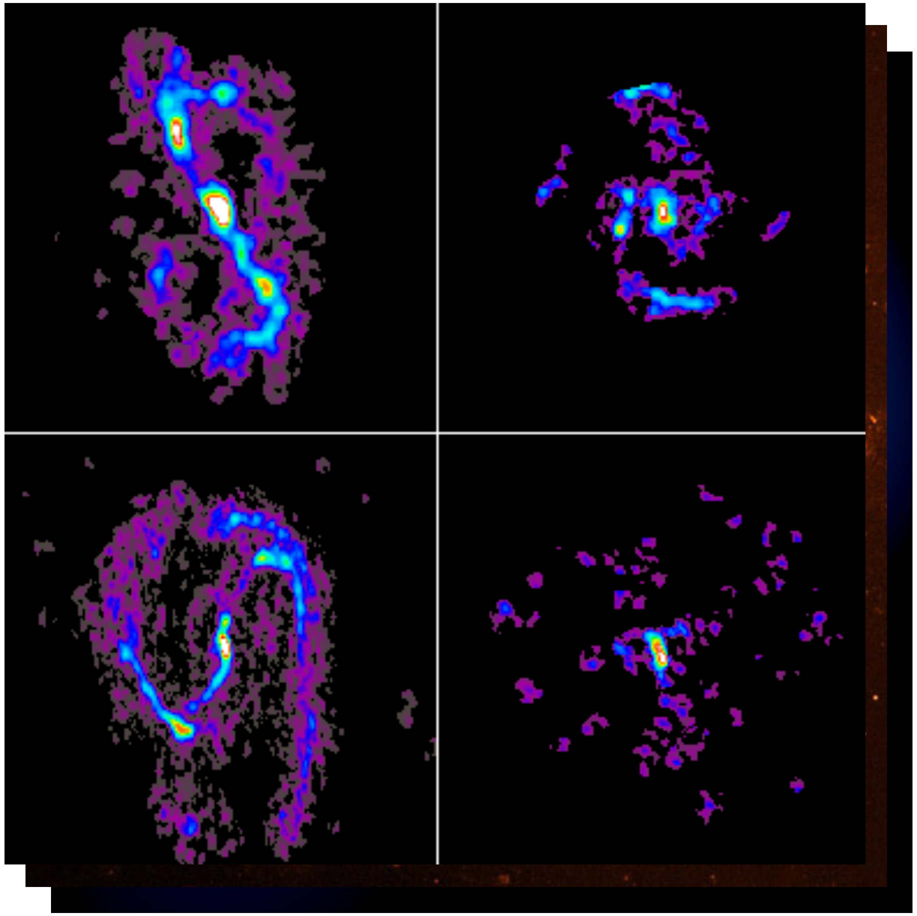

FIR/submm spectroscopy with Herschel:
results from the VNG and H-ATLAS
surveys
Maarten Baes
Jacopo Fritz
Naseem Rangwala
Pasquale Panuzzo
Ivan Valchanov
and many many others…

The ISM in galaxies

The ISM is violent and multiphase

- hot ionized gas
- HII regions
- dense molecular clouds
- diffuse ionized gas
- warm neutral gas
- cool neutral gas

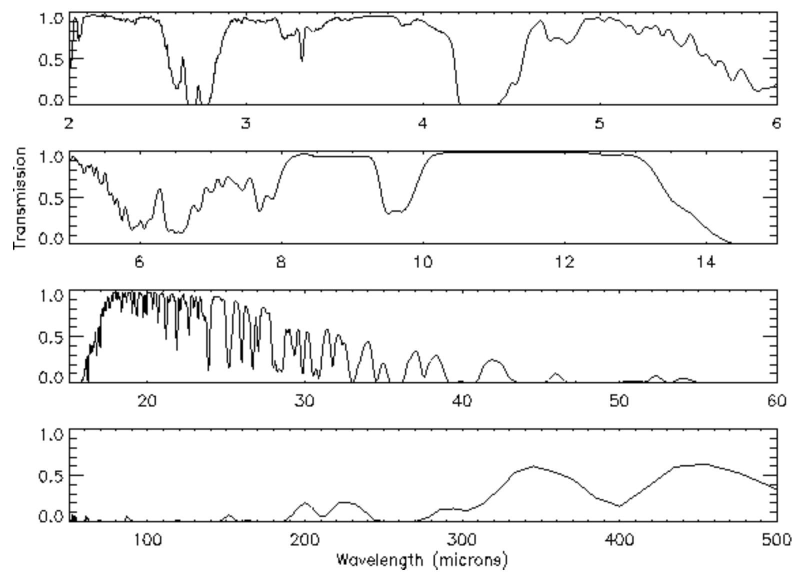
Contain the bulk of the ISM in normal star-forming galaxies. Heating and cooling mechanism are the more complex...

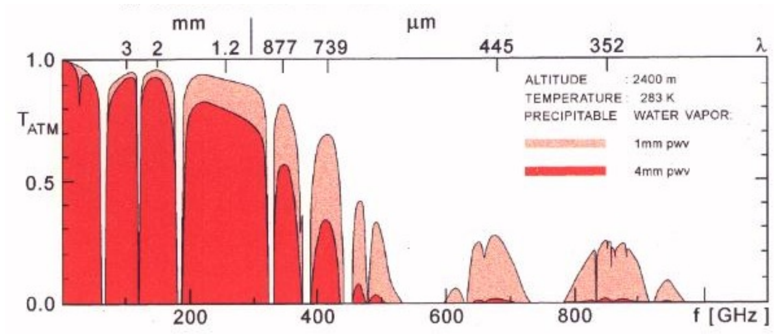


Heating and cooling in the ISM

A new exciting window on the ISM: spectroscopy in the FIR/sub-mm region.

- Contains diagnostic lines from the ionized, neutral and molecular ISM (including the lines that are dominate the cooling of the ISM)
- Continuum emission from cold dust





Problem: FIR/sub-mm observations are not easy to do…
Only low-J transitions of important molecules (CO, HCN…) can be done from the ground.

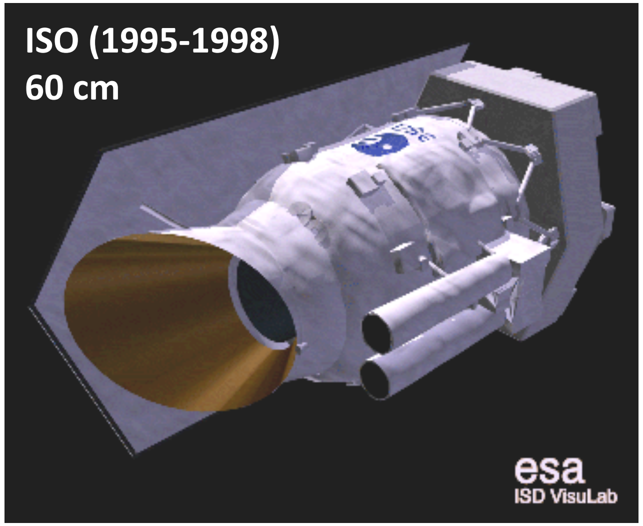
Important FIR/submm lines

[CII]	158 µm	Fine-structure lines of neutral atoms (and C^+ which has an ionization energy < 13.6 eV). Most important cooling lines of the neutral ISM
[OI]	63 µm	
[OI]	145 µm	
[CI]	370 µm	
[CI]	609 µm	
[NII]	122 µm	Fine-structure lines of ionized atoms. Important lines to probe the conditions in the ionized ISM (linked to SF or AGN).
[NII]	205 µm	
[NIII]	57 µm	
[OIII]	52 µm	
[OIII]	88 µm	
CO	sub-mm and mm	Many lines corresponding to rotational transitions in molecules. Ideal to probe the conditions in the molecular ISM.
OH		
H_2O		
HCN		
….		

Observing the cold ISM in galaxies

Options for FIR/sub-mm spectroscopy have been very modest

- IRAS: only continuum
- KAO FIFI: FIR up to 200 μm
- ISO LWS: FIR up to 200 μm
- Spitzer IRS: only up to 38 μm
- SOFIA: coming soon…



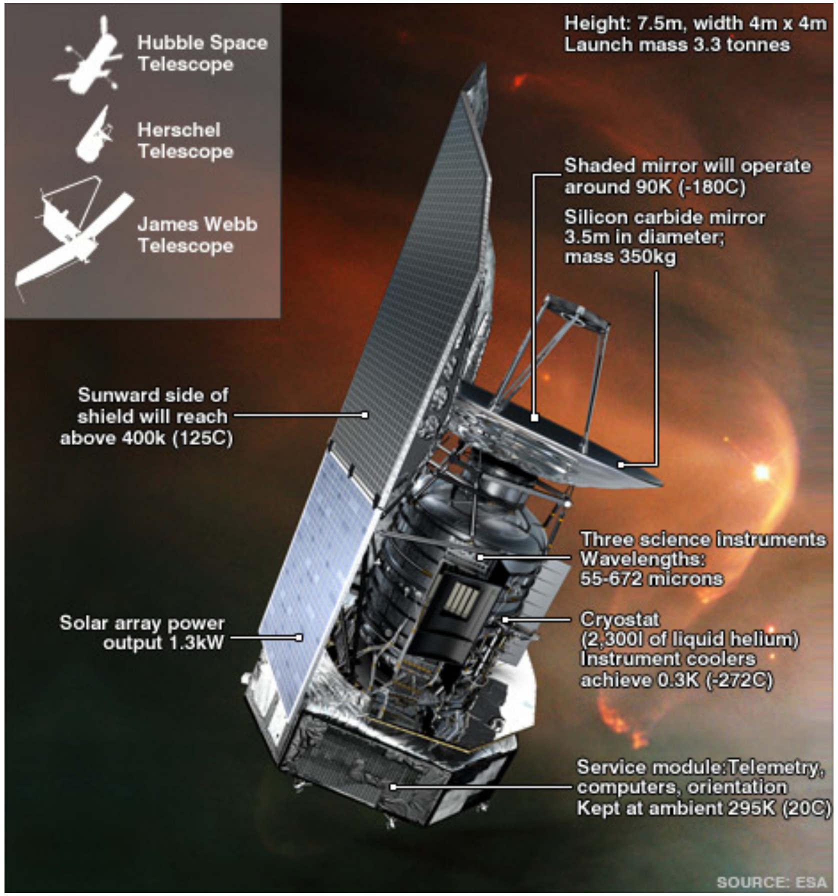
Herschel Space Observatory

Fourth cornerstone mission of ESA's Cosmic Vision 2005-2015
Contribution from NASA and CSA

Launched 14 May 2009, together with Planck

Main strengths of Herschel

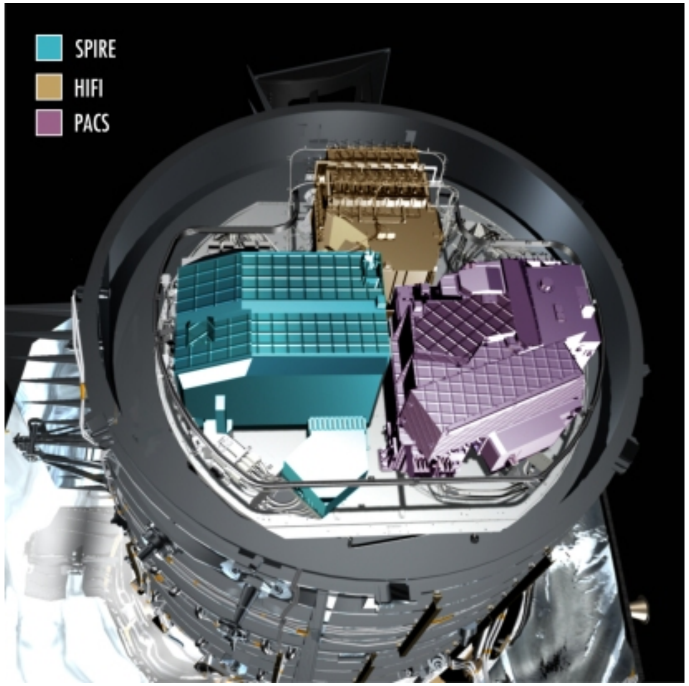
- Large, passively cooled, 3.5 m mirror
- Wavelength coverage to sub-mm wavelengths
- Position in L_2



Herschel instruments

Photodetector Array Camera and Spectrometer (PACS)

- imaging at 70, 100 and 160 μm
- integral-field spectroscopy (55-105 μm, 105-210 μm)
- resolution: 1000-5000



