Herschel, SOFIA and Laboratory Data

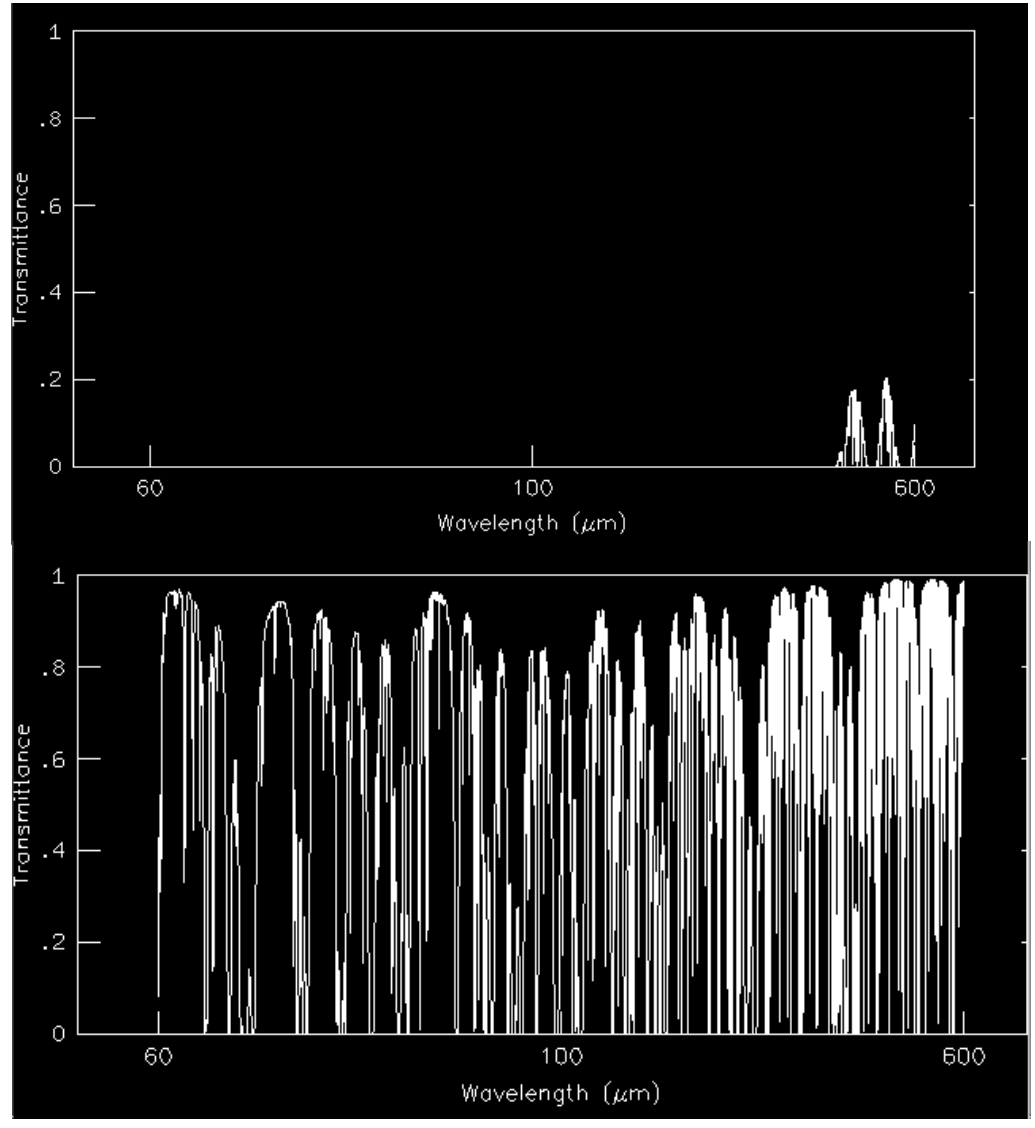
John C. Pearson

NASA Herschel Deputy Project Scientist, Jet Propulsion Laboratory, California Institute of Technology

Atmospheric Transmission

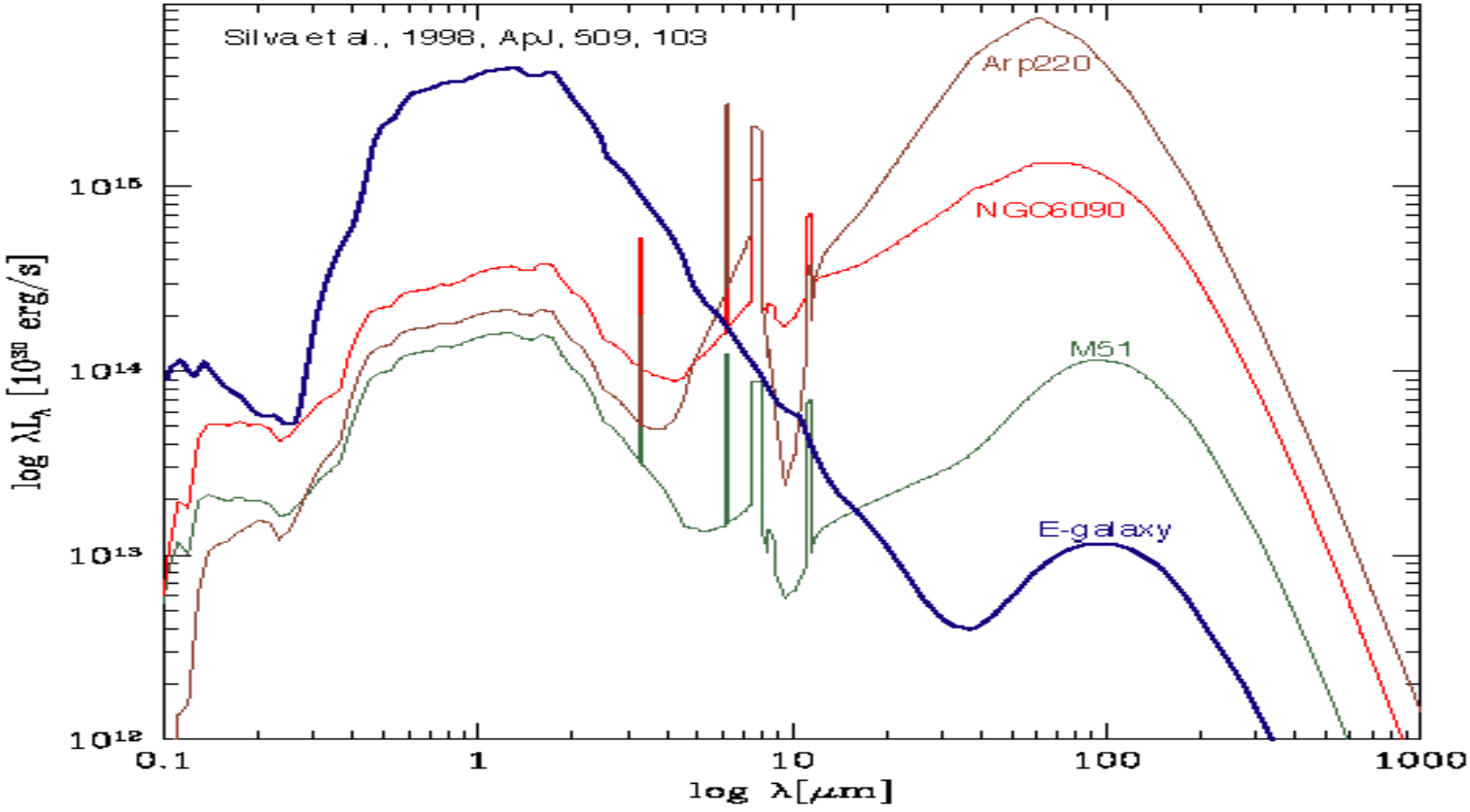
Typical transmission white
from Mauna Kea with
1mm H_2O, 45°
R = 5000

Typical transmission
"picket fence"
from SOFIA (~14km)
with 1µm H_2O, 45°
R = 5000



