# WATER in the DISK of DG Tau

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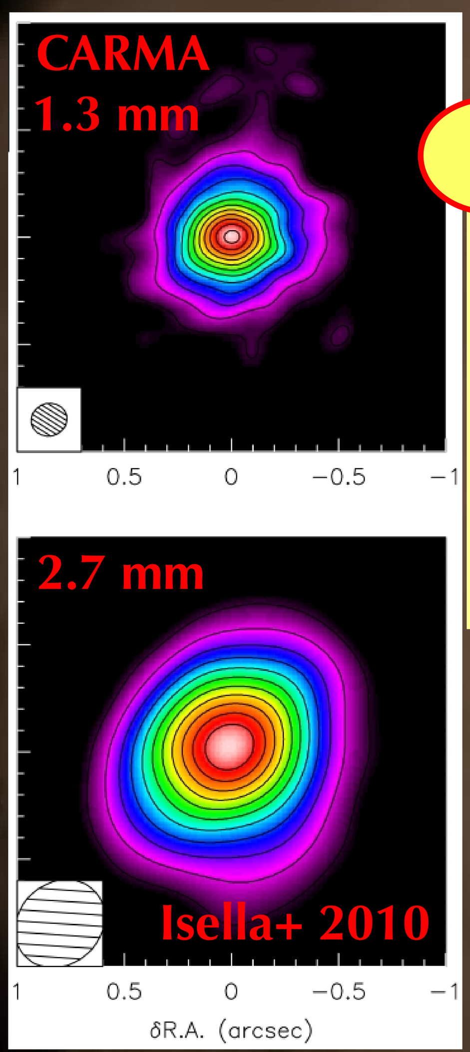
## Herschel/HIFI observations of DG Tau in o-$H_2O$ 557 GHz & p-$H_2O$ 1113 GHz lines

### Motivation for HIFI observations

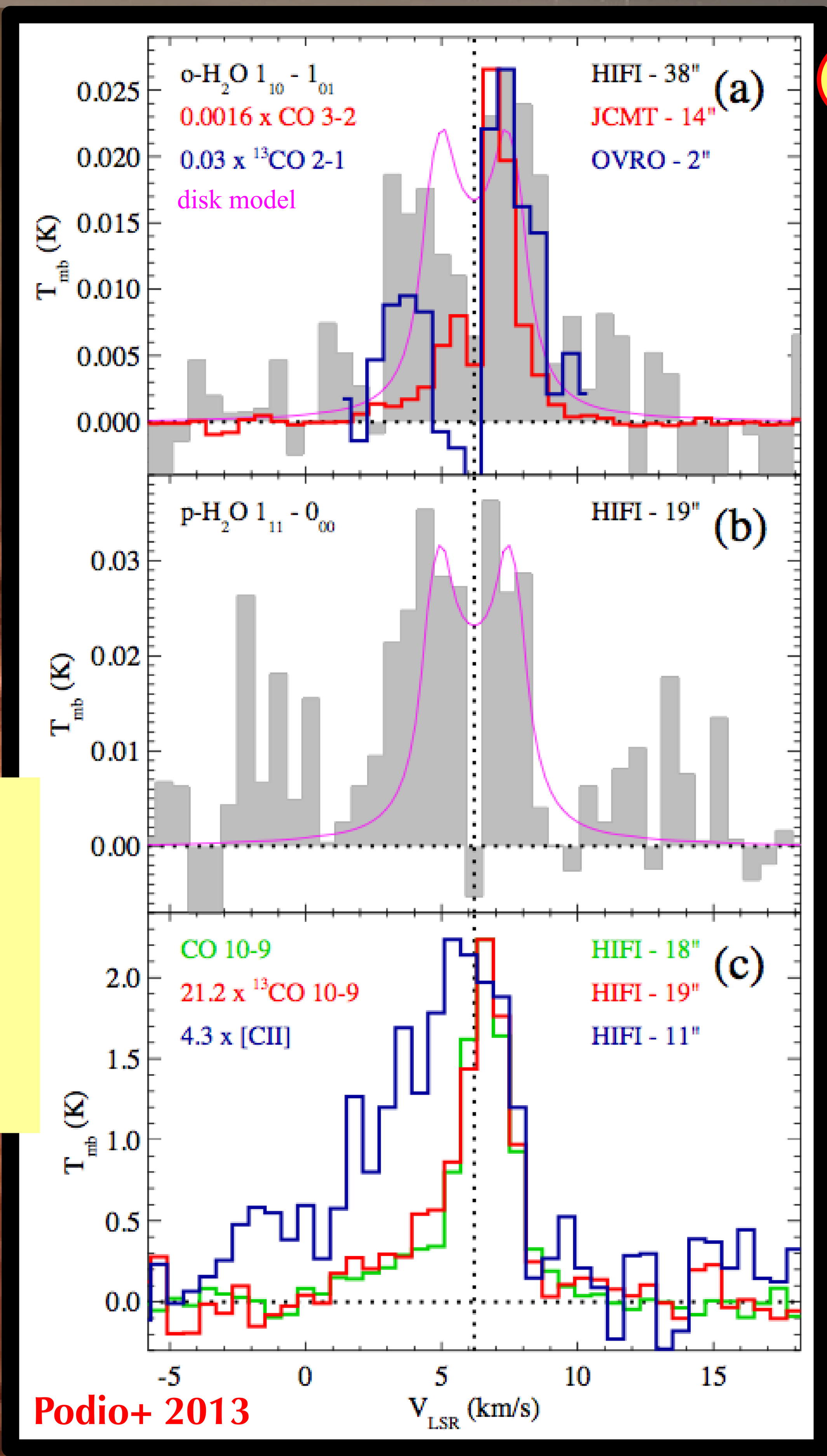
DG Tau is a young low-mass star (d=140 pc, M=0.7 M☉, L=1 L☉) associated with a disk, an envelope, and an optical jet (Testi+ 2002, Kitamura+ 1996, Eisloffel+ 1998).
PACS obs show unresolved $H_2O$ emission (Podio+ 2012).
We investigate the origin of $H_2O$ emission with HIFI and find that:

