Warm gas atmospheres of the protoplanetary disks seen by Herschel

Super-heated, gas rich and carbon poor?

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Outlook

- Thermo-chemical models of protoplanetary disk atmospheres
- Application on a prototypical disk, HD 100546
- Studying the dependence on input parameters
- Volatile carbon?

Thermo-chemical models

- Model the heating and cooling of the gas self-consistently with the chemistry (similar to PDR models)
- Use a new package of codes, based on Bruderer et al. 2009a,b, 2010, 2012 and benchmarked with various test problems.
- *Input*
  - Physical structure (density)
  - Stellar spectrum
  - Molecular data (e.g. chemical reaction rates)
  - Dust properties
  - Distance, inclination

  Output
  - Gas/dust temperatures (depending on position)
  - Chemical abundances (depending on position)
  - Molecular excitation (depending on position)
  - Line/continuum fluxes

goal: *simulated observations to compare with Herschel data*

Modeling flowchart

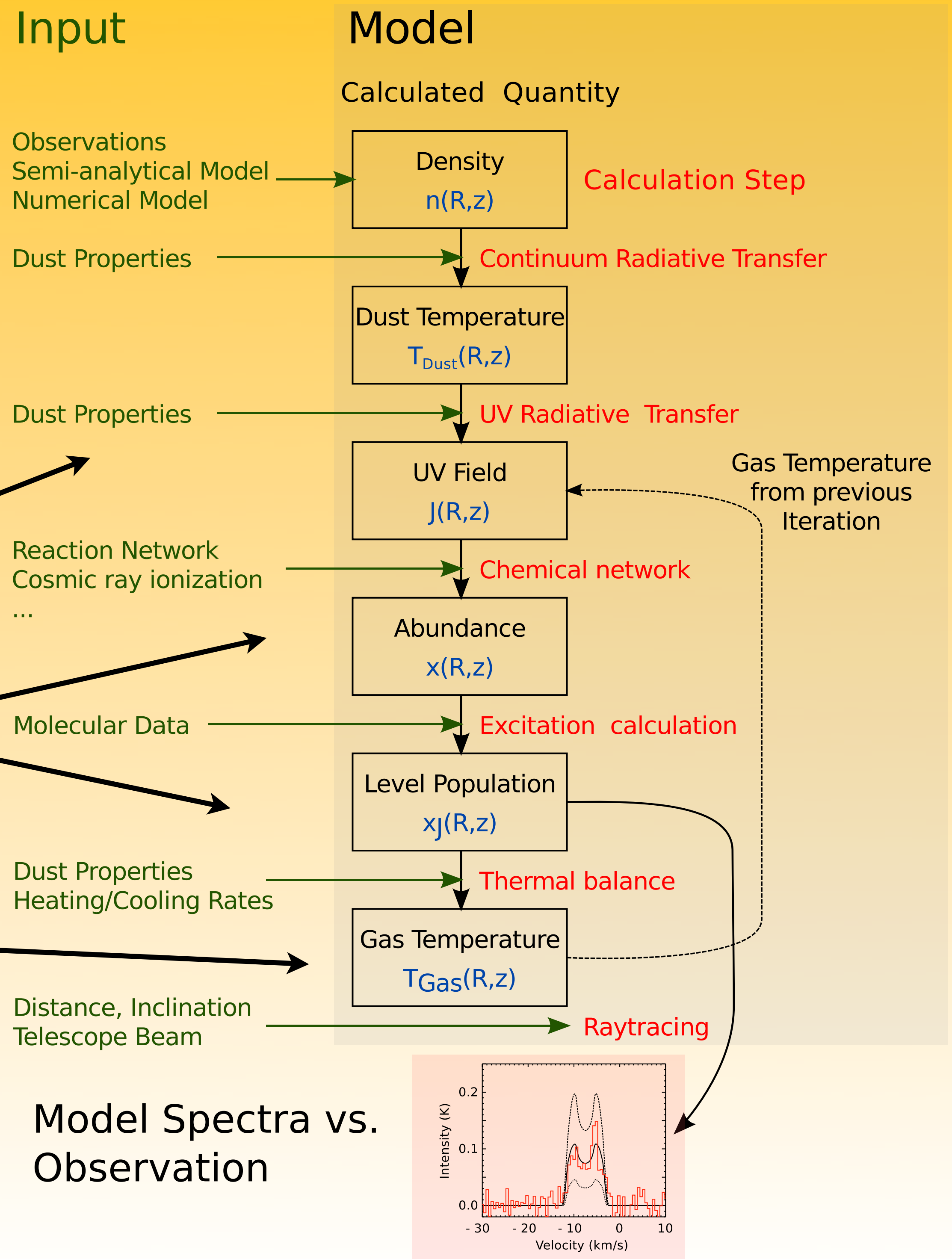
1.) provide a density structure

2.) calculate the dust radiative transfer for T_{dust} and local (continuum) radiation field

3.) calculate chemistry and molecular excitation

4.) calculate balance between heating and cooling rates and iterate over 2, 3 and 4

5.) do raytracing to obtain spectral cubes



HD 100546

- well-known, nearby (~ 100 pc) Herbig Be
- 13 AU inner hole: Planet formation?
- Well observed from X-ray to radio, in lines and continuum