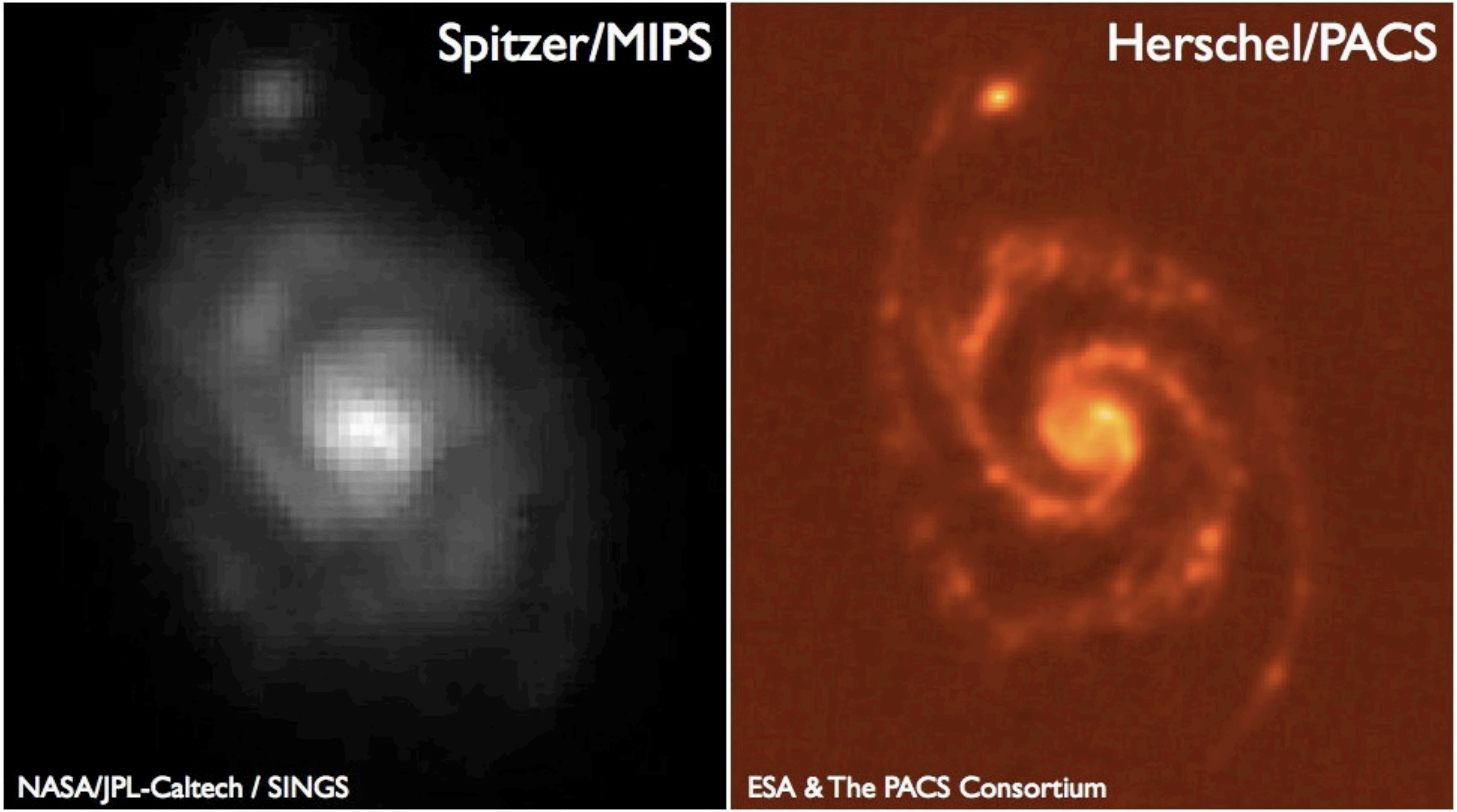
Spectral and Photometric Imaging Receiver (SPIRE)

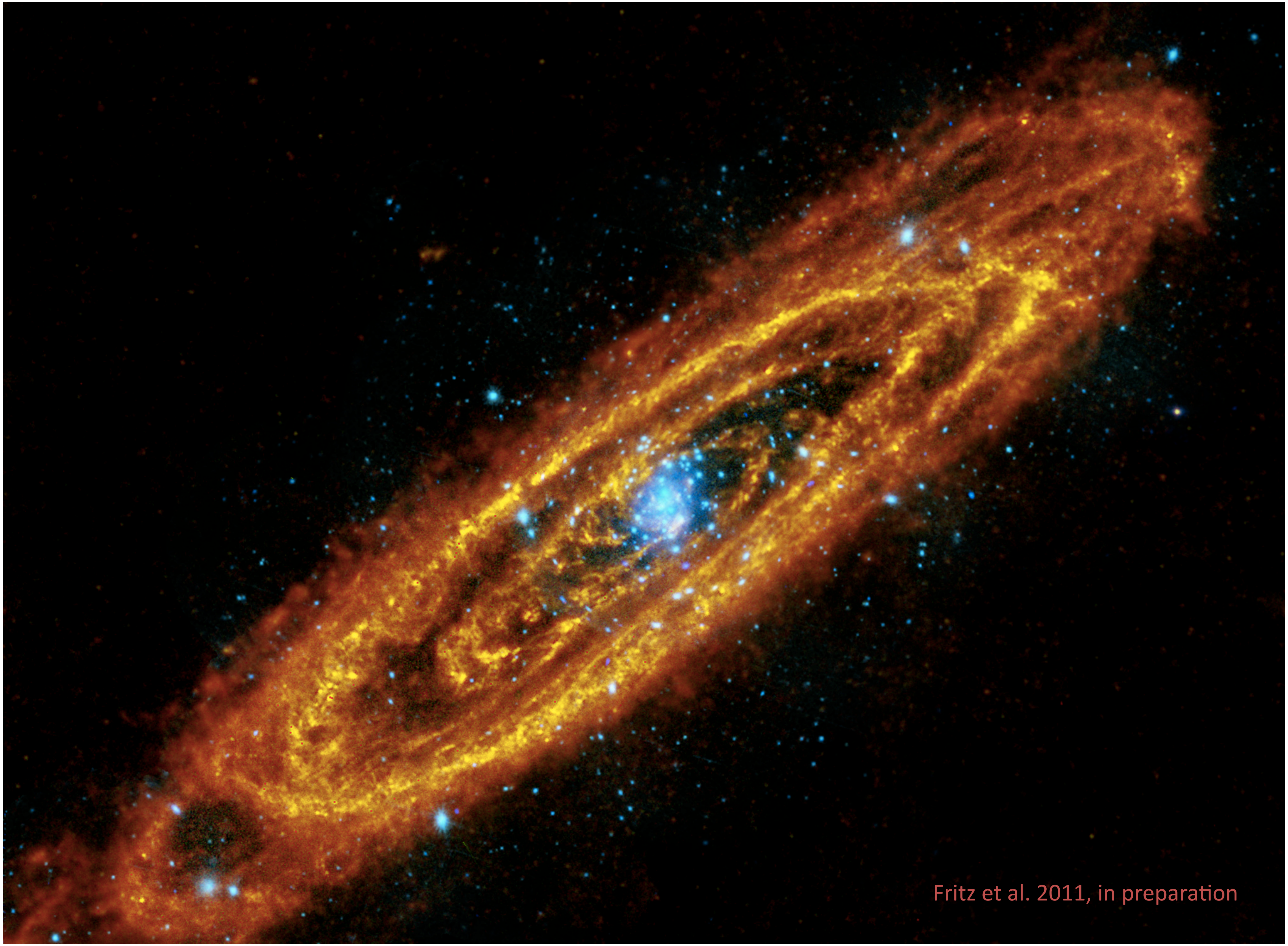
- imaging at 250, 350 and 500 μm
- imaging Fourier Transform spectrometer (194-672 μm)
- resolution: 40-1000 at 250 μm

Heterodyne Instrument for the Far Infrared (HIFI)

- seven-beam high-resolution spectrometer (157-625 μm)
- resolution: up to 10^7

Herschel first light...



