WATER IN PROTO-PLANETARY DISKS:
future perspectives with SPICA

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GASPS

SPICA workshop – Feb 7-8 2013

SPICA science goals

1. What are the conditions for planet formation and the emergence of life ?

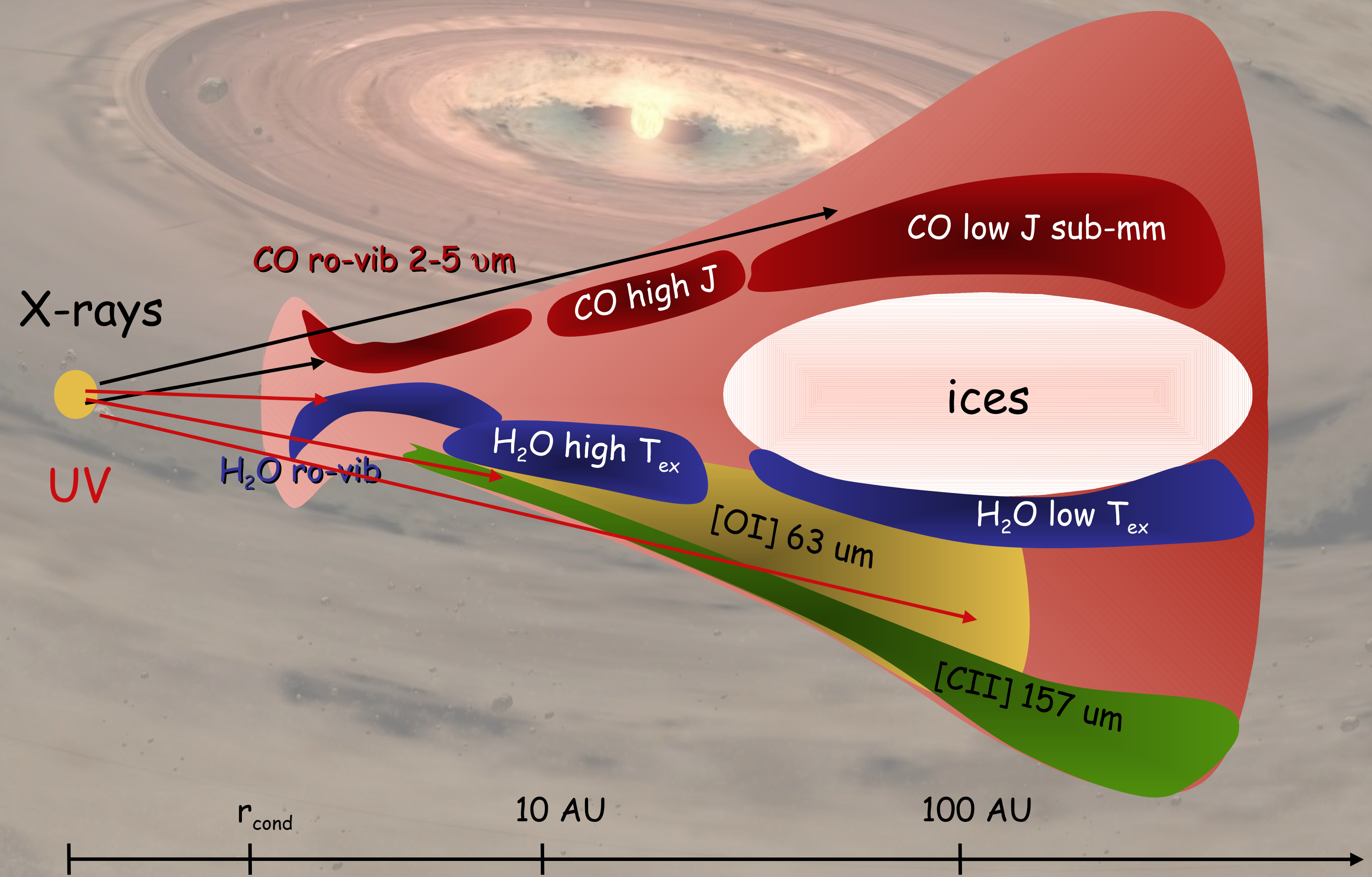
2. How does the Solar System work?

3. How did the Universe originate and what is it made of?

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

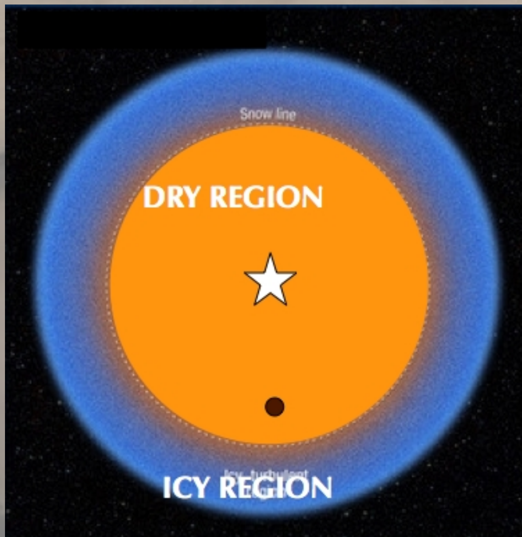
different lines probes the physical/chemical conditions of the gas located in different regions of the disk



What is the origin of WATER ON EARTH ?

