warm gas in 18 protoplanetary disks: the CO ladder probed from 50 to 500 K

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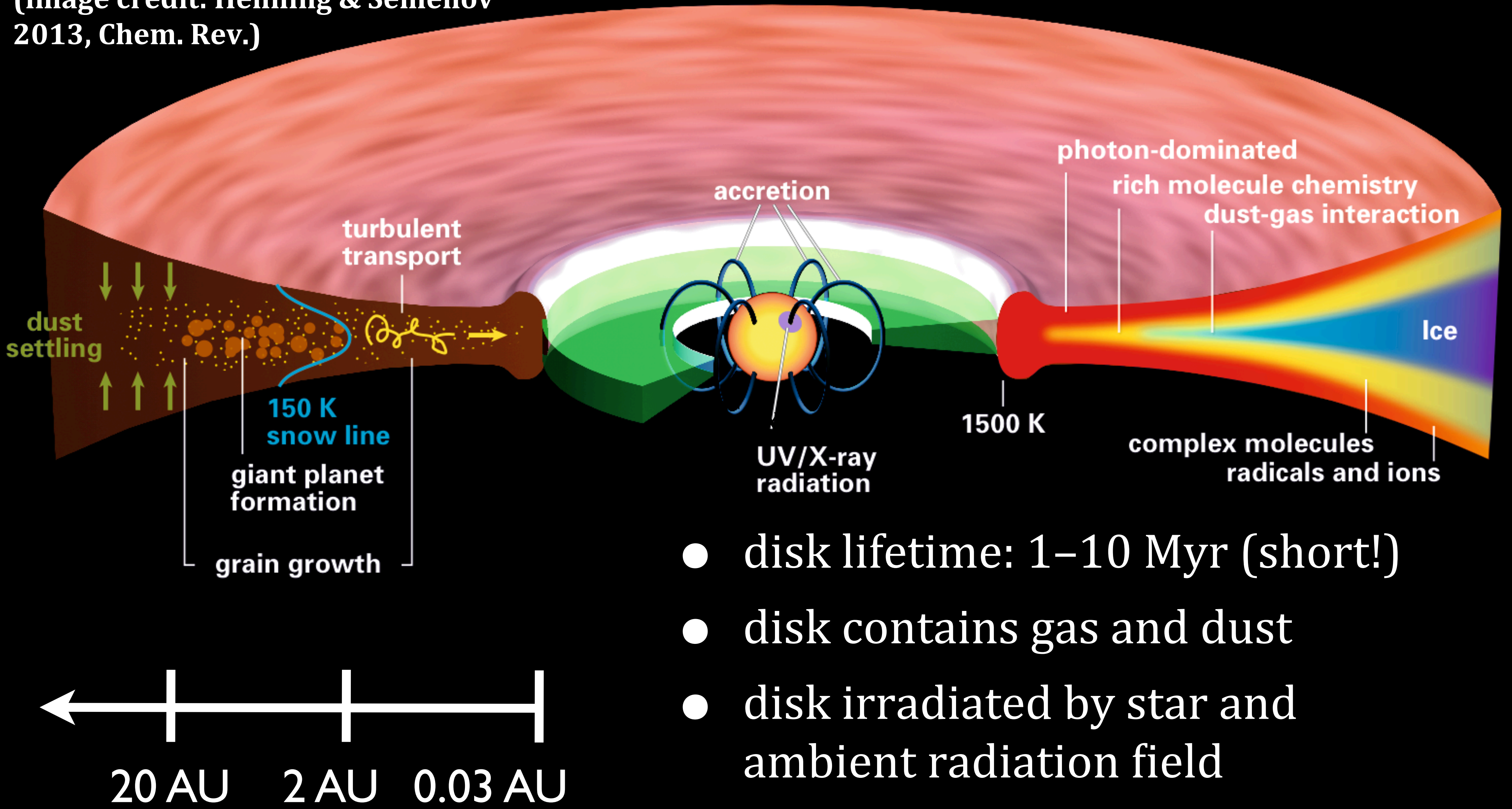
Peter Woitke (St. Andrews), Klaus Pontoppidan (STScI),
Göran Olofsson (Stockholm)

CSA ASC NSERC CRSNG ISIS Institute for Space Imaging Science

(image credit: NASA JPL)

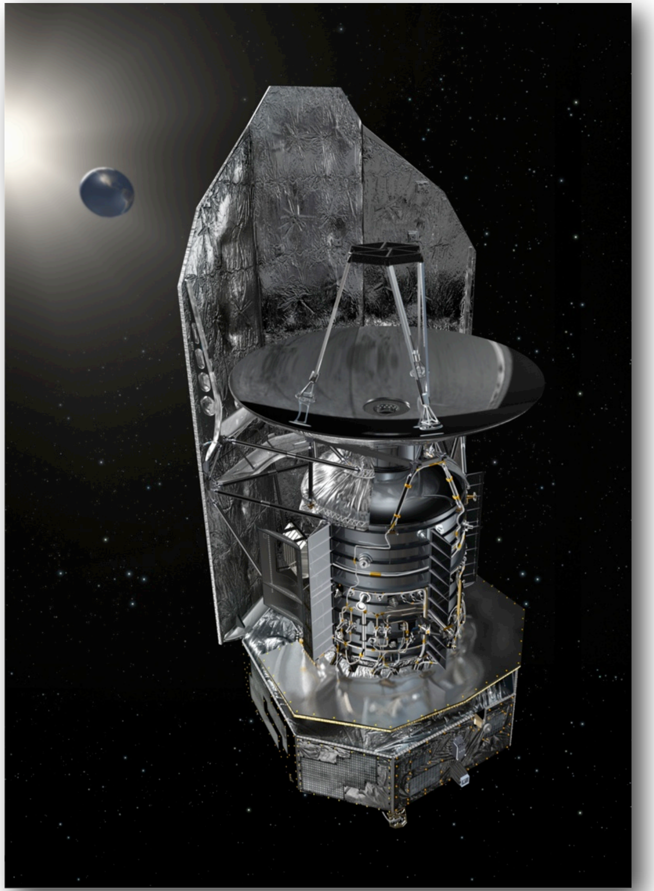
structure of a planet-forming disk

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

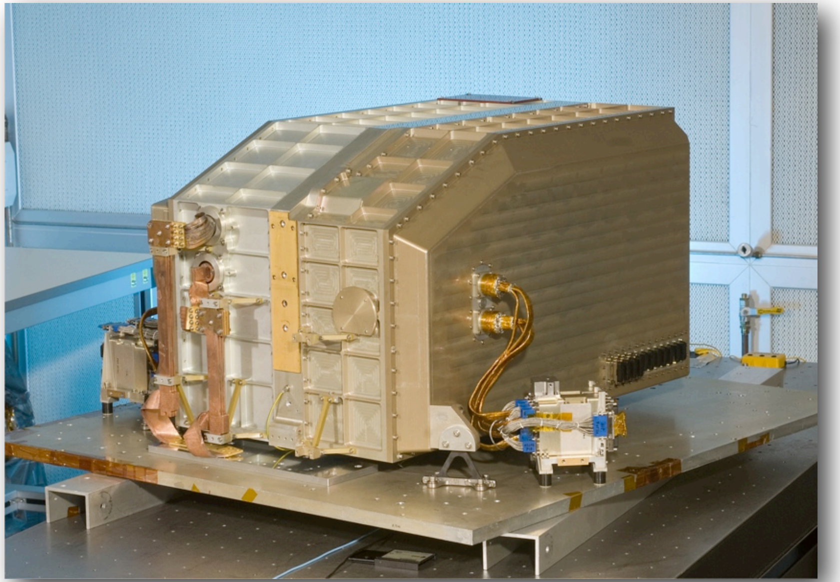


- disk lifetime: 1–10 Myr (short!)
- disk contains gas and dust
- disk irradiated by star and ambient radiation field

Herschel space observatory and SPIRE



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



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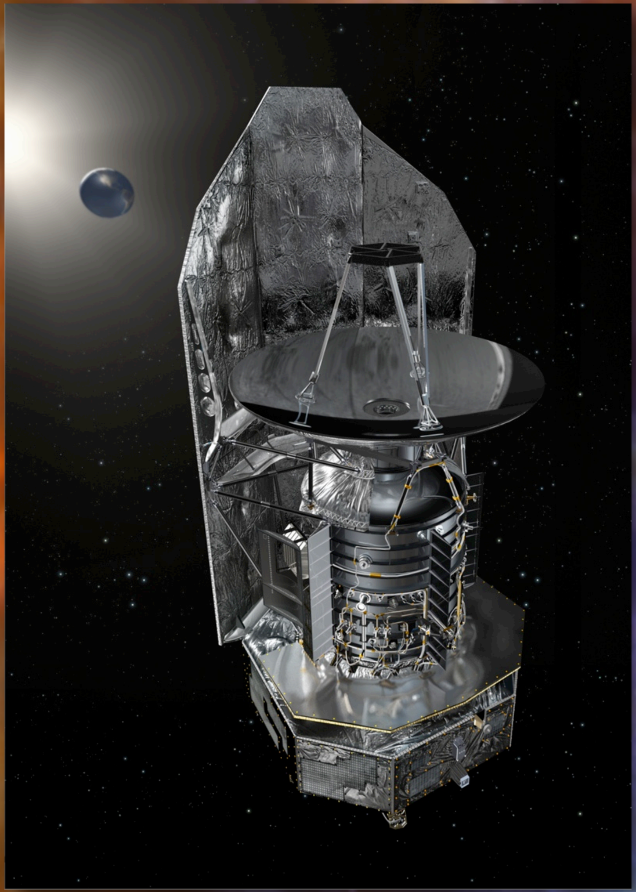

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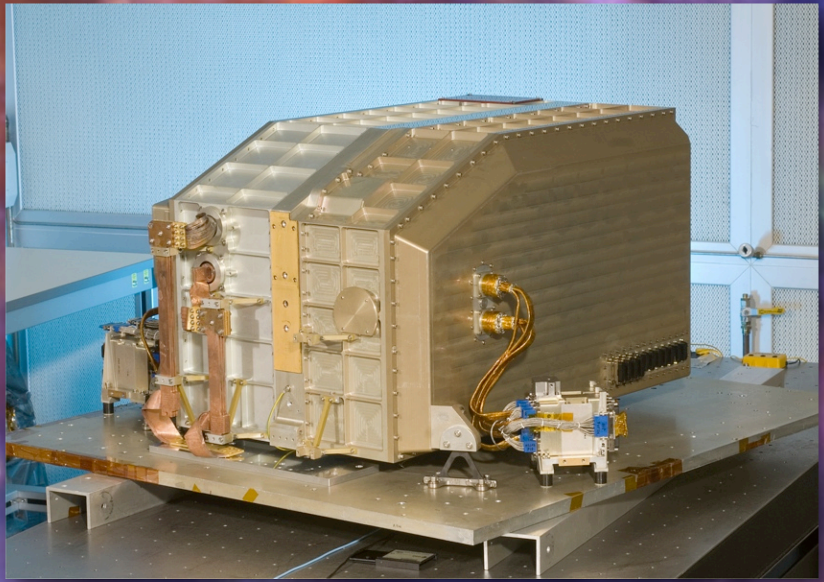

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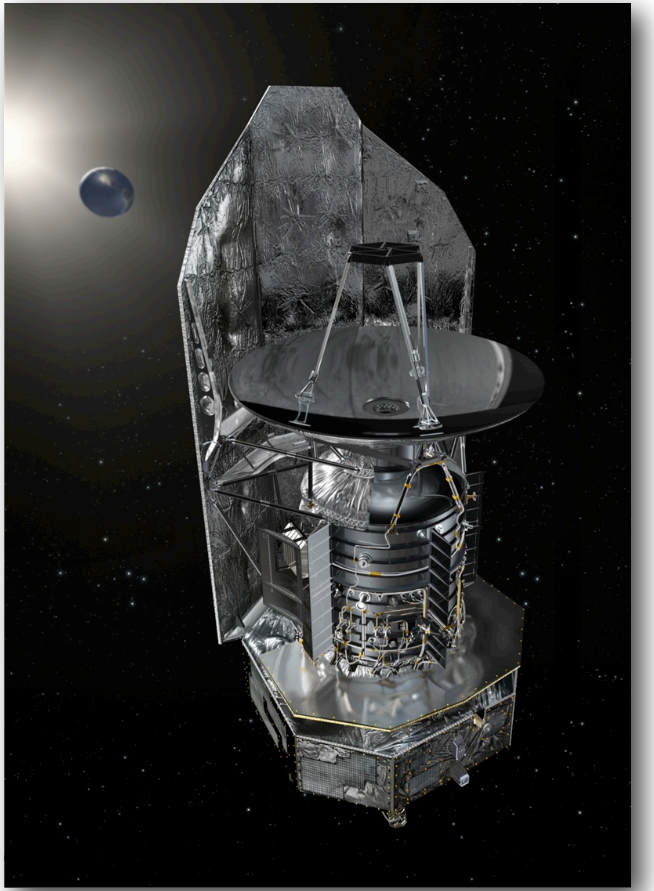

