Report on the ALMA/Herschel Synergy

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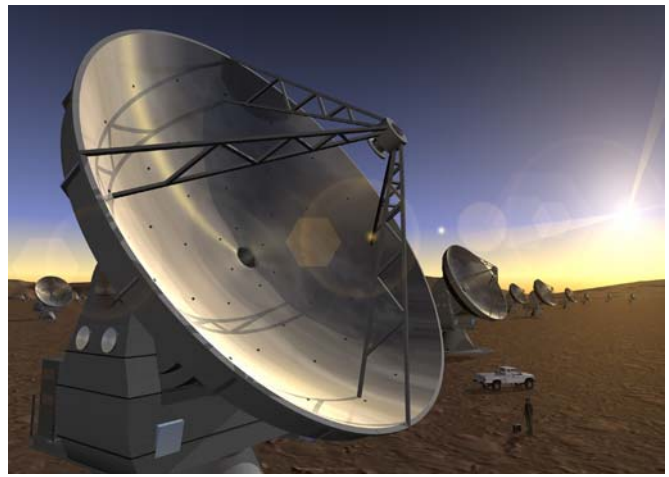
Two major developments

- Joint Herschel-ALMA meeting
  - Dusty04 in Paris October 2004; 200 participants
  - Proceedings just published
- FP6 ALMA enhancement proposal
  - Band 5 (160-210 GHz), contains H_2O at 183 GHz, and $H_2{}^{18}O$ at 203 GHz for 6 to 8 antennas

ALMA Description

- 64 dishes with 12m diameter. These will be moved systematically from compact to extended configurations
  - Low-noise, wide-band heterodyne receivers whose outputs are connected to a digital correlator allowing high spectral resolution.
- Will provide sensitive, precision imaging from 30 GHz (λ=1 cm) to 950 GHz (0.3 mm)
  - 350 GHz (0.87 mm) continuum sensitivity: about 1 mJy in one second
  - Angular resolution will reach ~0.05 arc seconds at 100 GHz (3 mm), and 10 km maximum separation of antennas
  - The FOV for a single pointing ranges from 4' (at 30 GHz) to 10" (at 900 GHz)



ALMA Science Drivers

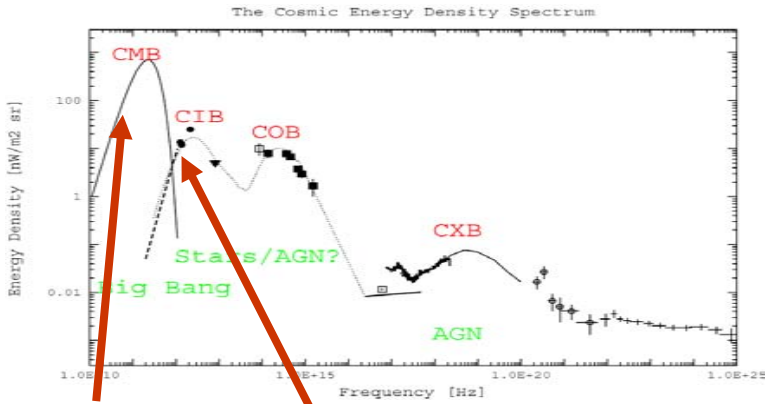
- Key drivers:
  - *High Fidelity* Images in Spectral Lines and Continuum
  - Measure dust broadband emission and spectral line radiation from atoms and molecules in high-z galaxies to obtain detailed morphology and kinematics:
  - Protostars and planet formation:
    - Angular resolution of few AU at 150 pc (nearest molecular cloud)

Herschel: A 3.5 m telescope at L2

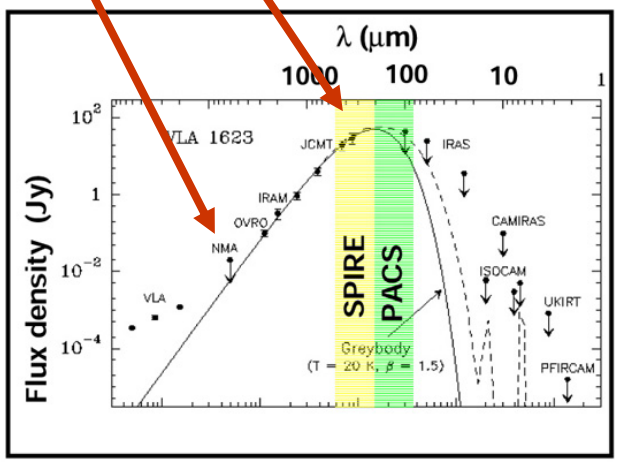
- HIFI: Heterodyne single pixel system
  - 480 to 1250 & 1410 to 1910 GHz
  - FWHP beamsize 12” to 45”
- SPIRE: Spectral and Photometric Imager
  - Bands at 250, 360 & 520 micrometers
  - FWHP beamsizes 17”, 24”, & 35”
  - Field-of -View (FOV) 4’ by 8’
- PACS: Photodetector Array Camera & Spectrometer
  - Bands at 60-85, 85-130 & 130-210 micrometers
  - FWHP beamsize 7.7” (64 by 32 pixels) to 15.4” (32 by 16 pixels)
  - FOV 1.75’ by 3.5’

Science to be done with Herschel

- HIFI: The study of the cycling of material from stars to the ISM
- SPIRE and PACS:
- To study how and when galaxies form
- To study the origin of planets, galaxies and the universe



ALMA wavelength range

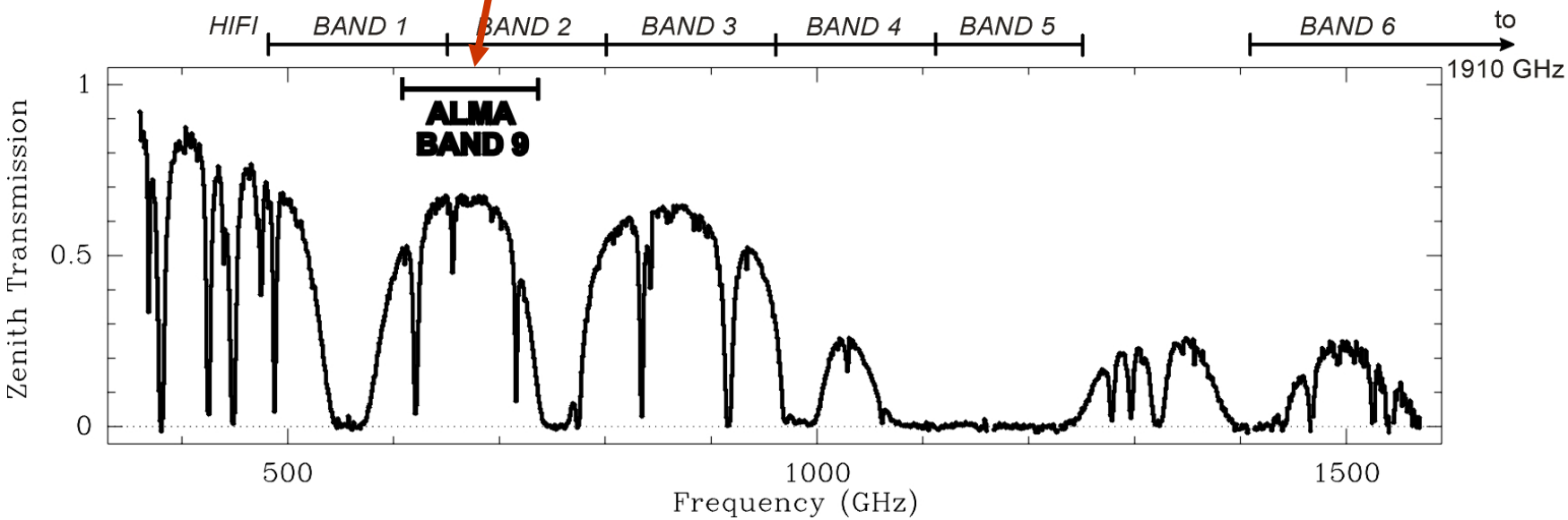


Herschel and ALMA Science: The Cool Universe

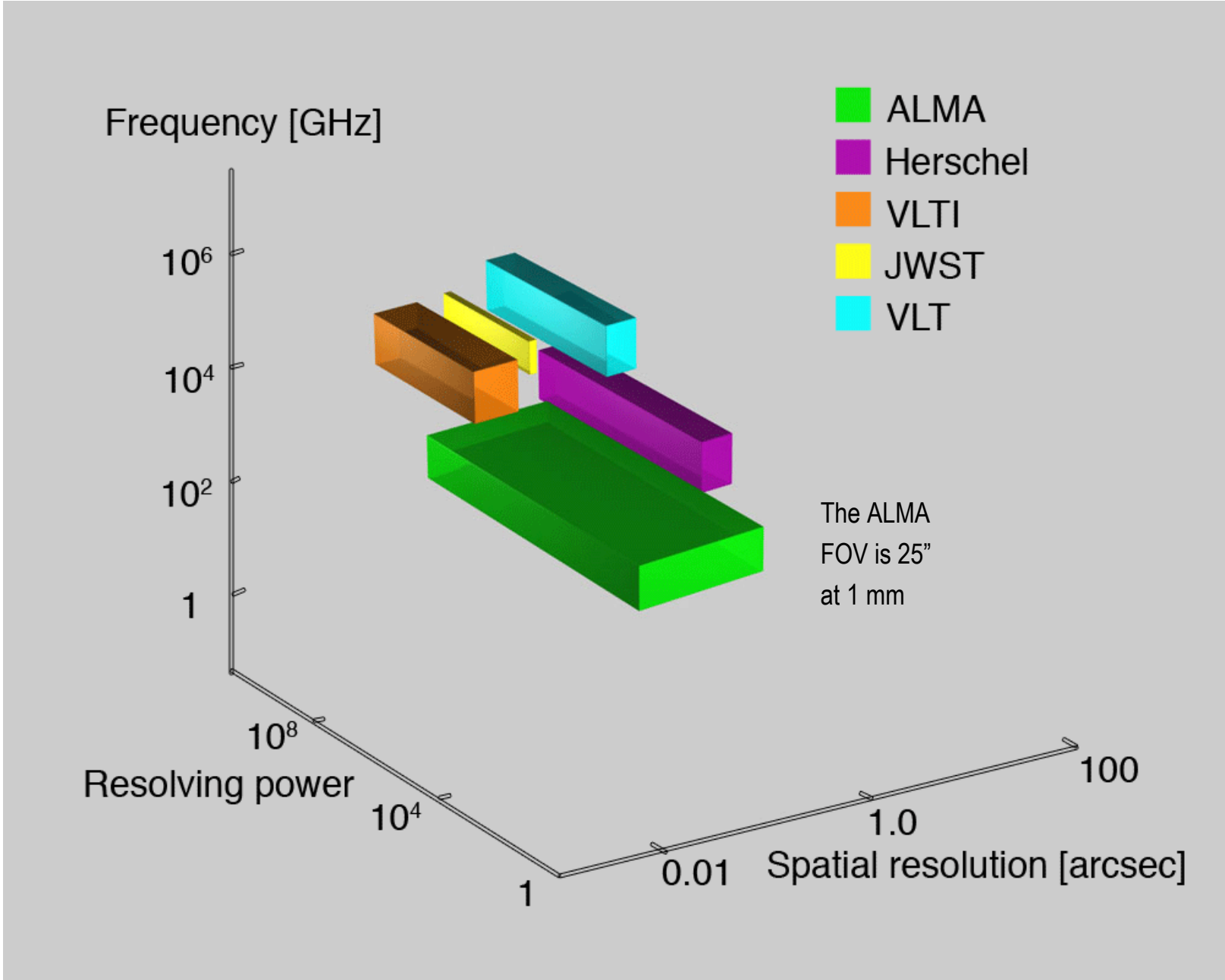
- ***Herschel is best suited for surveys, ALMA a follow-up instrument***