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

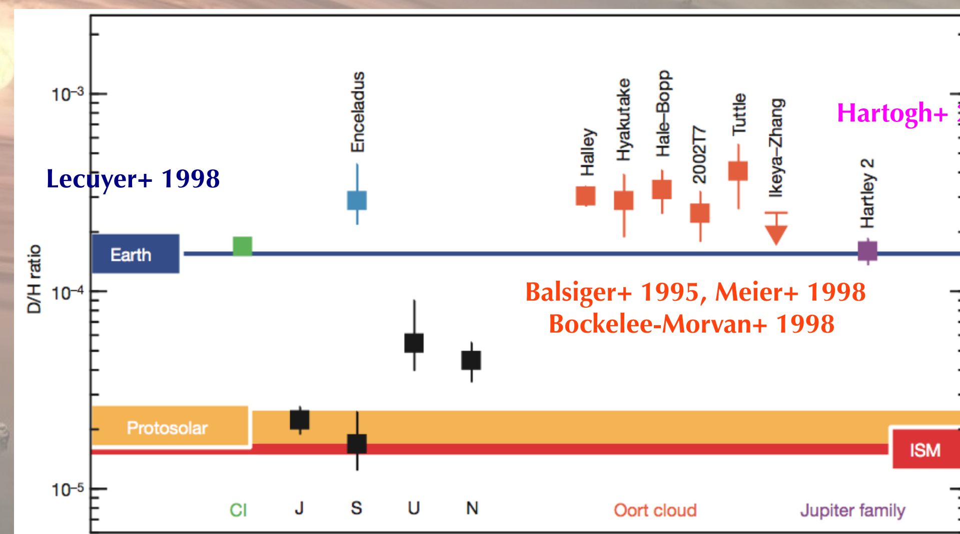
Matsui & Abe 1986
Drake 2005
Morbidelli+ 2000
Hartogh+ 2012



"DRY accretion"

+ late H_2O delivery by asteroids/comets

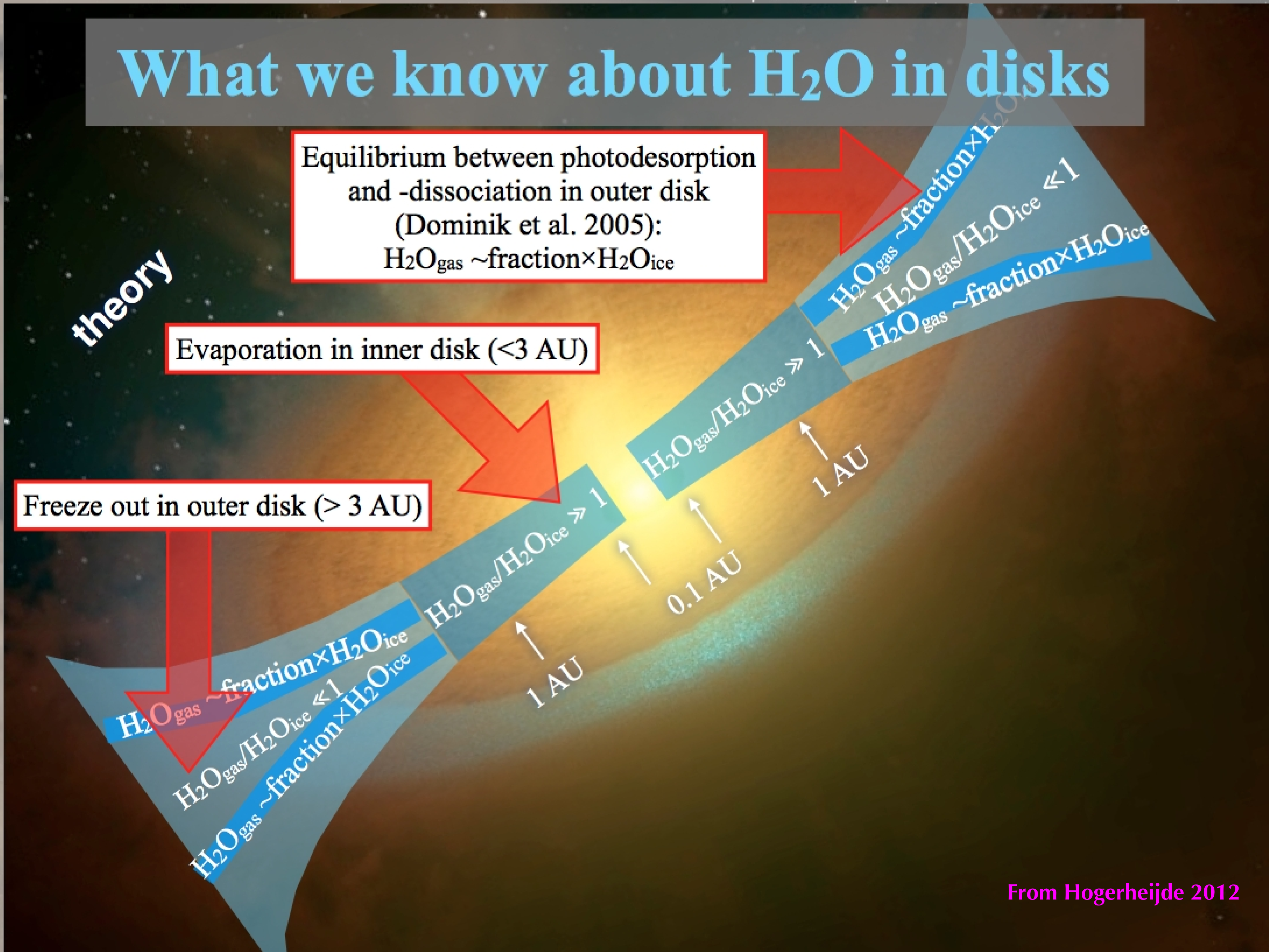
Earth --> (D/H) = (1.558 ± 0.001) 1e-4
~ D/H in Carbonaceus chondrites (ASTEROIDS) and Jupiter-family COMETS



