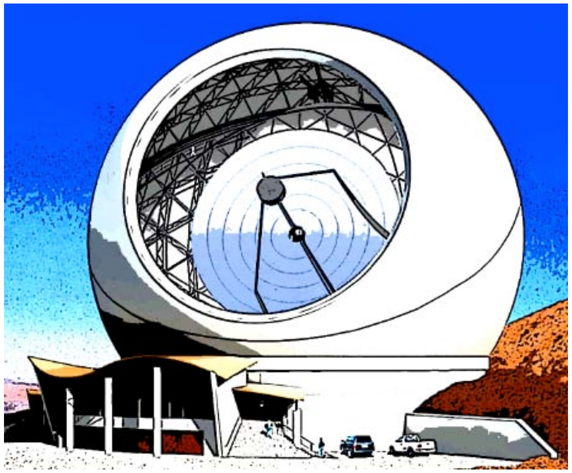


Very High Redshift Galaxies with, IRAM, ALMA and CCAT

Alain Omont
(IAP, CNRS and Université Paris 6) Herschel

On behalf of the H-ATLAS Team
and the IRAM Team

See W. Gear
J. Wardlow

Outline

➢ High-z (lensed) galaxies in Herschel-Atlas wide survey

• The H-ATLAS survey at high z ***see W. Gear***
Prediction and identification of strong lenses in first observations (SDP)

• Properties of the strong lensed SMGs already identified:
- SEDs, blind z_{CO}, imaging, molecular lines

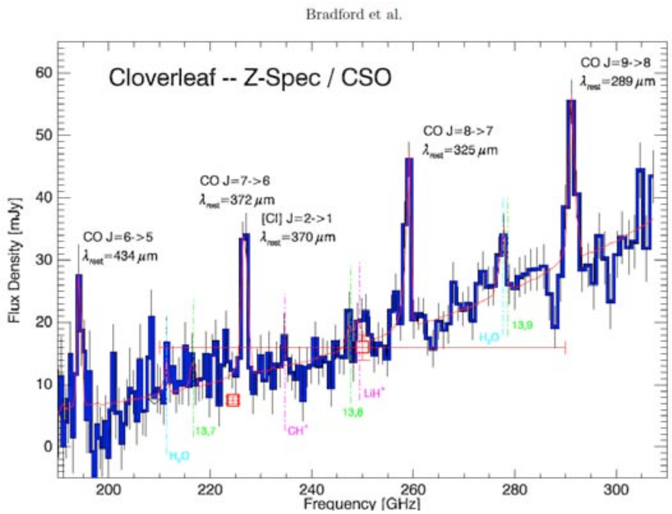
• Prospects for the whole sample of high-z lensed SMGs to be expected from H-ATLAS

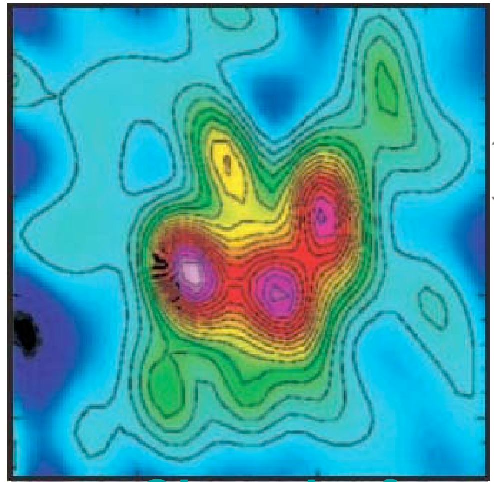
• Examples of ALMA programs possible with Herschel high-z lensed galaxies
- Redshifts
- High-resolution imaging
- High sensitivity spectroscopy
- Golden objects

➢ Role of CCAT for selecting best Herschel sources for ALMA

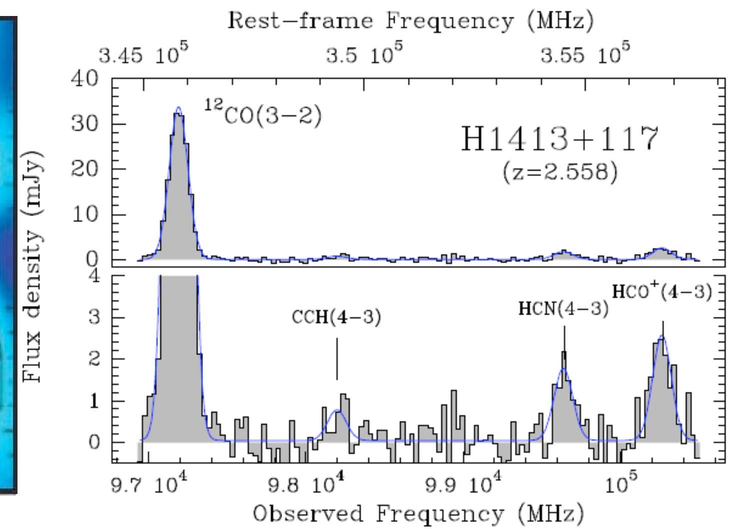
• Disentangling blended sources and providing accurate positions