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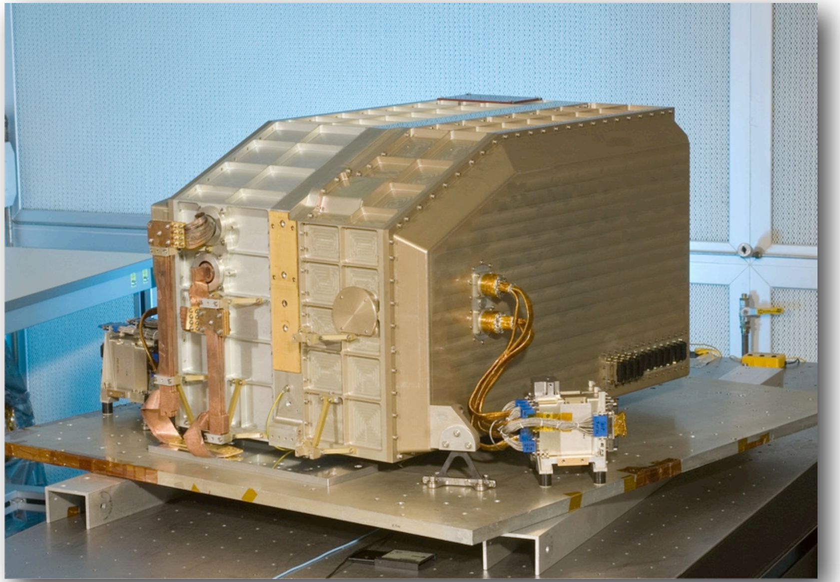

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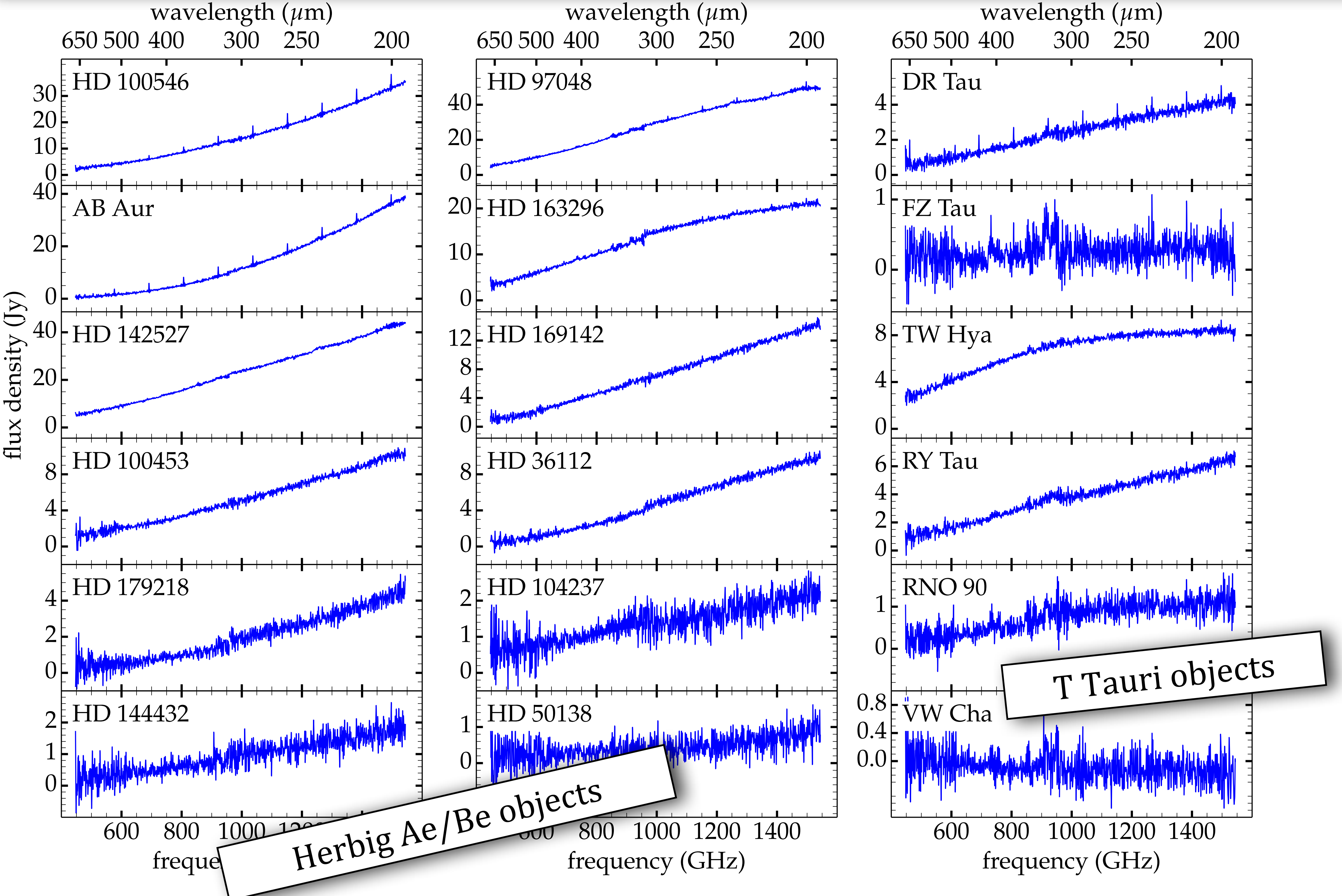
  - Photometer (camera)
  - multi-detector Fourier Transform Spectrometer for **spectral imaging:**
    200–700 μm / 500–1500 GHz

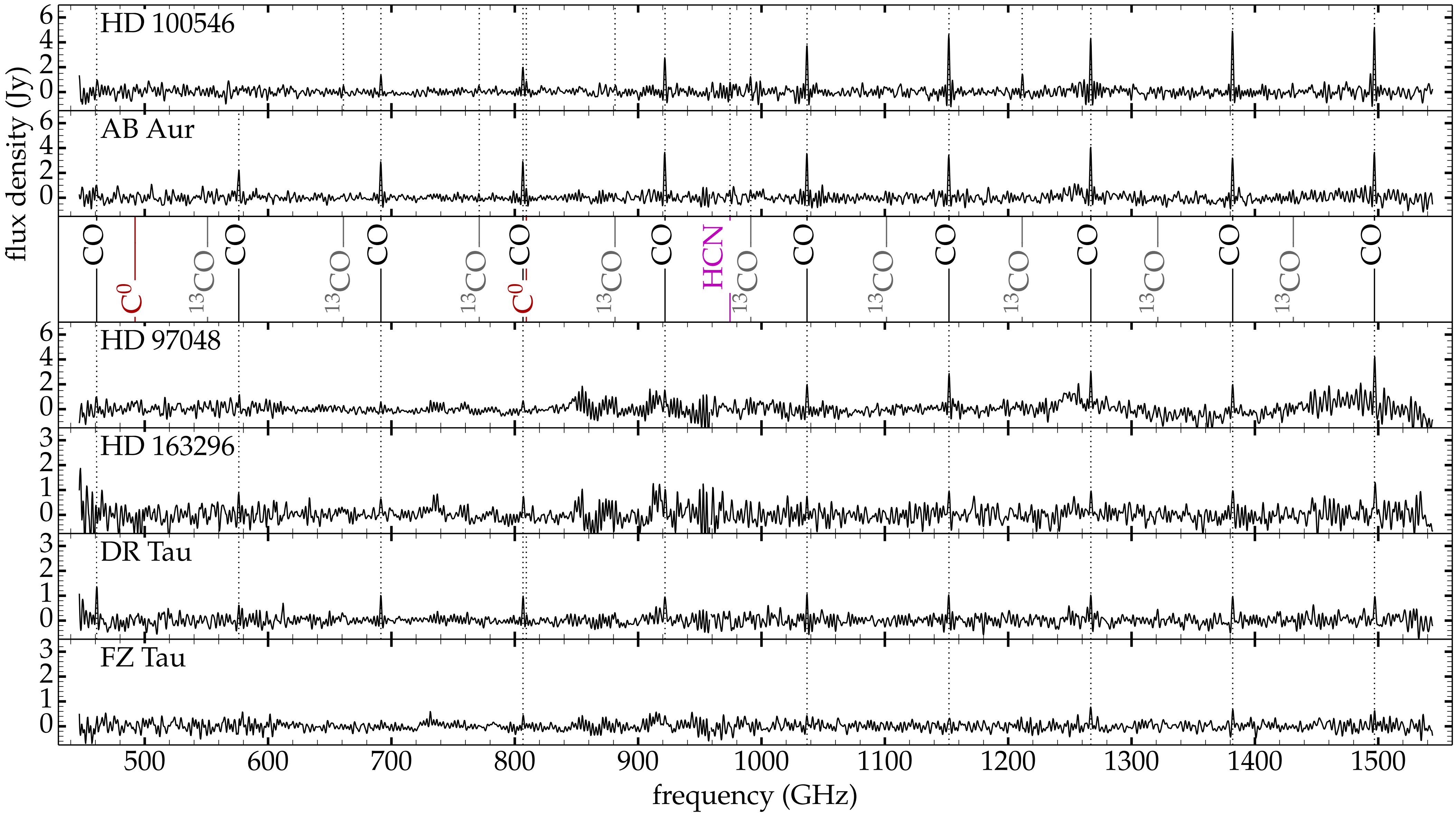
Herschel SPIRE survey of planet-forming disks

- total sample of 18 protoplanetary disks:
  12 Herbig Ae/Be stars, 6 T Tauri stars
  - majority of data from GT1 (P.I. Göran Olofsson)
  - additional data from two other programs (Klaus Pontoppidan, Jeroen Bouwman)
- detect dust continuum, ^{12}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