NASA/JPL-Caltech artist's concept

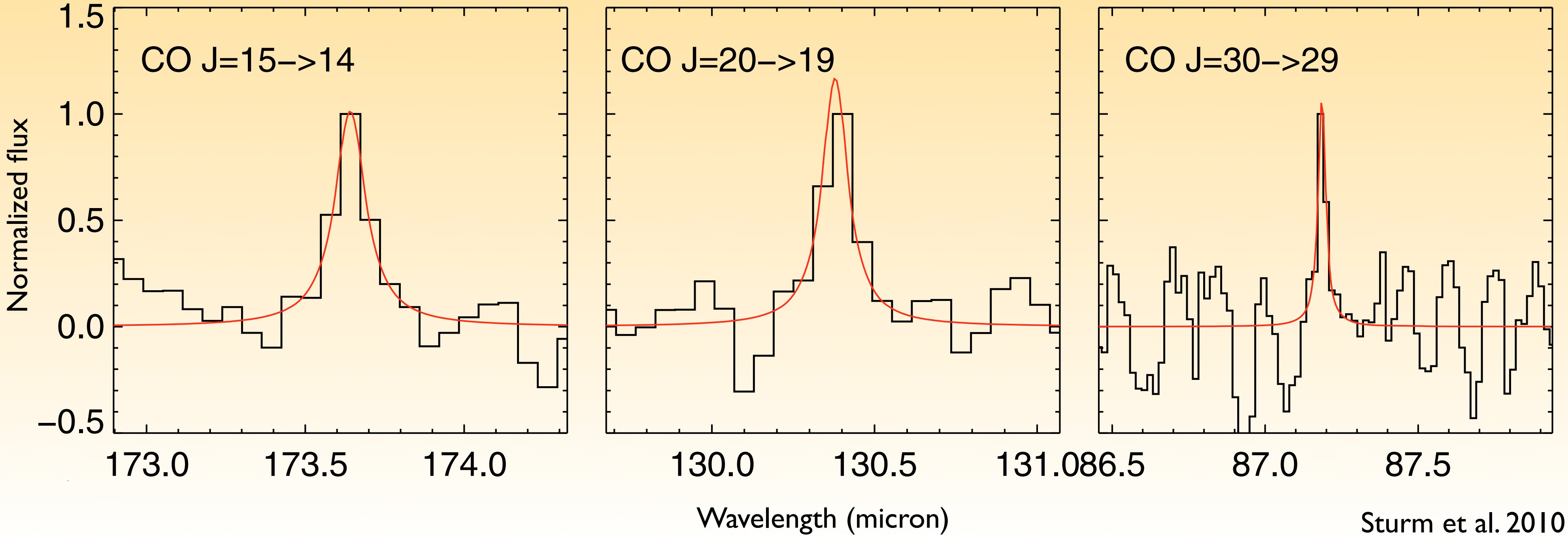
- SED fitting allows determination of dust density structure (Mulders et al. 2011)
- All main carbon bearing species observed: What happens to carbon? Bound in grains? Volatile?

HD 100546

- **Herschel-PACS** observations (Sturm et al. 2010)

  DIGIT open time key program (PI N. Evans)

  Detect e.g. CO (J_{up} ~ 14 to 31), [OI] 63, 145 μm and [CII] 158 μm



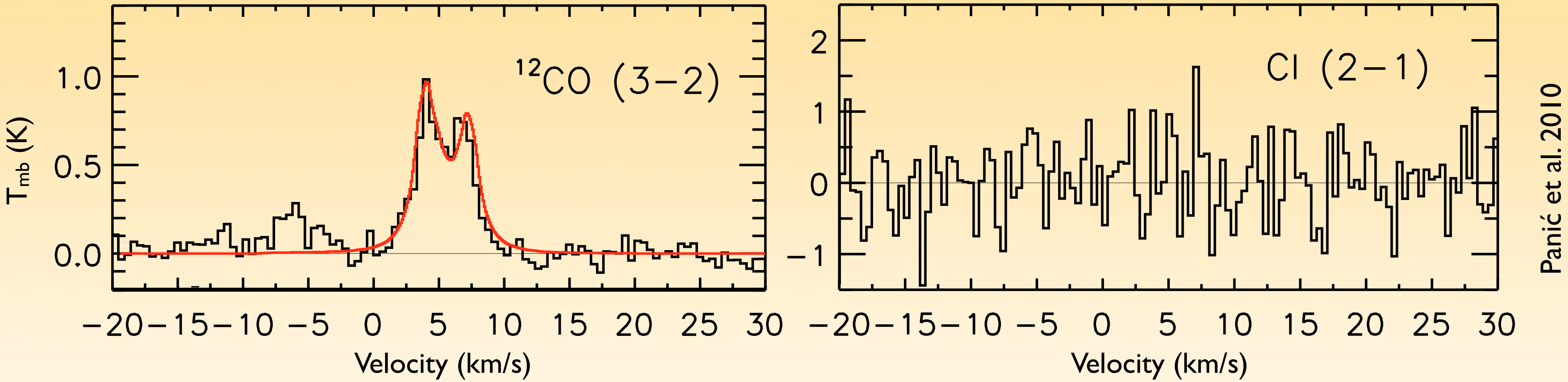
Sturm et al. 2010

HD 100546

- **APEX** observations (Panić et al. 2010)

