# warm gas in Herbig Ae/Be disks: the CO ladder probed from 50 to 500 K


## Matthijs van der Wiel

**Institute for Space Imaging Science (ISIS),**
**dept. of physics and astronomy, U of Lethbridge, AB, Canada**

David Naylor (UofL), Inga Kamp (Kapteyn, Groningen),
**François Ménard** (Grenoble & U. de Chile, Santiago), Wing-Fai Thi (Grenoble),
Peter Woitke (St. Andrews), Klaus Pontoppidan (STScI),
Göran Olofsson (Stockholm)

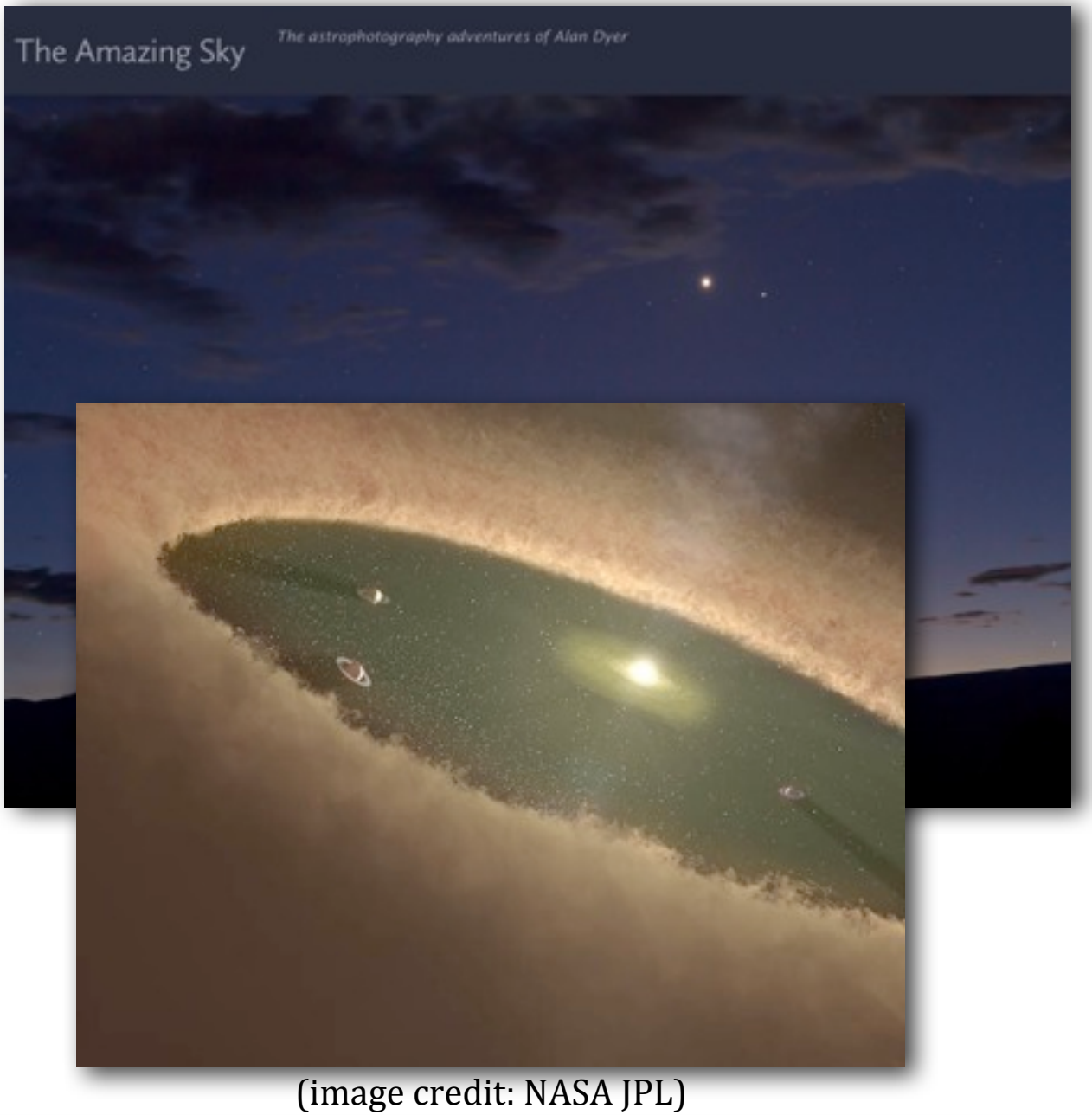


CSA ASC NSERC CRSNG ISIS Institute for Space Imaging Science


(image credit: NASA JPL)