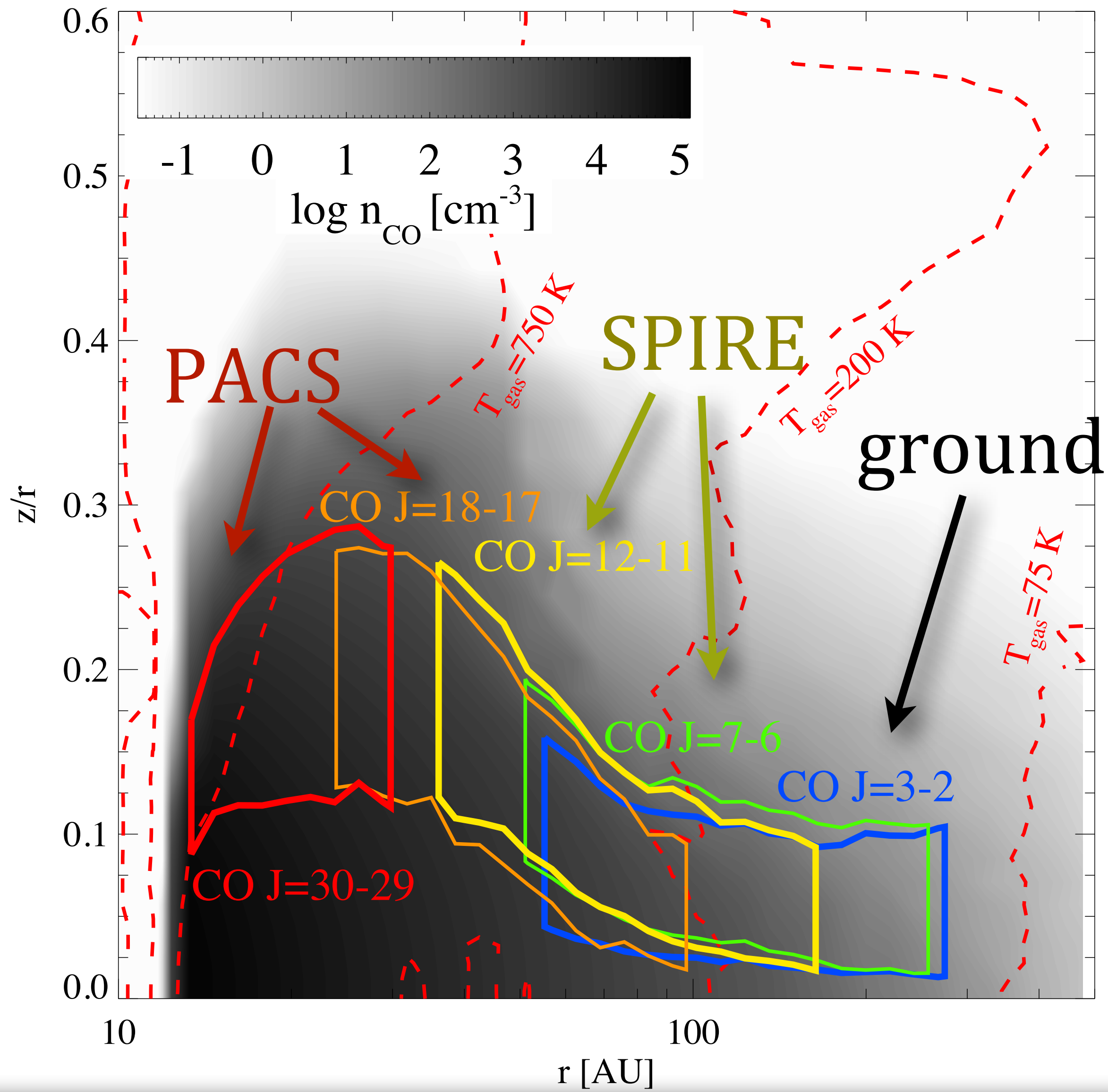
Herschel SPIRE dust continuum SEDs (Van der Wiel+, 2014)



Herschel SPIRE spectral line detections (Van der Wiel+, 2014)



- CO lines in SPIRE band trace upper level energies ~50–500 K, impossible to observe comprehensively from the ground



SPIRE probes warm molecular gas

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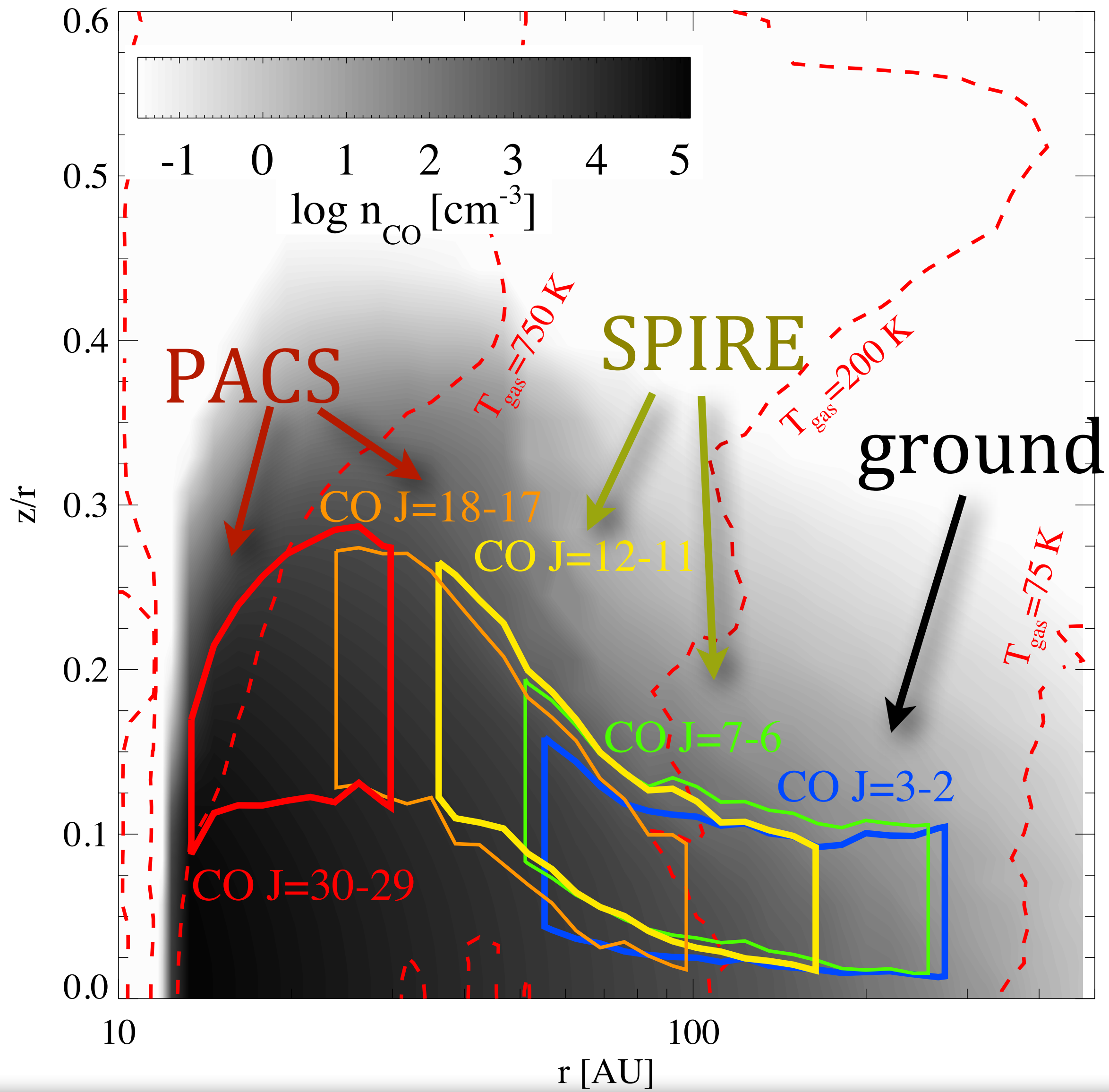

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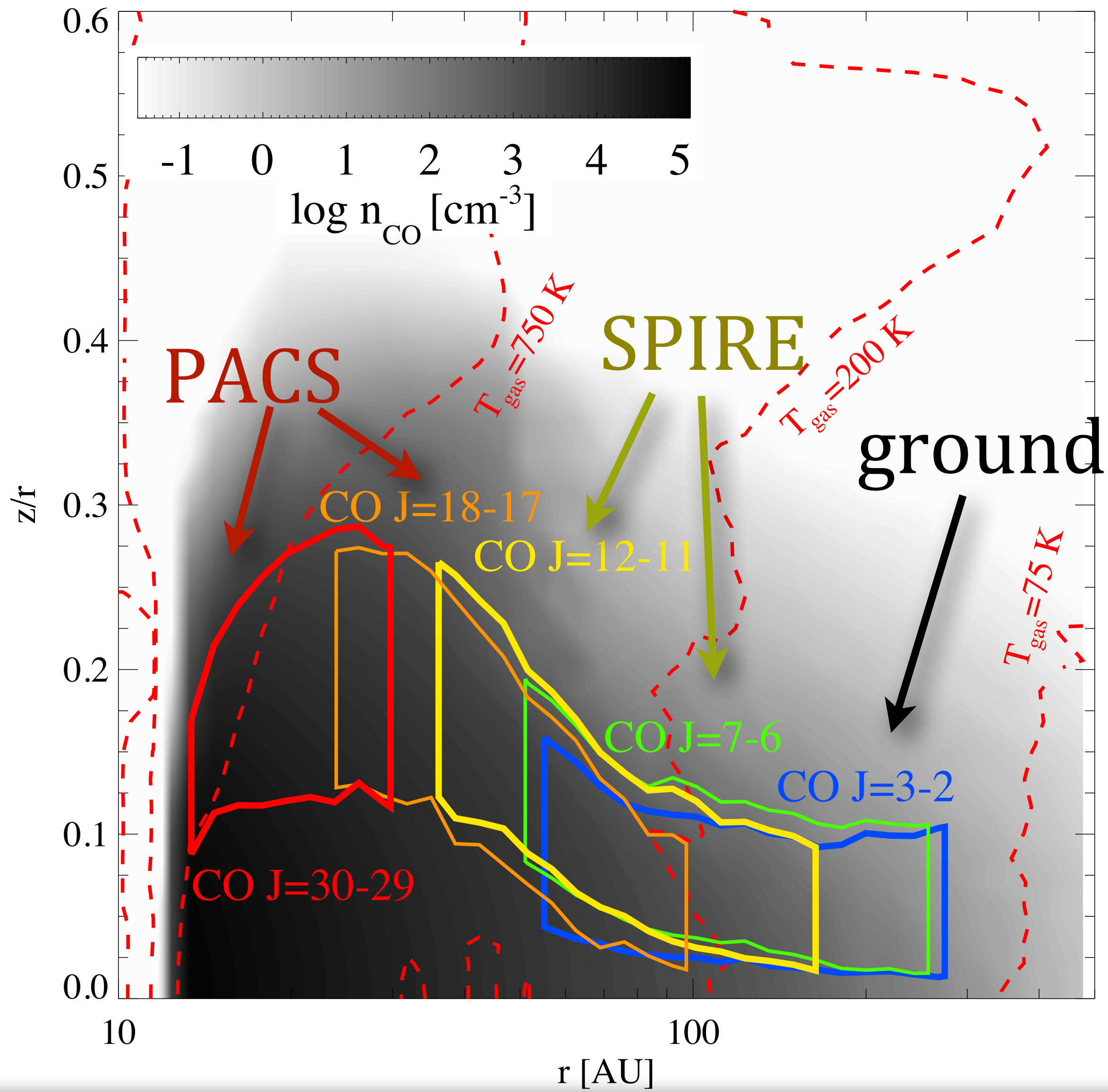
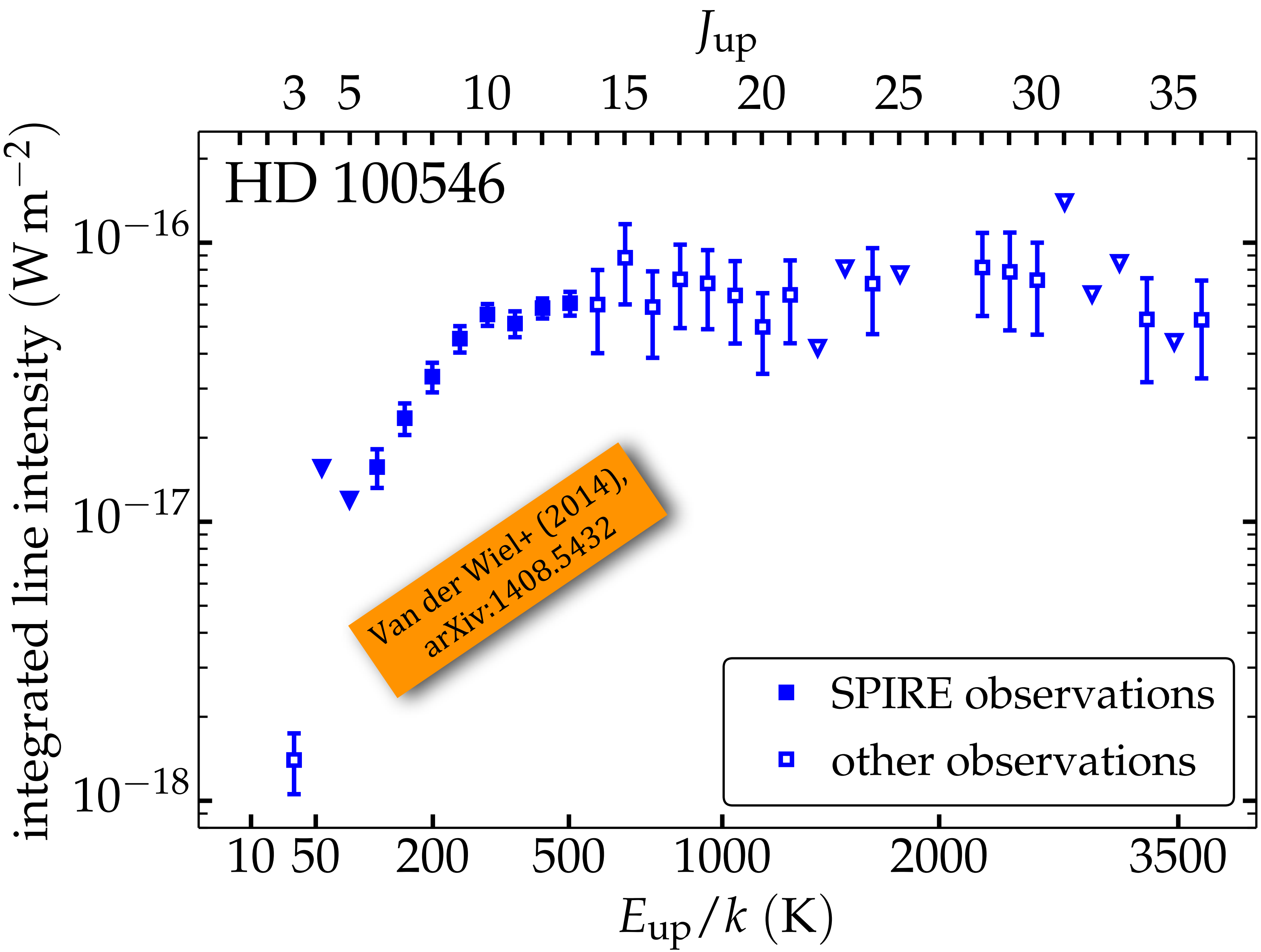
  - ^{13}CO is more optically thin
    ⇒ traces total amount of gas



