Herschel View on Atomic/Molecular Emission in Class II Sources: Outflows and Disks

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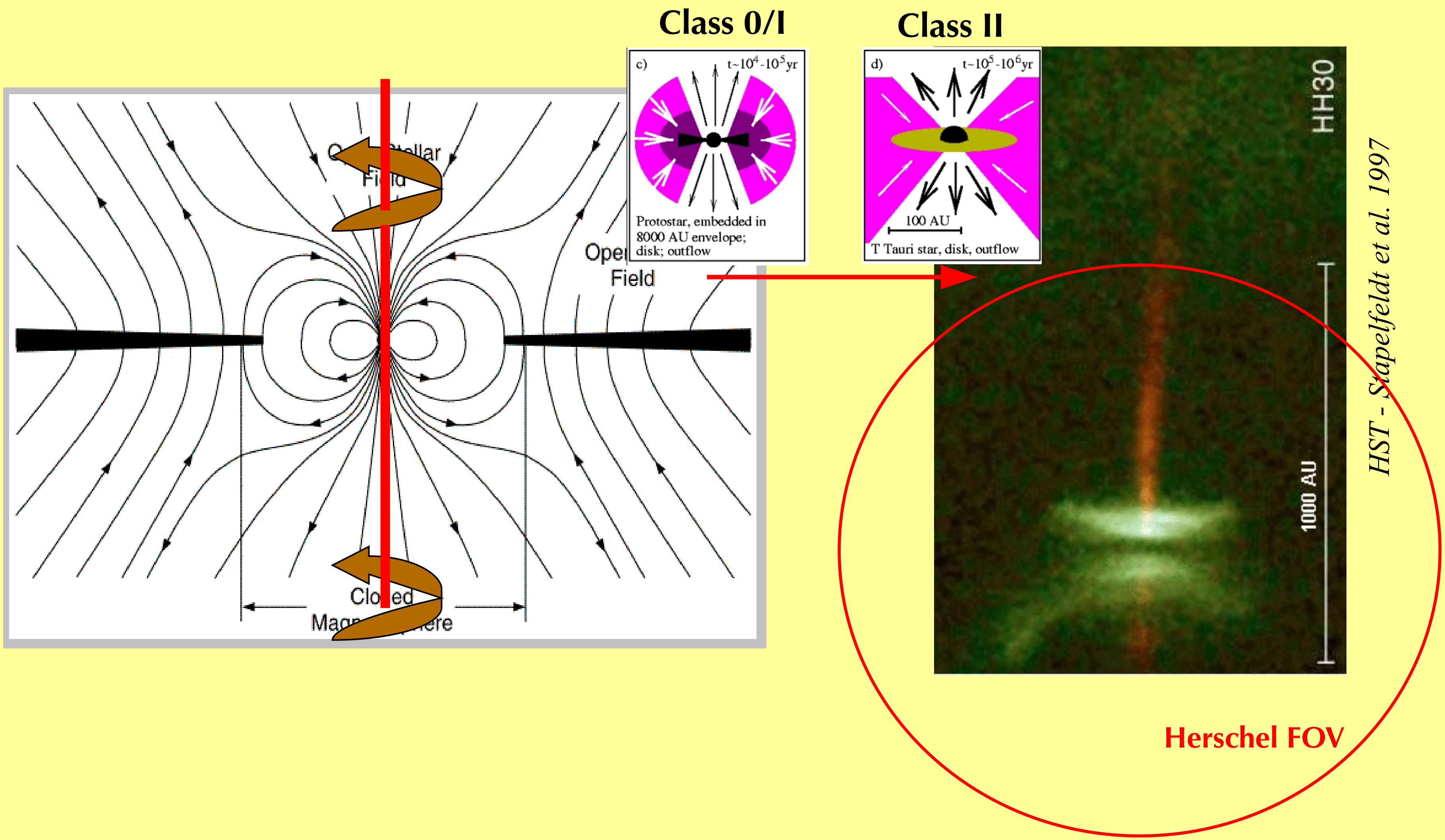
& the GASPS team

Accretion disks & stellar jets in the star formation process



GOAL of Herschel obs: to investigate the origin of atomic/molecular emission from Class II sources

GASPS: GAS in Protoplanetary System (PI: B. Dent)

Herschel/PACS survey of atomic/molecular gas and dust in ~ 200 disks
wide range of ages: 1-30 Myr
disk masses: 10^{-1} – 10^{-5} Msol
Class II/III sources
spectral types (A to M)
Nearby star-forming regions (Taurus, ηCha, βPic, Herbig Ae/Be, ...): d ~100-200 pc

Dent et al. 2013, see talk by W.F. Thi

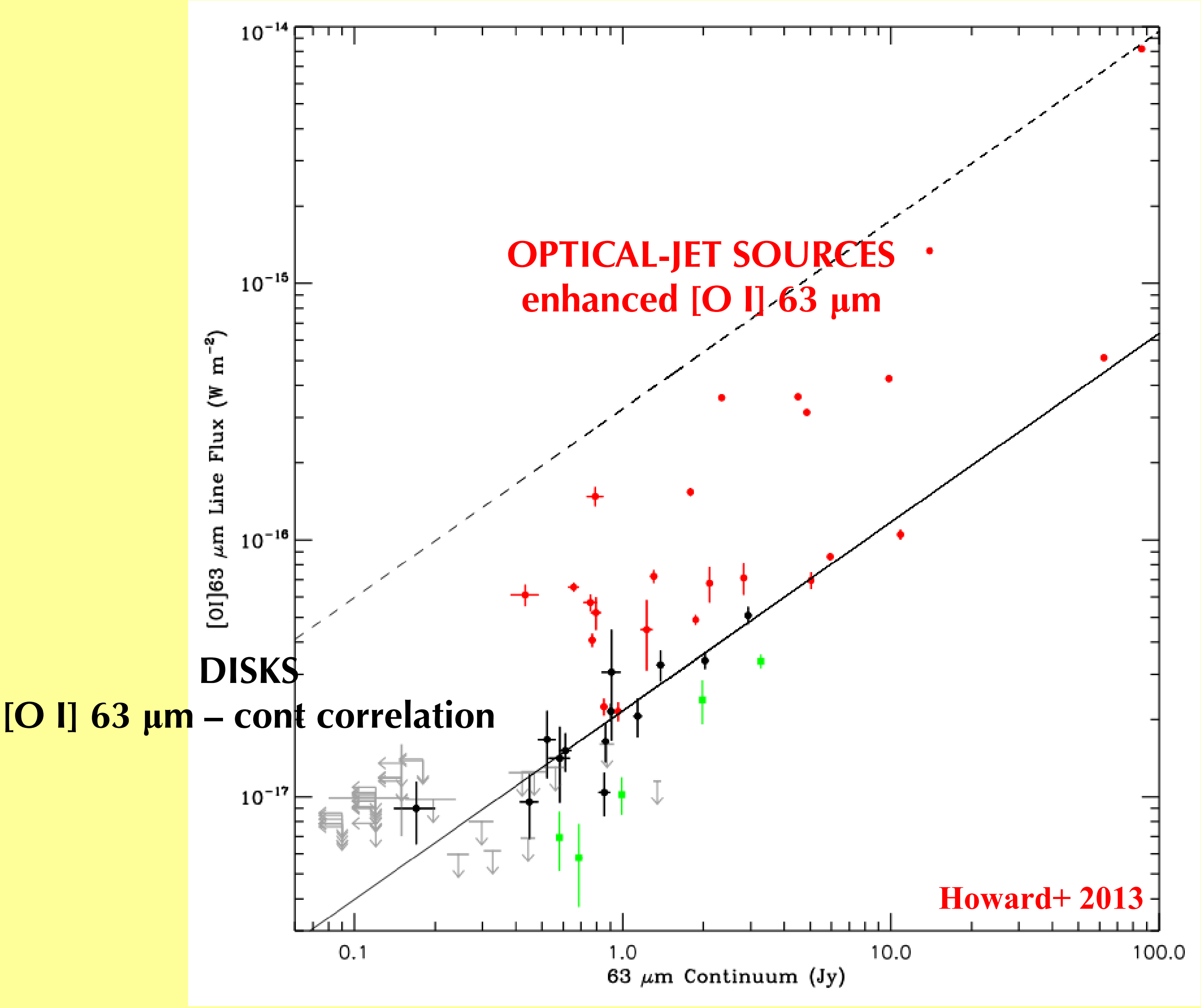
the GASPS survey includes OPTICAL-JET sources (late Class I/II sources in Taurus)

