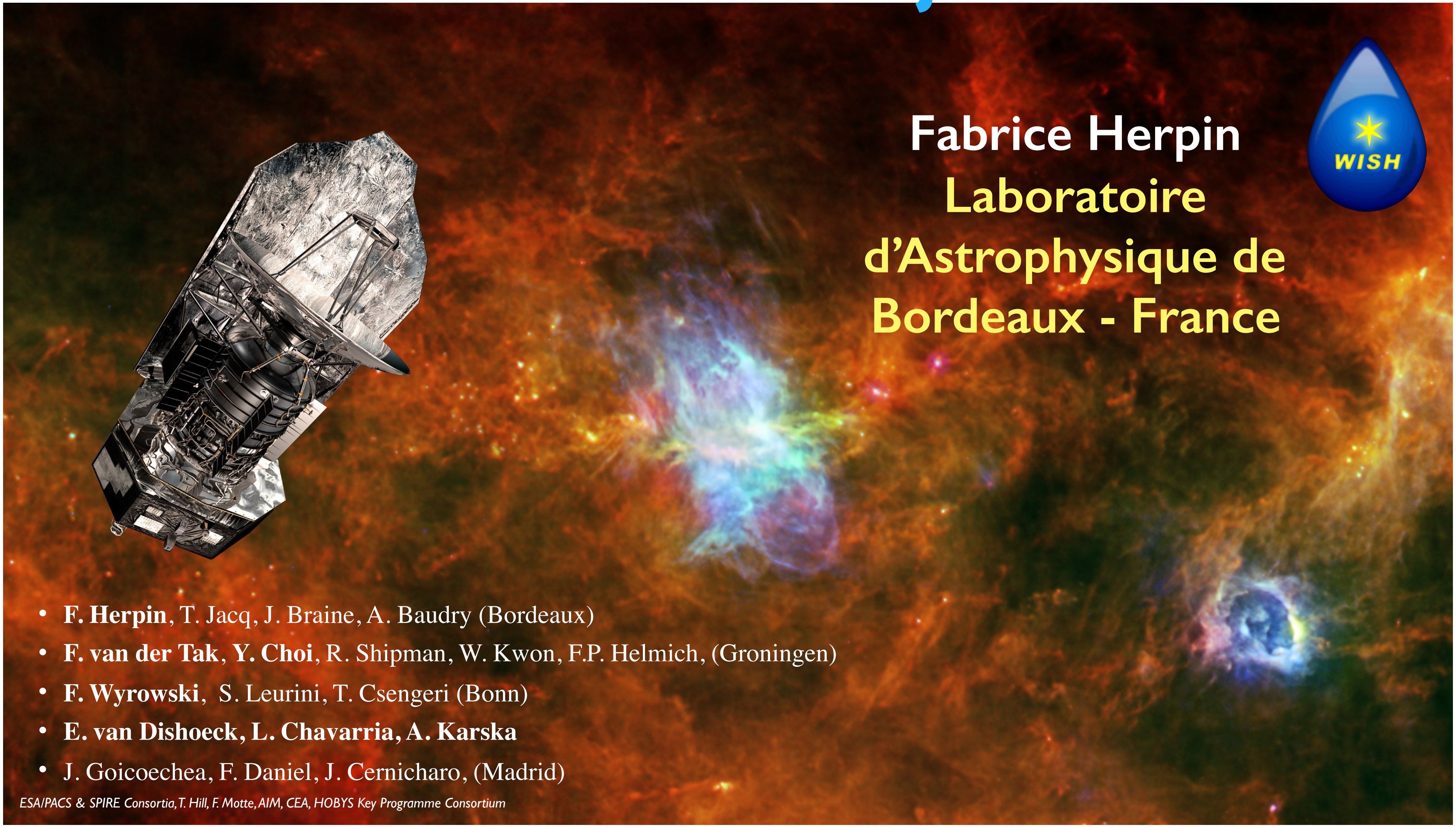
The Herschel-HIFI View of Massive Protostellar Objects