HD 100546 – CO ladder: observations vs. models



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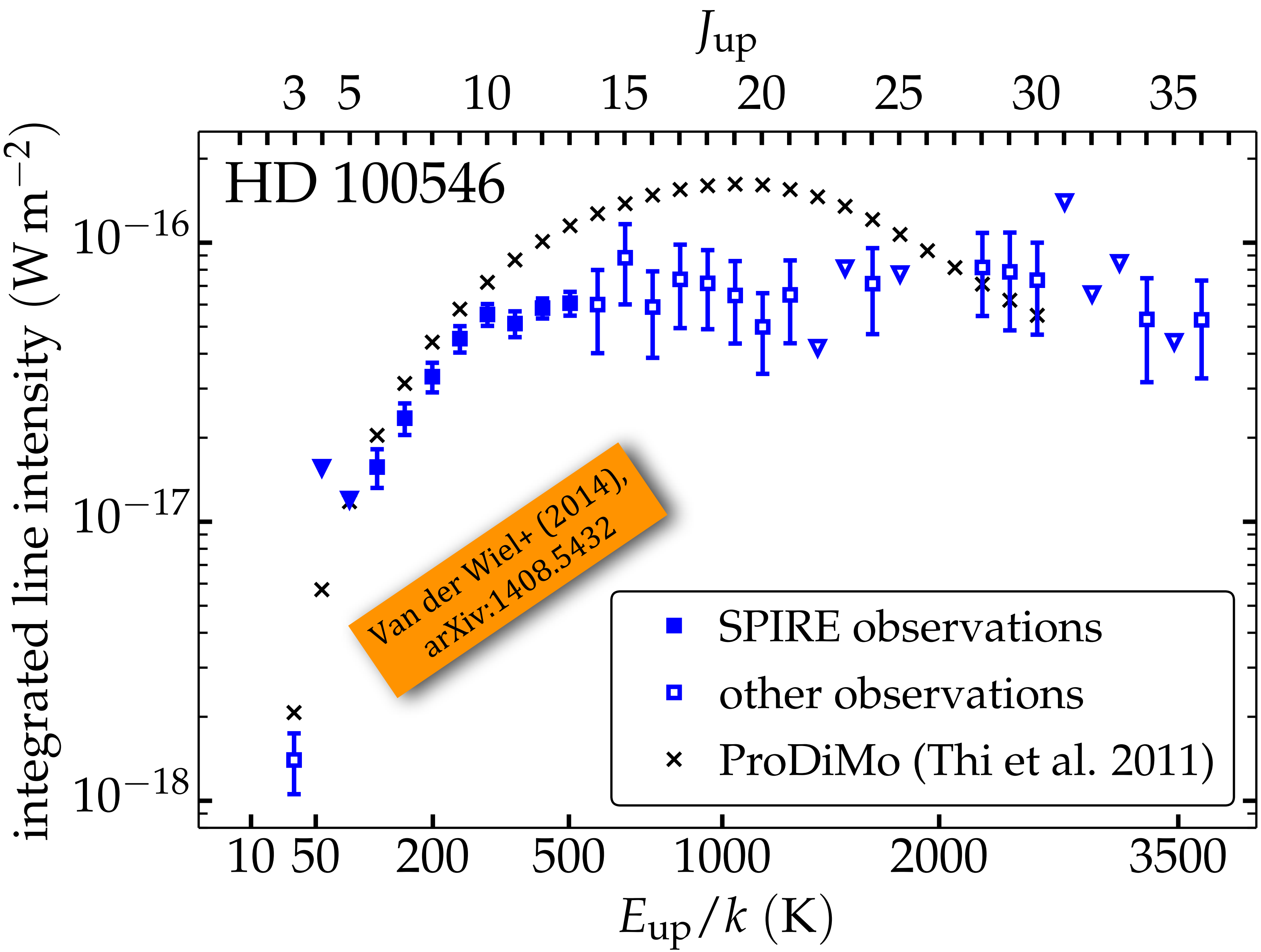

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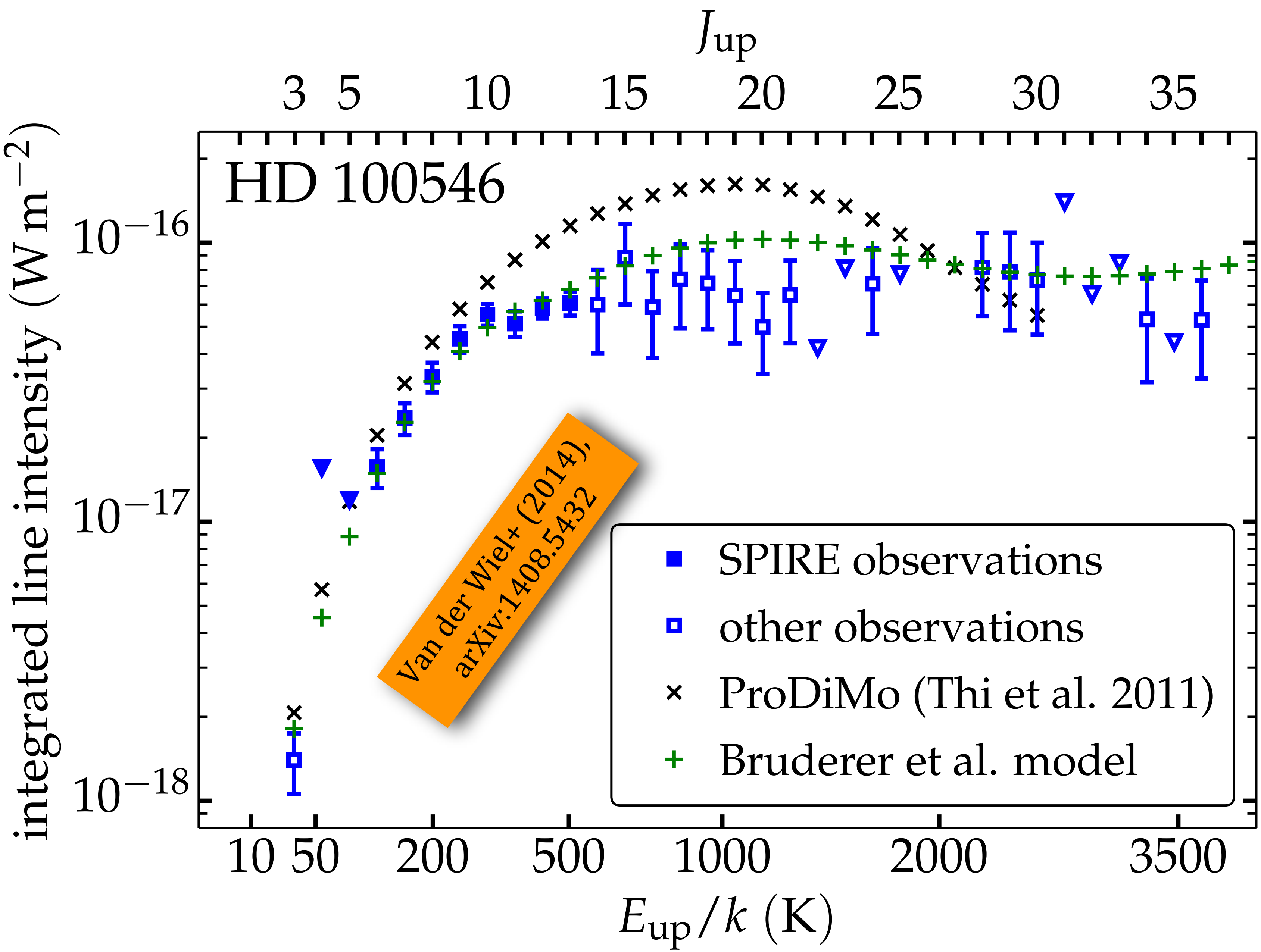
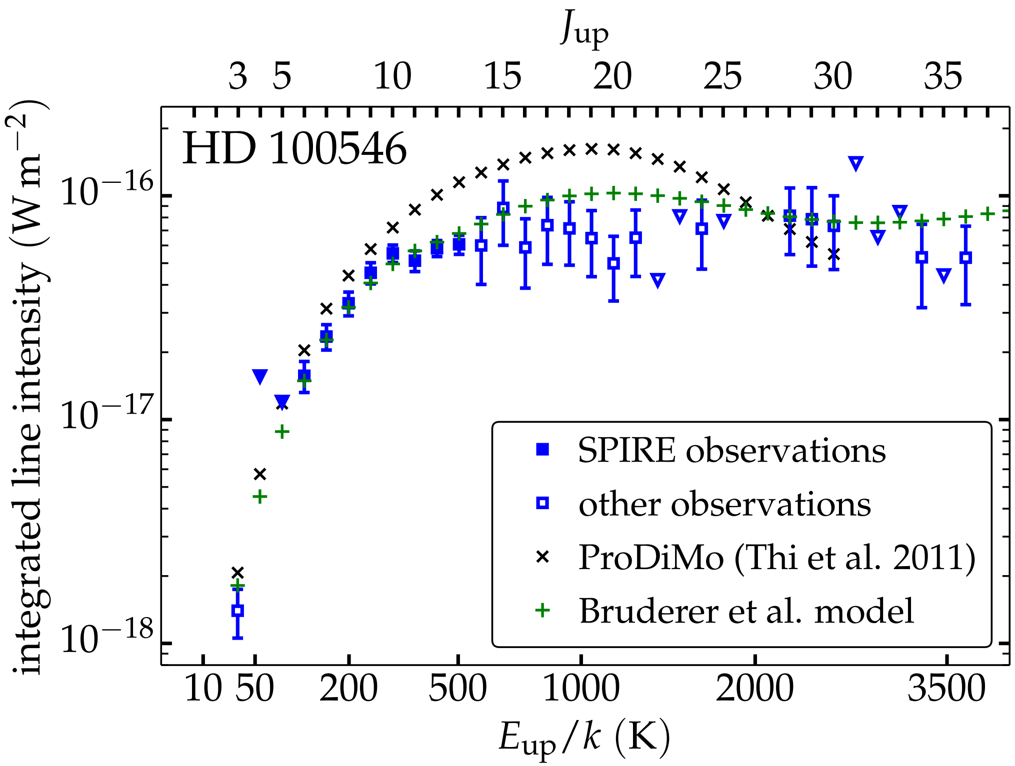
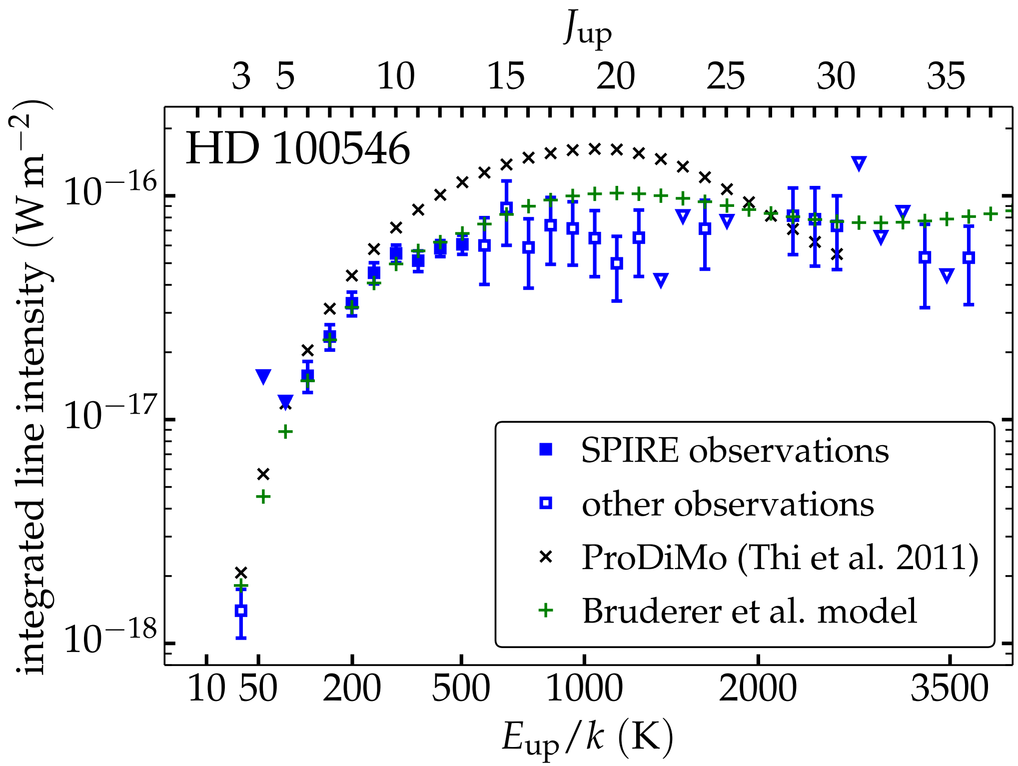