  - ALMA has a small Field Of View (FOV), but high angular resolution and sensitivity
  - Higher angular resolution to image the sources measured by Herschel
  - Follow up to sources discovered with PACS or SPIRE in longer wavelength dust emission
  - Also, surveys in CO to determine redshifts

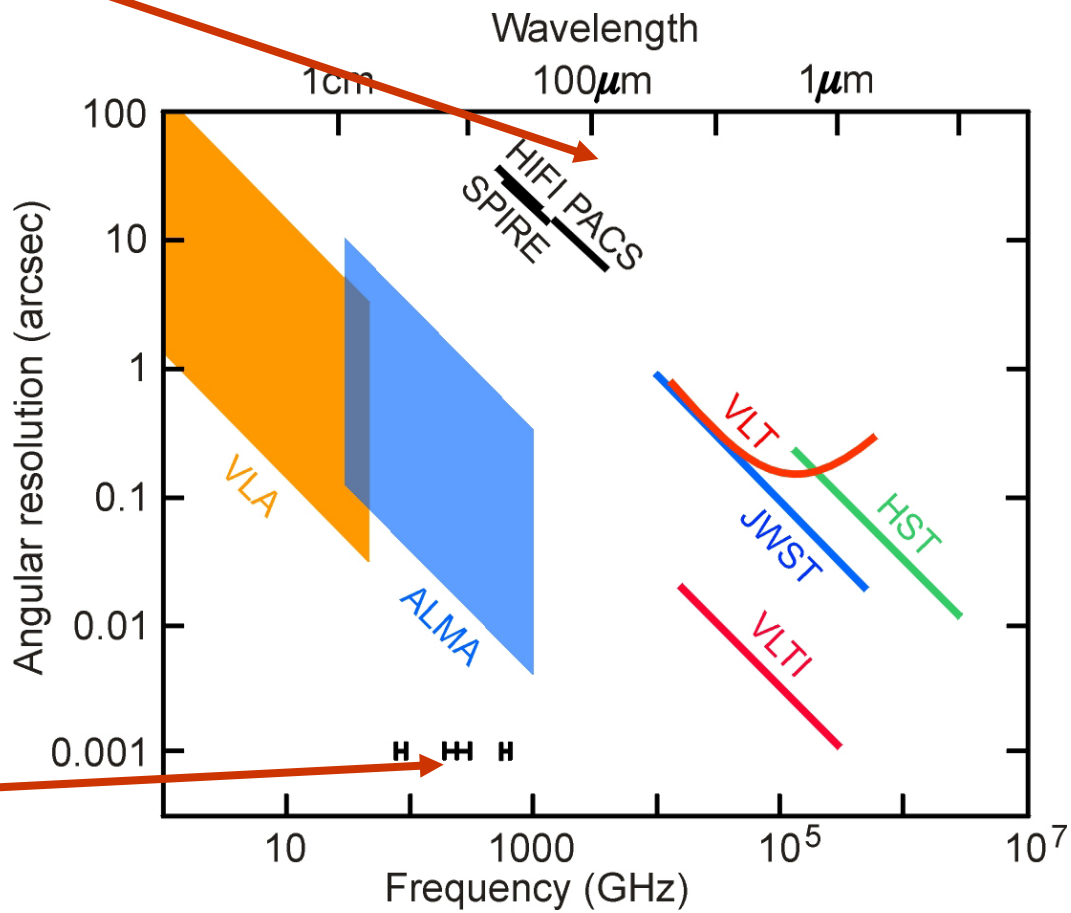
Band 9 of ALMA plotted on Herschel HIFI Bands



There is some overlap in wavelength, but mostly the coverage of ALMA and Herschel-HIFI are complementary

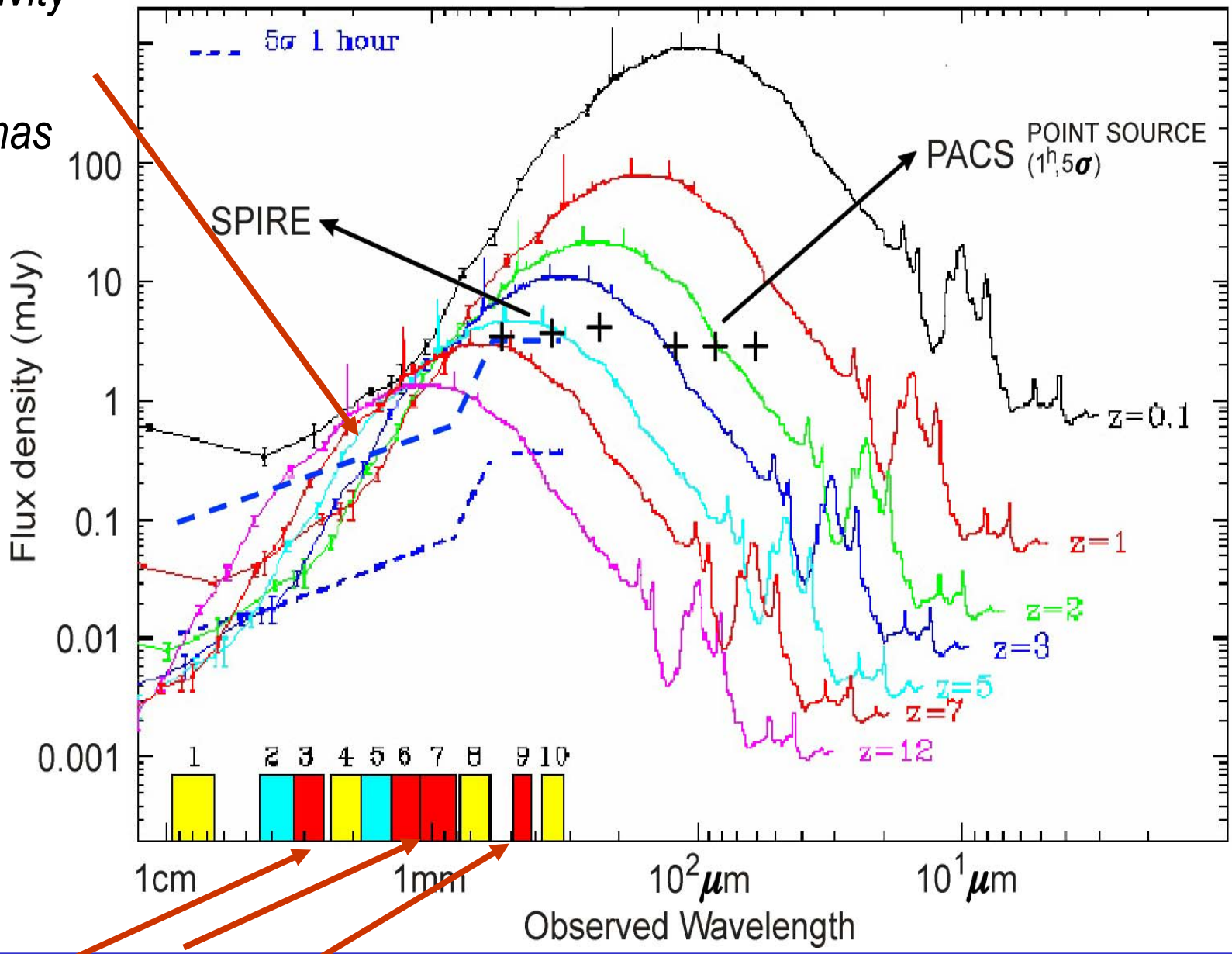

Frequency [GHz]
10^6
10^4
10^2
1
ALMA
Herschel
VLTI
JWST
VLT
The ALMA
FOV is 25”
at 1 mm
10^8
Resolving power
10^4
1
0.01
1.0
100
Spatial resolution [arcsec]