MOLECULAR LINES: H_2O, OH, high-J CO ($J \geq 18$)

ATOMIC LINES: [OI] 63, 145 um, [CII] 158 um

→ ***DISKS***
→ ***SHOCKS in the jet***
→ ***OUTFLOW cavities***

[O I] 63 um in Taurus/Auriga – disk or outflow emission ?



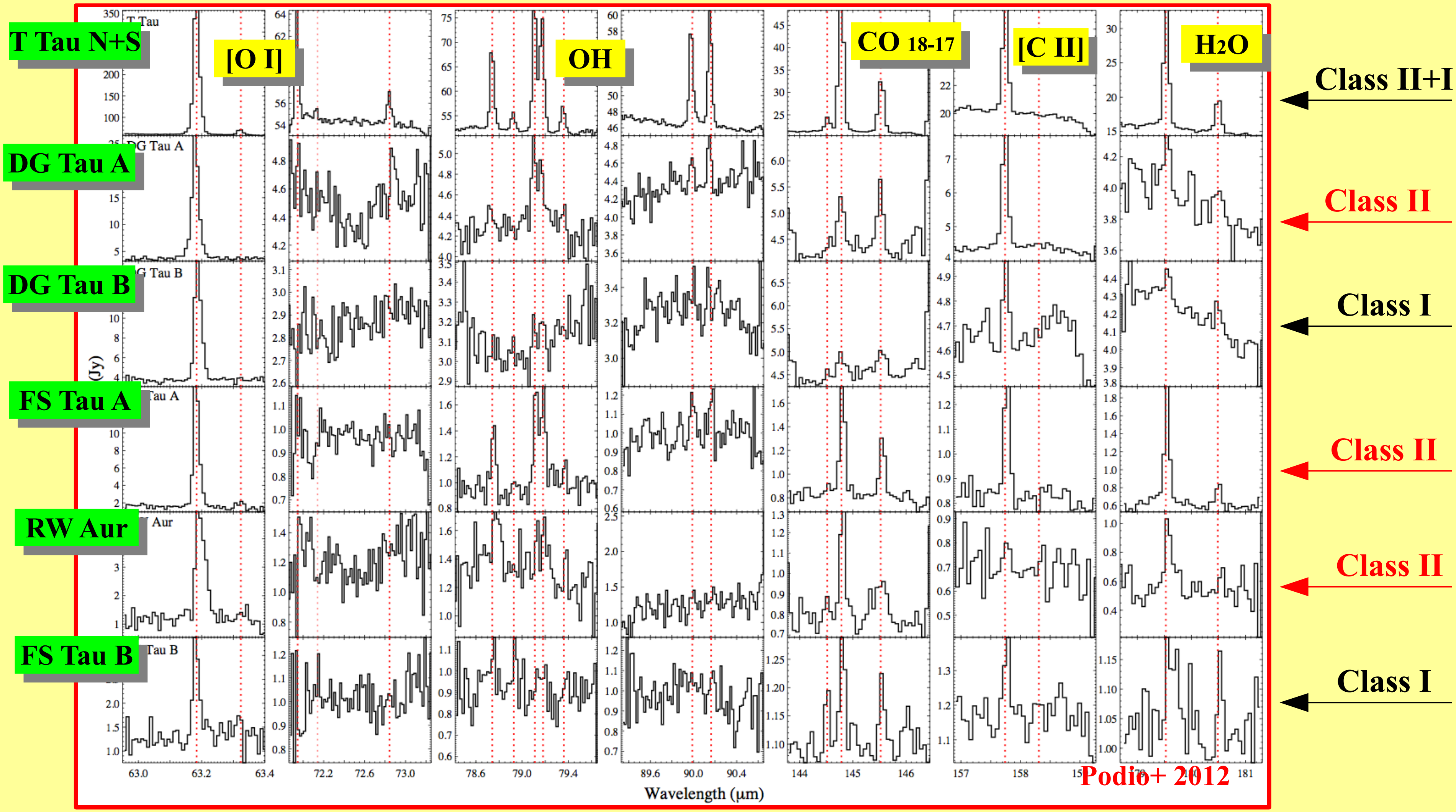
See posters

P72 - G. Sandell et al.
P84 - S. Vicente & I. Kamp

optical-JET SOURCES ---> FIR ATOMIC, MOLECULAR emission

ATOMIC LINES, i.e. [O I] 63 μm, [C II] 158 μm → **Extended**, velocity shifted

MOLECULAR LINES, i.e. high-J CO, OH, H_2O → **Unresolved** with PACS



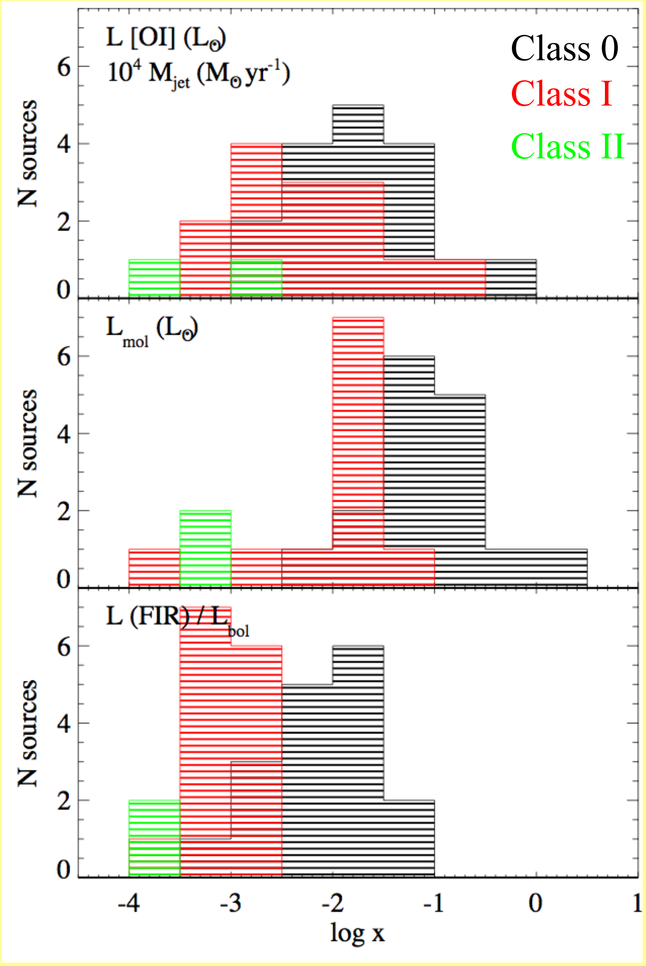
Thanks to Herschel sensitivity we can observe FIR emission associated to Class II !