• Analyzing proto-clusters through multi-object spectroscopy





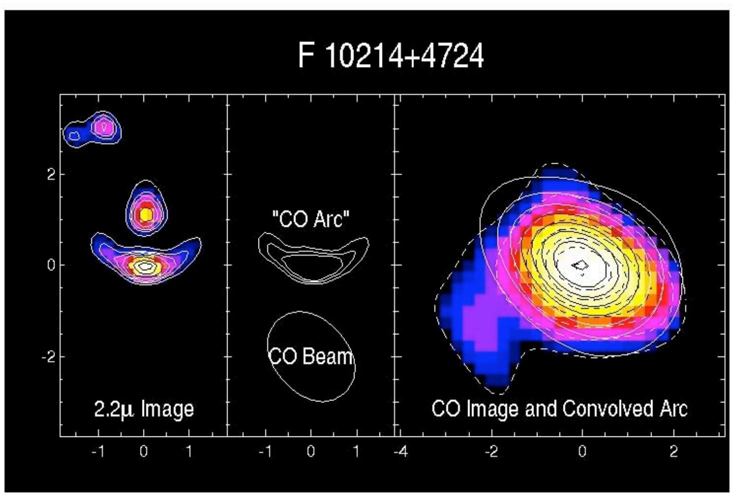
Cloverleaf

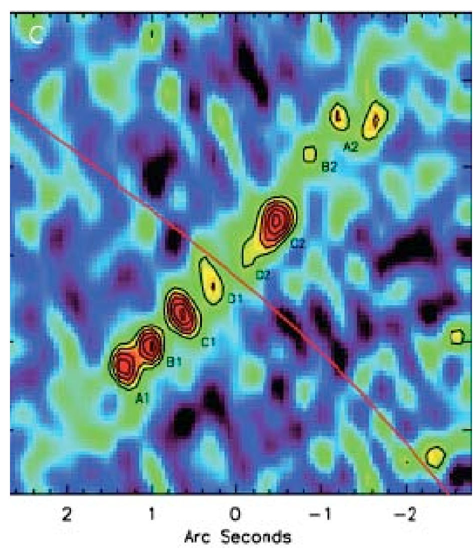


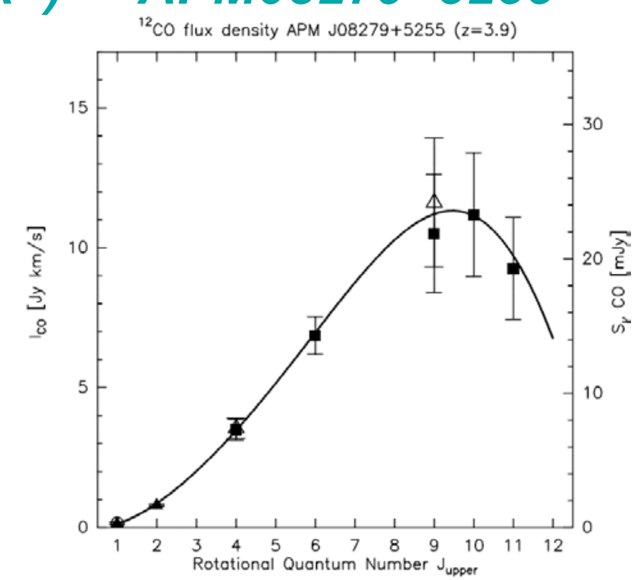
The power of gravitational lensing

Since 20 years lenses have marked the frontier of mm radioastronomy

Rowan-Robinson's galaxy *Eyelash (Swinbank+)* *APM08279+5255*



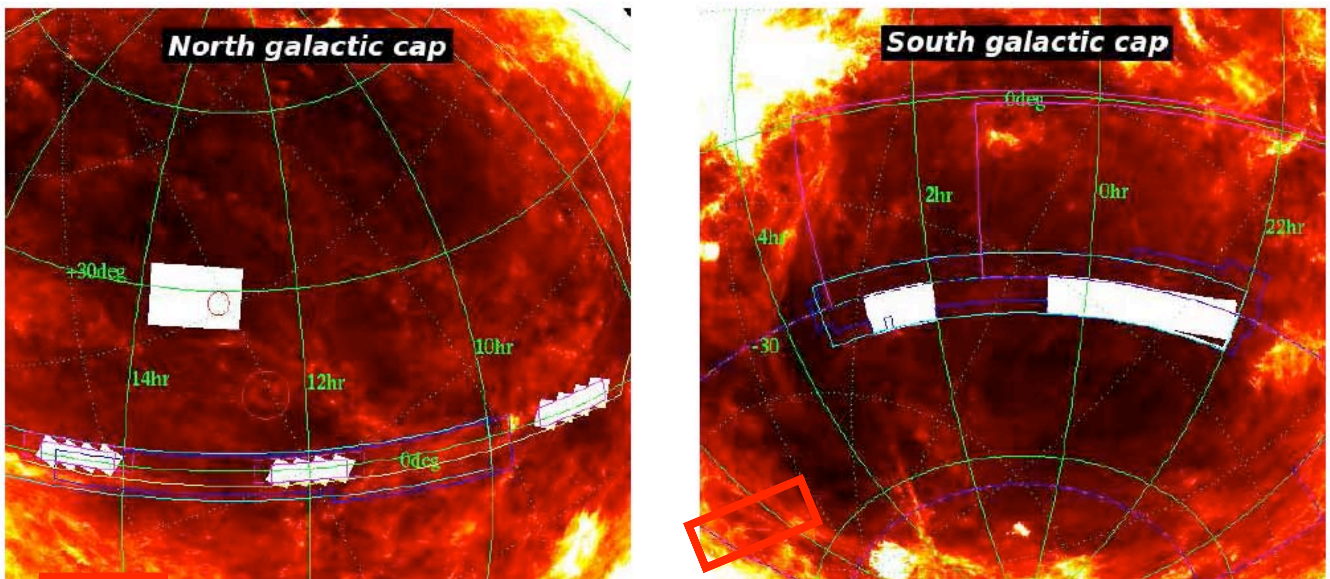




ASTROPHYSICAL
TERAHERTZ
LARGE
AREA
SURVEY

The H-ATLAS survey *see W. Gear*

OpenTime Key Project PIs: Steve Eales & Loretta Dunne



2.— The positi ns of the ATLA field shown as white blocks, superimposed on the IRAS 100 μm map of the sky, which trace

Total expected:
550 deg^2, ~600h

Current processed data for ~120 deg^2

- **Early data: SDP Field 14.4 deg2**
  Within 9h equatorial GAMA AAT spectroscopy field, plus SDSS, etc.
- **Sensitivity**
  - **Similar instrumental and confusion contributions to total noise**
  - **Total 5-σ limits are 33, 36, 45mJy/beam at 250, 350, 500μm, respectively**
- **Counts in Clements et al. 2010**

~500 5σ sources per deg^2 (mostly 250-350μm, slightly above the confusion limit)

>50% at z>1 → ULIRGs SMGs (~300 per deg^2)

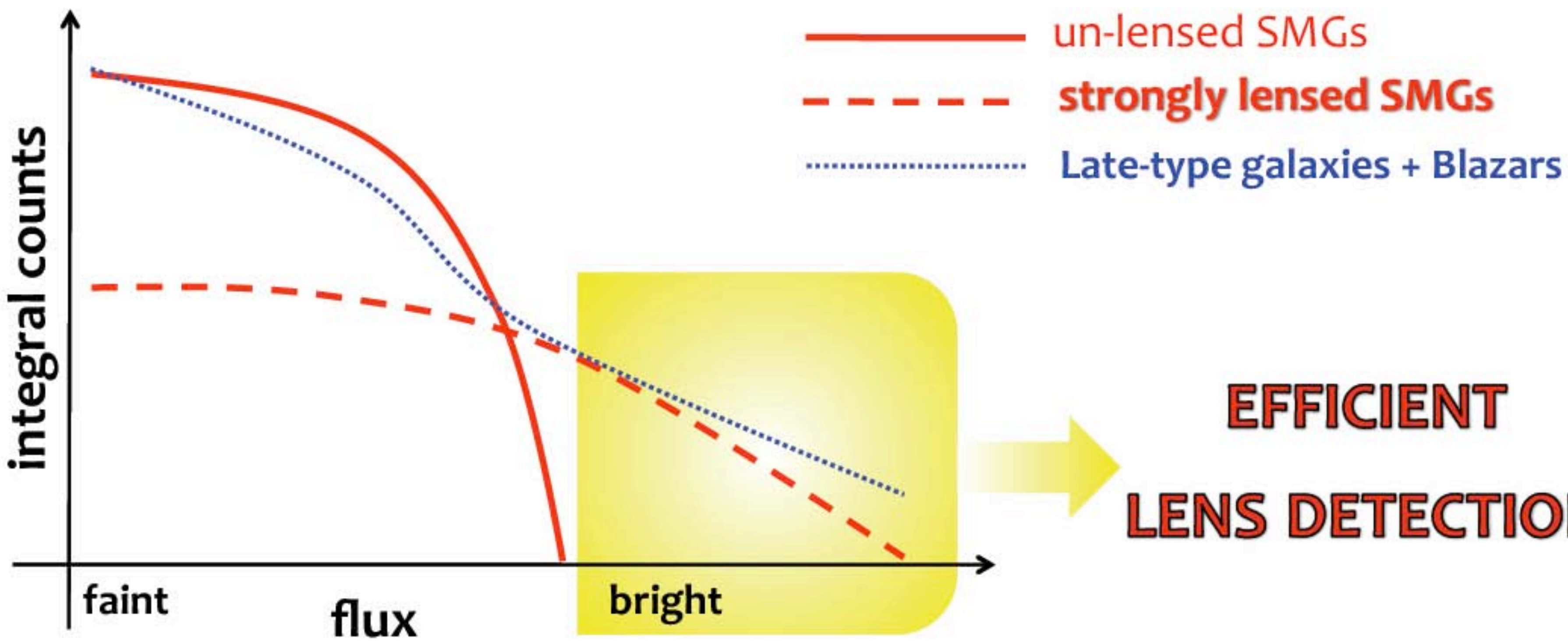
A LENSING SCIENCE CASE FOR H-ATLAS

Reproduced from
Negrello ESLAB2010
See J. Wardlow

Sub-mm surveys are ideal for finding lenses

Blain (1996), Perrotta et al. (2003), Negrello et al. (2007)

- **high redshift** → high efficiency for lensing
  Chapman et al. (2005)
- **steep counts** → strong *magnification bias*
  Coppin et al. (2006)