The ALMA FOV is 25” at 1 mm



ALMA Receiver Bands

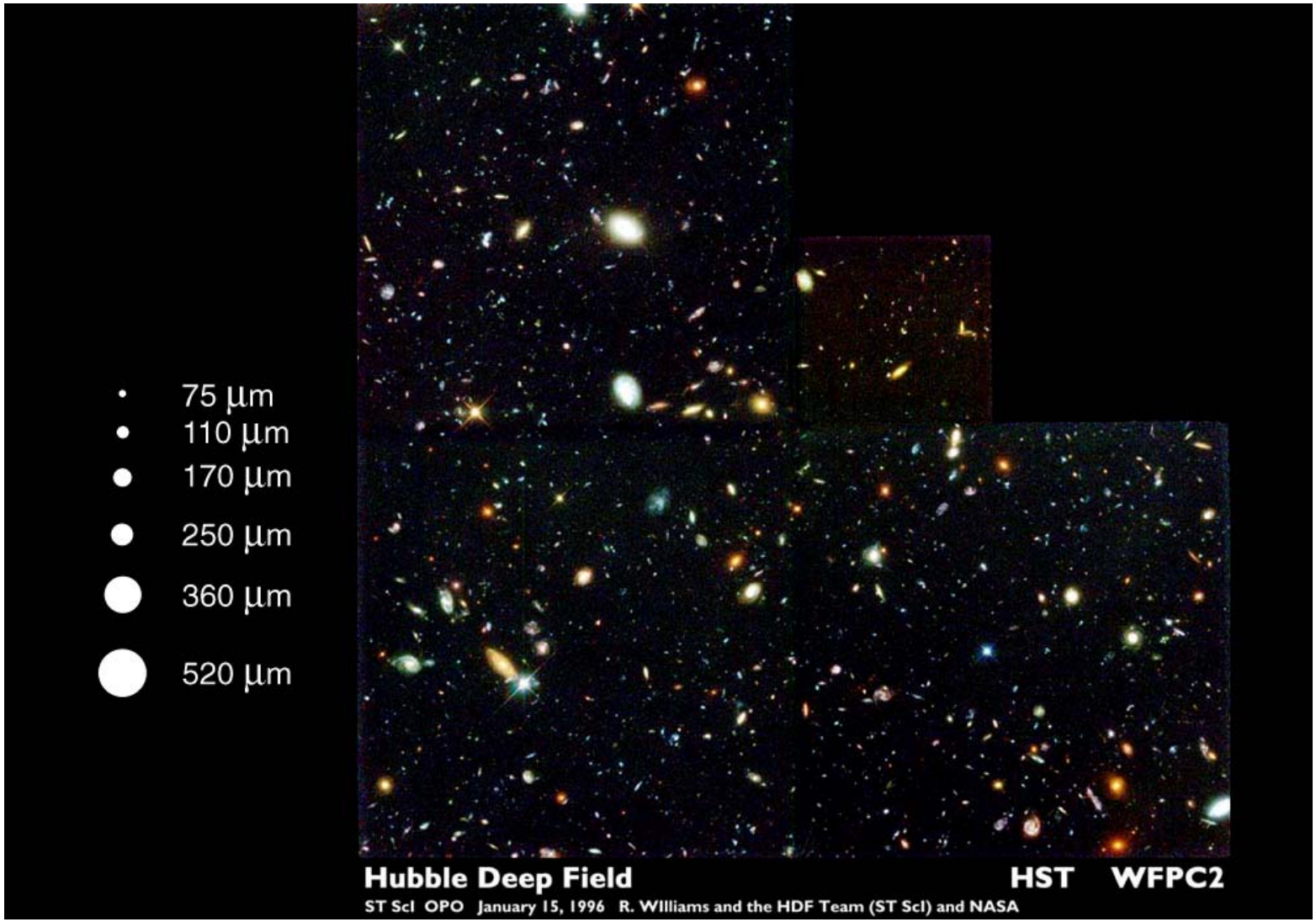
Sensitivity with 6 antennas

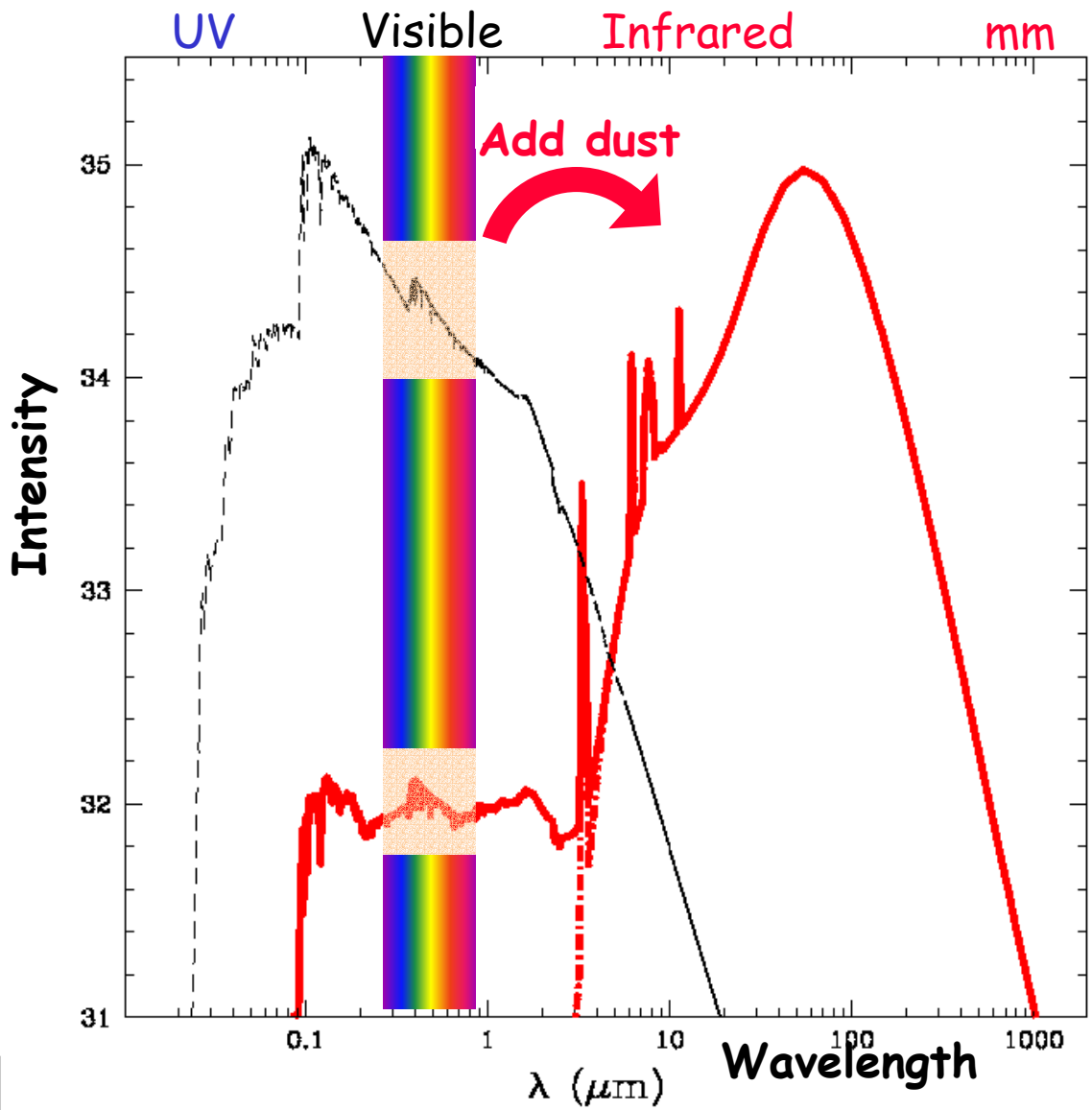


Bands 3, 6, 7 and 9 are basic

Sizes of the SPIRE and PACS beam sizes on the HDF north Field

This shows the limits of Herschel angular resolution. Herschel measurements need follow ups with higher angular resolution imaging




UV
Visible
Infrared
mm
Add dust
Intensity
35
34
33
32
31
0.1
1
10
100
1000
λ (μm)
Wavelength

Scientific Areas

- High Redshift Galaxies and Cosmology
- Active Galactic Nuclei & Star Formation in Galaxies
- Star and Planet Formation
- Water in the Universe
- Astrochemistry in Hot Cores and Envelopes of Evolved Stars
- Solar System

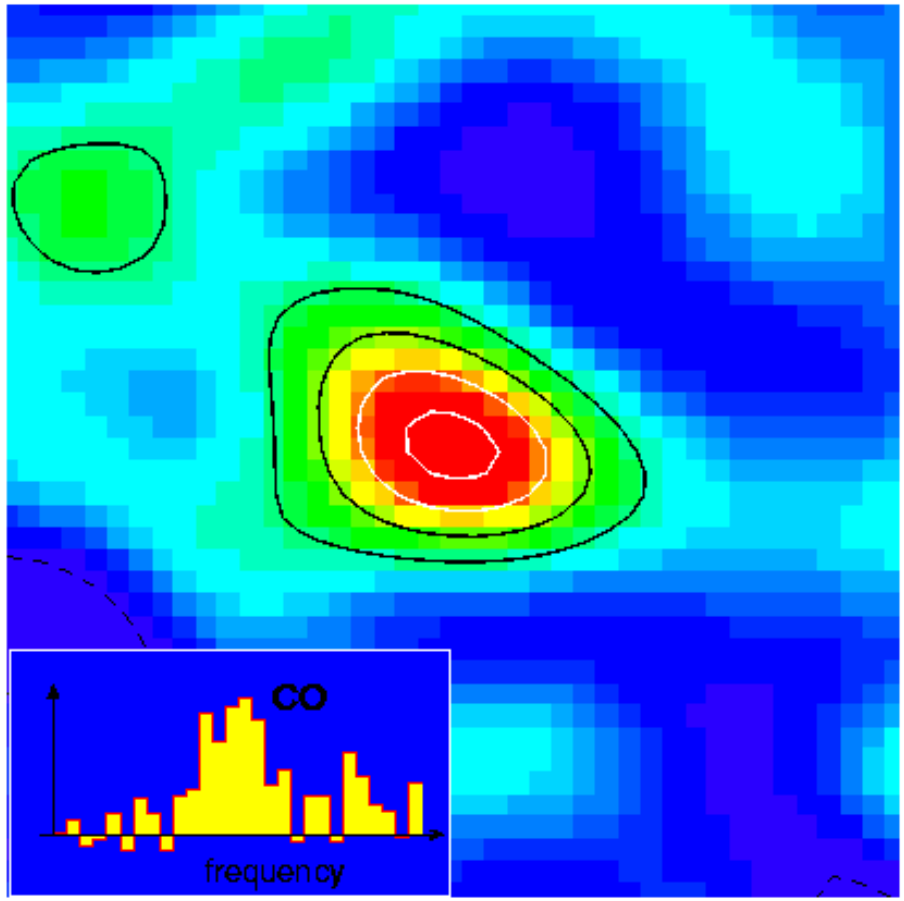
High Redshift Sources and AGN's

- High star formation rates, >>20 solar masses per year
- Most of the radiation emitted by stars is absorbed by dust and re-radiated in the 3 micrometer to 1 mm wavelength range
- The luminous IR galaxies trace regions where the concentration of galaxies is largest, and trace the formation of large scale structures.

