# DIGIT (Dust, Ice, and Gas in Time):

# Herschel-PACS Full Spectral Scans of Young Stellar Objects

## HD 100546 and DK Cha (IRAS 12496-7650)

Joel Green

With Tim van Kempen, Greg Herczeg, Jeroen Bouwman, Gwendolyn Meeus, and Bruno Merin


On behalf of the DIGIT Team (PI: Neal Evans)

Insignia: Tim van Kempen

# DIGIT (Dust, Ice, and Gas in Time): A Herschel Open Time Key Project

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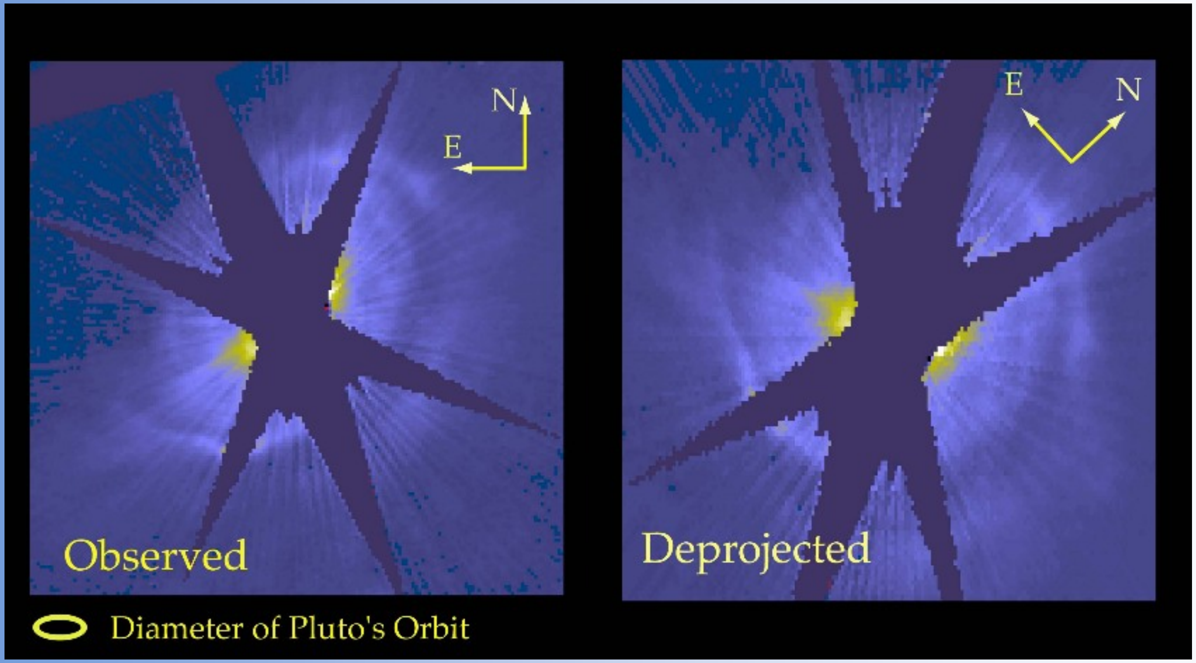
# DIGIT (Dust, Ice, and Gas In Time)

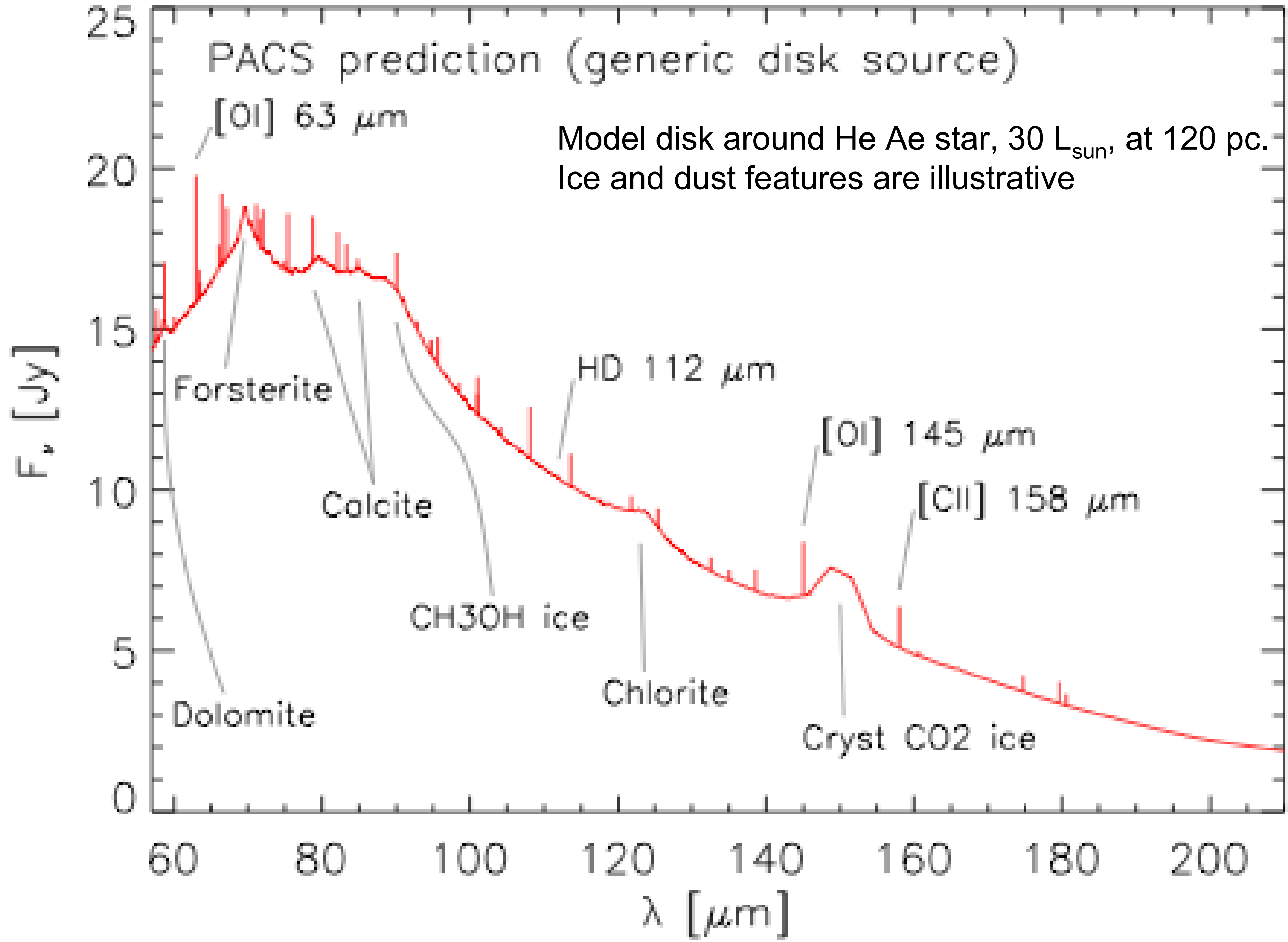
- **Follow the three components from embedded through disk phases**
  - **Range of masses, luminosities**
- **Sample from Spitzer programs and others**
  - **Embedded objects (31)**
  - **Disks (63): cTTS, wTTS, disks with holes/gaps**
- **Full PACS spectral scans on all embedded sources and ~ 30 of the brightest disks**
  - **Ice/dust features and some atomic/molecular lines as probes of physical structure + processes and chemical evolution**
  - **Complements existing Spitzer-IRS 5-40 μm spectra [Full 5-212 um scans!]**
- **PACS and SPIRE photometry on weaker disks (~ 30)**

# HD 100546



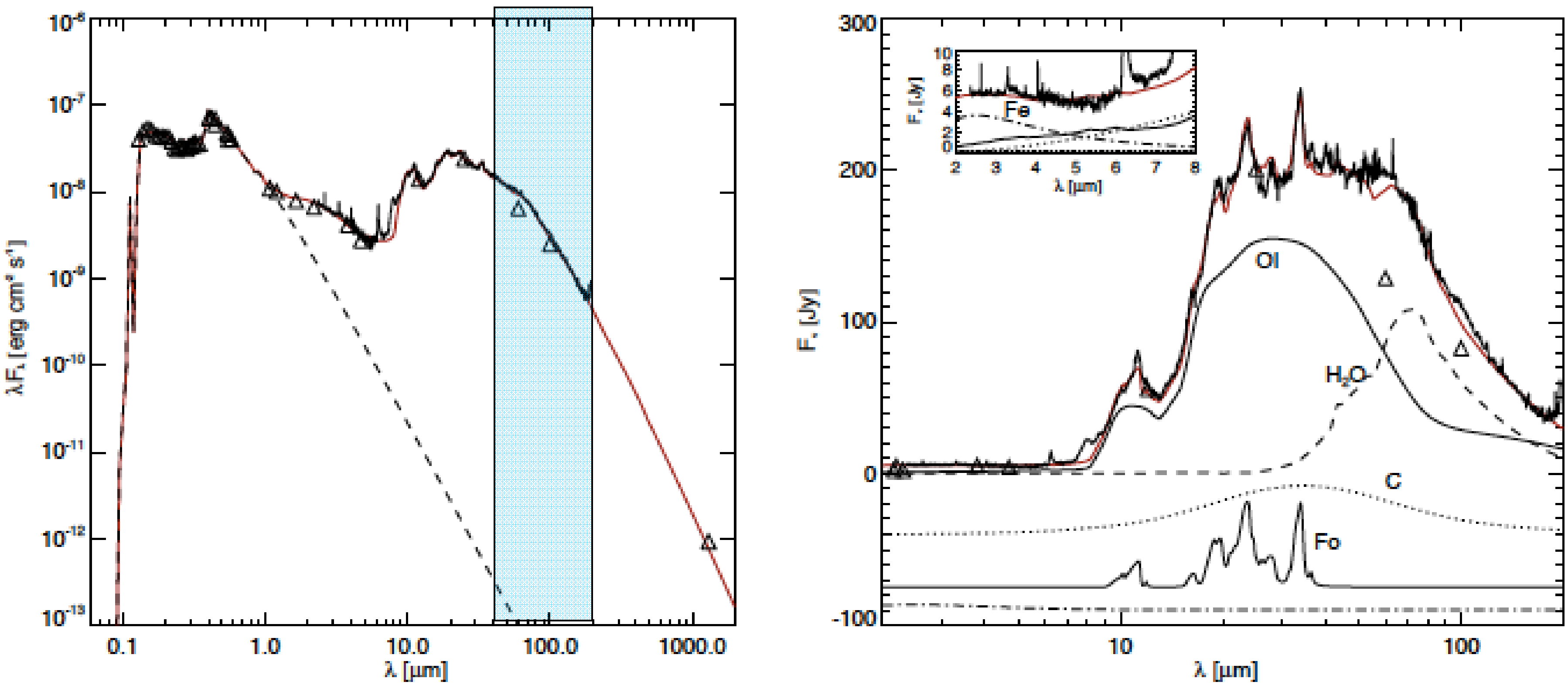

Augereau et al.
Grady et al.

