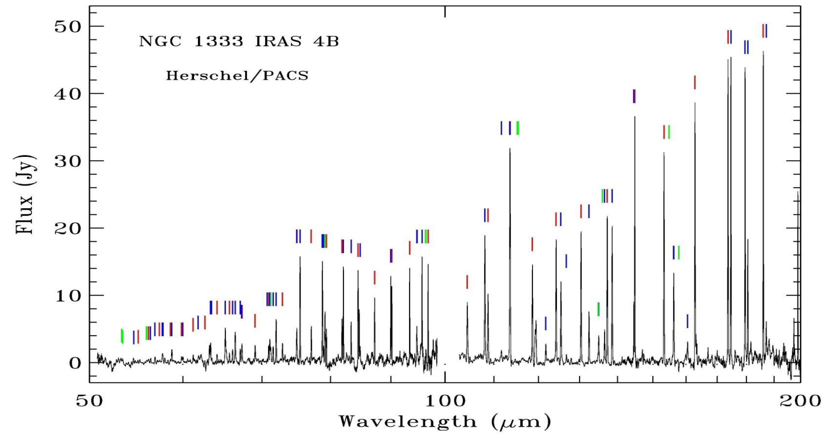
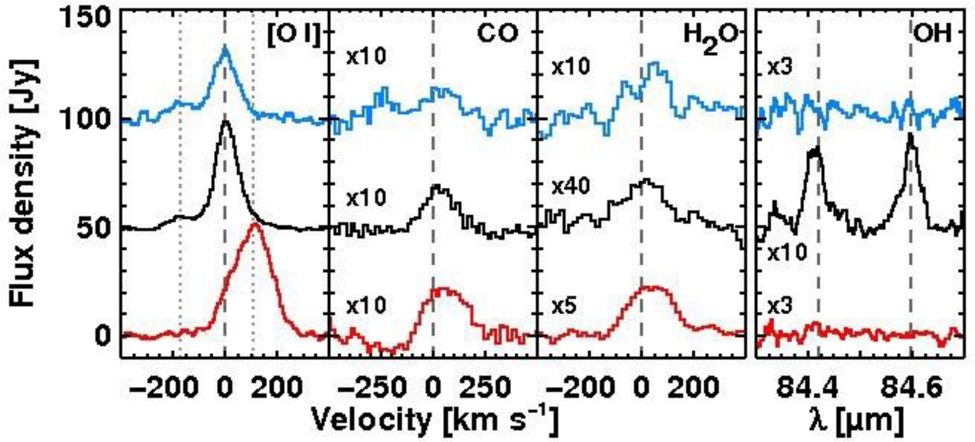
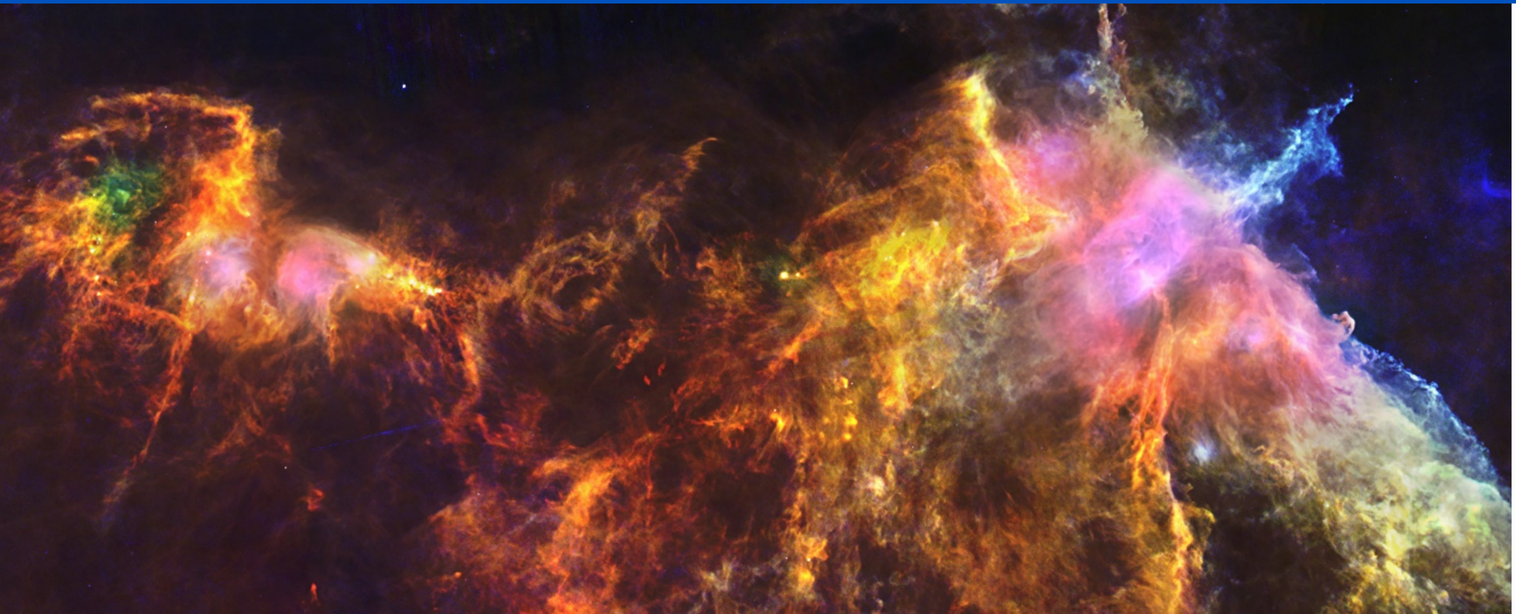


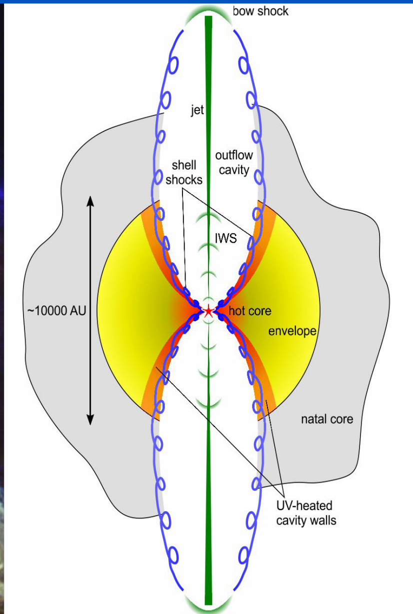


Galactic Star Formation

Lee Mundy (University of Maryland)

Paul Goldsmith (Caltech/JPL)

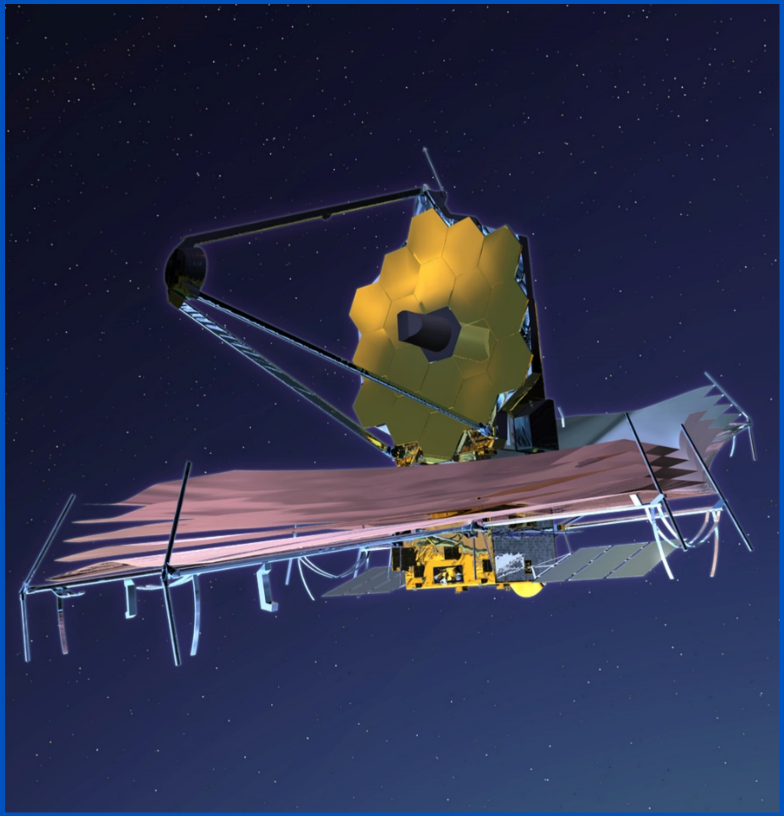




Context for a FIR mission

(from the star formation viewpoint)

JWST



ALMA

SPICA

WFIRST UV/O/IR

Context for a FIR mission
(from the star formation viewpoint)

ALMA: Molecular Gas Machine, Compact Dust

- Angullar resolution down to 0.1” and below
- Spectral resolution only limited by signal strength and choice
- Spectral line sensitivity excellent – below 850 GHz (350 µm)

  if in an atmospheric window
- Continuum sensitivity excellent (µJy/beam) for compact sources

  but worse for extended sources

In 10-15 years ALMA will have a tremendous archive of observations

Next generation instruments (array receivers?) will start being deployed

Context for a FIR mission

(from the star formation viewpoint)