AGN's: Herschel & ALMA

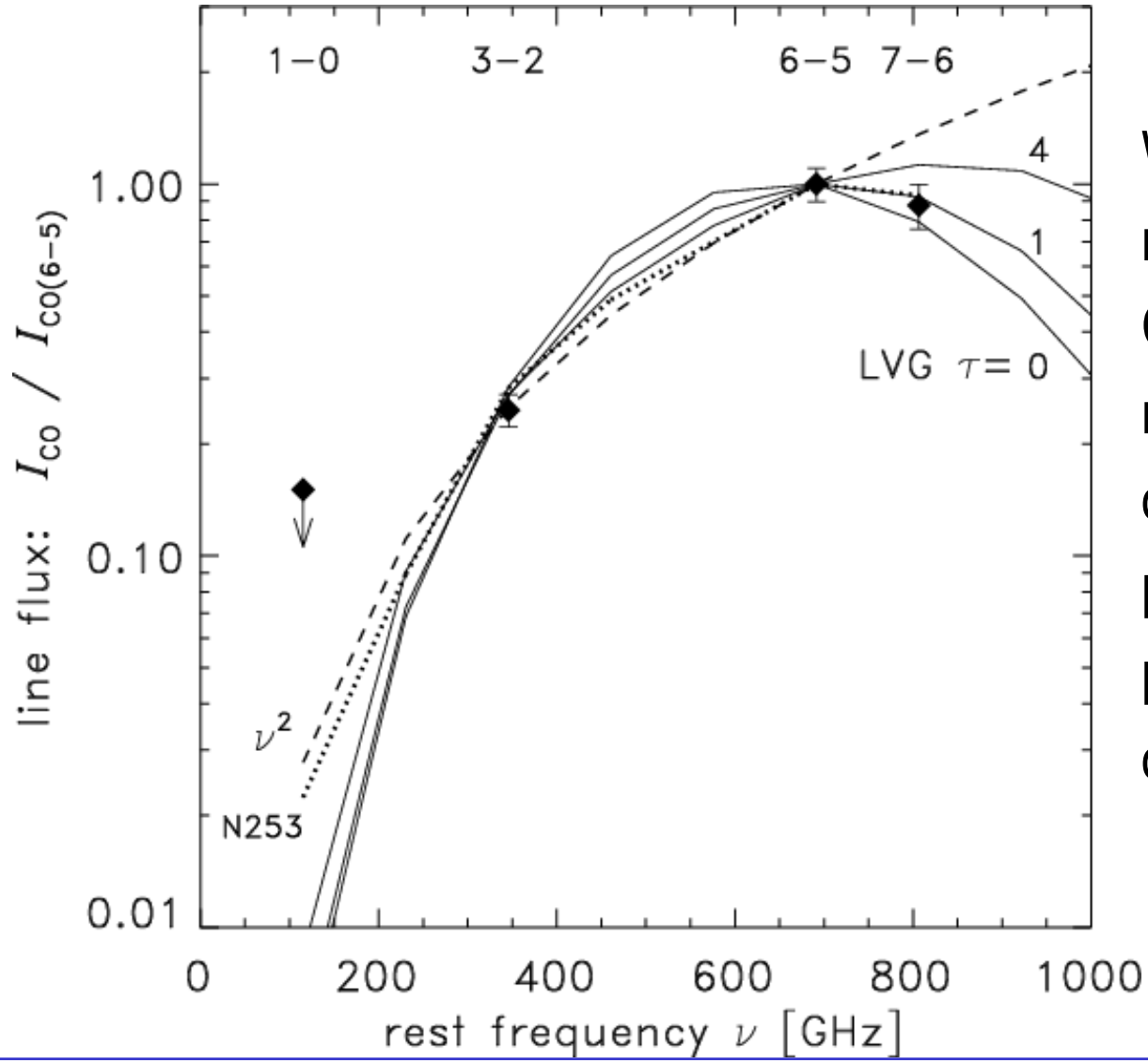
- Measure 1000's of sources with PACS and SPIRE, then follow up with longer wavelength continuum data with ALMA
  - spectral line measurements of CO and other species
- Herschel will sample the regime where most of the luminosity is radiated
  - High resolution images with ALMA allow a better determination of the size of emission sources ALMA would provide high resolution images to refine models.
  - Separate star formation and accretion in AGN's

Image of the redshift z=6.4 source in CO line emission

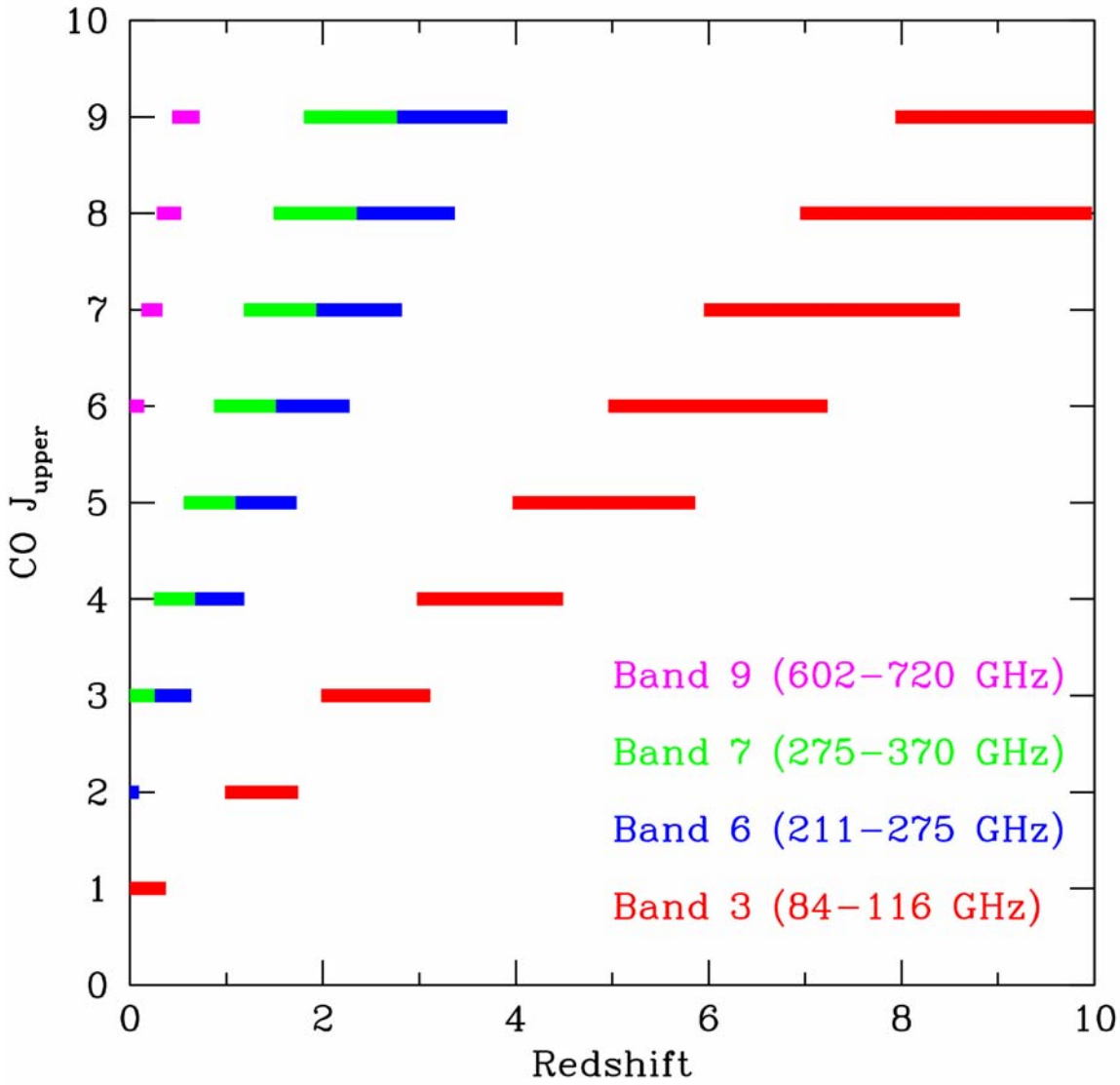


The CO emission was shown to be extended

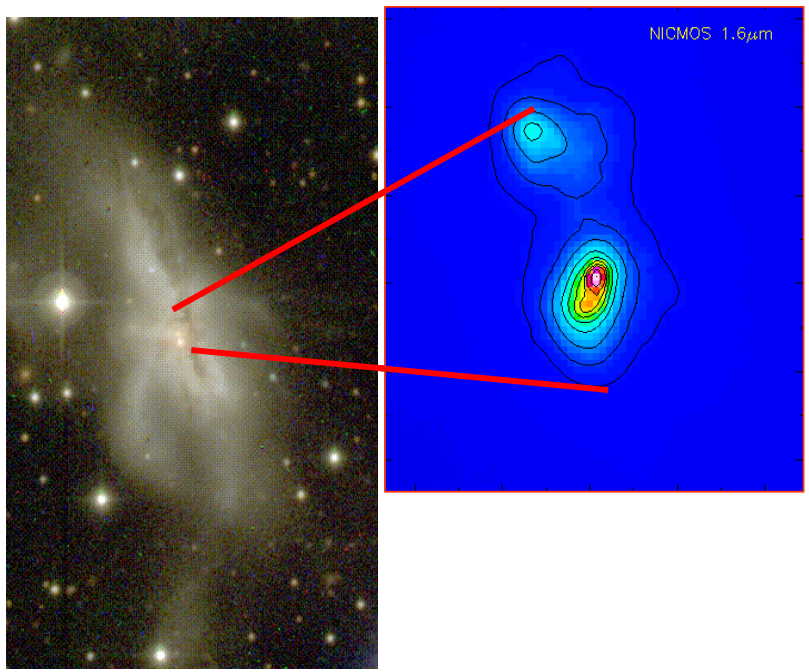
Normalized integrated CO line intensity

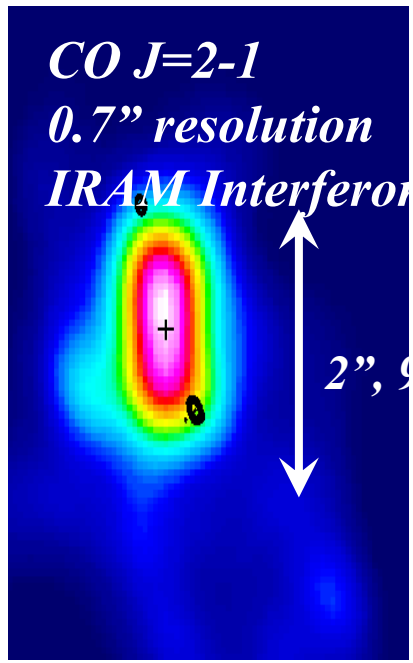


With a number of CO line measurements one can determine physical parameters of a source


CO J_upper
Redshift
Band 9 (602–720 GHz)
Band 7 (275–370 GHz)
Band 6 (211–275 GHz)
Band 3 (84–116 GHz)