"WET accretion"

hydrous mineral in the planetesimals
from which Earth formed

water location & mass in protoplanetary disks

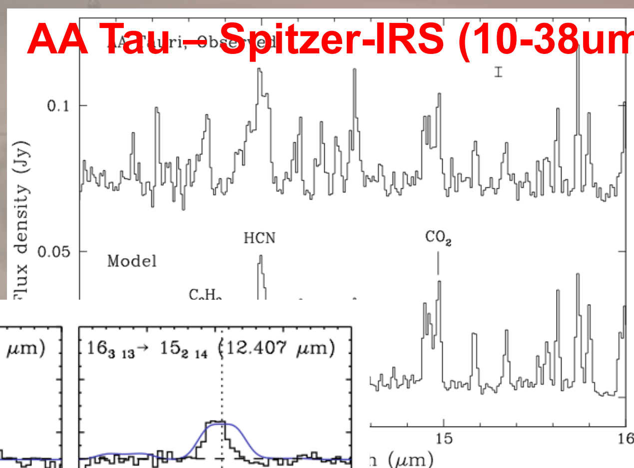


WATER in PROT DISKS before HERSCHEL

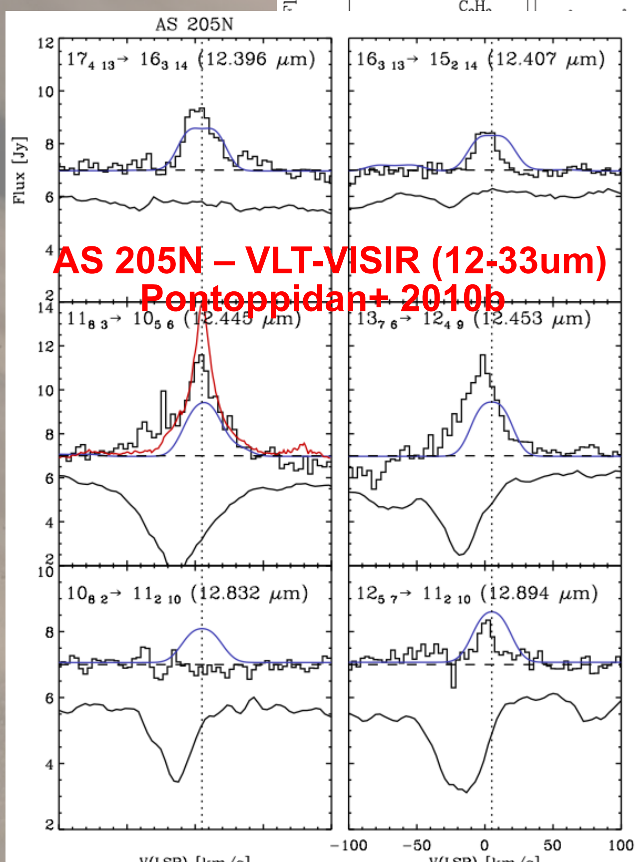
High-exc WATER from the HOT INNER DISK

Carr & Najita 2008
Salyk+ 2008
Pontoppidan+ 2010a

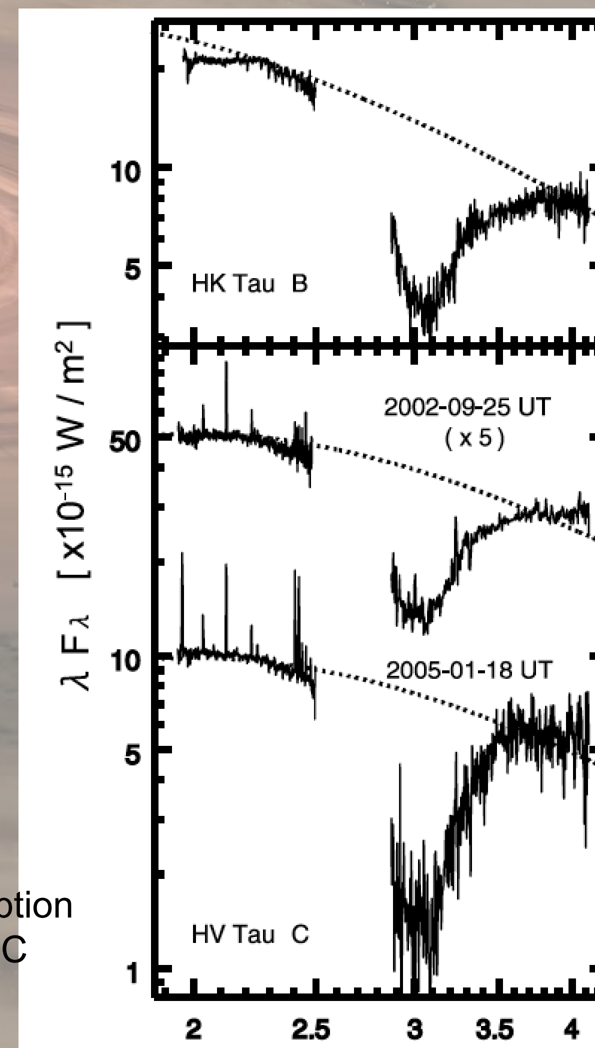
AA Tau – Spitzer-IRS (10-38um)