# motivation: how do planets form?

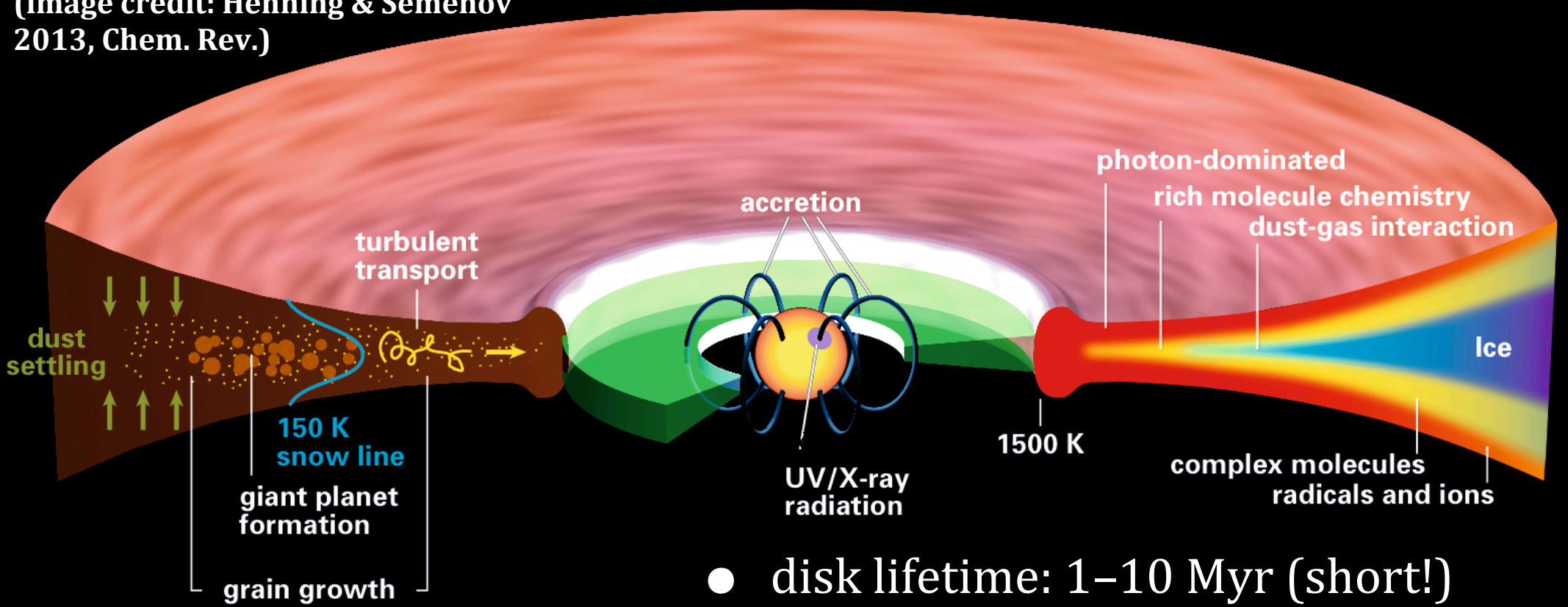
- **where** do planets form?
  - in circumstellar disks around young stars, *'protoplanetary disks'*

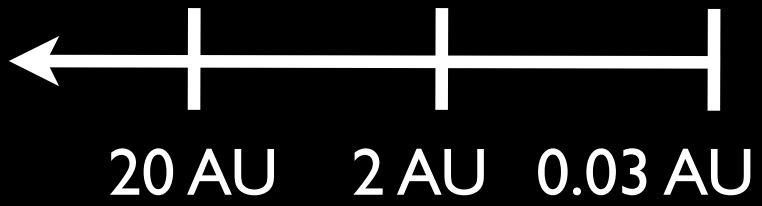



(image credit: NASA JPL)

# structure of a planet-forming disk

(image credit: Henning & Semenov 2013, Chem. Rev.)




- disk lifetime: 1–10 Myr (short!)
- disk contains gas and dust
- disk irradiated by star and ambient radiation field

# Herschel space observatory and SPIRE

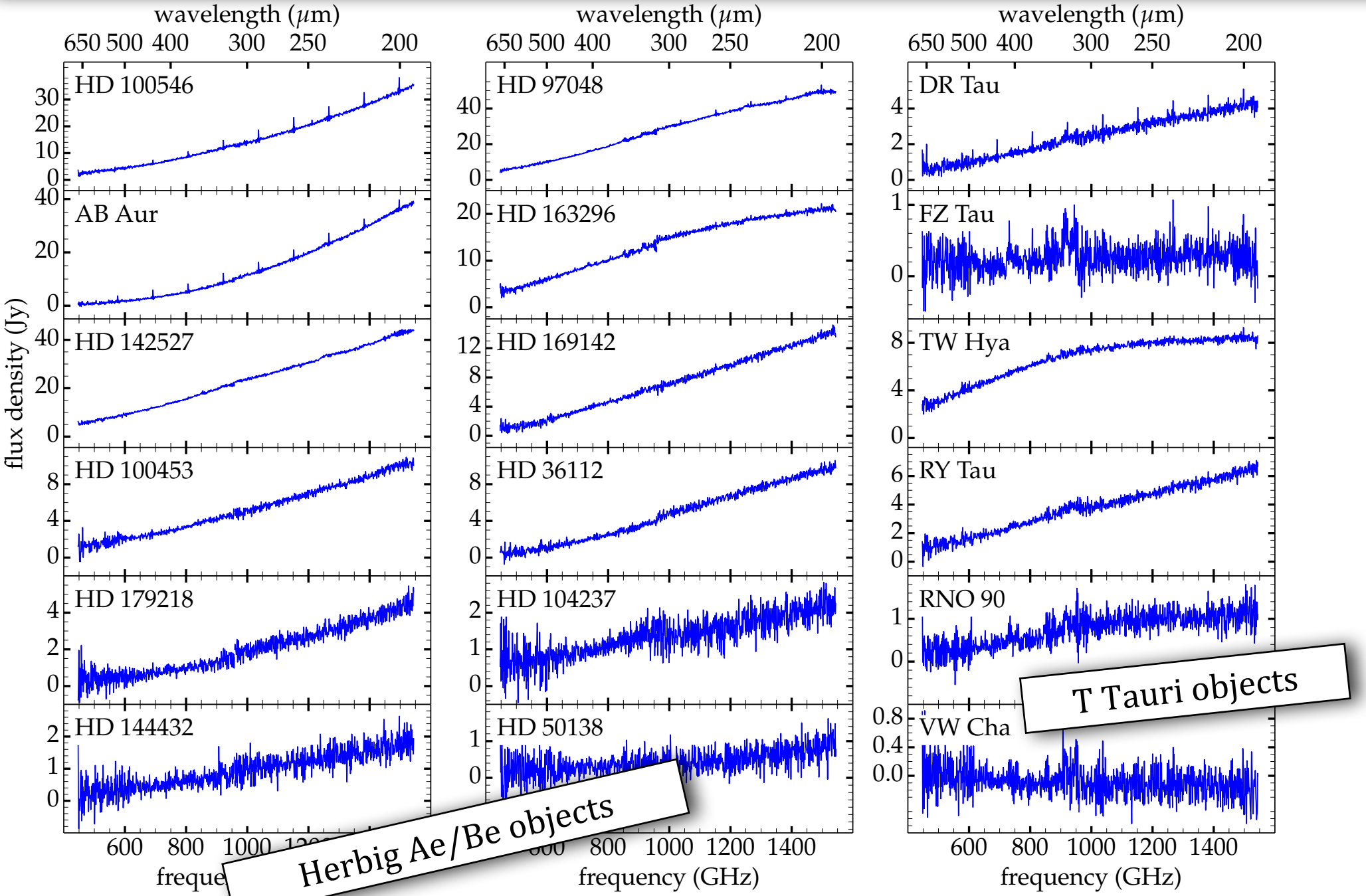
Herschel (ESA)
3.5 m mirror diameter
launched May 2009
mission ended April 2013