- 10 Myr Herbig Ae/Be source
- Rich in crystalline dust
- No ISM confusion
- Disk gap at 13 AU (or possibly a hole)
- Wall, or thin inner disk at > 4 AU



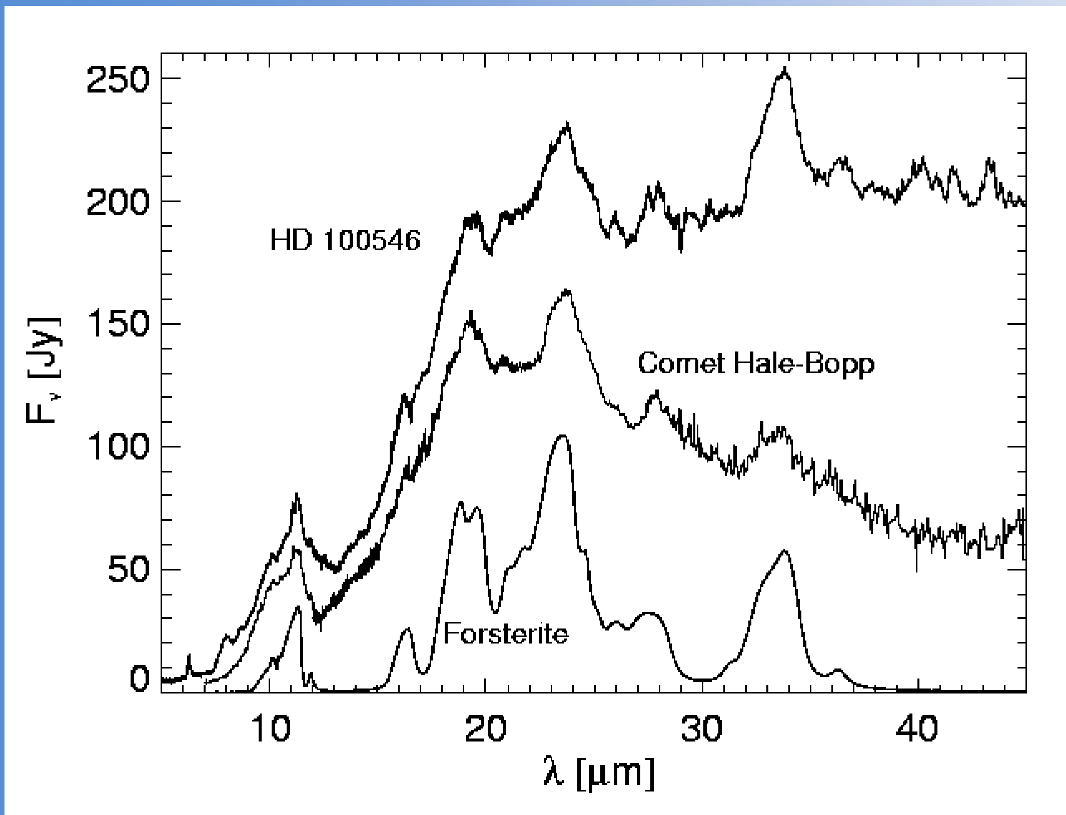
PACS prediction (generic disk source)
[OI] 63 μm
Model disk around He Ae star, 30 L_sun, at 120 pc.
Ice and dust features are illustrative
Forsterite
Calcite
CH3OH ice
HD 112 μm
[OI] 145 μm
[CII] 158 μm
Chlorite
Cryst CO2 ice
Dolomite
F_ν [Jy]
λ [μm]
0
5
10
15
20
25
60
80
100
120
140
160
180
200

# The Herbig Ae/BE star HD 100546




Left: Full SED of HD 100546. Right: ISO-SWS and ISO-LWS spectrum and model fit, showing the relevant contributions of the individual ice and dust species (Malfait et al. 1998, Bouwman et al. 2003)

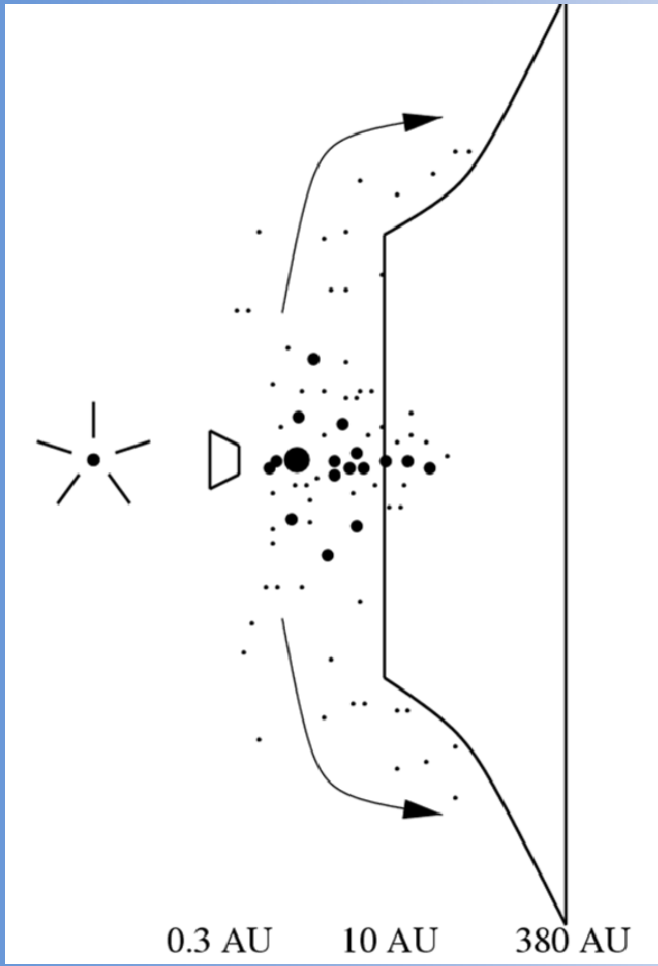
# Linking protoplanetary systems to the evolution of the solar system




- SED inconsistent with uniform flaring disk: gap
- Direct imaging, interferometry, spiral waves, high resolution spectroscopy point to massive planet opening gap
- Unusual strong forsterite bands and temperature distribution.

(Crovisier et al. 1997, Malfait et al. 1998, Bouwman et al. 2003, Min et al. 2005, Acke et al 2006)

# Linking protoplanetary systems to the evolution of the solar system

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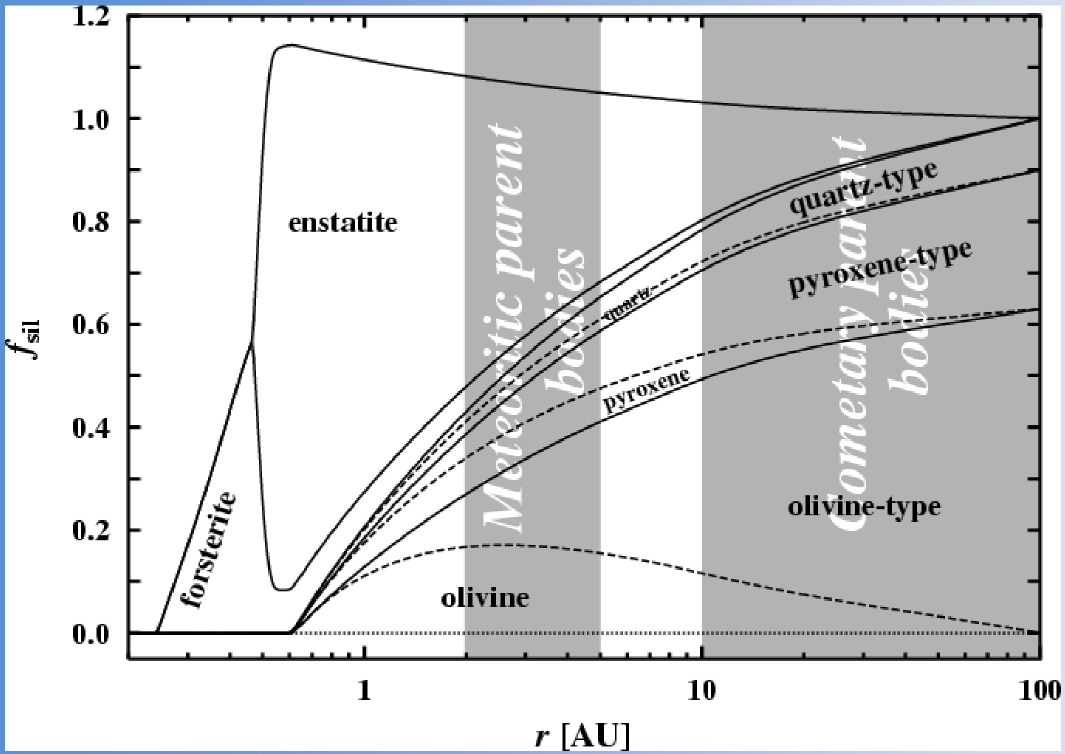
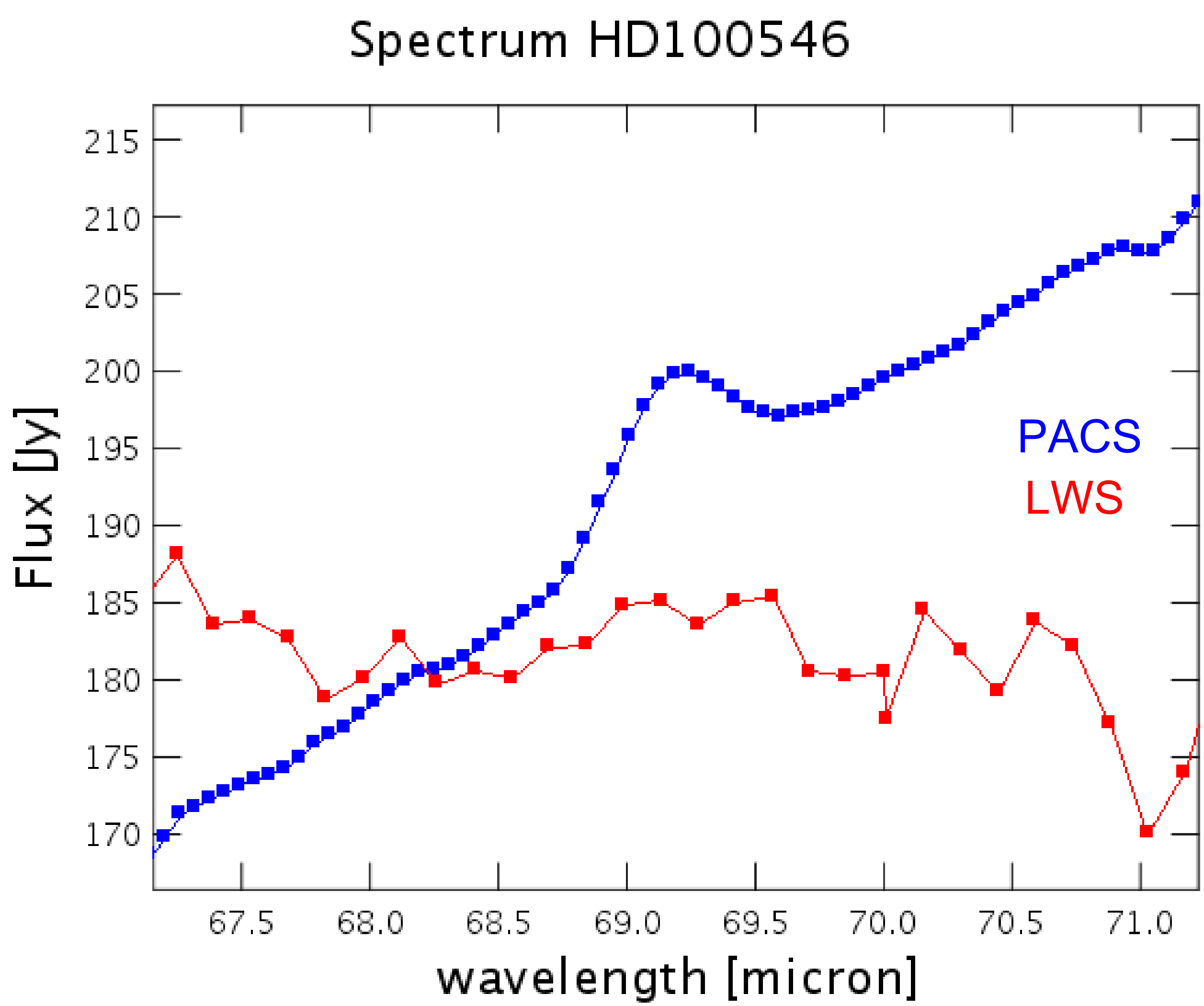
# Dust disk models




