WATER in PROTOPLANETARY DISKS
Herschel and beyond

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1st FISICA Workshop: *Science Goals of a Sub-arcsecond Far-infrared Space Observatory* – Rome – Feb 2014

PROTOPLANETARY DISKS are the birthplace of planets

the study of their physical and chemical structure is fundamental to comprehend the formation of our own solar system & extra-solar planetary systems

different lines probes the physical/chemical conditions of the gas located in different regions of the disk

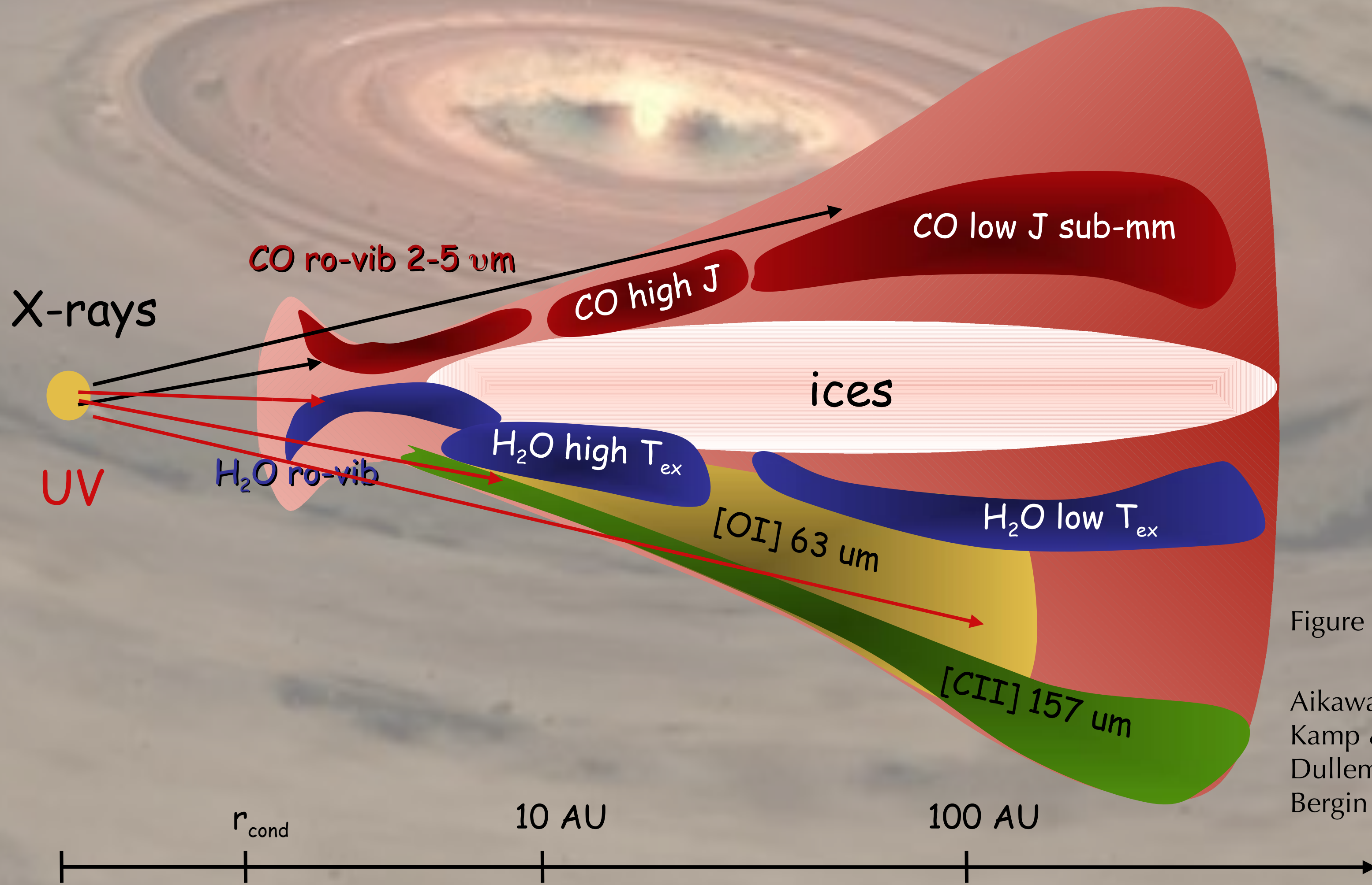


Figure by Inga Kamp

Aikawa et al. 2002
Kamp & Dullemond 2004
Dullemond et al 2007
Bergin et al. 2007

What is the origin of WATER ON EARTH ?

1 $M_\oplus$ = 5.9722e27 g
1 earth ocean = 1.5e24 g = 2.5e-4 $M_\oplus$

Total H_2O mass on earth:
Max: 50x oceans (Abe+ 2000)
Avg: 10x oceans (Ohtani+ 2005)

based on the water storage potential of minerals in the silicate Earth

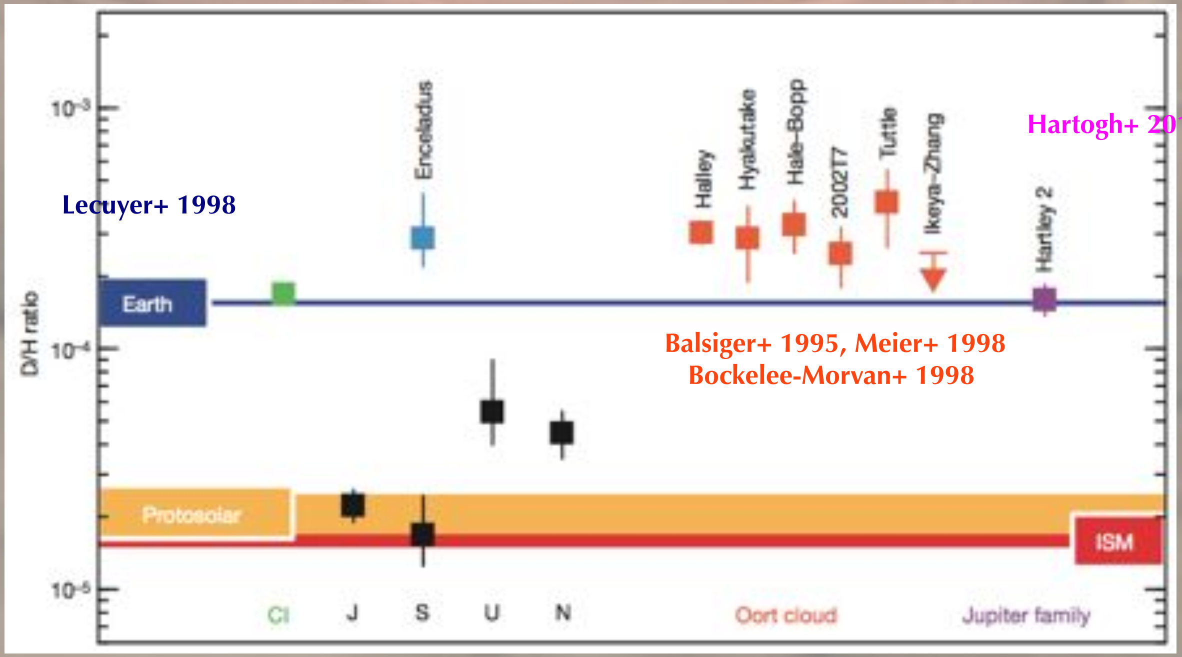
What is the origin of WATER ON EARTH ?