- SPIRE (Spectral and Photometric Imaging Receiver) designed, built and operated with Cardiff University (UK) as P.I. institute, and consortium including Lethbridge.
  - Photometer (camera)
  - multi-detector Fourier Transform Spectrometer for **spectral imaging:**
    **200–700 µm / 500–1500 GHz**

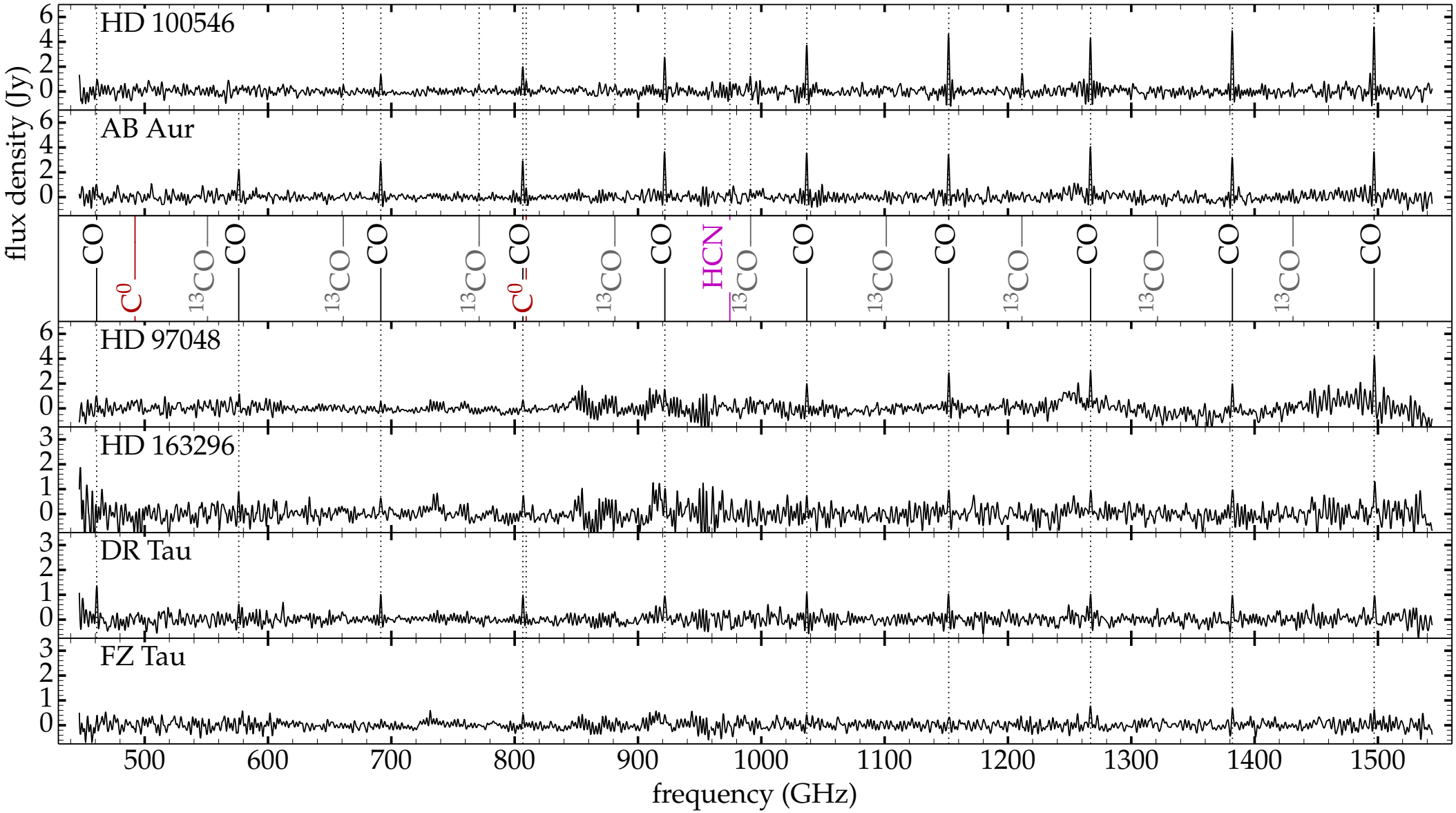
# *Herschel* SPIRE survey of planet-forming disks