  Detect CO (J_{up} = 3, 6 and 7)

  upper limits on [CI] 370 μm



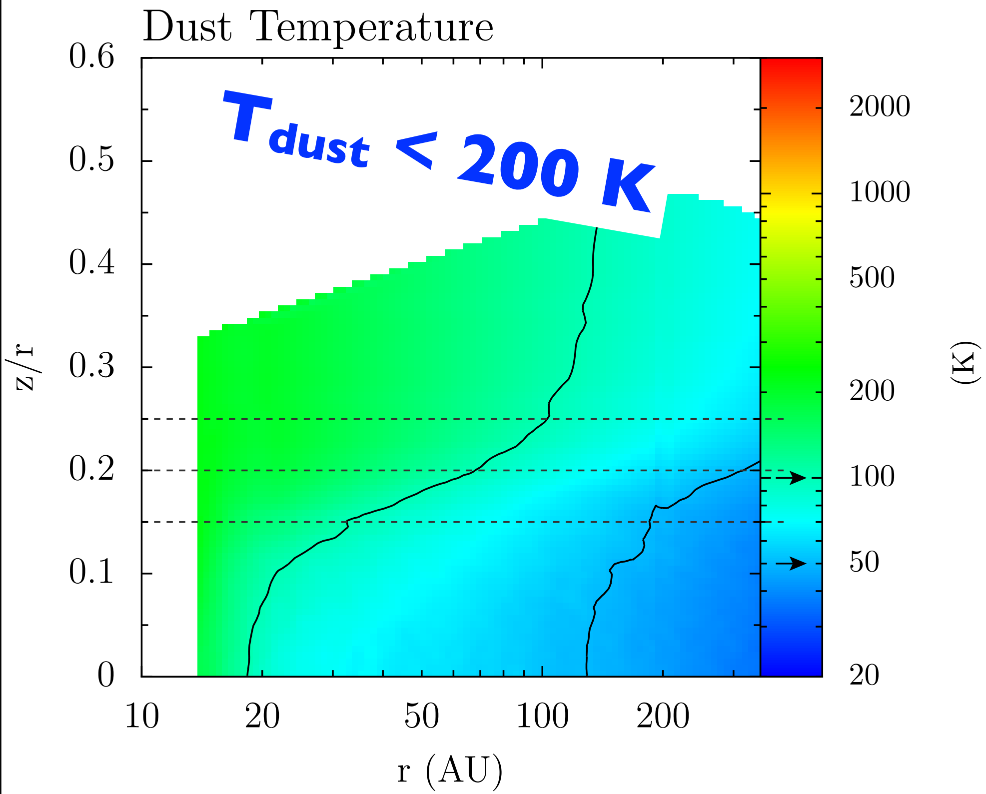
Non-detection of [CI] is a general trend beyond HD100546 (Hogerheijde & van Dishoeck, in prep.)

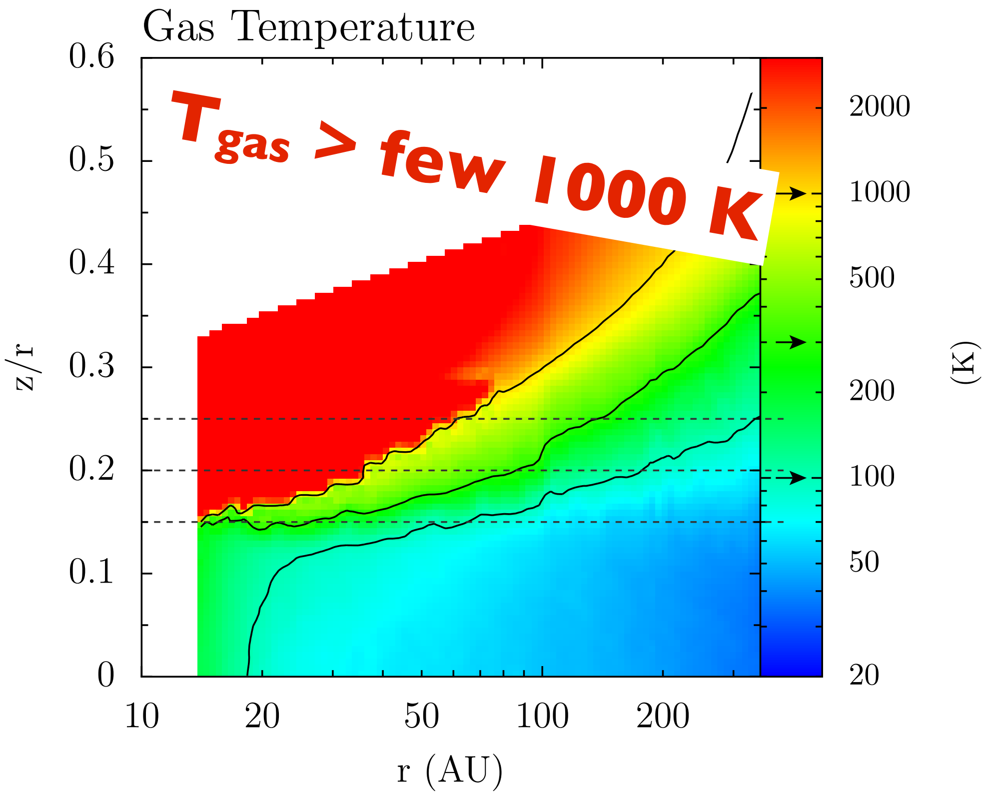
Questions

- What do high-J lines of CO tell about the disk atmosphere?
- All major inputs given from direct observations: Do the models reproduce the lines?
- Where does the emission come from?
- [CI] not detected, but predicted to be strong by previous models (e.g. Jonkheid et al. 2007): What does this mean?
- What can we say about the carbon budget in the outer disk, the material that somewhen ends up in the inner disk?

Super-heated, gas rich and carbon poor?