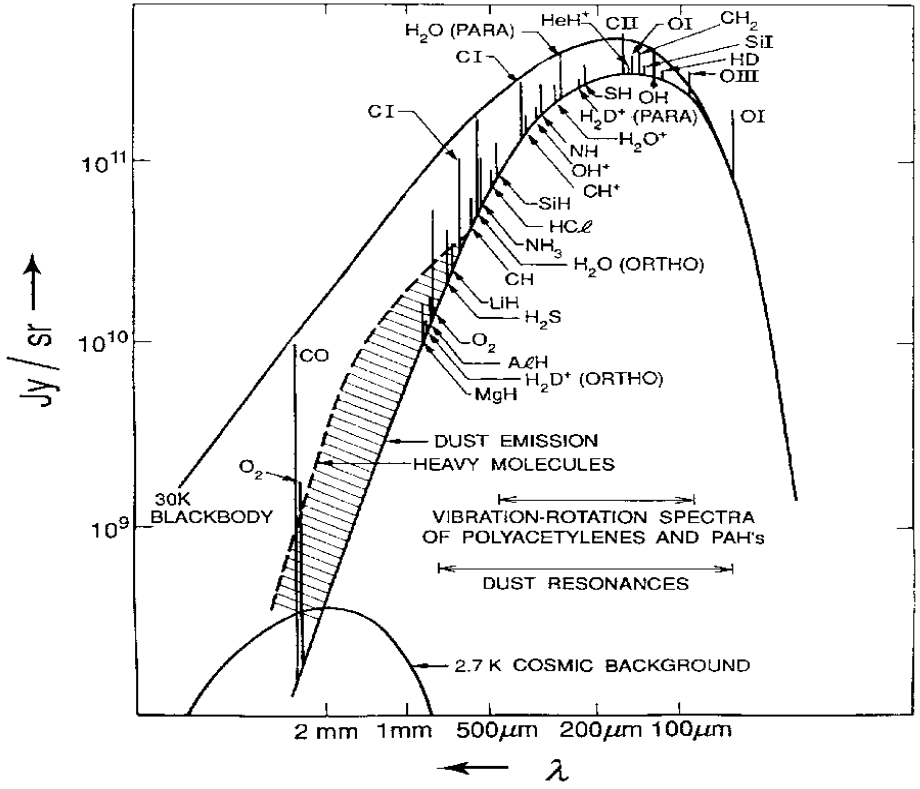
5 THz 0.5 THz

Far Infrared Astronomy



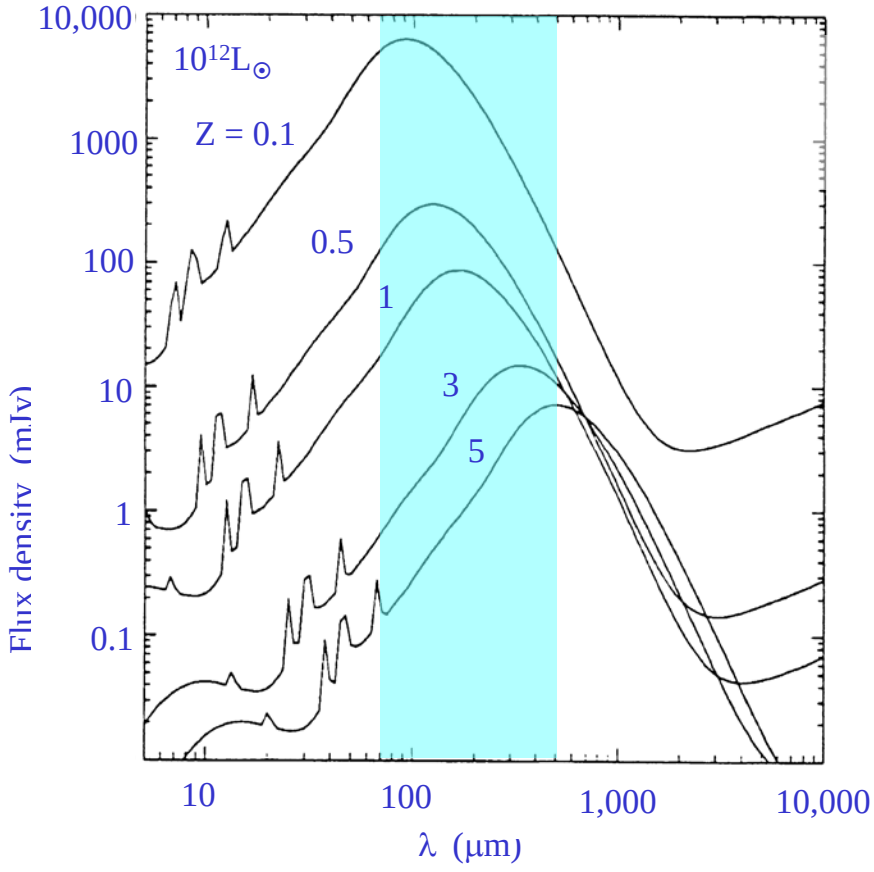
- **Spectral energy distribution of various galaxies**
  - **Dust & gas absorbs star light and re-processes it as heat in the Far Infrared**
  - **Starburst galaxies generally have more dust and gas**
    - **Arp220 is believed to represent typical Z=1-3 galaxy population**

Dust and Gas in the Far IR



- **Optically thick dust makes a transition to being optically thin in the Far-Infrared**
  - **Allows molecules to show emission lines within the dust**
  - **~150 different molecules have been identified in the ISM most in the Far-Infrared**
  - **Lines are all Doppler limited and trace chemical, dynamical and physical conditions**

Galaxies and Red Shifts



After Guiderdoni *et al*. MNRAS 295, 877, 1998

- **Peak of thermal dust emission is in the far infrared for Z=0-5**
- **Ideal wavelength range to study distant galaxies in both lines and continuum**
- **Source confusion (multiple galaxies per pixel) limits smaller telescopes at long wavelength**
- **Confusion limits measured for 250, 350 and 500 micron bands (5.8, 6.3, 6.8 mJ in 6, 10 and 14" beams)**
  - **Lower at shorter wavelength bands**
    - **Smaller beam**
    - **Distant galaxies over dust peak**

Herschel

The Herschel Space Observatory (Herschel)

- **Named for Wilhelm Herschel**
  - **Discoverer of Infrared radiation**
- **First comprehensive far infrared observatory in space**
- **Three instruments with 2500 Liters of superfluid He**
- **3.5 M Aperture @ 78 Kelvin**
- **ESA mission with NASA Participation**

Launch of Herschel & Planck

14 May 2009 at 13:12 UTC Together with Planck onboard an Ariane 5 ECA

Status: Operational all instruments working well
Life expectation: Spring 2013
One remaining open time call: ~Summer 2011

SPIRE - Spectral and Photometric Imaging Receiver

SPIRE 200-680mm PI: M.J. Griffin

3-band imaging photometer

- 250, 350, 500 μm, $\lambda/\Delta\lambda \sim 3$ (simultaneous)
- 4 x 8 arcminute field of view
- 2fλ feedhorn array

- Diffraction limited beams (17”, 24”, 35”)
- Point Source Detection Limit (5σ, 1 hour) ~3 mJy

Imaging FTS

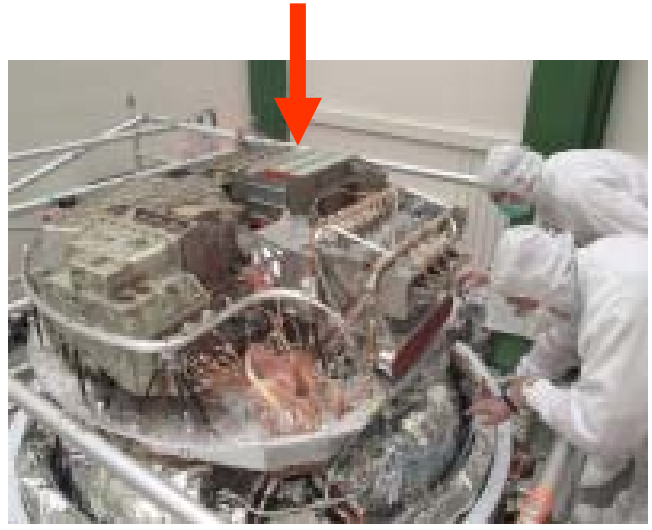
- 200-670 μm
- > 2 arcminute field of view
- Spectral Resolution to 0.04 cm^{-1}
- $\lambda/\Delta\lambda \sim 600$ at 250 μm

Observing Modes

- 3 band photometry Survey Optimized
- low to medium resolution spectroscopy
- Chop, jiggle or micro-step for mapping
- Beam steering mirror for point source peak up

Key Science Objectives

- Large Area Extragalactic Surveys
- Spectroscopy of Galaxies
- Initial mass functions in star formation



PACS - Photodetector Array Camera & Spectrometer

PACS 57-210μm PI: A. Poglitsch

2-band imaging photometer

- 57-72μm or 72-105μm simultaneously with 105-210μm
- 1.75 x 3.5 arcminute field of view
- Diffraction limited beams (6”, 9”, 14”)
- Point Source Detection Limit (5σ, 1 hour) ~5 mJy

Imaging spectrometer

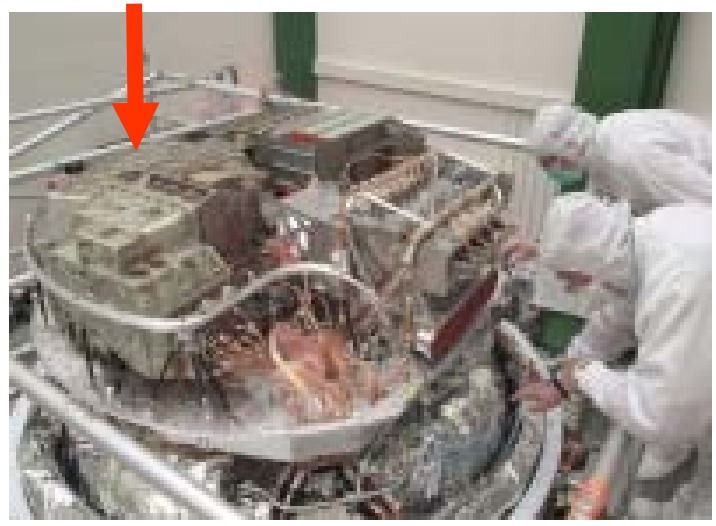
- 57-210 μm
- Simultaneous imaging of 50”x50” FOV (5x5 pixels)
- $\lambda/\Delta\lambda$ ~ 1000-3000 (Δv ~ 150-300 km/s), 16 pixels

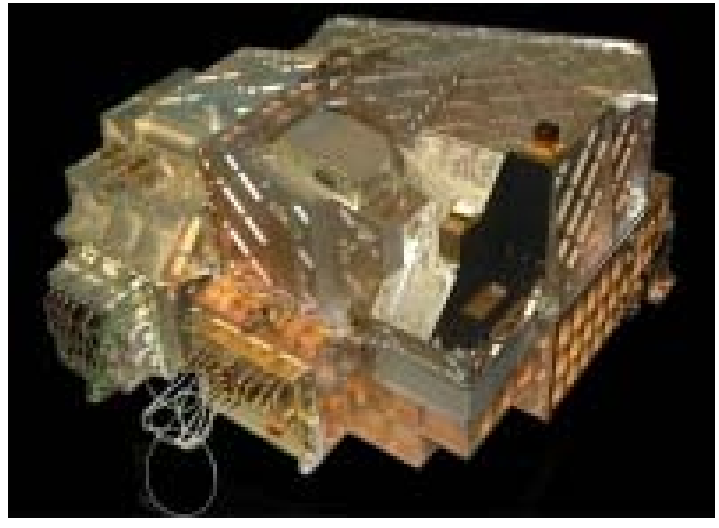
Observing Modes

- Dual band Photometry
- Single band Photometry
- Line spectroscopy
- Range spectroscopy

Key Science Objectives

- Large Area Extragalactic Surveys
- Spectroscopy of Galaxies
- Initial Mass Function of Cores and Clusters
- HD and the D/H ratio





HIFI- Heterodyne Instrument for Far Infrared

HIFI: 157-624μm PI: Frank Helmich

7 channel heterodyne receiver

- 5 dual polarization SIS bands from 480-1272GHz
- 2 dual polarization HEB bands from 1.44-1.91 THz
- DSB configuration >2.4 GHz IF each polarization
- Autocorrelation spectrometer to 134 kHz resolution
- Acousto-Optical spectrometer with 4 GHz coverage
- $\lambda/\Delta\lambda$ Minimum=f/1GHz, maximum 10^7

Observing Modes

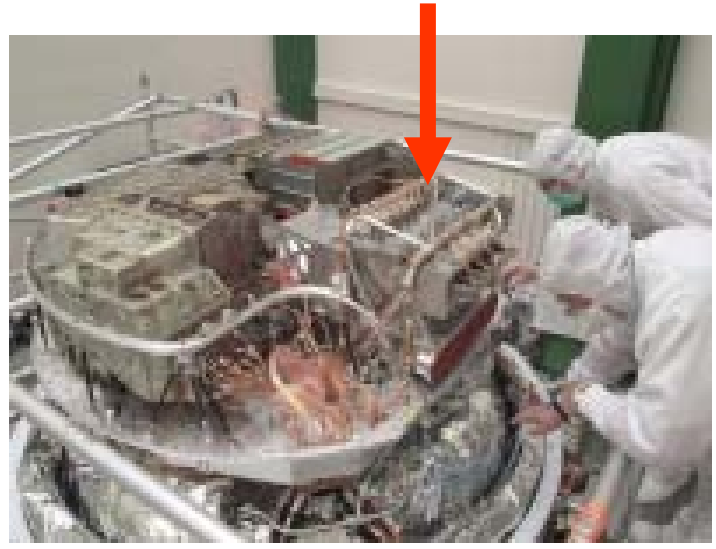
- Deep integration single pixel
- Spectral scan
- Position mapping of a single line