Matsui & Abe 1986
Drake 2005
Morbidelli+ 2000
Hartogh+ 2012

METEORITES show a gross correlation btw their H_2O content and their original heliocentric distance:
Carbonaceous chondrites from outer asteroids belt (~2.5-4 AU) ---> 10% H_2O
Enstatite chondrites from inner asteroid belt (~2AU) ---> dry, i.e. 0.05-0.1% H_2O

“DRY accretion” + late H_2O delivery by asteroids/comets

H/D ratio → unaltered in the Earth's crust over time
→ diagnostic of the isotopic composition of the planetesimal that delivered H_2O to Earth



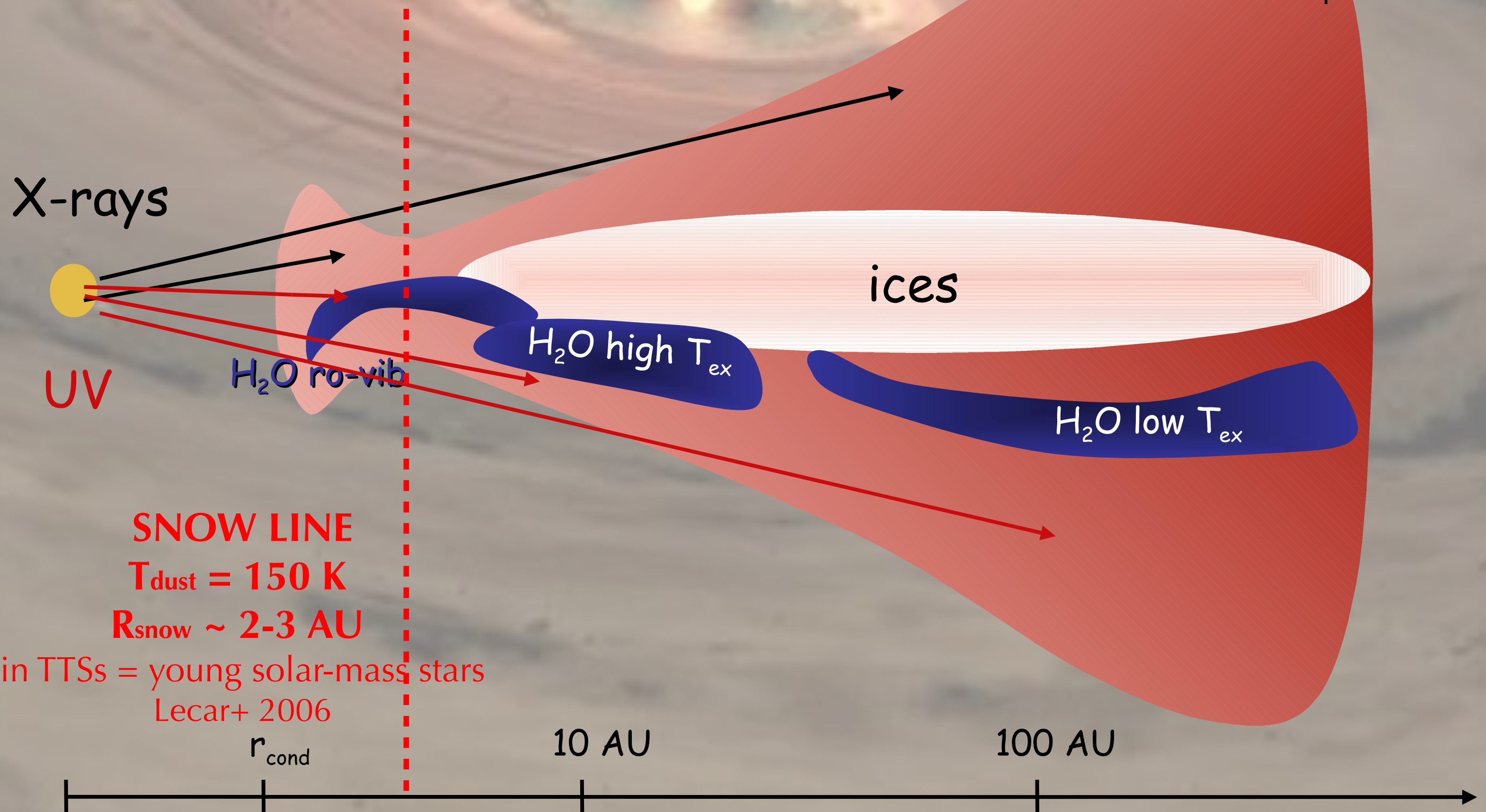
Earth --> (D/H) = (1.558 ± 0.001) 1e-4
~ D/H in Carbonaceus chondrites (ASTEROIDS) and Jupiter-family COMETS

H_2O location & mass in protoplanetary disks

R < R_{snow}
H_2O is evaporated
H_2O gas >> H_2O ice

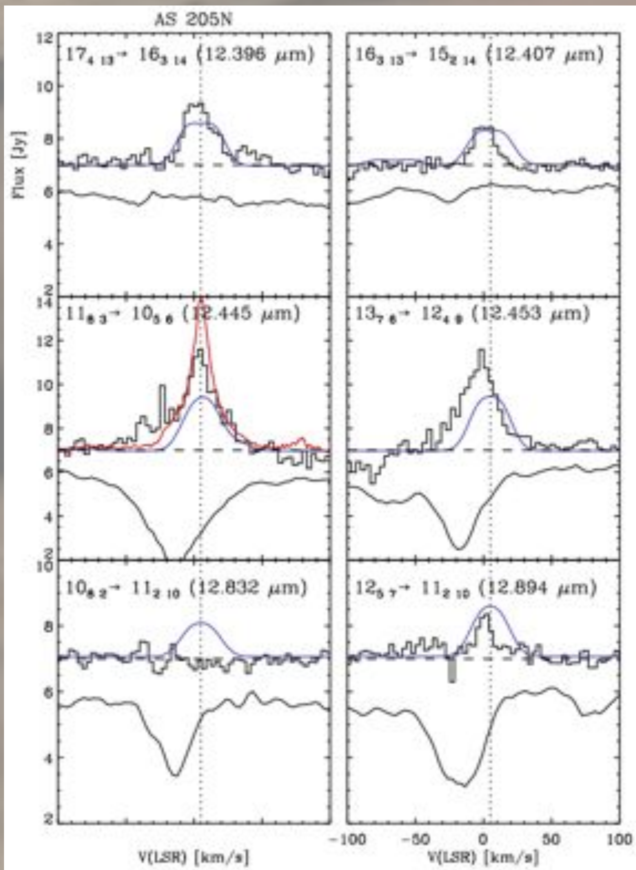
R > R_{snow}
H_2O frozen on dust grains
H_2O gas << H_2O ice

In the outer disk upper layers H_2O photo-desorbed & photo-dissociated
Dominik+ 2005
Ceccarelli+ 2005
Kamp+ 2013



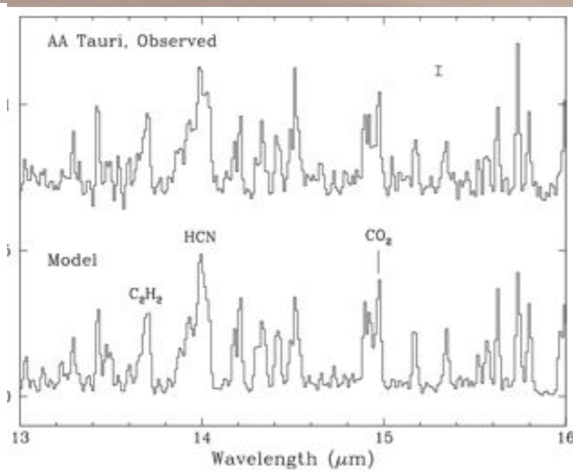
WATER in PROTOPLANETARY DISKS before HERSCHEL

High-exc rotational H_2O lines
from the HOT INNER DISK
(E_{up} ~2000-5000 K, T=500-600 K, R=0.5-5 AU)



AS 205N – VLT-VISIR (12-33um)

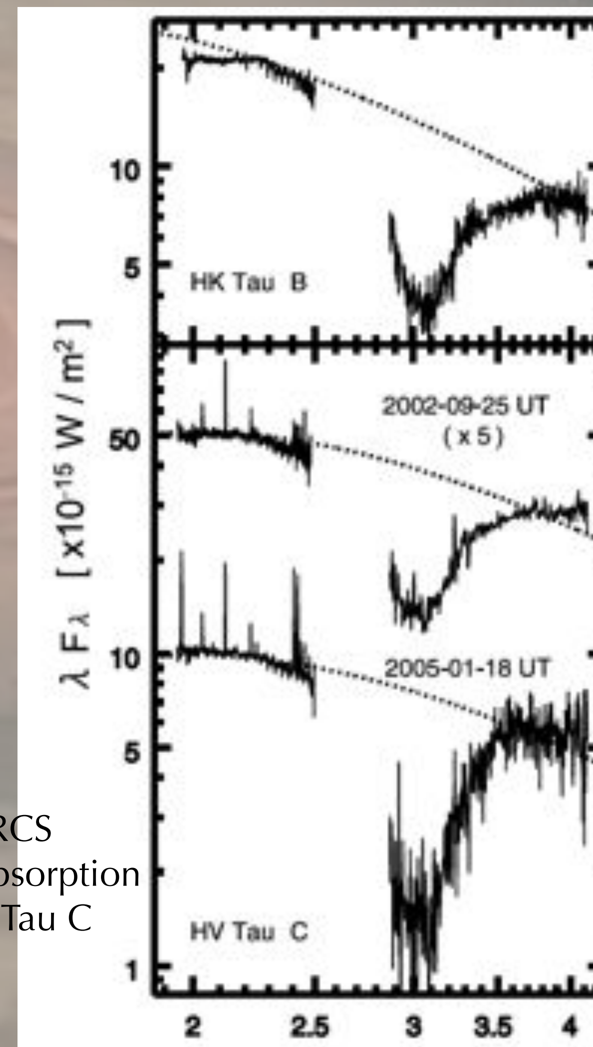
Pontoppidan+ 2010b



AA Tau – Spitzer-IRS (10-36um)