The warm atmosphere



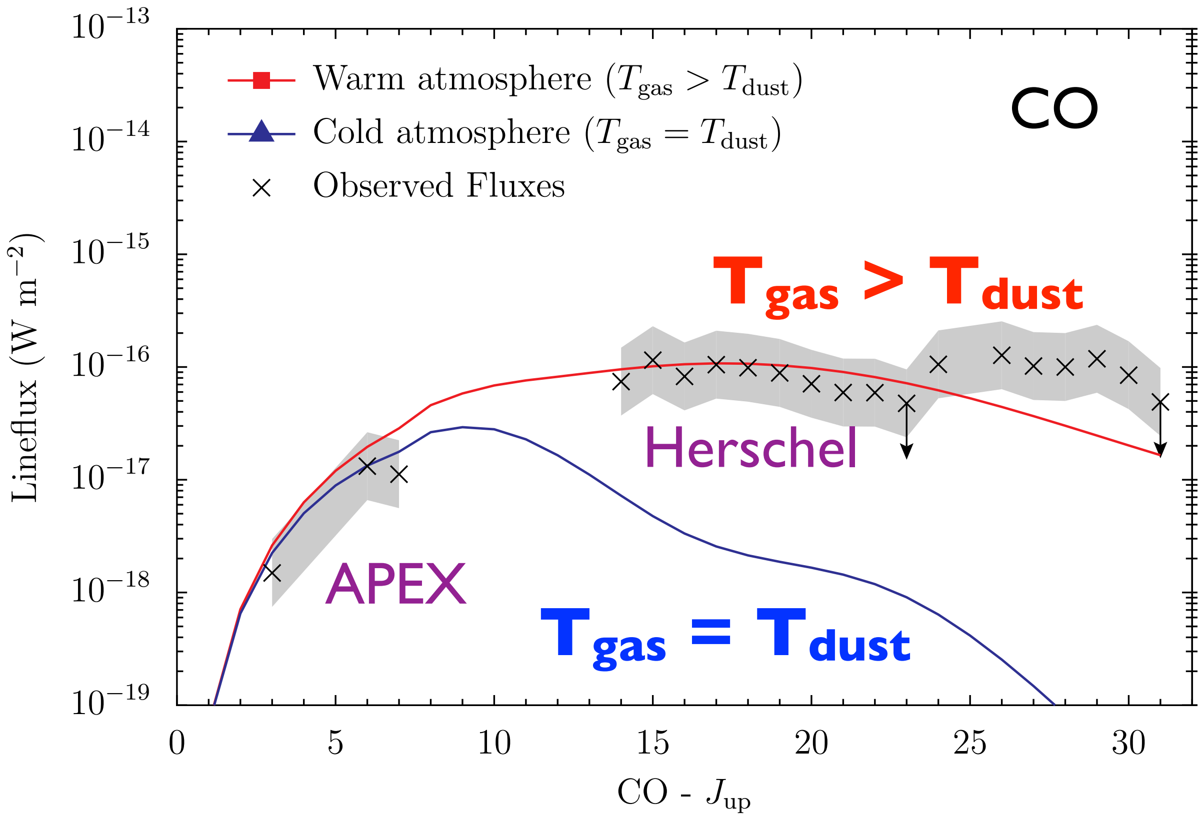


Balance between heating/cooling gives $T_{gas} > T_{dust}$

(also in e.g. Kamp & van Zadelhoff 2001, Jonkheid et al. 2004, Nomura & Millar 2005, Gorti & Hollenbach 2008, Woitke et al. 2009, Woods & Willacy 2009, Ercolano et al. 2009)

Photoelectric heating on grains/PAHs, H_2 pumping and other heating processes versus gas-grain accommodation, line cooling ([OI], [CII], CO, ^{13}CO, OH, H_2O,...) and other cooling processes.