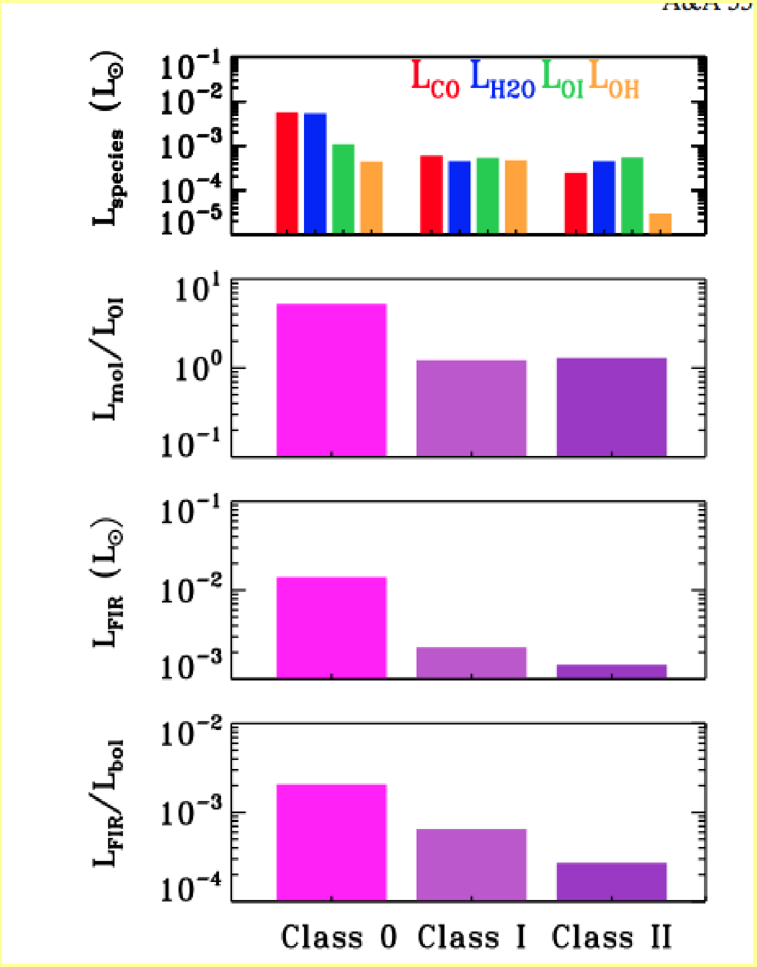
FIR cooling & mass loss rate: an evolutionary picture

[O I] cooling

Molecular cooling (H_2O, CO)

Outflow efficiency L_{FIR}/L_{bol}





Podio+ 2012

Karska+ 2013

Class 0	Giannini+ 2001 (ISO)
Class I	Nisini+ 2002 (ISO)
	Podio+ 2012 (PACS)
Class II	Podio+ 2012 (PACS)

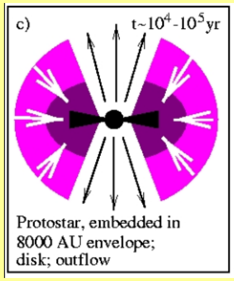
Class 0/I	Karska+ 2013 (PACS)
Class II	Podio+ 2012 (PACS)

Molecular emission: outflows or disks ?

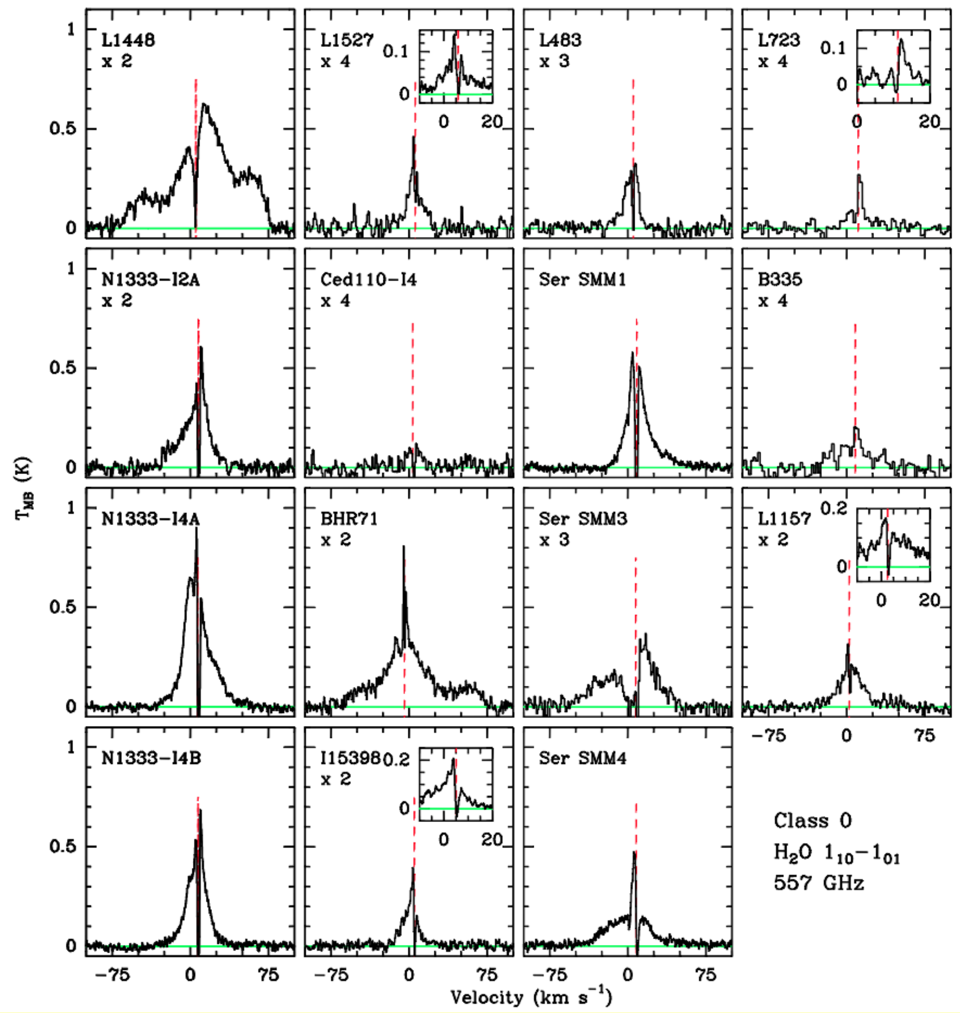
OT1 Herschel/HIFI observations (25 hours, PI: L. Podio)
→ line kinematics