**1.** Unlike CO, [C II] lines profiles (asymmetric, peak close to $V_{sys}$=6.3 km/s, bright blue wing) $H_2O$ lines show a narrow double-peaked profile
a strong kinematic evidence of keplerian rotating disk !

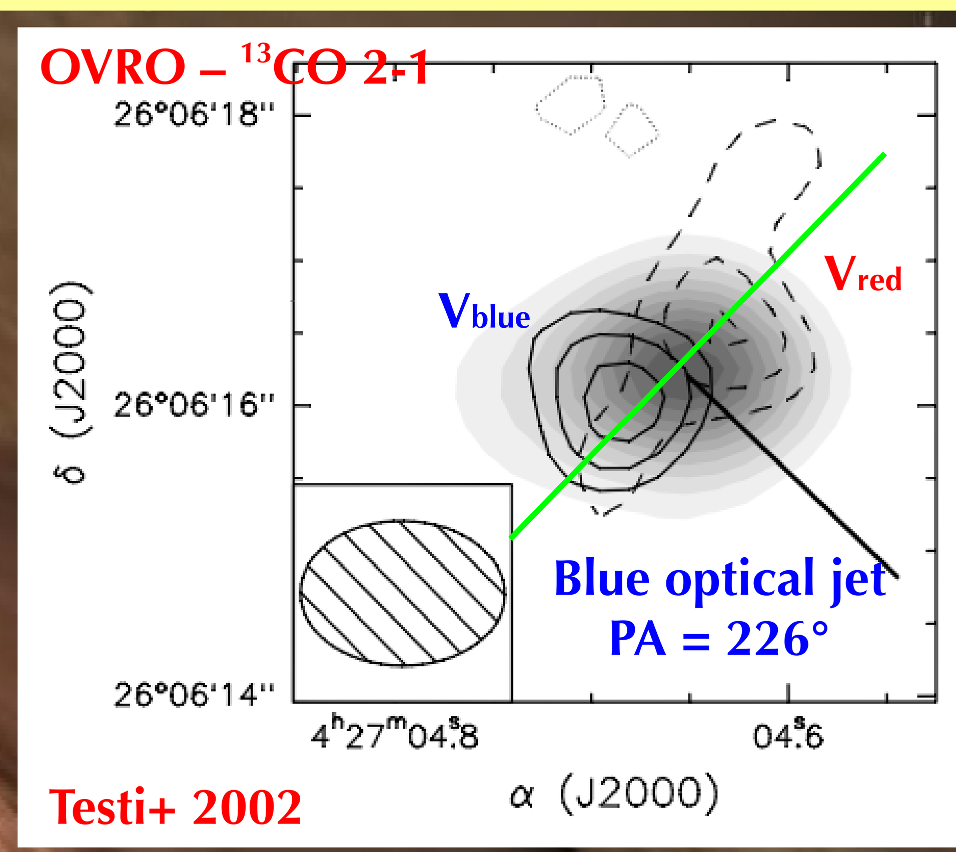



**2.** Assuming $H_2O$ lines originate in the disk the outer radius of the $H_2O$ emitting region (derived from peak separation) is in agreement with the dusty disk radius (from mm continuum maps, Isella+ 2010)