Carr & Najita 2008
Salyk+ 2008
Pontoppidan+ 2010a

water ice absorption
from the COLD OUTER DISK

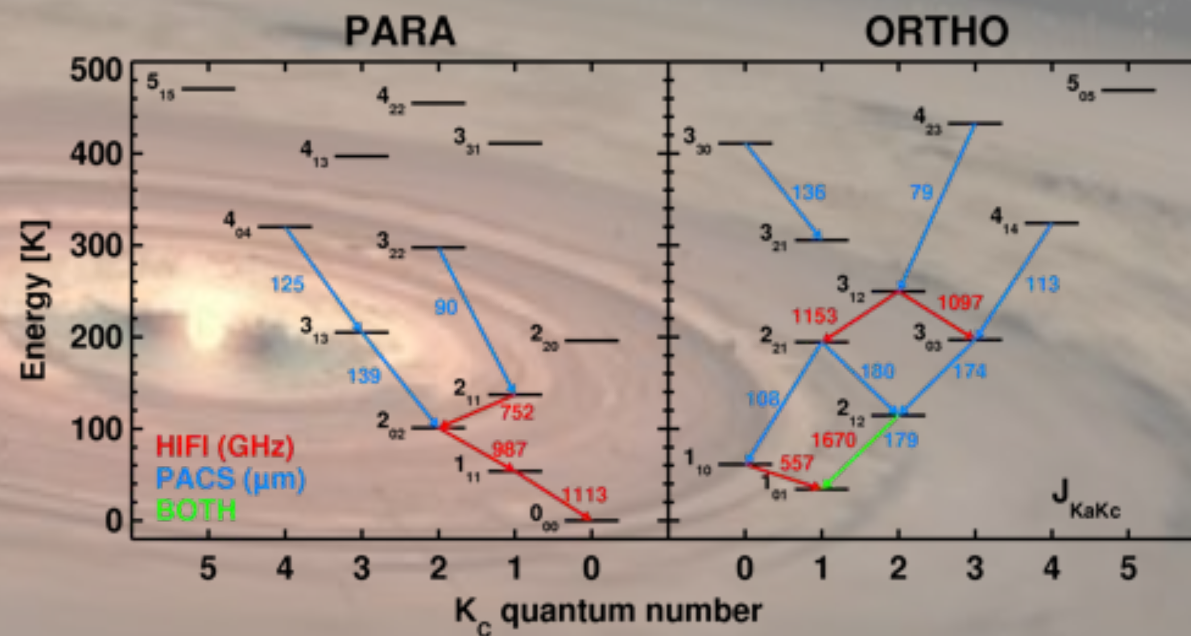


SUBARU/IRCS
3um water ice absorption
HK Tau B, HV Tau C

Terada+ 2007
Honda+ 2009

HERSCHEL:
A NEW WINDOW to DETECT WATER in PROT DISKS

May 14 2009 – April 29 2013
3.5m mirror – 55-672 um
3 instruments: PACS, SPIRE, HIFI

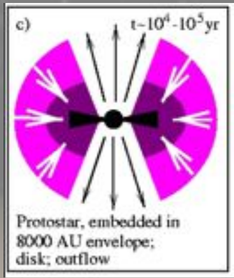


Guaranteed and Open Time Key Programs covering disks:

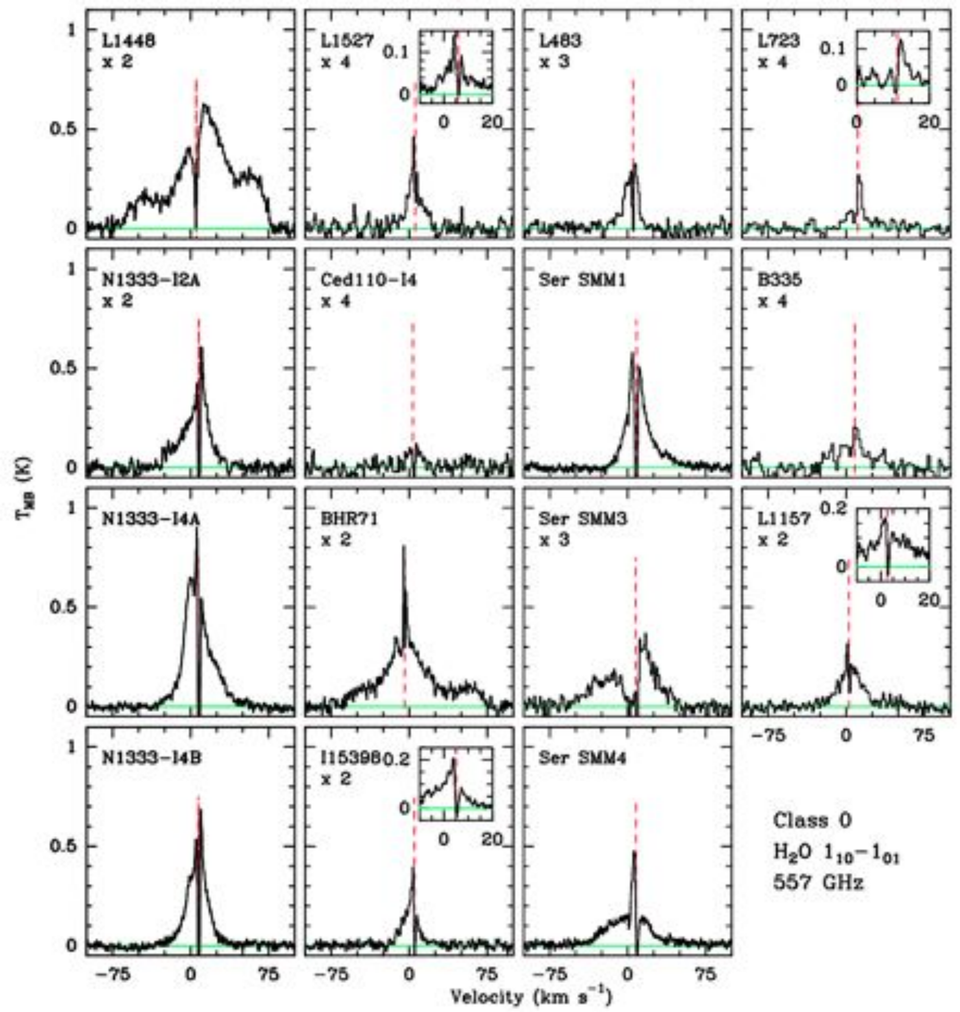
WISH – Water in star forming regions (PI: van Dishoeck)
DIGIT – Dust, ice, and gas in time (PI: Evans)
GASPS – GAS in Protoplanetary Systems (PI: Dent)
DUNES – debris disk program (PI: Eiroa)
DEBRIS – debris disk program (PI: Matthews)