- both models explain observed ^{12}CO ladder, within factor 3



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 (from fit to dust SED)



the case of HD 100546

- for HD 100546, **observed ^{13}CO is >10× stronger than ProDiMo model predicts**
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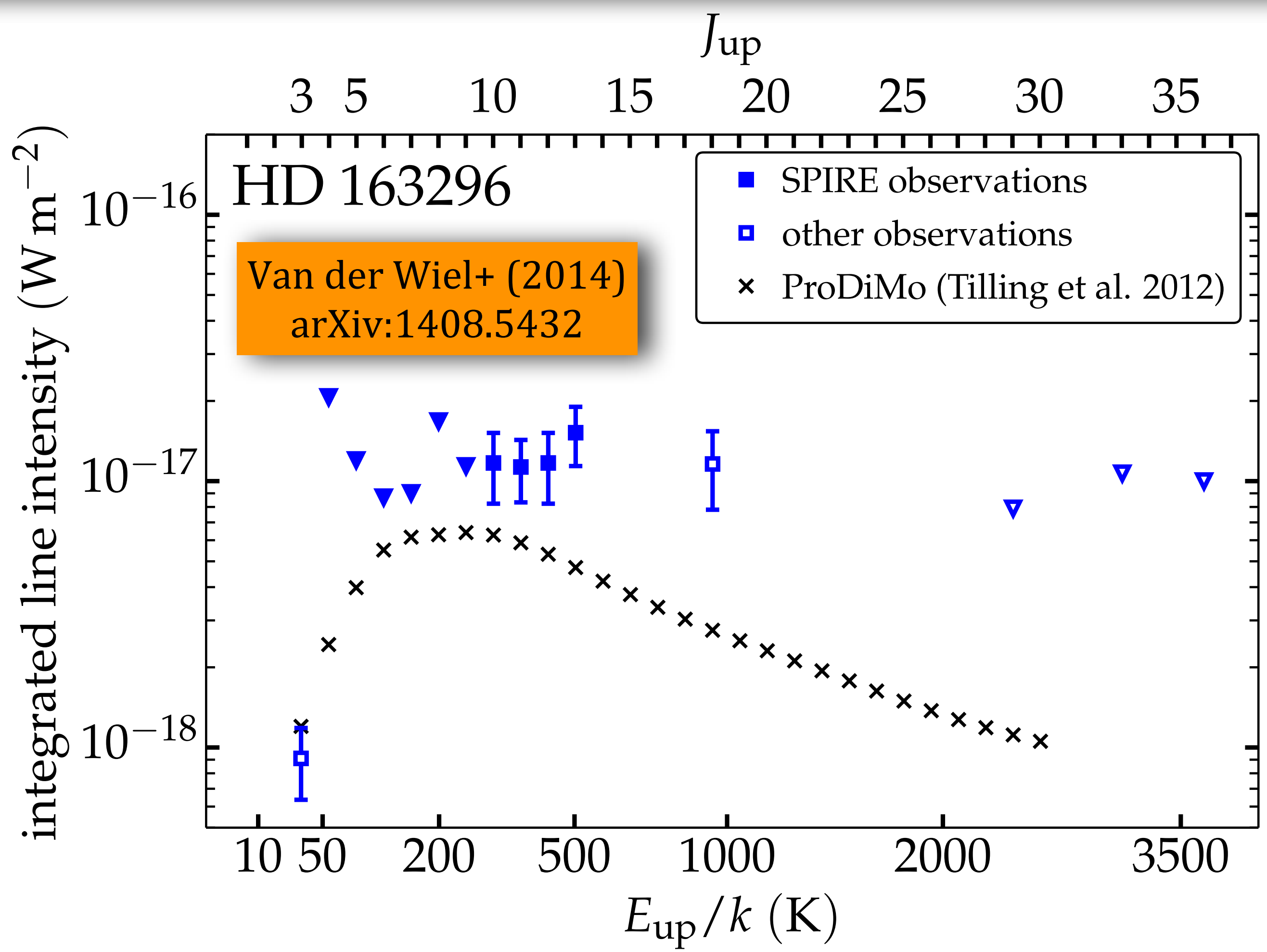
- some ideas to tweak T_{gas} in upper layers of disk:
  - flaring geometry..
  - PAH abundance..
  - dust opacity (UV penetration) ...

the case of HD 163296



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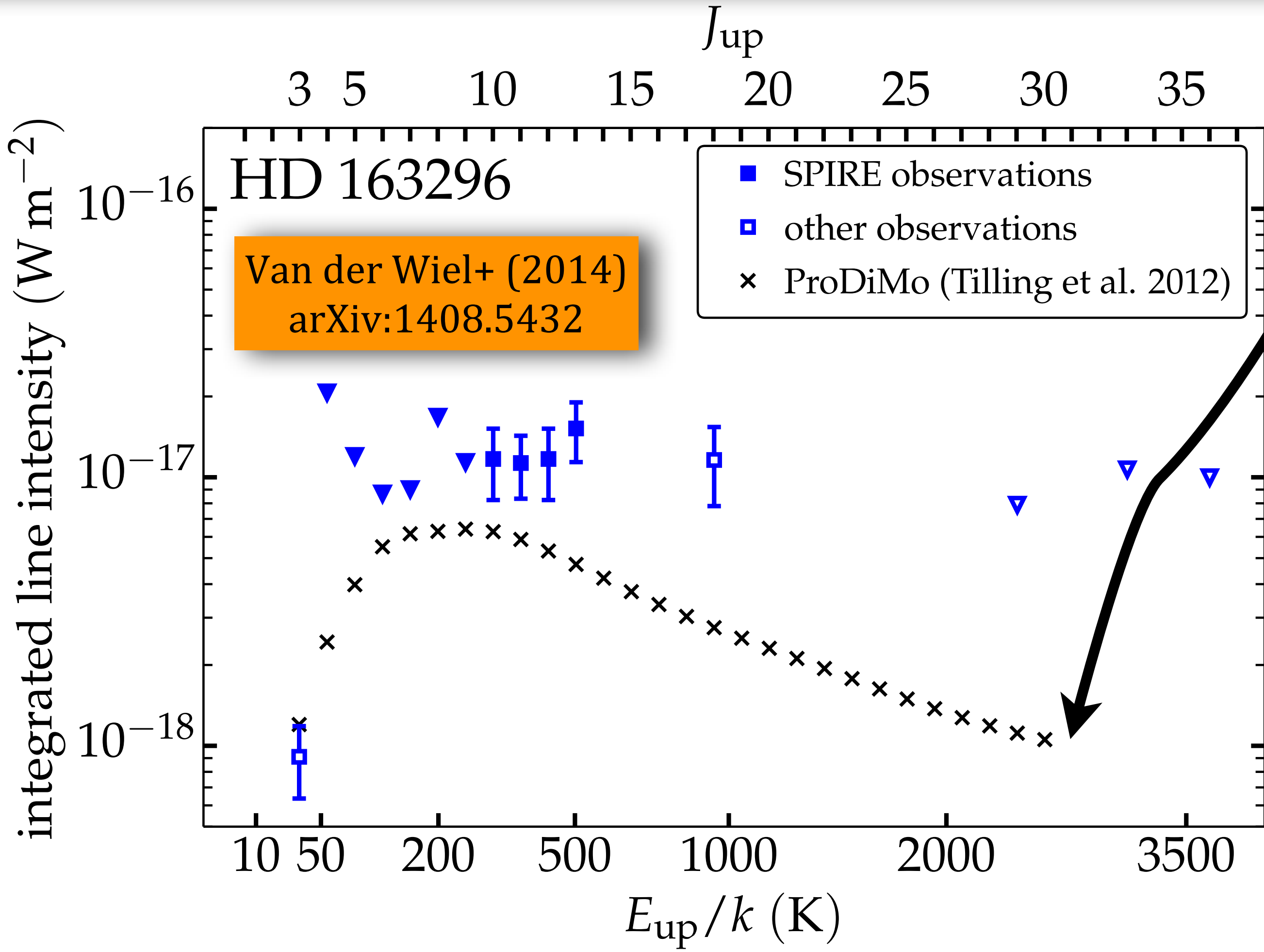

Existing ProDiMo model fails to explain observed mid- to high-*J* CO line strengths.

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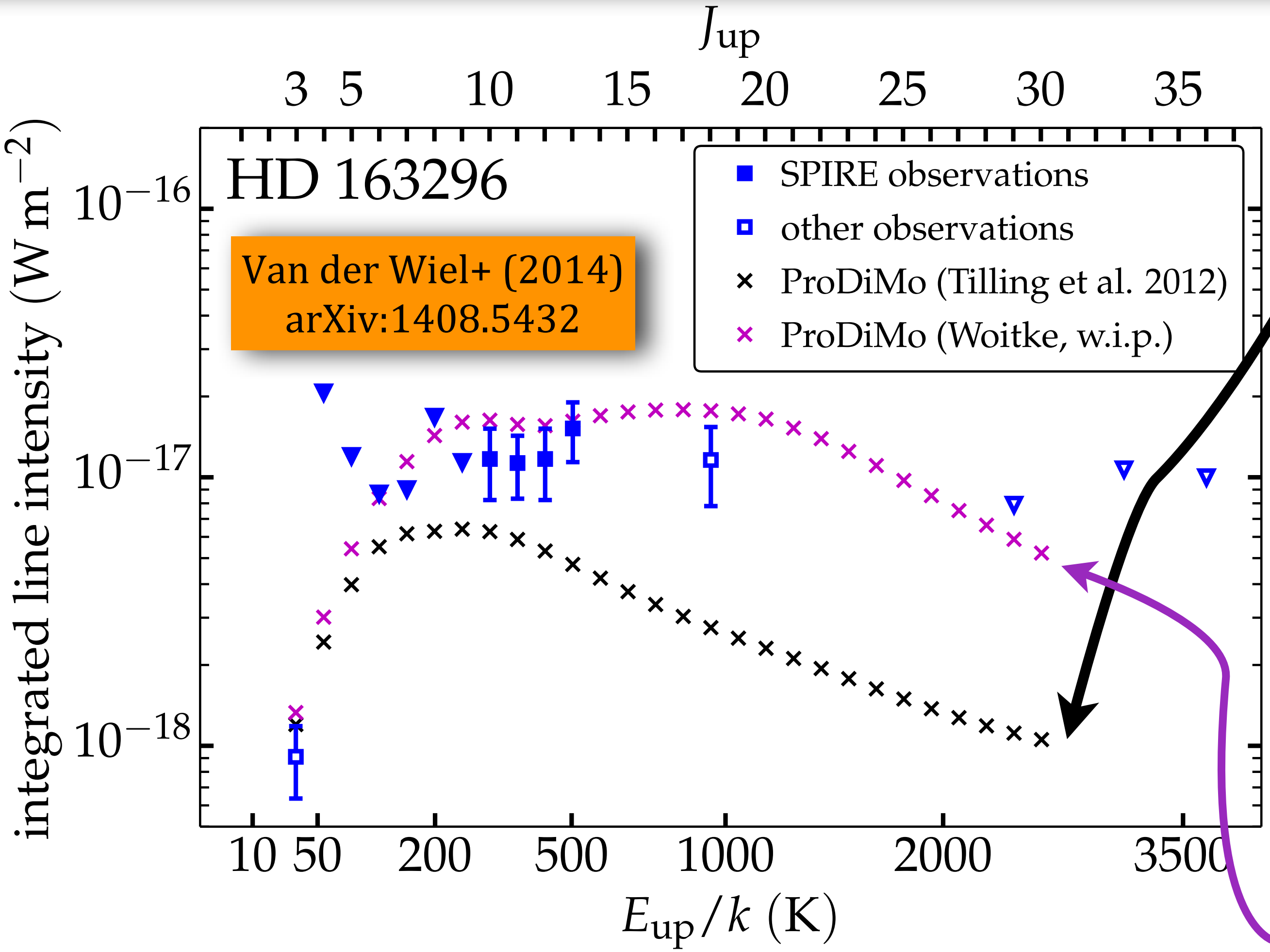