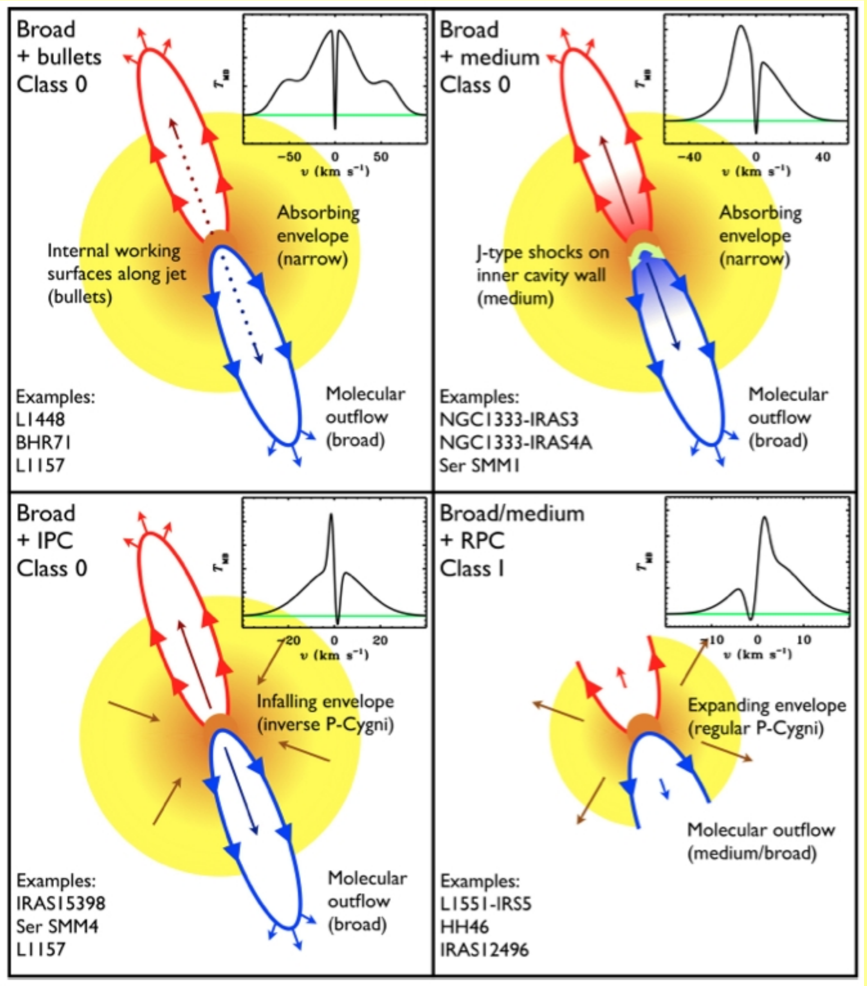
Low-exc H_2O 1_{10}-1_{01} (557 GHz, E_{up} ~ 61 K) from Class 0/I sources dominated by ENVELOPE + OUTFLOW emission

Class 0/I



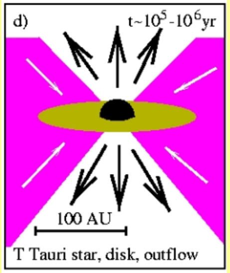
Kristensen+ 2012



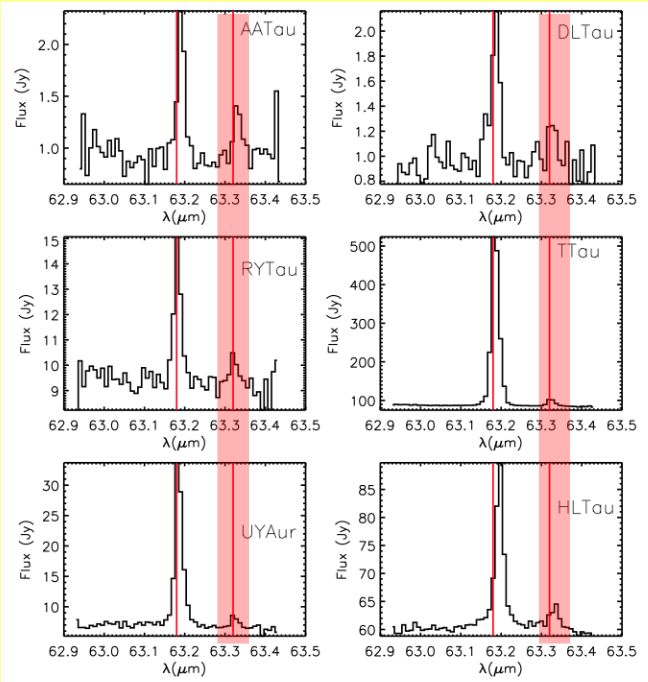


in Class II ?
High excitation H_2O lines from INNER DISK

Class II



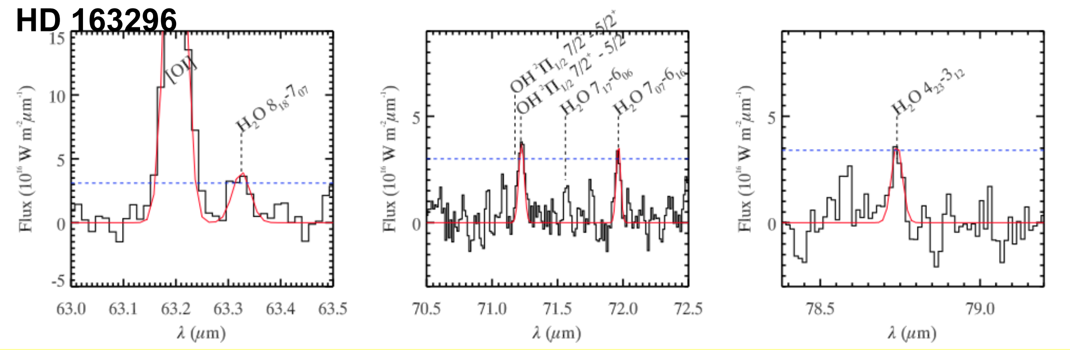
detected in 8 TTSs in Taurus ...



H_2O 63.32um
(E_{up} ~ 1007 K)