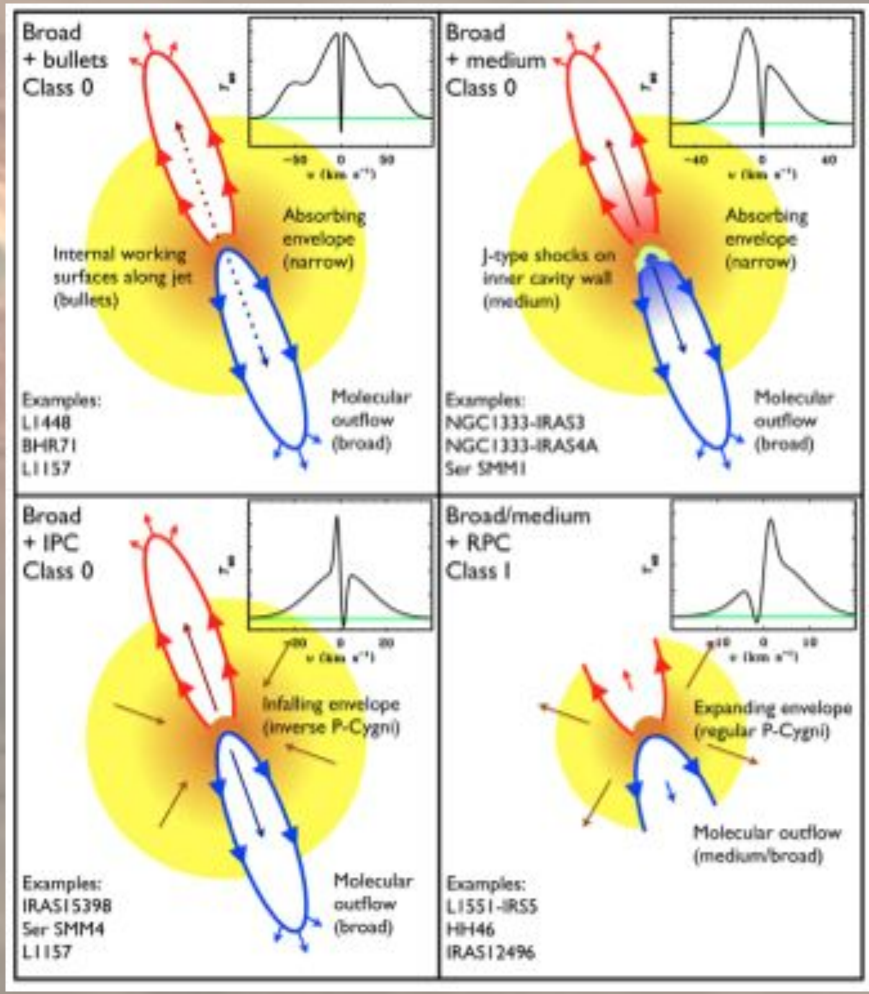
Low-exc H_2O 1_{10}-1_{01} (557 GHz, E_{up} ~ 61 K) from Class 0/I sources dominated by ENVELOPE + OUTFLOW emission

Class 0/I



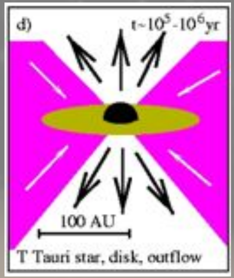
Kristensen+ 2012 - Herschel/HIFI



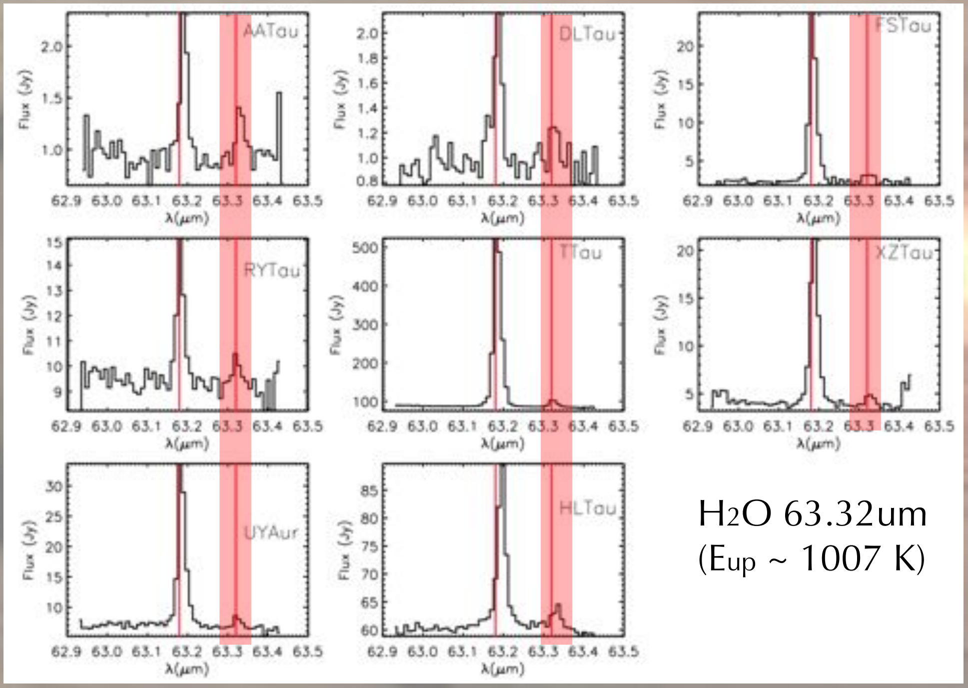


in Class II ?

Class II



High excitation H_2O lines from INNER DISK



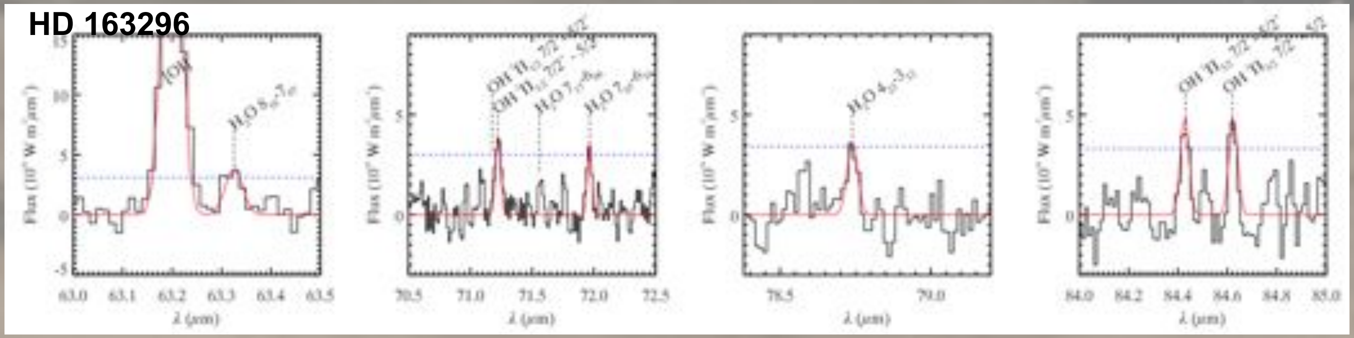
detected in 8 TTSs in Taurus ...