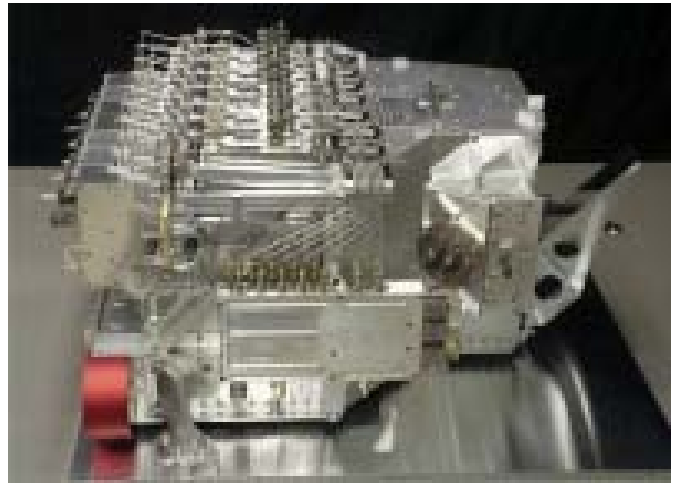
Key Science Programs

- Spectral Surveys (>30 objects)
- Role of Water in the Universe

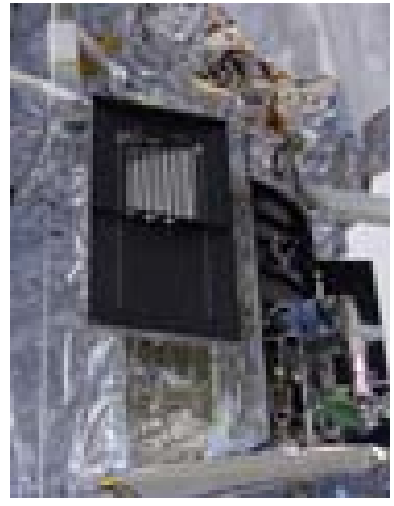
Core Science Objectives

- ISM in Milky Way
- Late Stages of Stellar Evolution
- Solar system
- ISM in Galaxies
- Star formation



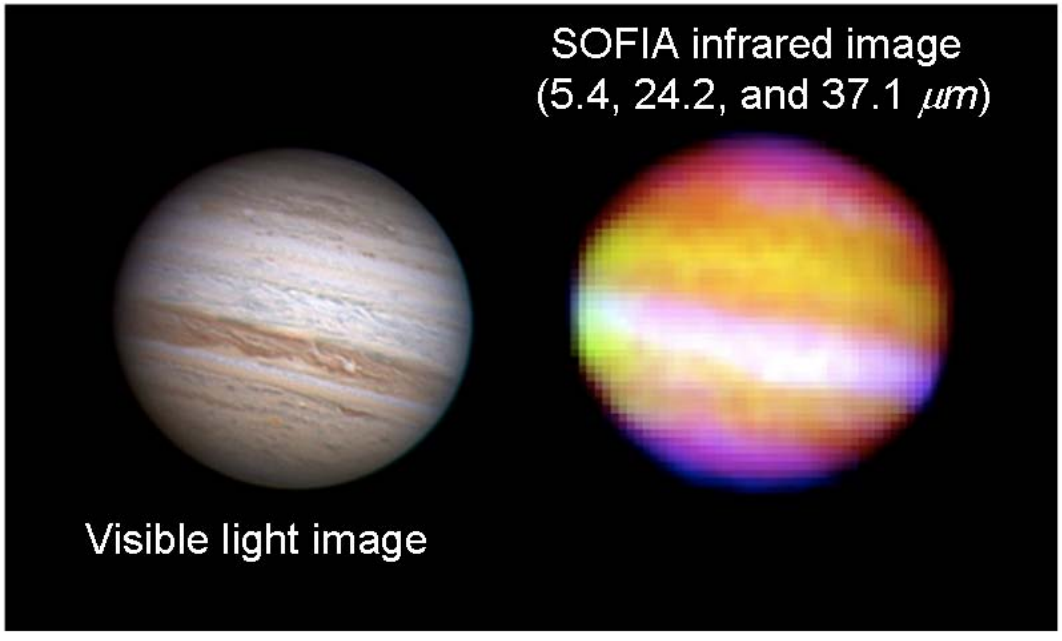


Focal Plane Unit



LO Unit

Stratospheric Observatory for Infrared Astronomy SOFIA

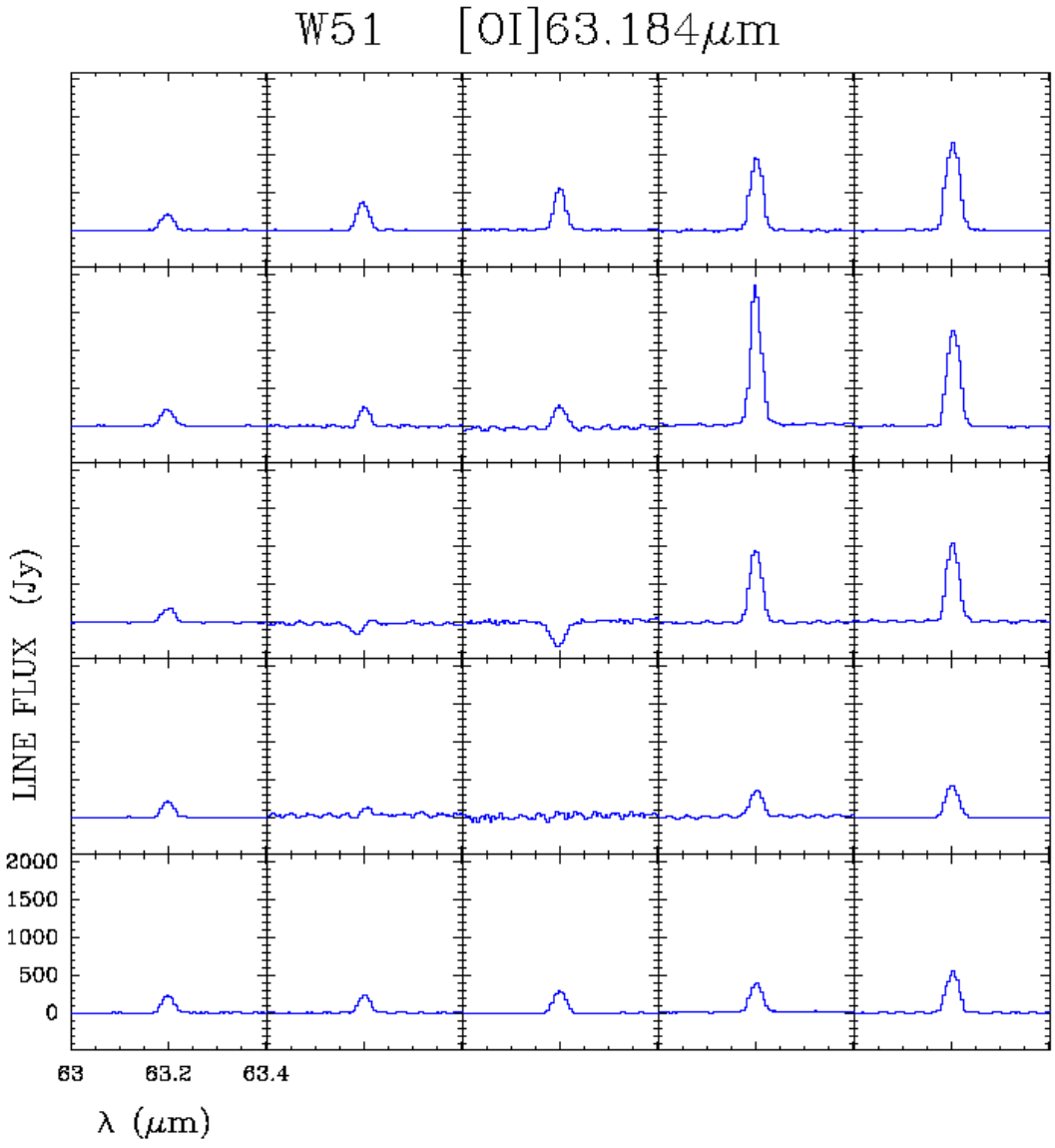


First light May 26, 2010 UT

SOFIA Instruments

- **HAWC** ***High-resolution Airborne Wideband Camera (bolometer camera R~10 53, 88, 155, 215μm)*** **PI: Dr. Al Harper U. Chicago**
- **EXES** ***Echelon-Cross -Echelle Spectrograph*** **(5-28 μm R=10^5, 10^4, or 3000) PI: Dr. Matthew J. Richter UCDavis**
- **FIFI LS** ***Field Imaging Far-Infrared Line Spectrometer*** **(Ge:Ga photoconductor 42-210 μm in two bands R to 6000) PI: A. Poglitsch MPE Germany**
- **FORCAST** ***Faint Object InfraRed CAmera for the SOFIA Telescope*** **(SiAs and SiSb arrays 5-25 μm and 25-40μm R~30 5/4 filters)PI: Dr. Terry Herter Cornell**
- **GREAT** ***German Receiver for Astronomy at Terahertz Frequencies*** **(Heterodyne 1.25-1.50, 1.82-1.92, 2.4-2.7, 4.7 THz R to 10^8) PI: Dr. Rolf Güsten MPIFR Germany**
- **FLITECAM** ***First Light Infrared Test Experiment CAMera*** **(1-5.5μm, J,H,K,L',M & KL' bands R=2000 grism) PI: Dr. Ian McLean UCLA**
- **HIPO** ***High-speed Imaging Photometer for Occultation*** **(0.3-1.1 μm 8 filters) PI: Dr. Edward W. Dunham, PI Lowell Observatory**