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Based on continuum data, HD 163296 was originally classified as 'flat' (Meeus+ 2001), but recent resolved images strongly suggest flaring in gas disk (De Gregorio-Monsalvo+ 2013).

⇒ increased T_{gas} in upper disk layers ⇒ stronger CO lines
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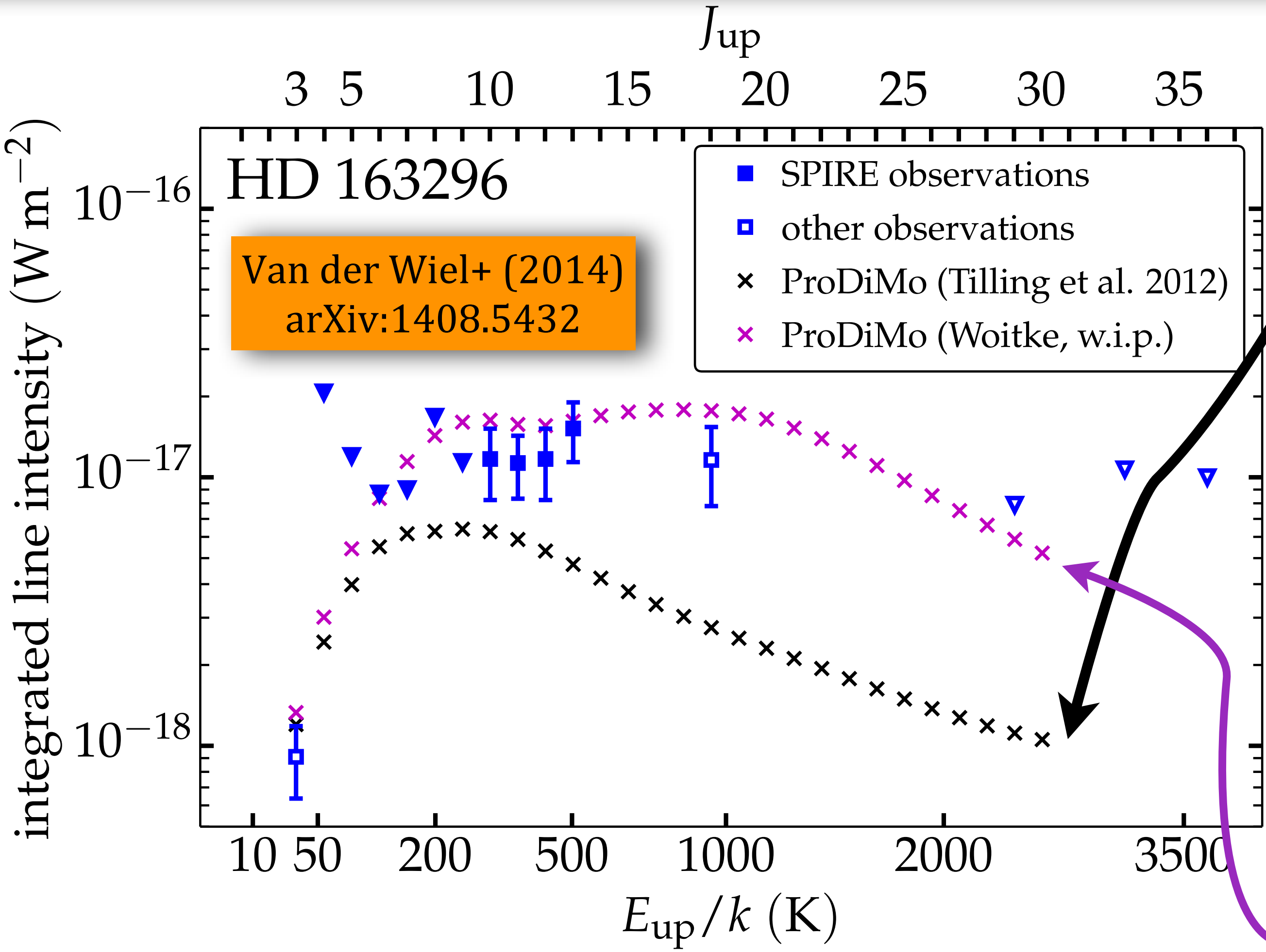

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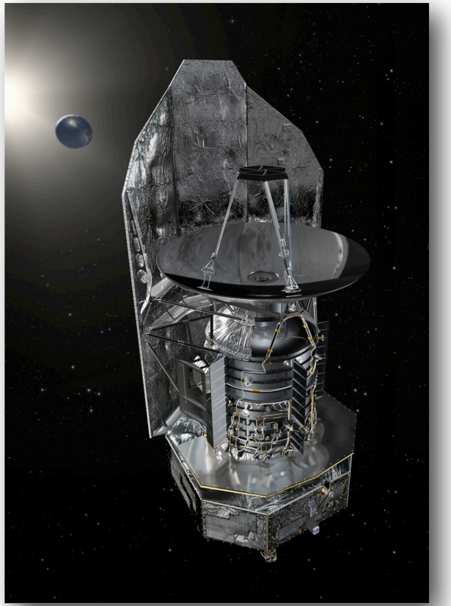
- 'work in progress' model not designed to fit CO ladder *exclusively*
- many other constraints included in optimization of model fit:
  • spectral lines of e.g., H_2O, [OI]; • dust SED; • image profile;
  • ALMA CO spatial and velocity profile; • CO scale height at 150 AU; ...

[CI] line at 809 GHz (370 μm) toward HD 100546

APEX, ground, Nov 2008
upper limit <0.85 10^{-18} W m^{-2}
(Panić+ 2010)
high calibration uncertainties

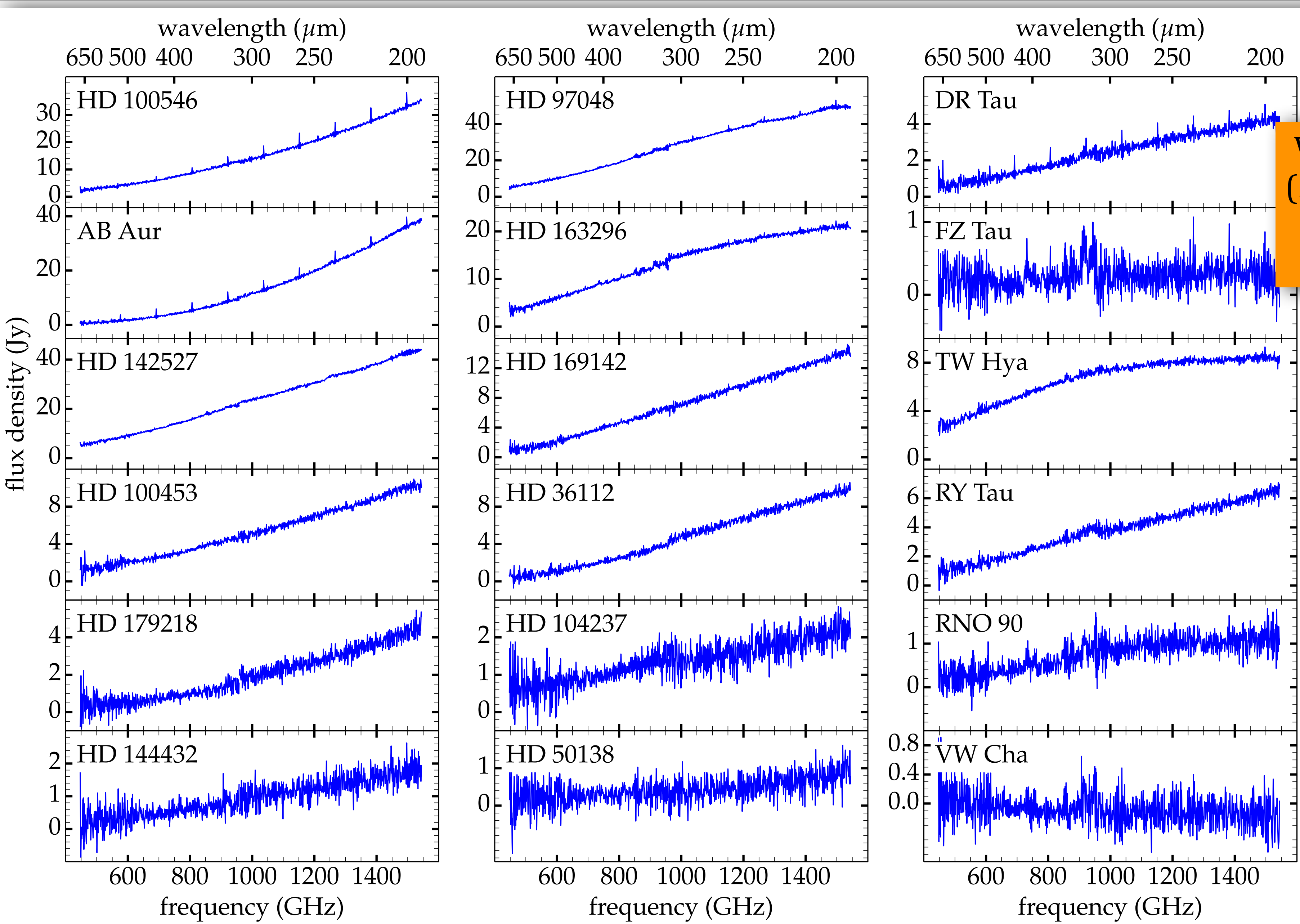
≠

Herschel SPIRE, space, Aug 2010
detection: (7.6±3) 10^{-18} W m^{-2}
(Van der Wiel+ 2014)
spectrally unresolved