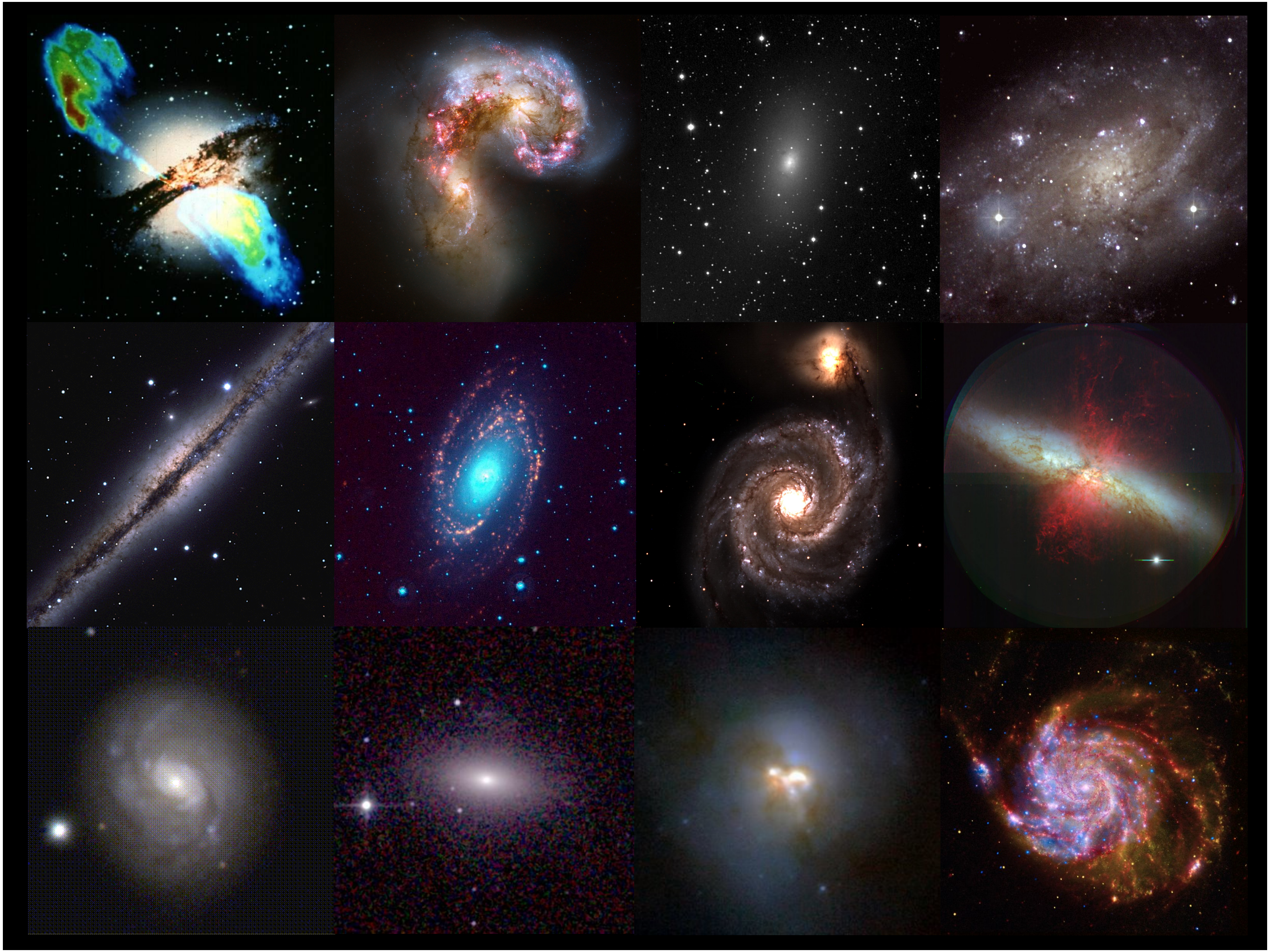

Fritz et al. 2011, in preparation

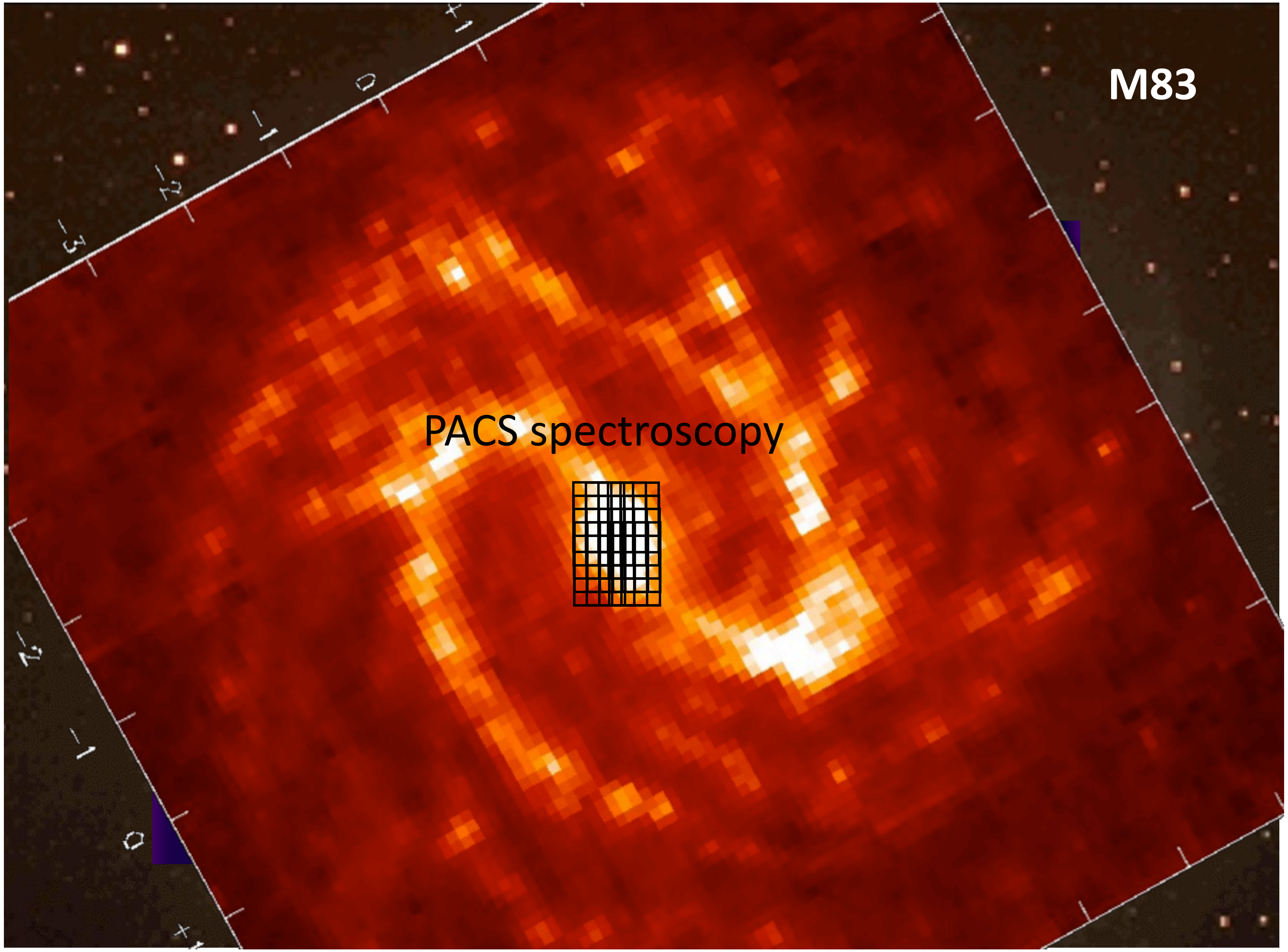
Very Nearby Galaxies Survey (VNG)

Detailed study of 13 large, prototypical galaxies

- deep PACS and SPIRE images
- PACS spectroscopy in several lines
- SPIRE FTS spectroscopy in the nucleus

Galaxy	FOV	PACS fields	SPIREphot	PACSphot	PACSspec	HIFI/FTS*	Total
M51	11'x7'	7	2.1	2.1	2.8	3	10.0 hr
M81	27x14'	18	5.4	5.4	5.2	3	19.0 hr
NGC2403	22x12'	14	4.4	4.4	4.4	3	16.2 hr
NGC891	13.5'x6'	9	2.2	2.2	3.3	3	10.7 hr
M83	13x12'	–	3.0	3.0	–	9*	15.0 hr*
M82	15x15'	–	3.7	3.7	–	9*	16.4 hr*
Arp220	2x1'	–	0.3(J)	0.3(J)	–	–	0.6 hr
NGC4038/39	6'x6'	–	1.5	1.5	–	–	3.0 hr
NGC1068	7x6'	–	1.6	1.6	–	–	3.2 hr*
NGC4151	6x5'	–	1.4	1.4	–	3	5.8 hr
CenA	26'x20'	16	6.9	6.9	4.1**	9*	26.9 hr*
NGC4125	6x3'	4	1.2	1.2	2.2	3	7.6 hr
NGC205	22'x11'	14	4.1	4.1	4.4	3	15.6 hr
Total			37.8 hr	37.8 hr	26.4 hr	21/27* hr	150.0 hr





AAT optical [C II] FIFI/KAO ISOCAM 7 µm

Very Nearby Galaxies Survey (VNG)

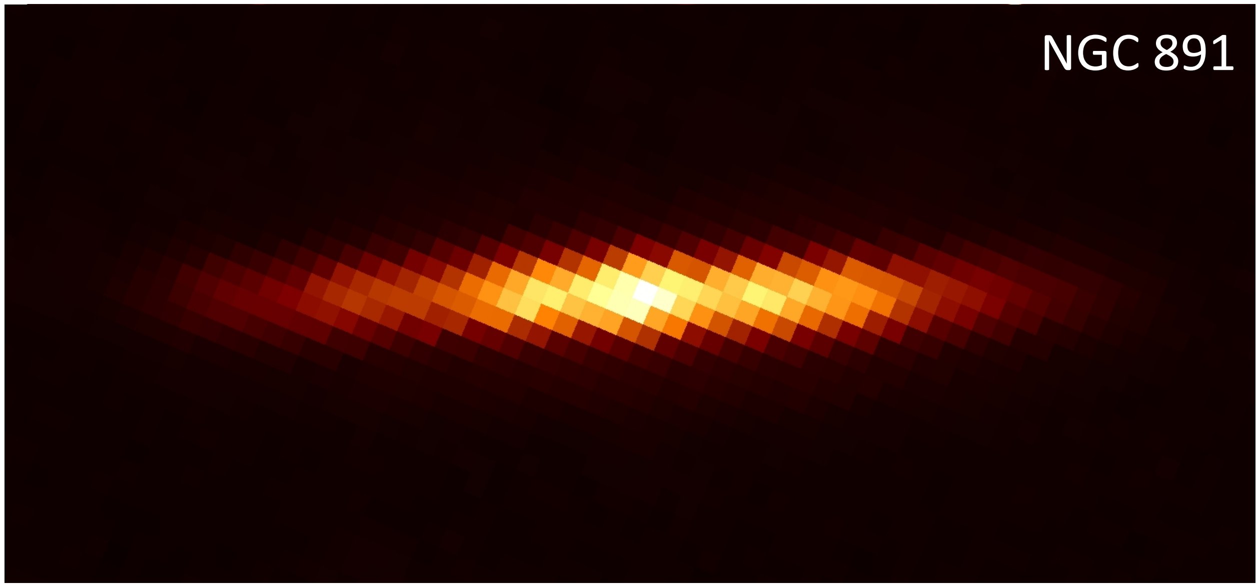
Detailed study of 13 large, prototypical galaxies

- deep PACS and SPIRE images
- PACS spectroscopy in several lines
- SPIRE FTS spectroscopy in the nucleus

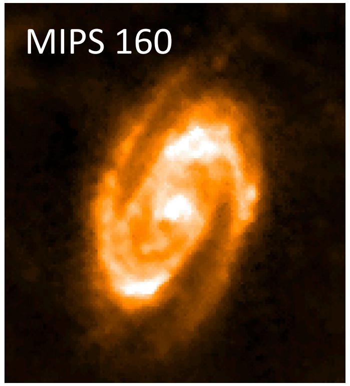
Most of the imaging data available

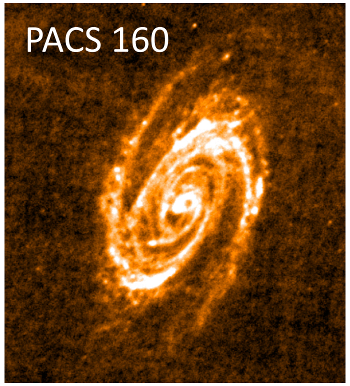
Some FTS and PACS spectroscopy already available…

[illegible]



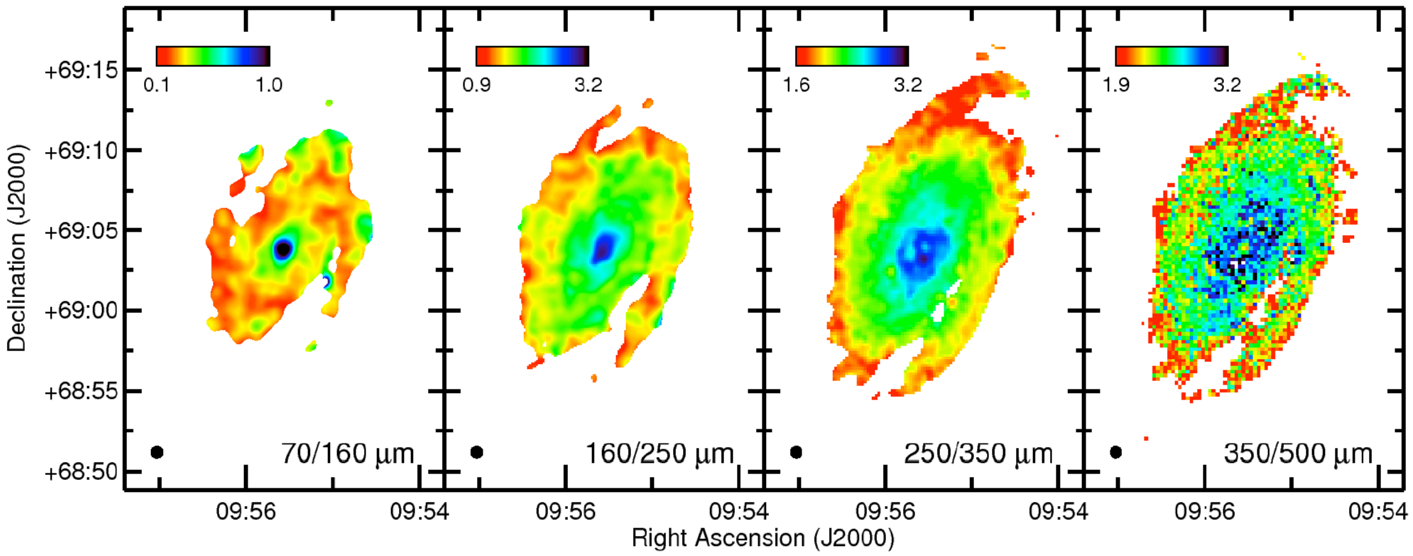
Interstellar dust in M81





Science Demonstration Phase observations of M81:
spectacular improvement of resolution compared to Spitzer

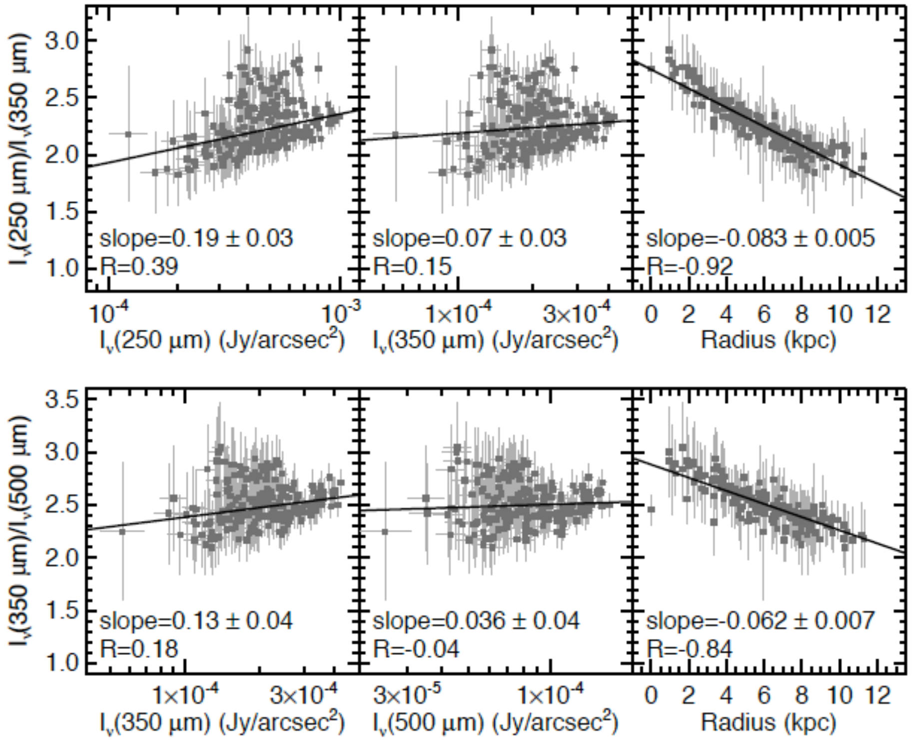
Bendo et al. 2010



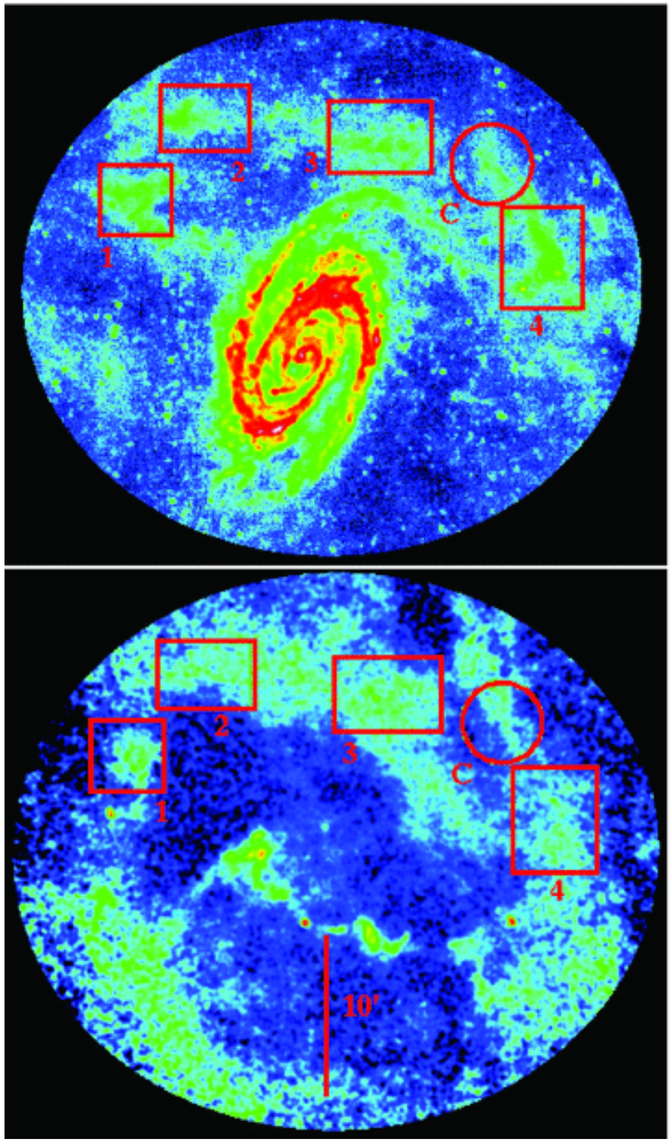
Bendo et al. 2010

250/350 and 350/500 ratios correlate with radius but not with surface brightness

160-500 μm emission traces 15-30 K dust heated by evolved stars in the bulge and disc.
70 μm traces dust heated by star forming regions and AGN.