EFFICIENT

LENS DETECTION

500 μm BRIGHTEST GALAXIES IN H-ATLAS SDP

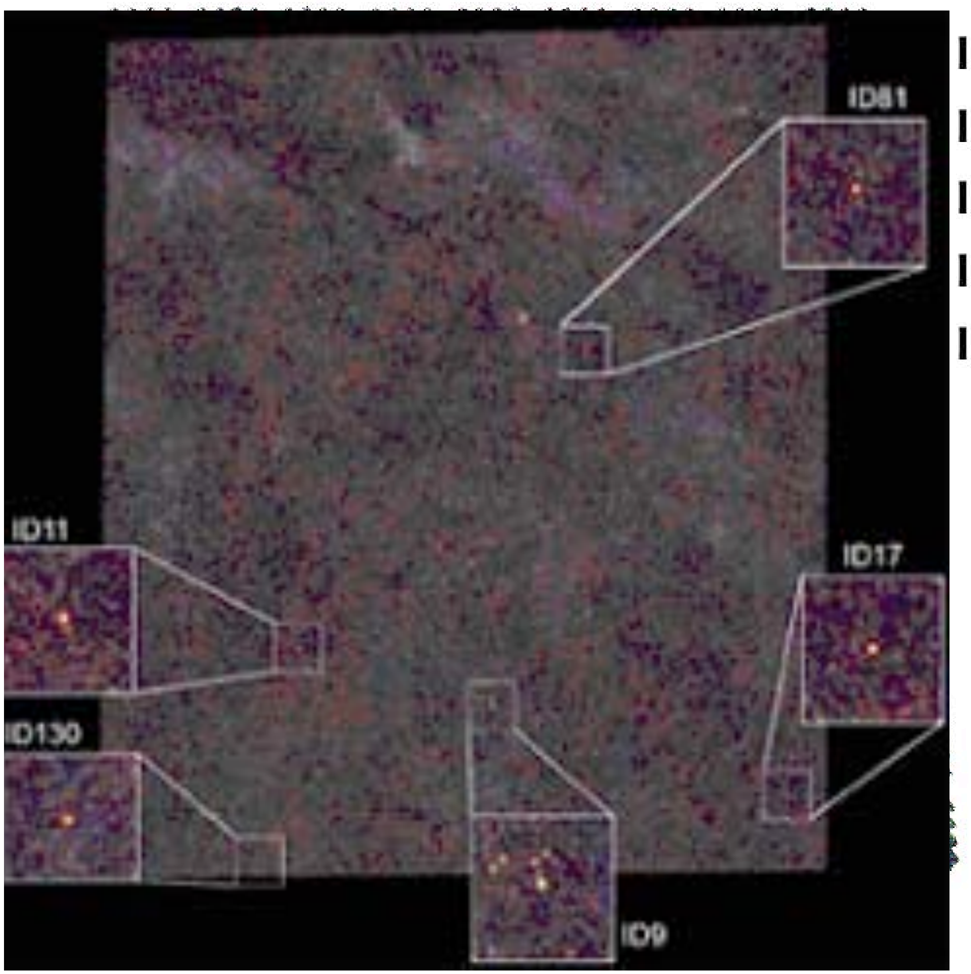
see W. Gear

H-ATLAS SDP field ~14.4 deg^2 7000 sources

11 sources with $S_{500\mu m}$ > 100 mJy

4 nearby galaxies (z<0.05), 1 blazar, 1 galactic blob

→ 5 high z candidates



ID9 : $S_{500\mu m}$ = 175 ± 28 mJy z = 1.577

ID11 : $S_{500\mu m}$ = 238 ± 37 mJy z = 1.786

ID17 : $S_{500\mu m}$ = 220 ± 34 mJy z = 2.308

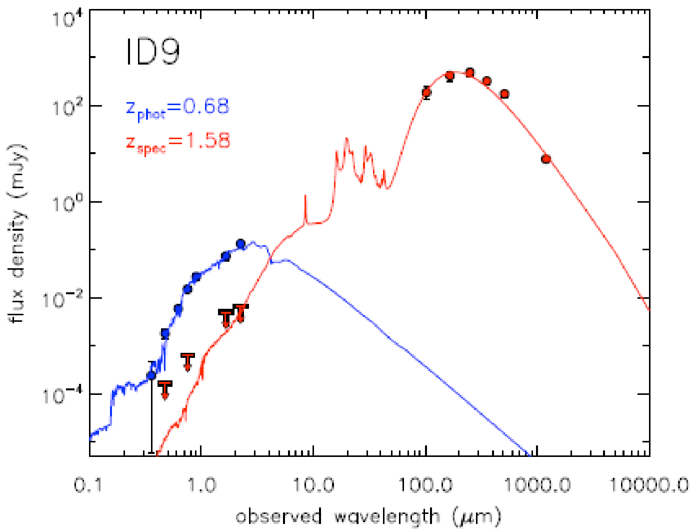
ID81 : $S_{500\mu m}$ = 166 ± 27 mJy z = 2.626

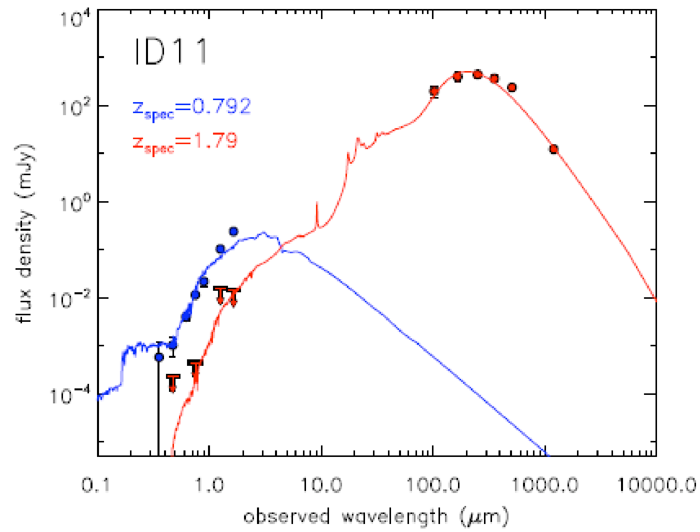
ID130 : $S_{500\mu m}$ = 108 ± 18 mJy z = 3.402

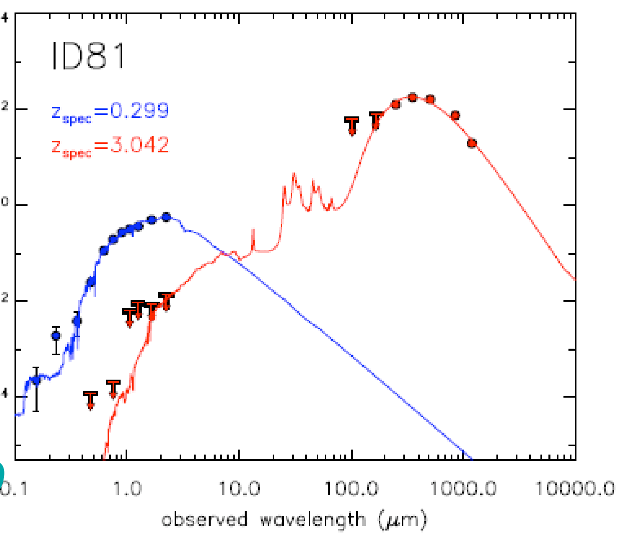
Negrello et al. 2010

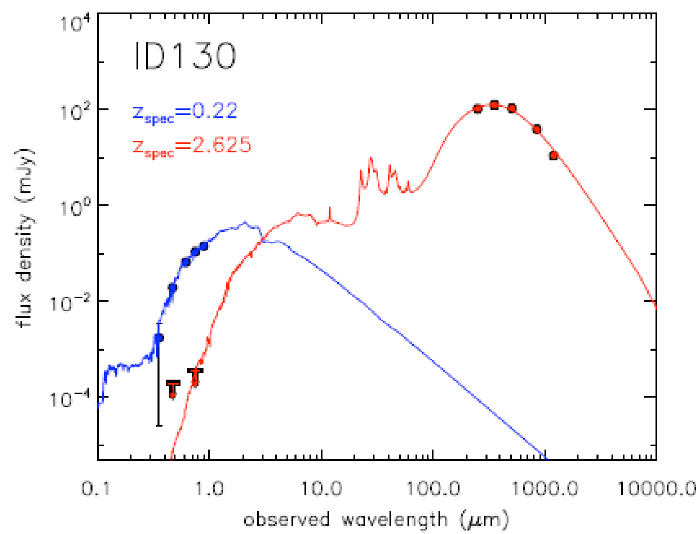
SED of lens candidates in H-ATLAS S DP field