AS 205N – VLT-VISIR (12-33um)
Pontoppidan+ 2010b



Water from the COLD OUTER DISK



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

Terada+ 2007
Honda+ 2009

HERSCHEL:
A WINDOW to DETECT WATER in PROT DISKS

ESAs fourth cornerstone mission

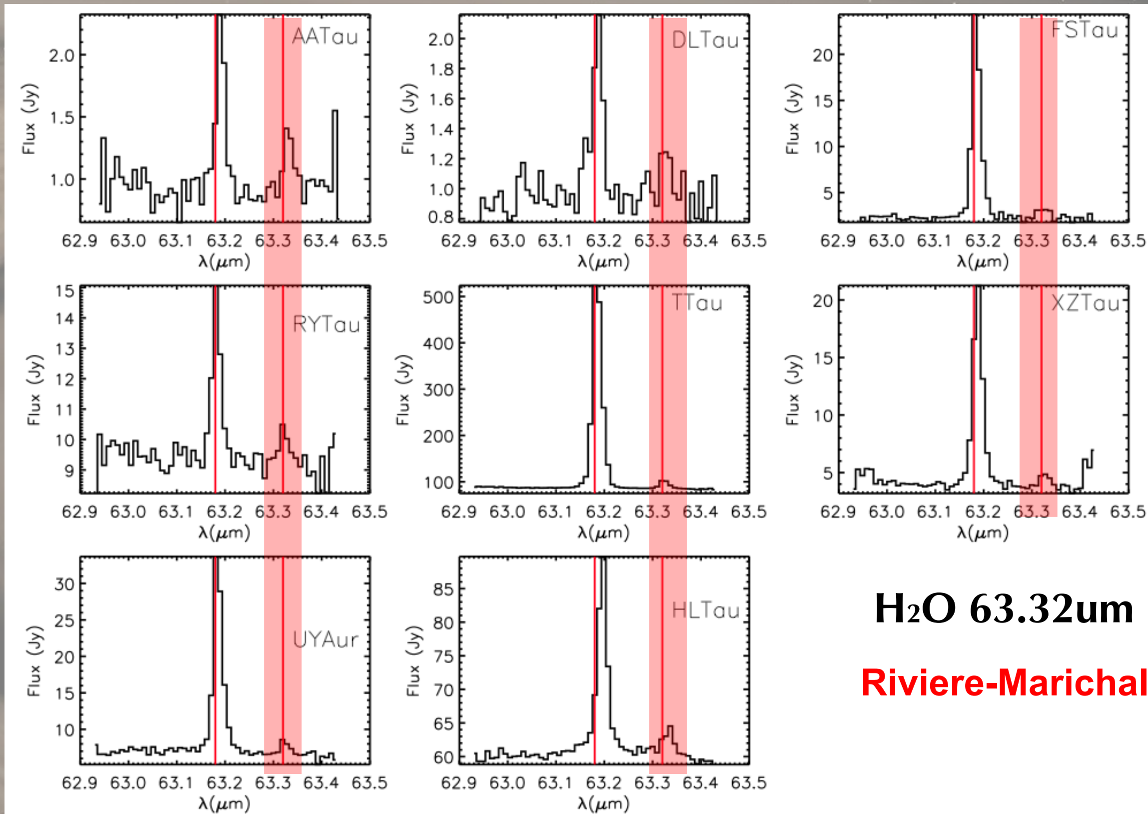
3.5m mirror – 55-672 um
Launched 14 May 2009
Orbit around L2
Mission lifetime 3+ yrs (GT&OT KP,OT1,OT2)

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: Bergin)
GASPS – Gas in protoplanetary systems (PI: Dent)
DUNES – debris disk program (PI: Eiroa)
DEBRIS – debris disk program (PI: Matthews)

HOT WATER from INNER DISK



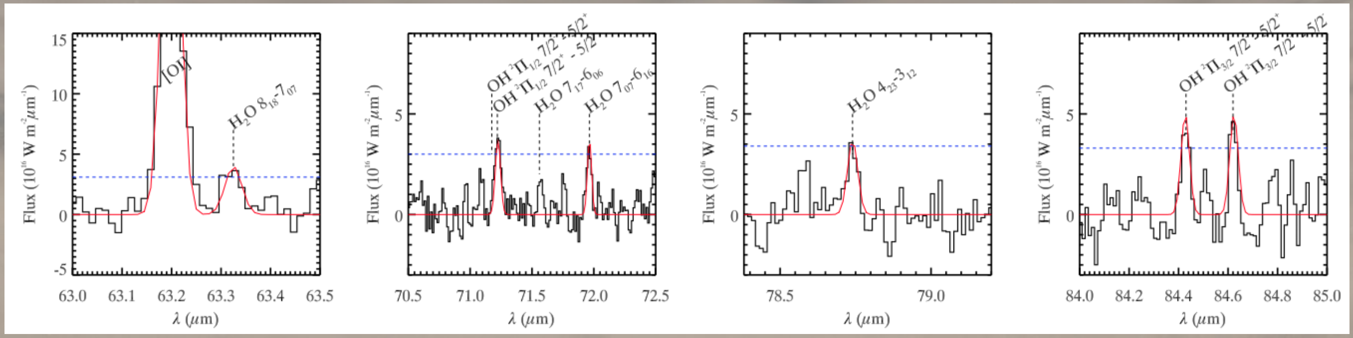
detected in 8 TTSs in Taurus ...