- Accretion disk model
- Detailed dust mixture
- Annealing
- Evaporation + re-condensation
- Coagulation
- Radial mixing

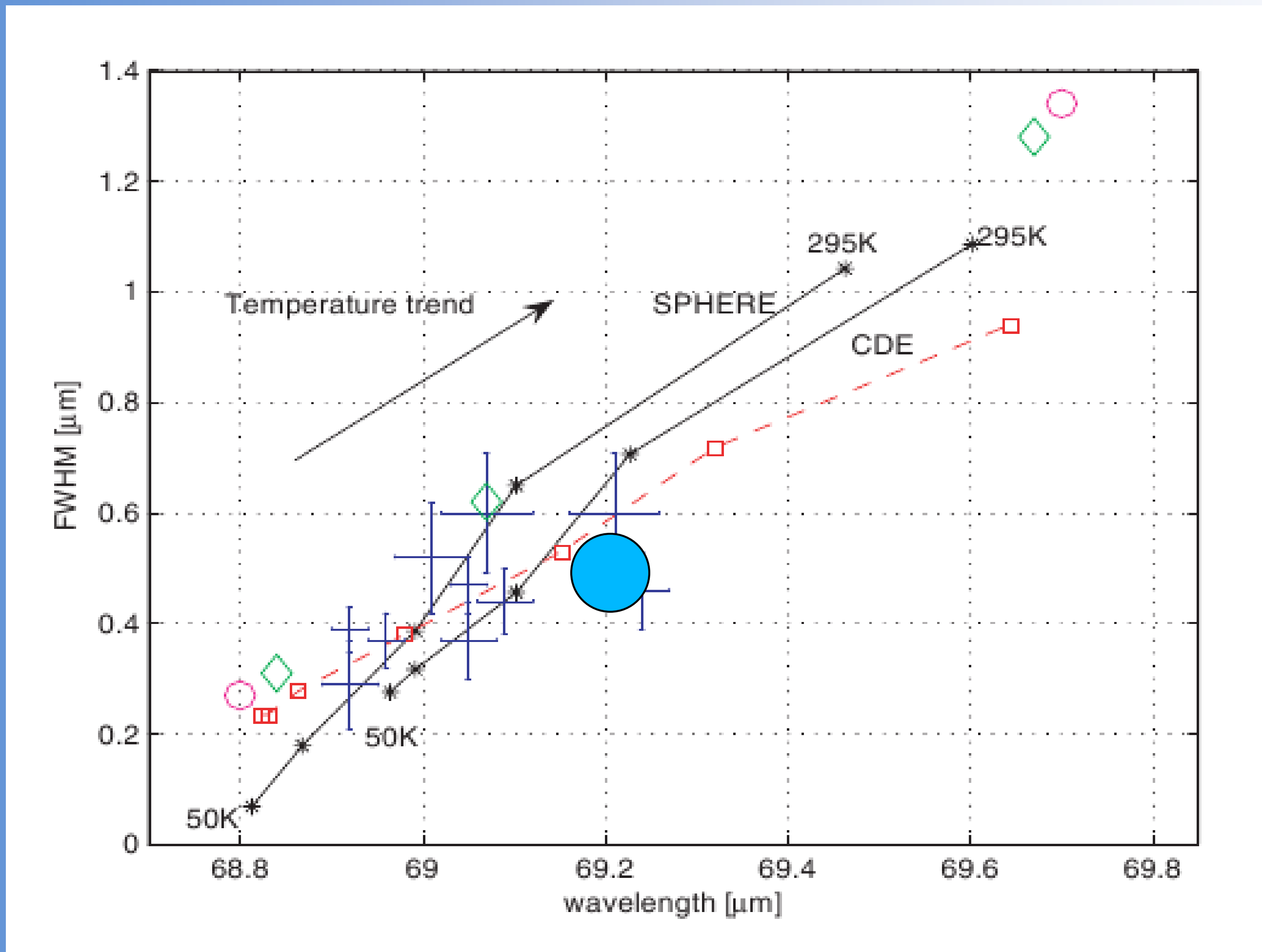
(e.g. Gail 2004, Keller & Gail 2004, Wehrstedt and Gail 2003, see also Keller et al. and Brocklee-Morvan et al.)

# The 69 µm Forsterite band



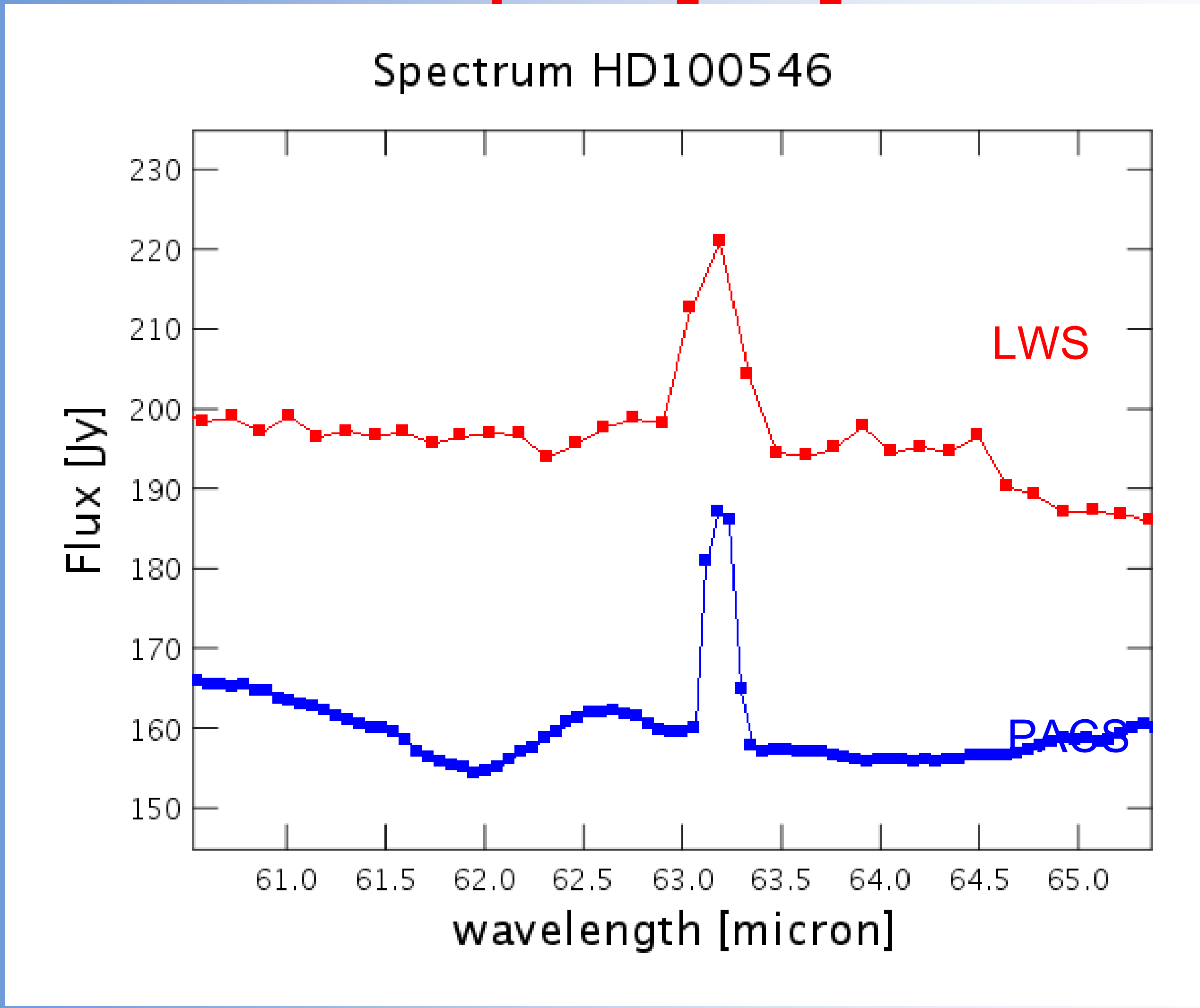

Sturm et al., in prep.