clear cases of double-source SEDs
z~0.2-0.8 elliptical galaxy + high-z ULIRG









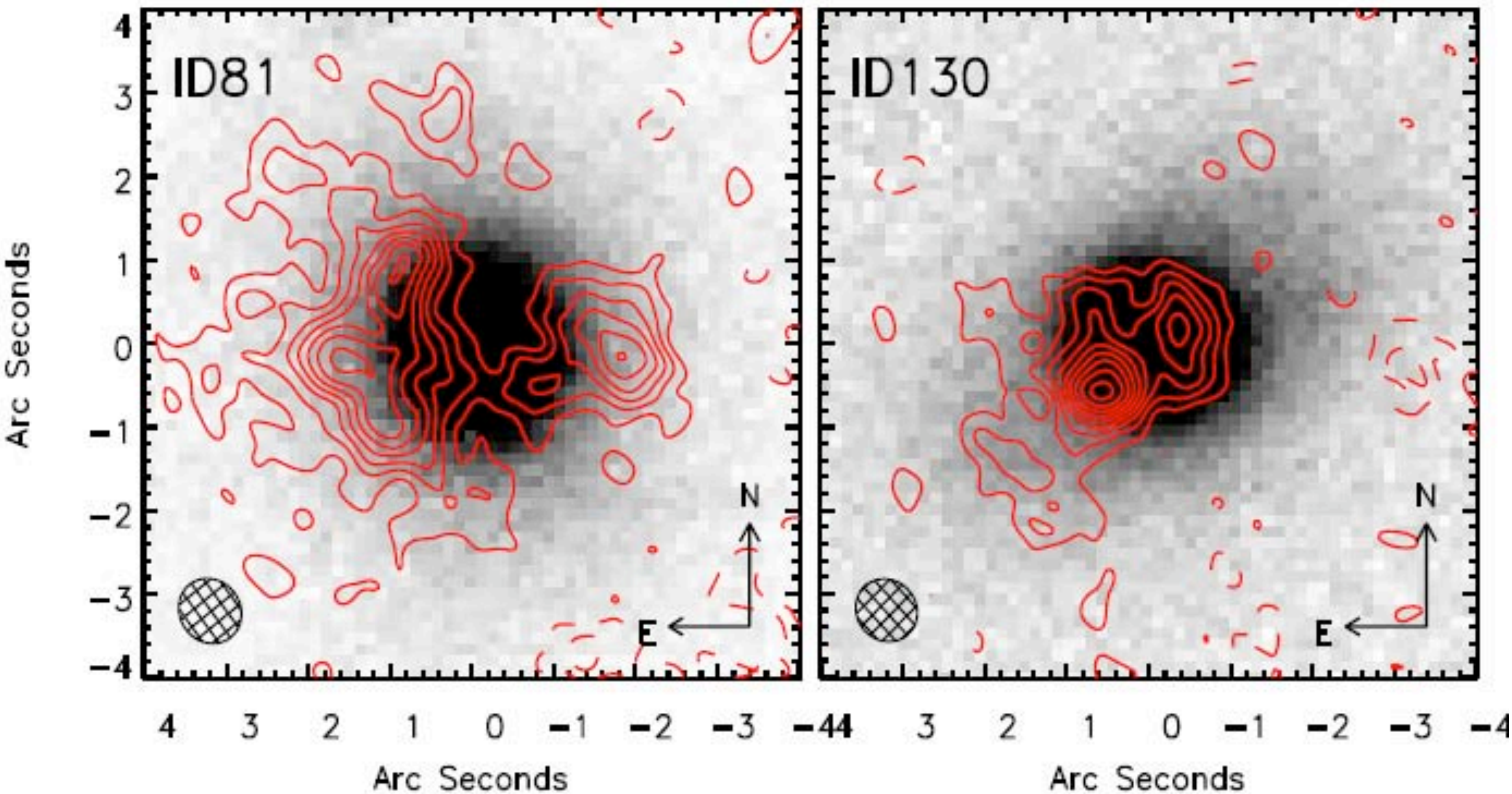
Negrello+2010

Best, highest-z H-ATLAS SDP lenses

Sub-Millimeter Array images at 870μm

Extended images: gravitational arcs on top of the lens galaxy

Red 870μm contours on top of I Keck image



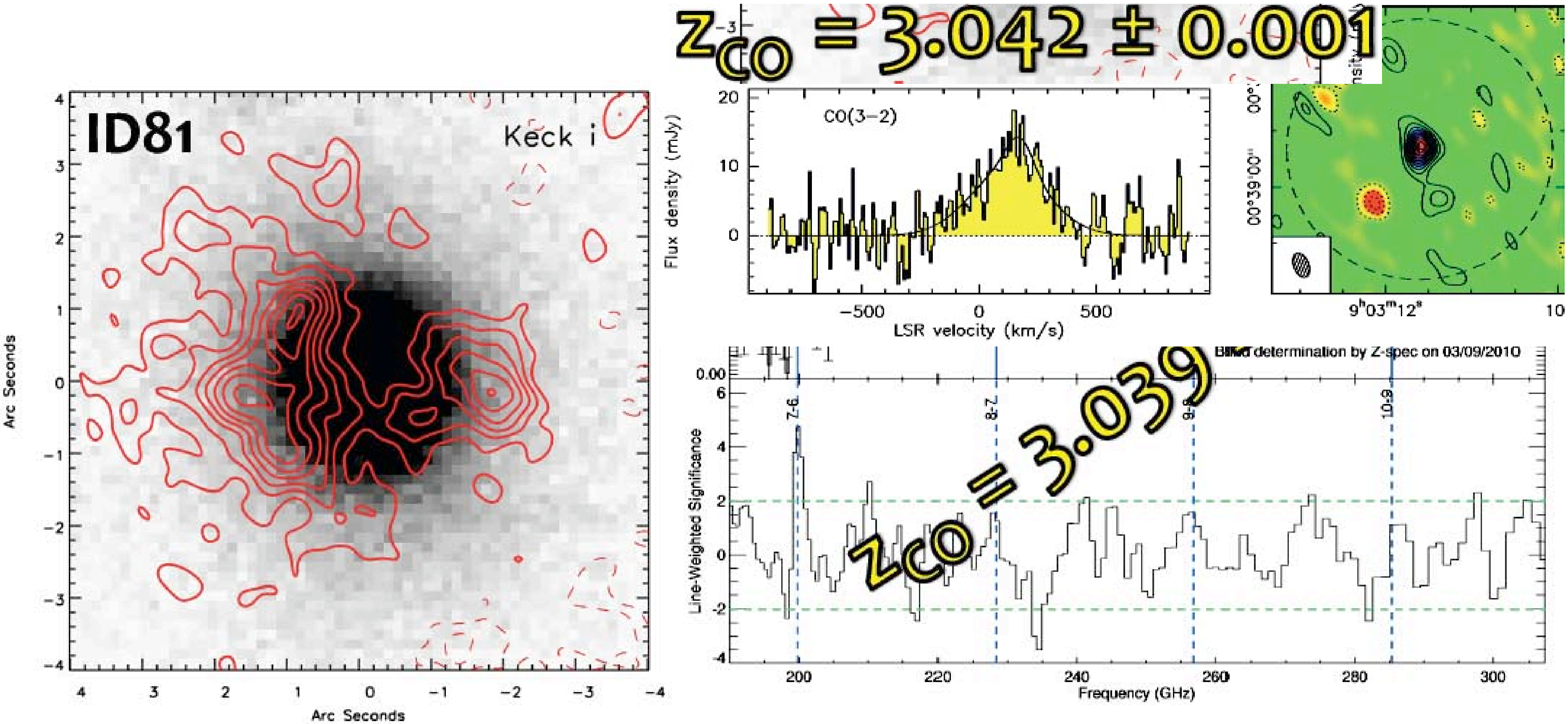
GRAVITATIONAL LENS CANDIDATES ID81

from Negrello ESLAB2010

see W. Gear

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

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

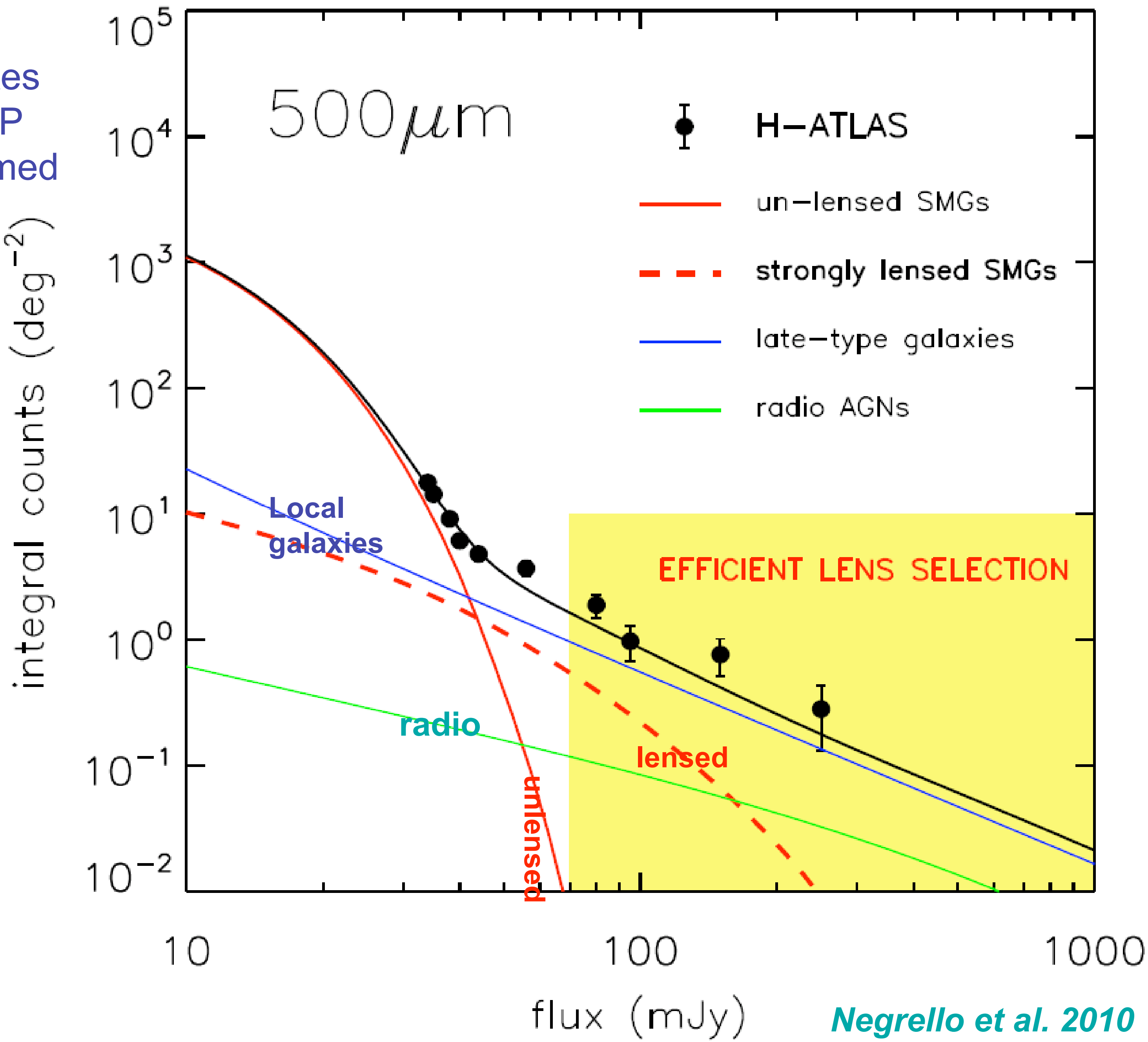


Redshifts of the 4 other candidates confirmed (1.5-2.6) by Zspec (+Zpectrometer, PdBI & CARMA)

Conclusion

The 5 lens candidates of the H-ATLAS SDP field are fully confirmed (z=1.5-3)