- 12 protoplanetary disks observed as part of SPIRE guaranteed time (P.I. Göran Olofsson, Stockholm)
- 6 more from two other programs (Pontoppidan, Bouwman)
- total sample 18 targets:
  12 Herbig Ae/Be stars, 6 T Tauri stars
- detect dust continuum, carbon monoxide (CO) rotational lines, some $^{13}CO$; upper limits on low-energy $H_2O$, $CH^+$
- data characteristics:
  - uninterrupted 450–1540 GHz / 666–195 μm range
  - angular resolution 17–41 arcsec ⇒ disks unresolved
  - spectral resolution $\nu/\Delta\nu \approx 400–1300$ ⇒ spectral lines unresolved
- diffuse, extended emission subtracted using off-center detectors in SPIRE array

# *Herschel* SPIRE dust continuum SEDs (Van der Wiel+, in prep.)



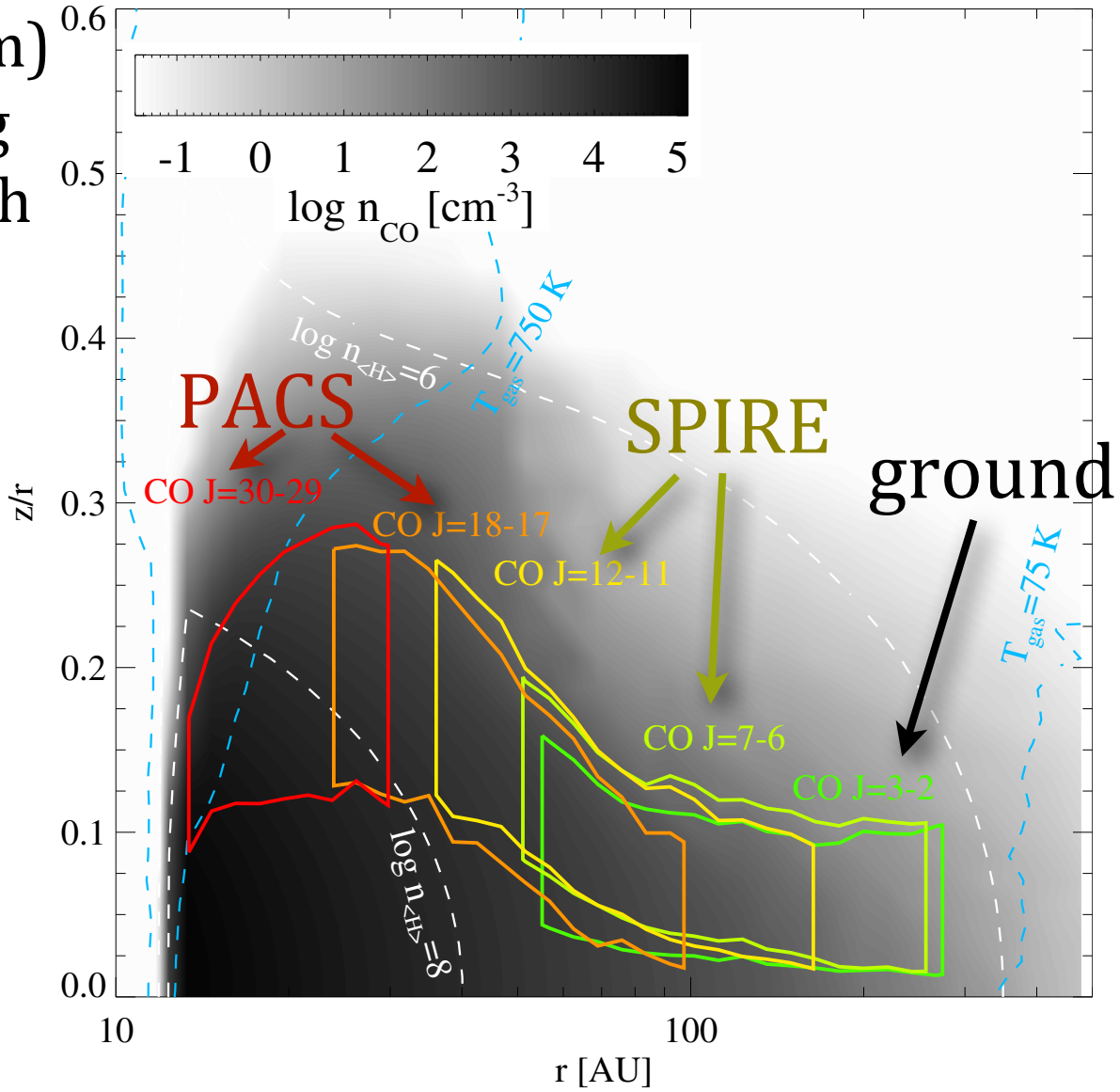
# *Herschel* SPIRE spectral line detections (Van der Wiel+, in prep.)