# Temperature Of Forsterite Grains




Pure forsterite (no Fe), 150 K

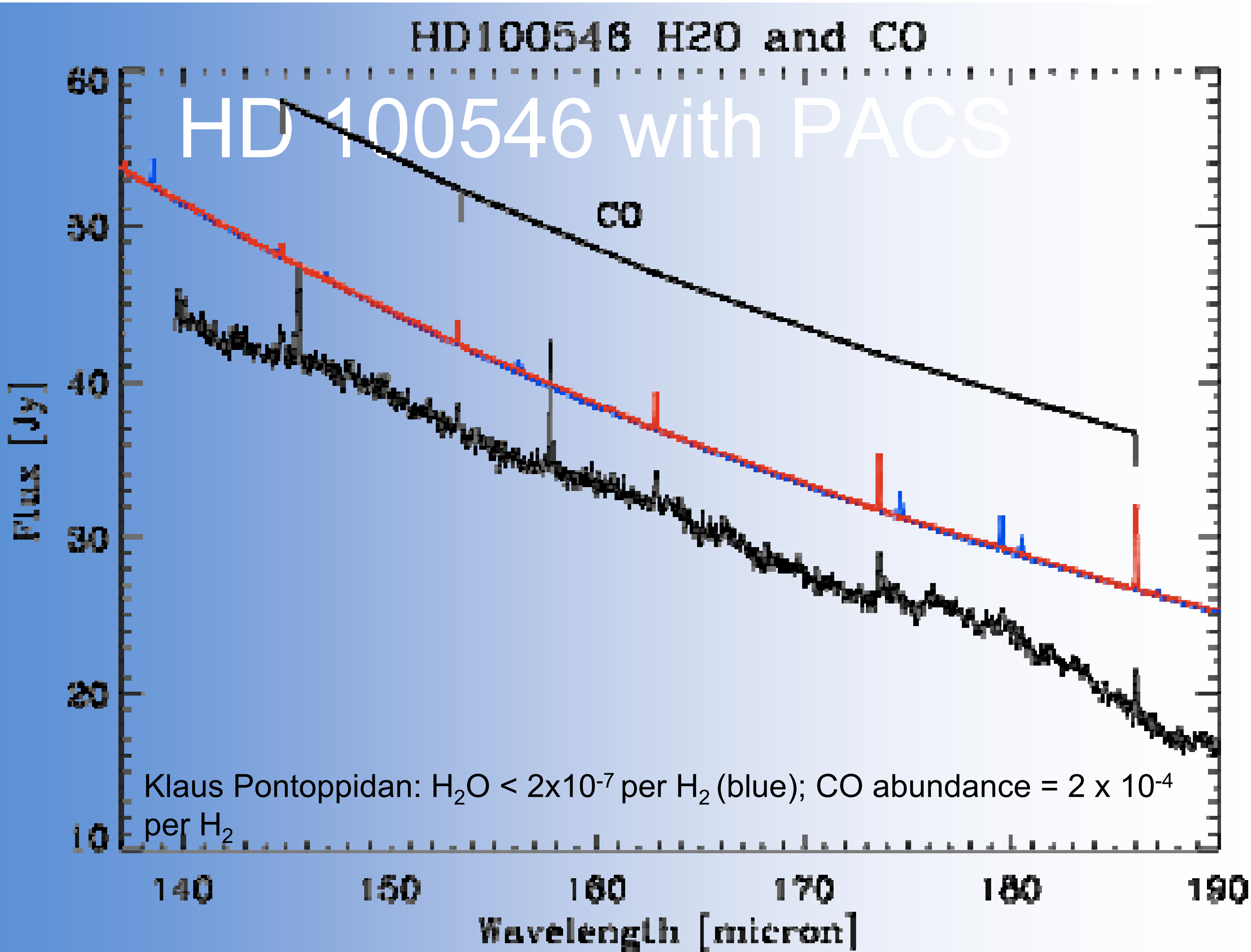
# The 63 μm [OI] line




Flux matches ISO within 20%

Flux reproduces models of irradiated disk surfaces (Jonkheid et al. 2007, Brinch et al., in prep.)

# HD 100546 with PACS

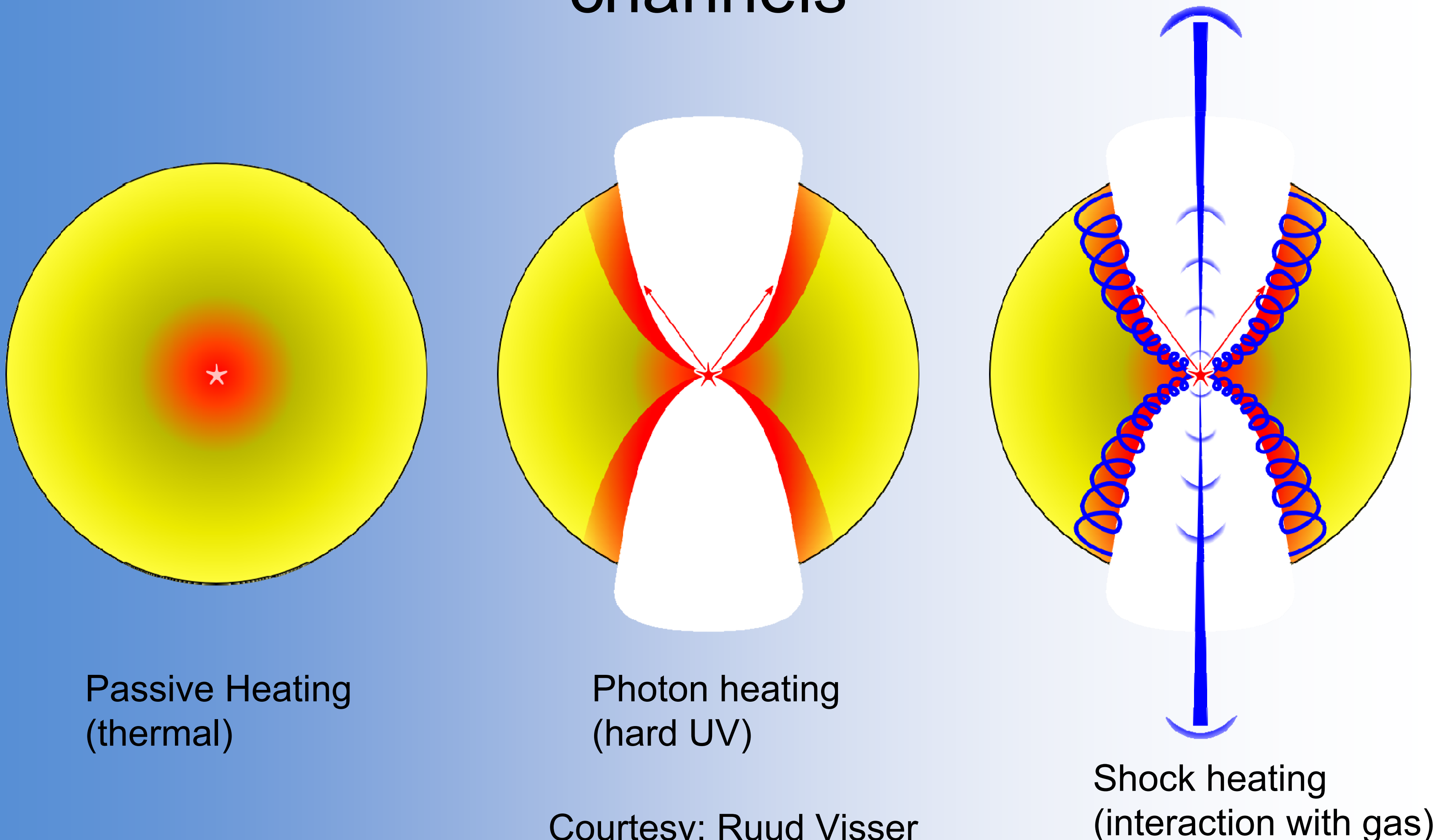



Klaus Pontoppidan: $H_2O < 2x10^{-7}$ per $H_2$ (blue); CO abundance = $2 \times 10^{-4}$ per $H_2$