Source counts are in full agreement with Negrello's models



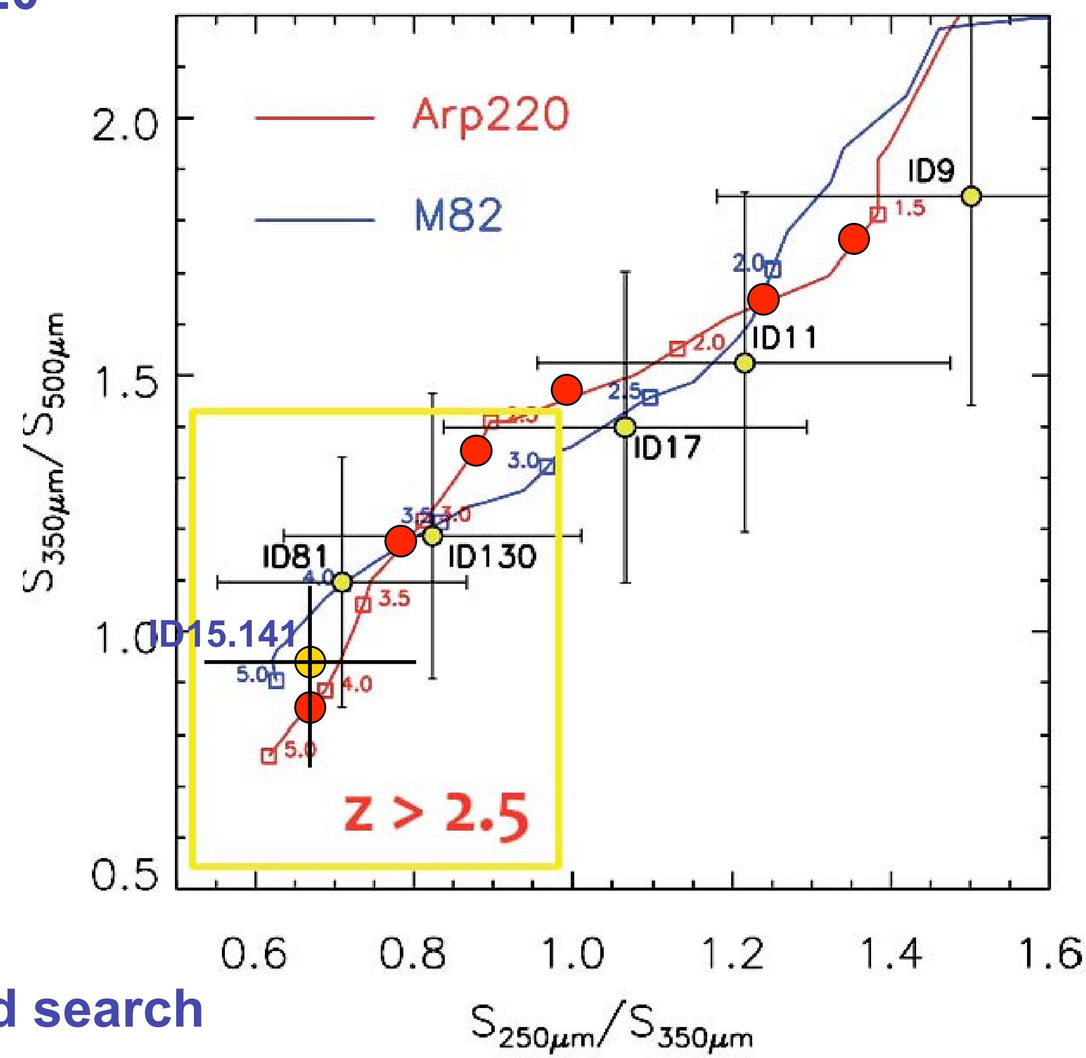
Negrello et al. 2010

Submmm photometric redshifts

Ratios S_{250}/S_{350} & S_{350}/S_{500} plus a template such as Arp220
→ submm z-phot

Good agreement with z_{CO} for 6 sources with z_{CO}

A good value of z-phot is important for searching z_{CO} with a limited bandwidth
Adding 1.2mm MAMBO flux helps: $S_{1.2mm}$=10-40mJy
Dannerbauer+



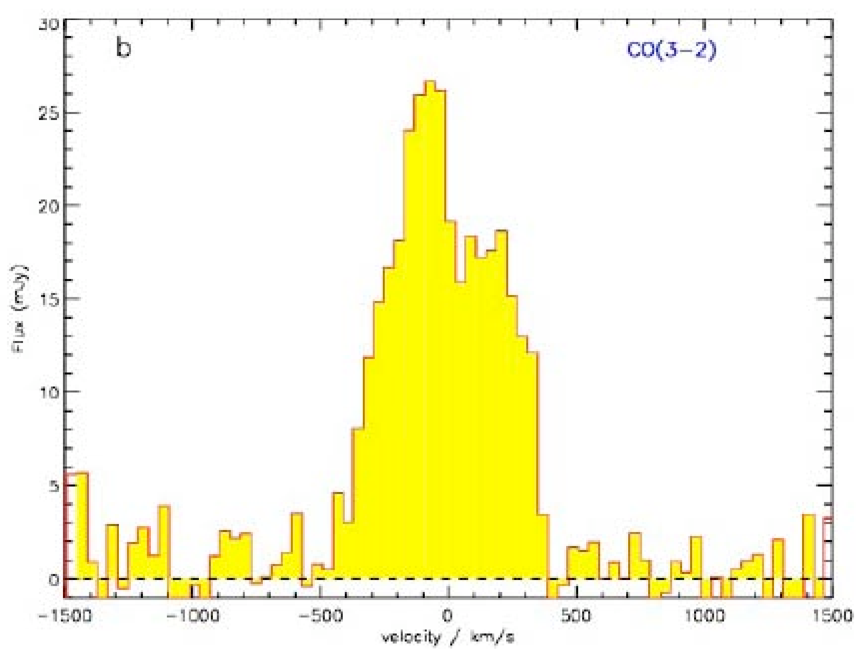
Measuring z_{CO} at z>~4 is difficult with Zspec, impossible with Zpectrometer
→ PdBI, EMIR or CARMA blind search
e.g. ID15.141 ***see W. Gear***

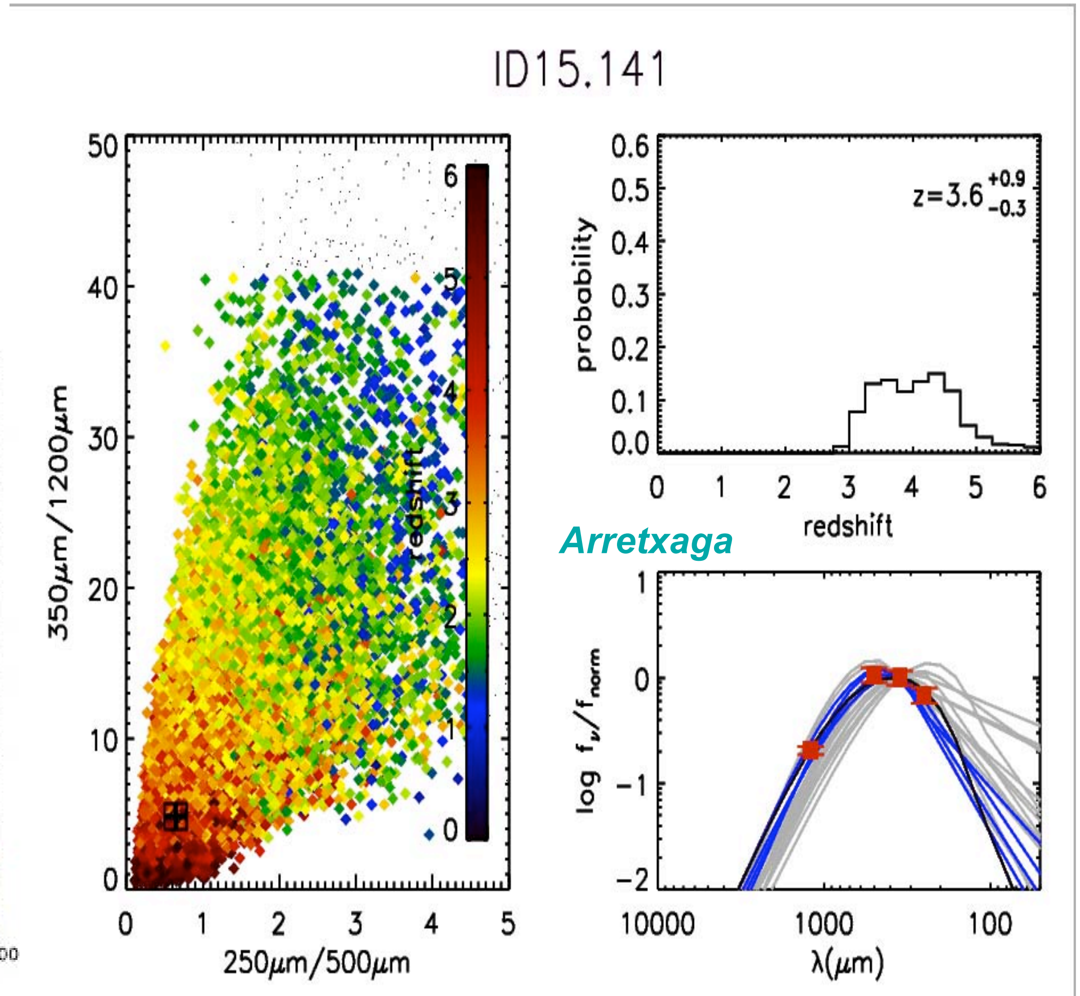
ID15.141 $S_{1.2mm}$=36mJy → blind z_{CO}=4.24 at PdBI