$R_{out}(H_2O)$ ~ 77-105 AU ~ $R_{out}$(dust)




**3.** $H_2O$ lines peaks are in the velocity ranges where $^{13}CO$ 2-1 interferometric maps trace a compact rotating disk (Testi+ 2002) (velocity gradient perpendicular to jet direction)




### Conclusions from 1. + 2. + 3.

CO, [C II] lines appear to be dominated by ENVELOPE/OUTFLOW emission

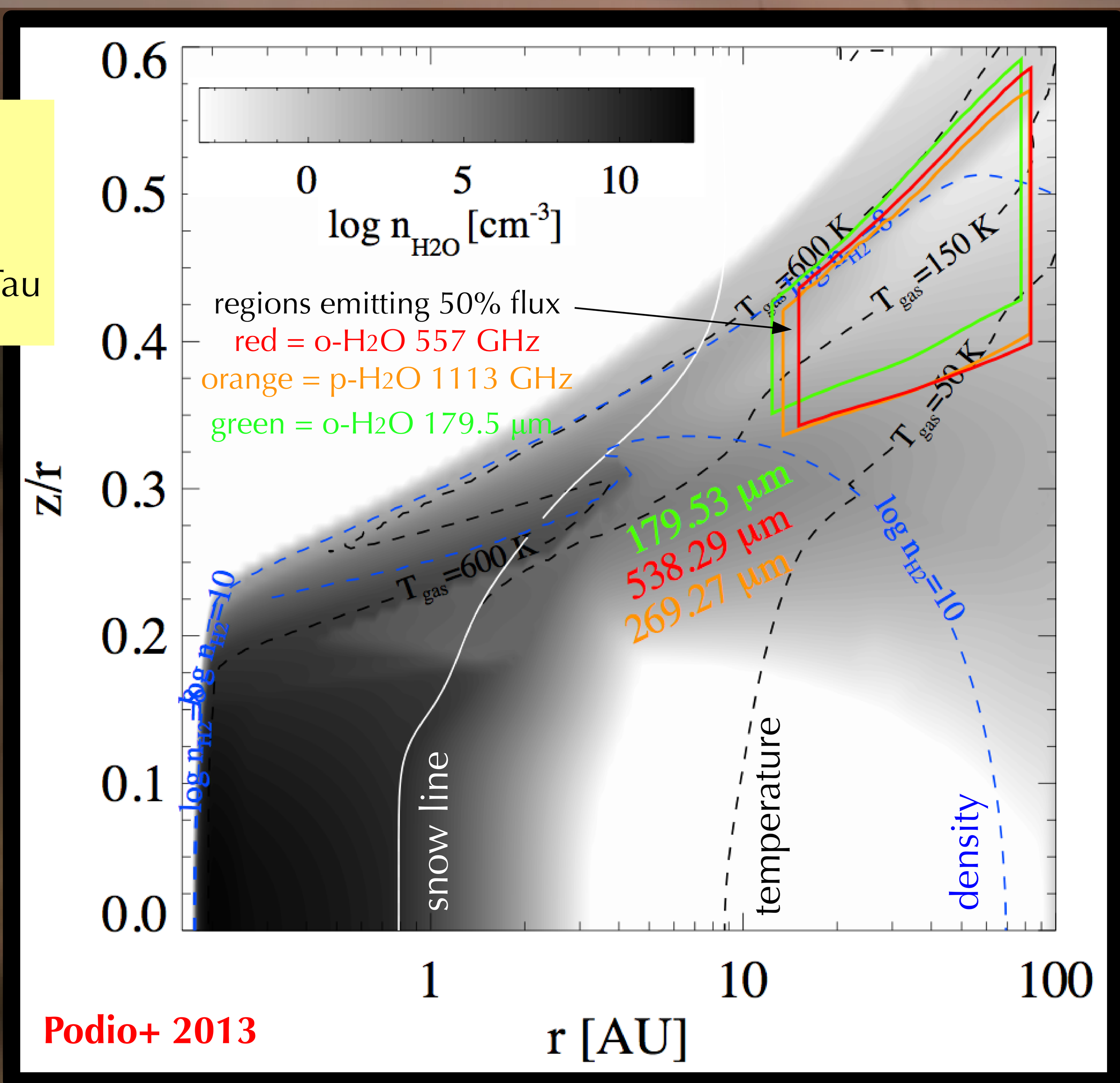
**$H_2O$ lines appear to be dominated by COMPACT emission from the OUTER DISK**