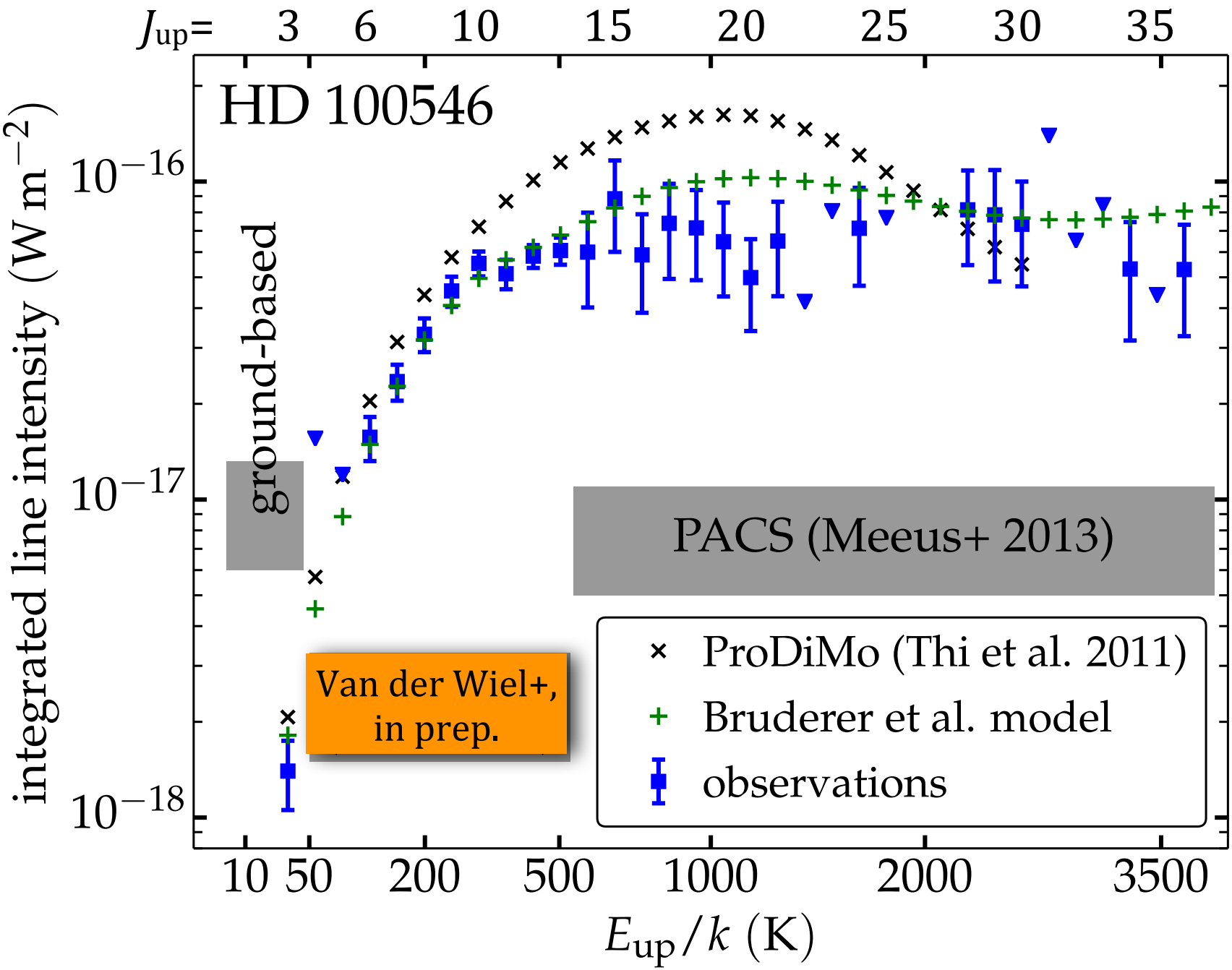

- SPIRE spectrometer is an FTS, so each spectral line has a Sinc line shape.
- line shape, including 'ringing', is well understood, so straightforward to fit.

# SPIRE probes warm molecular gas

- CO lines in SPIRE band trace upper level energies ~50–500 K, impossible to observe comprehensively from the ground
- brightest CO (and continuum) typically observed in flaring Herbig Ae/Be disks, although not exclusively
  - $^{12}$CO is optically thick
    ⇒ probes surface layer
  - $^{13}$CO is more optically thin
    ⇒ traces total amount of gas



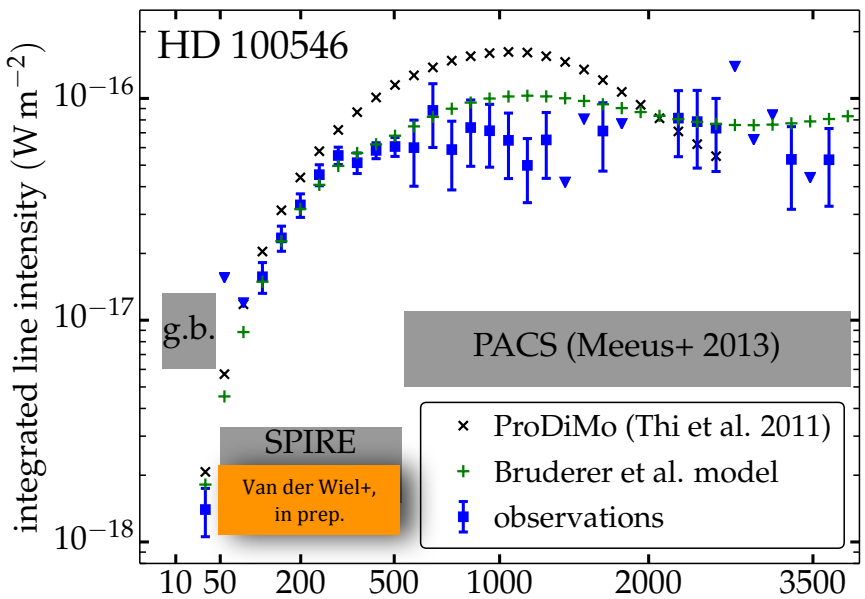
# HD 100546 – CO ladder: observations vs. models

