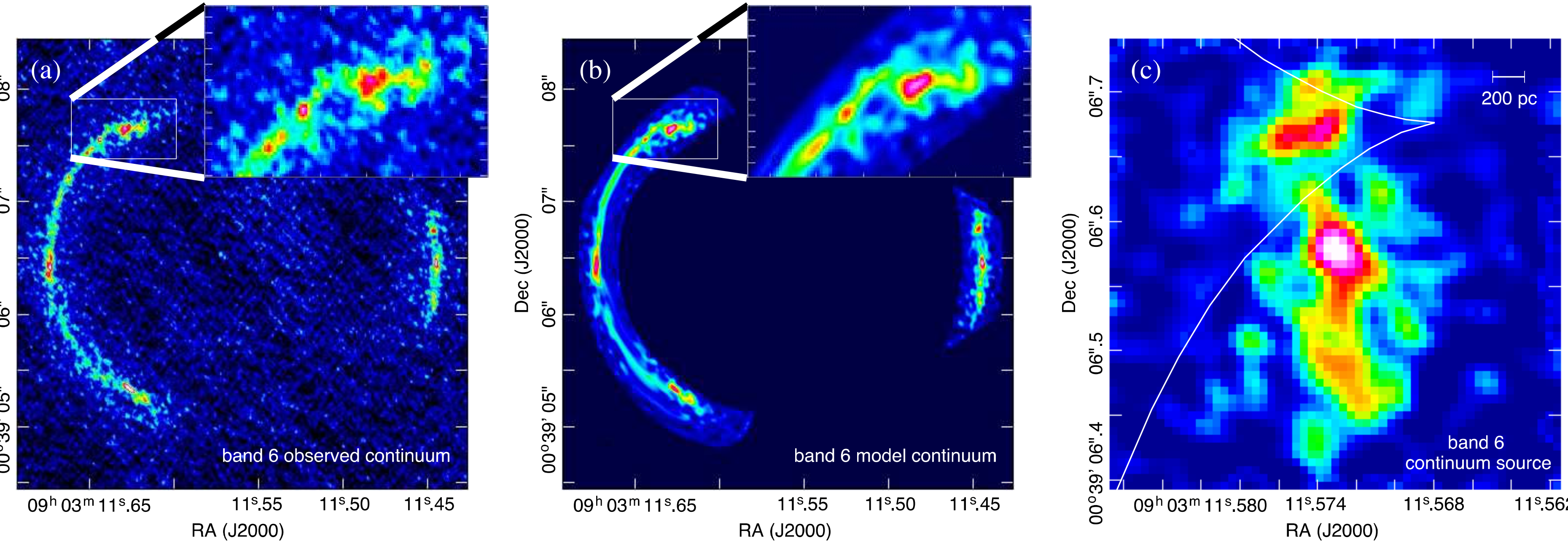
GAMA 9h
(53.4 deg²)
Science Demonstration Phase field
GAMA 12h
(53.6 deg²)
GAMA 15h
(54.6 deg²)
NGP field
(170.1 deg²)
SGP field
(269.5 deg²)
Dec (J2000)
RA (J2000)

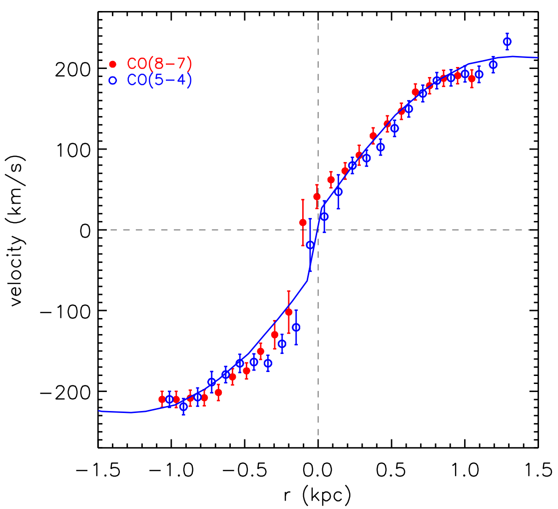
Science Projects

- Studies of star formation and the ISM in galaxies in the process of formation with a resolution of ≈50 pc
- Measurements of cosmological parameters
- Tests of theoretical halo mass functions