JWST: Stellar component, many of the ices

- Covering ~2 to 28 µm wavelength
- Excellent sensitivity to the stellar component
- Spectral sensitivity – R up to ~3,000

Of course in 15 years, JWST will be done

WFIRST may have come and gone – or still be there

A large UV/optical/NIR telescope might be there

Context for a FIR mission

(from the star formation viewpoint)

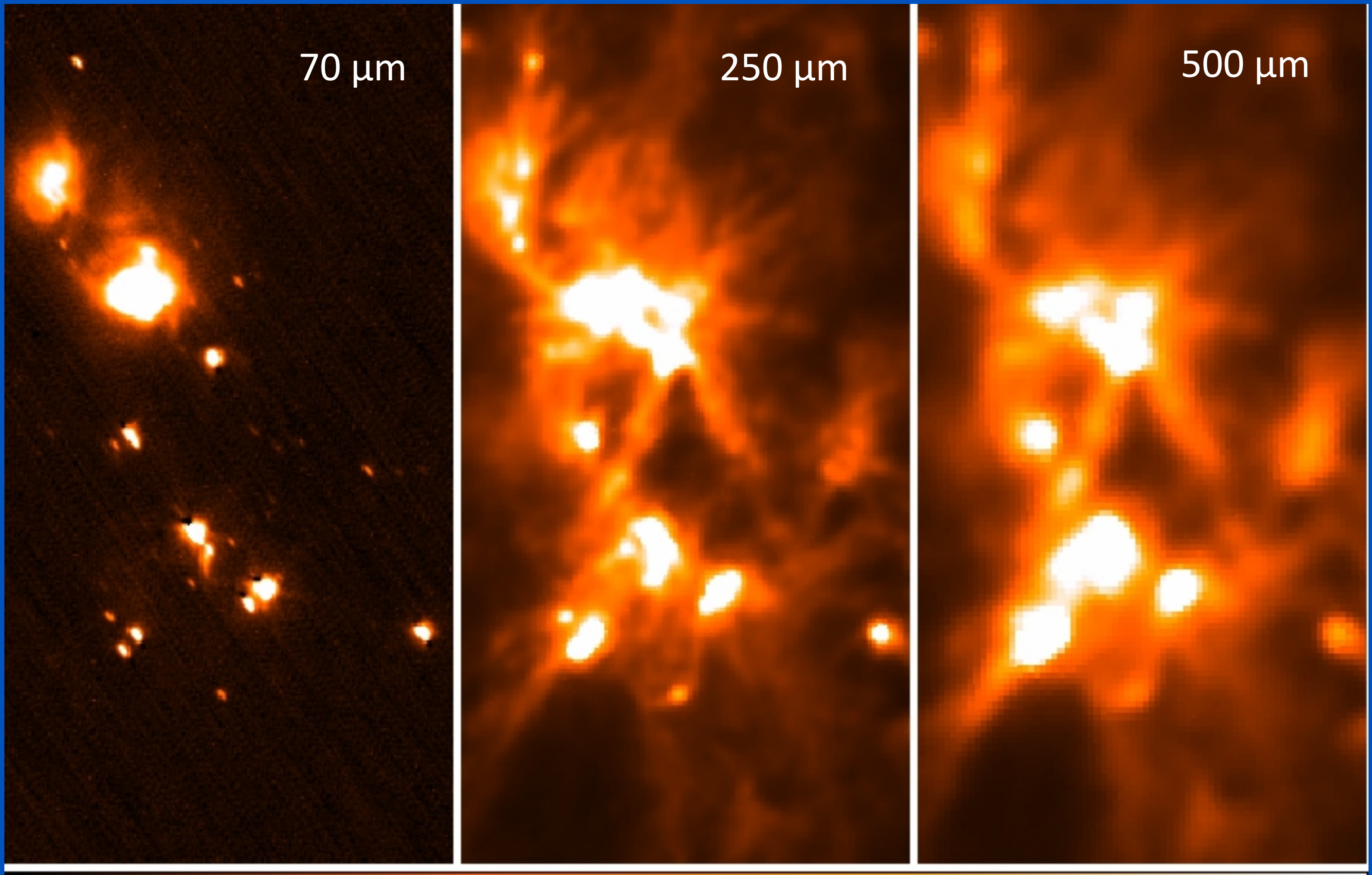
What the gaps and weaknesses?

- Unique atomic and molecular lines that are blocked by the atmosphere
- Embedded stars
- Wide field coverage
- Extended dust emission

And, of course, very young stars emit most of their energy between 28 μm and 350 μm.