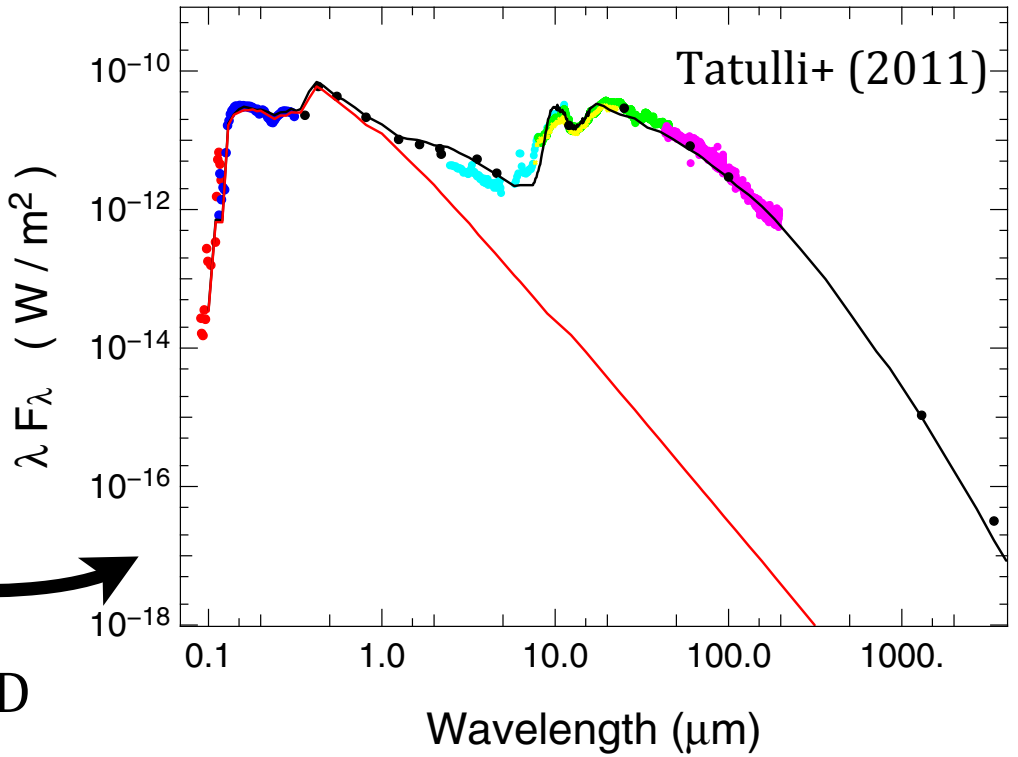


# physics and chemistry in the models

- both models explain observed $^{12}$CO ladder, within factor 3
- models include:
  - (2D) radiative transfer for dust and gas
  - photodissocation, chemistry (gas phase, grain surface)
  - detailed heating and cooling balance based on derived **hydrostatic structure**

typically starts from fit to broad wavelength dust SED



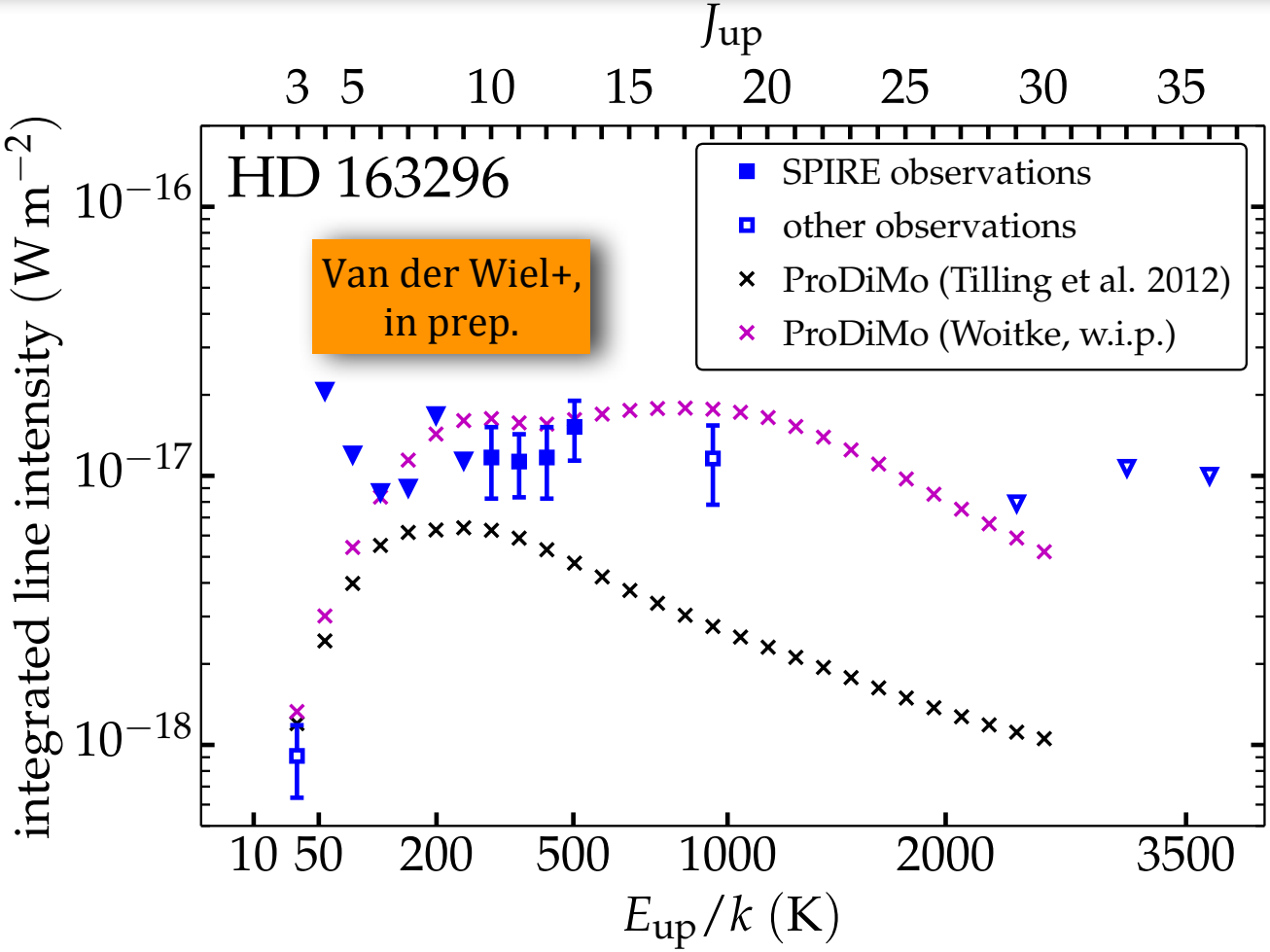
# possible adjustments to ProDiMo model – HD 100546