Riviere-Marichalar+ 2012

... and in 1 Herbig Ae/Be

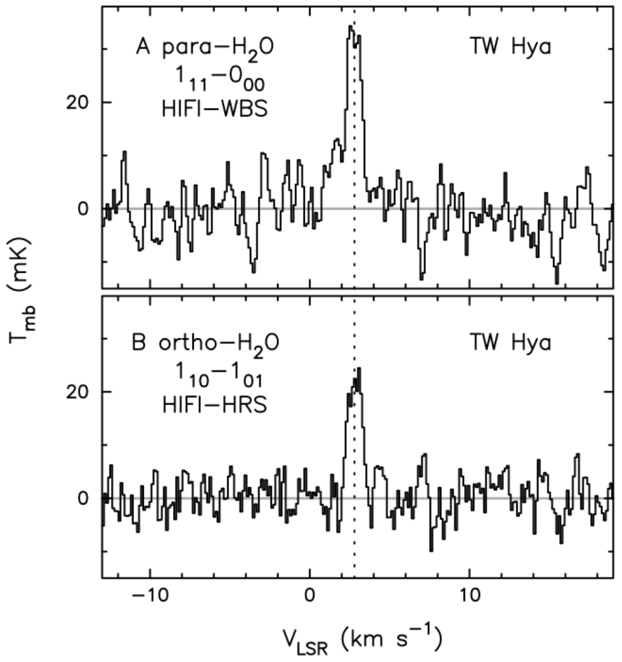


Meeus+ 2012, Fedele+ 2012

Low excitation H_2O lines from OUTER DISK

Hogerheijde+ Science 2011

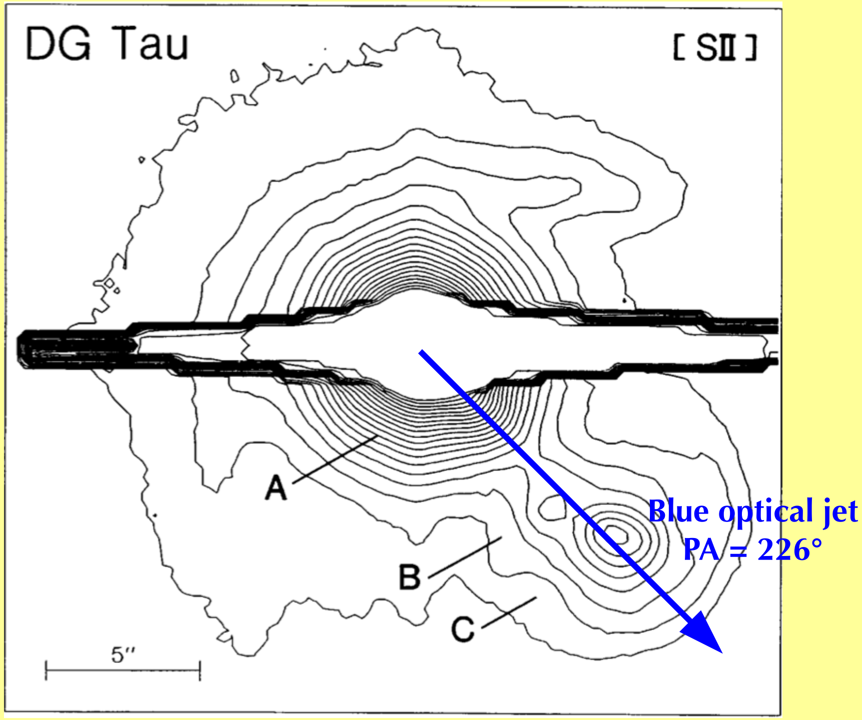
Kamp+ 2013



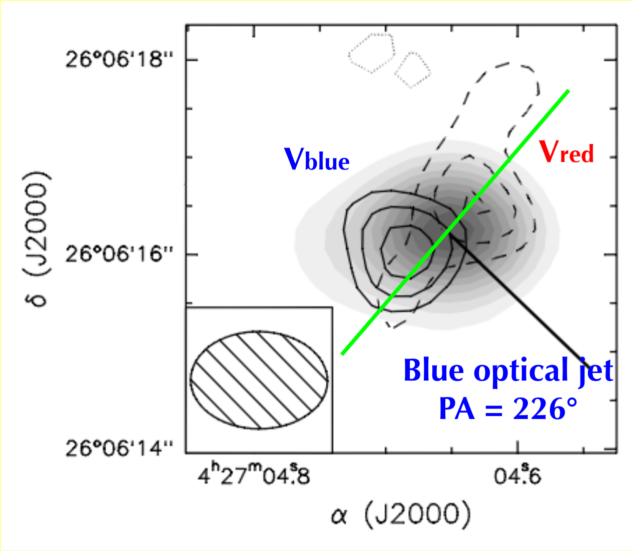
Herschel/HIFI observations of DG Tau

DG Tau is low-mass Class II source associated with:

- an optical blue-shifted jet (e.g., Eisloffel+ 1998)
- dispersing envelope seen in CO lines (Kitamura+ 1996)
- compact disk-like emission in ^{13}CO interf maps (Testi+ 2002)



Eisloffel+ 1998

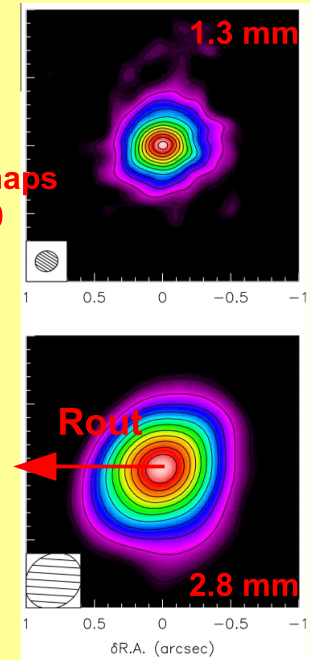


Testi+ 2002

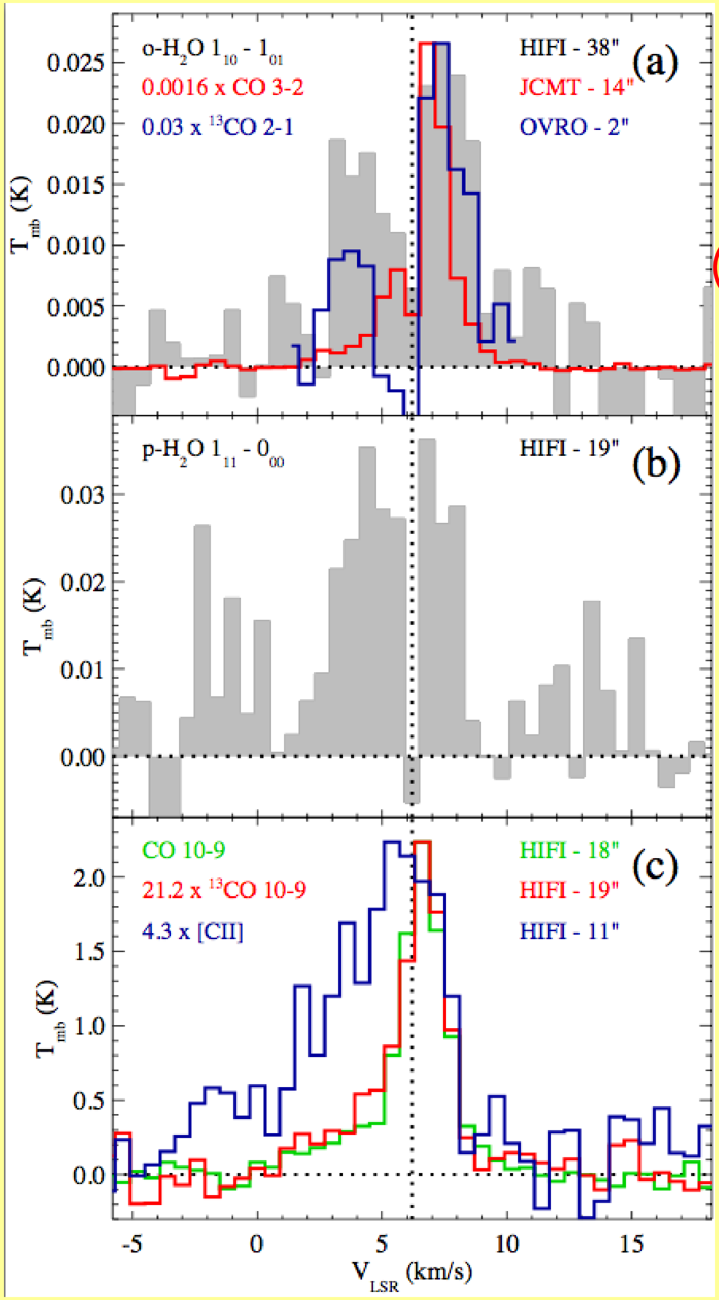
Herschel/HIFI observations of DG Tau
evidence of low-exc WATER emission from OUTER DISK !