Seeking Guidance from Herschel

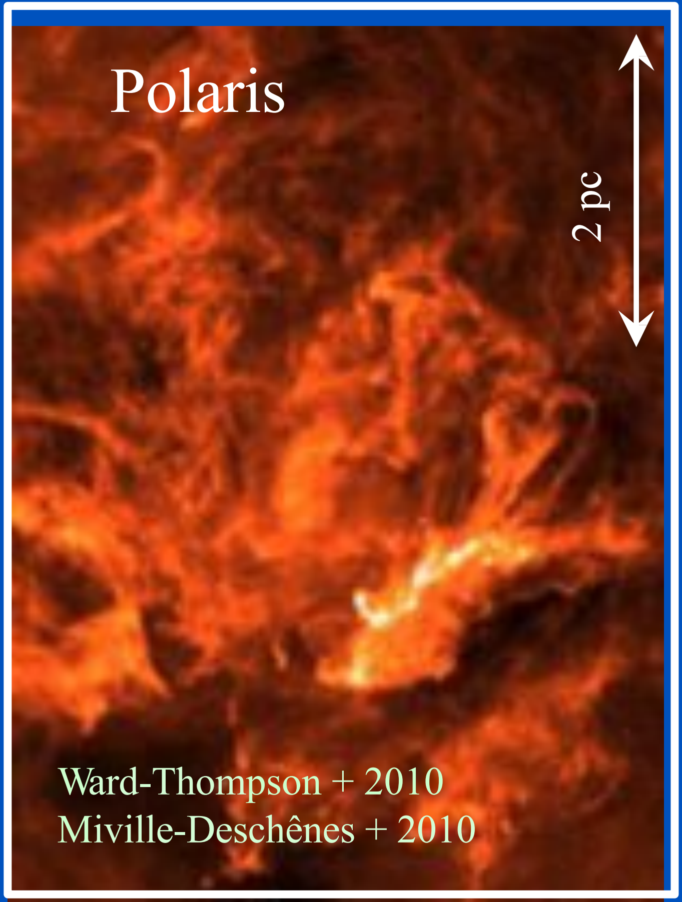
NGC 1333 SVS-13 Region dust emission

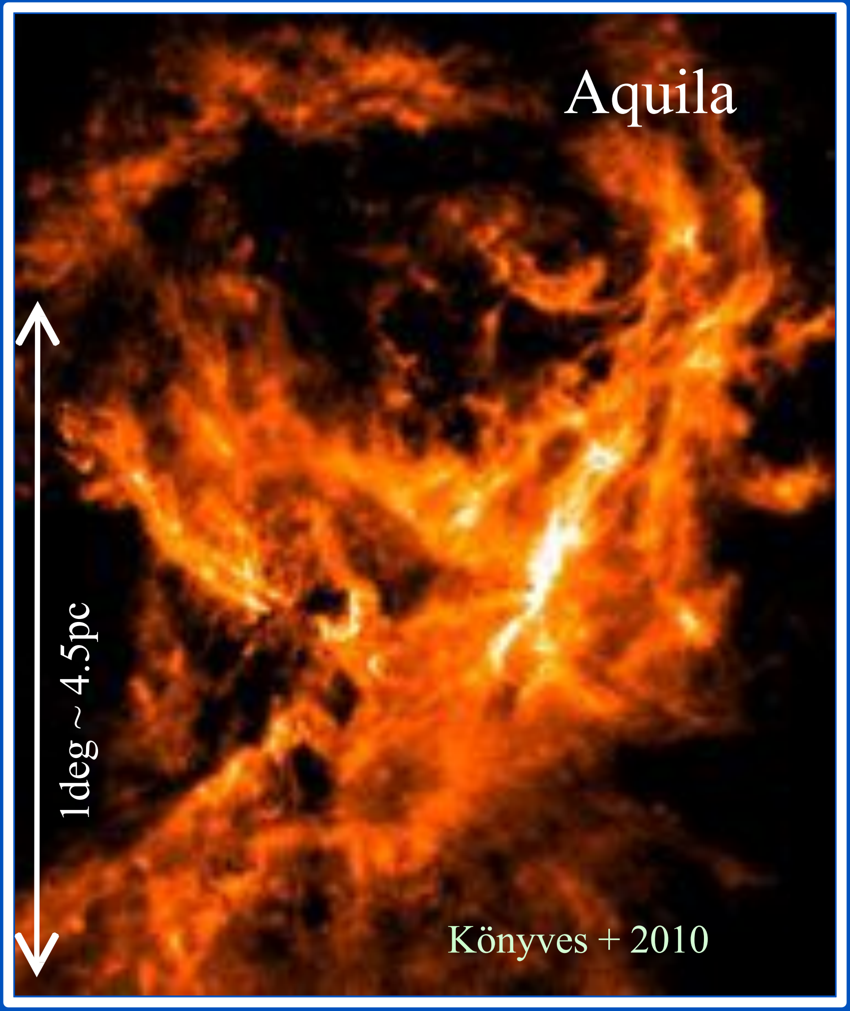


Seeking Guidance from Herschel

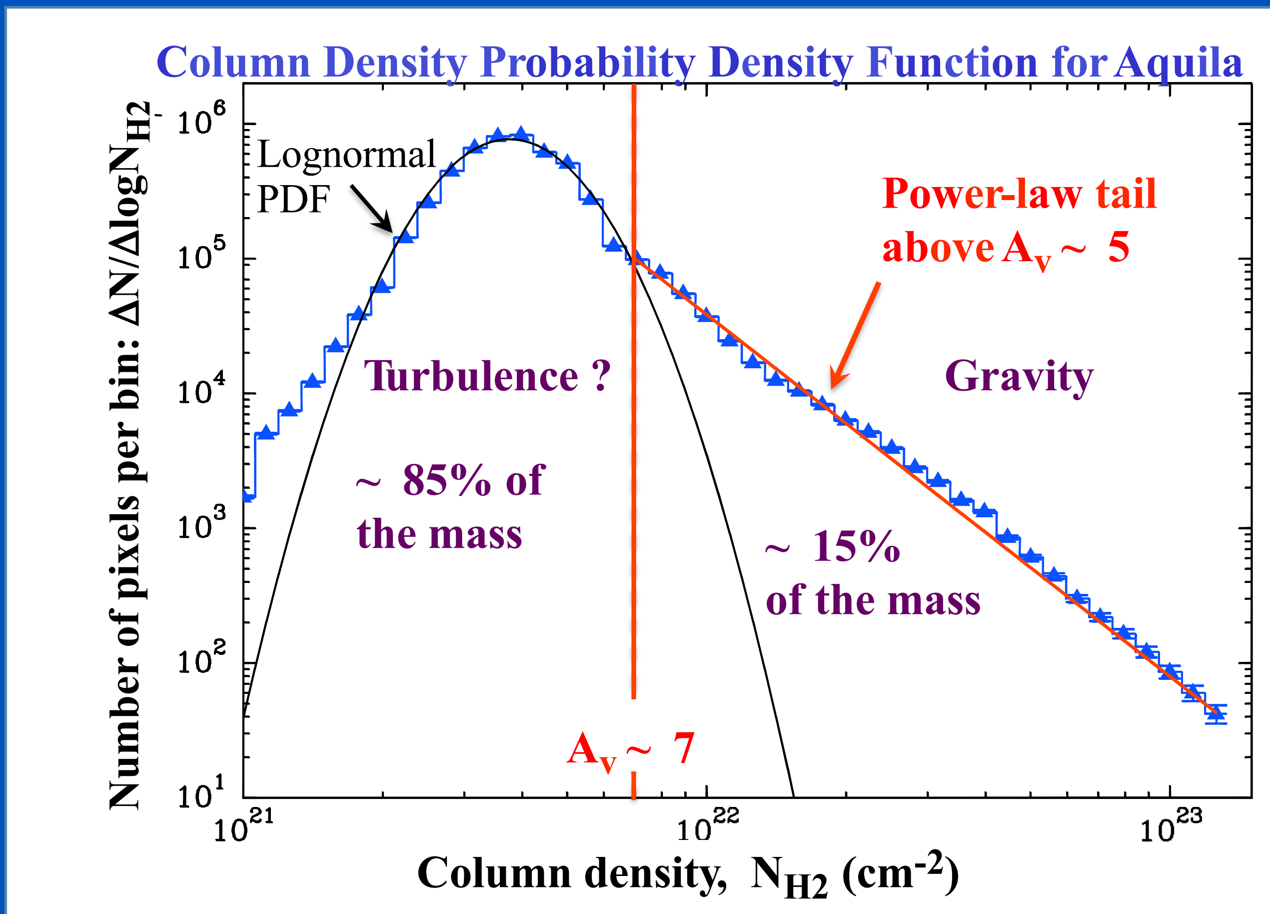
Dust emission is a great tracer of clouds and embedded star formation

Gould Belt Survey
PI: Andre





Mass budget in the Aquila cloud complex



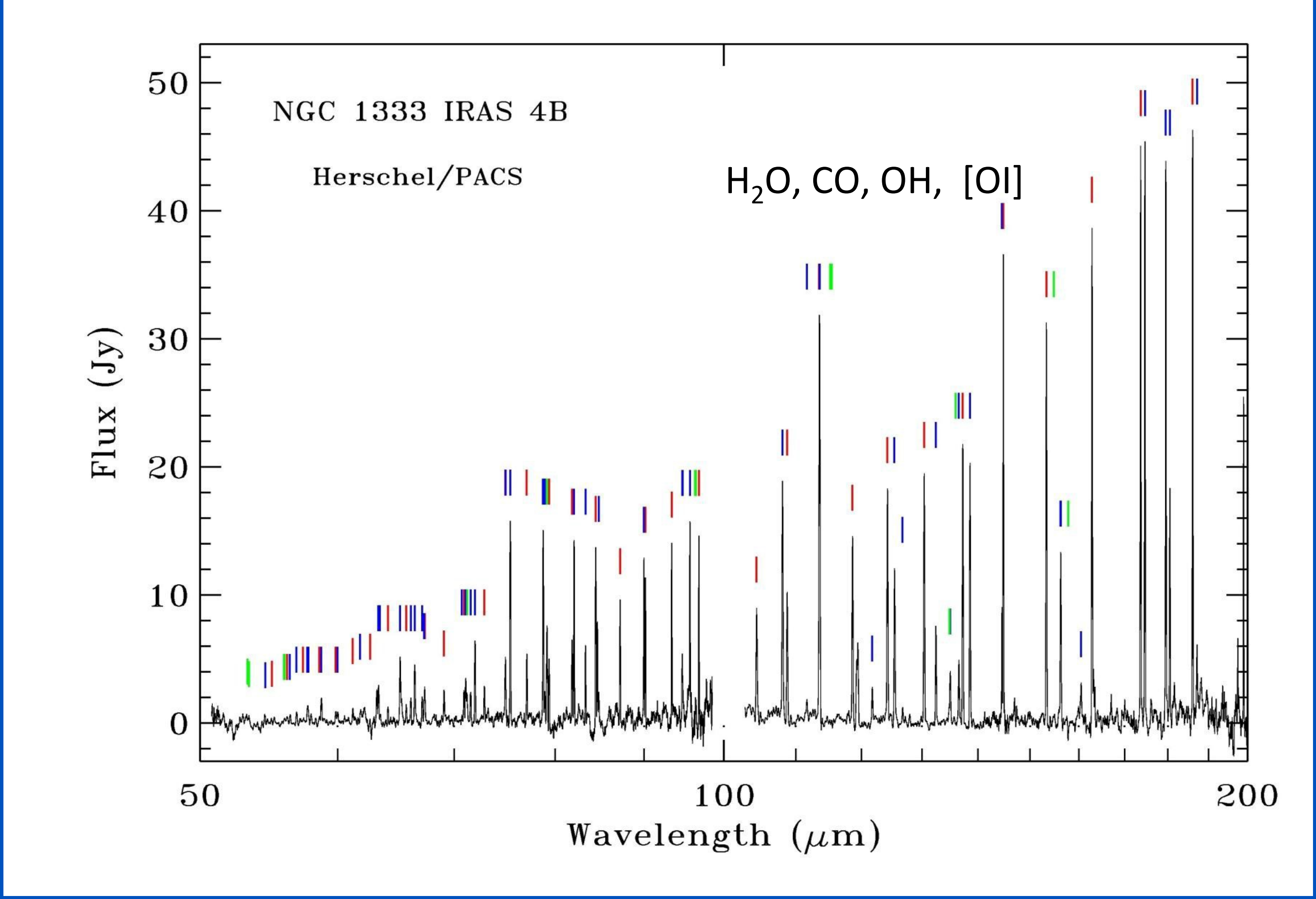
(See Schneider+2013 Schneider+2014 for other, similar column density PDFs from *Herschel*)

Könyves et al. in prep
Könyves et al. 2013

- **Below $A_V \sim 7$: ~ 20 % of the mass in filaments, < 1% in prestellar cores**
- **Above $A_V \sim 7$: > 50 % of the mass in \filaments, ~ 15 % in prestellar cores**