- for HD 100546,
  **observed $^{13}$CO is >10× stronger than model predicts**
  - not straightforward to adjust model for optically thin $^{13}$CO without compromising good fit to $^{12}$CO by existing model
- some ideas to tweak $T_{\rm gas}$ in upper layers of disk:
  - flaring geometry..
  - PAH abundance..
  - dust opacity (UV penetration) ...

# possible adjustments to ProDiMo model – HD 163296

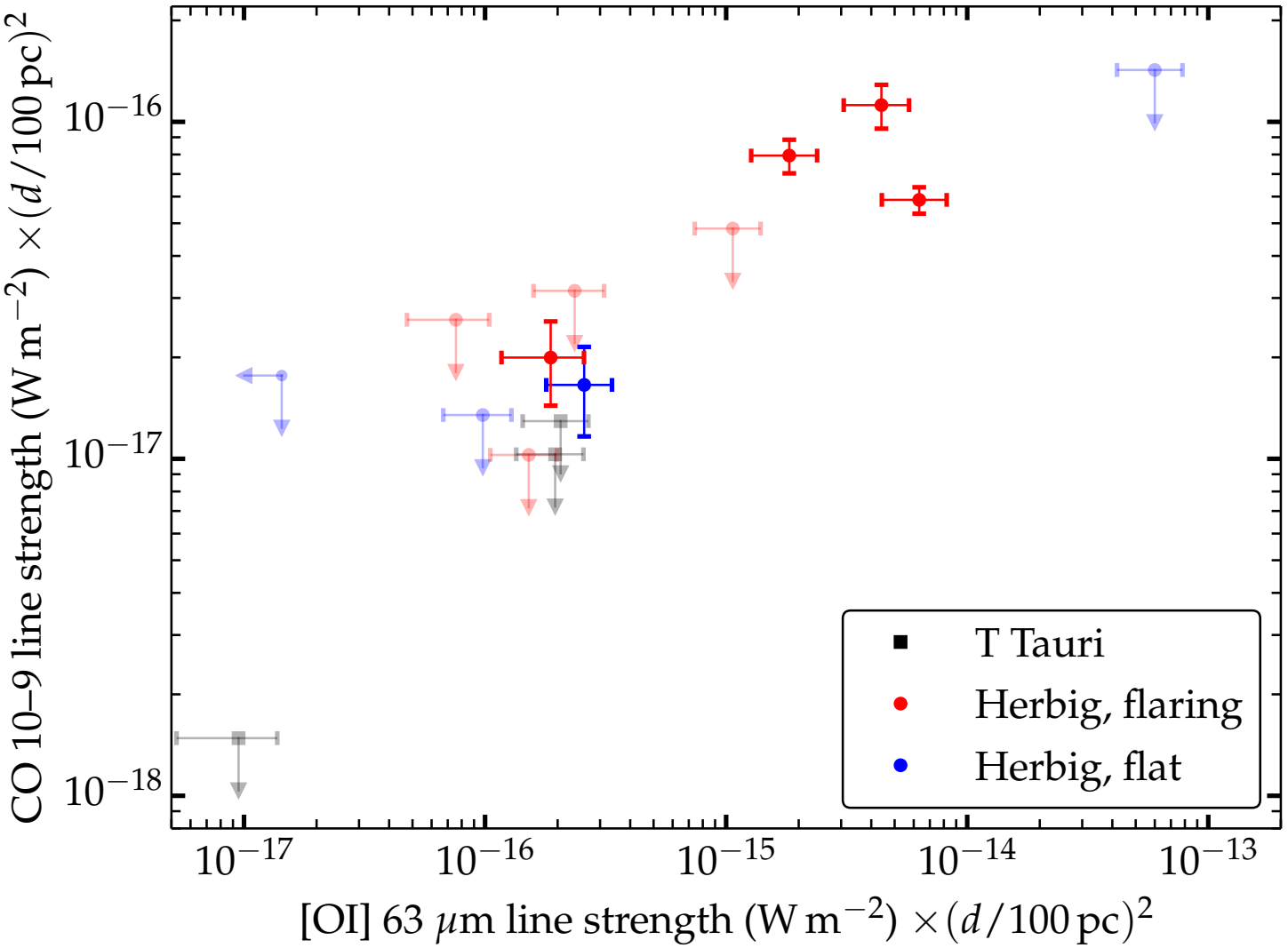
- ProDiMo model also exists for HD 163296 (Tilling+ 2012)
  - falls short of reproducing observed mid- to high-*J* CO
  - classification as 'flat' Herbig disk is based on continuum data, resolved images of gas distribution in HD 163296 show strong evidence of flaring (De Gregorio-Monsalvo+ 2013)
    ⇒ increased $T_{\rm gas}$ in upper disk layers ⇒ stronger CO lines
  - these and other aspects are going into revised model