- above two measurements are inconsistent!
  - for both, diffuse background is subtracted
  - SPIRE measurement:
    better absolute calibration, but kinematical origin unknown
- new, deeper observations with APEX will have the final word;
  *see next talk by **Mihkel Kama***
- if SPIRE measurement is confirmed, this may mitigate discrepancies with [CI] flux predicted by existing model descriptions

summary and conclusion



Van der Wiel+ (2014, MNRAS) arXiv: 1408.5432

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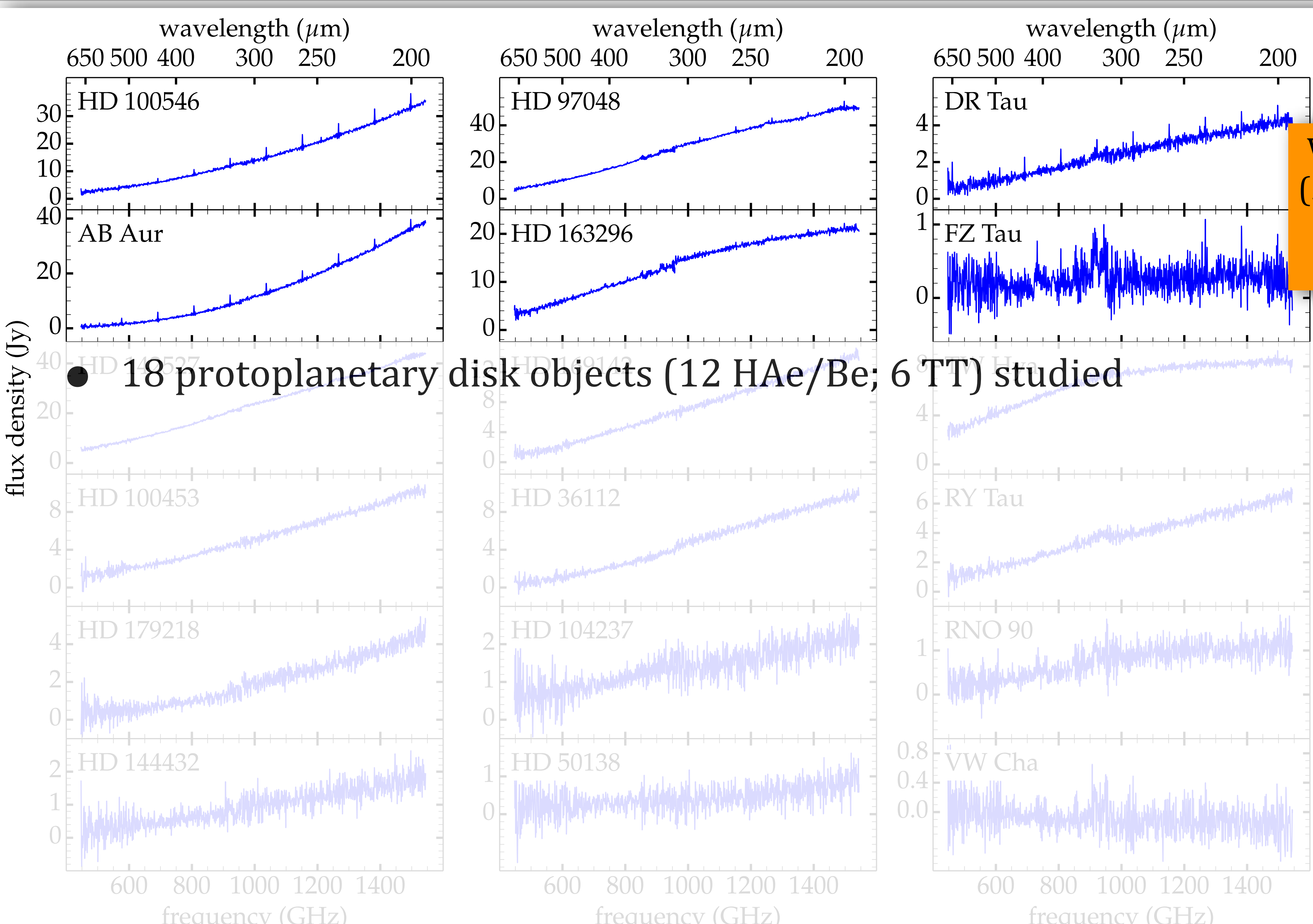

- 18 protoplanetary disk objects (12 HAe/Be; 6 TT) studied

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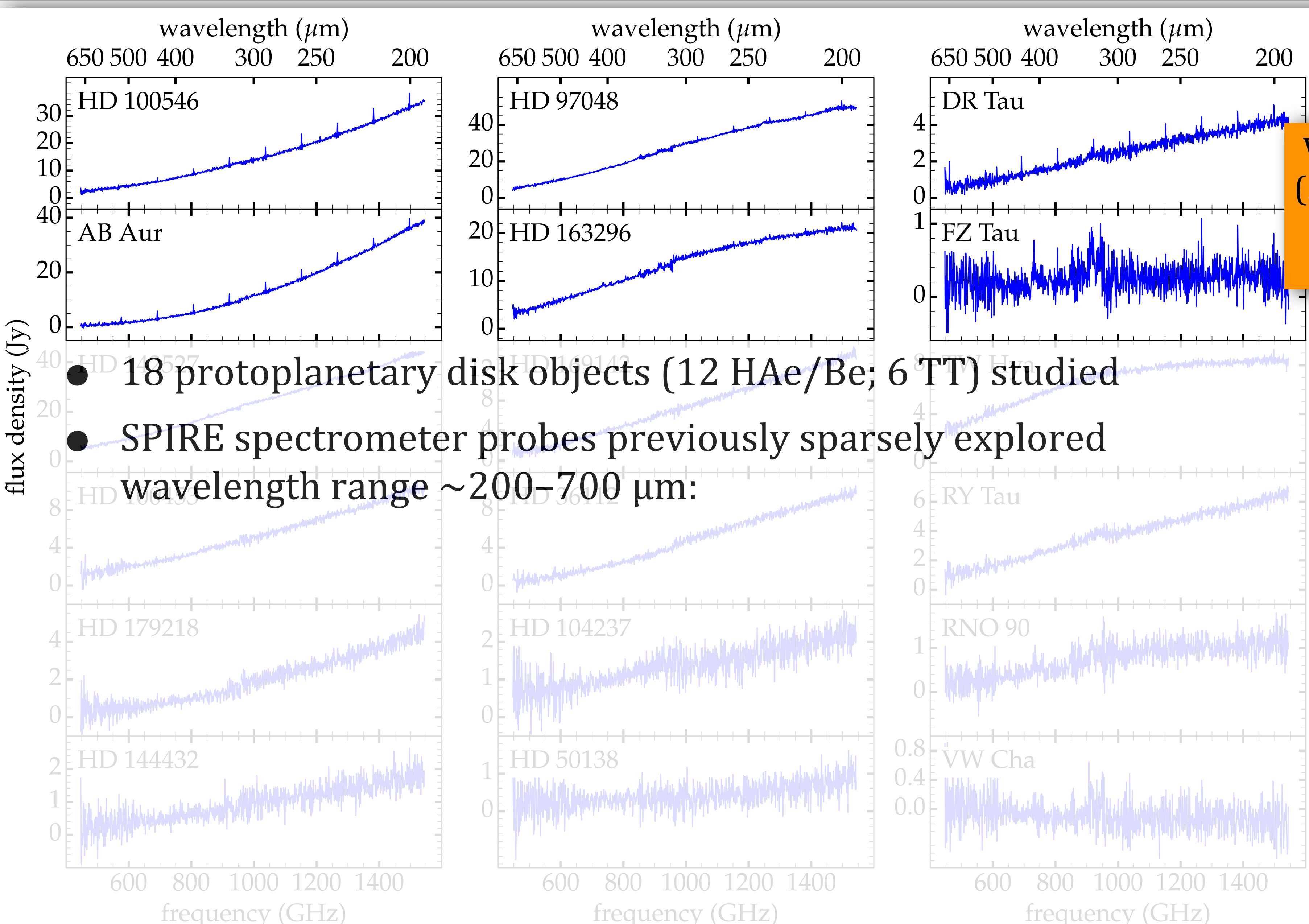

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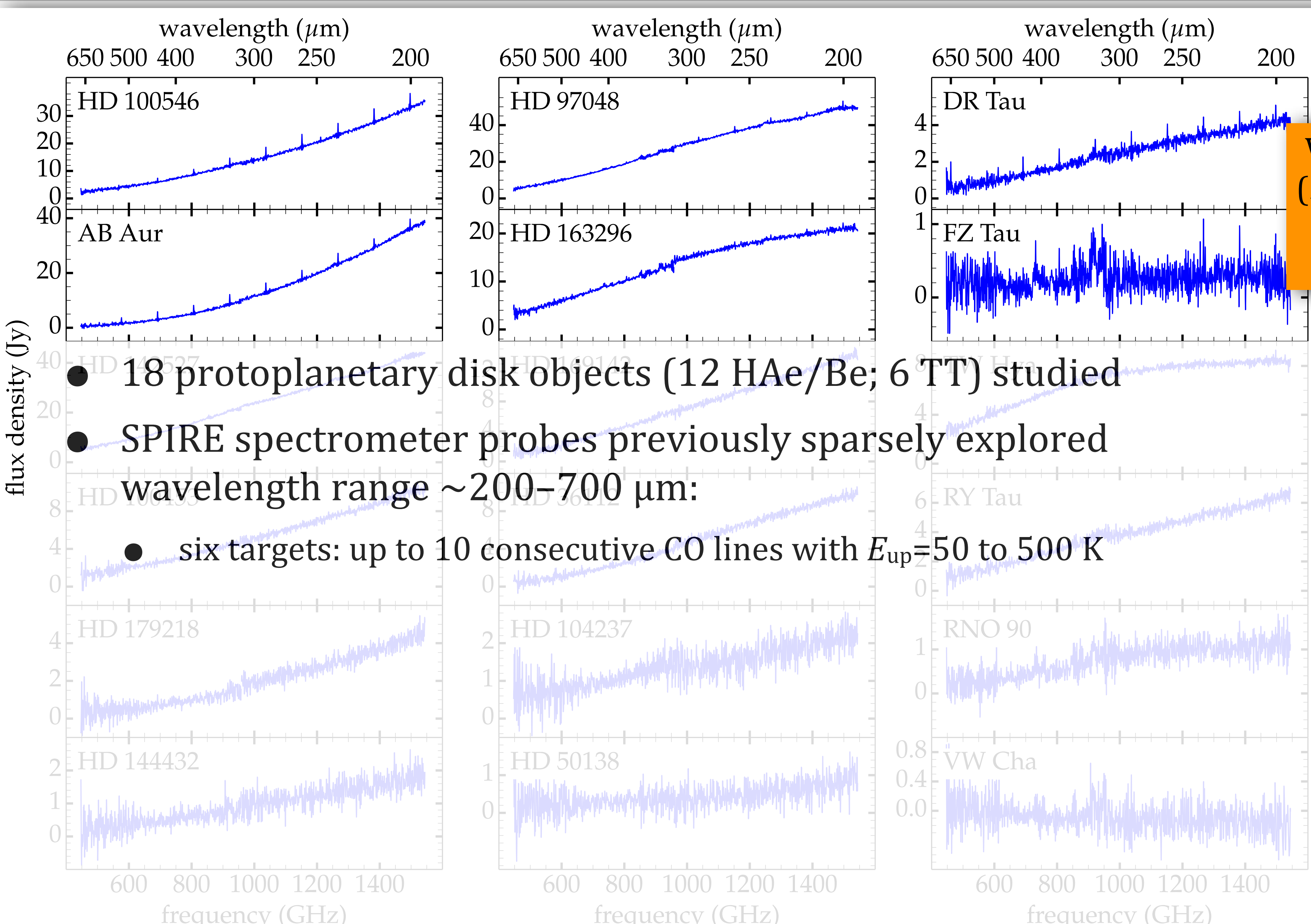