SDP 81

- Target for science verification of the ALMA high-resolution mode
- Redshift of 3.04 with a star-formation rate of 470 $M_\odot$ year^{-1}
- Star-formation efficiency (star-formation rate divided by the gas mass) ≈65 times greater than in Milky Way
- Gravitational magnification ≈16





- Images of the gas and dust with a resolution of ≈50 pc
- Clumps of gas and dust in a smoothly rotating disk
- Toomre Q parameter shows disk is collapsing
- No clear signs of an interaction

Dye et al. 2015; Hatsukade et al. 2015; and many others

Questions

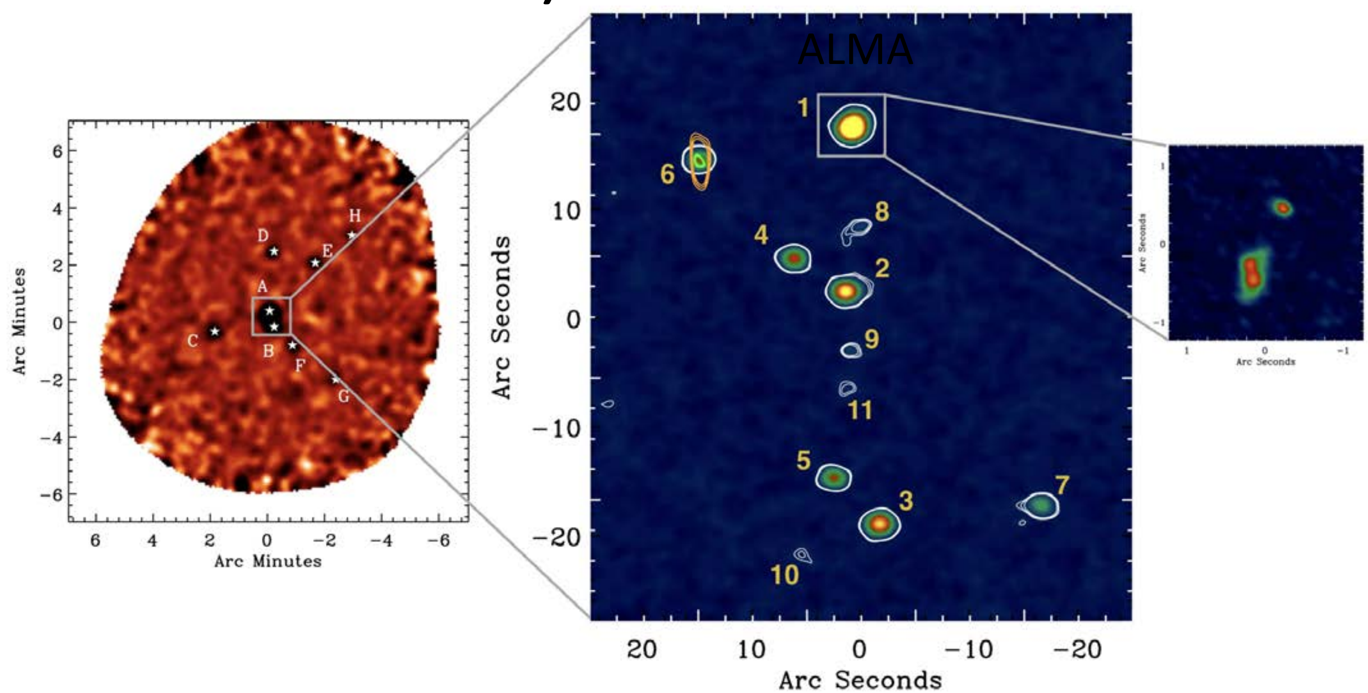
- Is the star formation also in clumps?
- Is there gas between the clumps?
- Does all galaxy formation consist of collapsing rotating disks (one other example – Tadaki et al. 2018)?
- How important are interactions?
- How do we compare these results with theory, since the resolution of hydrodynamical simulations (EAGLE, Illustris etc) is ≈0.7 kpc, not much different than the sizes of these sources.