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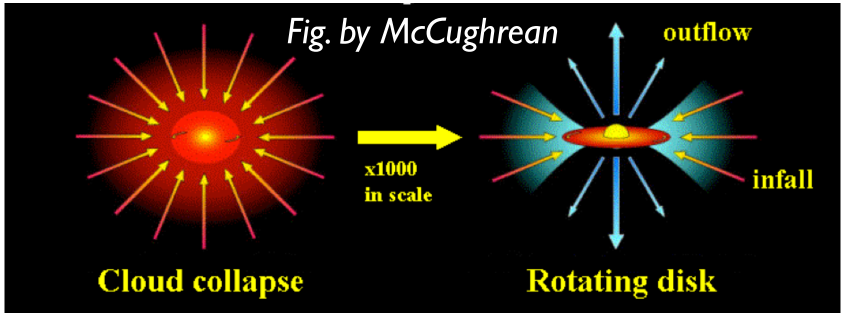
The high-mass star formation puzzle

Formation of massive stars not well understood. Classical scheme for low-mass star formation cannot be applied as such to OB stars.



Most problematic issue: **how to accumulate a large amount of mass infalling within a single entity despite radiation pressure.**

⟹ **Models considering a protostar-disk system** (e.g. Krumholz *et al.* 2005, Kuiper et al. 2010, 2015). Disk accretion and protostellar outflows enable the accretion process to continue for longer times and then to reach final star masses well above the upper mass limit of spherically symmetric accretion.

Two main theoretical scenarios, both requiring the **presence of a disk** and **high accretion rates**:
(a) ***turbulent core model*** with a monolithic collapse scenario (Tan & McKee 2002, McKee & Tan 2003);
(b) ***competitive accretion model*** involving the formation of a cluster (Bonnel & Bate 2006)

+ massive star formation triggered by **converging turbulent flows** is predicted by numerical simulations (e.g., Heitsch et al. 2008) and has been proposed for several objects (e.g., Csengeri et al. 2011).

How could water help?

➡ **Water is abundant**: while in cold regions water is mostly found as ice on dust grains, at temperatures T > 100 K the gas-phase water abundance increases by several orders of magnitudes as the ice evaporates (Fraser et al. 2001; Aikawa et al. 2008) $\Longrightarrow X_{in}$= a few10^{-4}

Confirmed by observations (e.g. in AFG2591with ISO and SWAS, Helmich et al. 1996, Snell et al. 2000):

$$X_{in} = 2{-}6 \times 10^{-5},\ X_{out} = 0.8{-}13 \times 10^{-9}$$

➡ **water might help cooling**

➡ **to discriminate between models?**

Turbulent core model implies supersonic turbulence in the protostellar envelope, while the competitive accretion model predicts subsonic cores, but still embedded in a supersonic envelope.

➡ **water + HIFI = probe of the gas dynamics**

High-mass protostars observations

Sample of
19 massive protostars

- pointed HIFI obs of 14 water lines, including $H_2{}^{18}O$, $H_2{}^{17}O$ + maps
- complementary PACS spectro data

evolution

mIR-quiet HMPOs

IRAS05358+3543
IRAS16272–4837
NGC6334-I
W43-MM1
DR21(OH)

mIR-bright HMPOs

W3-IRS5
IRAS18089–1732
W33A
IRAS18151–1208
AFGL2591

active protostar exhibiting **infall** of a massive envelope onto the central star and **strong outflows**. Mid-IR-quiet and bright categories based on the definition of Motte et al. (2007)

Hot Molecular Cores

G327–0.6
NGC6334-I(N)
G29.96–0.02
G31.41+0.31

temperature of the inner regions of the protostellar envelope has increased, exceeding the evaporation limits of molecules on the grains, hence enriching the envelope with **complex molecules** leading to the formation of a HMC.