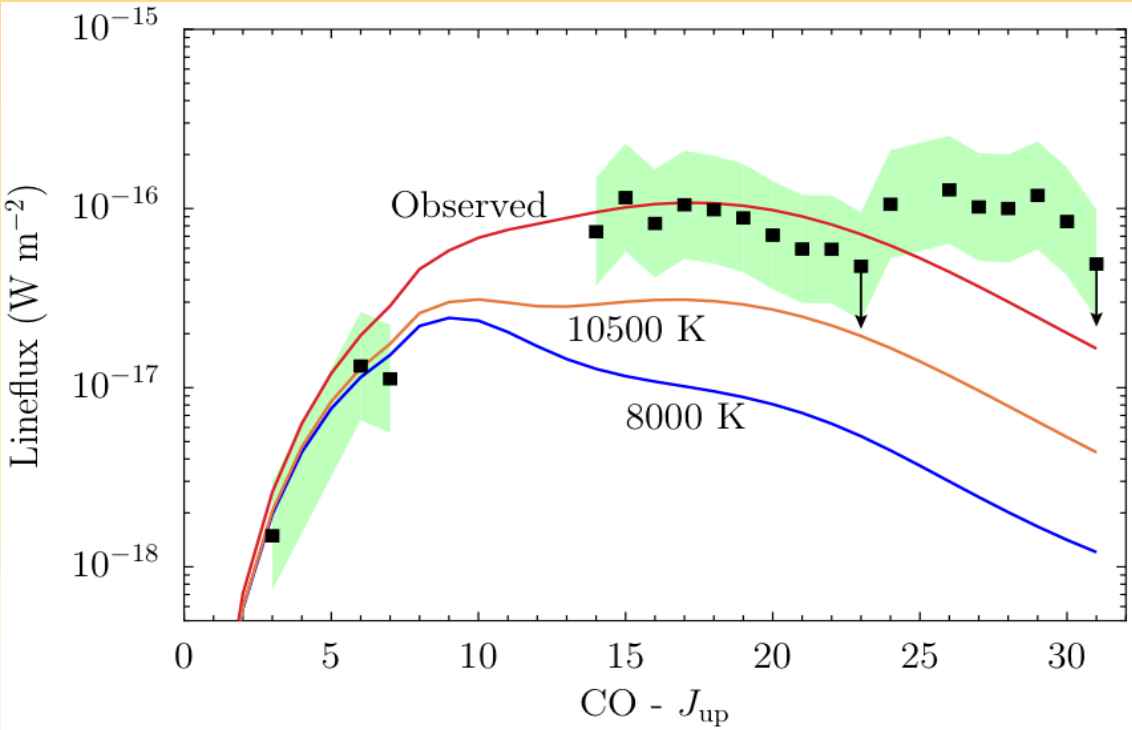
The warm atmosphere



Warm atmosphere with $T_{gas} > T_{dust}$ necessary to explain both high-J CO and [OI]

Dependence on parameters?

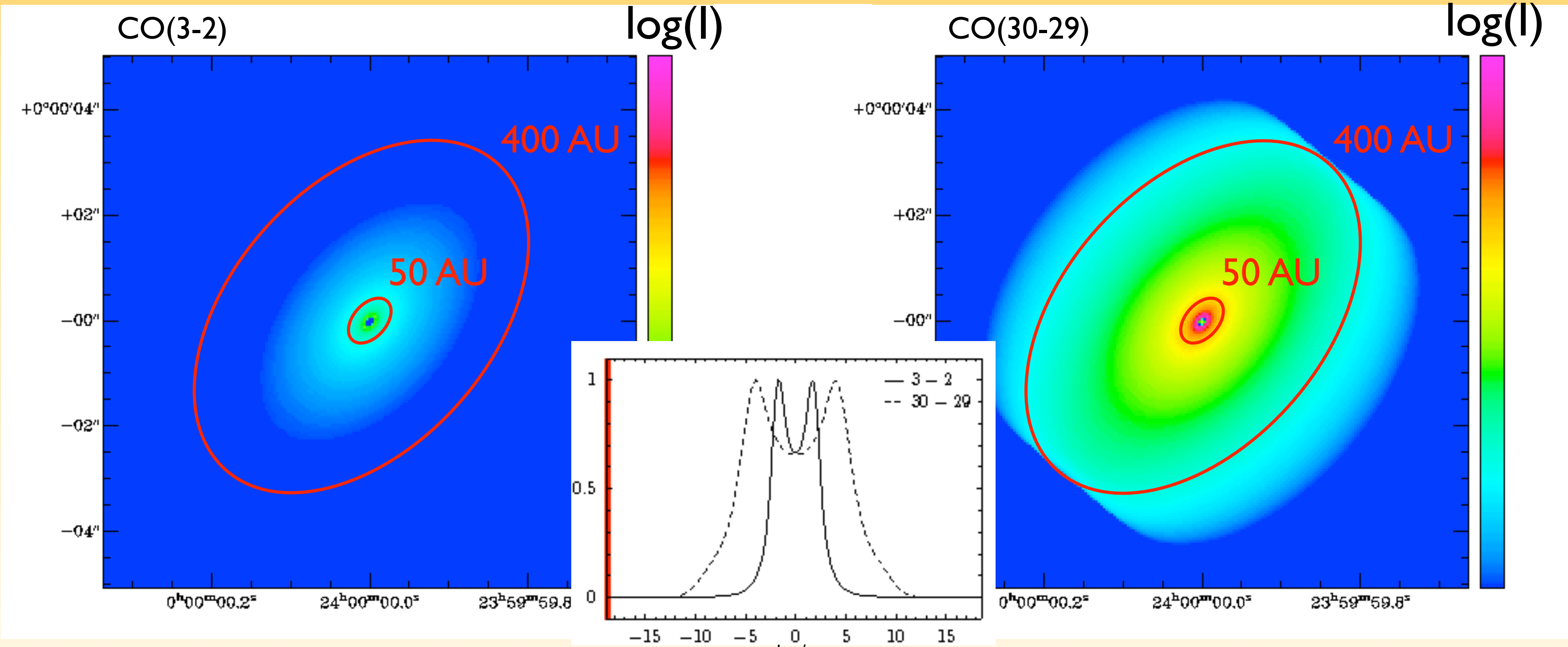
- Example: Different input (stellar) radiation fields
- Others parameters, like the PAH abundance: see arXiv:1201.4860



Cooler radiation field: Less CO dissociation, more efficient cooling, lower T_{gas} and thus less high-J CO

Where does the emission come from?