NGC6240-An AGN Case Study





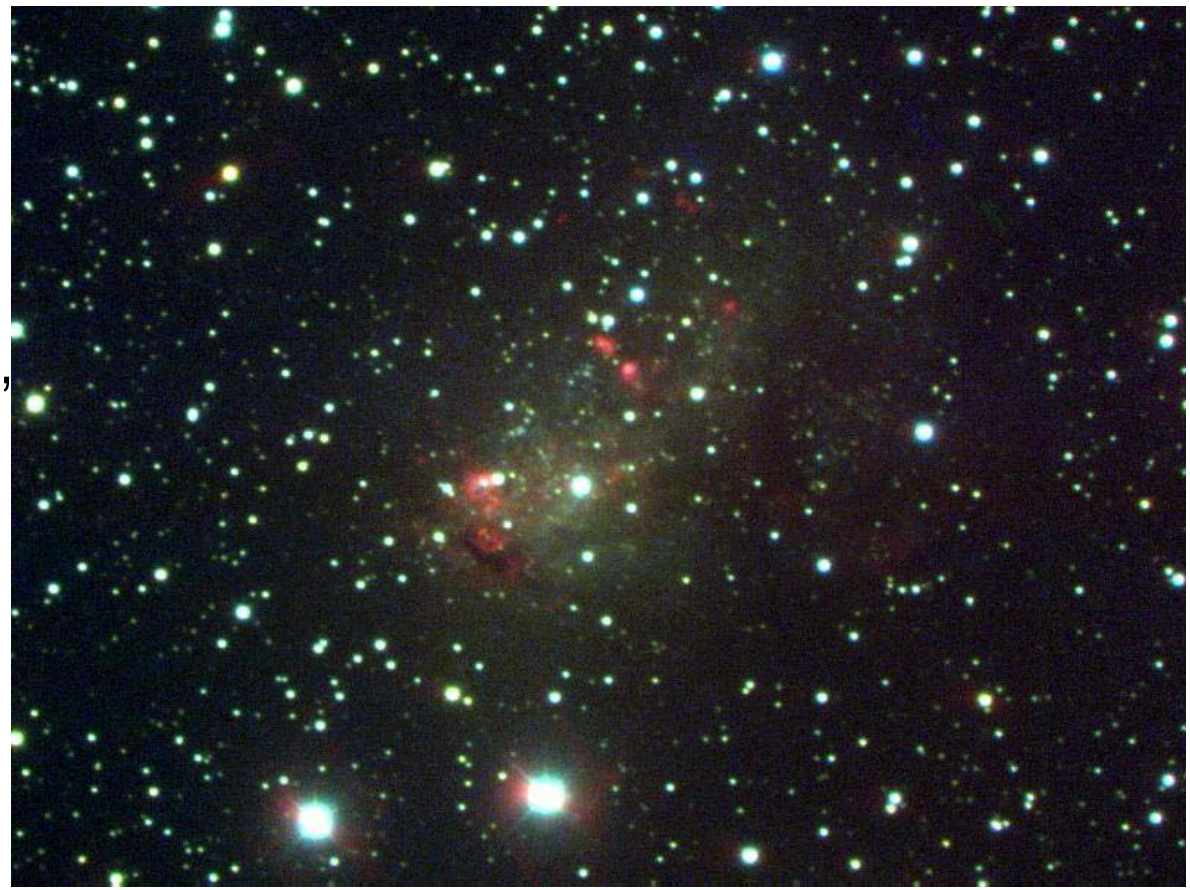
Nearby Galaxies

- Investigate star formation in other types of galaxies
  - At 10 Mpc, 0.1” is equivalent to 4.8 pc
- Compare to models, in regard to the influence of nearby surroundings, metallicity, mergers

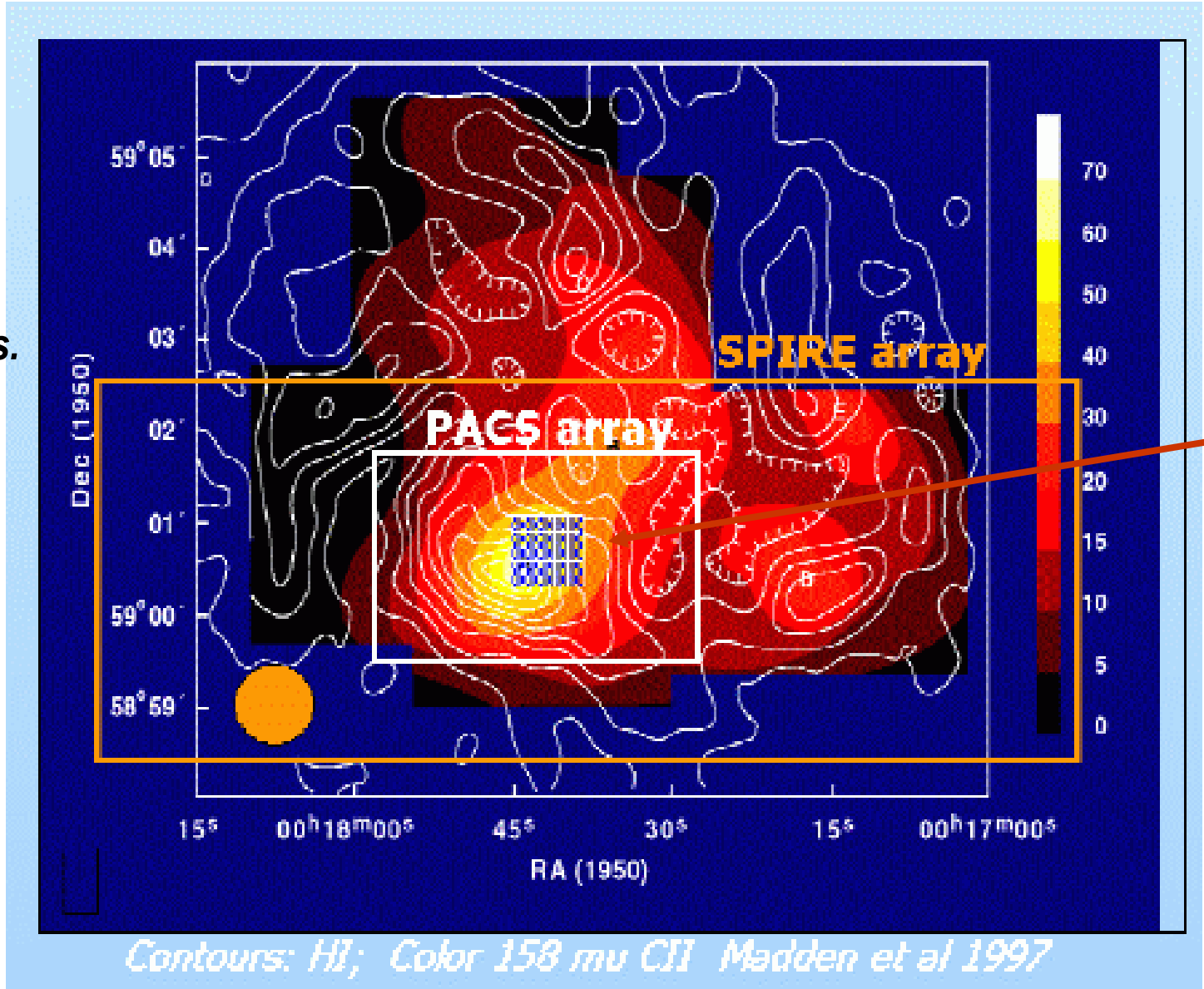
IC10-A Nearby Blue Dwarf Galaxy

D=0.7 Mpc;

Total size of the image is 10’



Boxes show FOV of Bolometers. The FOV of ALMA at 3 mm is the circle in the lower left