UC HII Regions

G5.89–0.39
G10.47+0.03
G34.26+0.15
W51N-e1
NGC7538-IRS1

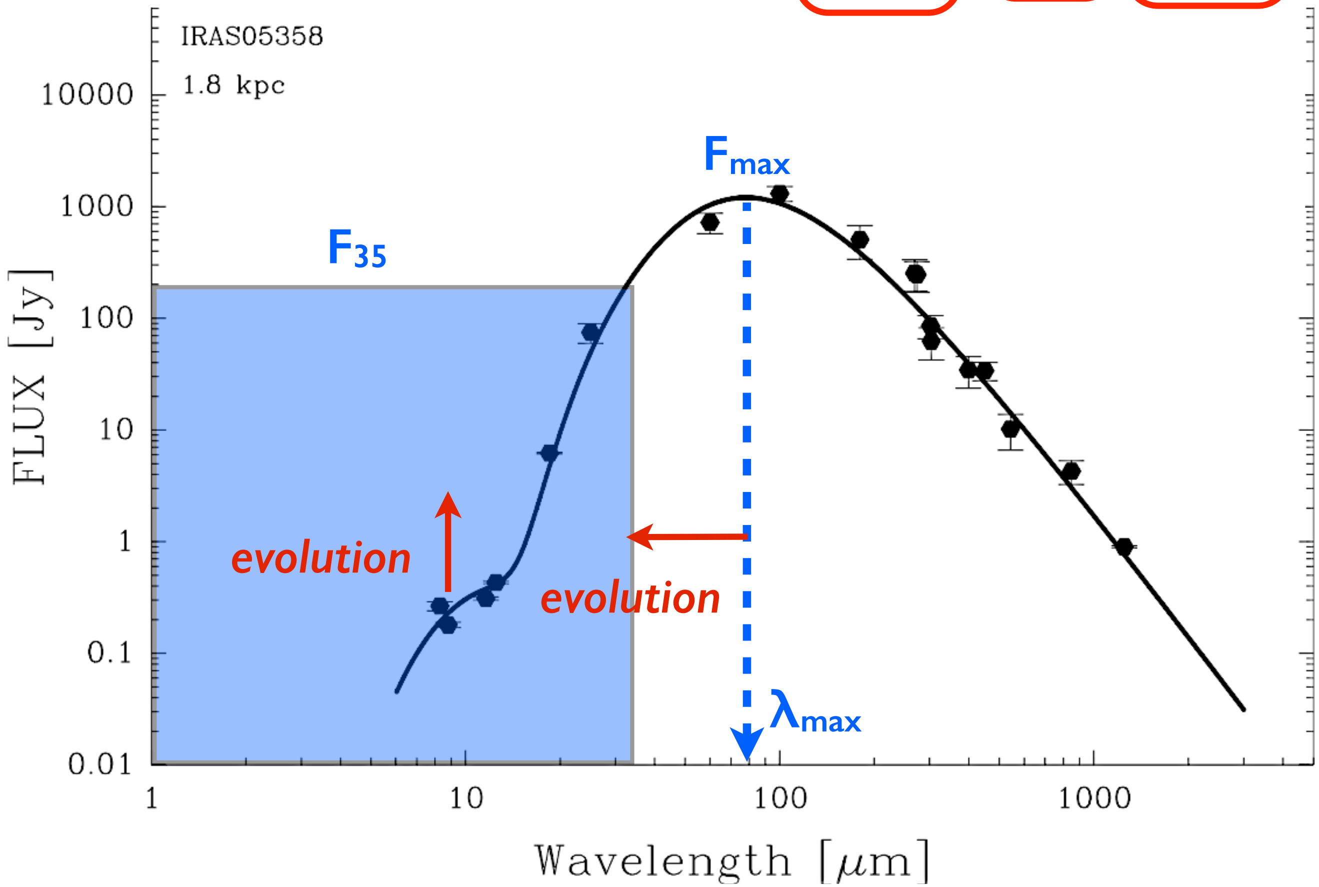
star gets hot enough to **ionize the surrounding gas**, leading to the formation of an UCHII