Interstellar dust in the M81 group



Diffuse FIR emission in the M81 group – often considered to be intra-group material.

Striking correlation between Herschel data and THINGS HI data in a very narrow frequency range (2-3 km/s). Suggests a Galactic cirrus origin for the diffuse FIR emission.

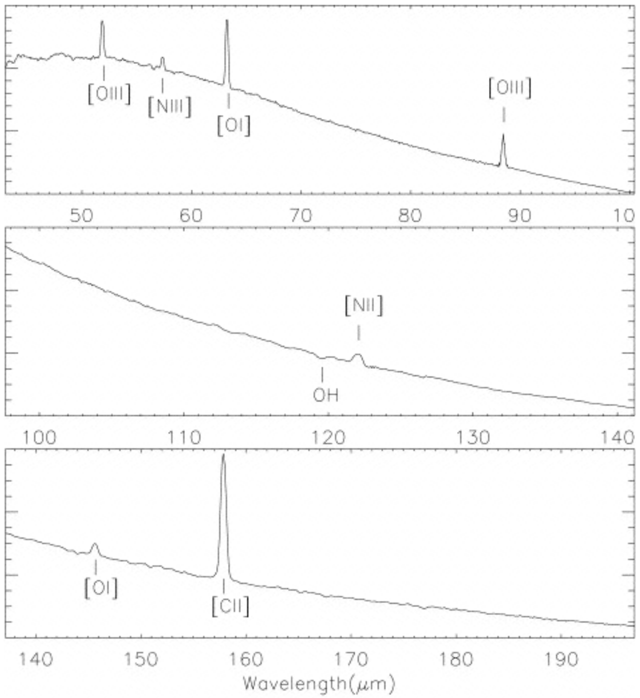
Davies et al. 2010


M82

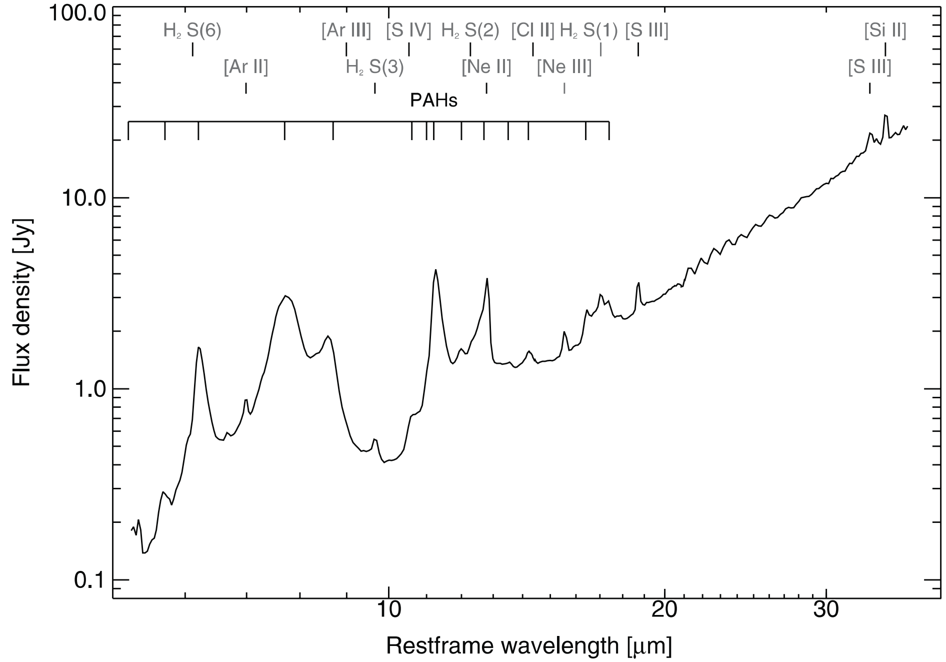
M82

Nearest (3.4 Mpc) powerful starburst galaxy with galactic fountain (outflowing ionized gas). Atomic lines prominent in ISO LWS spectrum.

Remarkable feature in Spitzer IRS spectrum: prominent H_2 rotational lines indicate substantial amount of warm molecular gas…



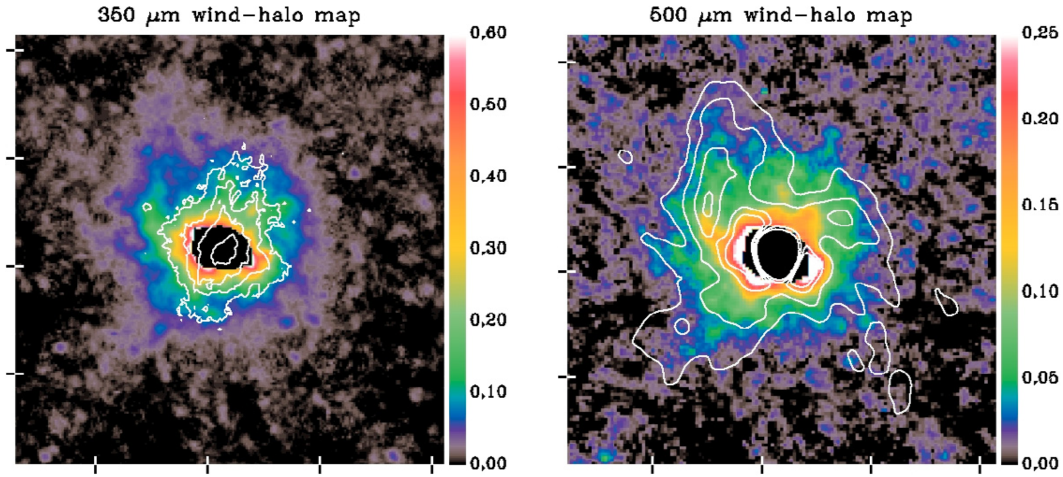
Colbert et al. 1999



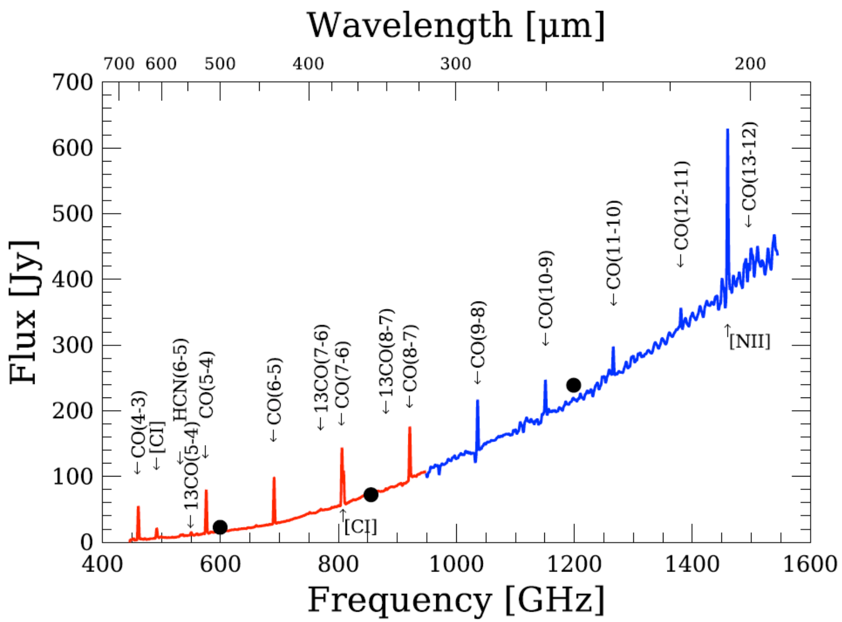
Beirão et al. 2008

SPIRE observations of M82

SPIRE imaging reveals strong dust emission in the halo and tidal streams. Direct proof of efficient enrichment of the ICM with metals.



Roussel et al. 2010

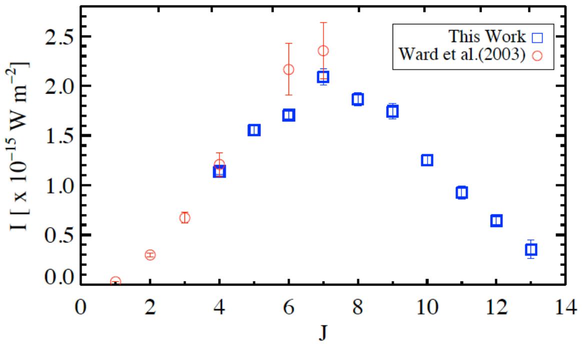


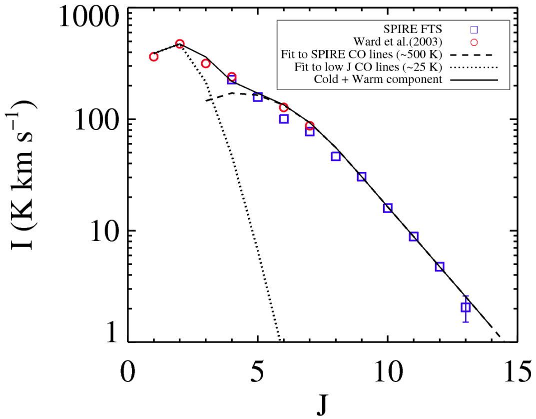
SPIRE spectroscopy of central 43”: detects mainly lines of CO and ^{13}CO.

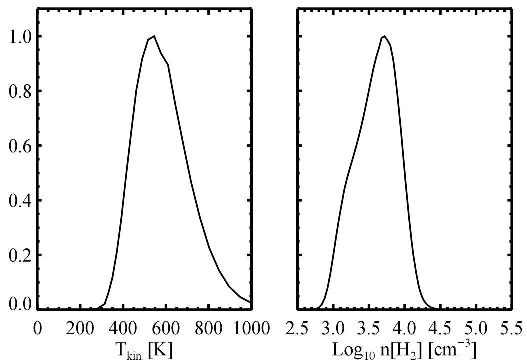
Combination of SPIRE spectroscopy and ground-based spectroscopy: continuous CO ladder from J=1-0 to J=13-12