1. double-peaked profile: strong kinematic evidence of keplerian rotating disk !

2. $R_{out}(H_2O) \sim 77\text{-}105$ AU $\sim R_{out}$(dust)

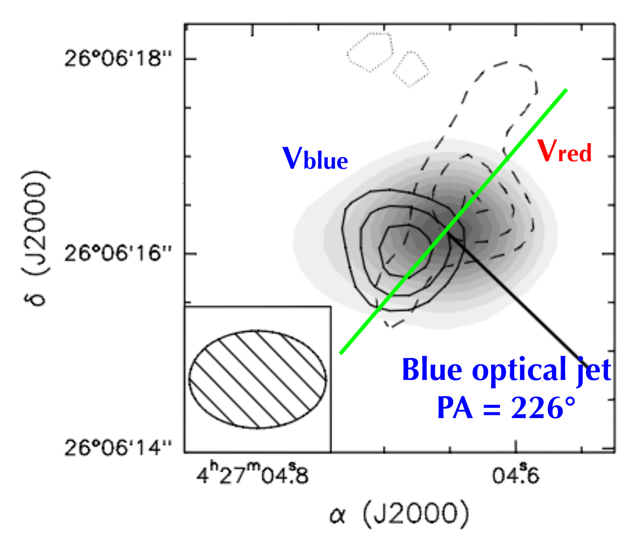


CARMA cont maps
Isella+ 2010



Podio+ 2013

3. H_2O line peaks in the velocity ranges where ^{13}CO 2-1 interf maps trace the disk rotation (V gradient perp to jet direction)



Testi+ 2002

DG Tau DISK model: the region emitting low-exc H2O lines

***Pro**toplanetary **Di**sk **Mo**dels* **(ProDiMo)**

Woitke+ 2009, Kamp+ 2010, Thi+ 2011
Aresu+ 2011, 2012, Meijerink+ 2012

uses global iterations to consistently calculate physical, thermal, chemical structure of protoplanetary disks.

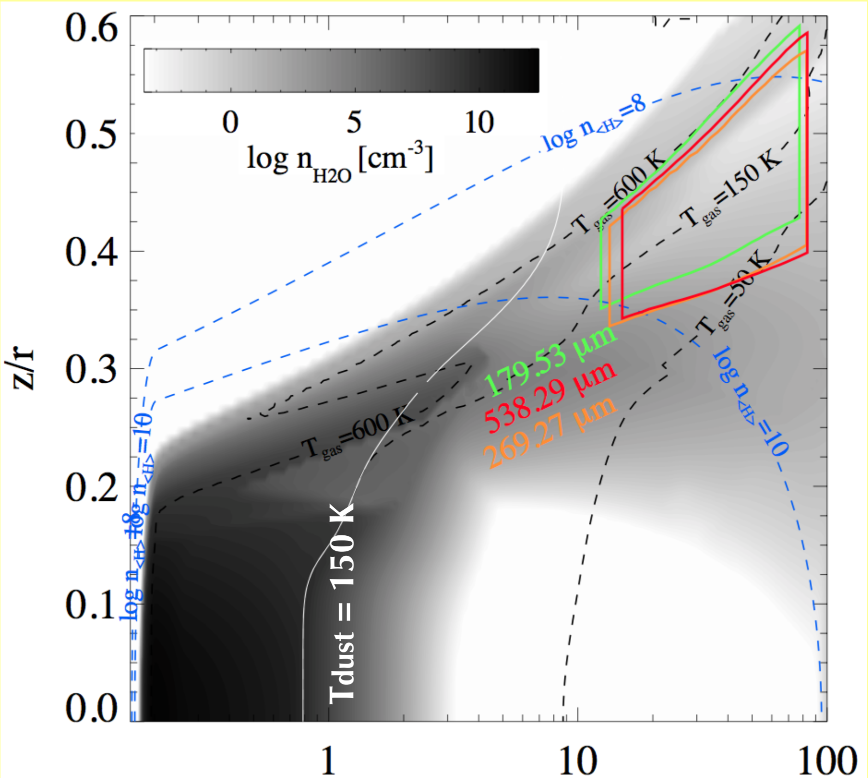
large chemical network: 120 species, ~1650 reactions

See talk by W.F. Thi

H_2O 557, 1113 GHz (HIFI)
H_2O 179.5um (PACS)
emitted by same disk region

R = 10 – 90 AU
T = 50 – 600 K
< nH > = 1e8 – 1e10 cm^{-3}

--> H_2O emission close to LTE
--> optically thick lines



Podio+ 2013

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

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

High dust opacity model

M_{dust} = 1e-4 $M_\odot$
a_{min} = 0.005um, a_{max} = 750um, q = 3

observed line fluxes in agreement with predicted ones within a factor 2

Model uncertainty related to: collisional rates, chemistry on dust grains (e.g. desorption and adsoprtion rates)
details of radiative transfer

Kamp+ 2013

Estimating the WATER RESERVOIR in the DISK of DG Tau

dust grain size distribution / disk dust mass
to reproduce cont emission at 1.3, 2.8 mm (Isella+ 2010):

“ low dust opacity ” model

$M_{disk} = 0.1\ M_\odot$
$H_2O_{gas} \sim 1e\text{-}6\ M_\odot \sim 0.37\ M_\oplus$
$H_2O_{ice} \sim 3e\text{-}4\ M_\odot \sim 100\ M_\oplus$

“ high dust opacity ” model

$M_{disk} = 0.015\ M_\odot$
$H_2O_{gas} \sim 1.7e\text{-}7\ M_\odot \sim 0.06\ M_\oplus$
$H_2O_{ice} \sim 2e\text{-}5\ M_\odot \sim 7\ M_\oplus$