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

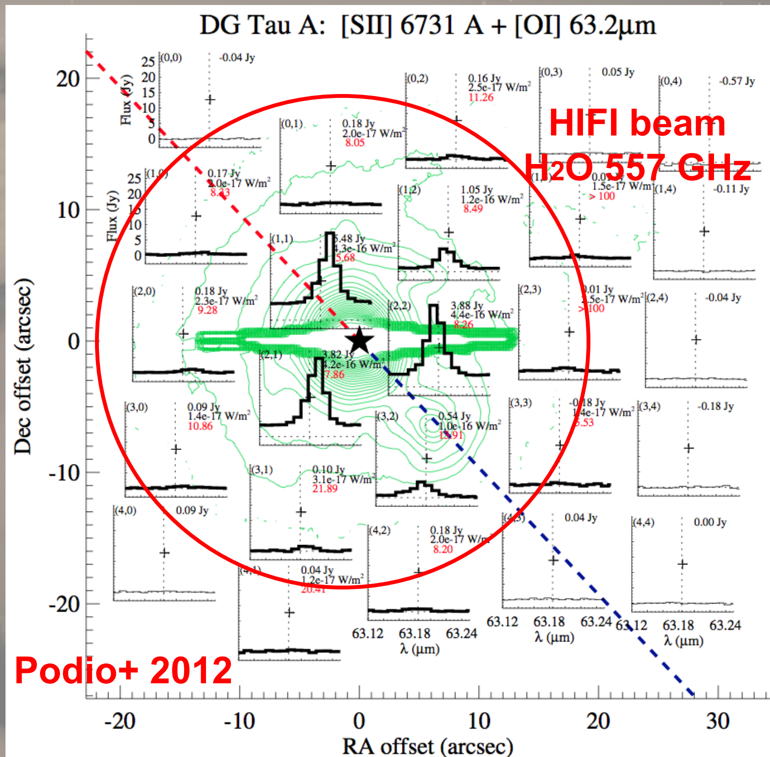
Riviere-Marichalar + GASPS 2012

... and in 1 Herbig Ae/Be !!

Meeus + GASPS 2012
Fedele + DIGIT/WISH 2013



Both high- low-exc H_2O emission from jet-driving sources



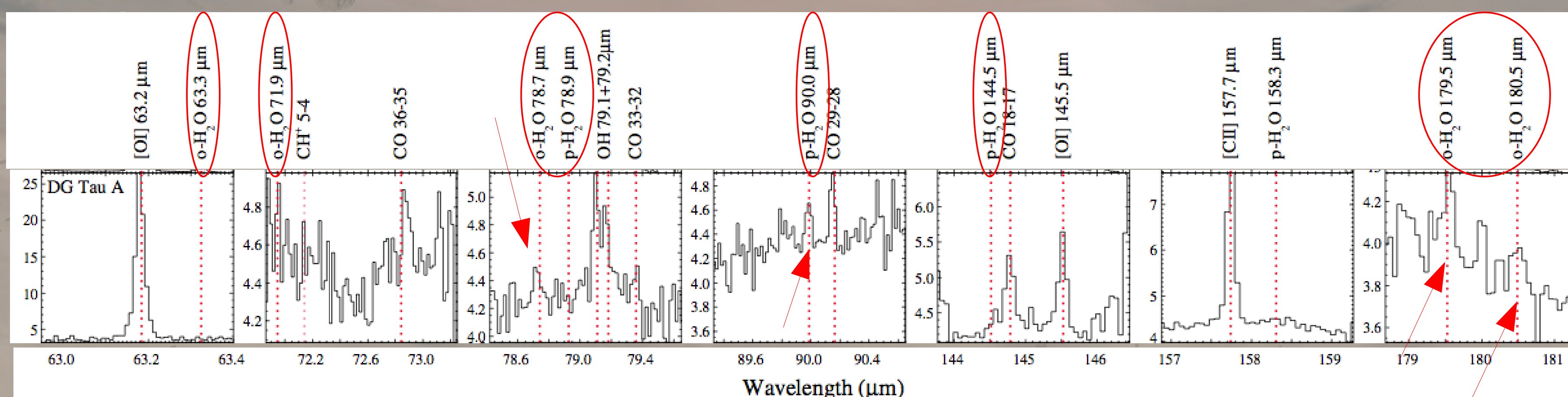
DG Tau

jet + disk + envelope

Atomic emission [OI], [CII] lines
extended along "optical-jet" axis, blue- red-shifted

Molecular emission H_2O, high-J CO lines
spectrally and spatially unresolved with PACS !!
(DV > 80 km/s, 1 spaxel = 9.4″ x 9.4″)

H_2O from jet, disk, or envelope ?

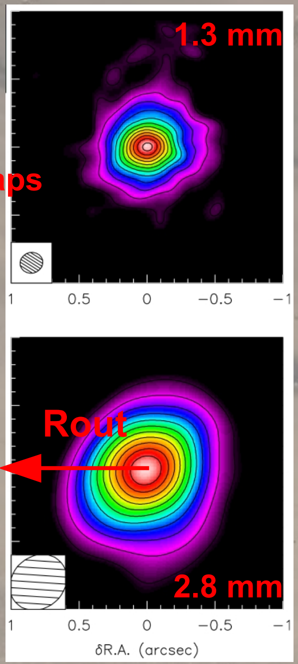


follow-up Herschel/HIFI observations
7 sources in H_2O, CO 10-9, [CII] (PI: L. Podio)