Panuzzo et al. 2010

CO ladder in M82







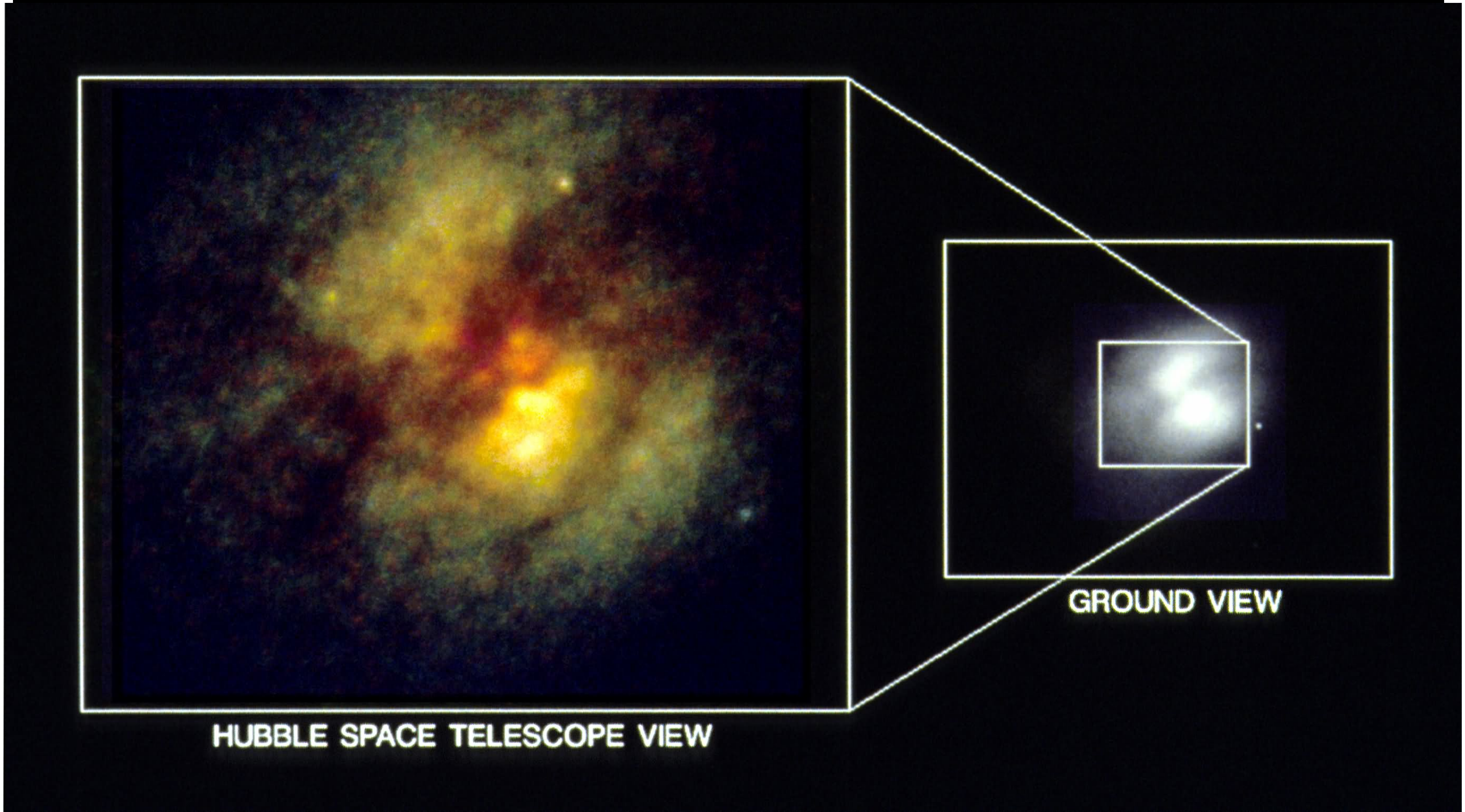
NLTE radiative transfer modelling: proves the existence of warm 500 K molecular gas in M82, next to the cold component (25 K) detected at low J.

At these <u>temperatures</u>, MIR H_2 lines (and not CO or [CII] lines) <u>are the dominant coolant of the ISM</u>. In agreement with Spitzer IRS spectrum.

Dominant heating mechanism of the warm CO gas: mechanical heating from stellar winds and supernovae (UV-powered PDR, X-ray powered XDR and cosmic rays are excluded).

Panuzzo et al. 2010

Arp 220

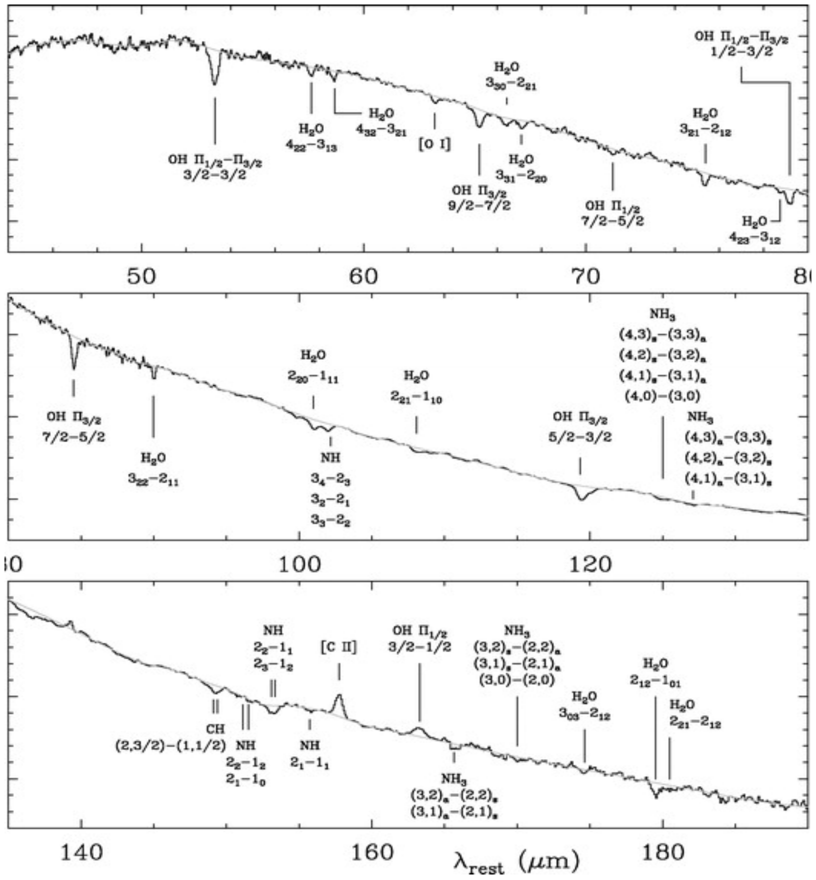


Arp 220

Nearest (77 Mpc) ULIRG with $L_{FIR} \approx 10^{12}\ L_{\odot}$. Contains 2 merging nuclei and a completely optically thick merger-induced star formation burst.

Huge reservoir of molecular gas available (about $10^{10}\ M_{\odot}$). FIR spectrum (ISO LWS) very different from M82 spectrum: many emission and absorption lines of molecules (OH, H_2O, NH, NH_3…)

Important unresolved question: does Arp 220 host an AGN (important as Arp 220 is often used as template for high-z galaxies)



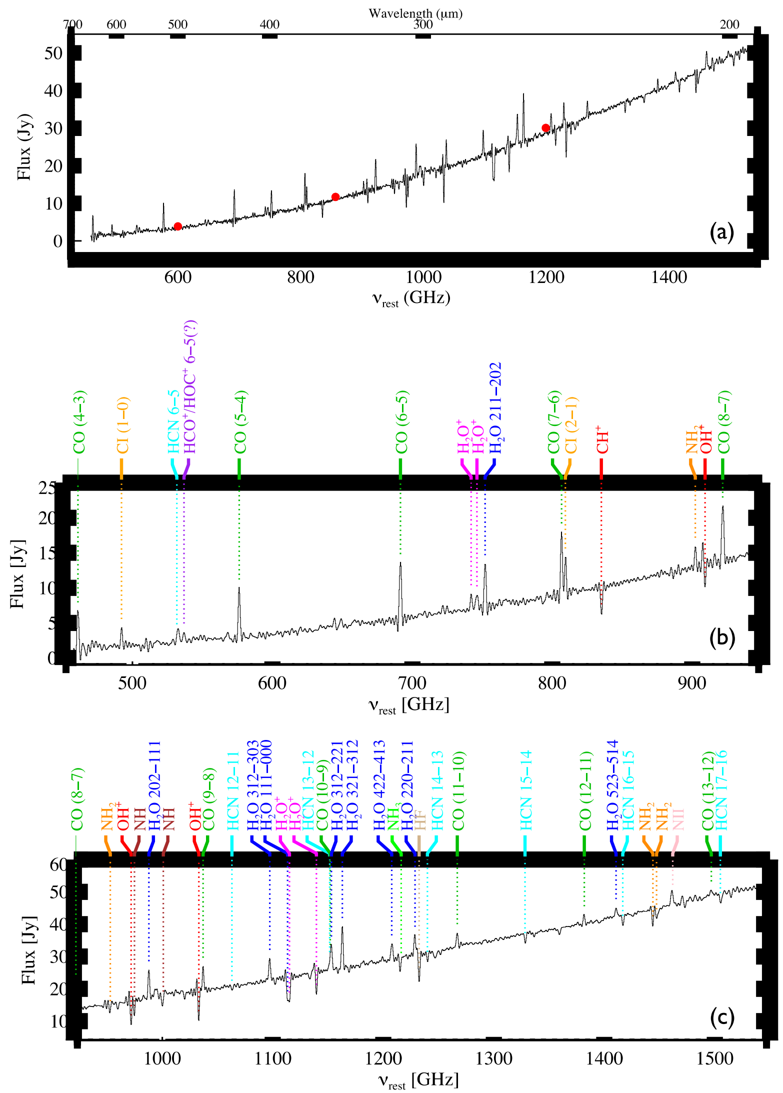
Gonzalez-Alfonso et al. 2004

SPIRE spectroscopy of Arp 220

Deep SPIRE FTS spectrum (200-670 μm) with very good calibration (5%) and an impressive set of lines.

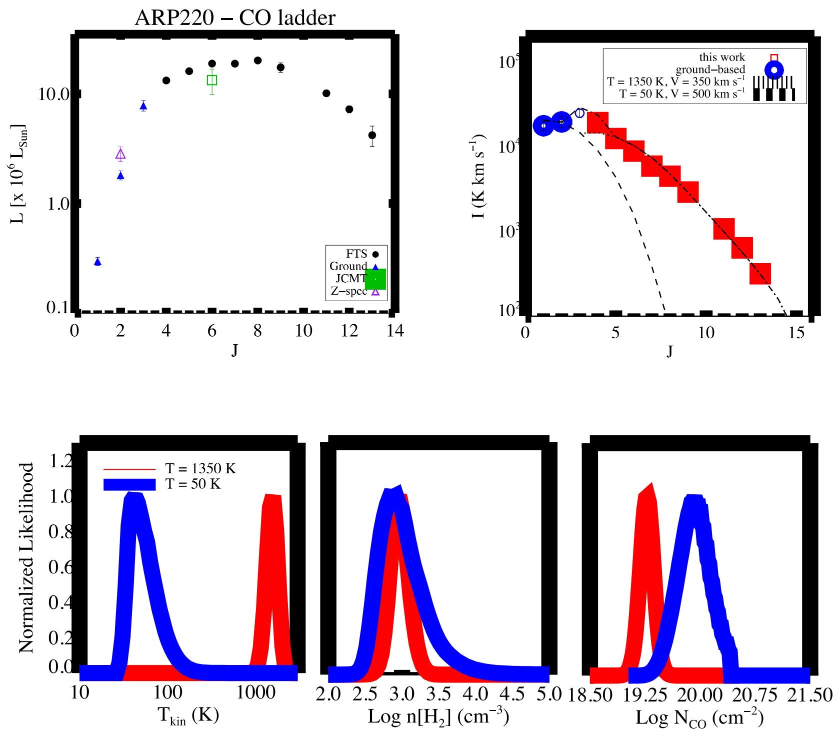
Emission lines of atoms (CI and [NII]) and molecules (CO, H_2O…). Impressive: total luminosity in H_2O similar to luminosity in CO lines: cooling by water is very important !

Also many molecular lines in absorption. Very prominent absorption lines from hybrids (H_2O^+, CH^+, OH^+). Their abundances support the presence of a hidden AGN.



Rangwala et al. 2011, submitted

CO ladder in Arp 220



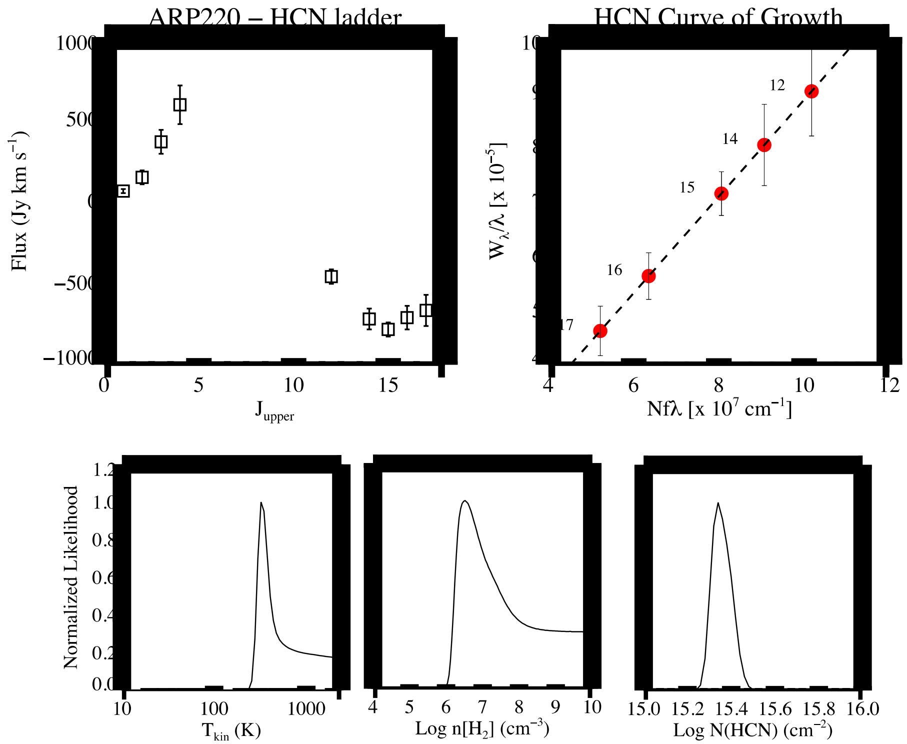
Similar approach as for M82: NLTE radiative transfer modelling of CO ladder (combination of ground-based and SPIRE lines).