SOFIA Projects

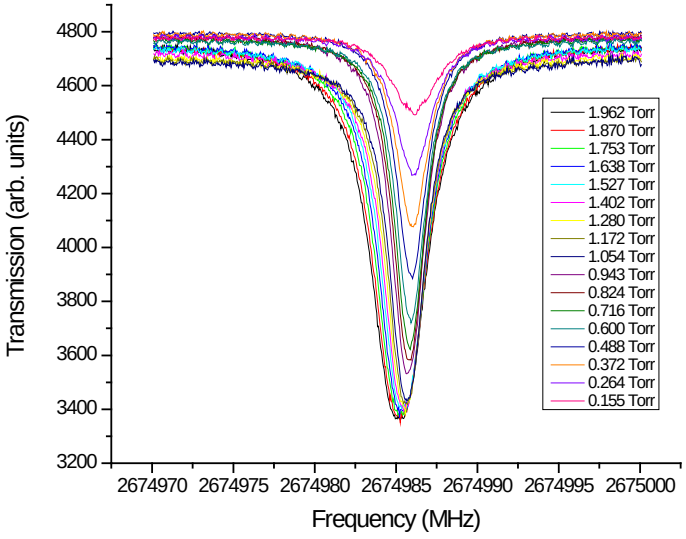


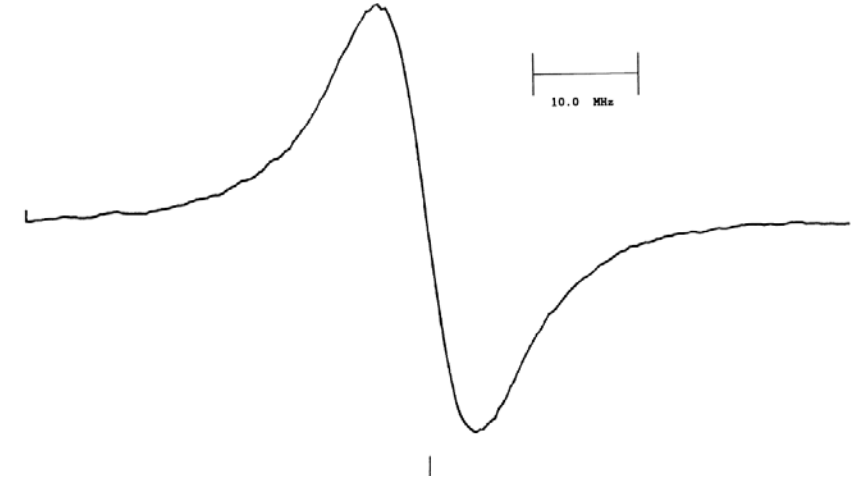
OI Herschel PRISMAS

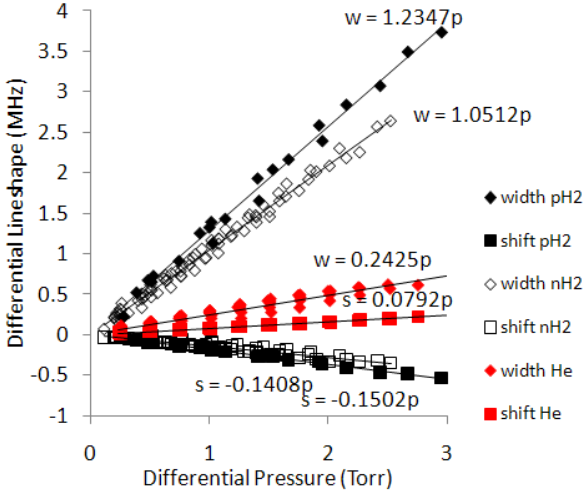
PACS resolution too poor to resolve line shape. Most shape is due to illumination of the slit. Absorption (and emission?) of OI shown here towards W51 is a serious problem for low resolution instruments

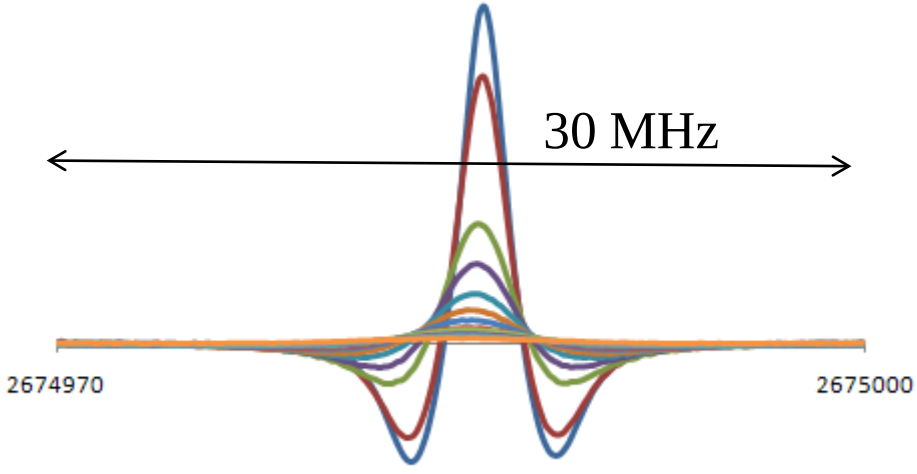
Sorting this out will be a SOFIA GREAT priority

HD, frequency shift and excitation





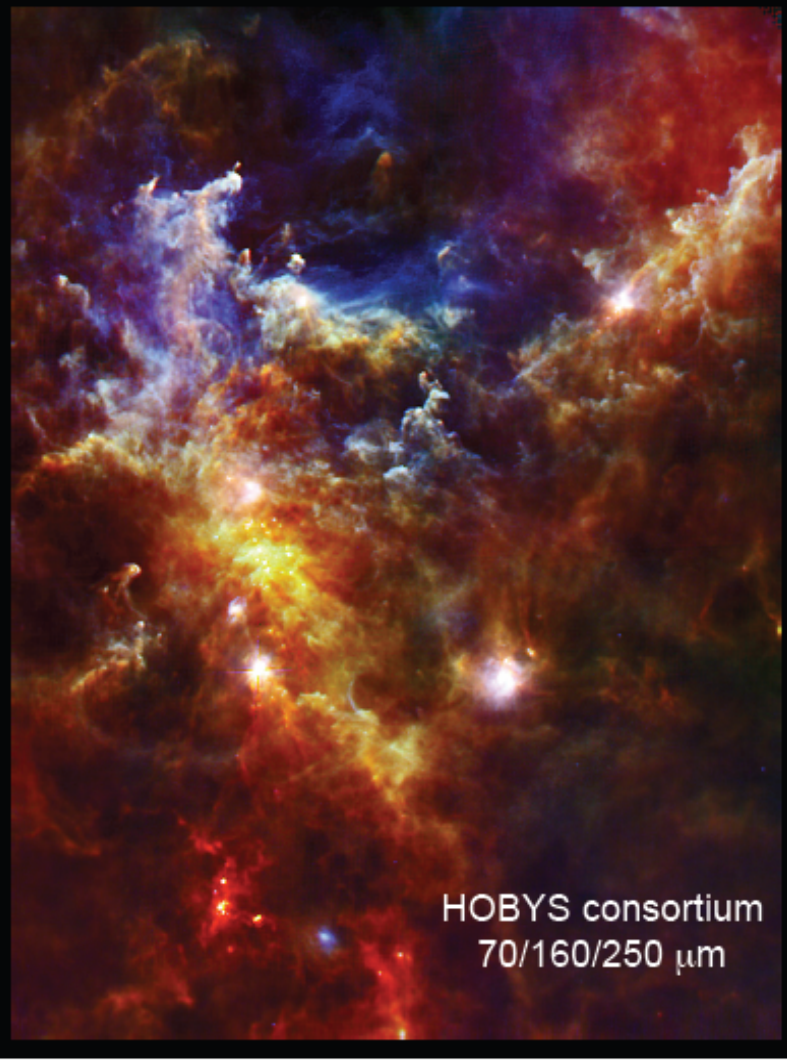




SOFIA GREAT project is HD
Poster by H. Gupta

Photometery-Dust Filaments Everywhere

The Rosette molecular complex with *Herschel*



- 1°x1° scan-map (5.3 hrs)

Rosette GMC 1.6 kpc, 2 x 10^5 $M_\odot$

Under the influence of 7 O stars

- Data reduction

HIPE scripts with baseline removal and MadMAP for PACS data

- Spatial dynamic range:

0.05 - 40 pc, up to 1 000 (PACS)

- Flux dynamic range

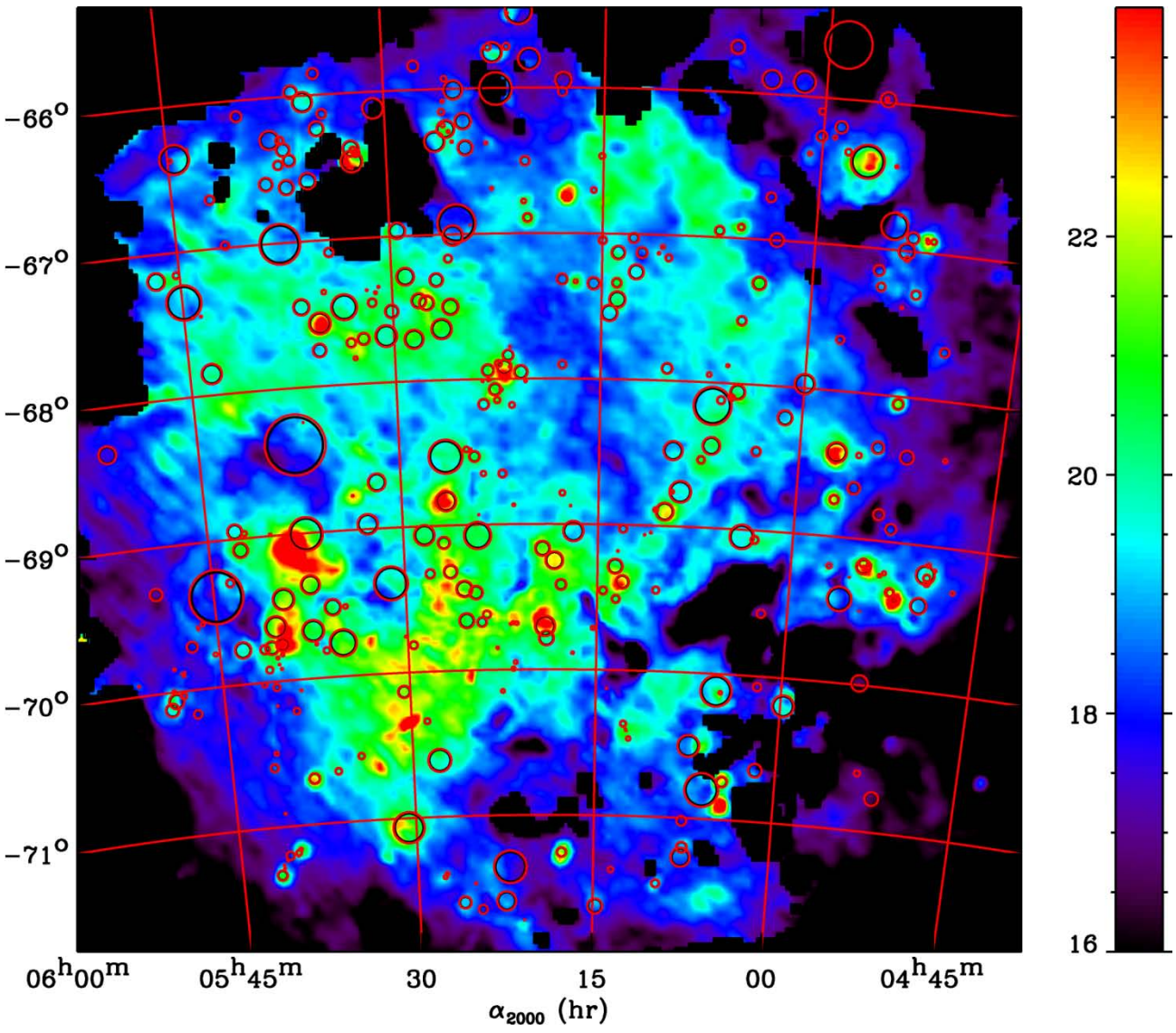
σ = several x instrumental sensitivity

Sensitive to 0.3 $M_\odot$ @ 160 μm

- A&A Sp. Issue: **Motte+, Schneider+, Di Francesco+, Hennemann+**

HOBYS - ESLAB 2010

Dust Temperature Maps-Radiation Field



T map derived from I_{160}/I_{100} using $\beta=2$ HII regions contours

This is the first time the dust T distribution can be evidenced over LMC at 4' resolution.