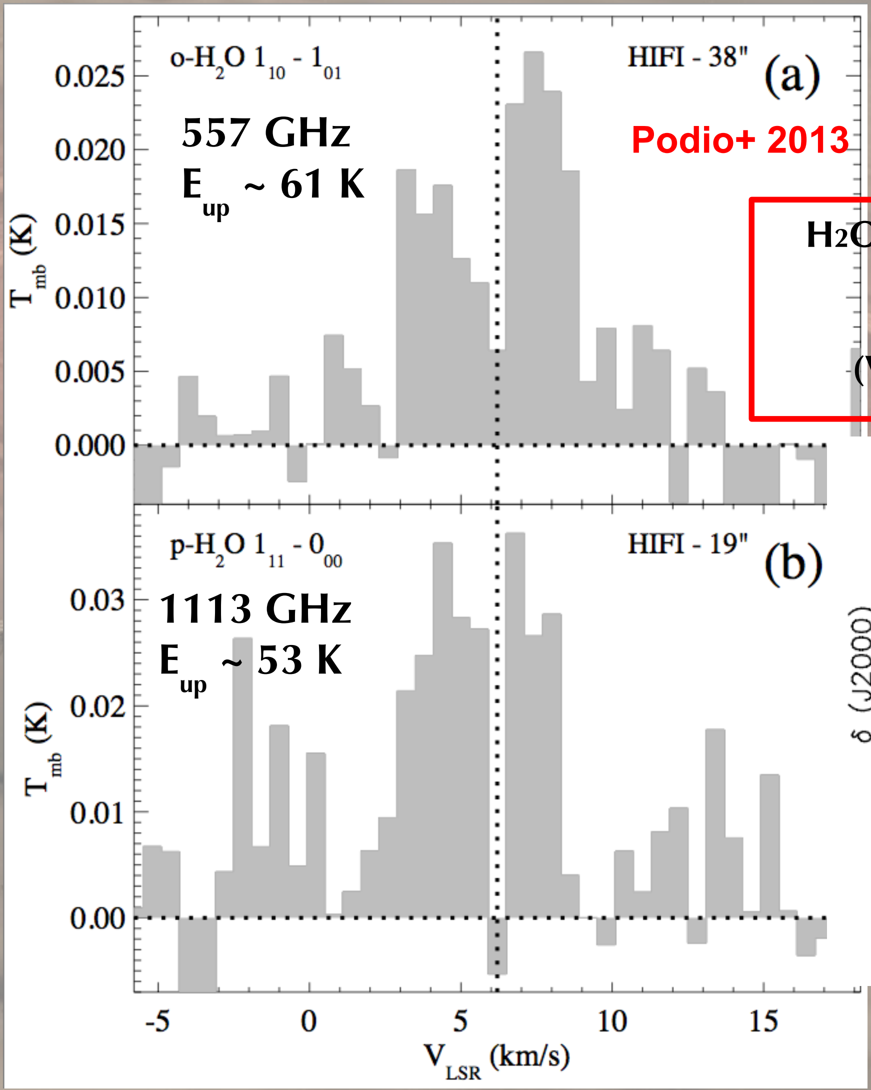
Herschel/HIFI observations of DG Tau
low-exc WATER emission from OUTER DISK !!!!

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

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

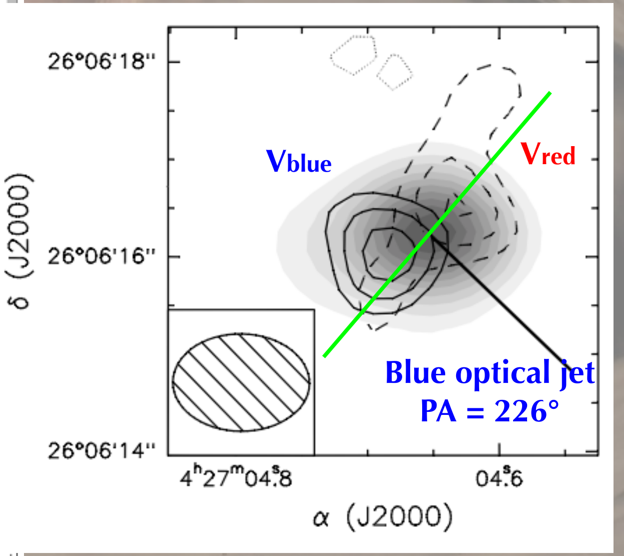


CARMA cont maps
Isella+ 2010



Podio+ 2013

H2O 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

DISK model: the region emitting low-exc H_2O lines

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

Woitke+ 2009, Kamp+ 2010, Thi+ 2011
Aresu+ 201, Meijerink+ 2012

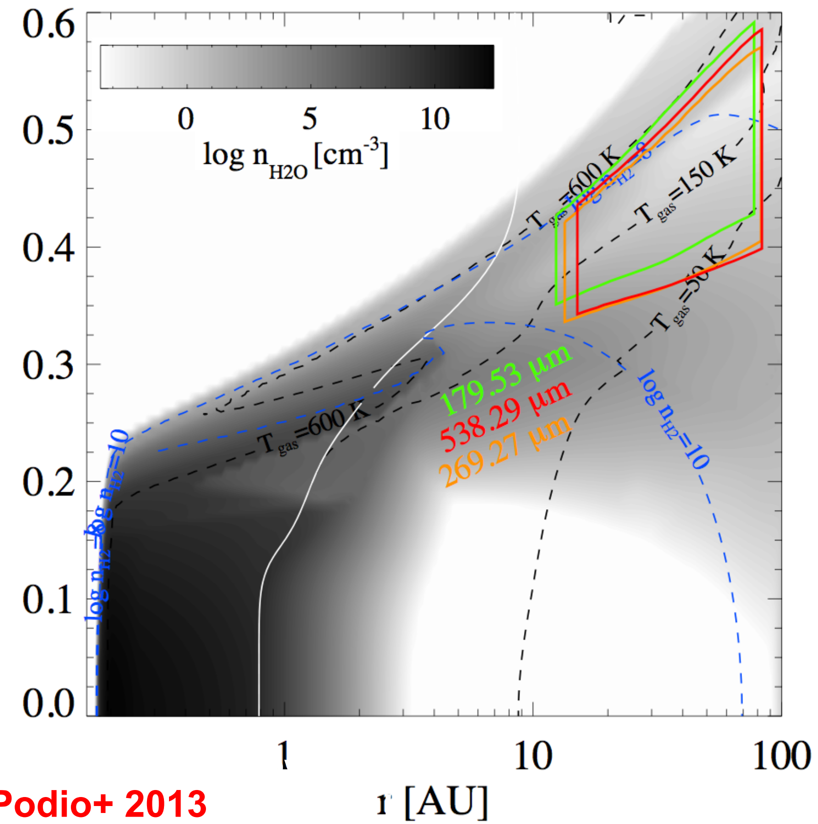
uses global iterations to consistently calculate
physical, thermal, chemical structure of protoplanetary disks.