- ALMA Cycle 5 – Observations of [CI] in a z=4.2 lensed system
- ALMA Cycle 5 – Continuum and CO observations of a sample of 8 lensed high-redshift Herschel sources with a resolution and sensitivity almost as good as for SDP 81
- ALMA Cycle 6 – Band 10 observations of SDP 81 (by combining Band 10 and Band 6, we can produce maps of the bolometric dust luminosity and therefore the star-formation rate

Searches for Protoclusters

1. By deep imaging around individual Herschel sources with high estimated redshifts (e.g. Oteo et al. 2018)

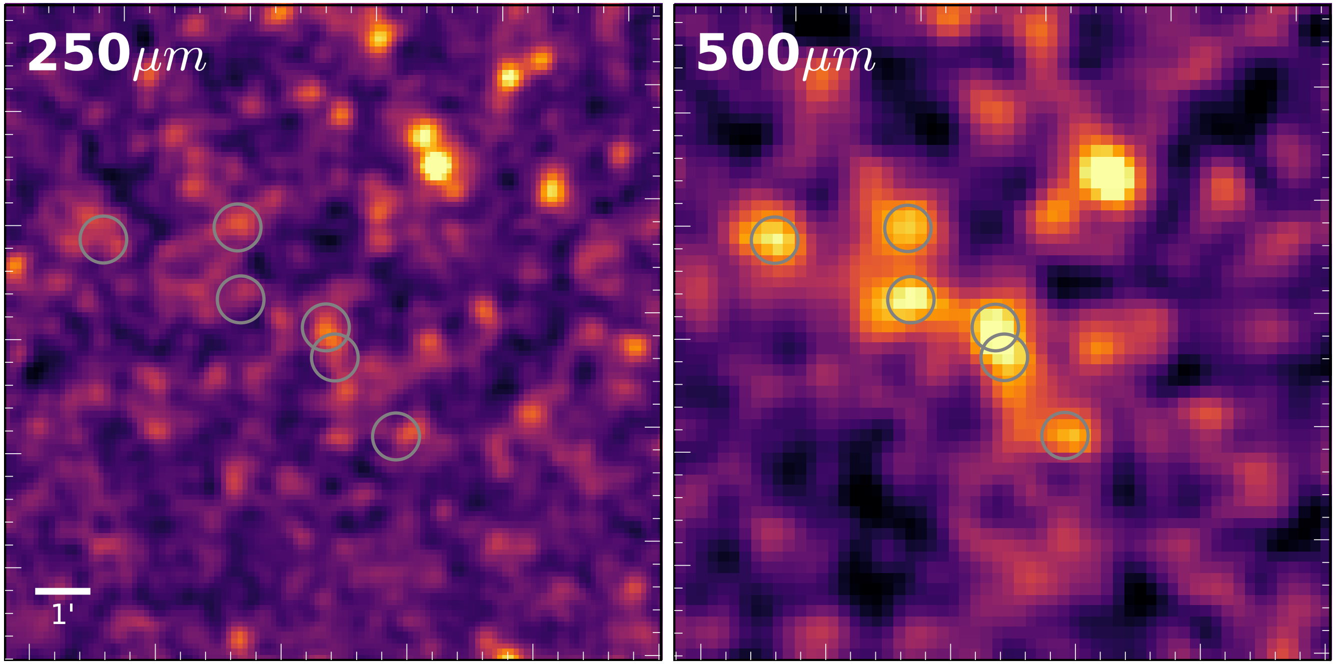
Laboca



ALMA

Z=4.002, total star-formation rate ≈6500 $M_{\odot}$ year^{-1}

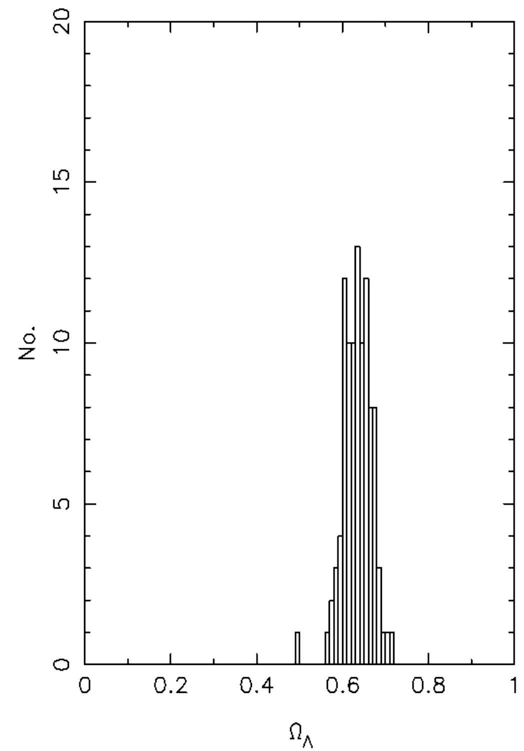
2. By looking at clustering of Herschel sources

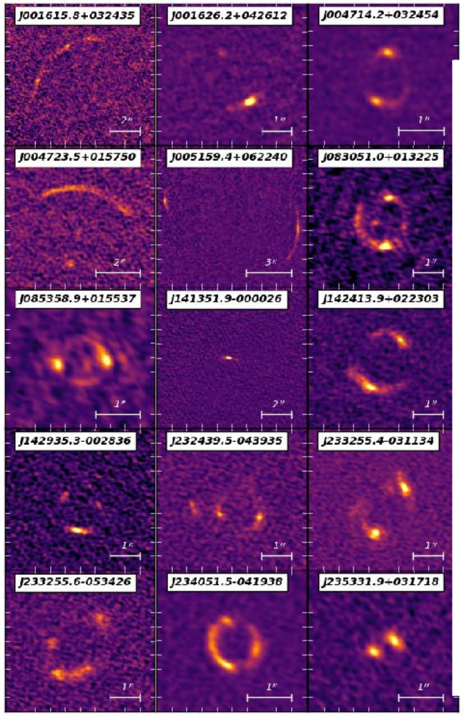


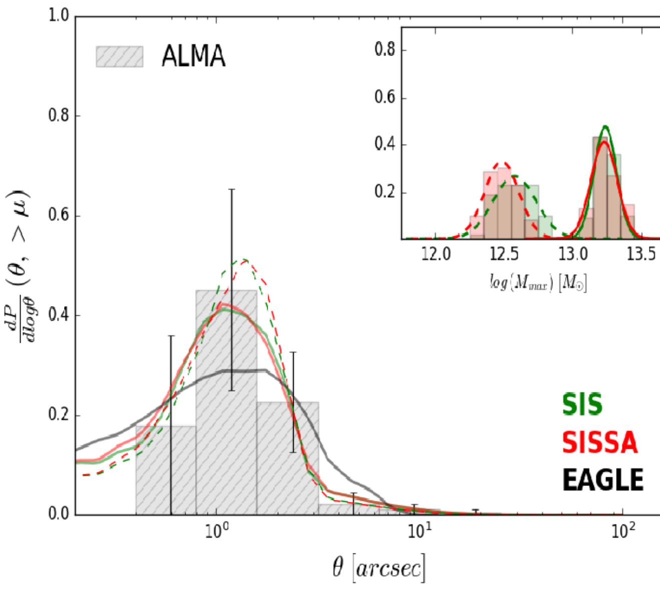
Cluster of sources visible at 500 μm but not at 250 μm, implying z ≈4 and a star-formation rate of ≈ 12,500 $M_{\odot}$ year^{-1}. ALMA programme underway…..