CO SLED can only be explained by combination of cold (50 K) and warm (1350 K) gas. Warm CO component contains only 10% of mass, but dominates the luminosity and the cooling.

Heating mechanism similar as for M82: XDR, PDR and cosmic rays are improbably, mechanical heating remains possibility.

Rangwala et al. 2011, submitted

HCN ladder in Arp 220



HCN can be a very good tracer for dense molecular gas (rotational transitions have critical densities 100-1000 times those of CO).

Low-J transitions detected from the ground, high-J transitions in absorption by SPIRE.

NLTE HCN ladder modelling: evidence for "infrared pumping mechanism" of photons at 14 μm. Requires an intense radiation field with T>350 K.

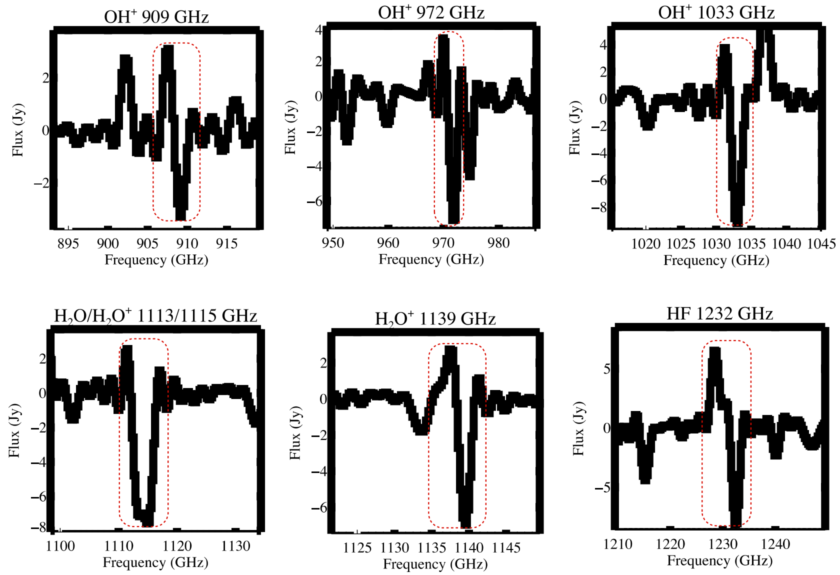
Rangwala et al. 2011, submitted

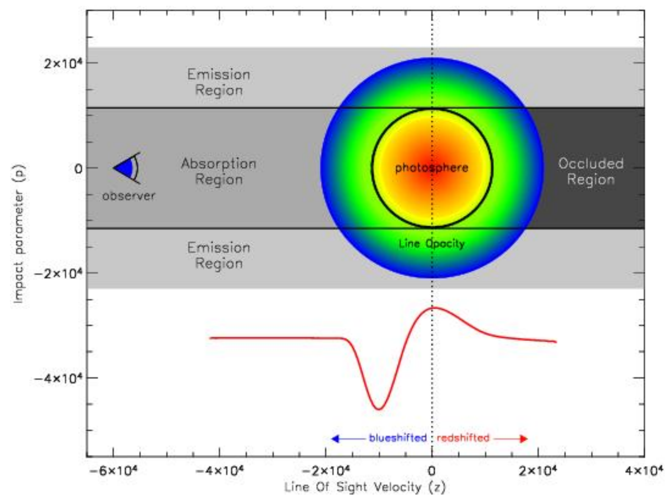
A molecular outflow in Arp 220

Remarkable line shapes of OH^+, H_2O^+ and HF lines: P Cygni profiles.

Strong signature of outflow activity. Direct evidence of feedback mechanism (very important ingredient in galaxy evolution studies).

Unfortunately, lines are not well resolved, so impossible to measure outflow velocity and outflow rate. Herschel HIFI follow-up observations of selected lines are scheduled.





Rangwala et al. 2011, submitted

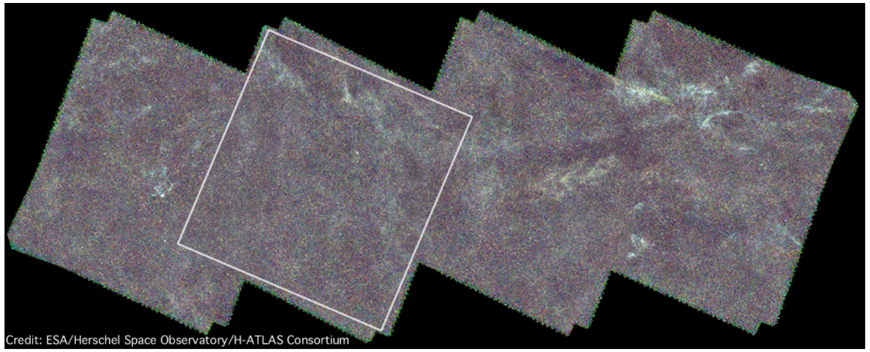
The Herschel ATLAS

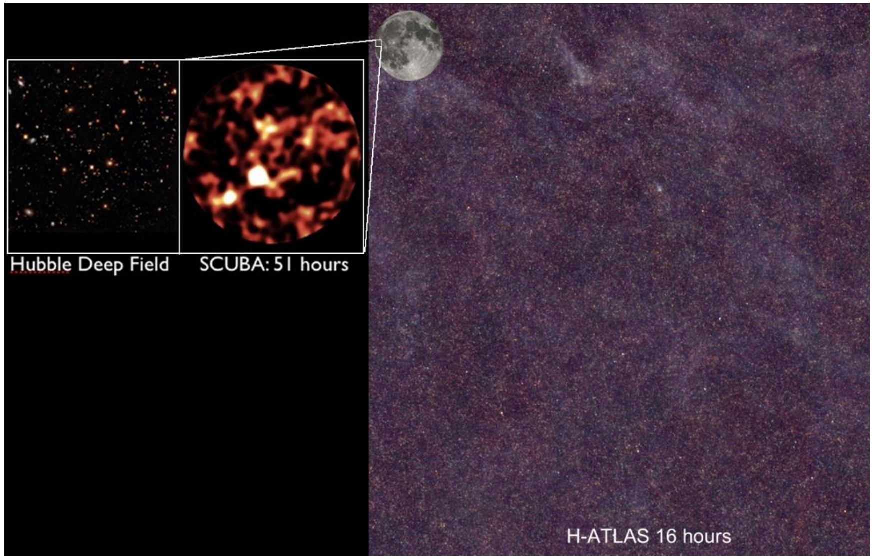
Widest area survey with Herschel (550 deg^2). Covers 5 bands with PACS and SPIRE (100-500 μm)

Consortium of 150+ astronomers worldwide, from galactic astronomers to cosmologists

Expected catalogue: about 10^5 sources, up to z>3

Primary aim: provide the kind of leap in the FIR/sub-mm that 2dF/SDSS made in the optical

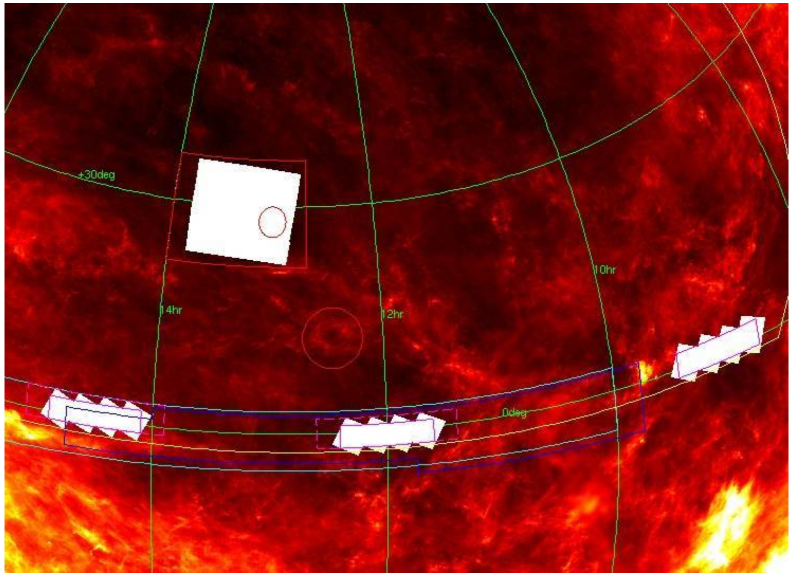


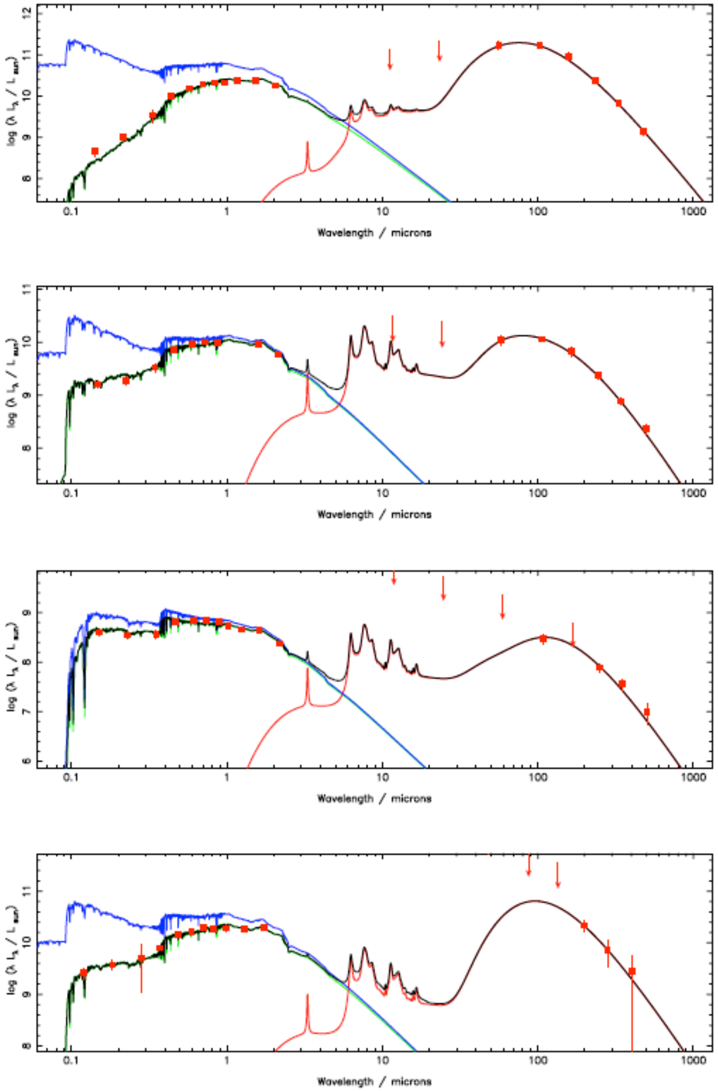


Eales et al. 2010

The Herschel ATLAS

Collaboration between H-ATLAS and GAMA consortia: redshifts and UV/optical/NIR imaging and spectra for many nearby (and distant) galaxies.

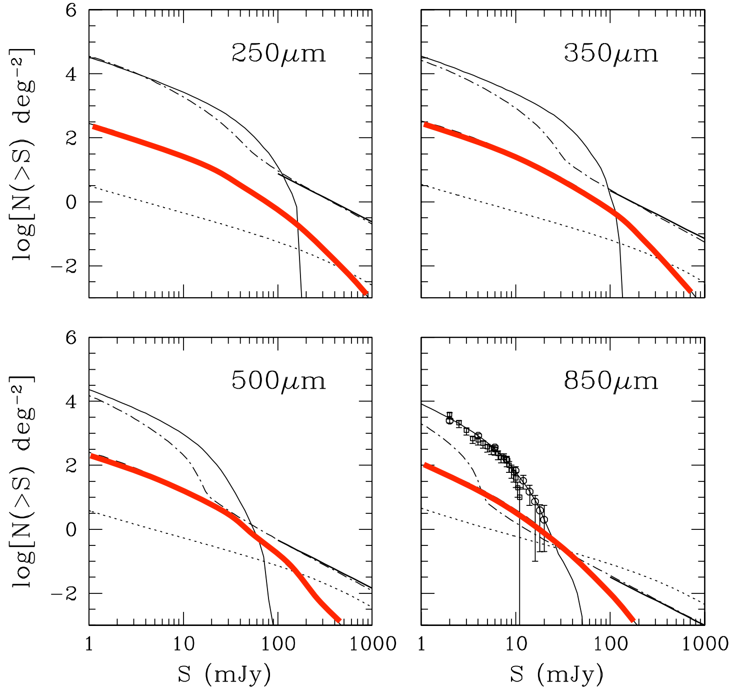




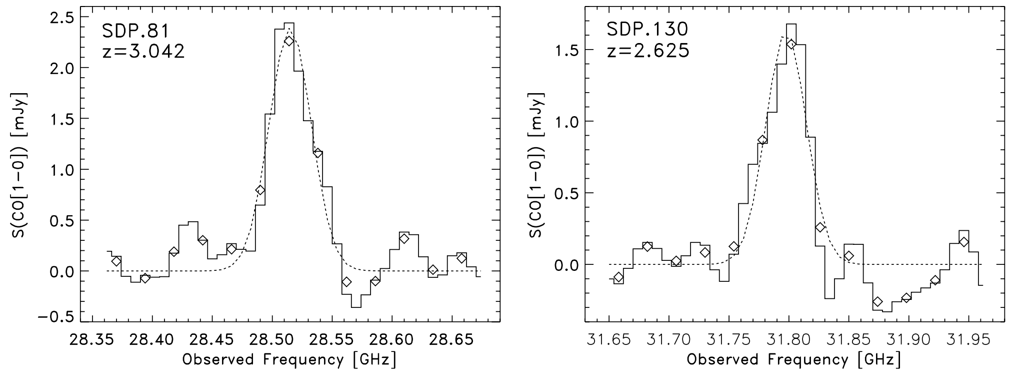
Gravitational lenses in H-ATLAS

Model predictions: strongly lensed sub-mm galaxies at high-z become a significant/ dominant population at sub-mm wavelengths.