Blind detection of 3mm CO(3-2) [four 3.6GHz wide setups]

Confirmation of zCO with 2mm CO(5-4)

Later detection of CO(7-6)



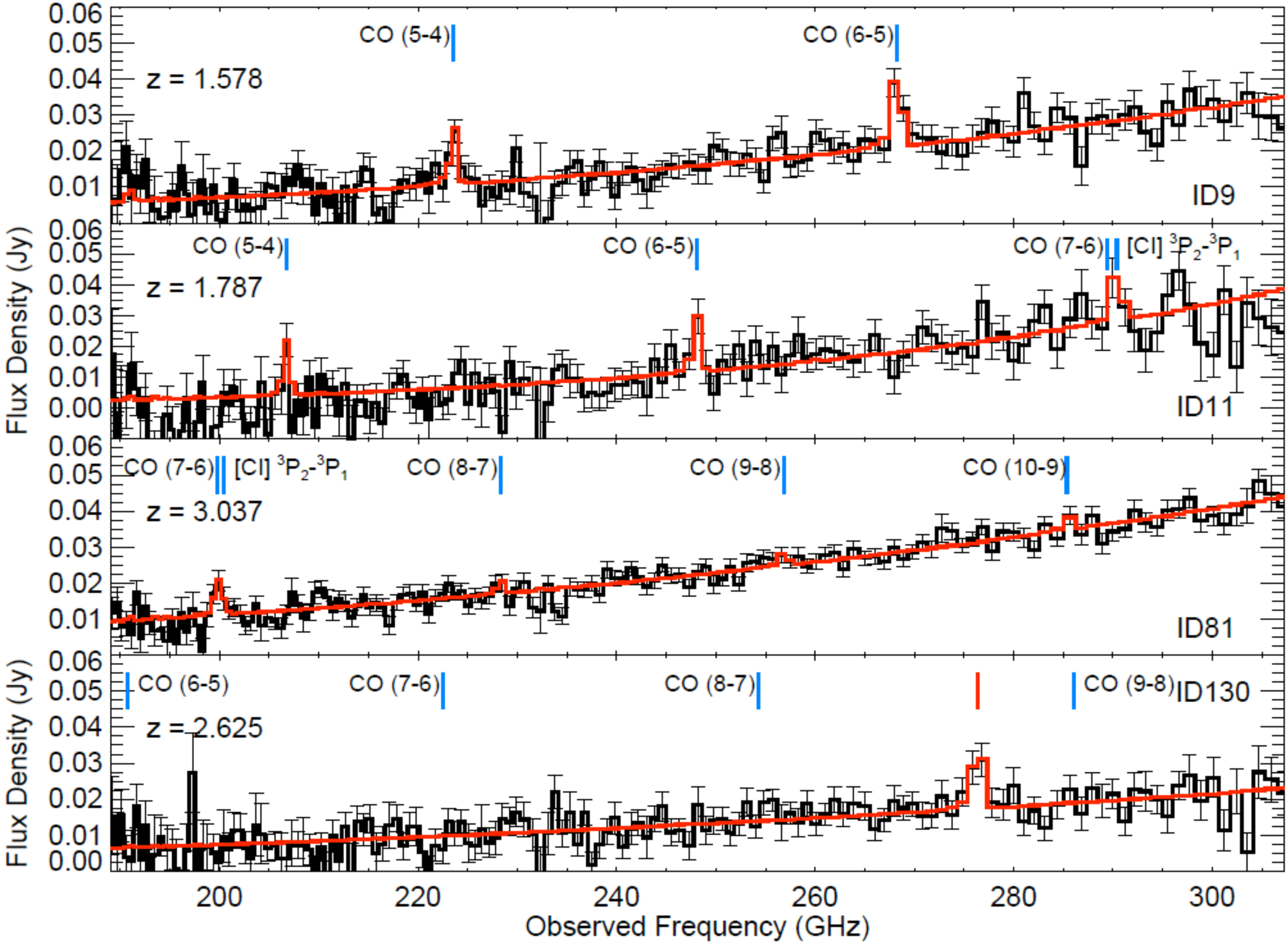


Intrinsic properties of the high-z lensed galaxies identified

- L_{IR}
  All apparent IR luminosities ~3-5 10^{13} Lo
  Typical expected amplifications of ~8-15 → ~2-6 10^{12} Lo → ULIRGs

- CO lines

Complete Zspec spectra ~200-300GHz *(Lupu et al. to be submitted to ApJ)*



CO (5-4)
CO (6-5)
z = 1.578
ID9
CO (5-4)
CO (6-5)
CO (7-6)
[CI] $^3P_2$-$^3P_1$
z = 1.787
ID11
CO (7-6)
[CI] $^3P_2$-$^3P_1$
CO (8-7)
CO (9-8)
CO (10-9)
z = 3.037
ID81
CO (6-5)
CO (7-6)
CO (8-7)
CO (9-8)
ID130
z = 2.625
Flux Density (Jy)
Observed Frequency (GHz)
0.00
0.01
0.02
0.03
0.04
0.05
0.06
200
220
240
260
280
300

Intrinsic properties of the high-z lensed galaxies identified

• L_{IR}

All apparent IR luminosities ~3-5 10^{13} Lo

Typical expected amplifications of ~8-15 → ~2-6 10^{12} Lo → ULIRGs

• CO lines:

- Complete Zspec spectra ~200-300GHz *(Lupu et al. to be submitted to ApJ)*

Several CO lines. Turnover <~CO(6-5) in several sources

However, strong CO(8-7) in ID17 (also tentative detection of H_20)

- CO profiles from PdBI and CARMA, widths ~200-500 km/s

• → normal SMGs (hints of AGN in a few)

• C^+ detected in ID15.141 (z=4.24) at APEX
low ratio C^+/CO *(Cox et al. in prep.)*

Prospects for the whole sample of high-z lensed SMGs to be expected from Herschel

- 5 lenses in SDP 14.4 deg^2 would extrapolate to 215 into the 720 deg^2 to be observed by H-ATLAS+HerMES surveys

  However there is indication that the density could be smaller in other fields

  Anyway the total number of lenses with S_{500} > 100 mJy should be **> 100**

- The number of sources increases rapidly in the range S_{500} ~ 60-80 mJy

  With many sources with $S_{500} > S_{350}$, probably at z >~4 (MAMBO proposal)

  These lenses could be the best way to assess the relative number of bright SMGs at z > 4

  Some of them could be the tip of the luminosity function of unlensed SMGs

  They are also detected in great number in 1.1-1.4 mm surveys such as SPT *(Vieira et al. 2010)*

Anyway, there will be 100's of strongly lensed sources available for ALMA

Large effort at IRAM this Winter

to confirm and characterizeH-ATLAS strong lenses

- **High-resolution PdBI observations of 6 H-ATLAS lenses**

  Cox & Ivison et al. ~90h

  CO lines J_{up}=3-7 (depending on z)

  will resolve the CO on scales of ~300pc

  tracing the internal excitation variations & star-formation within representative high-z ULIRGs

  Also a small PdBI project to confirm strong H_2O emission in ID17

- **Finding a large sample of lensed galaxies at z>4** ***(120 deg^2)***

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- **Finding a large sample of lensed galaxies at z>4** *(120 deg^2)*

3 steps:

- Select ~25 500µm-peakers without evidence of being local (S_{500}>60mJy)
- 1.2mm MAMBO observations to better constrain z-phot (and confirm they are indeed high-z sources)
- Blindly find z_{CO} at 3 mm at PdBI in ~10-20 best candidates

Plus MAMBO extension to prominent H-ATLAS 350µm-peakers,
with redshift measurement with Zspec or Zpectrometer
(plus HerMES sources) altogether ~100 sources observed with MAMBO

Large effort at IRAM this Winter

to confirm and characterize H-ATLAS strong lenses

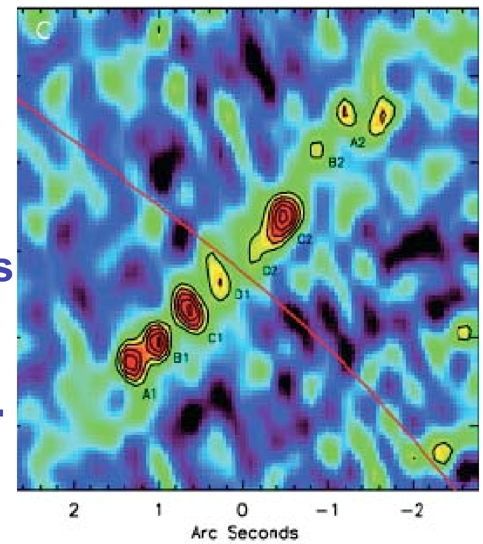
→Begin to product a very large sample of lenses with various goals:

- Studying high-z sources below the confusion limit
- Check lensing dark matter structures
- Search for a few ‘golden lenses’ with several high-z galaxies
- Explore SMGs at z>4
- Prepare detailed studies with ALMA of structure & dynamics at high-resolution, with deeper sensitivity

Examples of ALMA programs possible with Herschel lenses

- **Blind CO redshift determination and the highest redshifts**

  - Finding redshifts for 100's sources remain a major issue
  - z_{CO} is a must. May be extremely rapid with ALMA (1-2 3mm frequency settings)
  - Devise the best strategy



- **ALMA high-resolution imaging of strong lenses**

  - The example of SMMJ2135 (Eyelash) (Swinbank et al.2010) shows how very detailed investigations of its ISM are possible
  - ALMA can do that in the continuum, CO lines & C^{+}line etc.
  - Structure of the ISM and SF; AGN molecular torus
  - Dynamics: rotation, M_{dyn}, mergers, outflows, etc.