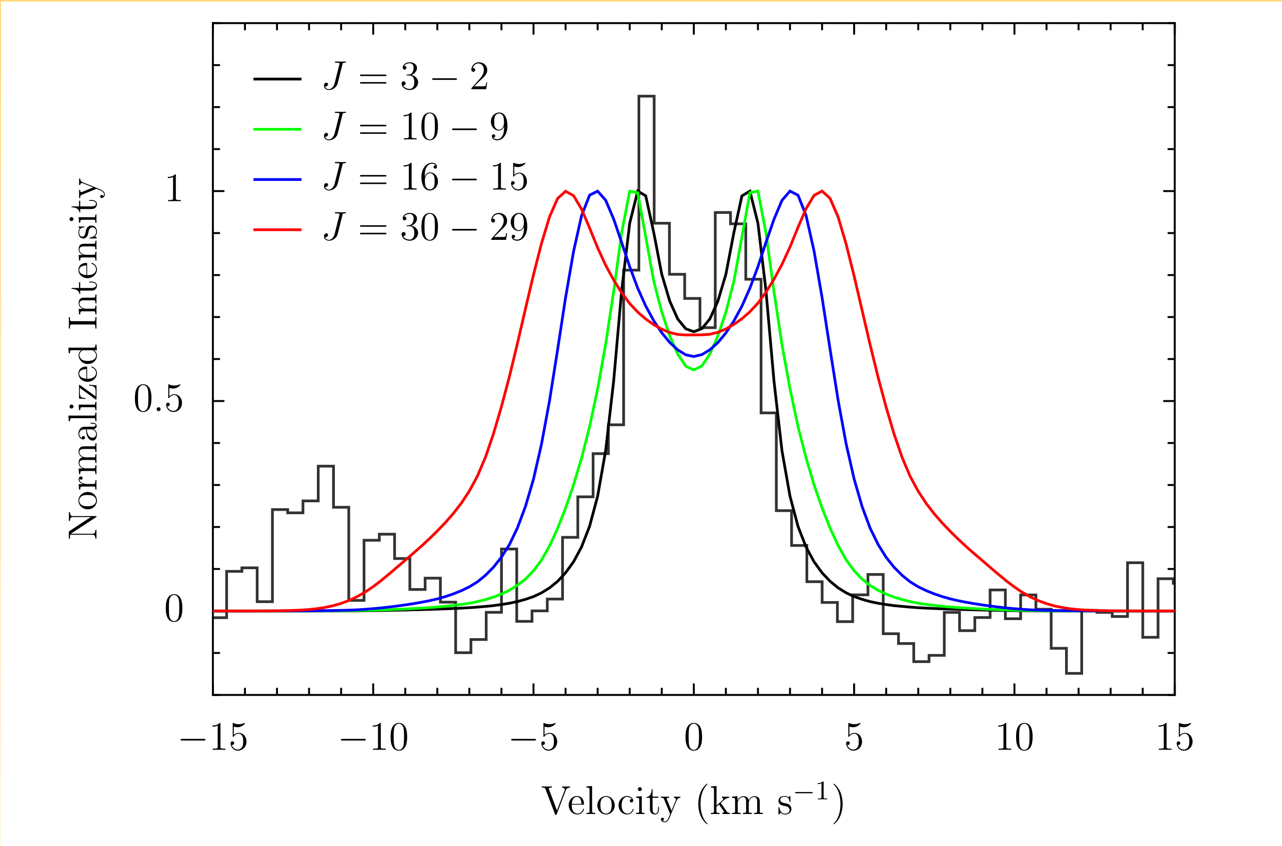
Intensity at different velocity channels



Trace different regions: CO(30-29) mostly from the inner ~ 50 AU, CO(3-2) from the whole disk

Where does the emission come from?

The higher-J, the broader the line?



HIFI can observe up to CO(16-15)
Stay tuned: Approved OT2 proposal to observe it!

Super-heated, gas rich and carbon poor?

Volatile Carbon?