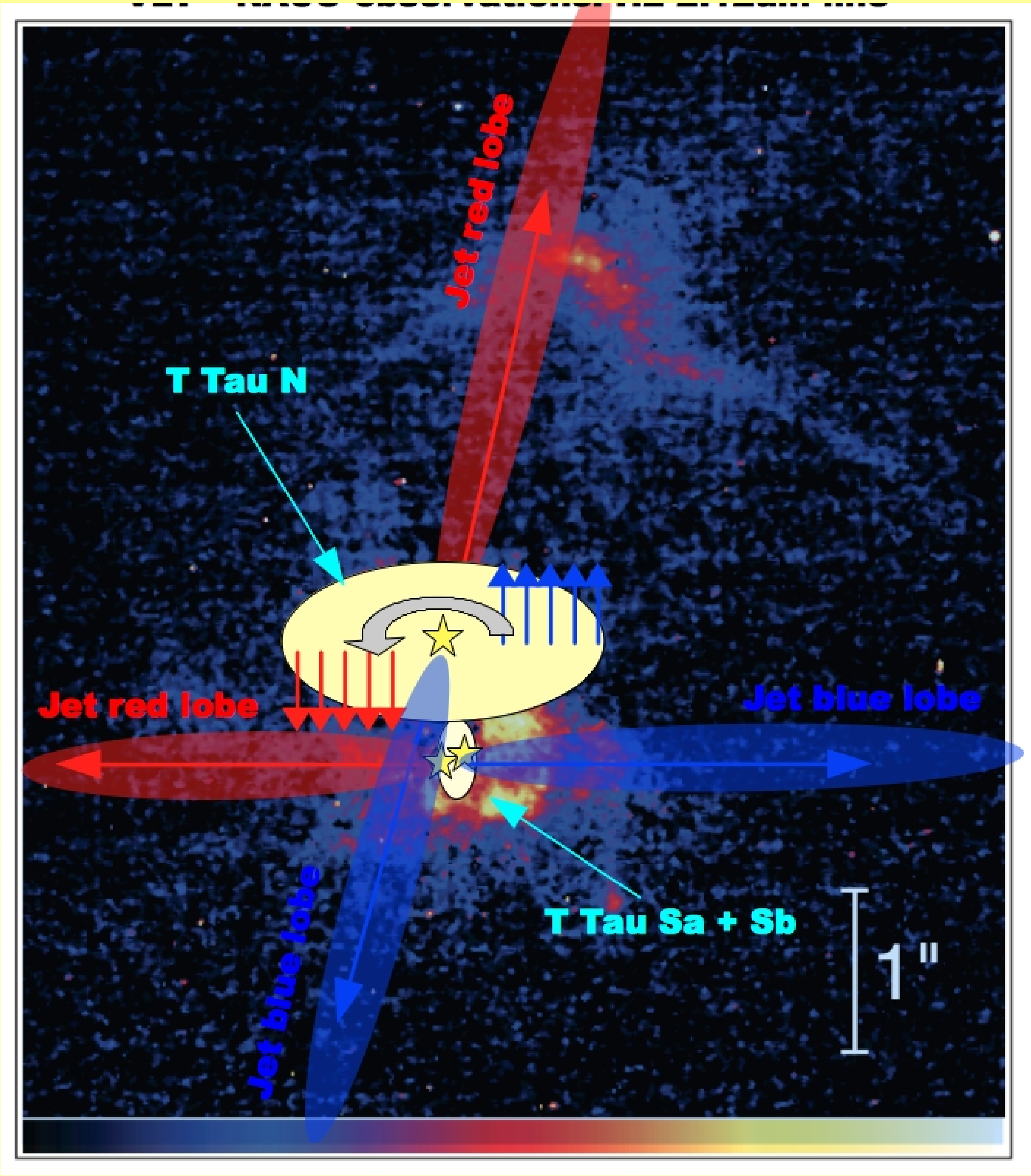
Since H_2O lines are optically thick
disk and water masses are constrained with one order of magnitude uncertainty

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

$M(H_2O) \sim 7 - 100\ M_\oplus \sim$ 1e4 - 1e5 earth oceans

→ supports the “DRY ACCRETION” scenario
water can be delivered on terrestrial planets
by means of icy bodies forming in the outer disk

Herschel/HIFI observations of T Tau



VLT-NACO - H_2 2.12um
Herbst+ 2007

TRIPLE SYSTEM
T Tau N (Class II)
T Tau Sa, Sb (Class I or II ?)
Dyck et al. 1982
Kohler et al. 2008
Luhman et al. 2010

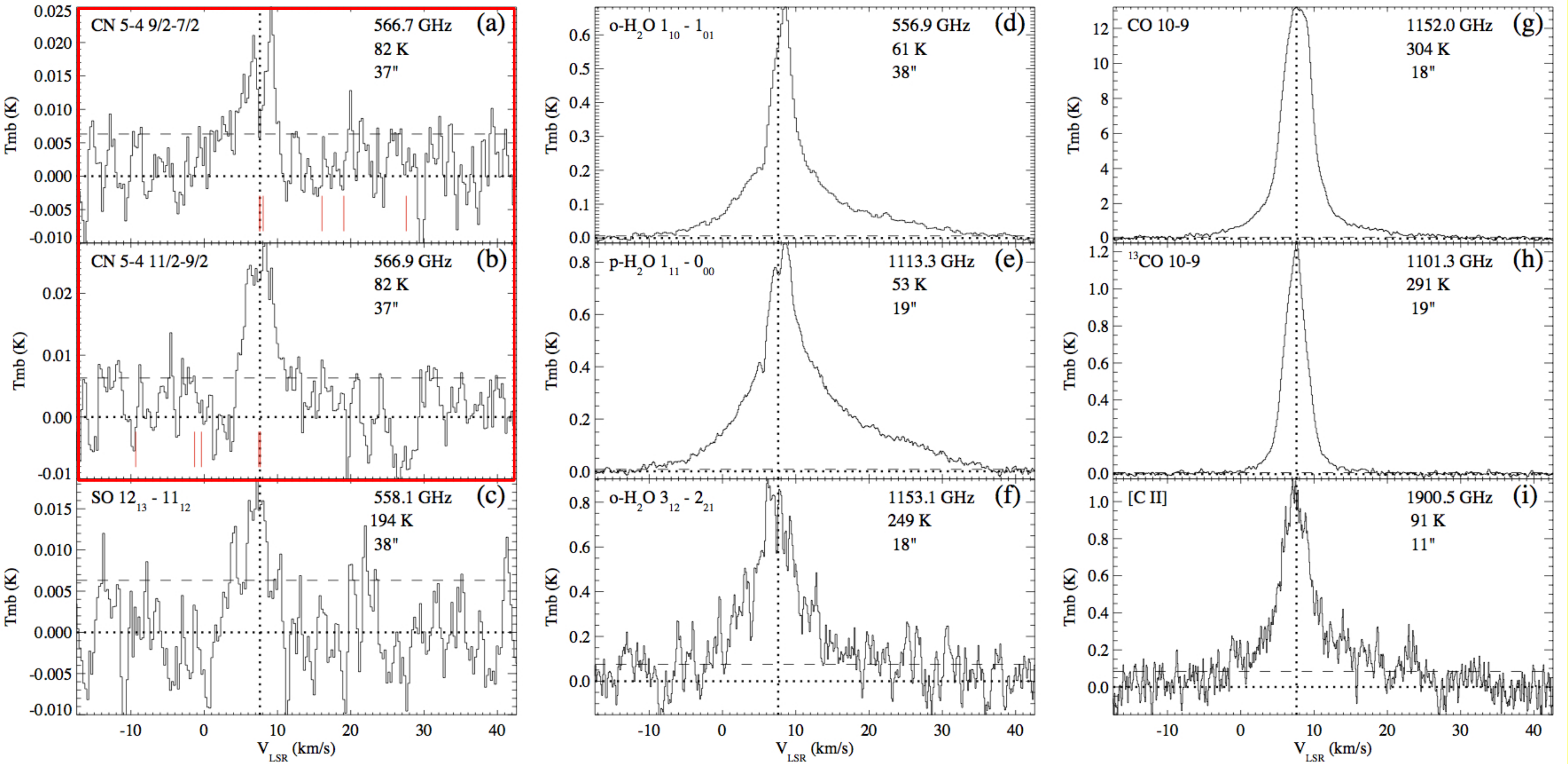
S-N, E-W OUTFLOWS
Bohm & Solf 1994
Eisloffel & Mundt 1998
Solf et al. 1999
Herbst+ 2007

T Tau N: almost face-on DISK
Guillotteau+ 2011, 2013
Ratzka+ 2009

Herschel/HIFI obs of T Tau – envelope, outflows and disk em

CN lines: disk ?