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

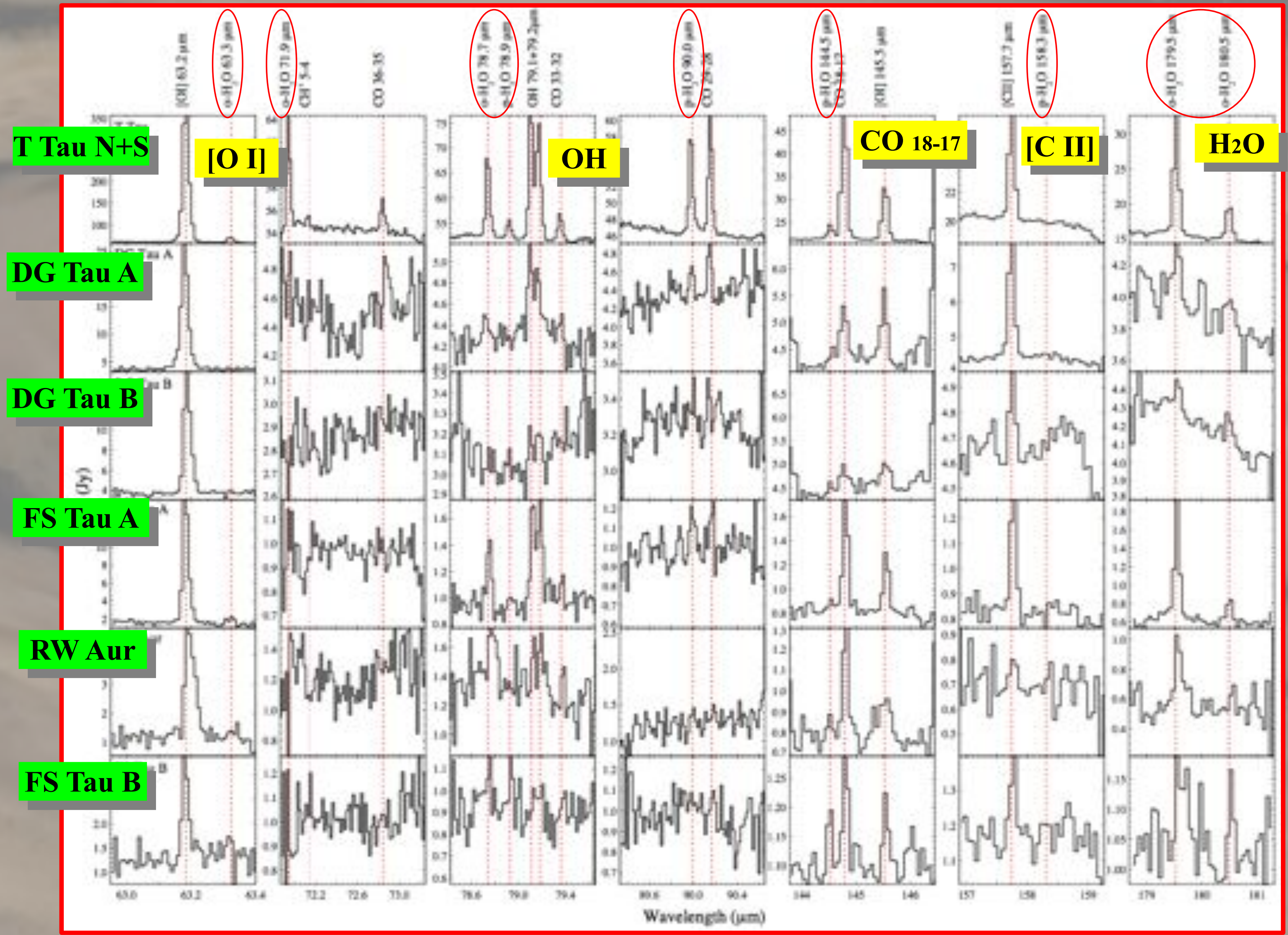
Riviere-Marichalar+ 2012

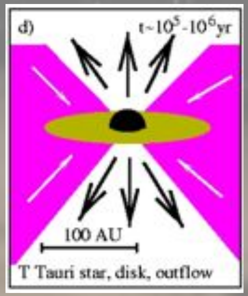
... and in 1 Herbig Ae !!

Meeus+ 2012
Fedele+ 2013



Low- and high- exc H_2O (E_{up}~100-1000 K) in jet-driving sources





Herschel/PACS obs

Podio+ 2012

Origin of H_2O emission ??

Herschel/PACS obs:

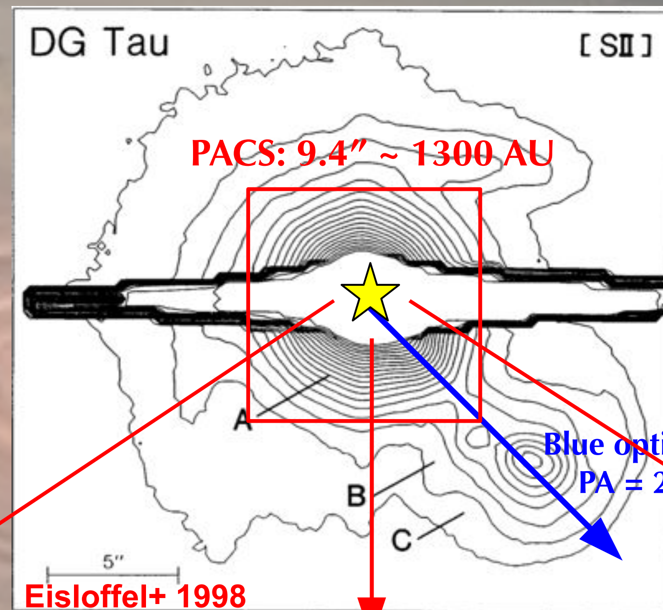
LOW SPATIAL RESOLUTION

1 spaxel = 9.4″ x 9.4″

LOW SPECTRAL RESOLUTION

DV > 80 km/s

H_2O emission spectrally and spatially unresolved !!



Young solar-analog DG Tau

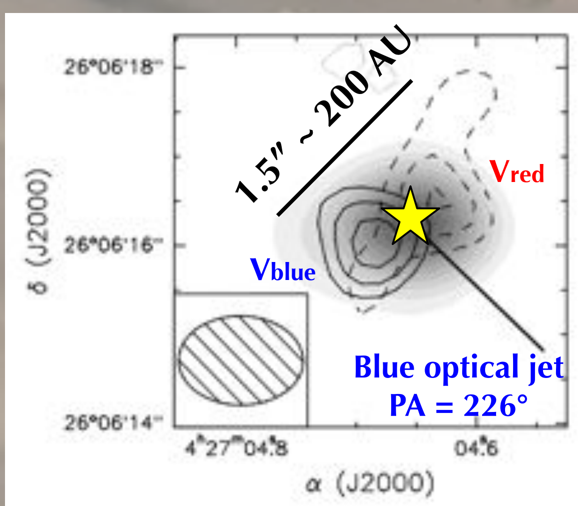
D = 140 pc

$M_* = 0.7\ M_\odot$

$L_* = 1\ L_\odot$

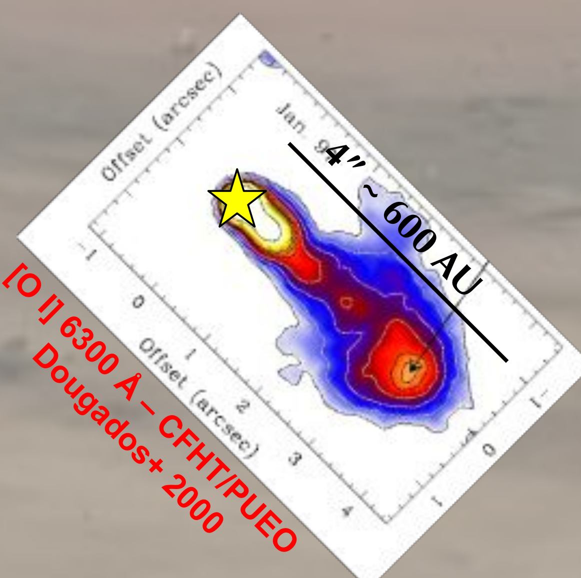
age = 2.5 Myr

DISK ?



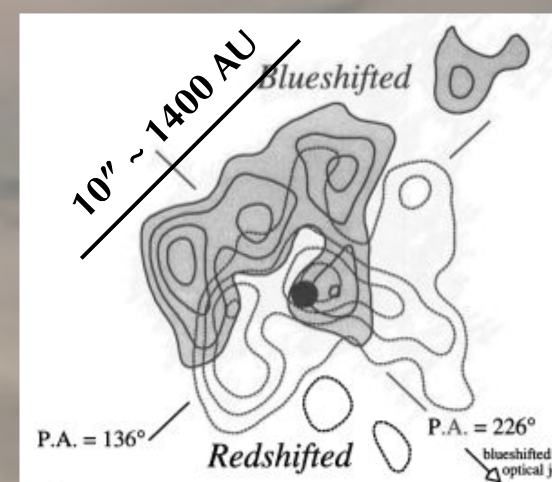
[13]CO 2-1 – OVRO – Testi+ 2002

or JET ?



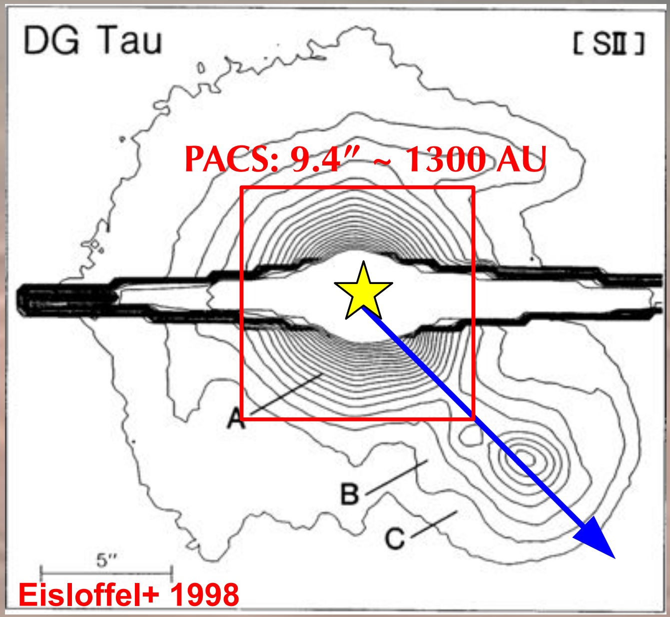
[O I] 6300 Å – CFHT/PUEO Dougados+ 2000

or ENVELOPE ?