Practical Cosmology with Lenses

- With measurements of mass from the lensing and from the stellar velocity dispersion for a sample of 100 lensed systems, we can estimate Ω_Λ with a precision of 5% (Eales 2015)
- With several hundred lensed systems, we can test theoretical models of the halo mass function (Amvrosiadis et al. 2018)



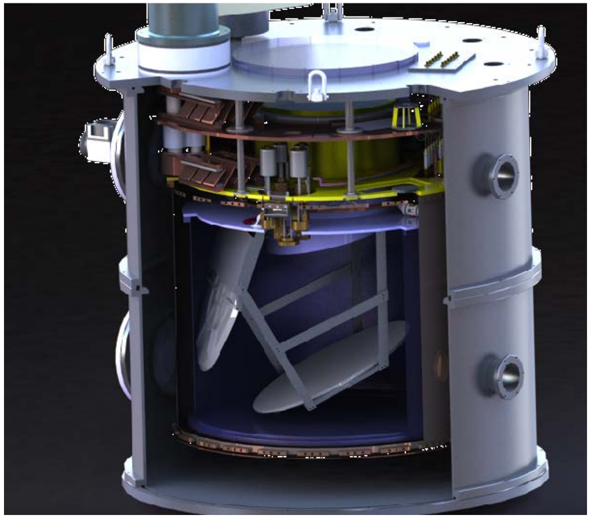




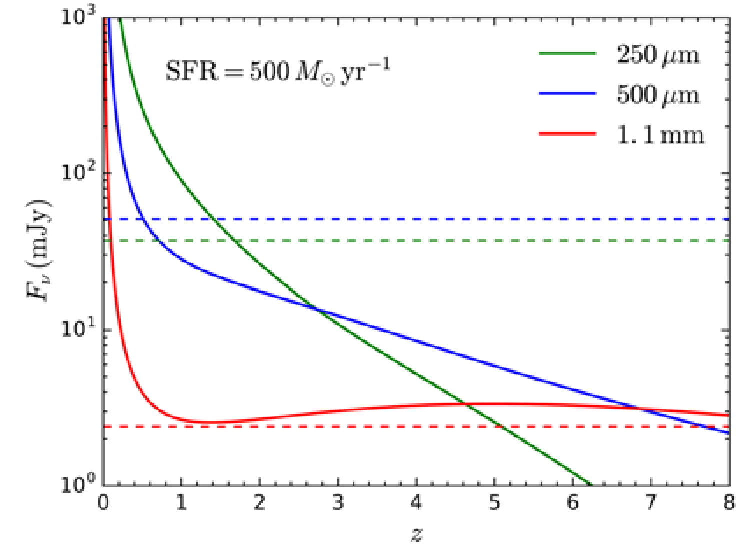
A Decade of Failure

- For cosmological studies, we need redshifts and maps for 100-200 lensed sources
- We found the first lensed sources in 2010 but we have only so far measured redshifts for ≈30 lensed sources and obtained high-resolution ALMA continuum maps of ≈20. Since it is now 2018, this isn't very good!
- We have applied for a large project on NOEMA to measure redshifts for Herschel lensed sources close to the NGP (P.I.s Cox, Bakx and Dannerbauer)
- Need a lot of ALMA time to obtain redshifts for sources in the south and to obtain high-resolution ALMA maps. Need collaborators in other ALMA partners

MUSCAT



- The Mexico-UK Submm Camera for Astronomy (MUSCAT) is an array of 1,500 kinetic inductance detectors
- It will be installed on the Large Millimetre Telescope this winter
- In our guaranteed time, we plan to survey 50 square degrees of the GAMA equatorial fields at 1.1 mm
- This will be the first survey sensitive to dust-obscured galaxies at z > 4
- If we achieve photon-limited sensitivity, we will detect ≈10^4 galaxies and 10^2 protoclusters at z>4
- Strong overlap with work being carried out with SUBARU



Conclusions

- ALMA observations of lensed galaxies are a powerful way of investigating star formation and the ISM in galaxies in the process of formation. First results suggest that there is a `collapsing disk' phase in the formation of a galaxy
- With a few hundred lensed systems, one can in principle measure cosmological parameters and test theoretical halo mass functions
- The wide-area H-ATLAS finds very rapid cosmic evolution at low redshift, which is not predicted by analytical and hydrodynamical simulations
- With the wide-field surveys at 1.1 mm with MUSCAT, we will be able to extend the study of dust-obscured galaxy formation out to $z \approx 9$
- We need collaborators to make the most of the Herschel lensed sources and the MUSCAT survey