Our sample: evolutionary status

Object	d [kpc]	L_{bol} [$10^3 L_\odot$]	M_{env} [$M_\odot$]	$L^{0.6} M_{env}^{-1}$	$\lambda_{F_{max}}$ [μm]	F_{35}/F_{total} %
NGC6334I(N)	1.7	1.9	3826	0.02	220.6	0.7
W43-MM1	5.5	23	7550	0.05	131.7	0.5
DR21(OH)	1.5	13	472	0.6	100.0	1.7
IRAS16272-4837	3.4	24	2170	0.2	108.0	3.5
IRAS05358+3543	1.8	6.3	142	1.4	81.1	7.7
W33A mid-IR bright	4.0	44	698	0.9	85.2	9.7
NGC6334I HMC	1.7	260	750	2.4	84.7	12.0
NGC7538-IRS1 UCHII	2.7	130	433	2.7	70.0	20.6

evolution

mid-IR quiet

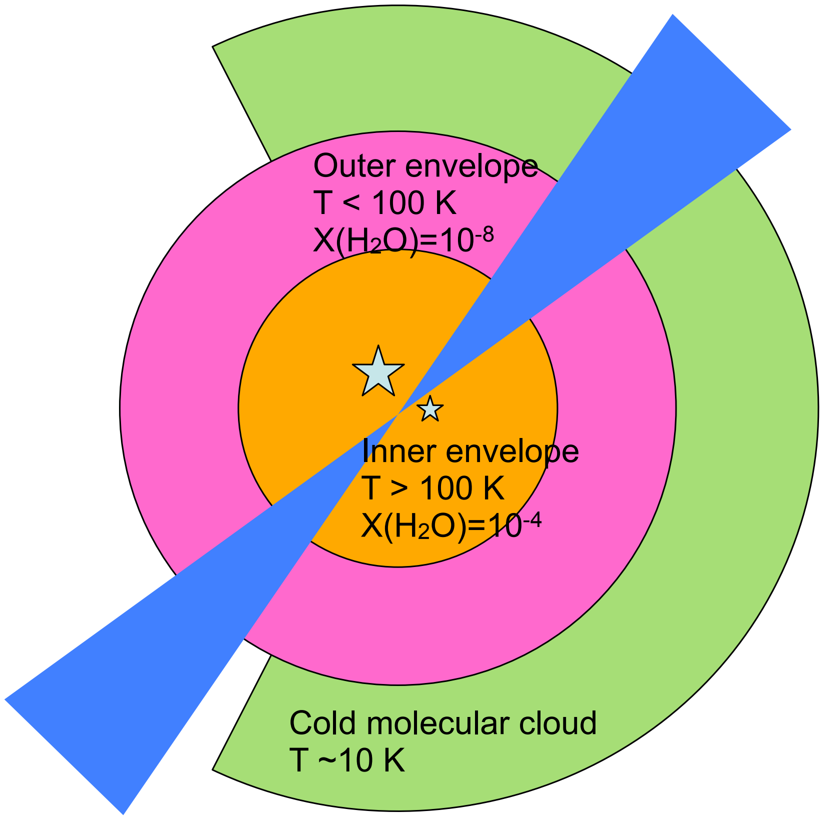


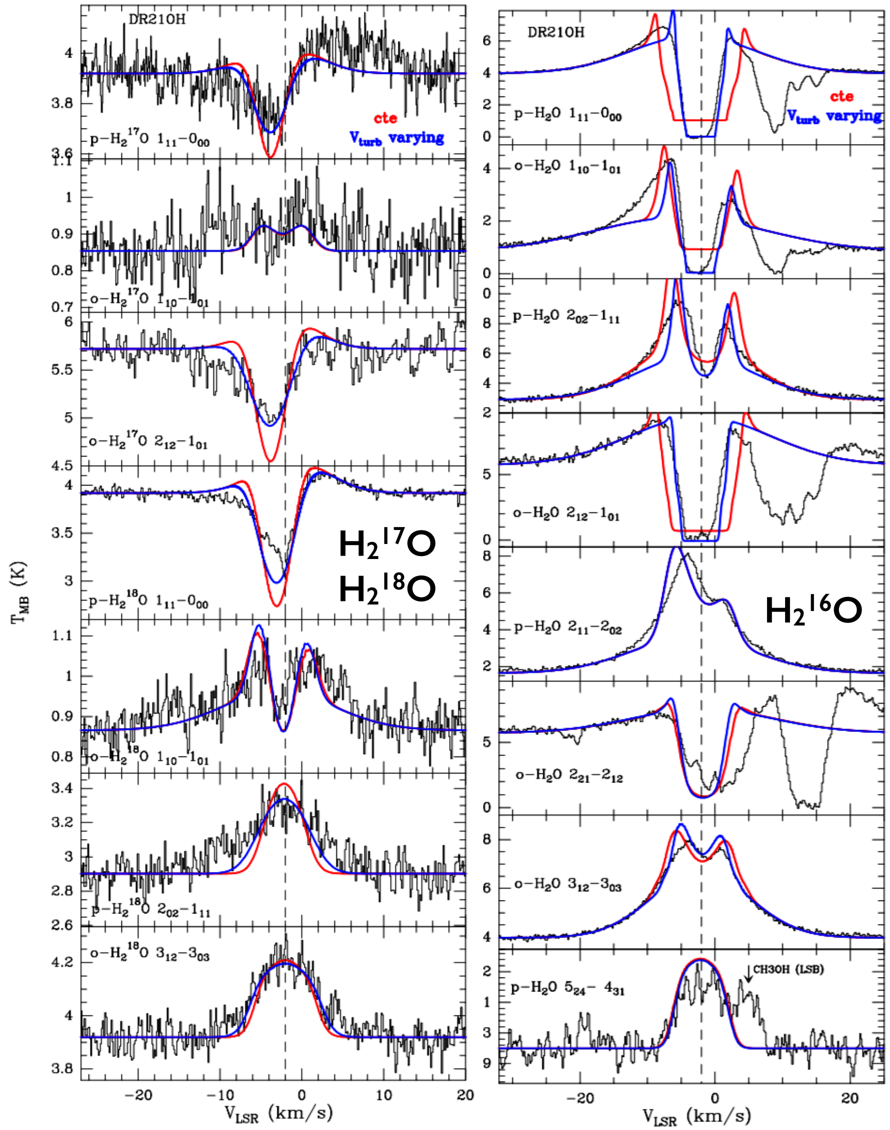
H_2O line profiles: model

Herpin et al (2012, 2016)

- Source model using Whitney-Robitaille (2003)
- Line modeling with RATRAN-1D
  (Hogerheijde & van der Tak 2000)

Water abundance jump in the inner envelope (> 100 K)





We have tested:

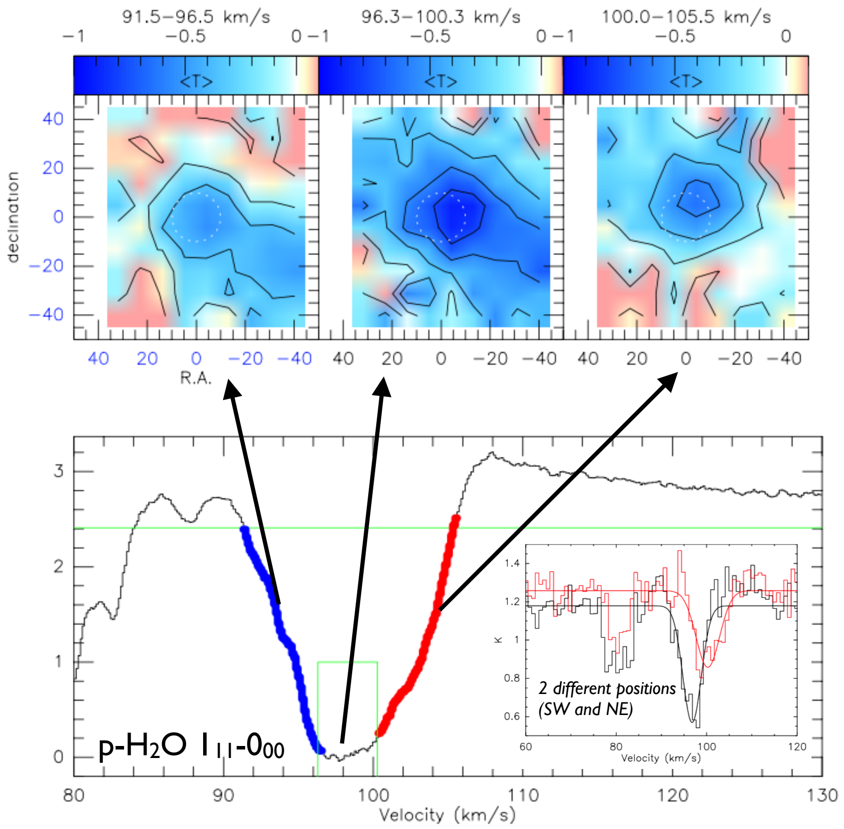
✓X_{in}, X_{out} = step-profile, V_{turb} = cte

✓X_{in}, X_{out} = step-profile, V_{turb}=f(R)

Abundances and dynamics results (1): What do the maps tell us?