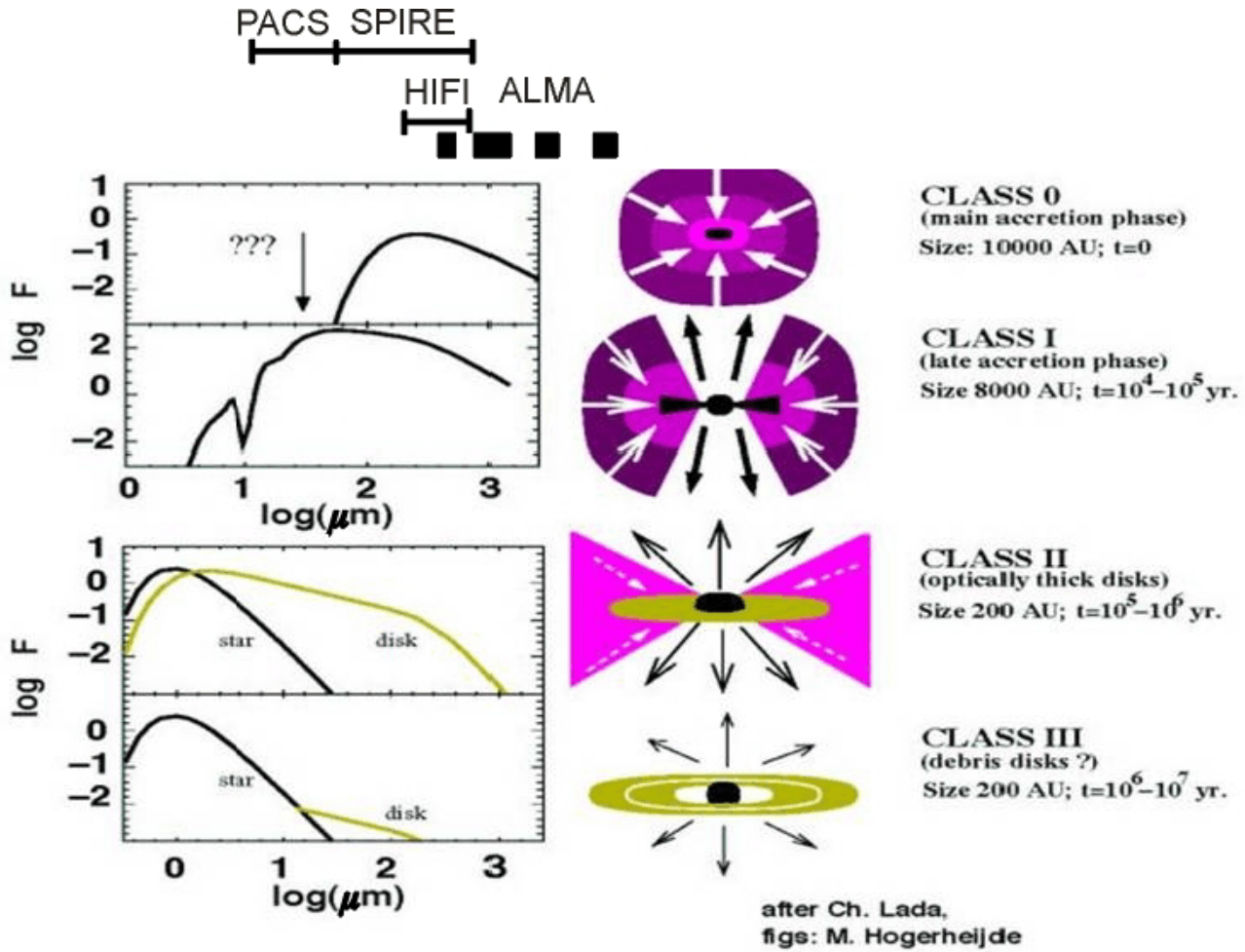


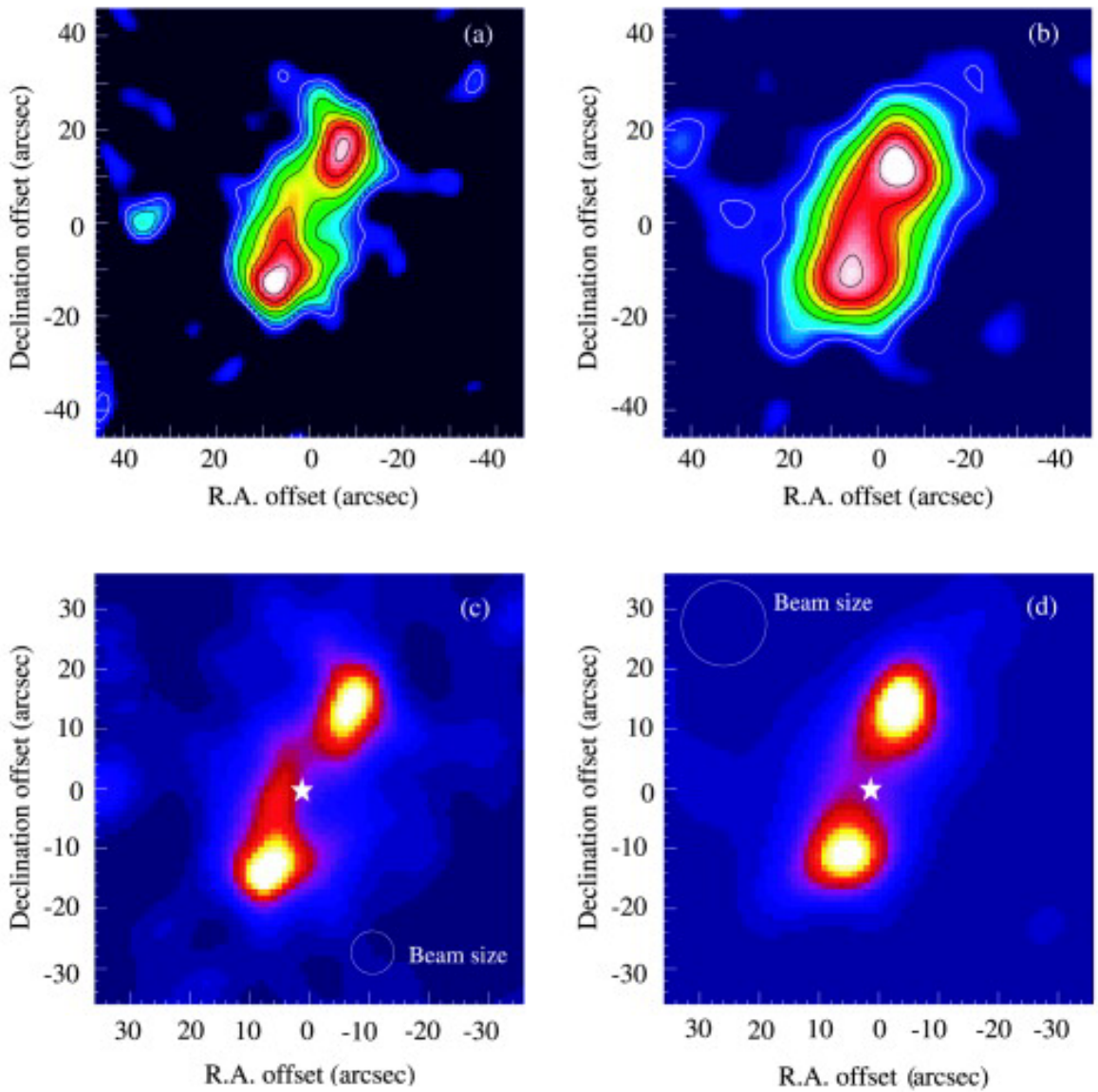
Smallest box is the integral field spectrometer In PACS

Star Formation in our Galaxy

- We can study different stages of star formation in individual sources
- We believe that the basic physical laws are understood but the relative importance of various effects is not known
- The study of low mass star formation will allow us to understand how our solar system formed
- In this study we group ‘protostars’ and ‘debris disks’

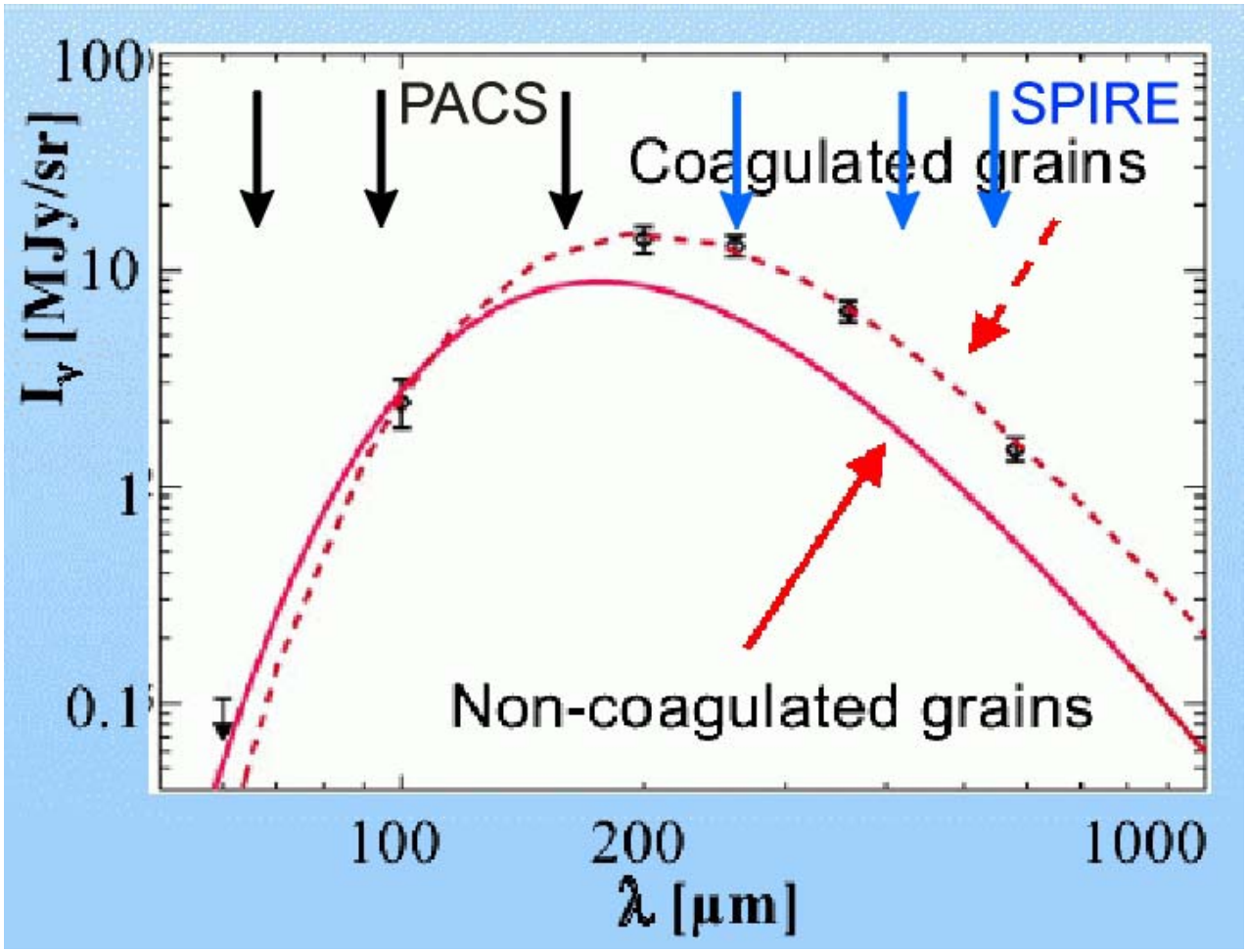
Sketch of Protostar Development



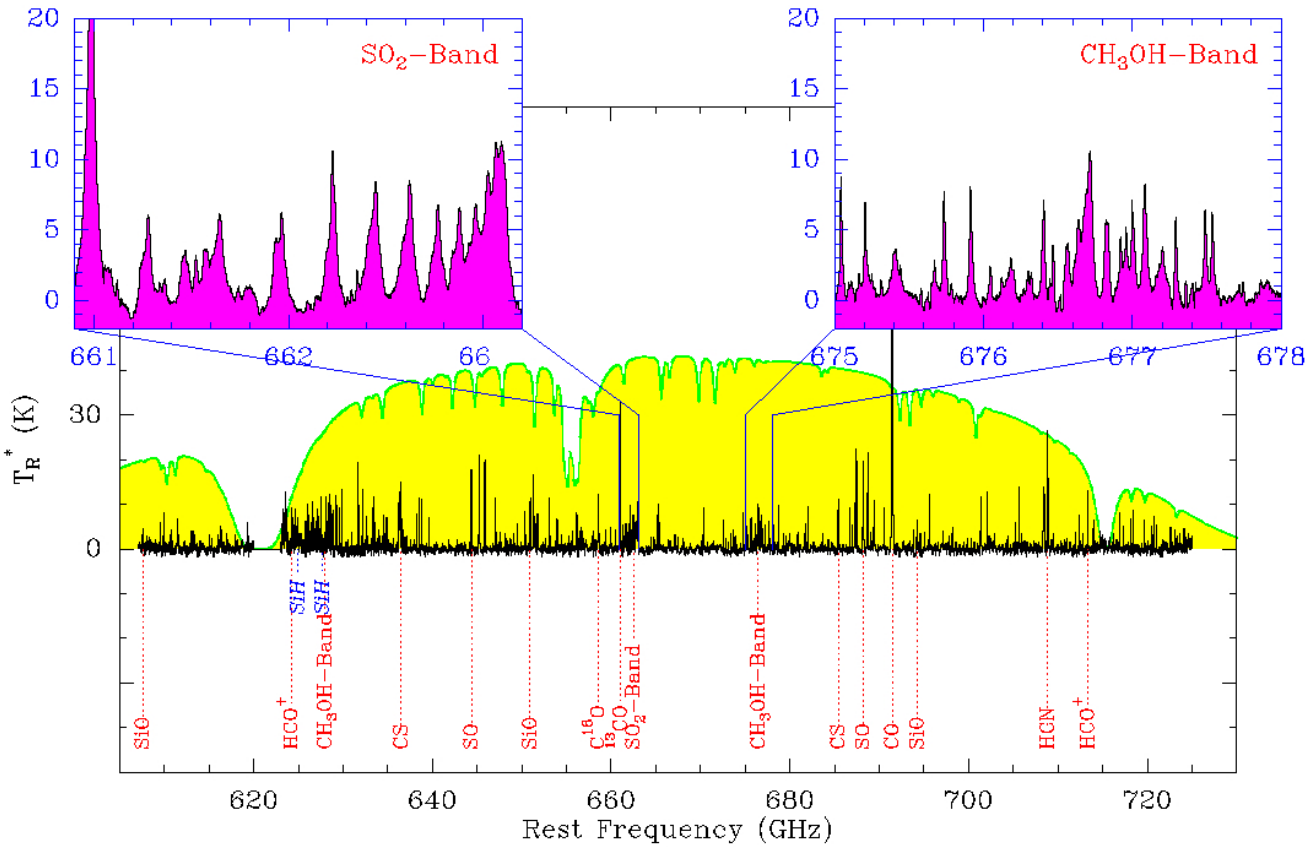


450/850 micrometer images of Fomalhaut. The contours are 13 and 2 mJy/beam. Below are deconvolved images (data from JCMT and SCUBA)