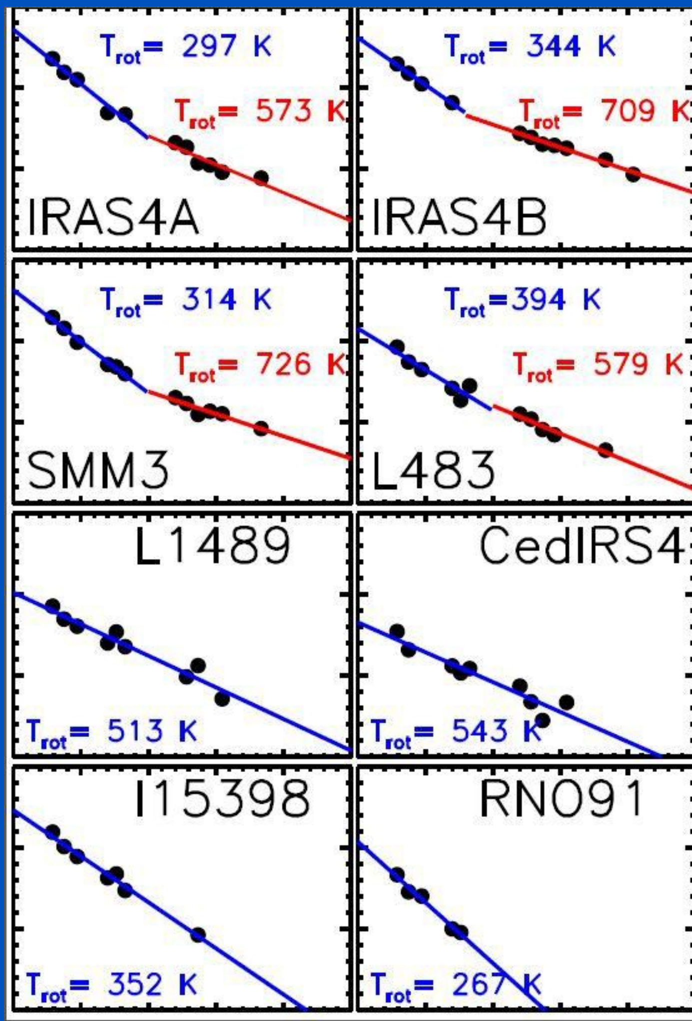
Seeking Guidance from Herschel

Spectral region from 50-200 μm is rich



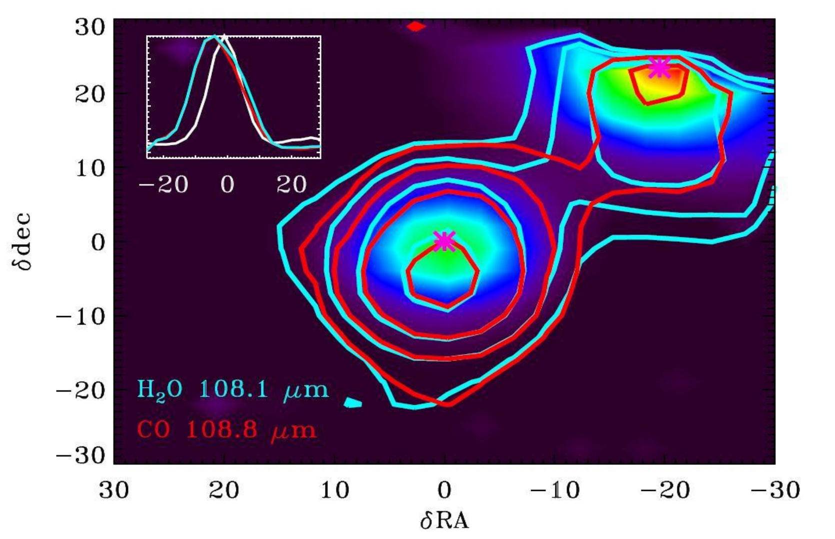
Seeking Guidance from Herschel

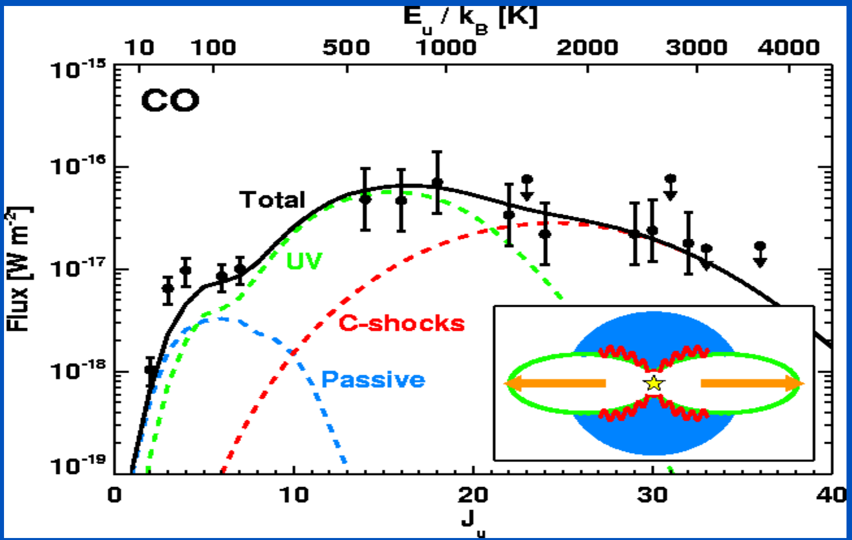
High J CO lines are excellent tracers of warm and hot molecular



Herczeg et al 2012

WISH team results

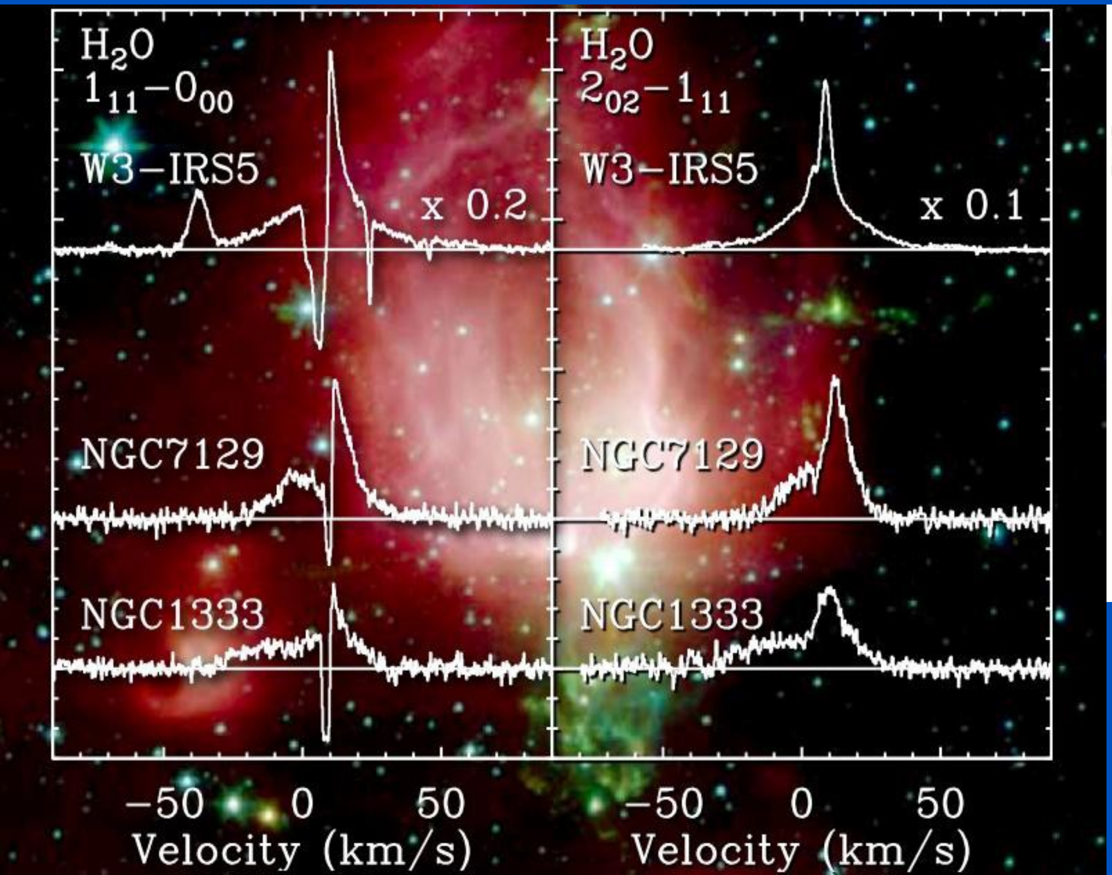


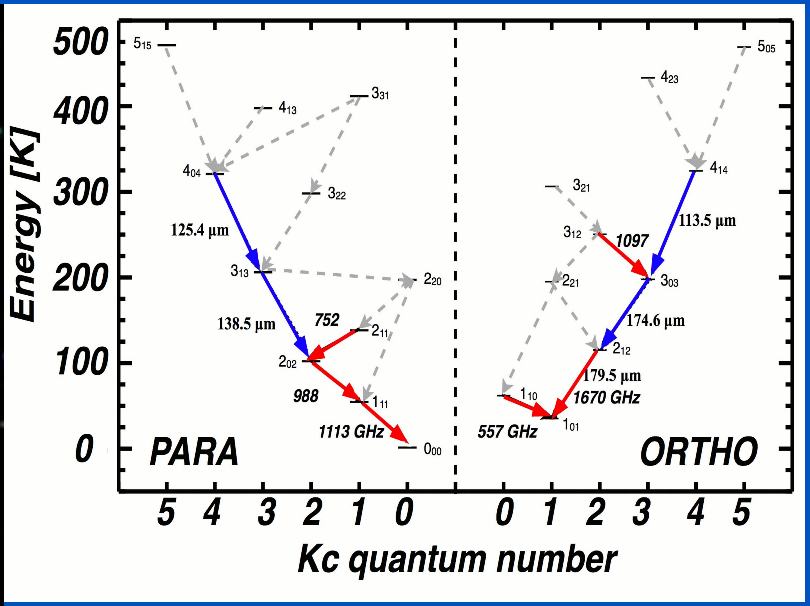


Seeking Guidance from Herschel

The water lines at 100-500 µm are worth the price of admission
Covers a range of energies