Extensive follow-up campaign of possible H-ATLAS 500 μm peakers: confirmation of high redshifts and lens nature of various sources.

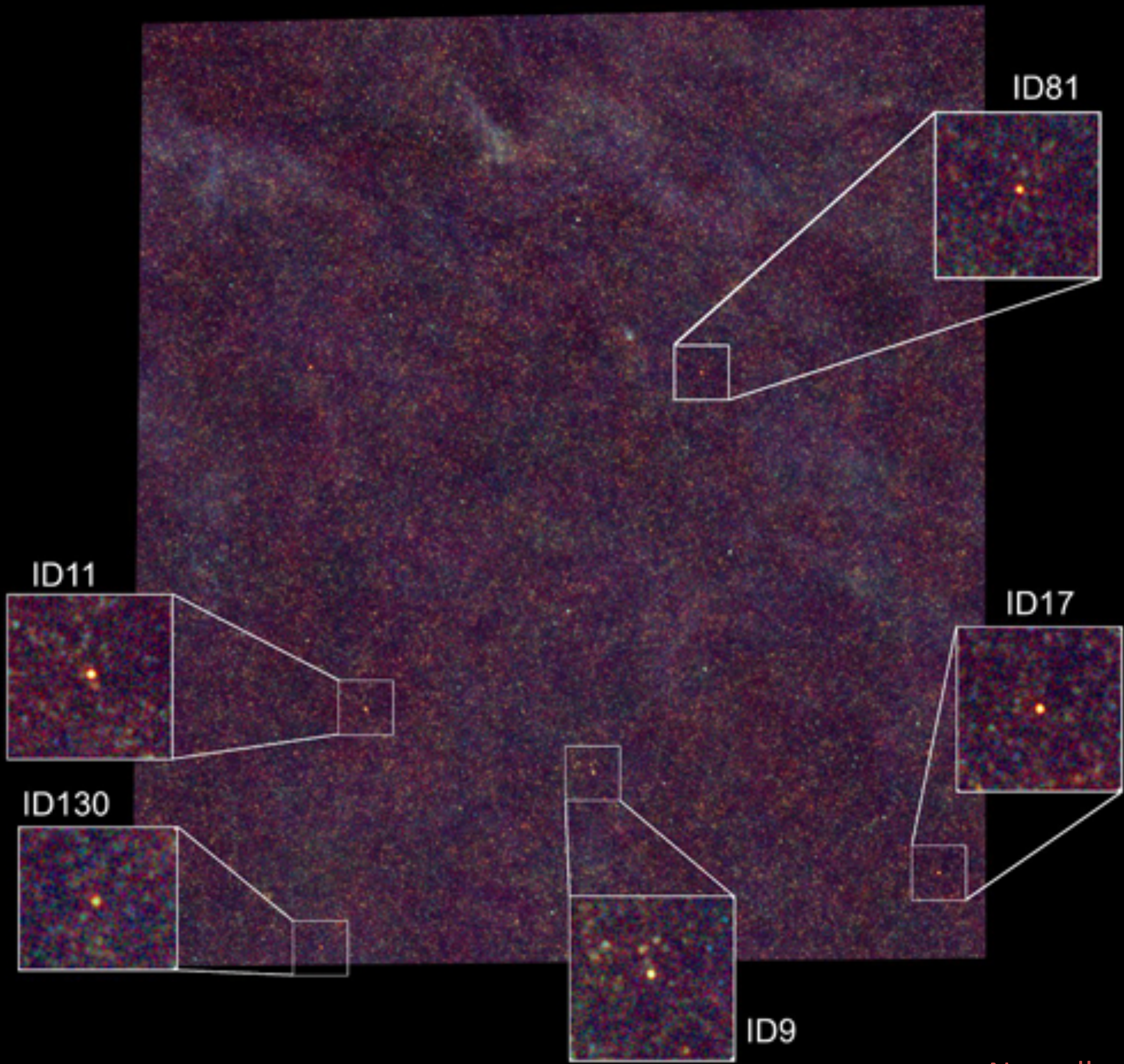


Negrello et al. 2008



Frayer et al. 2010

Gravitational lenses in H-ATLAS



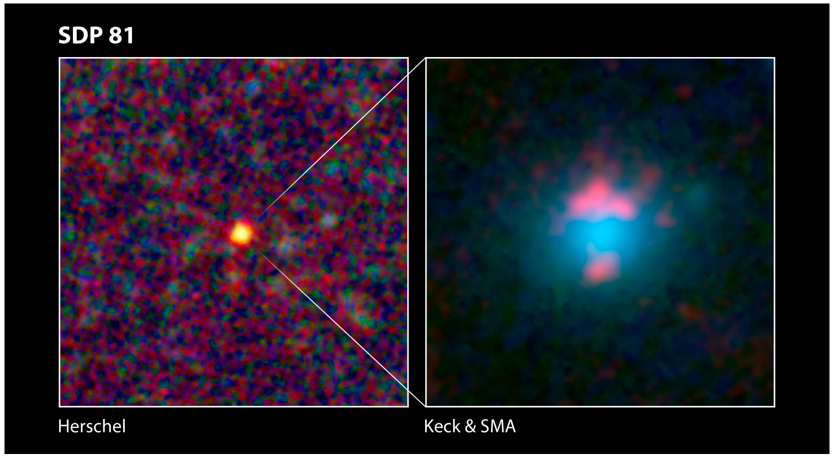
Negrello et al. 2010, Science

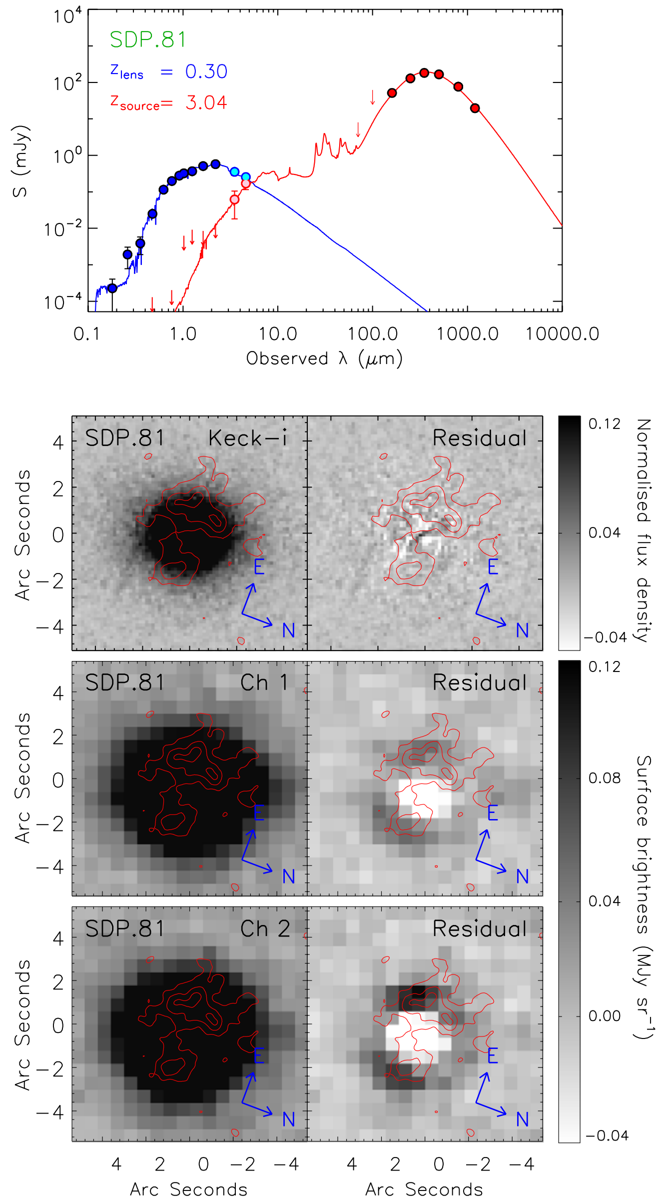
H-ATLAS lenses: an example

SDP.81 = sub-mm source at z = 3.04
Redshift determined from ground-based CO spectroscopy.

Lensing nature confirmed using high-resolution SMA observations.

Lens modelling (IRAC + Keck): lens is foreground early-type galaxy at z = 0.30.





Hopwood et al. 2011

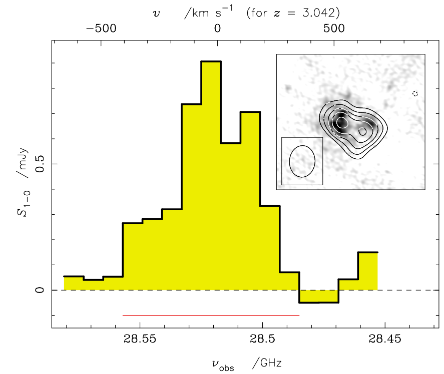
Physical conditions in high-z lenses

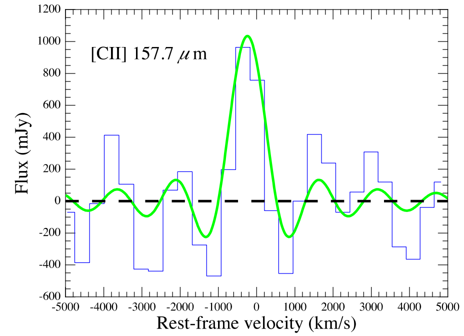
Unique targets for investigation of physical conditions in high-z galaxies (magnification factor typically 25) !
Follow-up spectroscopy program for high-z H-ATLAS lenses

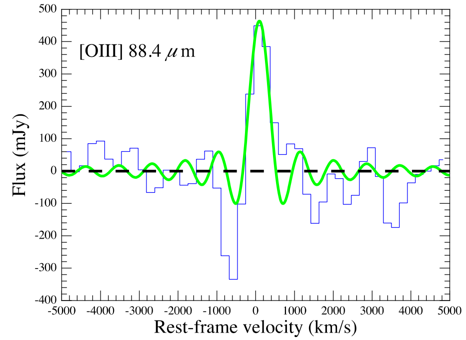
- Ground-based observations: molecular lines (CO, H_2O)
- SPIRE FTS: atomic fine-structure lines

[CII] and [OIII] detected in SDP.81.
Modelling of physical conditions: extreme star-formation (UV radiation field 200 times the local Galactic ISRF)

Many more detections (and statistics) to be made in near future. The best is yet to come !







Valtchanov et al. 2011, in press

Summary

1. FIR/sub-mm domain is a fascinating region to study the physics of the ISM: both dust and (ionized, neutral and molecular) gas.

2. Herschel is fantastic (imaging and spectroscopy 70-670 µm) !

3. Very Nearby Galaxies Survey: detailed study of 13 prototypical galaxies.
   Many fascinating photometry results, first spectroscopy results
   - Warm and dense molecular gas in M82 and Arp 220, probably heated by mechanical energy from starburst
   - Many molecular species (including hybrids) and strong molecular outflow in Arp 220

4. H-ATLAS: large-scale sub-mm survey with multi- follow-up programs.
   Sub-mm/mm spectroscopy of gravitationally lensed sub-mm galaxies offers unique possibility to study the ISM in high-z galaxies.

FIR/submm spectroscopy with Herschel: results from the VNG and H-ATLAS surveys

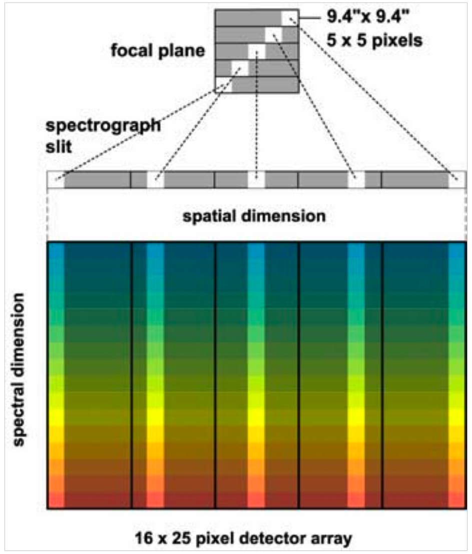
Maarten Baes
Jacopo Fritz
Naseem Rangwala
Pasquale Panuzzo
Ivan Valchanov

and many many others…

PACS fact sheet

PACS is one of three science instruments for ESA's Herschel mission. It operates either as an imaging photometer or an integral field spectrometer over the spectral band from 55 to 210 μm.