Coherent variations of the dust temperature are clearly evidenced.

T map has defects (stripes) imposed by IRAS 100 μm map: Waiting for Herschel

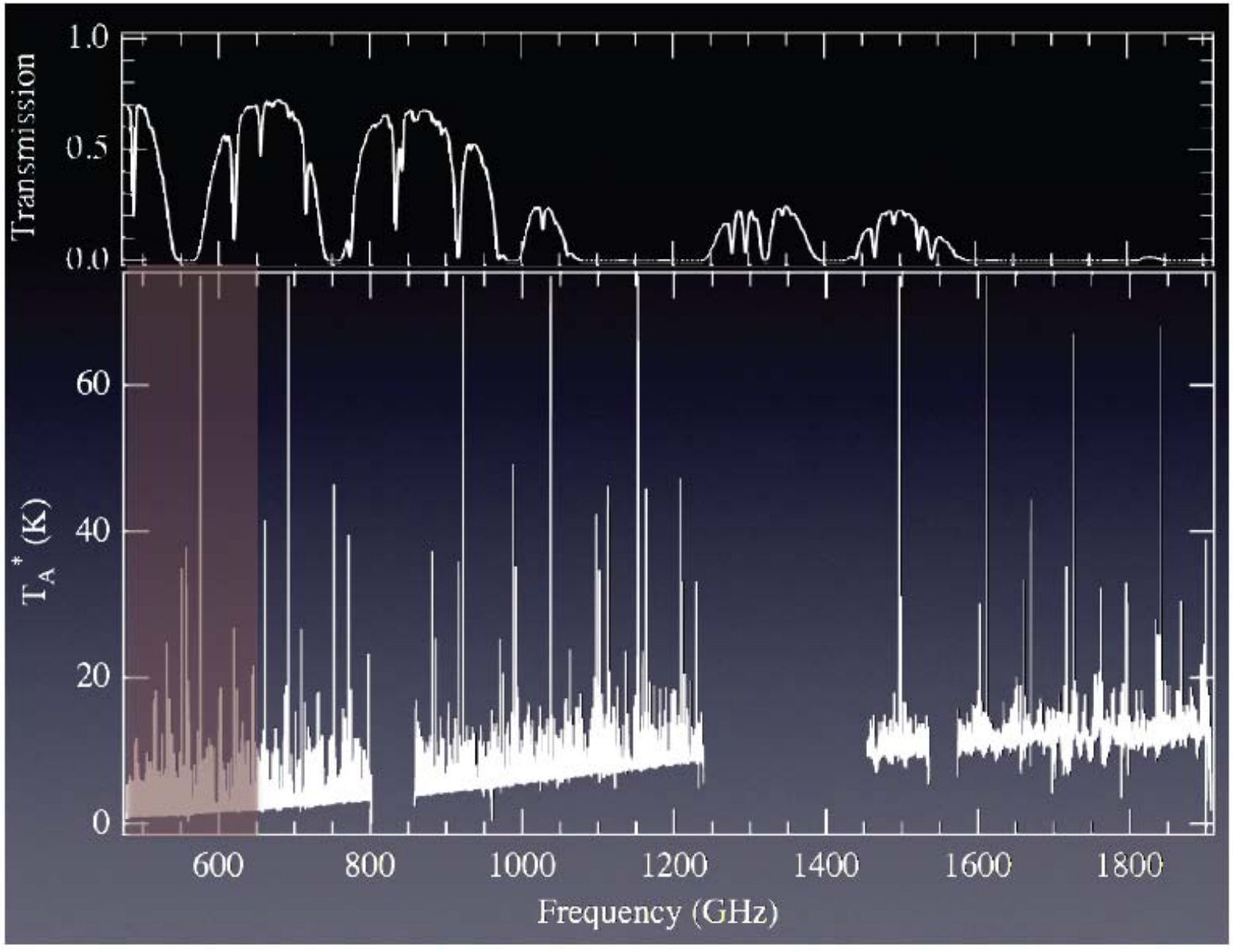
Very important: It's our map of the radiation field

Herschel Heritage Survey

Dust Properties

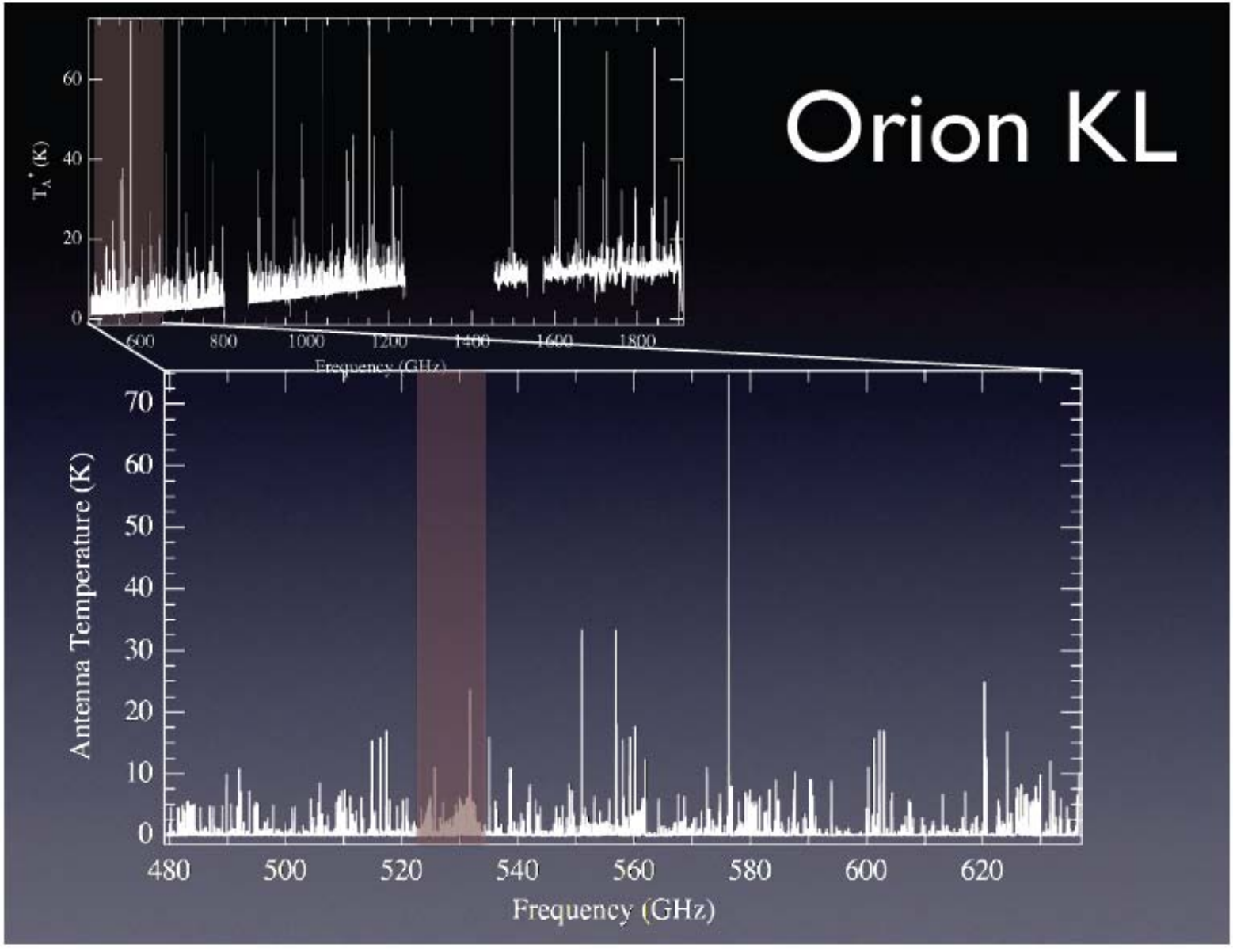
- **Grey or black body temperature is dependent on optical depth**
  - **Not thick then it is not a true blackbody**
- **Emission in thin dust is dependent on material**
  - **No good finger print on dust properties**
  - **No easy way to "guess" dust properties**
- **Interaction of dust and gas**
  - **Chemical and thermal**
- **Interaction of magnetic fields with dust**
  - **How charged does it have to be?**
  - **Is this material dependent?**
- **Radiation processing by dust**
  - **Chemistry in solid state and material dependence**