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}

--> LTE emission
--> optically thick lines



Podio+ 2013

H_2O
formation & destruction reactions

1	31	55 NN:	H2	+ OH	-> H2O	+ H
12	1160	3563 DR:	H3O+	+ e-	-> H2O	+ H
15	1232	4052 AD:	H2	+ O-	-> H2O	+ e-
16	1246	4084 RA:	H	+ OH	-> H2O	+ PHOTON
17	1463	10273 NN:	H2exc	+ OH	-> H2O	+ H
4	373	1192 IN:	C+	+ H2O	-> HOC+	+ H
14	816	2951 CE:	H+	+ H2O	-> H2O+	+ H
16	1300	4205 PH:	H2O	+ PHOTON	-> OH	+ H

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

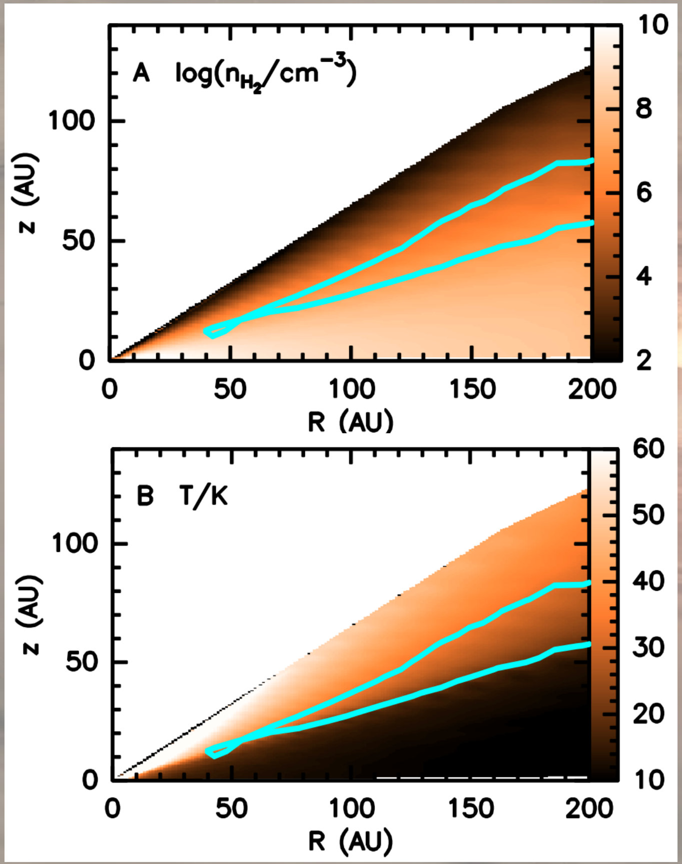
$M_{disk} = 0.01 – 0.1\ M_\odot$
$\geq$ Minimum Mass of the Solar Nebula (MMSN) before planets formation

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

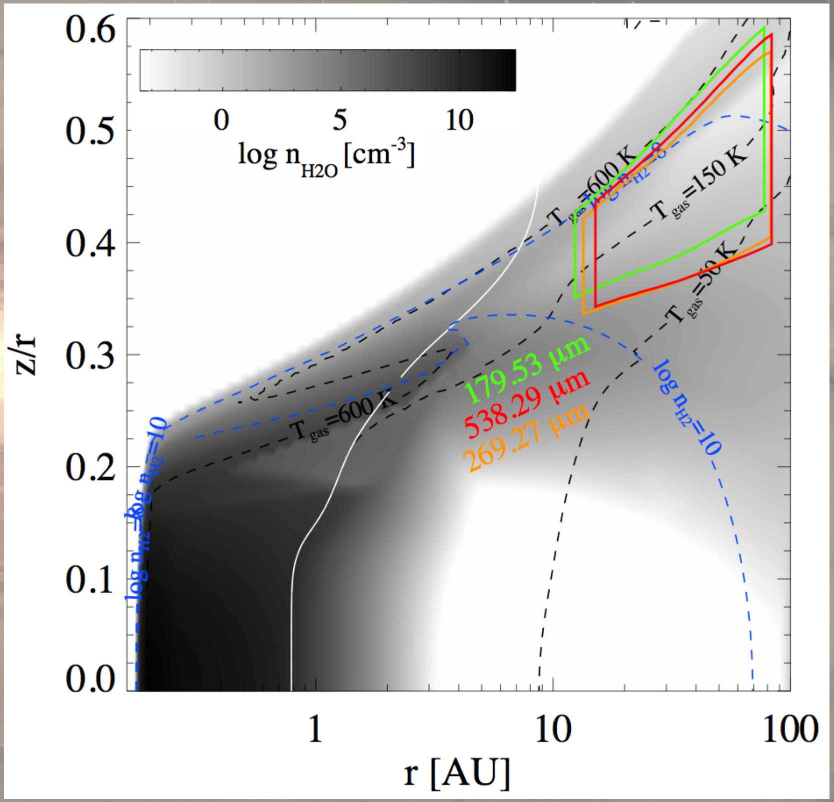
→ **supports the scenario of**
impact delivery of water on terrestrial planets
by means of icy bodies forming in the outer disk

ONLY 2 detections of WATER from the outer disk !!