# possible adjustments to ProDiMo model – HD 163296



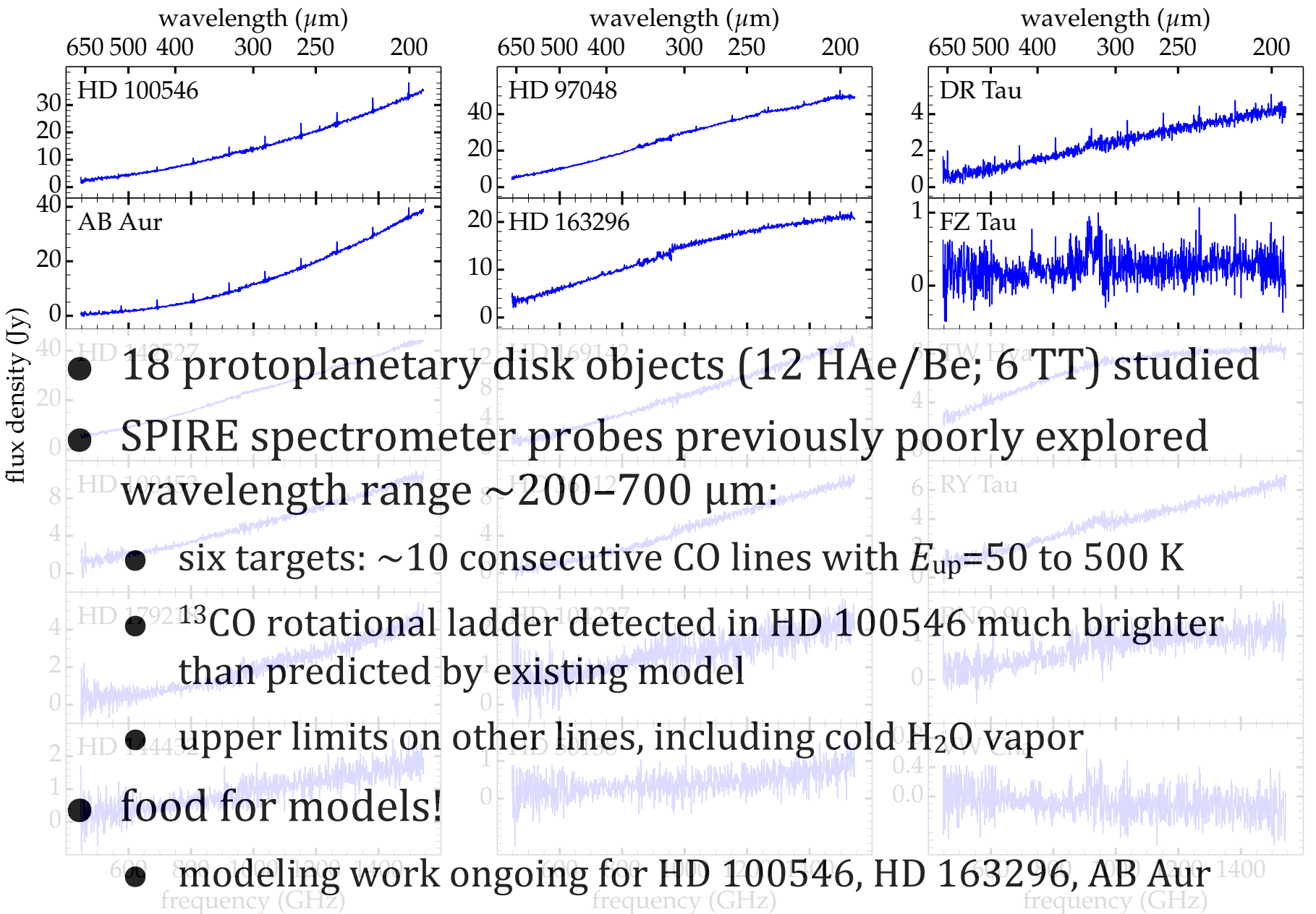

- 'work in progress' model not designed to fit CO ladder *exclusively*
- many other constraints included in optimization of model fit:
  - spectral lines of e.g., $H_2O$, [OI]; • dust SED; • image profile;
  - ALMA CO spatial and velocity profile; • CO scale height at 150 AU; ...

# correlation or random scatter?




- [OI]63µm / CO 10–9 seem related; thought to originate in same region in disk
- but: based on only 5 targets detected in both lines; rest are upper limits

# summary and conclusion




- 18 protoplanetary disk objects (12 HAe/Be; 6 TT) studied
- SPIRE spectrometer probes previously poorly explored wavelength range ~200–700 μm:
  - six targets: ~10 consecutive CO lines with $E_{up}$=50 to 500 K
  - $^{13}$CO rotational ladder detected in HD 100546 much brighter than predicted by existing model
  - upper limits on other lines, including cold $H_2O$ vapor
- food for models!
  - modeling work ongoing for HD 100546, HD 163296, AB Aur

# thank you

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