Disk models from Mulders et al. in prep

# Embedded protostellar structure

## Complex + multiple heating/cooling channels




Courtesy: Ruud Visser

# DK Cha PACS SED scan

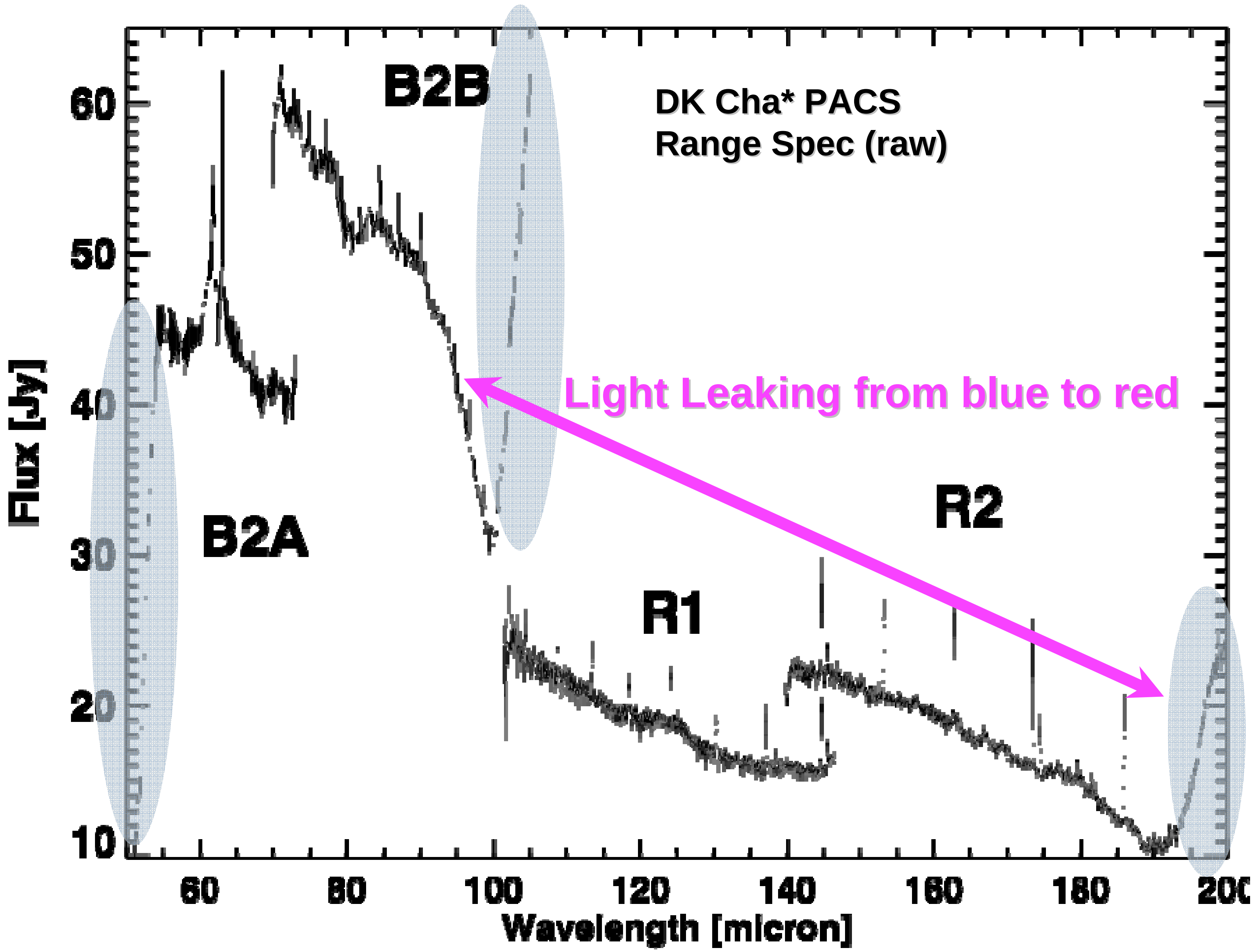
**van Kempen et al. in prep**

**Properties: L = 25 $L_{sol}$, Compact, nearly face-on outflow, Class I**

**ISO-LWS detected CO lines (J=19-18 and higher (Giannini et al. 1999)**
**CHAMP$^{+}$ detected CO 6-5 and 7-6 (quiescent+outflow)**

**No simple model fits both APEX and ISO data (van Kempen et al. 2009)**

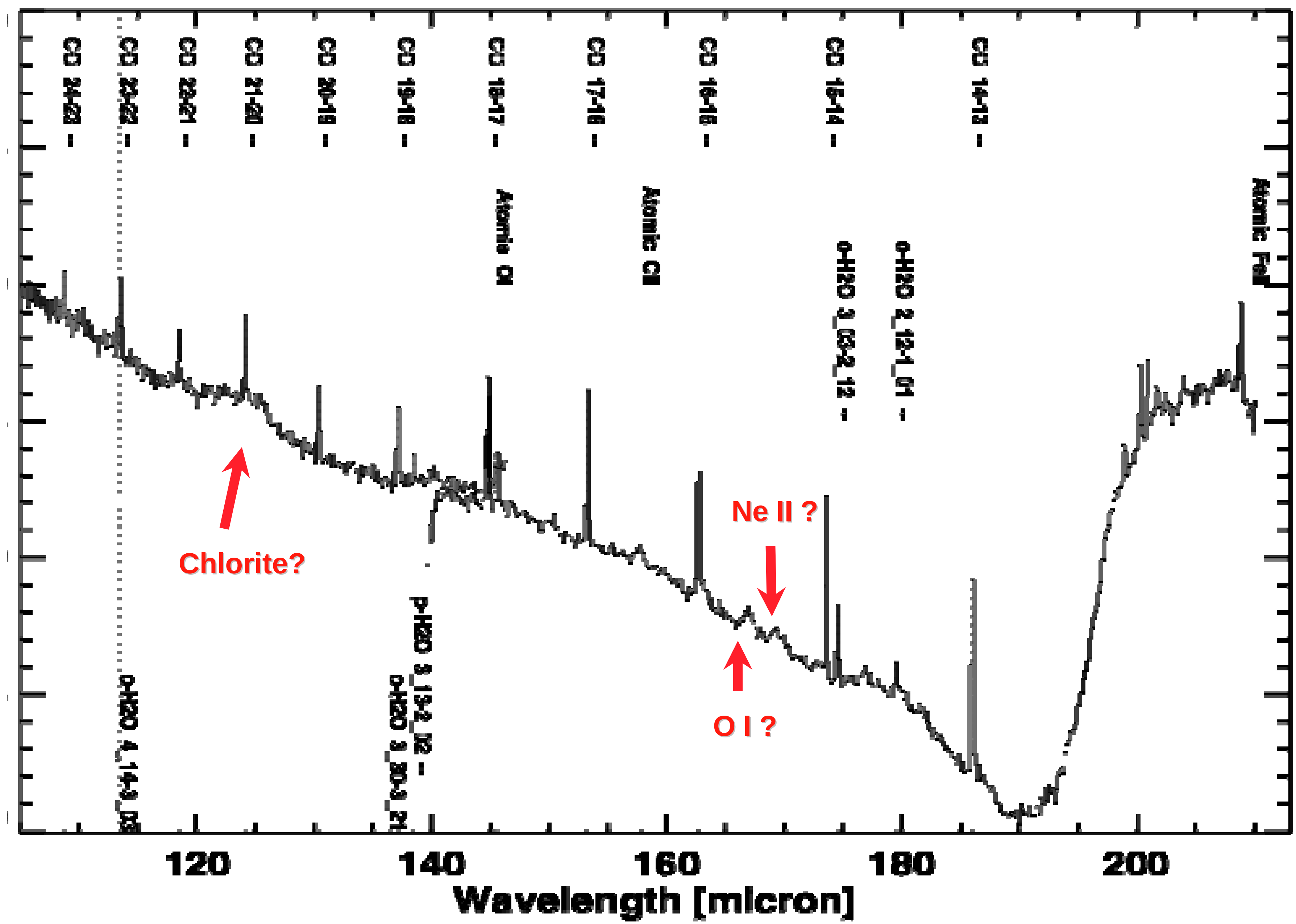
- 2 PACS AORs taken last Friday
- Received on Tuesday
- Reduced yesterday by Bruno Merin
- Analyzed way too late last evening/night



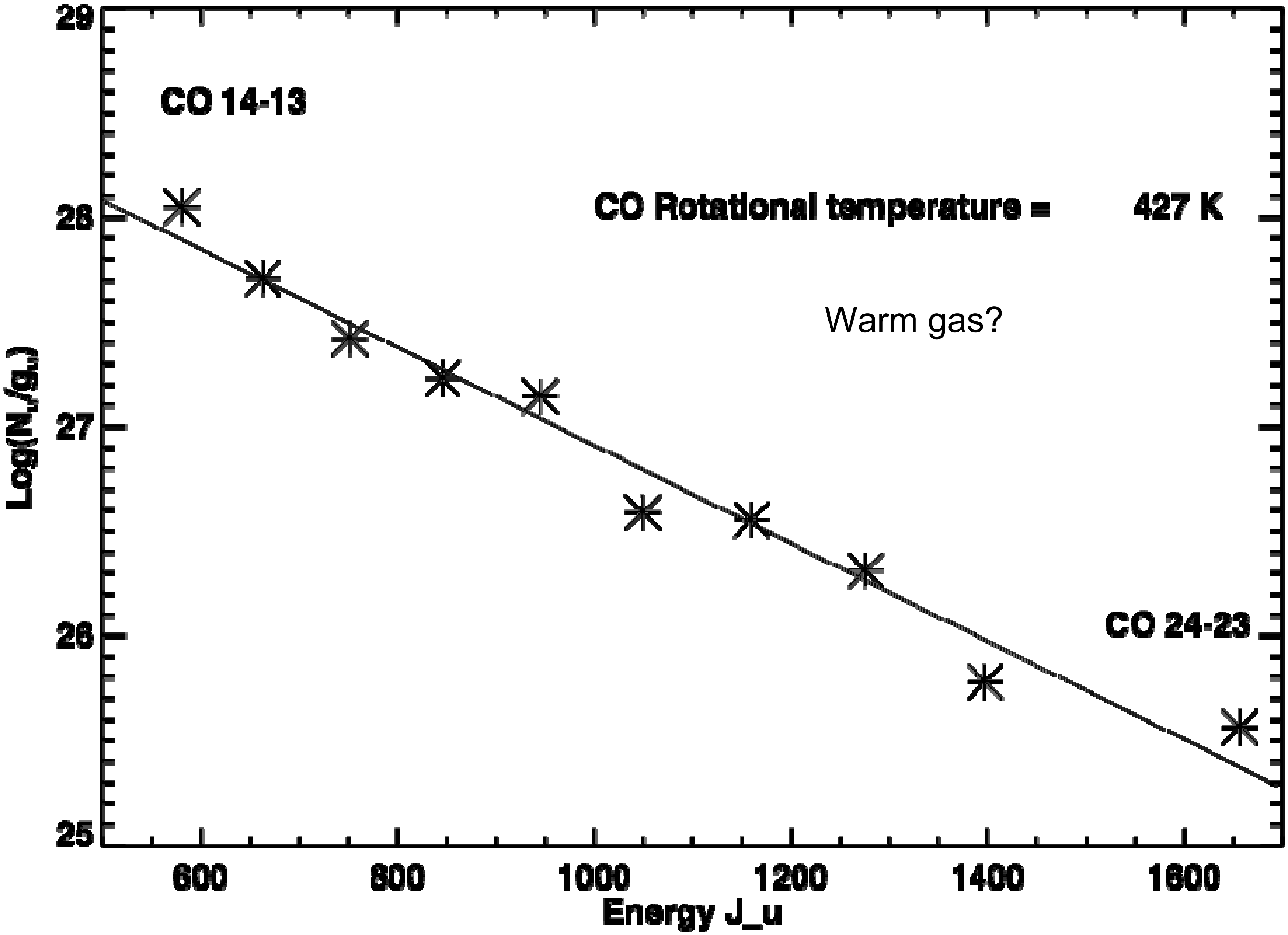
DK Cha* PACS
Range Spec (raw)
B2B
B2A
R1
R2
Light Leaking from blue to red
Flux [Jy]
Wavelength [micron]
10
20
30
40
50
60
60
80
100
120
140
160
180
200