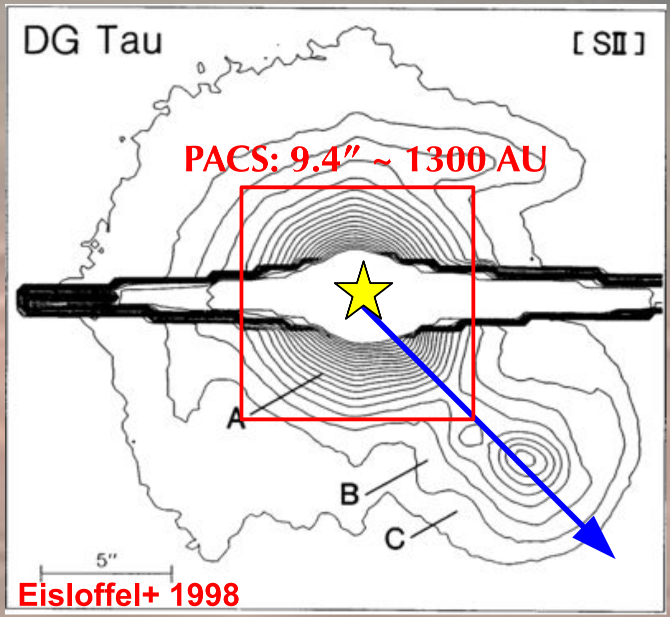


[13]CO 1-0 – Kitamura+ 1996

How to constrain the origin of H_2O emission ??



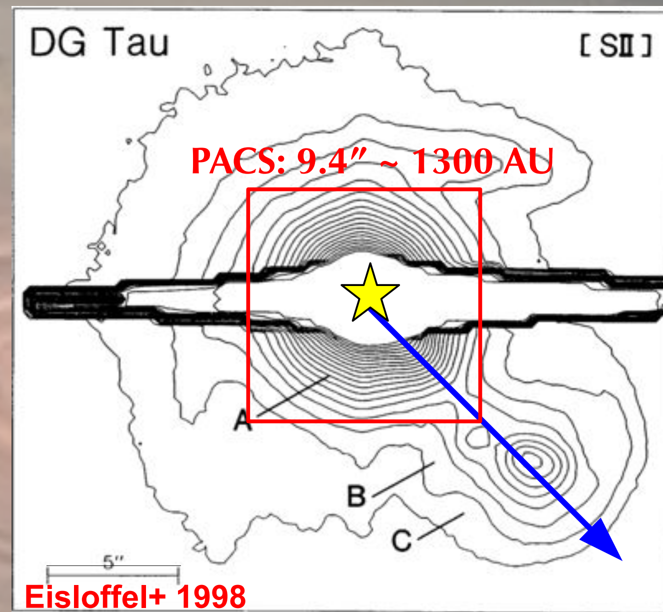
How to constrain the origin of H_2O emission ??



FAR INFRARED SPACE INTERFEROMETER ??

How to constrain the origin of H_2O emission ??

HIFI: 40″ ~ 5300 AU
for H_2O 557 GHz



or ... Herschel/HIFI observations

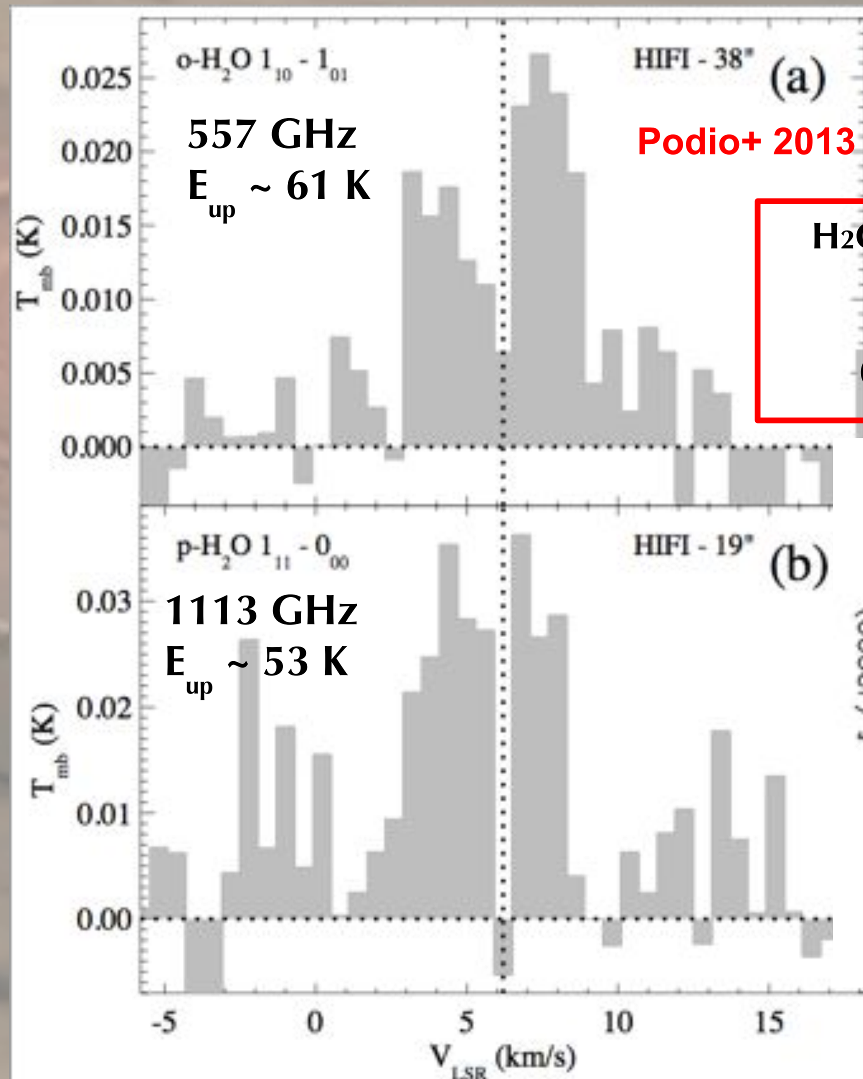
NO SPATIAL RESOLUTION (beam ~11″ - 40″)
BUT high spectral resolution (~ 0.5 km/s) !!

OT1 program to observe 7 jet-sources in H_2O, CO 10-9, [C II]
(25 hours, PI: L. Podio)

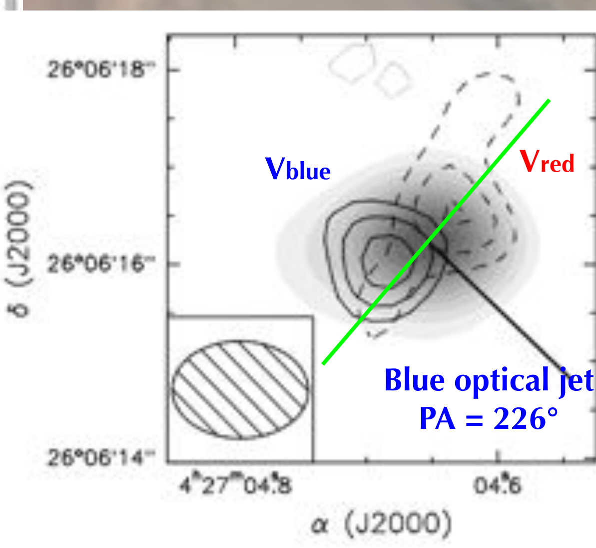
Herschel/HIFI observations of DG Tau
low-exc WATER emission from OUTER DISK !