time

diffuse clouds

C^+

molecular clouds

CO_{gas}

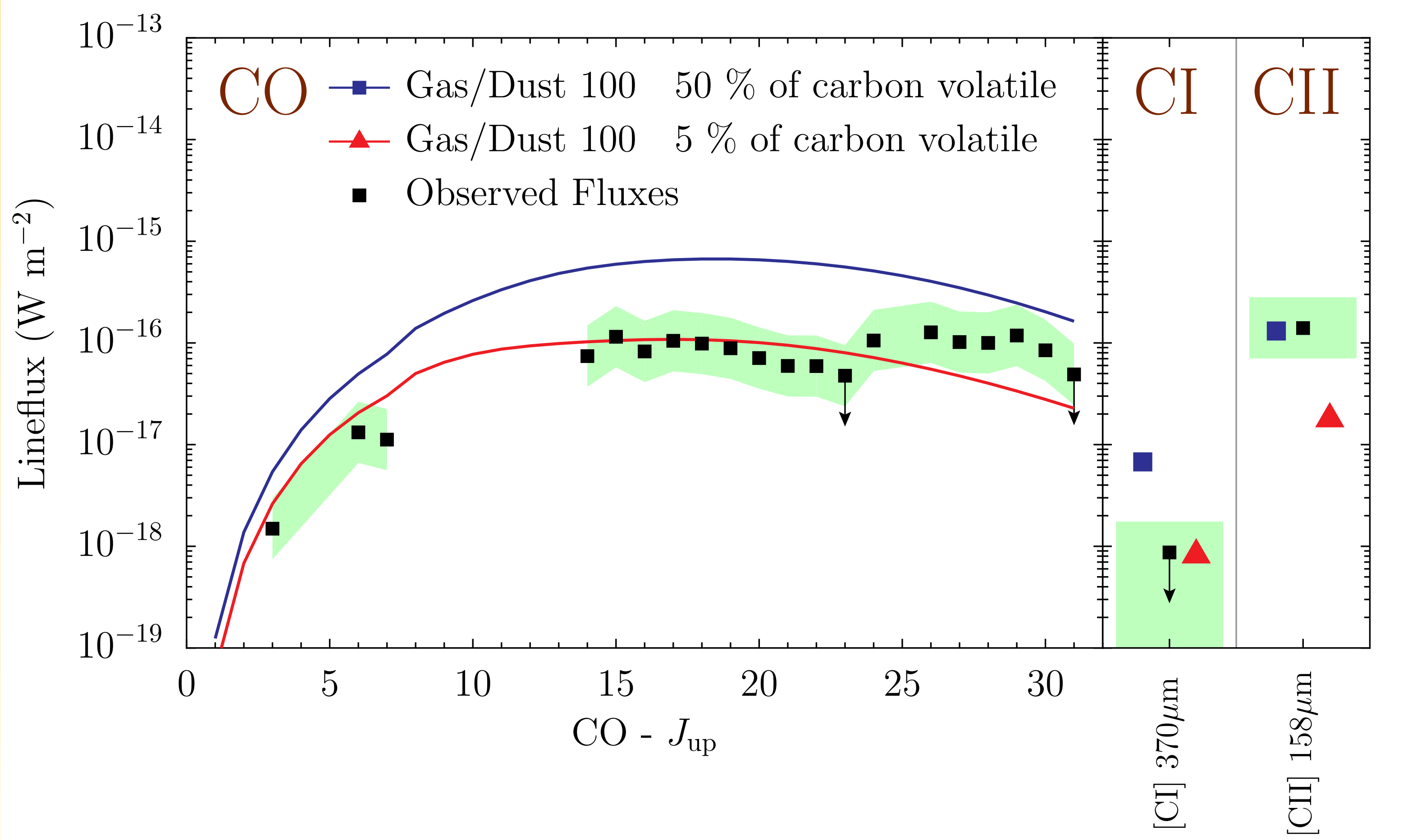
dense cores

CO_{ice}

disk atmospheres

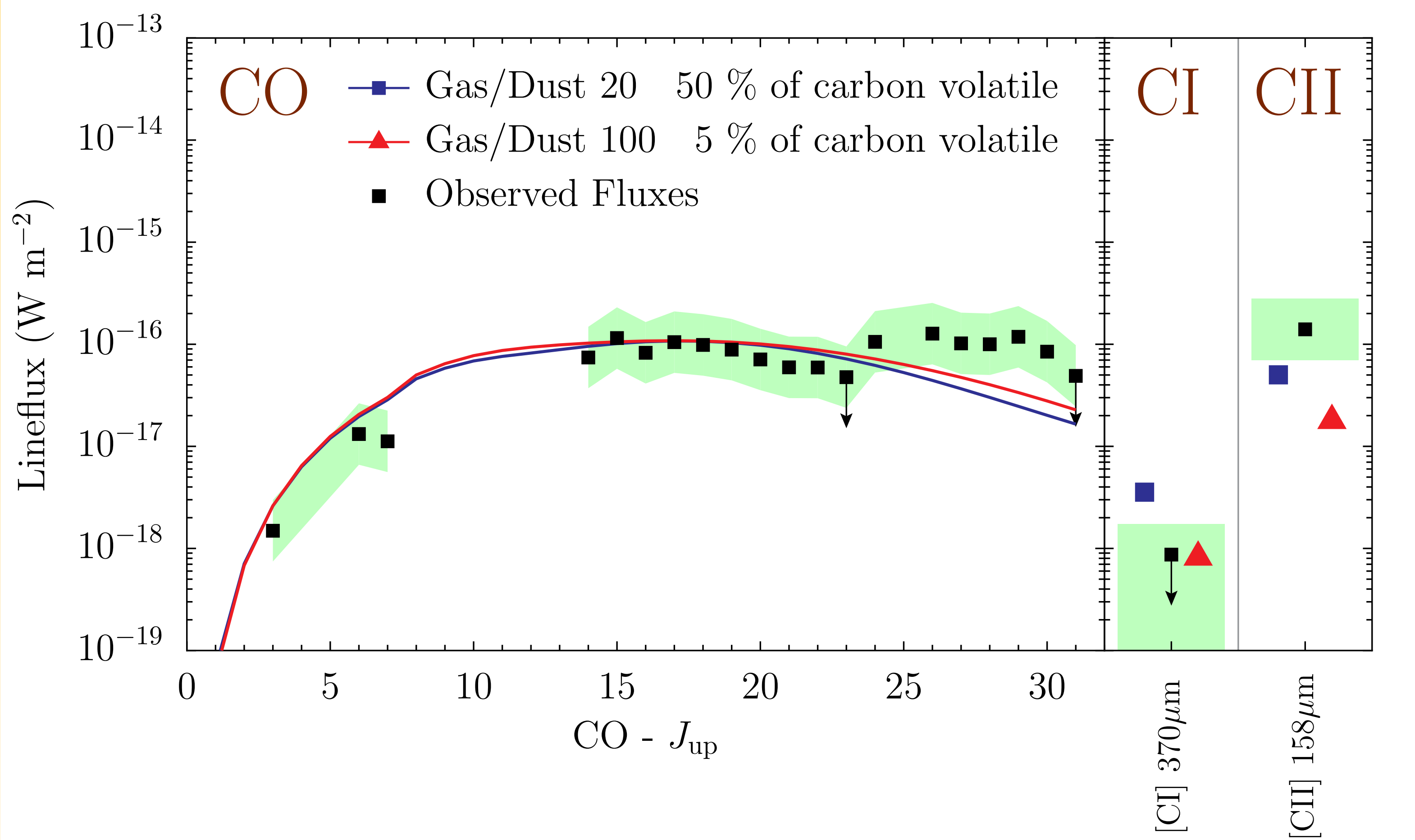
CO_{gas} ???