Dust Spectra and Herschel Bolometer Bands

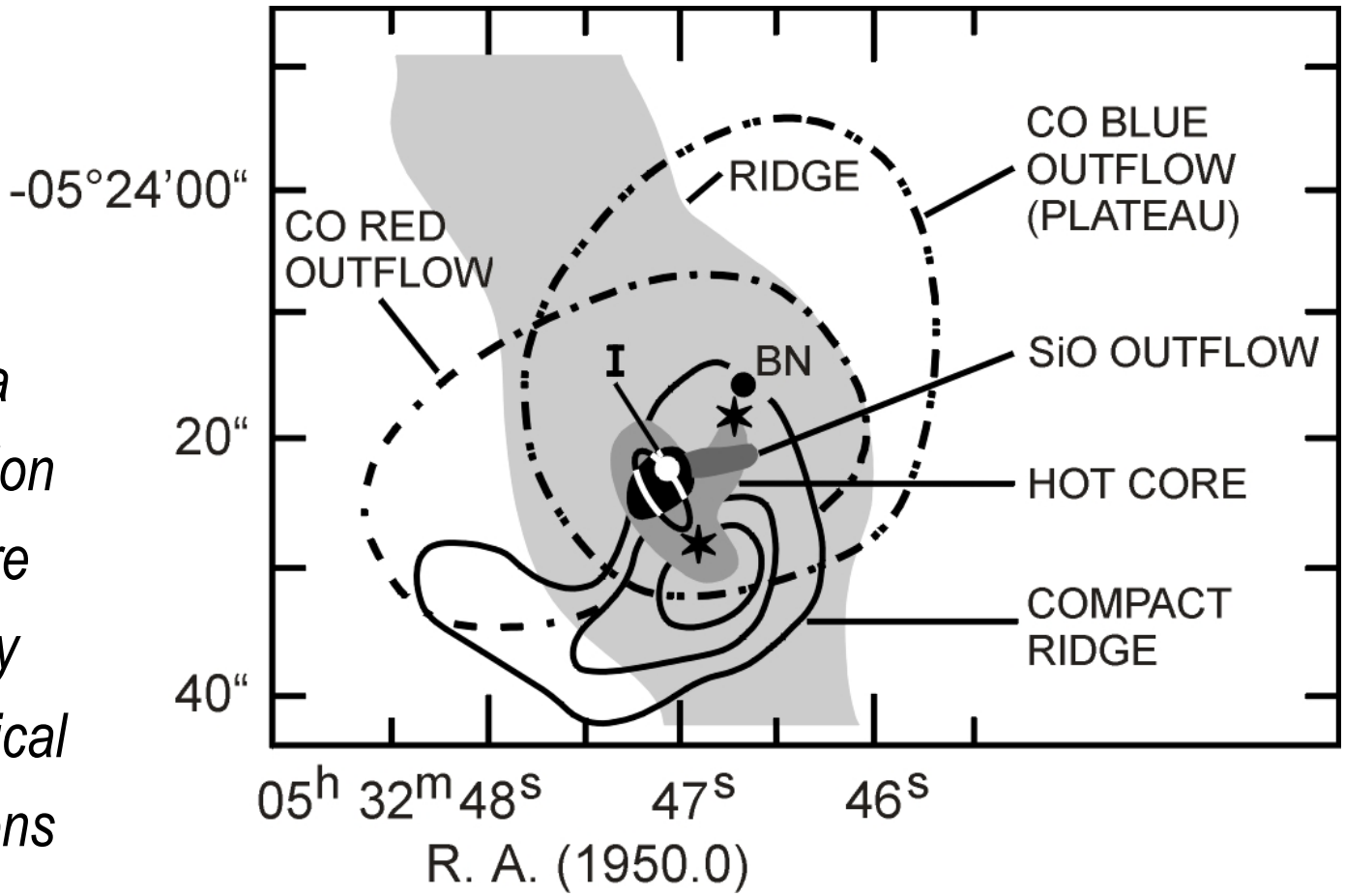


Orion KL Spectrum from Ground

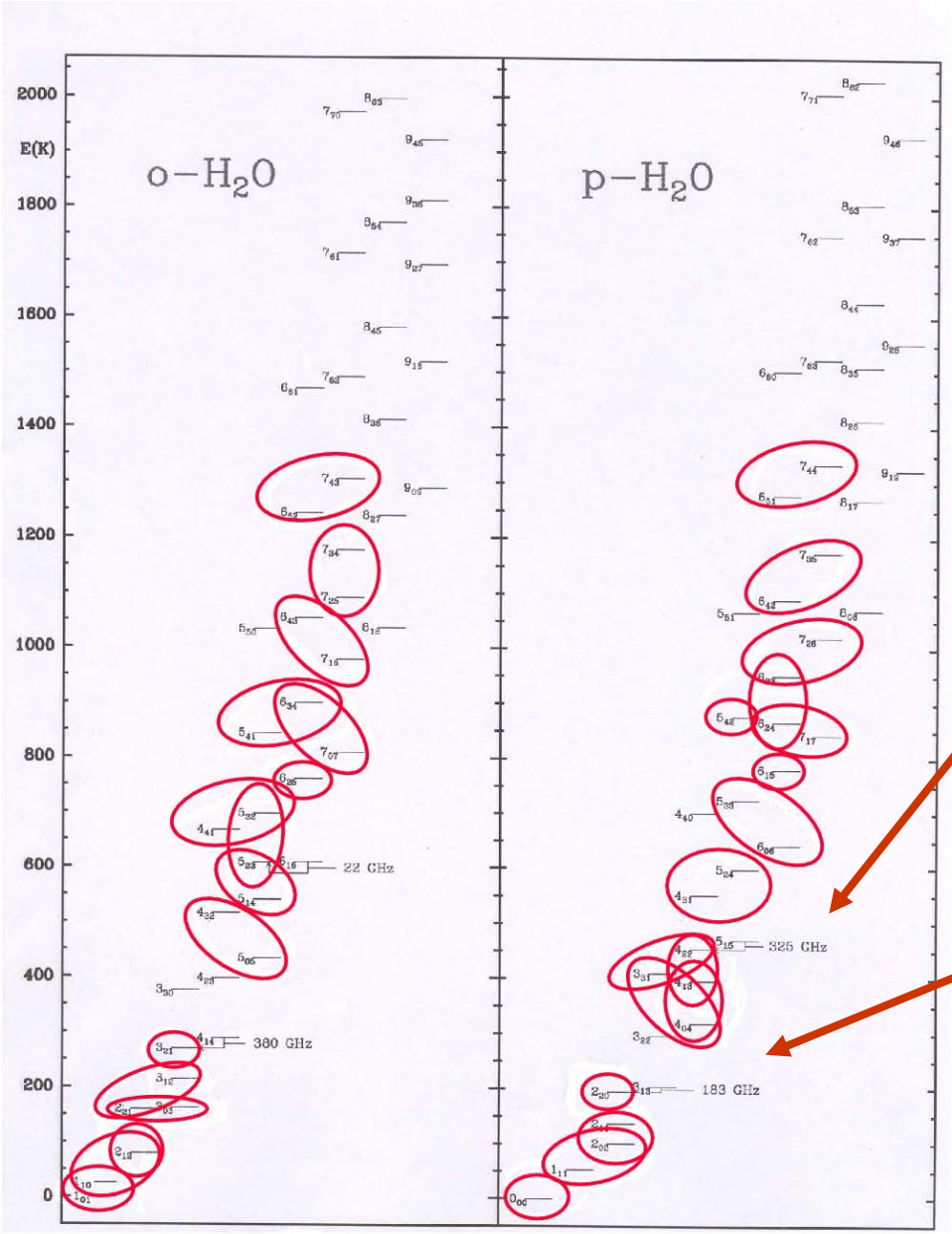


Orion KL: The Classical Hot Core Source

Within a 20" region there are a variety of physical conditions



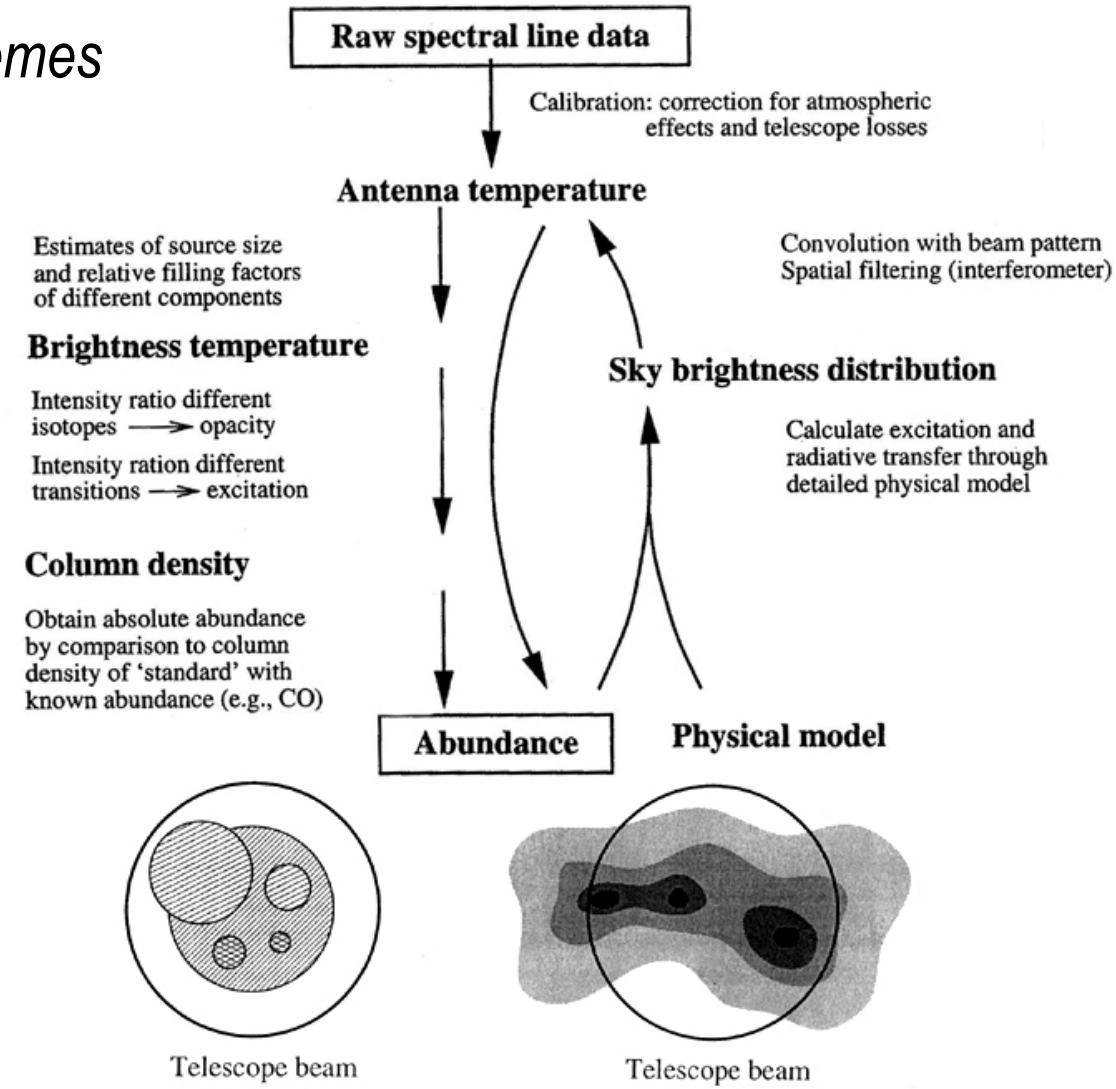
Red circles show the water Lines that can be measured with HIFI