TW Hya
Hogerheijde+ 11



DG Tau
Podio+ 13



1st detection in TW Hya

d = 50pc, ~10 Myr
M_{acc} ~ 1e-9 $M_\odot$/yr → $f_{UV} = L_{UV}/L_* = 0.018$
H_2O sub-thermally excited in a region at T ~ 20-40 K
disk: R_{out}=200 AU, M_{disk}=0.003–0.02 $M_\odot$
M (H_2O) ~ 1.5 $M_\oplus$

2nd detection in DG Tau

F(H_2O) ~ 19 - 26x brighter
d = 140pc, ~2.5 Myr
M_{acc} ~ 5e-7 $M_\odot$/yr → $f_{UV} = L_{UV}/L_* = 0.2$
H_2O excited close to LTE in a region at T ~ 50-600 K
disk: R_{out}=100 AU, M_{disk}=0.015–0.1 $M_\odot$
M (H_2O) ~ 7-100 $M_\oplus$
a few-100x H_2O than TW Hya !

WATER in protoplanetary disks: the future with SPICA

SPICA (T~6 K) will be up to 2 orders of magnitude more sensitive than Herschel !

SAFARI: ~2e-19 W/m^2, 5 sigma, 1 hr

Will allow a ***systematic search of low-exc H_2O line at 179.5um*** in protoplanetary disks

Herschel: clear detection of low-exc H_2O only in two protoplanetary disks:

1. A closeby source (TW Hya, Hogerheijde+ 2011)
2. A source associated with very intense UV and X-ray field (DG Tau, Podio+ 2013)

Mid-IR Camera/Spectrometer: high-R (~20 000 – 30 000) spectra at 5-38um

Will allow recovering ***H_2O lines spectral profile !***

High-exc H_2O lines (E_{up} ~ 1000-5000 K) were spectrally unresolved with Herschel/PACS and Spitzer

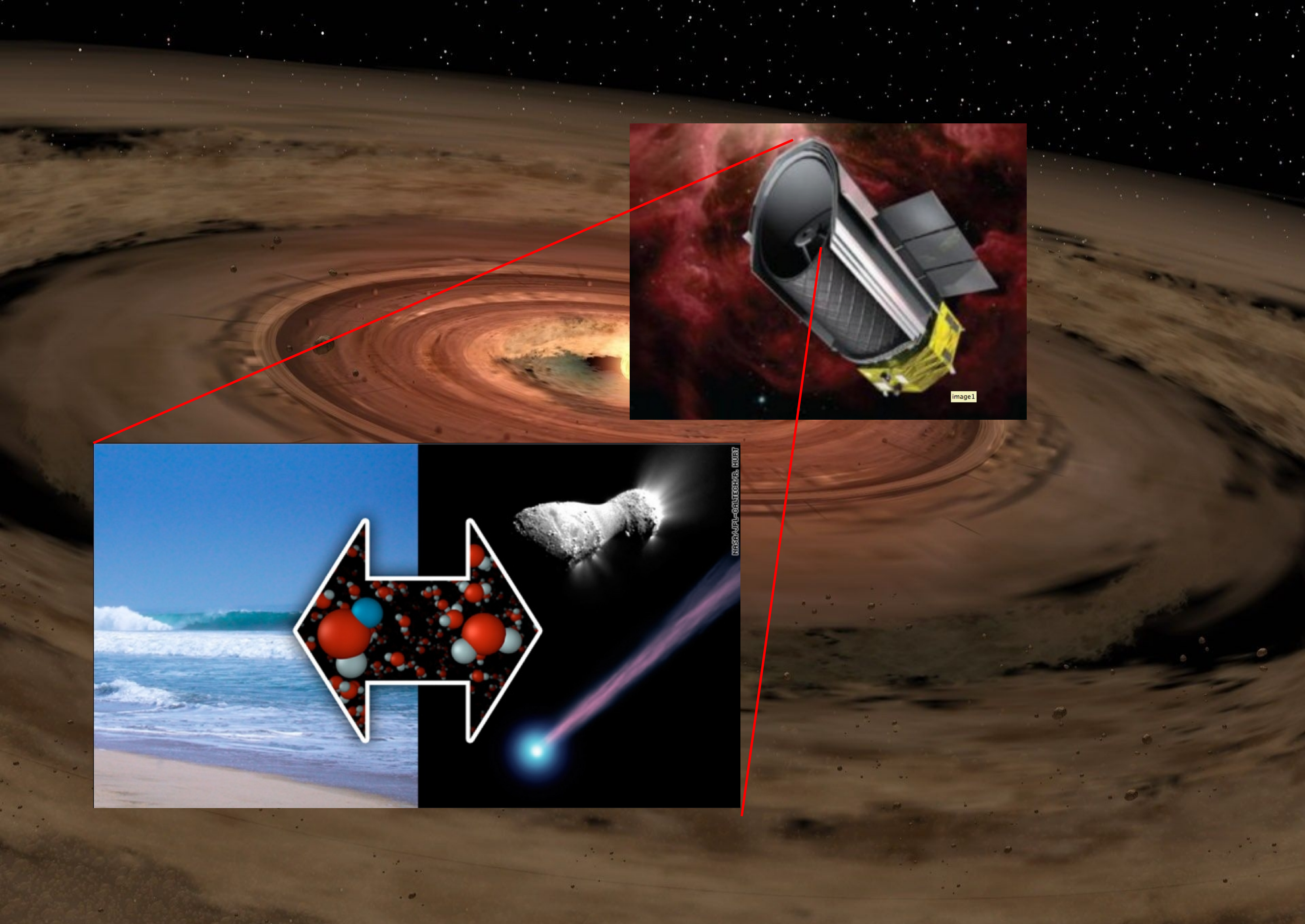
Only partially resolved from ground with VLT-VISIR (Pontoppidan+ 2010b)

Observations of HD 1-0, 2-1 at 112, 56um → to constrain M_{disk}

Present estimates of M_{disk} are based on:

- dust thermal emission … BUT assumption on dust opacity & dust-to-gas ratio !
- CO emission lines → but they are optically thick !

HD is a good tracer of gas in the disk because it follows the distribution of H_2 (Bergin+ 2013)



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