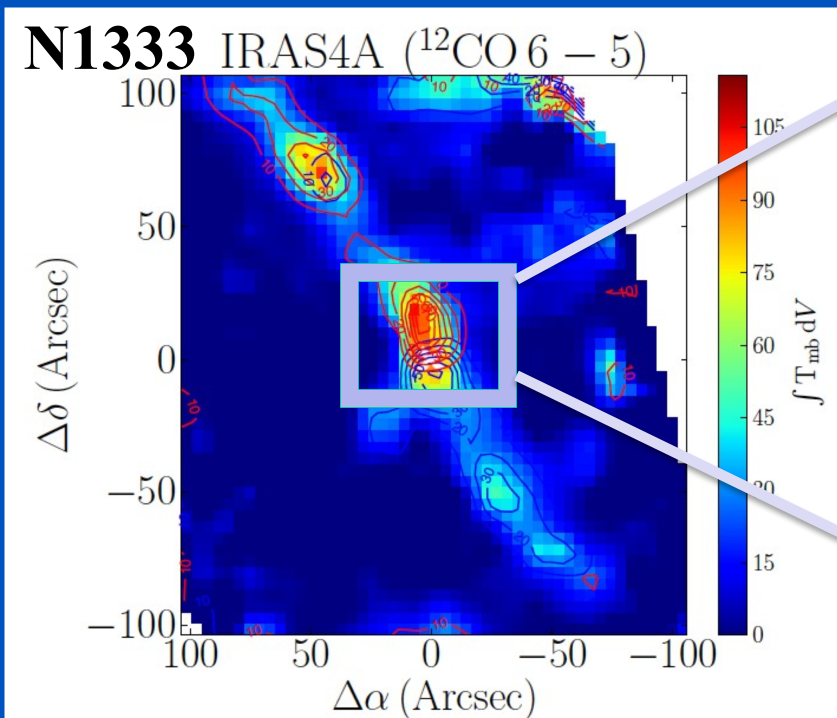
Complex line shapes





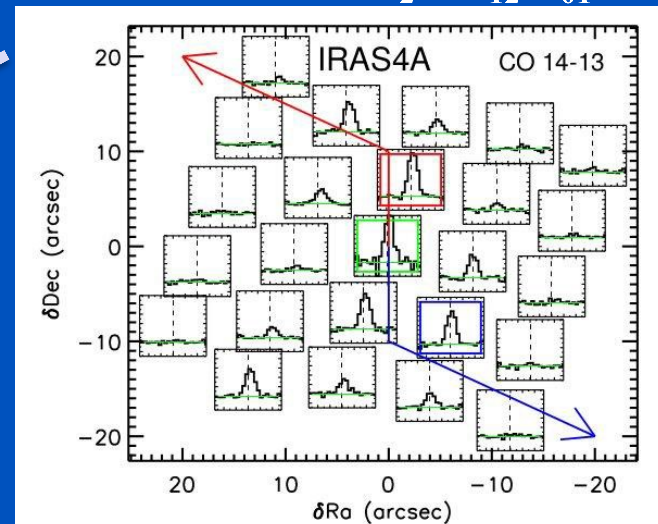
Seeking Guidance from Herschel

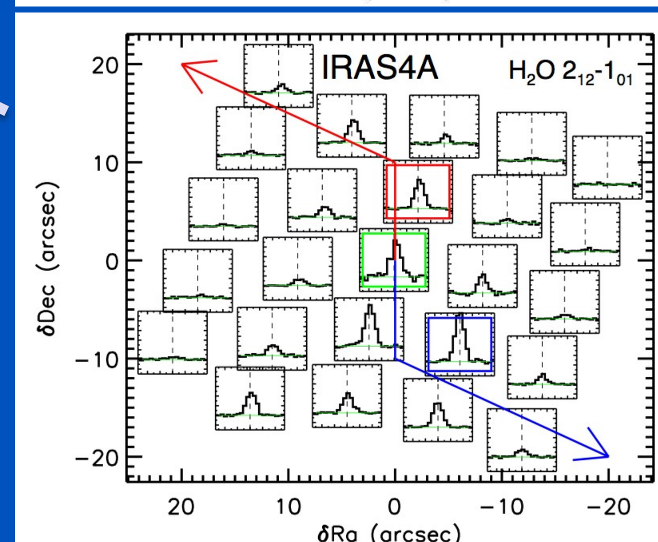
APEX-CHAMP+ CO 6-5



Yildiz et al 2012

Herschel/PACS
CO 14-13 vs H_2O 2_{12}-1_{01}





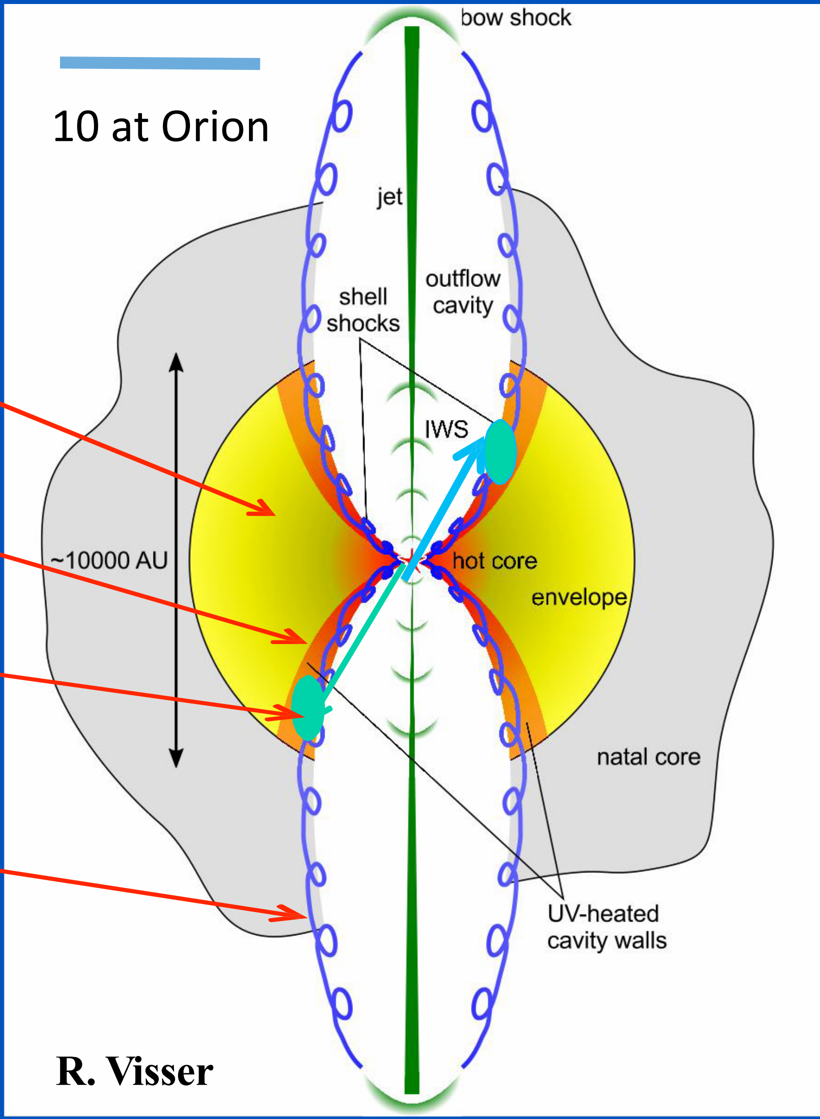
Karska et al 2015

Water follows outflow and high-*J* CO, not low-*J* CO

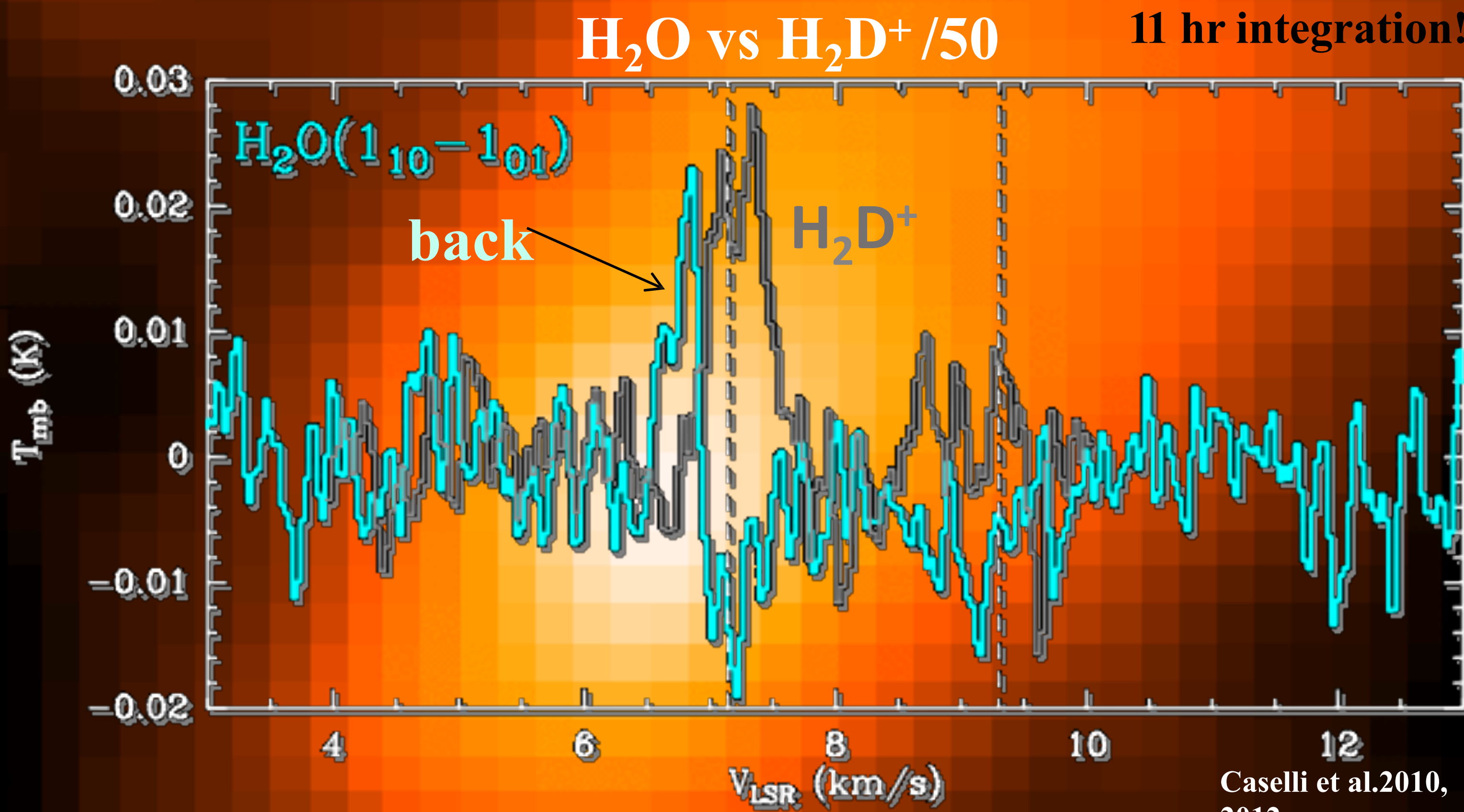
Seeking Guidance from Herschel

Warm and hot water emission has many components

- Quiescent envelope