HIFI Spectrum of Orion KL

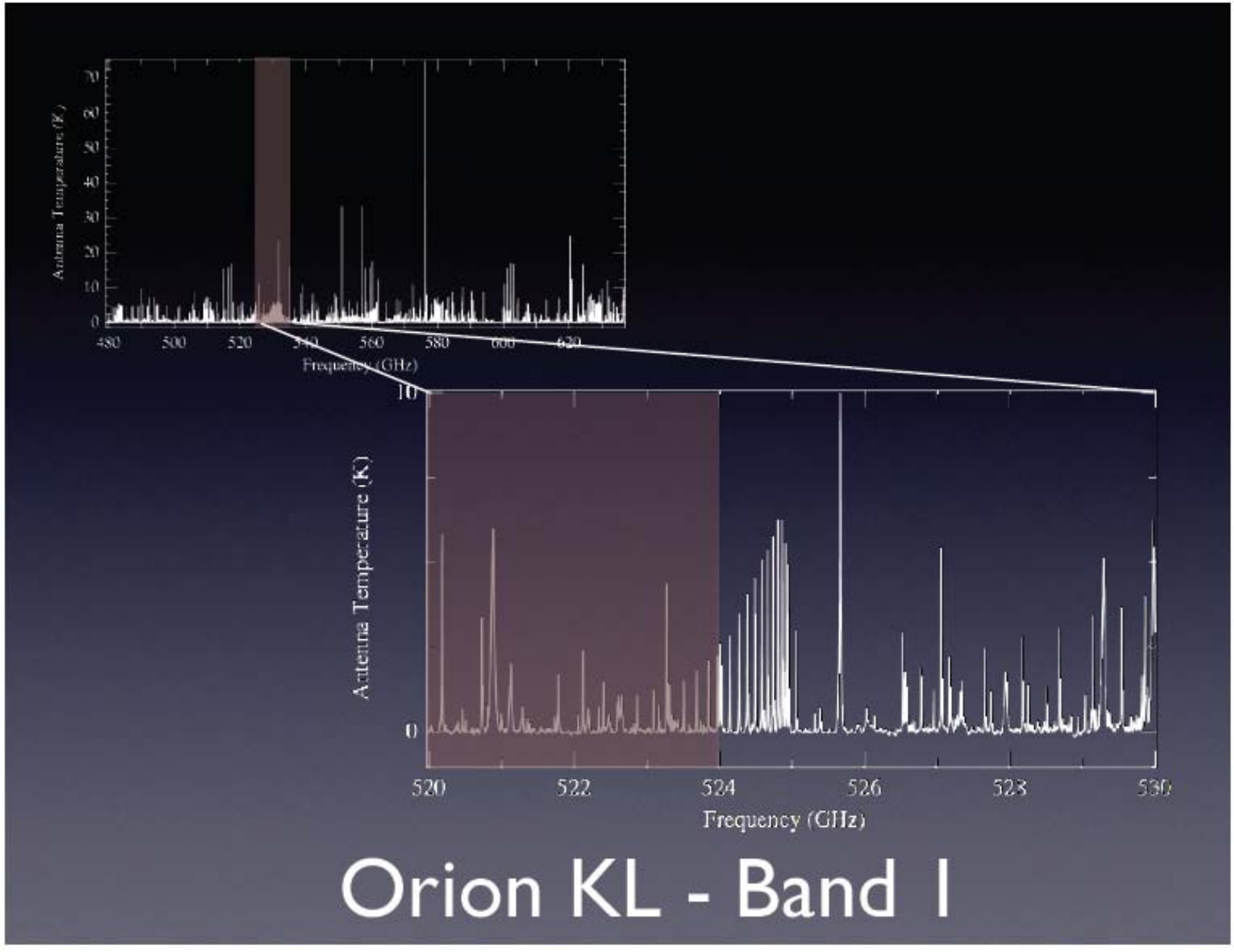


Herschel
HEXOS

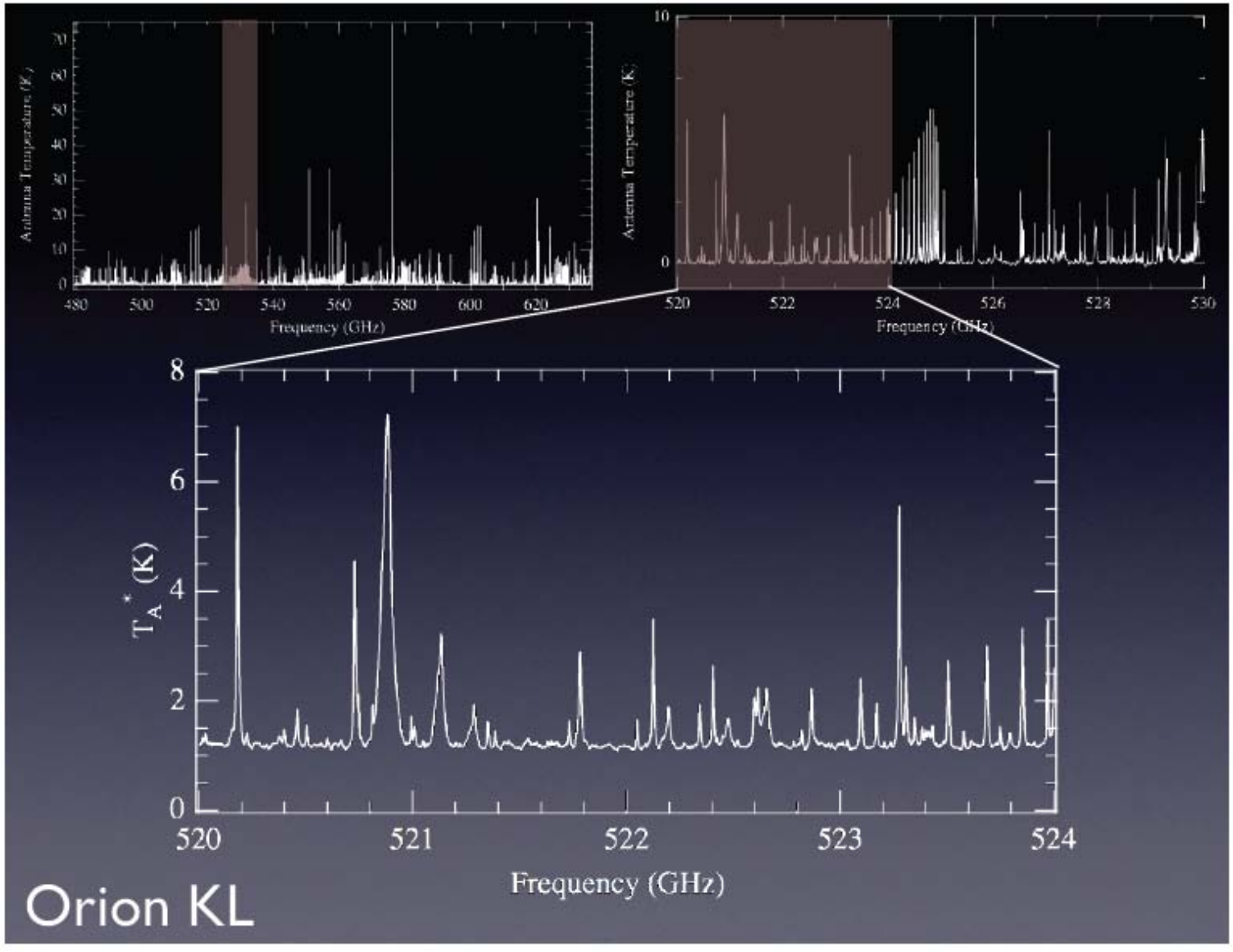
A Blow up of the Spectrum



Orion KL blown up again



Orion Blown Up Again

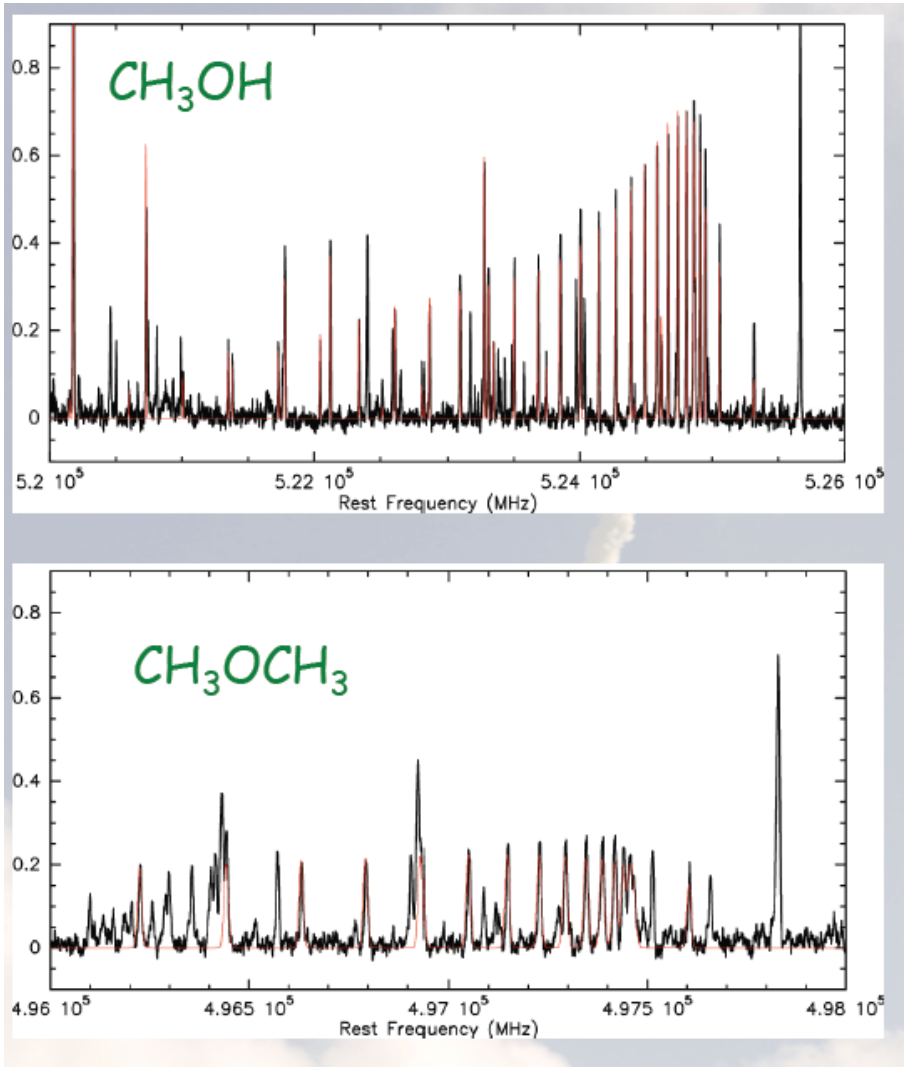


Noise is ~50mK
Some standing wave is present (LO-mixer period) the rest is all signal.

Most numerous features are SO_2 and methanol

Poster on methanol Pearson et al.