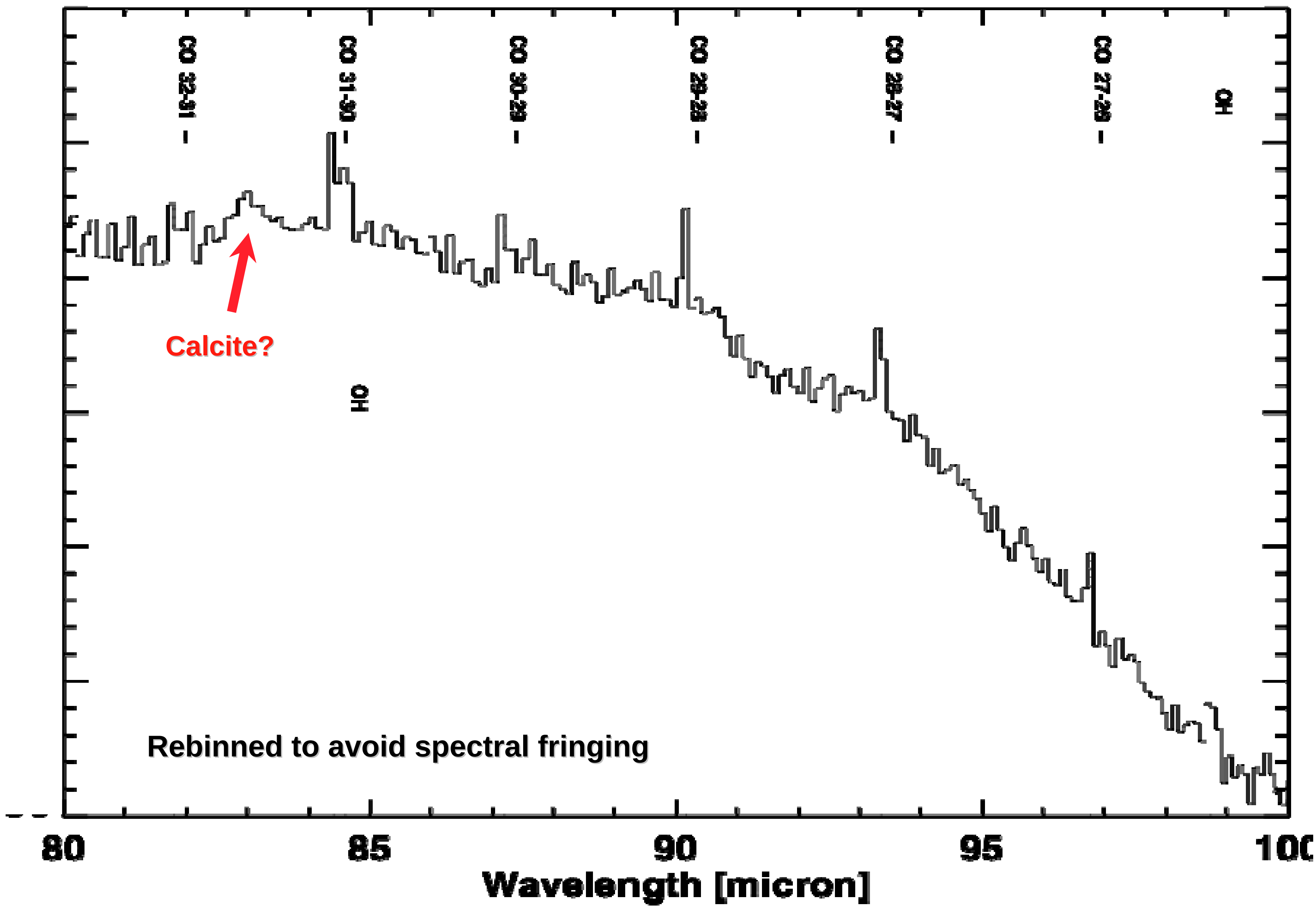
# First Impressions/caveats:

- Data size are huge and very memory intensive
- different AORs do not match up (yet): calibration uncertainty - TBD (line_up done by hand)
- Fringing: bad pixels/flatfielding - TBD (rebinning helps)
- Edge effects (e.g. leaking at > 200 micron in R2, edge drops/rises in B2A and B2B)
- Lots of gas lines
  Continuum follows black-body spectrum, as expected of embedded source

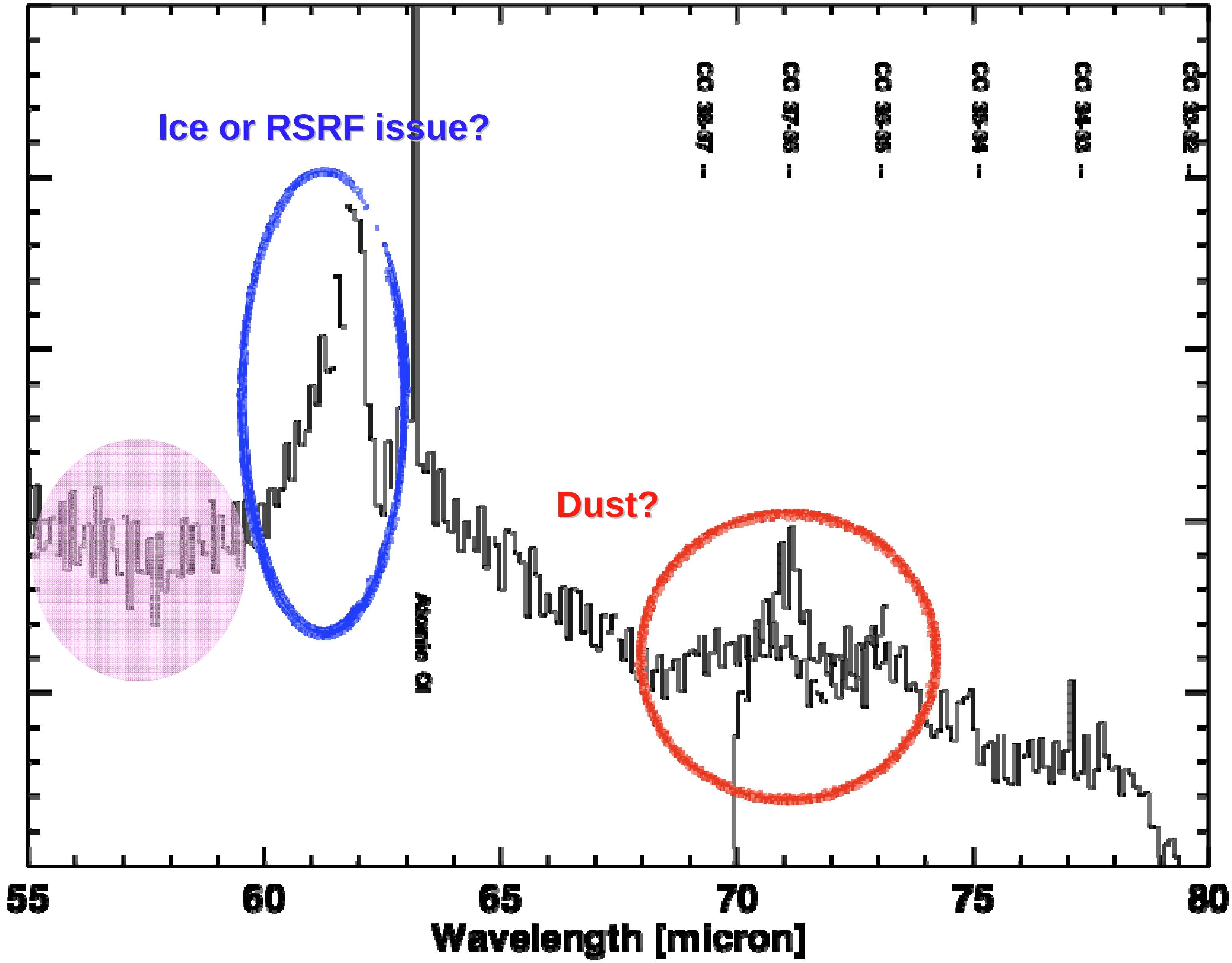


CO 24-23
CO 23-22
CO 22-21
CO 21-20
CO 20-19
CO 19-18
CO 18-17
CO 17-16
CO 16-15
CO 15-14
CO 14-13
Atomic OI
Atomic CII
o-H2O 3_03-2_12
o-H2O 2_12-1_01
Atomic FeI
o-H2O 4_14-3_03
p-H2O 3_13-2_02
o-H2O 3_30-3_21
Chlorite?
Ne II ?
O I ?
120
140
160
180
200
Wavelength [micron]

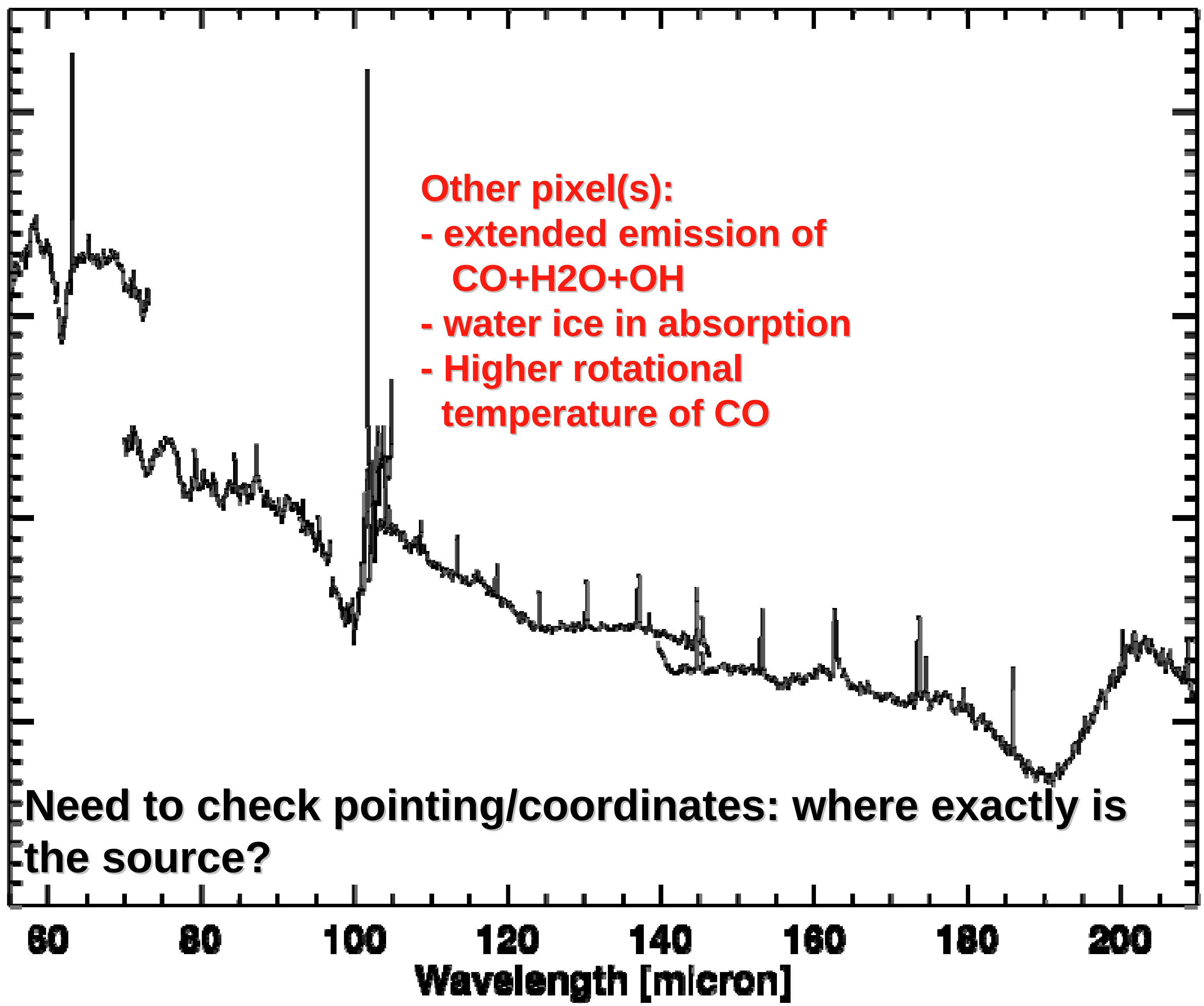

CO 14-13
CO Rotational temperature = 427 K
Warm gas?
CO 24-23
Log(N_u/g_u)
Energy J_u
29
28
27
26
25
600
800
1000
1200
1400
1600