  - Narrow absorption/emission
- UV-heated cavity walls
  - Narrow emission CO mid-J
- Currently shocked gas
  - H2O broad, CO high-J
- Entrained outflow gas
  - CO low-J



The prestellar core L1544



Caselli et al.2010, 2012

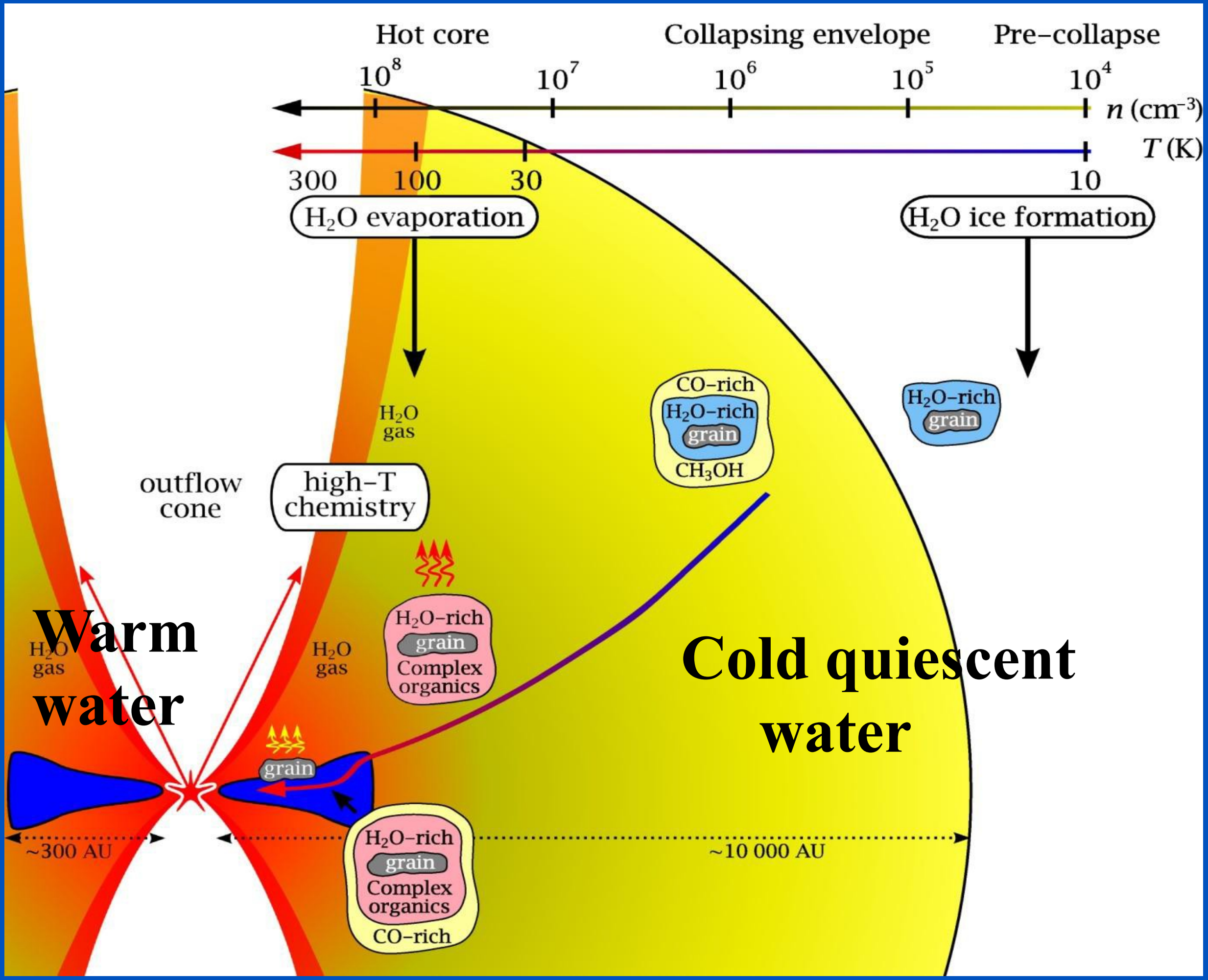
- Emission requires high central density ~10^7 cm^{-3}
- Profile indicates infall of 0.1 km/s at 1000 AU

1.3 mm continuum map from Ward-Thompson et al. (1999)

Seeking Guidance from Herschel

The cold water emission can trace infall

In general, embedded young stars are complicated:



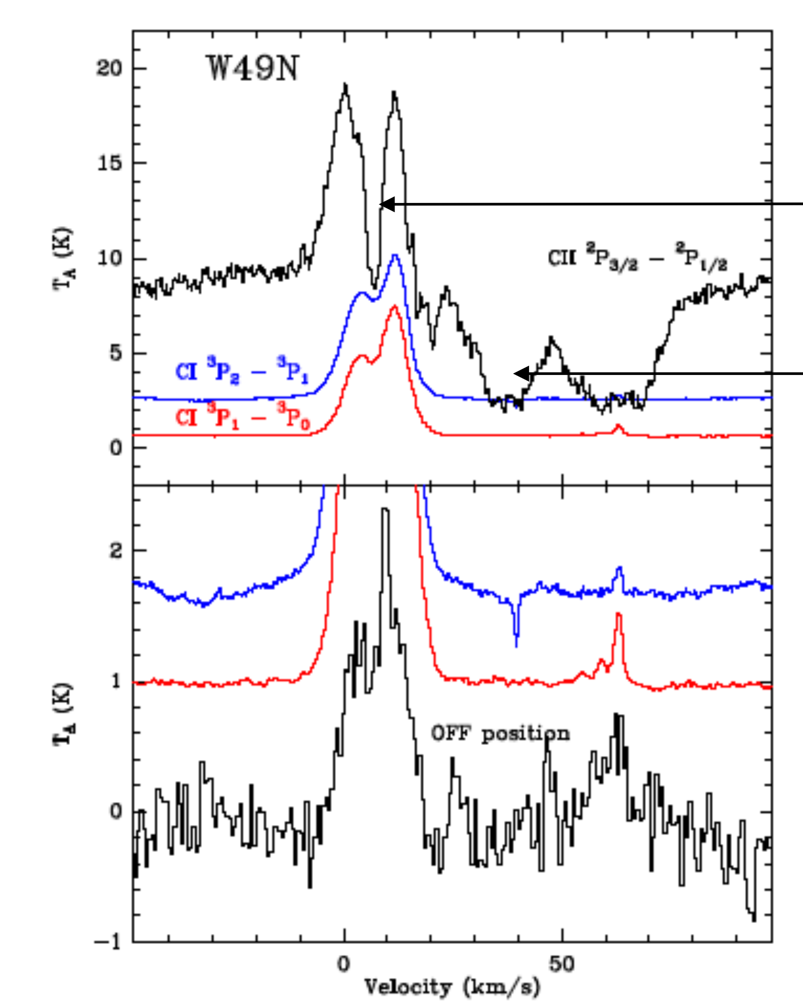
- Envelope
- Outflow
- Shocks
- UV radiation
- Disk

Visser et al. 2009
Herbst & van Dishoeck 2006

Herschel and SOFIA Have Carried Out Impressive Absorption Observations of Important Species –

Background Sources = Distant Massive Young Star Clusters

Absorbing Material = Milky Way Gas Along Line of Sight



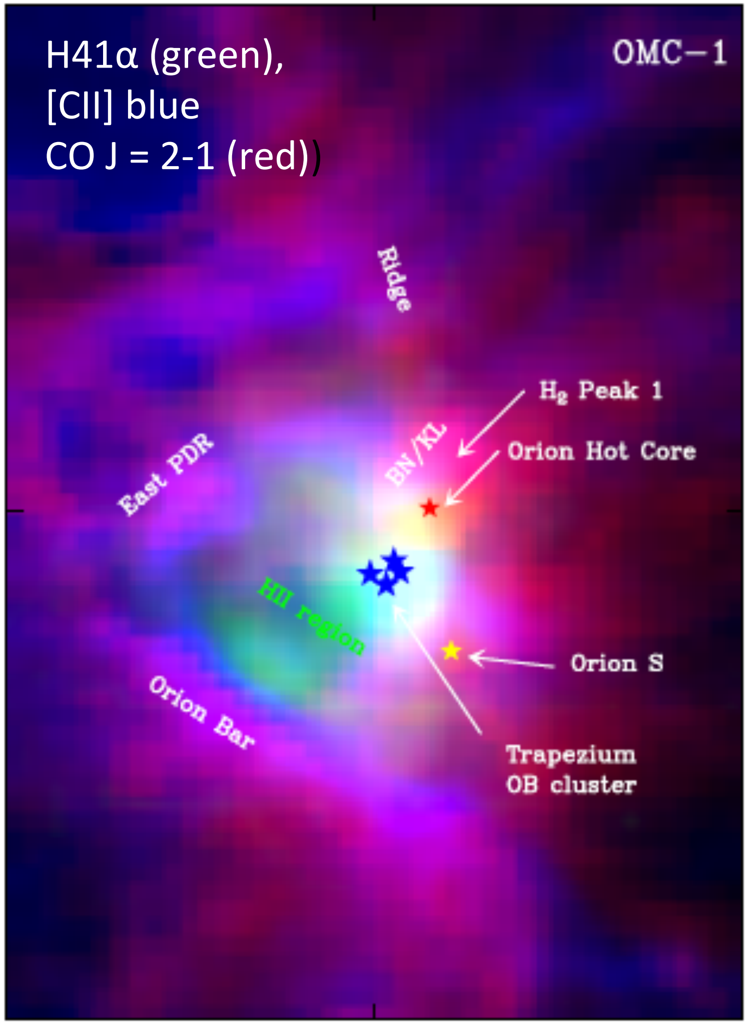
Emission from W49 GMC with some self absorption due to envelope of the cloud

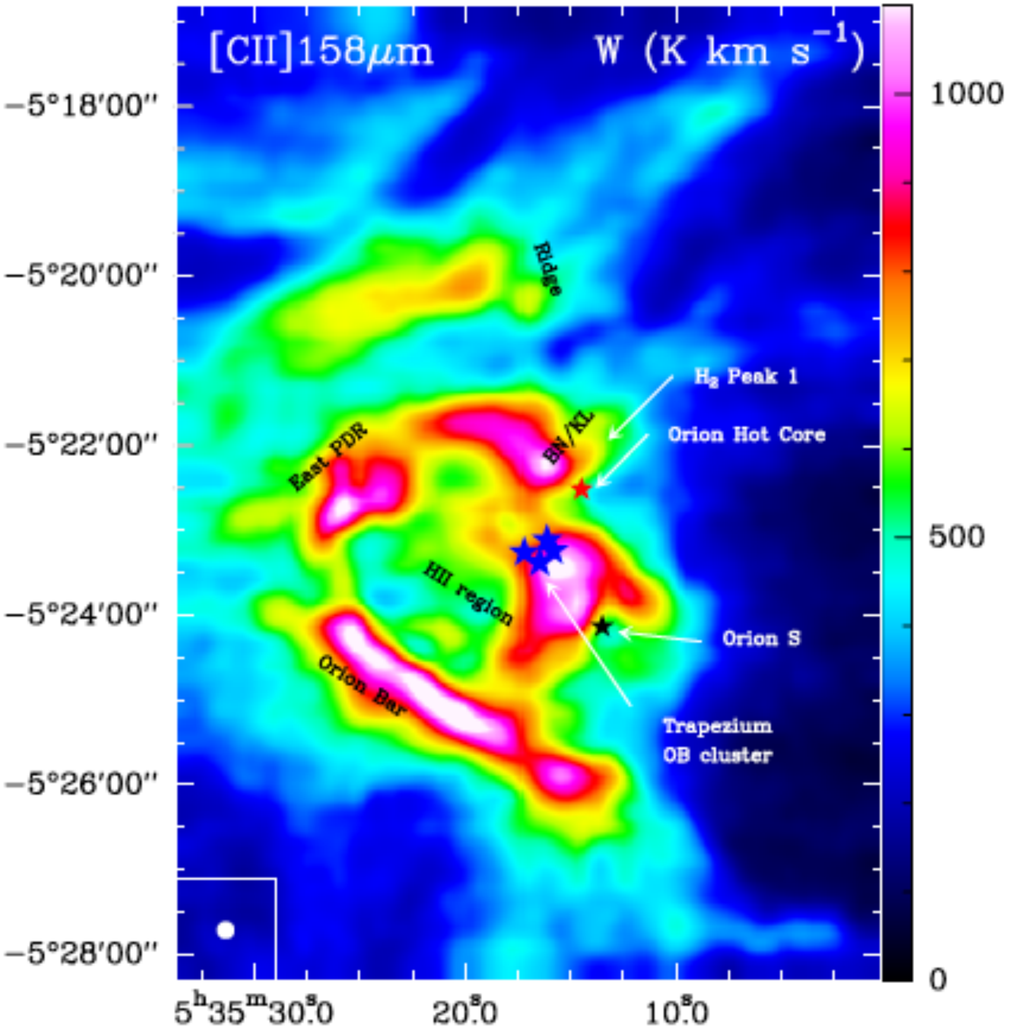
Absorption from diffuse clouds along the line of sight, which are at much different velocities and are entirely separate from W49

Herschel: [CII] Towards W49 (Gerin et al 2014)

First Detailed Large-Scale Velocity-Resolved Map of GMC: Orion in [CII]