Volatile Carbon?



less volatile carbon (with respect to cosmic abundance) yields lower fluxes of CO, [CI] and [CII]

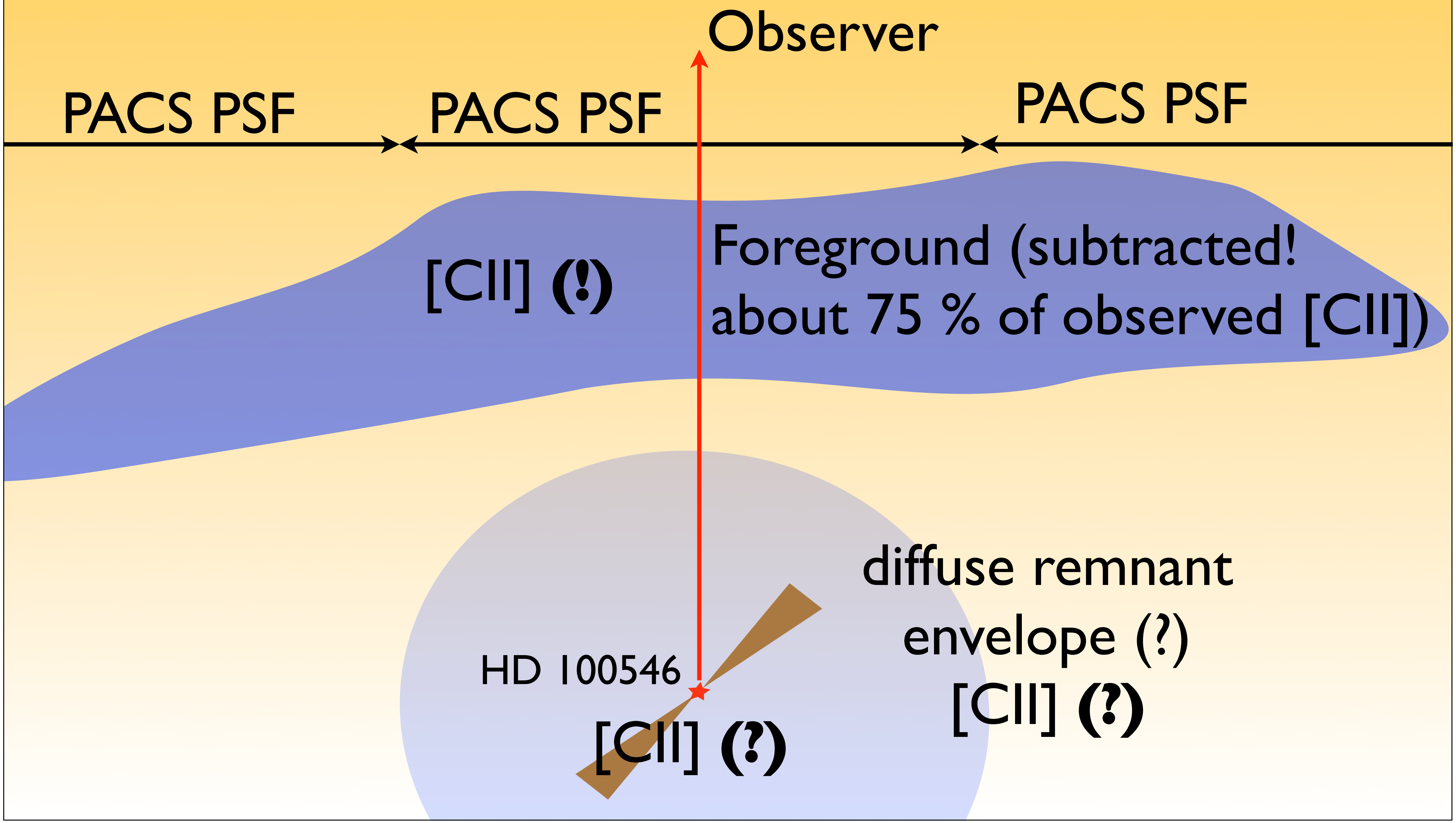
Volatile Carbon?



Higher gas/dust ratio (higher gas density) drives more carbon into CO

Can reproduce CO with [CI] for high gas/dust ratio and low abundance of volatile carbon, but underestimates [CII]

Where does [CII] come from?



Volatile Carbon?

time

diffuse clouds

C^{+}

molecular clouds

CO_{gas}

dense cores

CO_{ice}

disk atmospheres

CO_{gas} ???

$CO_{2\ ice}$ / CH_3OH_{ice}

complex organics?

Volatile Carbon?

- Can explain the upper limit of [CI] together with the CO ladder and [OI] for high gas-to-dust ratio, but low amount of volatile carbon. But this underproduces [CII].
- [CII] likely from a diffuse remnant envelope!

  Herschel OT2 - Will observe [CII] with HIFI
- We thus prefer the solution with high gas-to-dust, but a low abundance of volatile carbon. Where has the carbon gone? Complex organics?
- Can we find evidence for a volatile carbon-poor atmosphere in other disks?

Conclusions / Takeaway

- We can reproduce the Herschel FIR line detections towards a (prototypical) protoplanetary disk without much tuning
- Warm atmosphere ($T_{gas} > T_{dust}$) needed to reproduce the high-J CO
- High-J CO from radii of a few 10 - 50 AU
- Evidence for a gas-rich, but atmosphere that is poor in volatile carbon: Where has the carbon gone?

  Complex organics?