- **High sensitivity molecular (and atomic) spectroscopy**

- **Golden objects**

Examples of ALMA programs possible with Herschel lenses

- *Blind CO redshift determination and the highest redshifts*
- *ALMA high-resolution imaging of strong lenses*

- **High sensitivity molecular (and atomic) spectroscopy**

  - Comprehensive dataset of lines (e.g. SMM J2135 Swinbank+2010)

  - Detailed checks of the interstellar chemistry →PDRs, XDRs, shocks etc

  - Deuterated species (→ chemistry) and isotopologues ^{13}CO, $C^{17}O$, $C^{18}O$, $H^{18}O$ → nucleosynthesis + radiative transfer

  - Specific classes of sources: AGN, radio loud, various intrinsic L_{IR} ~10^{11}-10^{13} Lo, various environments; megamasers OH, H_2O

- Golden objects

Examples of ALMA programs possible with Herschel lenses

- *Blind CO redshift determination and the highest redshifts*
- *ALMA high-resolution imaging of strong lenses*
- *High sensitivity molecular (and atomic) spectroscopy*
- **Golden objects**

- "Golden lenses", with two background sources lensed by the same galaxy, making possible cosmological tests that are independent of the mass of the lens.

- Radio loud strongly lensed sources with possibility of observing absorption molecular lines in the intervening lens galaxy or in the radio galaxy

- Etc.

A very wide SPIRE shallow survey such as HSLS (see J. Wardlow) would tremendously increase the number of strongly lensed galaxies and populate rare classes of objects for comprehensive ALMA studies

Role of CCAT for selecting best Herschel sources for ALMA

- Analyzing proto-clusters through multi-object spectroscopy
- Disentangling blended sources and providing accurate positions

Role of CCAT for selecting best Herschel sources for ALMA

Analyzing proto-clusters through multi-object spectroscopy

➢ Providing redshifts for high-z Herschel sources is probably the most important issue for their exploitation

- Even for the very strongest lensed sources, measuring the redshifts of several hundreds sources will take years.
- However, they are only the very tip of the iceberg. There are thousands of weaker lenses potentially interesting, as well as tens of thousands of unlensed sources
- They will be key for addressing various major problems such as those discussed above about beating confusion, analyzing dark matter lensing halos, 'golden lenses', high sensitivity gains, and others including
  - Clustering of ULIRGs at high z (proto-clusters, filaments …)
  - Star formation in the first massive galaxies at z>5
  - Star formation in standard galaxies at the epoch of reionization through strong gravitational amplification
- Measuring redshifts for that, even in a very small part of high-z Herschel sources will be an enormous task

➢ CCAT is unique for that in two respects:
  - Directly measuring CO and C+ redshifts with its MOS
  - Disentangling blending and providing accurate positions for NIR MOS

Role of CCAT for selecting best Herschel sources for ALMA

Disentangle blended sources and provide accurate positions

- Even at 250µm the Herschel beam is very large (~18''). The difficulty of associating SPIRE sources with optical/NIR sources is worse than with SCUBA. This may prevent NIR redshift searches even with JWST

- Blending may plague SPIRE photometry especially at 350-500µm.

- Reobserving with CCAT some areas selected from SPIRE data, will overcome these problems, e.g. for:
  - near-IR redshift determination
  - analyzing fields with rich multi-λ data
  - proto-cluster studies, including at z >~ 5
  - detecting sources below the Herschel confusion limit associated with Herschel structures
  - detecting double galaxy occupancies of dark matter halos
  - analyzing Planck overdensities

This will much improve the use of Herschel data and their follow-up with ALMA

Summary

➢ With Herschel (together with SPT), wide submm surveys at poor resolution are already there for thousand sq. deg.

➢ This warrants background complementary information to best
- tailor CCAT programs at high z, in order to thus feeding ALMA
- (and JWST) with best sources

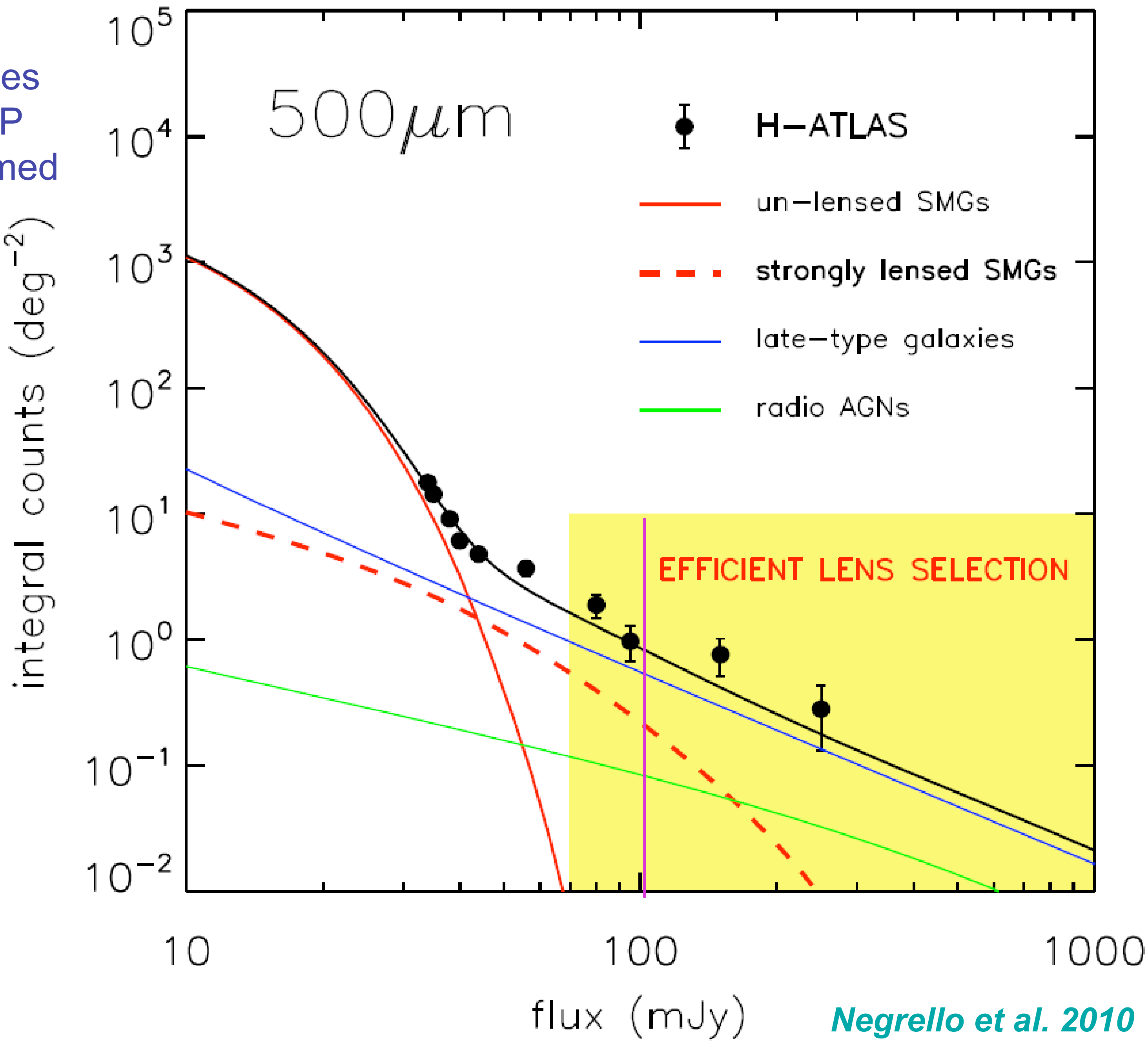
➢ Priorities for exploiting Herschel sources with CCAT seem:
- Measuring redshifts with CCAT/MOS
- Finding and deeply investigating high-z DM structures
- Exploring highest redshifts, >~4-5, up to reionization
- Exploiting gravitational amplification by finding the best lenses
- for ALMA (and JWST)
- We also need very wide 870μm surveys *(see J. Wardlow, M. Fich)*

Conclusion

The 5 lens candidates of the H-ATLAS SDP field are fully confirmed (z=1.5-3)