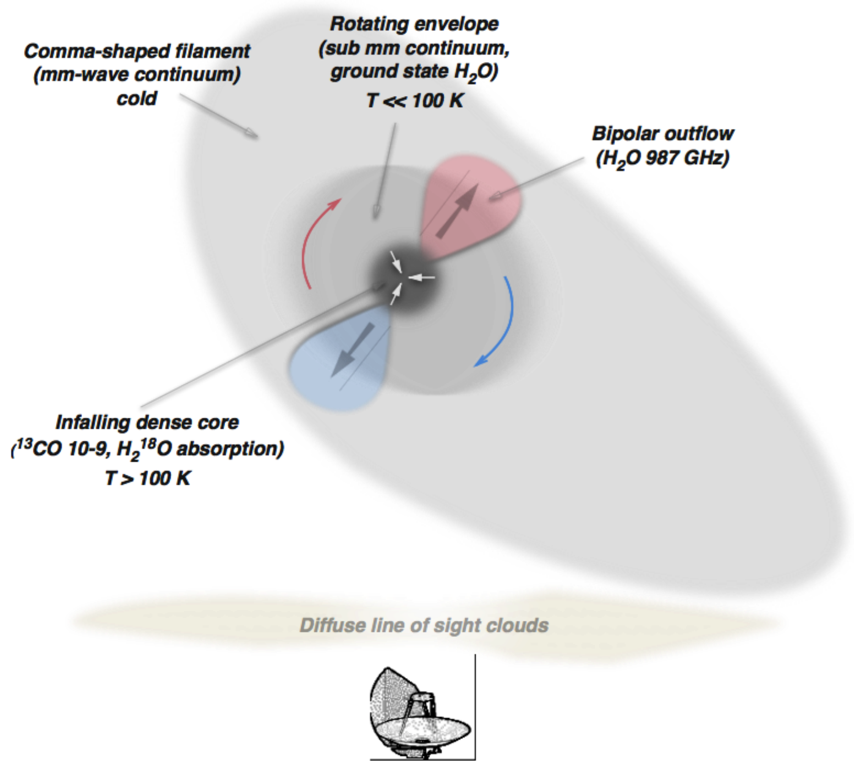
Jacq et al. (submitted)

W43MM1



Red and blue materials have different locations

⇒ **velocity gradient,** possibly due to **rotation**, in both the envelope ($r \gtrsim 0.5$pc) and the protostellar core ($r \gtrsim 0.2$pc).



⟹ part of the water absorption due to *cold foreground material,* surrounding the MM1 core.