Projection of focal plane onto spectrometer arrays



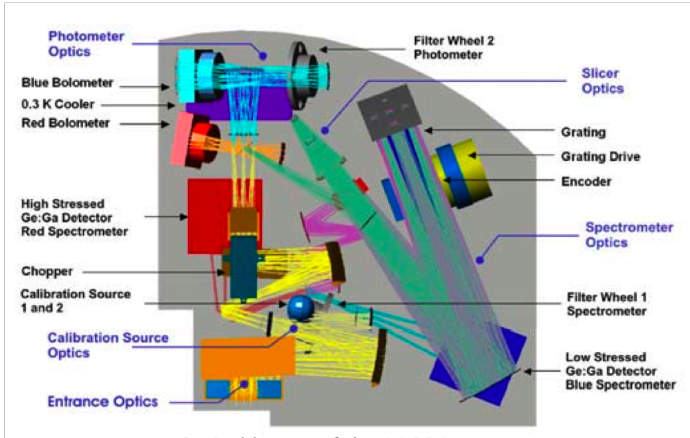
Integral Field Spectrometer

Simultaneous 55-105 & 105-210 μm spectroscopy.

47"x47" (5x5 pixels) FOV rearranged via an image slicer on two 16x25 Ge:Ga detector arrays.

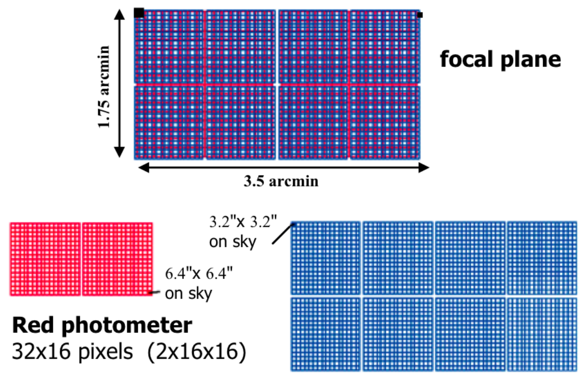
$\lambda/\Delta\lambda \sim 1000\text{-}5000$

Point source line sensitivity:
$\sim 4\text{-}10 \times 10^{-18}$ W/m^2 (5σ, 1h)



Optical layout of the PACS instrument

Projection of focal plane onto bolometer arrays



Blue photometer
64x32 pixels (4x2x16x16)

Imaging Photometer

Simultaneous two-band (same FOV) 60-85 μm *or* 85-130 and 130-210 μm fully sampled imaging.

Two filled bolometer arrays: 32x16 and 64x32 pixels

Point source detection limit:
~ 3-5 mJy (5σ, 1h)

PACS is being designed and built by a consortium of institutes and university departments from across Europe under the leadership of Principal Investigator Albrecht Poglitsch located at Max-Planck-Institute for Extraterrestrial Physics, Garching, Germany. Consortium members are: Austria: UVIE; Belgium: IMEC, KUL, CSL; France: CEA, OAMP; Germany: MPE, MPIA; Italy: IFSI, OAP/OAT, OAA/CAISMI, LENS, SISSA; Spain: IAC.

For more information HSC website: http://herschel.esac.esa.int/ and additional links provided therein

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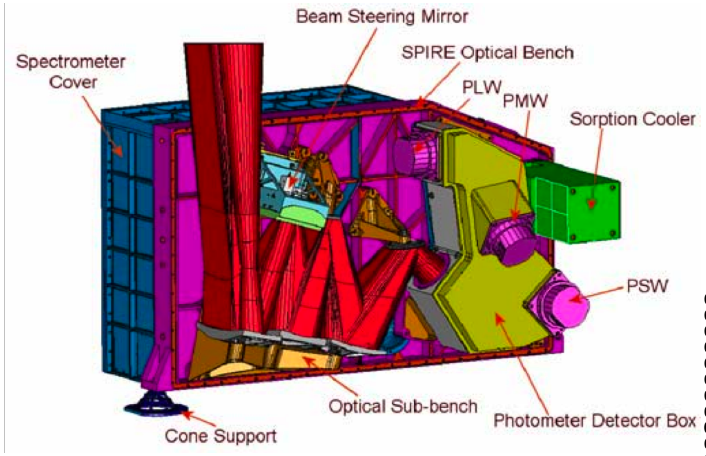
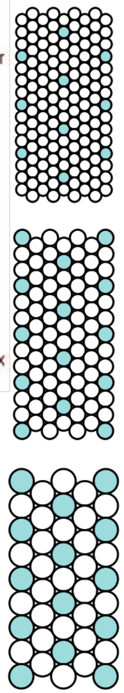
SPIRE fact sheet



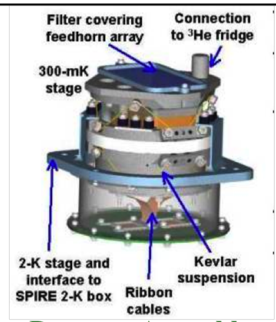


General

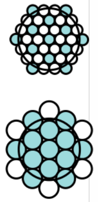
Beam Steering Mirror

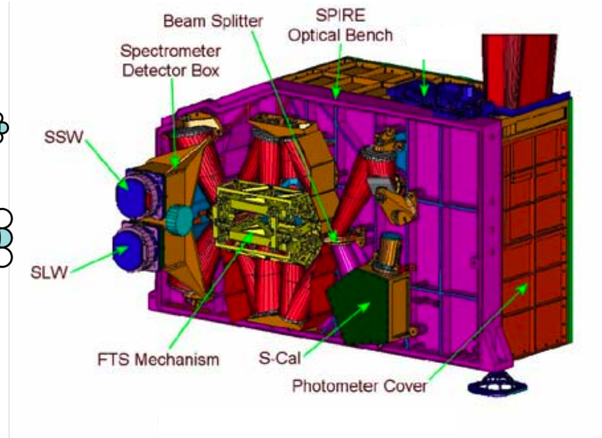
T= 0.3 K by ^{3}He sorption cooler

Hexagonal Spider-web bolometer arrays



Detector Assembly





Imaging Photometer

Simultaneous observation in 3 bands

139, 88, and 43 pixels

Wavelengths: 250, 350, 500 μm

$\lambda/\Delta\lambda \sim 3$

FOV 4' x 8', beams 18", 25", 36"

Imaging Fourier Transform Spectrometer

Simultaneous imaging observation of the whole spectral band

37 and 19 pixels

Wavelength range: 194-672 μm

$\lambda/\Delta\lambda$ = 40, 160, or 1000 at 250 μm

FOV 2.6' circular, beams 16", 34"

Estimated Photometer Sensitivities

Wavelengths (μm)	250	350	500
Point Source (mJy, 7-point mode)	1.8	2.2	1.7
Small map (mJy, 5σ, 1hr)	6.2	8.4	7.1
Large map (mJy, 5σ, 1hr)	3.7	5.3	4.6

Estimated Spectrometer Sensitivities

Wavelengths (μm)	200-315	315-500	500-670
Point Source (10^{-17} Wm^{-2}, 5σ, 1hr, res 0.04 cm^{-1})	2.5-4	2-3	3-4
2.6' map (10^{-17} Wm^{-2}, 5σ, 1hr, res 0.04 cm^{-1})	~15	~10	~15
Point Source (mJy, 5σ, 1hr, res 1 cm^{-1})	85-125	70-110	110-130
2.6' map (mJy, 5σ, 1hr, res 1 cm^{-1})	~500	~400	~500

The SPIRE Consortium: SPIRE is being designed and built by a consortium of institutes and university departments from across Europe, Canada and the USA, under the leadership of a Priciple Investigator (Professor M.J. Griffin) located at the University of Wales, Cardiff. The member institutes are: Astronomy Technology Centre (ATC), Edinburgh; Observatoire de Meudon (DESPA), Paris; CEA, Service des Basses Temperatures (SBT), Grenoble; Goddard Space Flight Center (GSFC), Maryland; Instituto de Astrofisica de Canarias (IAC), Tenerife; Insitut d'Astrophysique Spatiale (IAS), Orsay; Imperial College London; Instituto di Fisica dello Spazio Interplanetario (IFSI), Rome; Jet Propulsion Laboratory (JPL), Pasadena; Laboratoire de Marseille (LAM), Marseille; Mullard Space Science Laboratory (MSSL), Holmbury St. Mary; Padova Observatory, Padova; University of Wales, Cardiff; Rutherford Appleton Laboratory (RAL), Chilton; CEA, Service d'Astrophysique (Sap), Saclay; University of Lethbridge, Canada; Stockholm Observatory, Sweden

For more information HSC website: http://herschel.esac.esa.int/ and additional links provided therein

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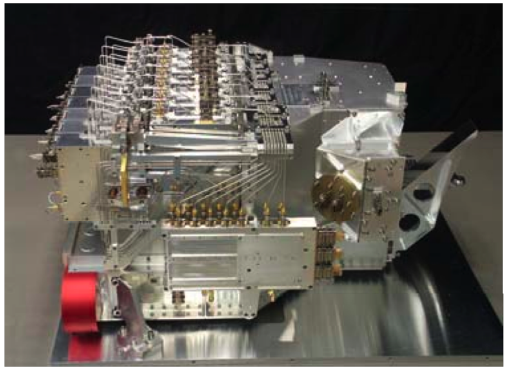
HIFI fact sheet

Principal Investigator: Thijs de Graauw, SRON, Groningen, The Netherlands
Co-PIs: Tom Phillips, Caltech; Emmanuel Caux, CESR; Jürgen Stutzki, U. Köln



General Features

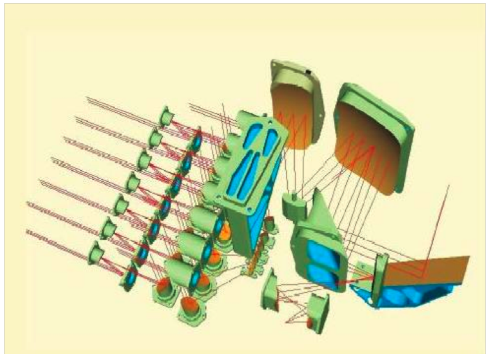
Broad coverage of the FIR and sub-mm

Instantaneous IF bandwidth of 4 GHz

Resolving power of up to 10^7 (0.3-300 km/s)

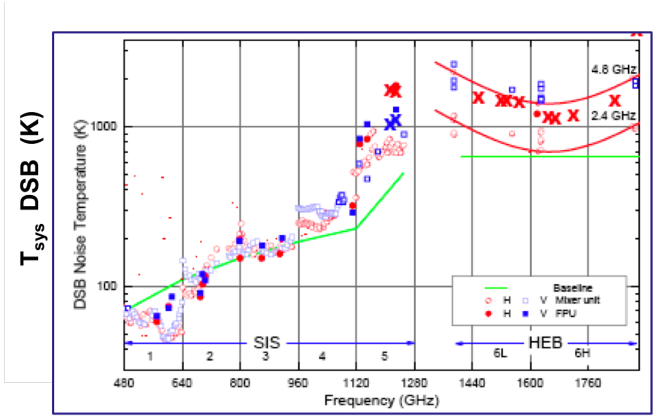
Diffraction-limited (12" – 47") beam

Seven bands utilizing low-noise dual-polarisation superconducting SIS and HEB mixers



Common Optics Light Path

The Common Optics Assembly containing seven mixer bands – five pairs of SIS mixers and two pairs of HEB (Hot Electron Bolometer) mixers, the calibration assembly, and the Local Oscillator inputs.



The Common Optics system combines seven beams and provides a beam chopper for the HIFI Instrument Modes which include: dual beam-switching, position-switching, on-the-fly mapping, frequency-switching, and cold-load switching. Dual acousto-optical (wide band - WBS) and autocorrelator (high resolution - HRS) backend spectrometers provide frequency resolutions of: 140 kHz, 280 kHz, 560 kHz (HRS), and 1.1 MHz (HRS & WBS).

HIFI sensitivity: Near-quantum noise limit sensitivity (goal < 3 hν/k)
HIFI calibration accuracy: 10% baseline requirement; 3% goal

SIS Technology — HEB Technology

THz: 0.48 → 0.64 → 0.80 → 0.96 → 1.12 → 1.27 — 1.41 → 1.91

HIFI Bands: 1 | 2 | 3 | 4 | 5 — 6 | 7

µm: 625 → 468 → 375 → 312 → 268 → 236 — 213 → 157

For more information HSC website: http://herschel.esac.esa.int/ and additional links provided therein

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