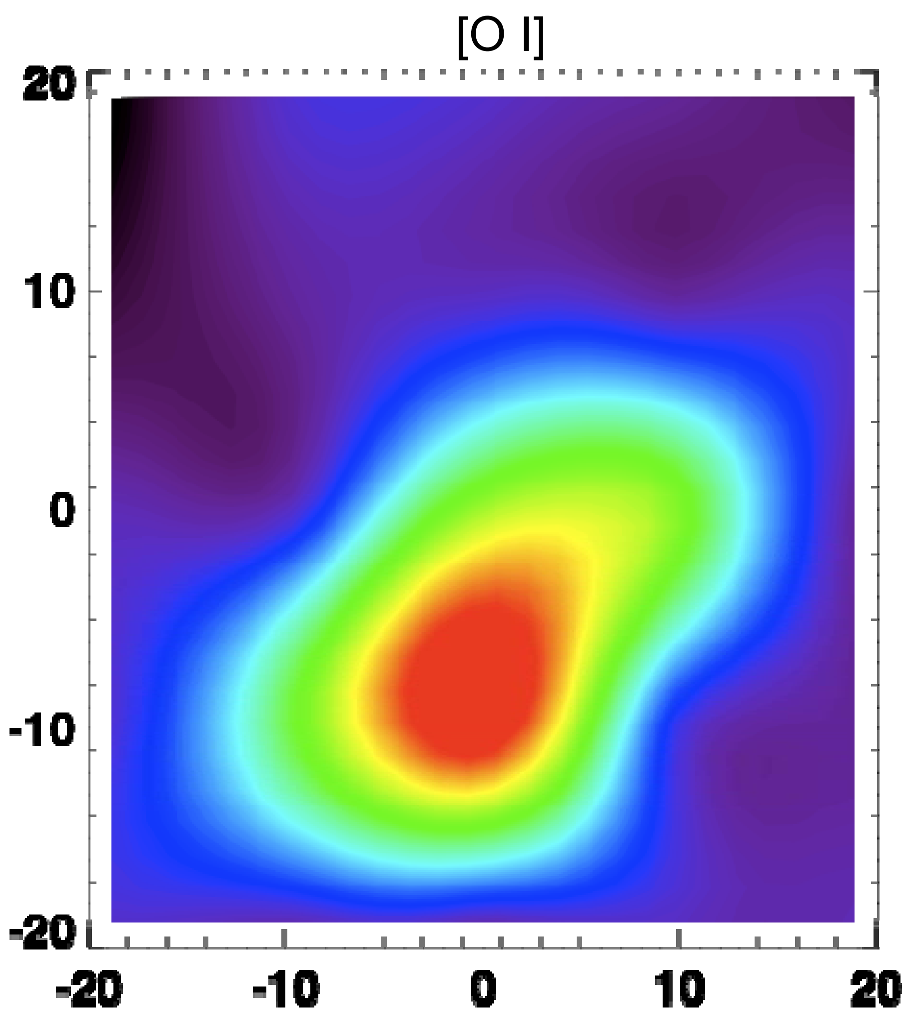
CO 32-31
CO 31-30
CO 30-29
CO 29-28
CO 28-27
CO 27-26
OH
OH
Calcite?
Rebinned to avoid spectral fringing
80
85
90
95
100
Wavelength [micron]

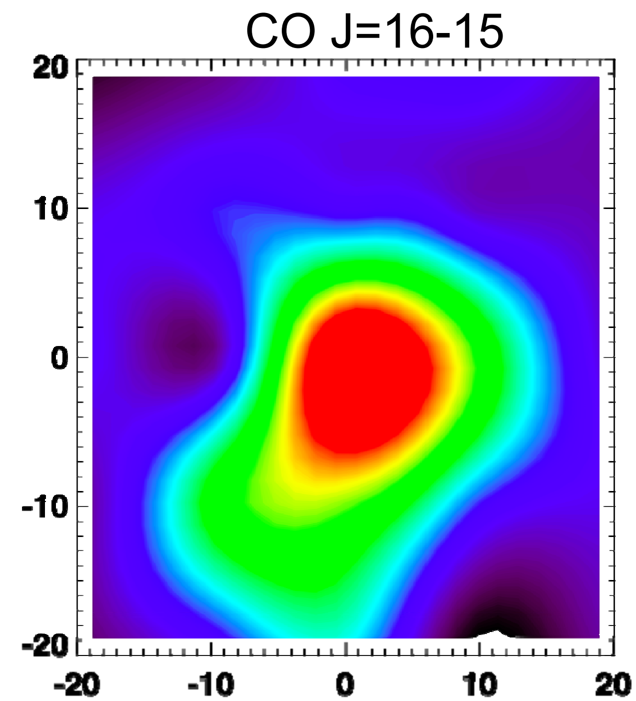


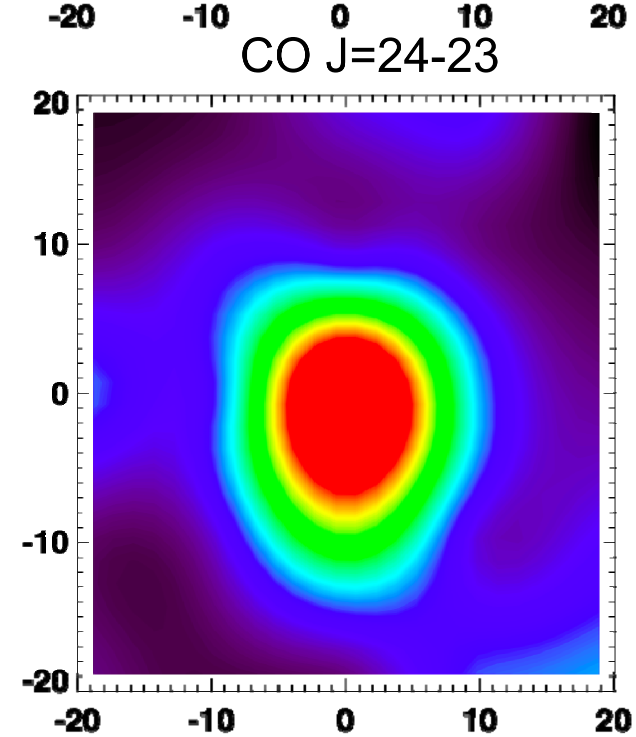
Ice or RSRF issue?
Dust?
CO 38-37
CO 37-36
CO 36-35
CO 35-34
CO 34-33
CO 33-32
Atomic OI
55
60
65
70
75
80
Wavelength [micron]


Other pixel(s):
- extended emission of
CO+H2O+OH
- water ice in absorption
- Higher rotational
temperature of CO
Need to check pointing/coordinates: where exactly is
the source?
60
80
100
120
140
160
180
200
Wavelength [micron]

Flux distribution of CO lines indicates different conditions (temperature? Density? shock velocity?)



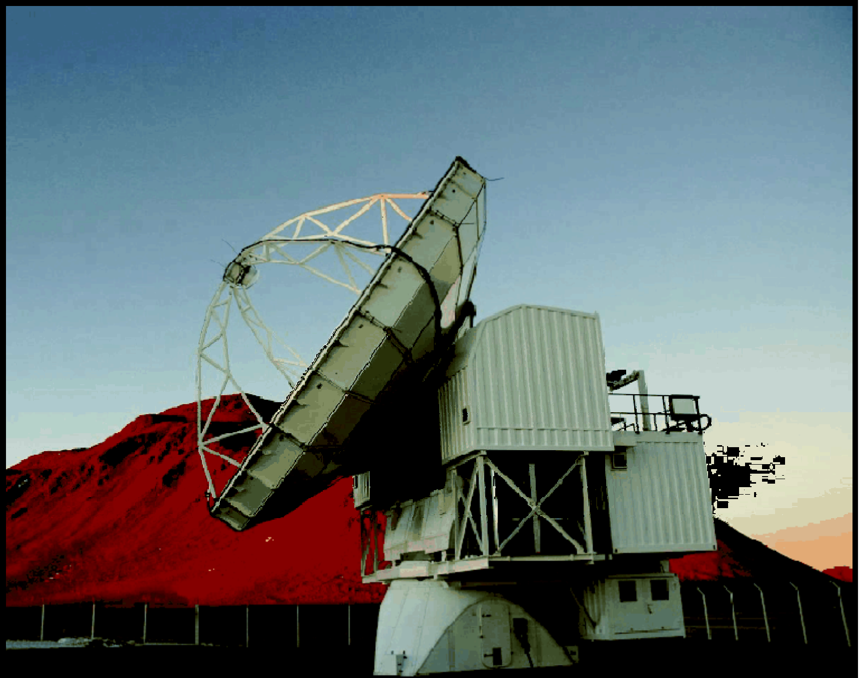



# Conclusions


- Immense amount of information on
  GAS, ICE and DUST in just one source, one pixel
  25 pixels to analyze over >150 micron range
- Extended gas emission, $H_2O$ + CO + OH + Atomic lines
- Ice in absorption AND emission
- Dust features in embedded protostar
- **VERY COMPLEX STRUCTURE : 3D MODELLING NEEDED**
- Excellent test complementary cases for evolution from protostar to disk!!!