## Modeling $H_2O$ emission from the disk of DG Tau with ProDiMo

We use a parametric disk model with the ProDiMo code (*Pro*toplanetary *Di*sk *Mo*dels) (e.g., Woitke+ 2009, Kamp+ 2010) to calculate $H_2O$ emission from the disk of DG Tau

"LOW DUST OPACITY" DISK MODEL: STAR AND DISK PARAMETERS

| | | |
|---|---|---|
| Effective temperature | $T_{eff}$ (K) | 4000 |
| Stellar mass | $M_*$ ($M_\odot$) | 0.7 |
| Stellar luminosity | $L_*$ ($L_\odot$) | 1 |
| UV excess | $f_{UV}$ | 0.2 |
| UV power law index | $p_{UV}$ | -0.3 |
| X-rays luminosity | $L_X$ (erg s$^{-1}$) | $10^{30}$ |
| Disk inner radius | $R_{in}$ (AU) | 0.16 |
| Disk outer radius | $R_{out}$ (AU) | 100 |
| Disk dust mass | $M_{dust}$ ($M_\odot$) | $1\ 10^{-3}$ |
| Dust-to-gas ratio | dust-to-gas | 0.01 |
| Solid material mass density | $\rho_{dust}$ (g cm$^{-3}$) | 3.5 |
| Minimum grain size | $a_{min}$ ($\mu$m) | 0.005 |
| Maximum grain size | $a_{max}$ (cm) | 5 |
| Dust size distribution index | $q$ | 3.5 |
| Disk inclination | $i$ (°) | 38 |
| Surface density $\Sigma \approx r^{-\epsilon}$ | $\epsilon$ | -1 |
| Scale height at $R_{in}$ | $H_0$ (AU) | 0.008 |
| Disk flaring index $H(r) = H_0 \left(\frac{r}{R_{in}}\right)^{\beta}$ | $\beta$ | 1.2 |
| Fraction of PAHs w.r.t. ISM | $f_{PAH}$ | 0.01 |




### The disk region emitting $H_2O$

$H_2O$ 557, 1113 GHz (HIFI), 179.5 µm (PACS) are emitted by an outer disk region at R=10-90 AU, T=50–600 K, $<n_H>$=1e8–1e10 cm$^{-3}$

- $H_2O$ lines are optically thick, close to LTE
- line fluxes are reproduced within a factor 2

### Disk and water mass

disk and water masses are constrained with one order of magnitude uncertainty depending on the assumed dust grain size distribution / dust mass (from cont emission at 1.3, 2.7 mm, Isella+ 2010)

*"low dust opacity" model*
$M_{disk}$ = 0.1 M☉
$H_2O_{gas}$ ~ 1e-6 M☉ ~ 0.37 M⊕
$H_2O_{ice}$ ~ 3e-4 M☉ ~ 100 M⊕

*"high dust opacity" model*
$M_{disk}$ = 0.015 M☉
$H_2O_{gas}$ ~ 1.7e-7 M☉ ~ 0.06 M⊕
$H_2O_{ice}$ ~ 2e-5 M☉ ~ 7 M⊕

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1M⊕ = 5.97 $10^{27}$ g
1Earth ocean = 1.5 $10^{24}$ g

## Results & implications

**$H_2O$ lines in DG Tau appear to be dominated by disk emission. Disk modeling indicates:**

**$M_{disk}$ = 0.01 – 0.1 M☉ ≥ Minimum Mass of the Solar Nebula (MMSN) before planets formation**

**M($H_2O$) ~ 7 - 100 M⊕ ~ 1e4 - 1e5 earth oceans**

**These results support the scenario of impact delivery of water on terrestrial planets by means of icy bodies forming in the outer disk (e.g., Matsui+ 1986)**