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

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

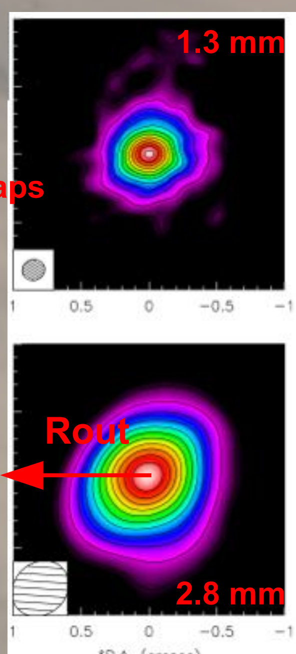


3. H_2O line peaks in the velocity ranges
where ^{13}CO 2-1 interf maps
trace the disk rotation
(V gradient perp to jet direction)



Testi+ 2002

CARMA cont maps
Isella+ 2010



Modeling H_2O emission from the DISK of DG Tau

Low dust opacity model

"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

Fischer+ 2011
Siess+ 2000
Gullbring+ 2000
Gudel+ 2007
Akeson+ 2005
Isella+ 2010
Eisloffel & Mundt 1998

dust size distribution & dust mass to reproduce cont at 1.3, 2.8 mm (Isella+ 2010)

BUT equally reproduced by high dust opacity & lower dust mass

High dust opacity model

Mdust = 1e-4 Msun

ρ_dust = 2.5 gr/cm-3, a_min = 0.005um, a_max = 750um, q = 3

DISK model: the region emitting low-exc H_2O lines

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

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

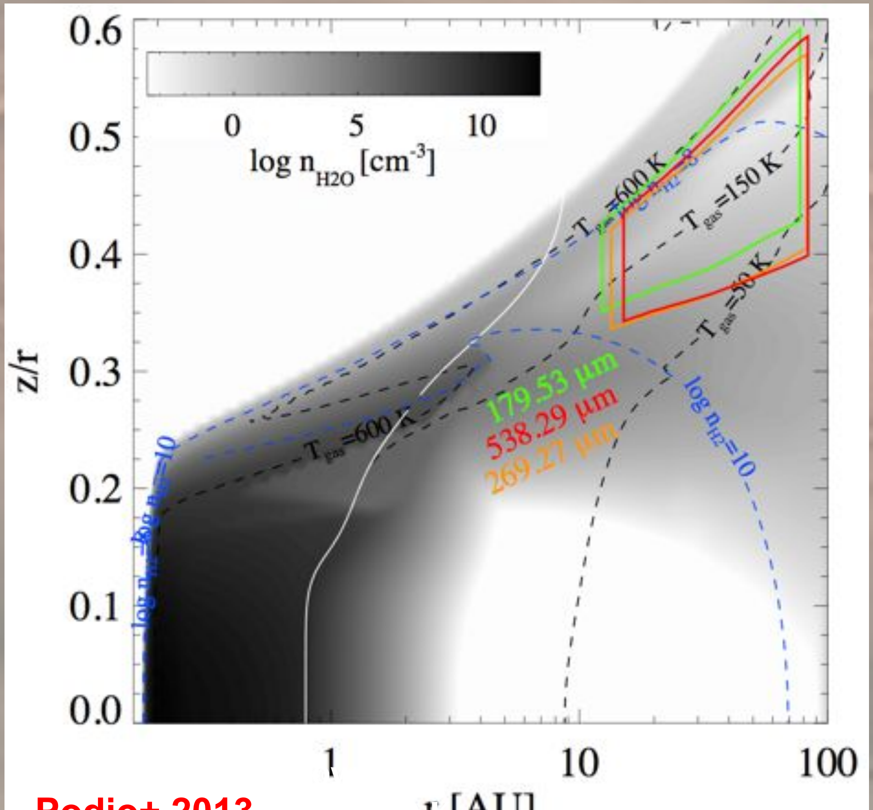
uses global iterations to consistently calculate
physical, thermal, chemical structure of protoplanetary disks.

large chemical network: 120 species, ~1650 reactions

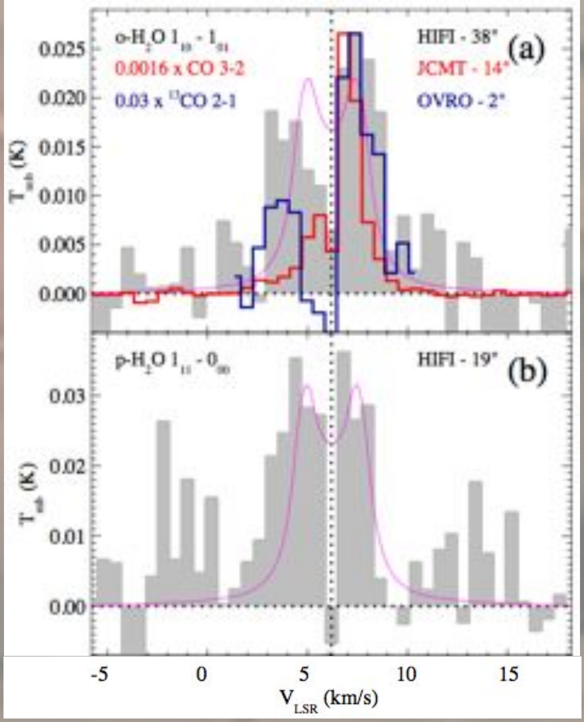
H_2O 557, 1113 GHz (HIFI)
H_2O 179.5um (PACS)
emitted by same disk region

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

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



Podio+ 2013



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

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

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

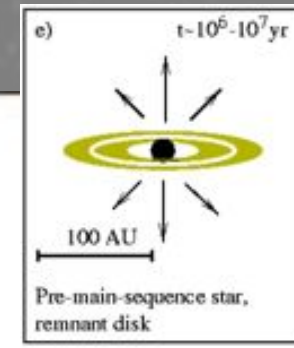
Since H_2O lines are optically thick
disk and water masses are constrained with one order of magnitude uncertainty

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

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

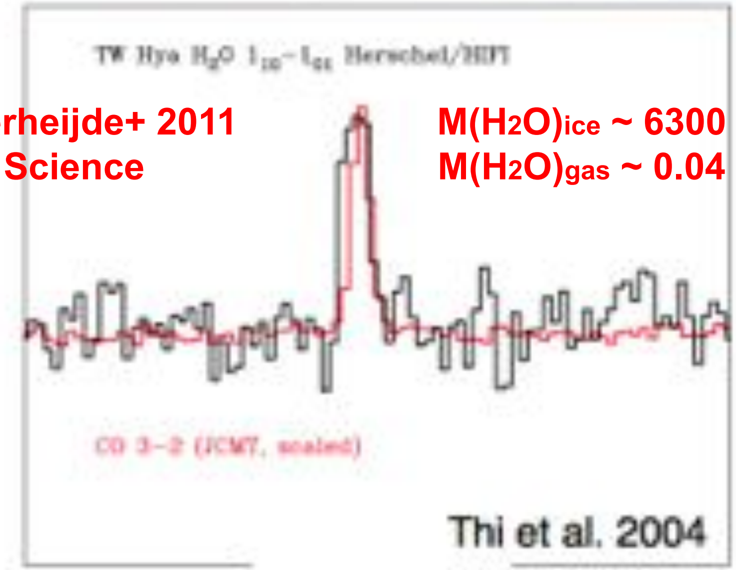
→ **supports the scenario of**
impact delivery of water on terrestrial planets
by means of icy bodies forming in the outer disk

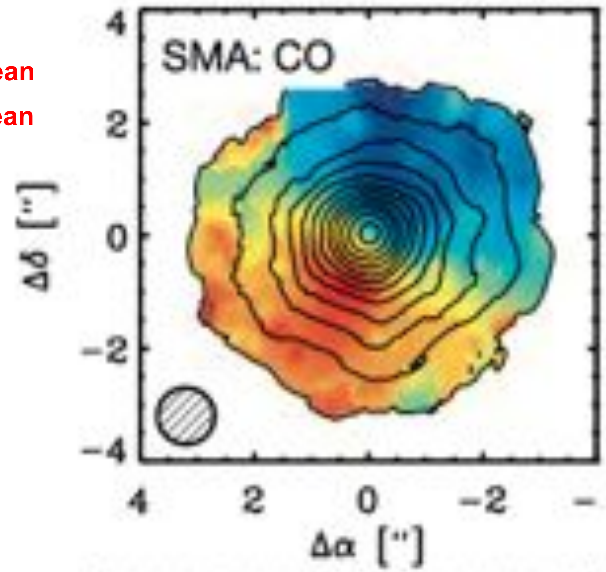
Clear detection of low-exc H_2O from more evolved sources