Source counts are in full agreement with Negrello's models

Natural cut at S_{500} ~70-100 mJy



Negrello et al. 2010

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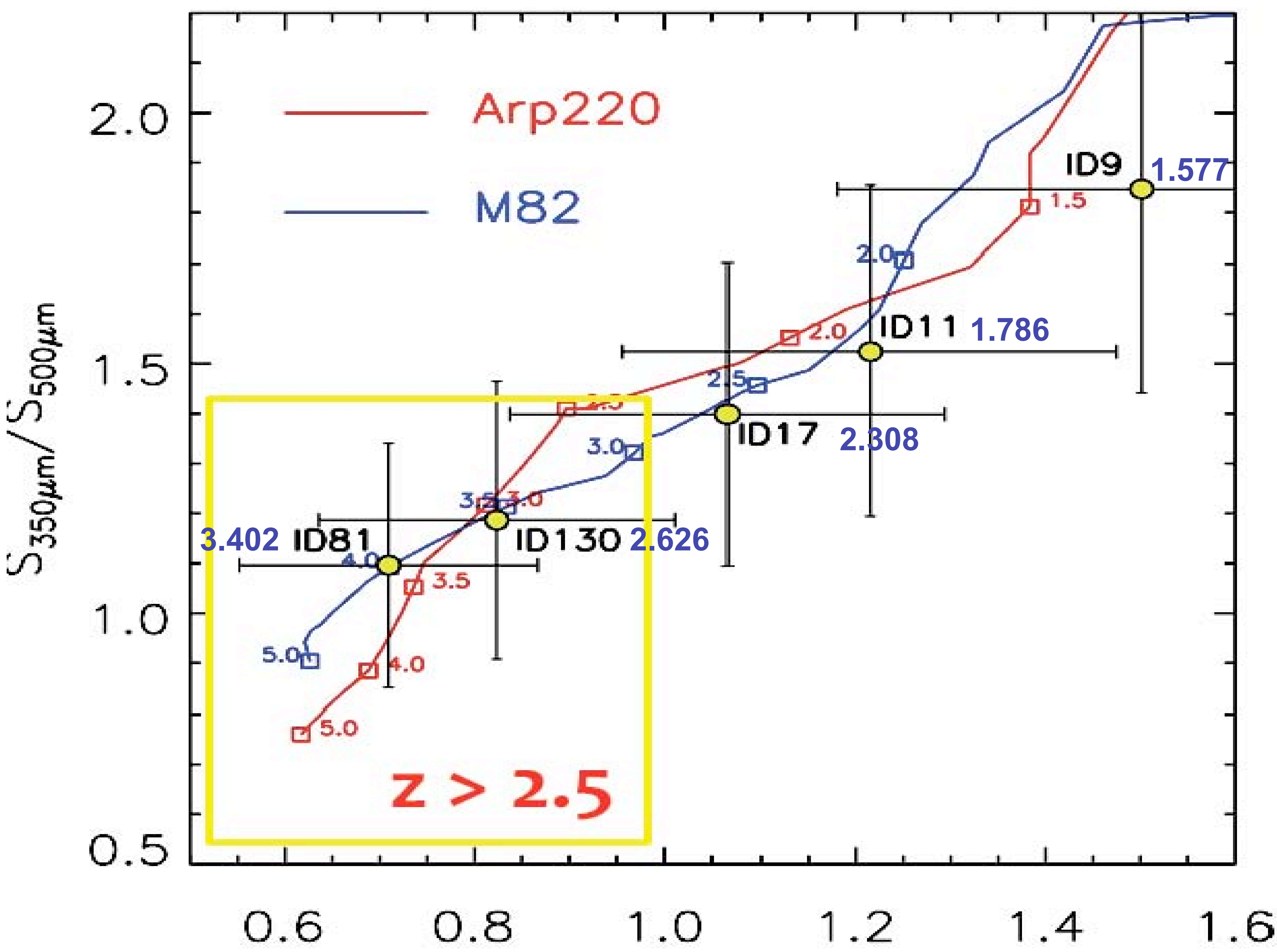


Arp220
M82
$S_{350\mu m}/S_{500\mu m}$
2.0
1.5
1.0
0.5
0.6
0.8
1.0
1.2
1.4
1.6
ID9 1.577
ID11 1.786
ID17 2.308
ID130 2.626
3.402 ID81
1.5
2.0
2.5
3.0
3.5
4.0
5.0
z > 2.5

Prospects, strategy and questions

- **There will be 100's of strongly lensed sources available for ALMA**

  - Object selection in function of goals

  - Systematic studies of specific classes if populated enough

  - Muli-λ studies: EVLA, JWST, HST, etc.

- However we could like to have even more strong lenses as could be provided by the proposed Herschel-SPIRE Legacy Survey (HSLS) that would cover 4000 $deg^{2.}$

This would allow in particular to populate rare classes of objects for comprehensive ALMA studies, e.g.

- highest redshifts, z>4 even z>5
- strong AGN of various types - radio loud
- $L_{IR}> 10^{13}Lo$, $L_{IR}<10^{12}Lo$
- H2O mega-masers
- cluster lensing - extremely strong amplification, etc.

- Studies of the lensing galaxies through ALMA observations will have important cosmological applications

But detailed lensing models are needed for inferring properties of lensed SMGs

- **Anyway, ALMA will have a fantastic time with such sources!**

Herschel high-z extragalactic wide surveys

- H-ATLAS 550 deg^2
- HerMES 70 deg2 deeper

  Both mostly SPIRE (250, 350, 500µm) close to confusion limit

- Plus
- PACS surveys: smaller areas, deeper
- HLS: lensing clusters,

  Etc.

- Proposed HSLS 4000 deg^2, purely SPIRE

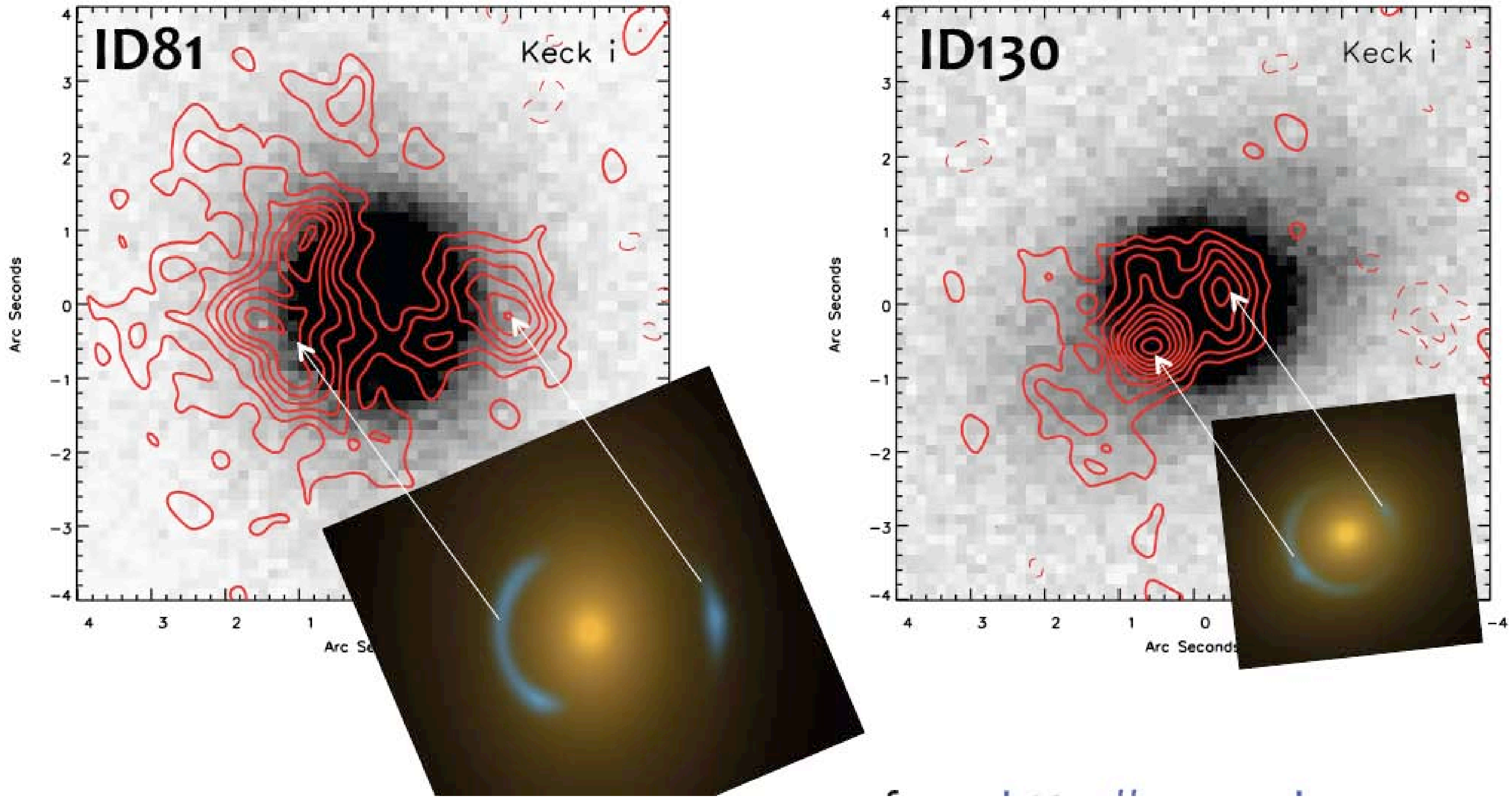
  Etc.

Gravitational Lens candidates ID81 – ID130

Sub **M**illimeter **A**rray follow-up at **870 μm**

(*very-extended*, *sub-compact* and *compact* configurations)

Extended images: gravitational arcs on top of the lens galaxy



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