# DK Cha* (IRAS 12496-7650)

•Isolated, nearly face-on, embedded protostar with a powerful, compact (30”) outflow, L=25 $L_{sun}$
•ISO-LWS detected strong high-J CO lines up to J=19-18 (Giannini et al)
•Spectrally-resolved APEX-CHAMP+ maps of CO 6-5 and 7-6, reveal both outflowing and quiescent warm gas



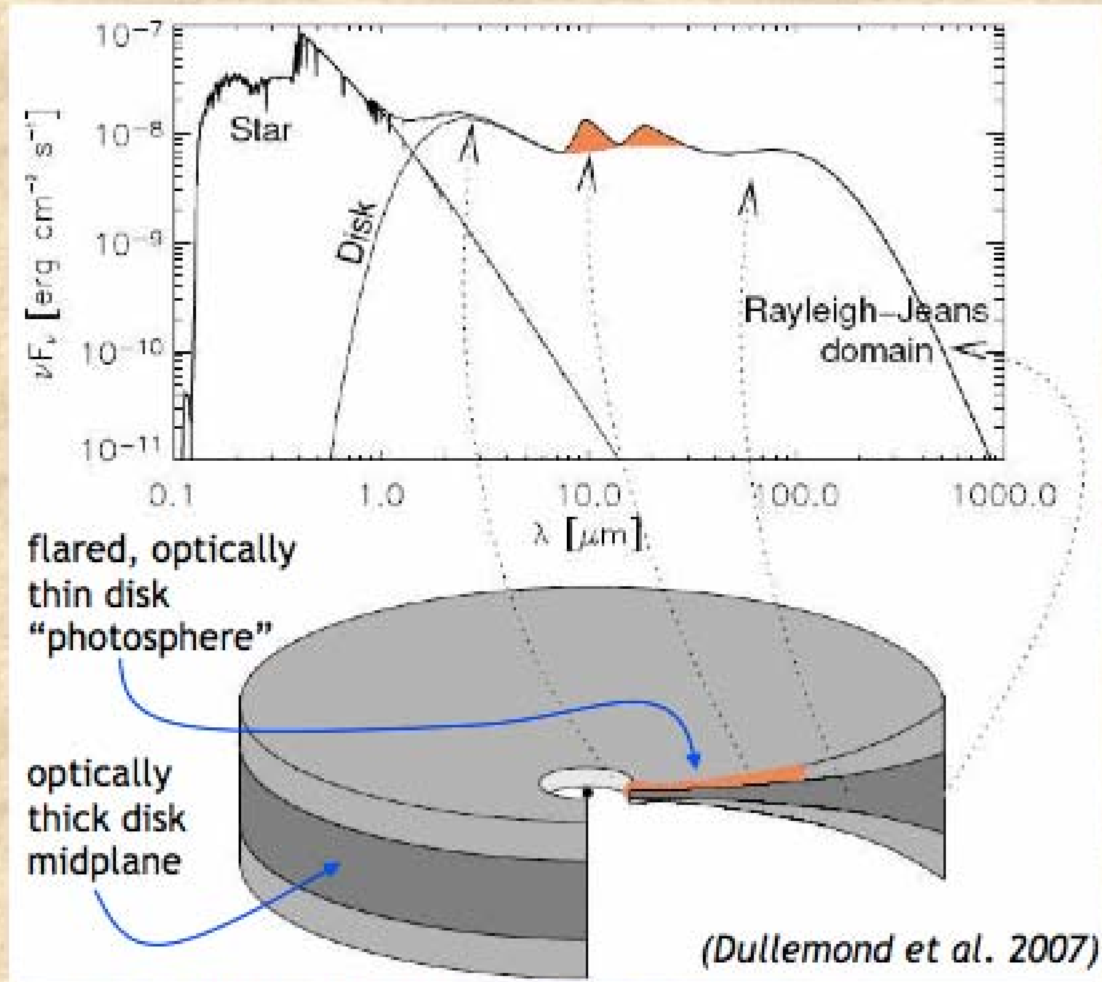
No simple model can fit both the APEX and ISO data (van Kempen et al. 2006,2009)

To the rescue: PACS Range Scan

# Conclusions


•PACS Range Scan successful (need to resolve “fringing” and RSRF issues)
•HD 100546 shows evidence for cold crystalline dust and gas (ice TBD)
•DK Cha exhibits a forest of lines of multiple components (e.g. outflows, envelope, disk)
•Future outlook: statistically significant sample of dust, ice, and gas in disks and embedded objects

# A "Typical" Circumstellar Disk




near-IR (1-4 μm): <0.05-0.1 AU

mid-IR (4-30 μm): 0.1-10 AU

far-IR (30-100 μm): 10-100 AU

Furlan et al.

# The Harsh Life of a Dust Grain

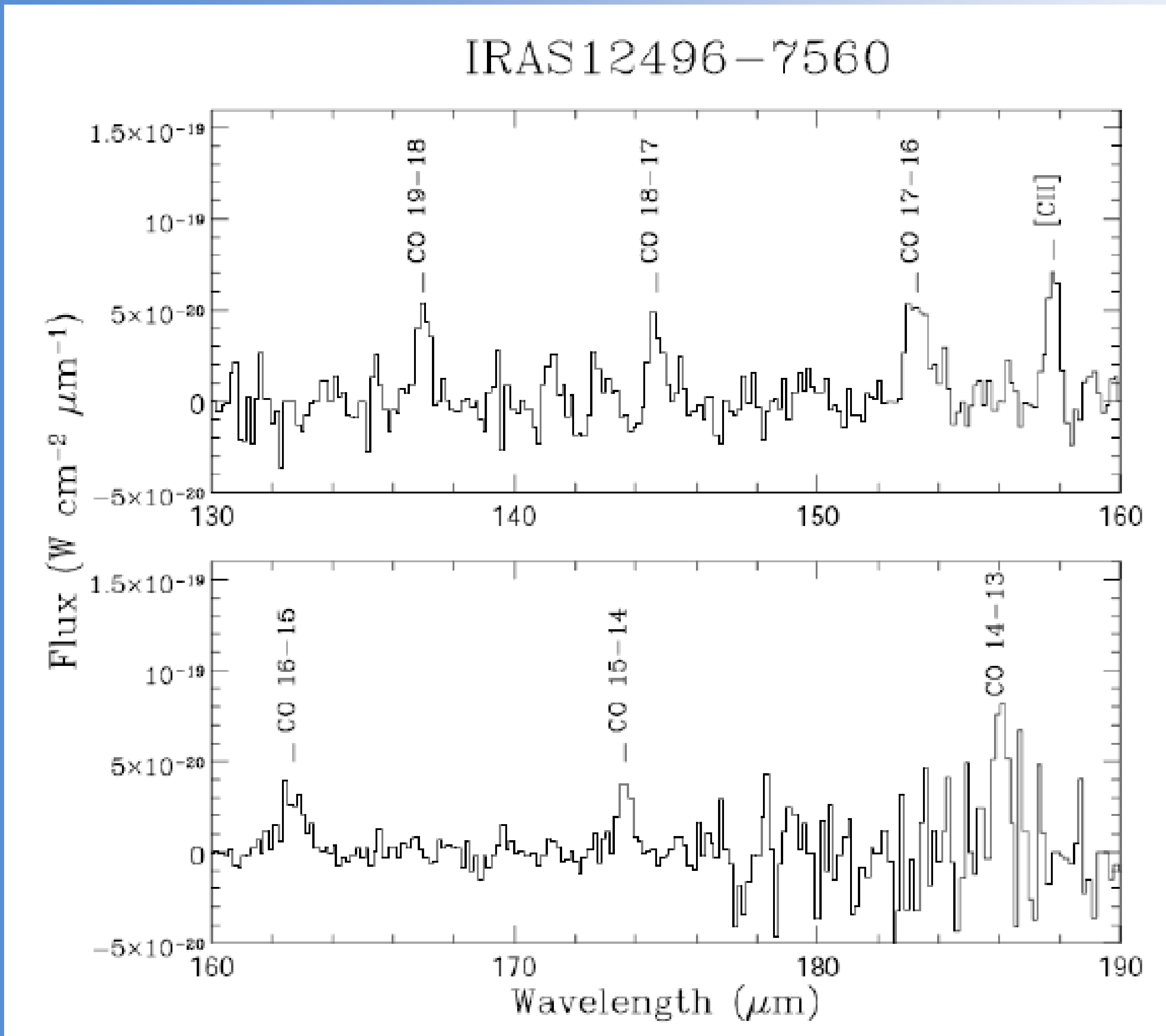
- Planetary nebulae (circumstellar dust shells) exhibit crystalline dust grains
- Dust is damaged by radiation after entering the ISM and becomes pristine
    - No evidence for silica ($SiO_2$) in the ISM
- Yet we observe crystallized dust in most circumstellar disks (except for disks with radial holes) and comets (Hale-Bopp, Tempe 1, 81P/Wild 2; see STARDUST), which formed early and far out in our solar system
- Crystallization requires heating to 1000 - 1400 K and cooling
- When and where did the crystalline dust get formed?
    - In-situ vs. radial mixing

# DIGIT Vital Statistics

- TOTAL: 94 sources (30 embedded, 64 disks)

- 12 HIFI + PACS Spec Embedded Sources
- 1 HIFI only Embedded Source (PACSSpec for this source is located in other scan)
- 17 PACS Spec Embedded Sources (see WISH for HIFI spec)
- 7 Sample 1 Full Disks
- 14 Sample 2 Full Disks
- 12 Forsterite only PACS Disks
- 31 SPIRE+PACS Photometry Disks
- DIGIT on the web: http://peggysue.as.utexas.edu/DIGIT/

# DK Cha (continued)




The ISO-LWS spectra of DK Cha (Giannini et al. 1999). There are clear detections of multiple CO lines, ranging from 130 to 190 µm.

# DIGIT (Dust, Ice, and Gas In Time)

- 250 hrs/ 94 sources
- 30 embedded protostars, plus 64 disk sources ranging from B to M in spectral type (intermediate and low mass), selected from nearby (a few x 100 pc) molecular clouds (Tau, Oph, Cha, Per, Ser, Lup)
- Full disks/ disks with gaps; crystalline dust vs. amorphous at Spitzer wavelengths; embedded objects will exhibit outflows, ice (water, carbon dioxide, and others); gas emission
- PACS spectroscopy (52-210 um), PACS photometry (70, 100, 160 um)
- SPIRE photometry (to determine disk masses)
- HIFI spectroscopy for embedded sources not in the WISH guaranteed time key project (to detect water)
- DIGIT on the web: http://peggysue.as.utexas.edu/DIGIT/