This transition in ALMA Band 7

This transition in ALMA band 5 (a weak maser line and 18-O)

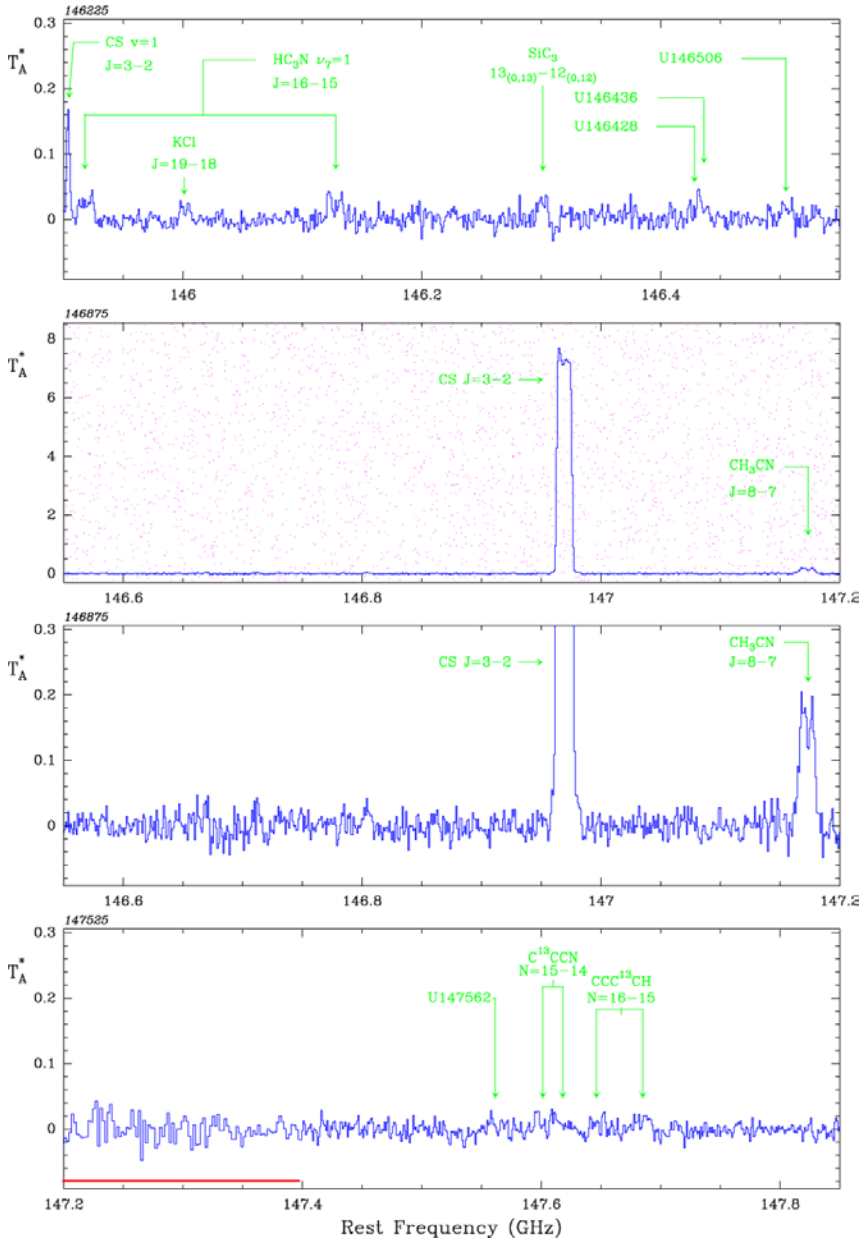
A Comparison of analysis schemes

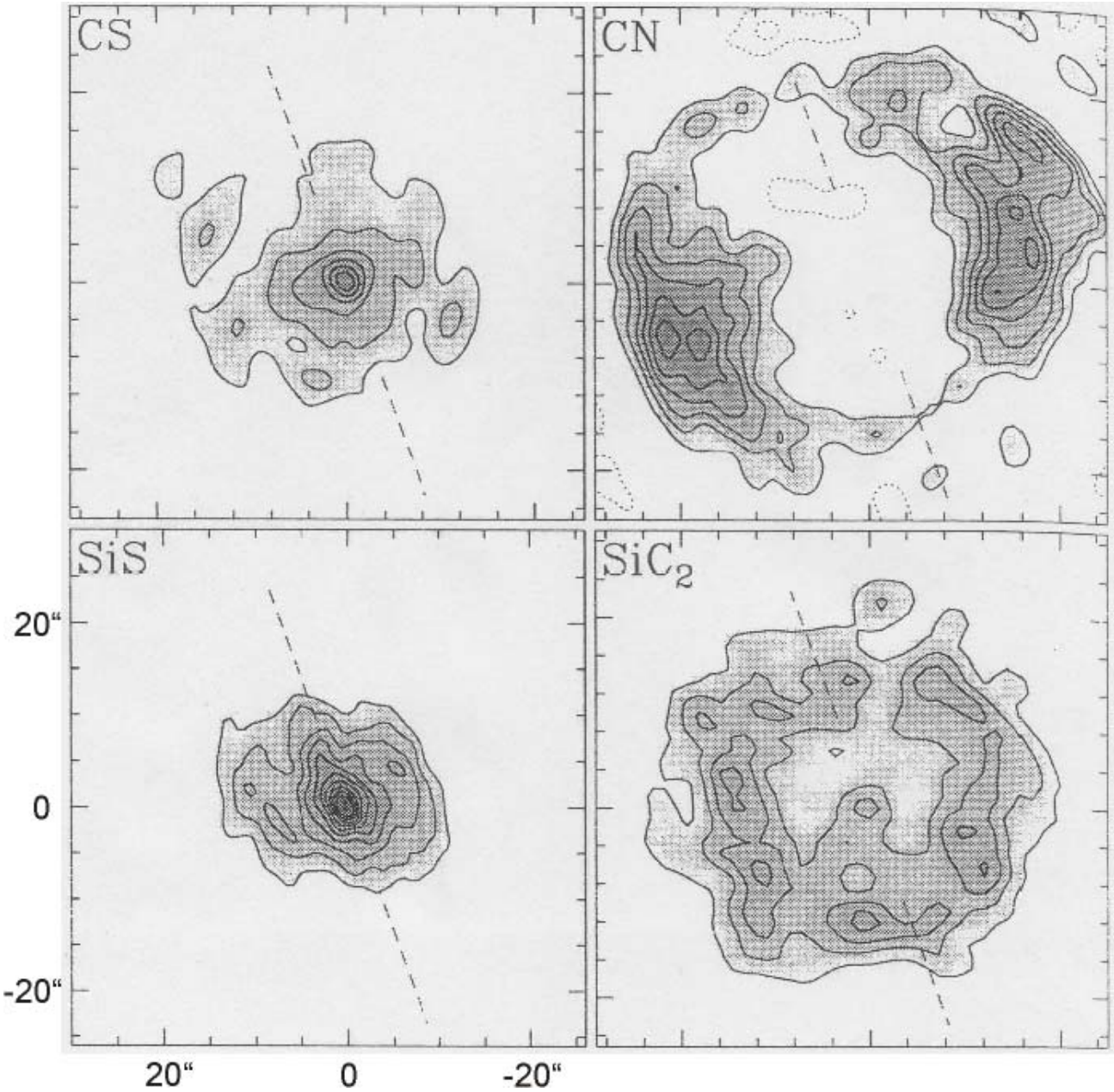


Main Sequence & Evolved Stars

- In broadband continuum, ALMA should be able to detect high mass stars in our Galaxy, and evolved stars even in the LMC
- In evolved stars such as IRC+10216, ALMA will be able to image molecular and dust emission
  - Herschel can be used to search for water vapor in the envelopes of such stars

Sample spectra from IRC+10216 (R Leo), a nearby carbon star





Images of some molecules in IRC10216, a nearby carbon star

Solar System Objects

- Herschel can easily measure outer planets, and moons of these planets, as well as Trans Neptune Objects
  - Highly accurate photometry
  - Water on the giant planets and comets
  - Follow up would be HDO, to determine D/H ratio
- ALMA and Herschel might be used to measure a common source at a common wavelength to set up a system of amplitude calibrators
  - ALMA provides high resolution image, but also records the total flux density

Recommendations for Future Work

- Overall, Herschel is best suited for surveys, while ALMA a follow up instrument
  - ALMA has a small FOV, but high angular resolution and sensitivity
  - Higher angular resolution to image the sources measured or detected by Herschel
  - Also follow ups to PACS or SPIRE surveys in CO or in longer wavelength dust emission
  - Complementary line surveys with HIFI and ALMA
- In combining results we need well established calibrations
- In analyzing the results, need a much more sophisticated system
  - This is a part of the EU FP6 program 'The Molecular Universe' and the science support within the ALMA European Regional Center
- Bring the two communities together for the development of a far IR interferometer in space