Hegerheijde+ 2011 Science

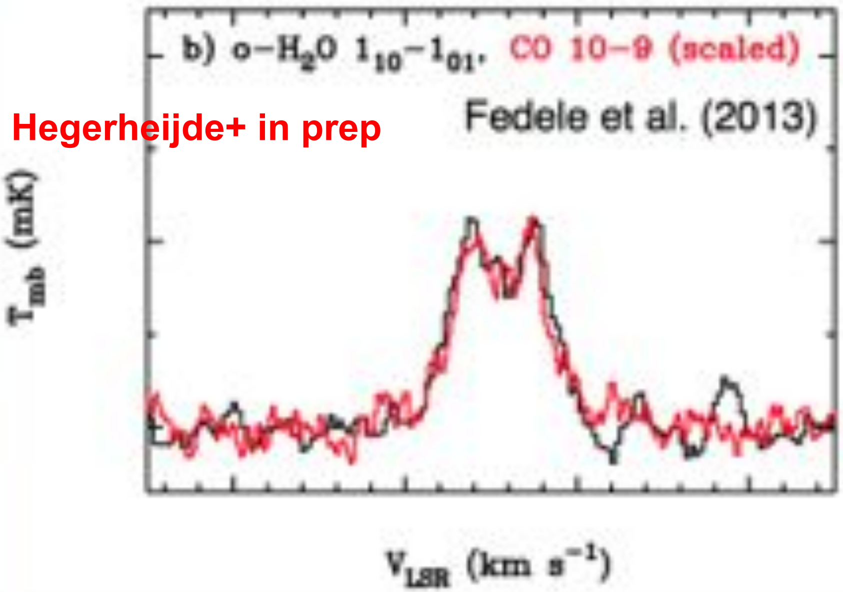
$M(H_2O)_{ice}$ ~ 6300 M_{ocean}
$M(H_2O)_{gas}$ ~ 0.04 M_{ocean}

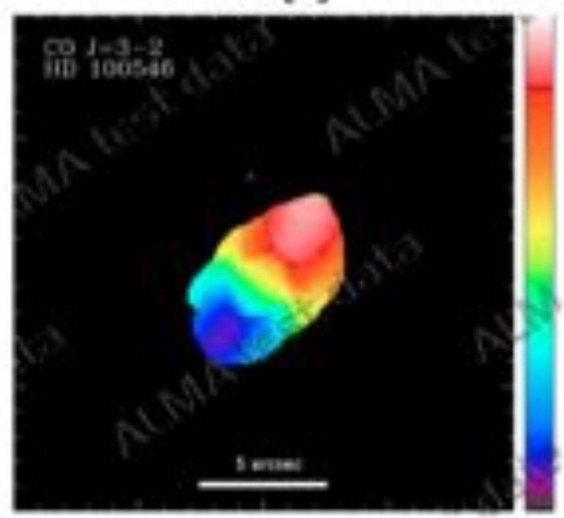




Andrews et al. (2011)

Hegerheijde+ in prep

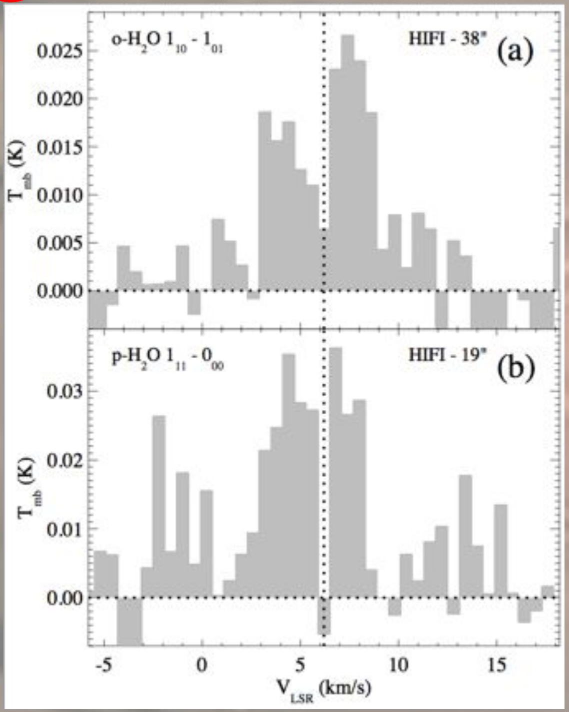




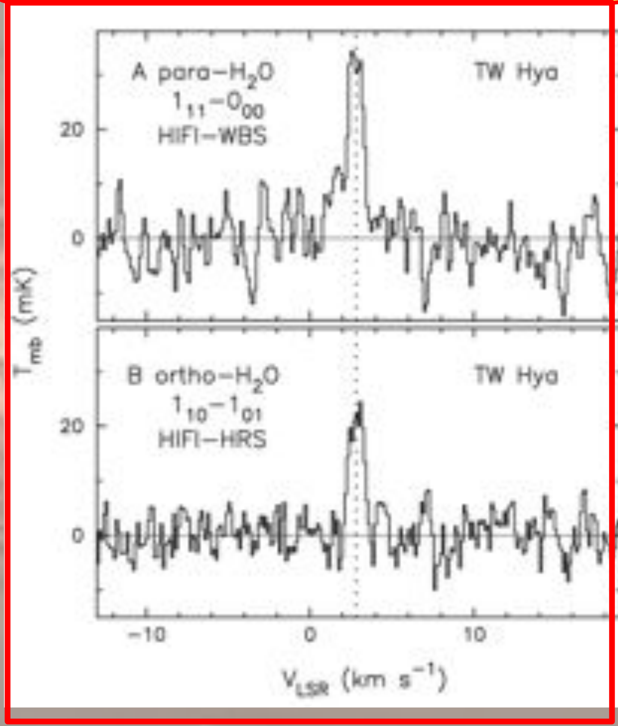
From M. Hogerheijde presentation Herschel conference

Detections of water in disks with Herschel

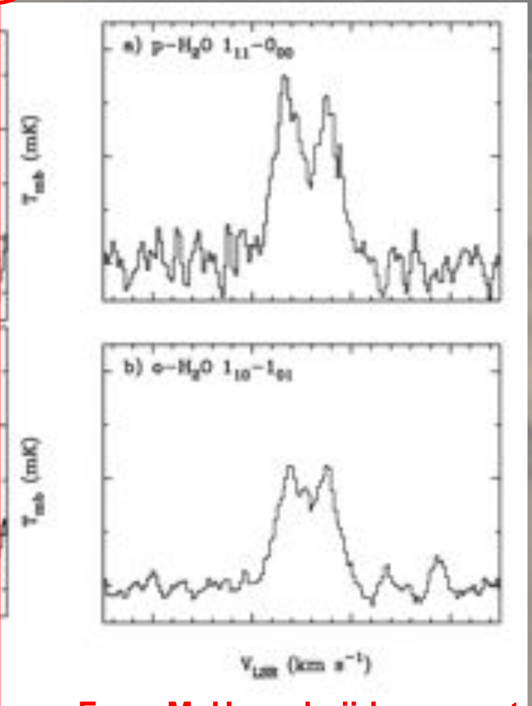
2. DG Tau (Podio+ 13)



1. TW Hya (Hogerheijde+ 11)



3. HD 100546 (Hogerheijde+, in prep)



From M. Hogerheijde presentation
Herschel conference

OT1-OT2 programs on disk sources (PI: Hogerheijde): 200 hours of observing time

<u>---> detection only in 2 sources (TW Hya, HD 100546)</u>

---> upper limits for 5 sources (DM Tau, AA Tau, HD 163296, LkCa15, MWC 480)

OT1 program on jet sources (L. Podio): 26 hours of observing time

<u>---> disk origin only in 1 source (DG Tau)</u>

---> H_2O by envelope/outflow in T Tau, FS Tau + upper limits for 4 sources (DG Tau B, RW Aur, HD 163296, AB Aur)

Limits of Herschel observations and FUTURE perspectives

SENSITIVITY LIMIT !

----> Only three detections of low-exc H_2O from outer disk

NO SPATIAL INFORMATION !!!!

(PACS ~ 9.4″ ---- HIFI ~ 11″- 40″)

----> <u>difficult to disentangle envelope/jet/disk emission</u>

----> <u>only *indirect* constraints on H_2O location in the disk (from the line profile)</u>

To study H_2O in disks WE NEED

- **<u>A new telescope in the FIR !</u>**
- **<u>Higher sensitivity !</u>**
- **<u>Sub-arcseconds spatial resolution !</u>**
  + spectral resolution

FAR INFRARED SPACE INTERFEROMETER !!