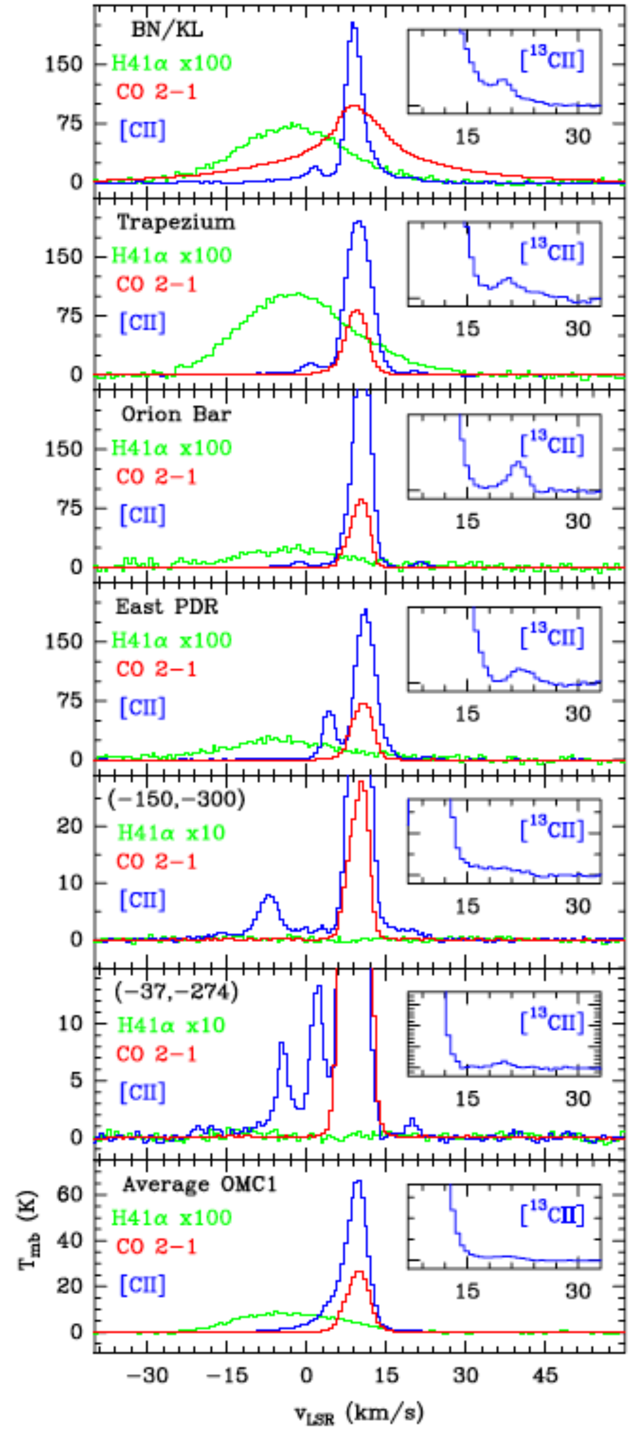
Goicoechea et al. (2015 in prep.)



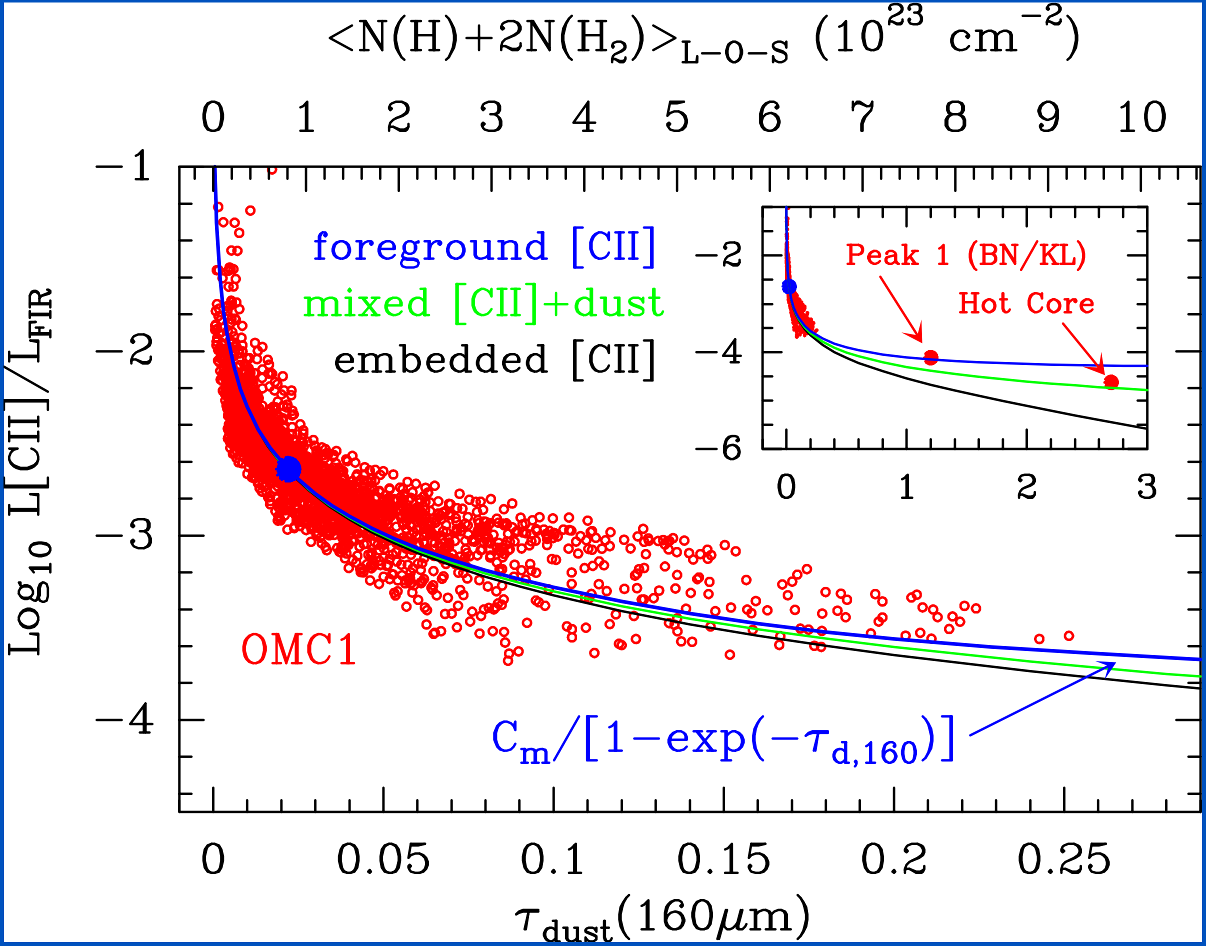


[CII] Emission from Orion

- Large-scale emission (~0.9 pc x 1.4 pc) traced interface of molecular cloud; low-G_0 PDR
- Generally [CII] emission is optically thin; maximum $\tau \sim 3$ from ^{13}CII
- Spatial-kinematic imaging allow separation of components
  - 85% from PDR region and HII region
  - 15% from "CO Dark H_2"
- Strongest emission peaks have $T_A \sim 150$ K and likely come from gas with $T_k > 250$ K
- Systematic trends observed in I([CII])/I(FIR)



Systematic Variation of L[CII]/L_{FIR}



Variation of ratio consistent with

(1) constant L[CII]

and

(2) L_{FIR} α (1-exp(-τ_{dust}))

Central LOS have greater N(H) and thus τ_{dust} with ~ constant L[CII]

Too much N(gas) and N(dust) leads to "C^+ Deficit"

Lessons from Herschel

The simple lessons learned for our current purpose:

- Better angularl resolution is needed to make a significant improvement from Herschel in the dust continuum
- High spectral resolution (<1 km/sec; R ~ 3 x 10^5) is needed to properly sort out complex line shapes – which contain very physically relevant information
- High angular resolution (distance dependent) is need to spatially separate different physical components emitting

You really want high spectral and angular resolution more than higher sensitivity

When you can't have it all

Focus on what you need to answer a few important questions:

1. We need to understand the evolution of atomic ISM to form molecular clouds and the gravitationally bound regions within them where new stars form.

    - FIR fine structure lines, particularly [CII] essential , [OI] , H_2O low energy levels
    - Large scale area surveys to get complete information on a range of clouds
    - High spectral resolution to follow kinematics and complex line shapes

"From structure formation to stars: following the energy flow"

"From structure formation to stars: following the energy flow"

Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	100-500
Angular resolution	arcsec	10"
Spectral resolution, ($\lambda/\Delta\lambda$)	dimensionless	300,000 or greater
Continuum sensitivity	μJy	
Spectral line sensitivity	10^{-19} W m^{-2}	
Instantaneous FoV	arcmin	as many pixels as possible
Number of target fields	dimensionless	100's
Field of Regard	sr	

Want to map large areas – square degrees

When you can't have it all

2. The collapse of cores and the first stages of star formation are physically complex: infall, outflow, molecular depletions, shocks, circumstellar disks, envelopes. The FIR provide unique, chemically simple tracers for these complex environments:

- FIR fine structure lines, H_2O, OH (complements what ALMA would do)
- Lee would chose to compromise spectral resolution to get angular resolution – Paul would chose spectral resolution
- Large survey of different stages and masses

"The anatomy of a star at birth"

“The anatomy of a star at birth”

Desired Measurement Capabilities

Parameter	Units	Value or Range
Wavelength range	μm	100-500
Angular resolution	arcsec	< 1” ; more is better
Spectral resolution, $(\lambda/\Delta\lambda)$	dimensionless	1,000 – 3,000
Continuum sensitivity	μJy	
Spectral line sensitivity	10^{-19} W m^{-2}	
Instantaneous FoV	arcmin	
Number of target fields	dimensionless	50-100
Field of Regard	sr	

Want a large sample of sources
Few square arcminutes for each source

Unfortunately the low-lying transitions of water are at wavelengths >180 μm where angular resolution is hard won.

Callisto: 6-m → 7.4" at 180 μm 16" at 400 μm

IFIS: 36-m → 0.5" at 180 μm 1.2" at 400 μm

Thank you