NGC 6334 & More of the Same

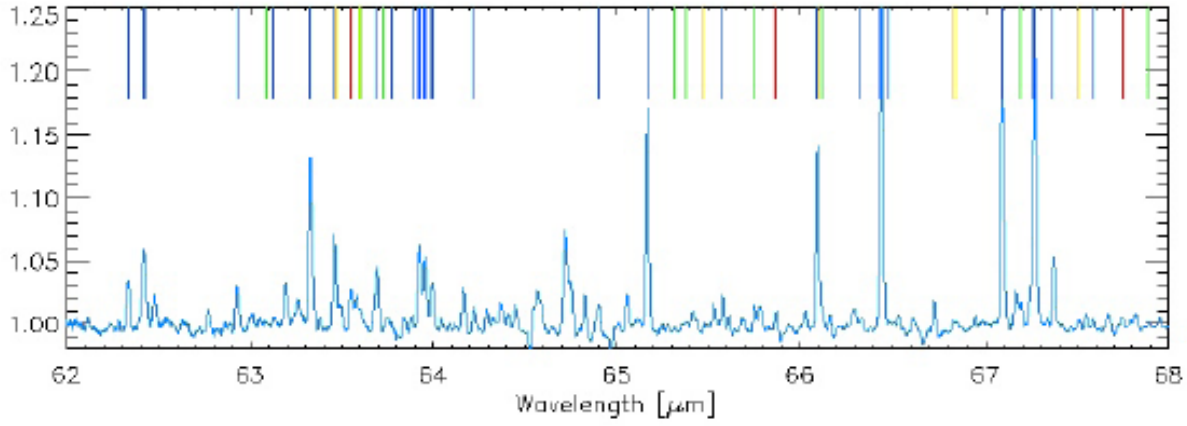


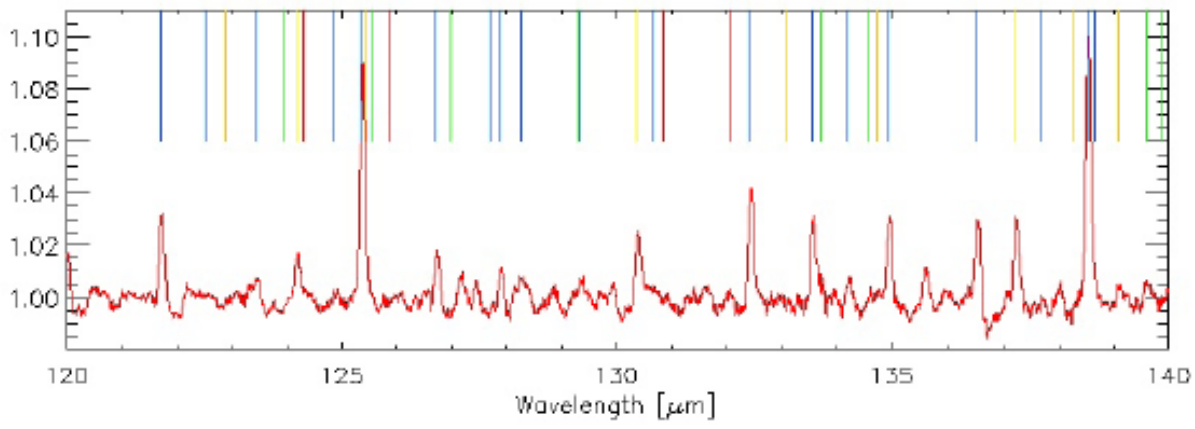
NGC 6334I from Herschel CHESS

Lots of the usual “weeds” not as bright as Orion, but it is further away

Must model the entire spectrum of the complex molecules before you can assign the weaker lines

PACS R~3000 Spectroscopy





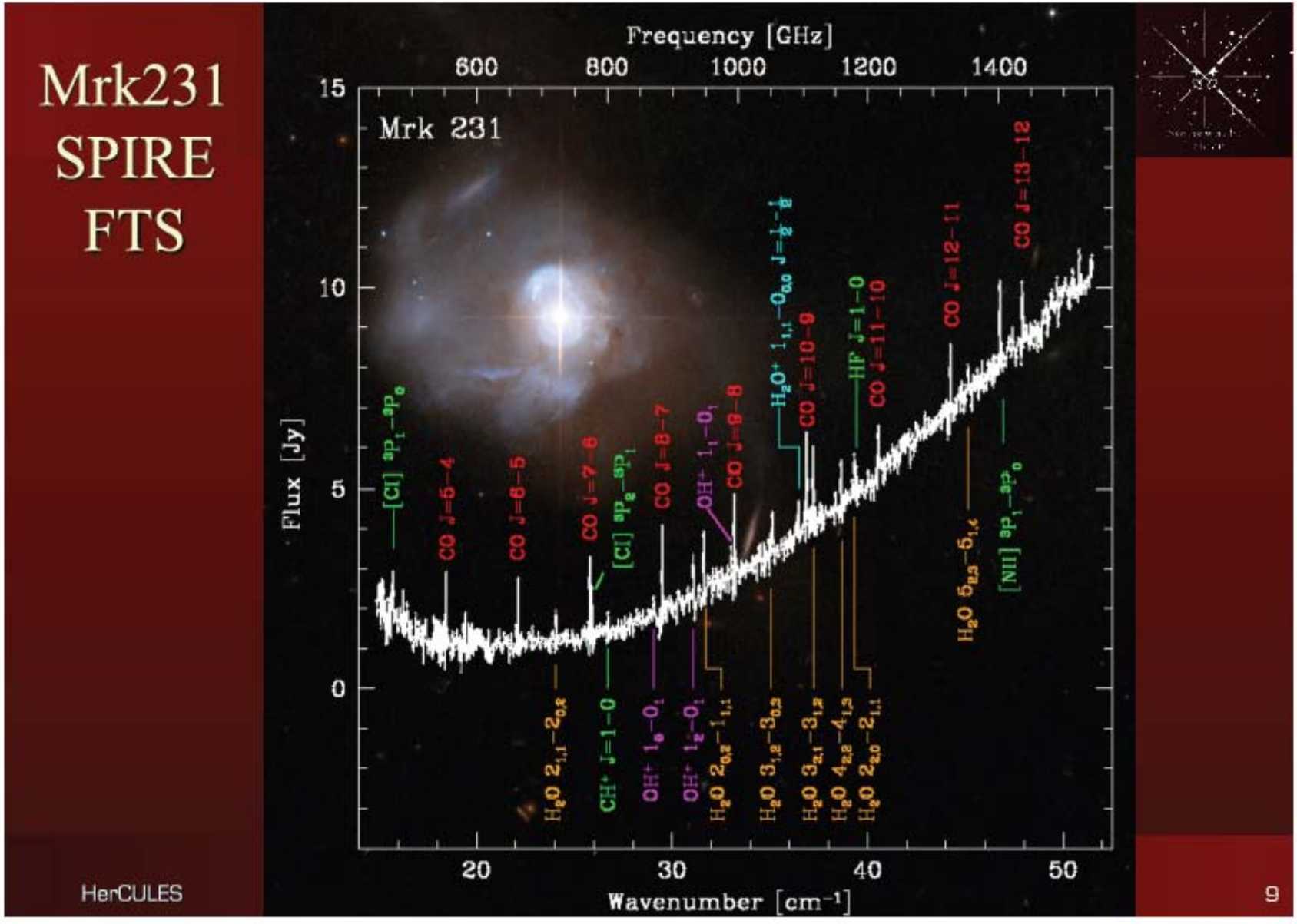
Velocities corrected to rest frame, strong water lines over-plotted;
$H_2{}^{16}O$=blue
$H_2{}^{18}O$=green
$H_2{}^{17}O$=orange
HDO=red
CO=yellow

Lines from 4 water isotopes are detected.