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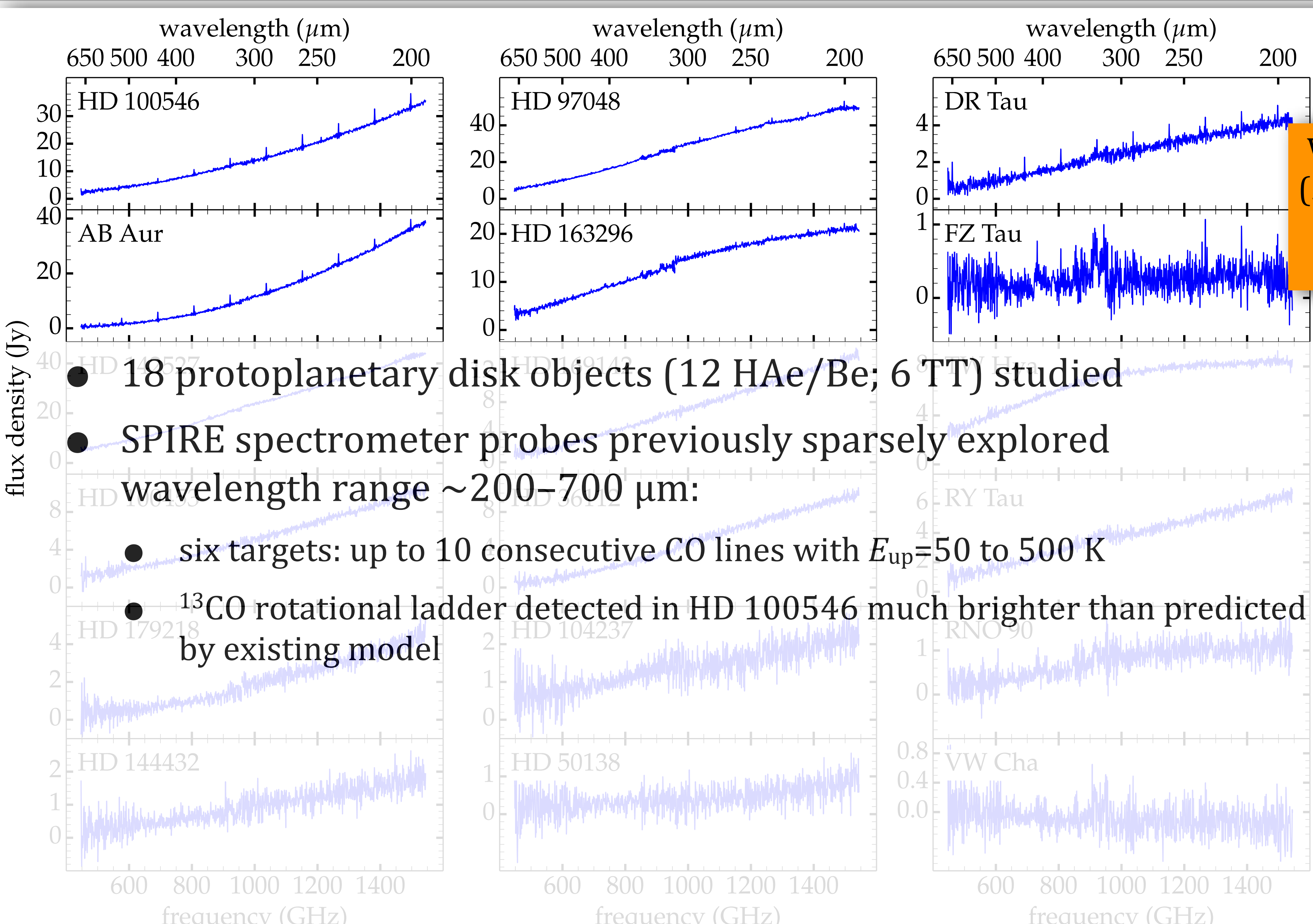

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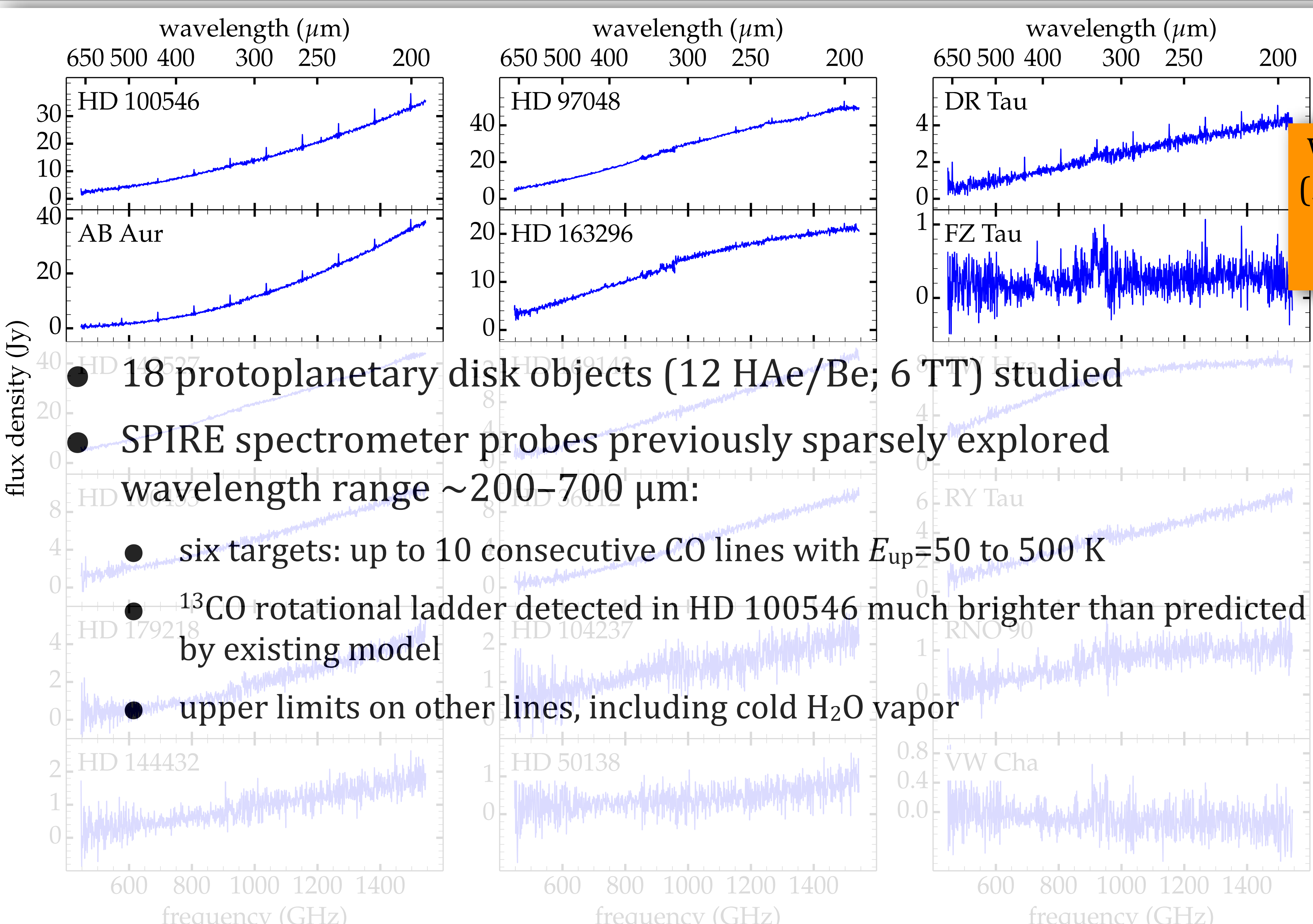

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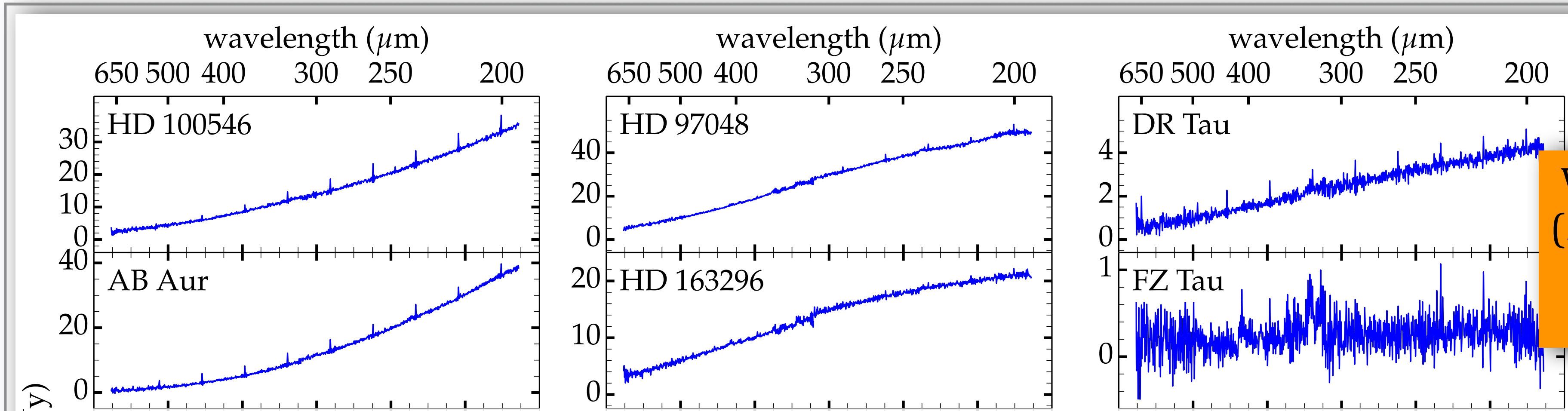

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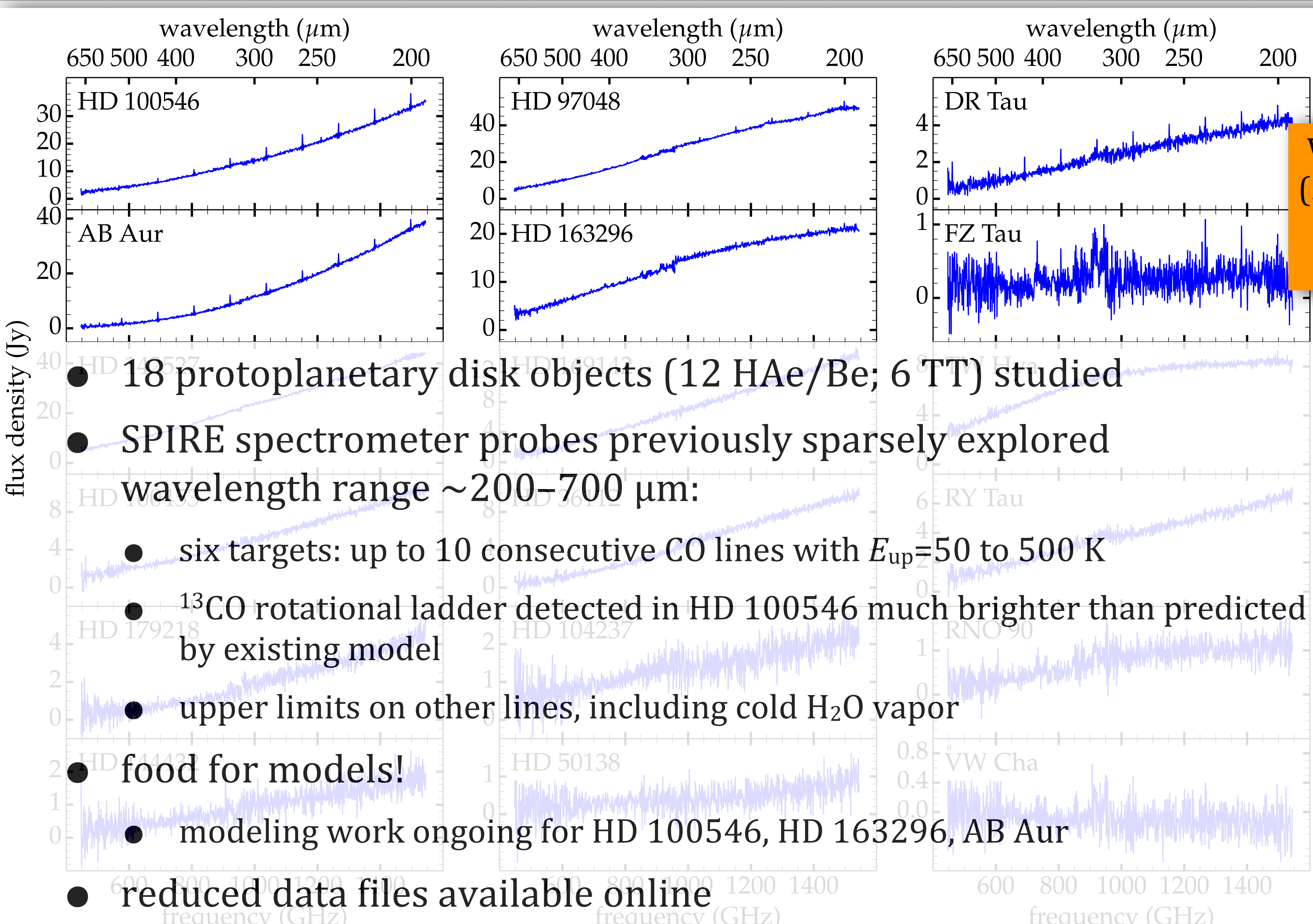

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- reduced data files available online

thank you

This work is supported by CSA, NSERC and the EU FP-7 programme.

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