H_2O, CO, [C II] lines: envelope + outflow



Podio+ in prep

CN → confusion-free probe of disk kinematics (Chapillon+ 12, Guillotteau+ 13)

- CN 2-1: less confusion by residual cloud em than in ^{13}CO -- high disk detection rate (>50%) in TTSs/HAeBe
- CN 5-4: Eup, ncr > than CN 2-1 -- hyperfine components separated by 0.2 – 0.5 km/s < peak separation

T Tau DISK model: the region emitting CN lines

***Pro**toplanetary **Di**sk **Mo**dels* **(ProDiMo)**

Woitke+ 2009, Kamp+ 2010, Thi+ 2011
Aresu+ 2011, 2012, Meijerink+ 2012

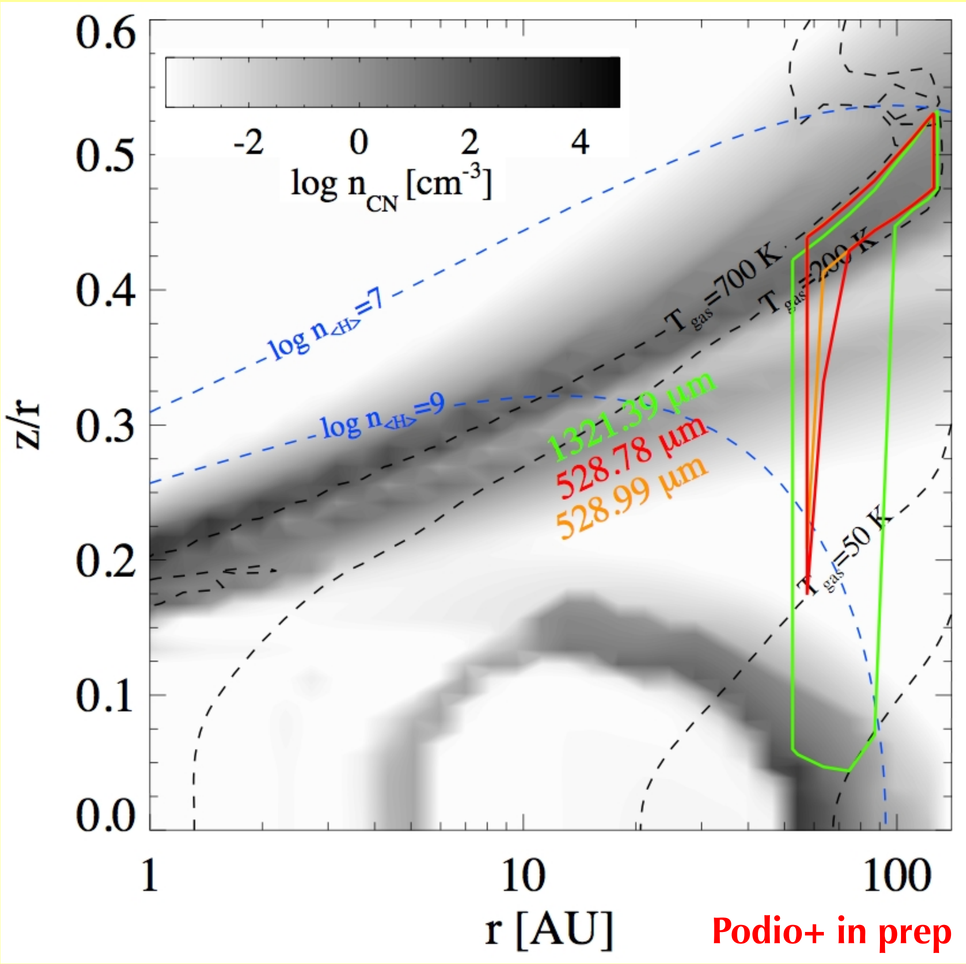
uses global iterations to consistently calculate physical, thermal, chemical structure of protoplanetary disks

large chemical network: 120 species, ~1650 reactions

See talk by W.F. Thi

CN lines by disk region

R = 50 – 140 AU
T = 30 – 700 K
<nH> = 1e7 – 1e10 cm^{-3}



T Tau disk model: star and disk parameters

Effective temperature	$T_{\rm eff}$ (K)	5250
Stellar mass	M_* ($M_\odot$)	2.1
Stellar luminosity	L_* ($L_\odot$)	7.3
UV excess	$f_{\rm UV}$	0.1
UV power law index	$p_{\rm UV}$	0.2
X-rays luminosity	L_X (erg s^{-1})	2 10^{31}
Disk inner radius	$R_{\rm in}$ (AU)	0.1
Disk outer radius	$R_{\rm out}$ (AU)	140
Disk dust mass	$M_{\rm dust}$ ($M_\odot$)	1.3 10^{-4}
Dust-to-gas ratio	dust-to-gas	0.01
Solid material mass density	$\rho_{\rm dust}$ (g cm^{-3})	2.5
Minimum grain size	$a_{\rm min}$ (μm)	0.005
Maximum grain size	$a_{\rm max}$ (μm)	1000
Dust size distribution index	q	3.5
Settling $H(R,a) = H(R)\ \frac{a}{a_{\rm set}}^{-s_{\rm set}/2}$	$s_{\rm set}$	0.5
Minimum grain size for settling (μm)	$a_{\rm set}$	0.25
Disk inclination	i (°)	30
Surface density $\Sigma \approx r^{-\epsilon}$	ϵ	-1
Scale height at $R_{\rm in}$	H_0 (AU)	0.0032
Disk flaring index $H(r) = H_0 \left(\frac{r}{R_{\rm in}}\right)^\beta$	β	1.25
Fraction of PAHs w.r.t. ISM	$f_{\rm PAH}$	0.01

Ratzka+ 2009

observed line fluxes in agreement with predicted ones within a factor 1.4

Conclusions

Herschel allowed observing atomic/molecular emission by late Class I, Class II

Herschel / PACS obs

ATOMIC EMISSION, i.e. [O I] 63 μm, [C II] 158 μm → associated with jets (**Extended**, velocity shifted)

MOLECULAR EMISSION, i.e. high-J CO, OH, H_2O → origin is unclear (**Unresolved** with PACS)

FIR cooling & mass loss rate decreases as the source evolve from Class 0 to Class II

Herschel / HIFI obs

Kinematics is crucial to understand the line origin !

H_2O lines in Class 0/I → dominated by envelope/outflow emission
In Class II → may probe the disk

CN lines → effective confusion-free disk tracer

What's next ?

Final test on line origin with spatially resolved maps of $H_2{}^{18}O$, CN lines with PdBI and ALMA