Wavelength calibration is quite good already, fine tuning to come still

W Hya PACS-Consortium

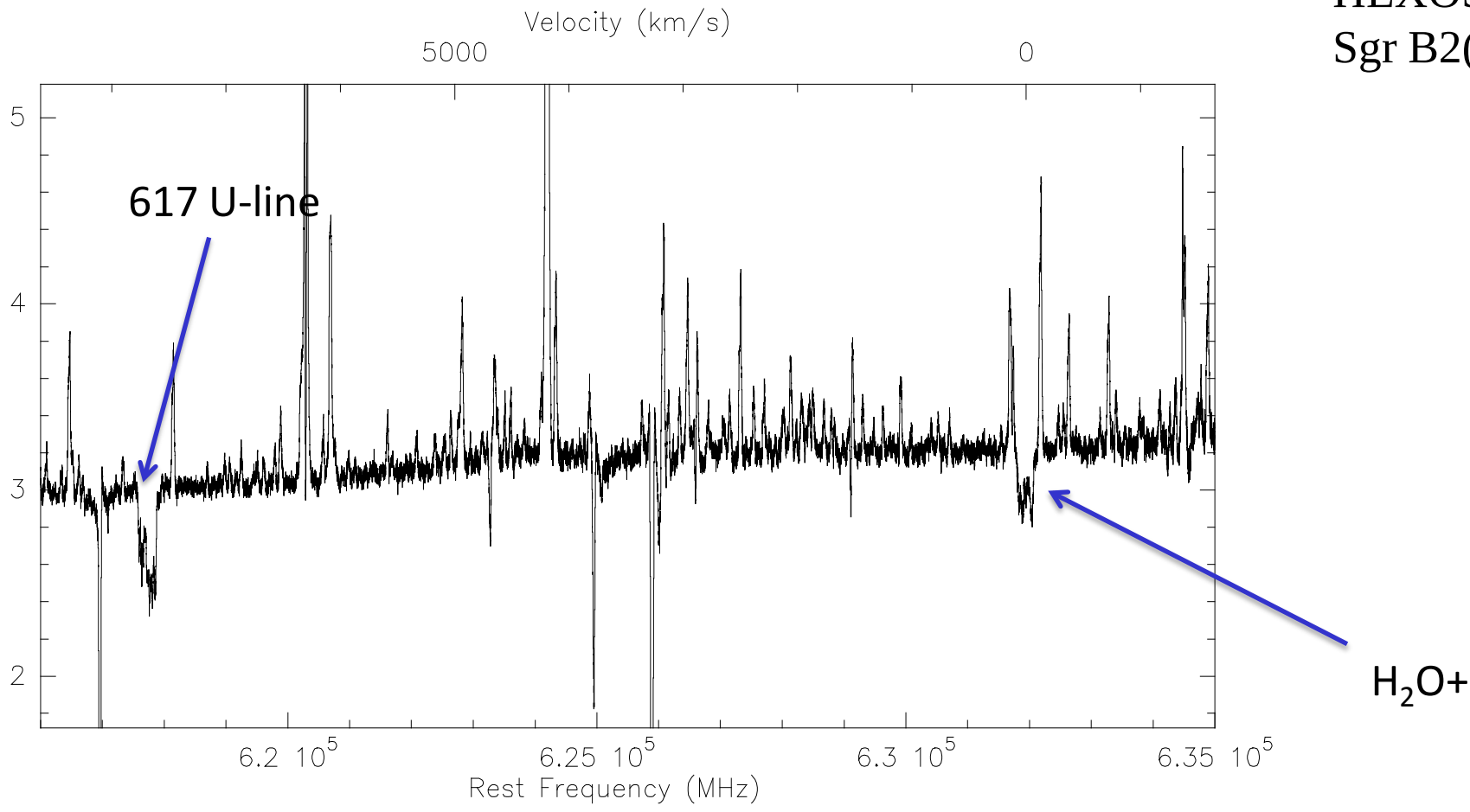
SPIRE R~600 Spectroscopy



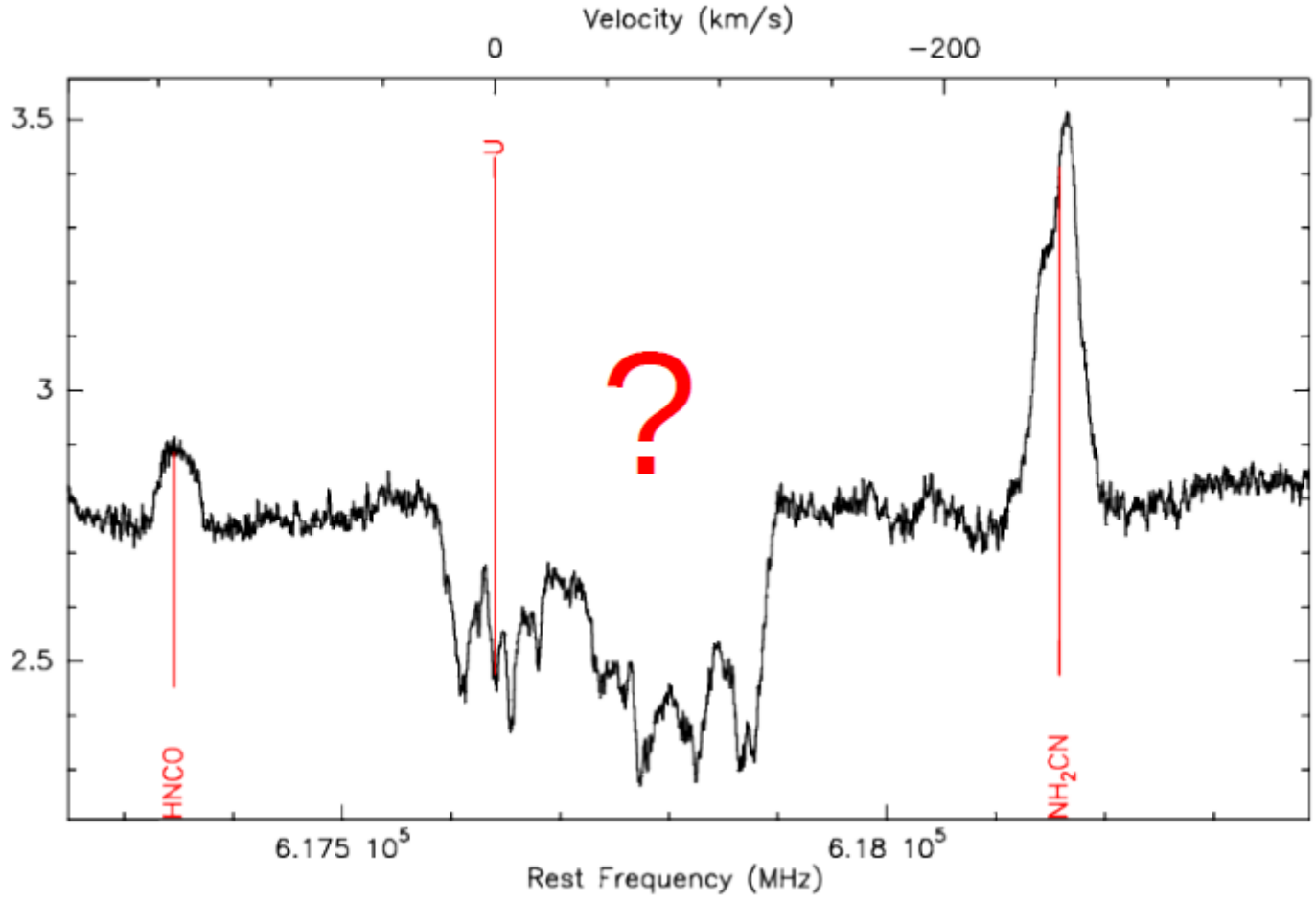
Surprises Everywhere

1; 3 SGR B2(M) DECONV-SSBSB HIF-01-WH-1B O: 08-MAR-2010 R: 08-MAR-2010
RA: 00:00:00.000 DEC: 00:00:00.00 (2000.0) Offs: 0.0 0.0 Eq
Unknown Tau: 0.000 Tsys: 1.000 Time: 5.7000E-02 El: 2.00
N: ***** I0: 1.5447E+05 V0: 62.00 Dv: -0.2703 LSR
F0: 631832.444 Df: 0.5000 Fi: 122651.056
B ef: 1.000 F ef: 0.000 G im: 0.000

HEXOS
Sgr B2(M)

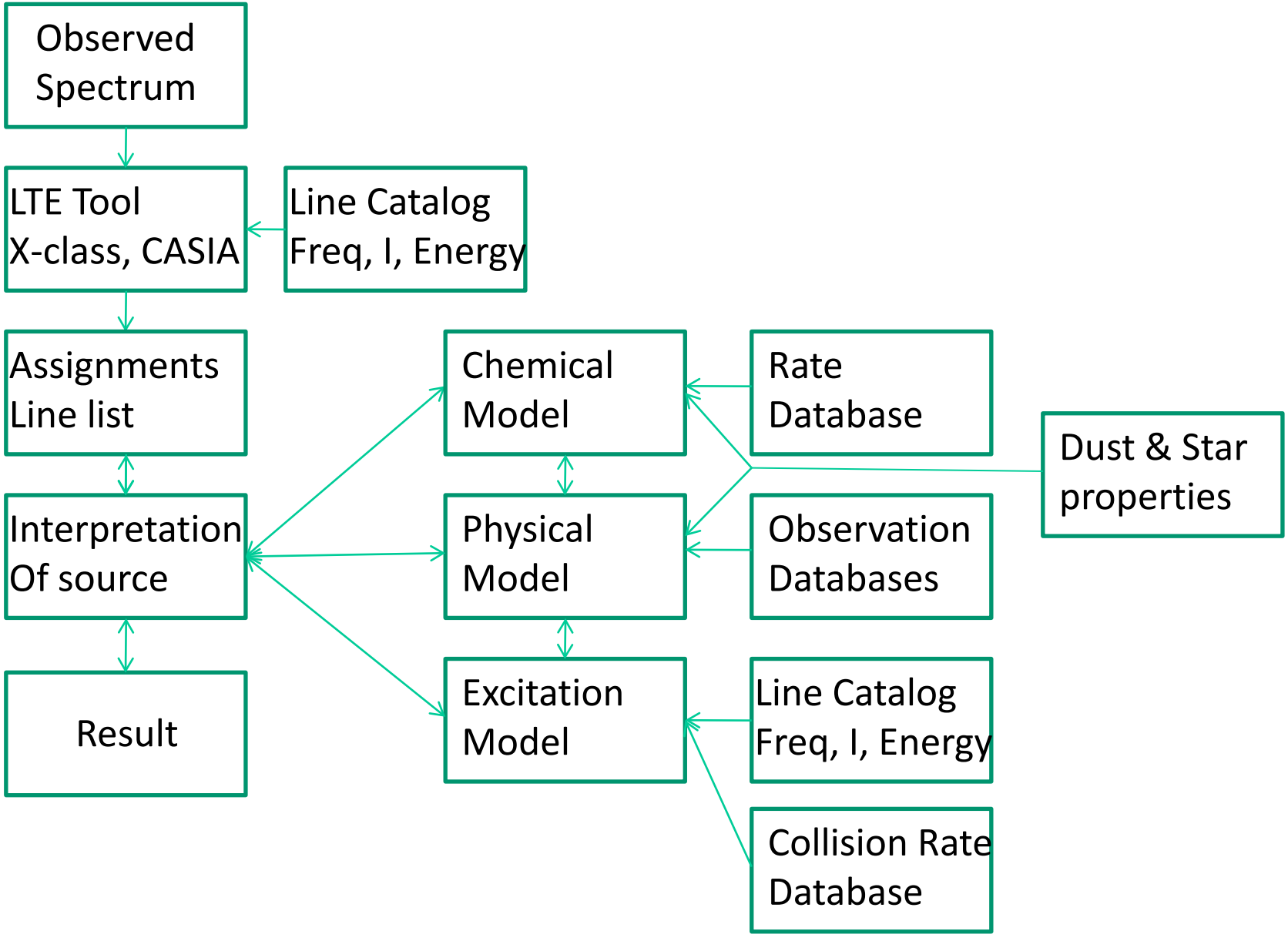


U-Line in all components to Sgr B2(M)



Some fundamental spectroscopy is missing no obvious ID in spite of lots of effort
What ever it is it is everywhere: All spiral arm components

Interpretation of Data



Data Needs

- **Basic spectroscopy: dipole moments, transition frequencies, molecular Hamiltonian models, potential molecules**
- **Machine readable catalog of measured and predicted lines**
  - **Need to be possible to group by molecule**
  - **If you have methanol *ALL* the lines are there the only *question* is how strong**
  - **ALL includes ^{13}C, ^{18}O, ^{17}O, D….**
- **U-Lines are ones that don't make it this far**
- **Interpretation:**
  - **Chemical reaction rates as function of temperature (Gas phase and surface)**
  - **Collisional excitation rates vs o-H_2 and p-H_2**
    - **Big problem for big molecules (probably could be done statistically)**
    - **Big problem for most ions**
- **Machine readable is required for calculating complex systems**

Status of Data 1/1

- **Data on known astrophysical molecules is in reasonable shape below 600 GHz**
  - **Catalogs now contain all the known molecules that have data**
  - **Data gets progressively worse above (little lab work)**
    - **SOFIA starts at 1.25 THz**
    - **Herschel starts at 480 GHz**
  - **Some abundant fundamental molecules are still missing!**
  - **Many isopologues remain to be studied or are limited to low frequency data**
- **No infrared (Vibrational) catalog exists**
  - **Atmospheric and Planetary only have about 45 molecules**
- **No visible/UV (electronic spectra) catalog exists**
  - **Electronic spectra of some highly abundant molecules e.g. HCO^+ are unknown**
- **Atomic data is cataloged but many lines need higher precision measurements**

Status of Data 2/2

- **Chemical rates all exist and are cataloged**
  - **Many are estimated (Guessed)**
  - **Little temperature dependence available**
  - **Surface (what surface?) chemistry is in poor shape**
- **Collision rates are generally in trouble**
  - **Nearly no experimental data (bench marks)**
  - **Quantum calculations for a few simple systems e.g. H_2O-H_2**
    - **Unresolved issues between the few low temperature experiments and theory**
  - **Very little of anything for larger molecules, ions, radicals**
  - **Statistical and first order treatments could solve much of the data gap**

Acknowledgement

This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Thanks to the Herschel key projects for providing numerous examples of Herschel observation. Support from the NASA Herschel Science Center for analysis of Herschel data is acknowledged