Modeling of the corrected spectra

⇒ **lower water outer abundance**

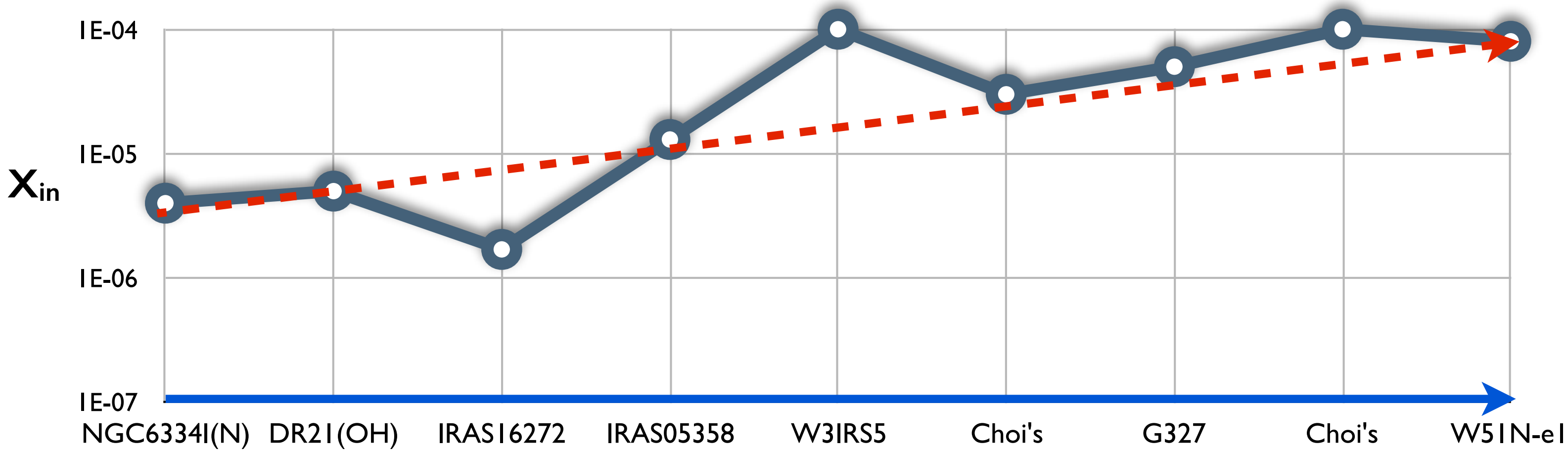
decreased from 8 10^{-8} to 8 10^{-9}

Abundances and dynamics results (2)

evolution

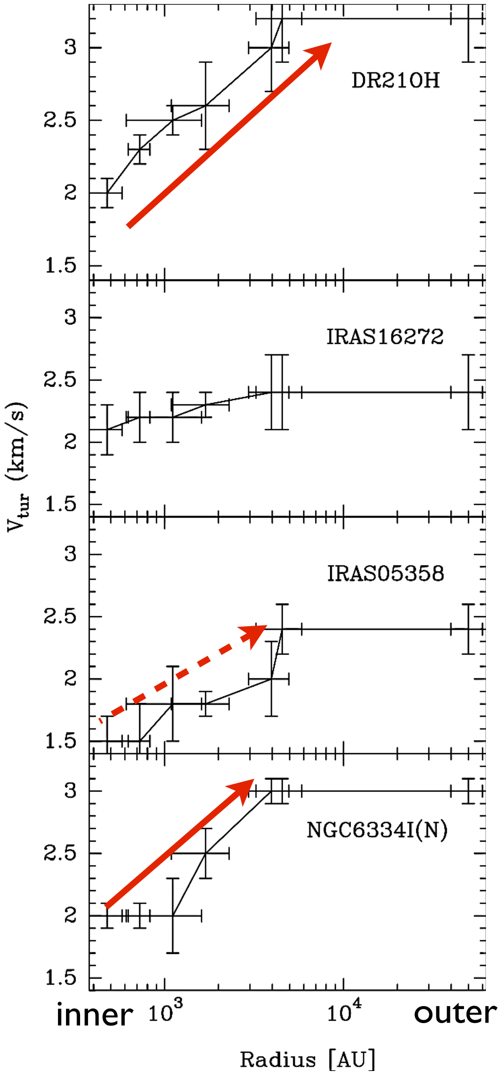
mid-IR quiet *mid-IR bright* *HMC* *UCHII*

Parameter	NGC6334I(N)	W43MM1	DR21(OH)	IRAS16272	IRAS05358	W3IRS5	Choi's sample	G327-0.6	Choi's sample	W51N-e1
X_{out}	a few 10^{-8}									
X_{in}	-									+
V_{turb}	2.1-2.5	2.2-3.5	2-3.2	2.0	1.5-2.4	2.0	1.-1.5	2.6-3.0	1.5	3.5
$V_{exp/inf}$	-0.7	-2.9	-1.5	-0.2	+3.0	2.0	+2.0	-3.2	+2.0	-4



Chavarria et al. (2010)
Herpin et al. (2012)
Herpin et al. (2016)
Choi et al. (2015)
Choi et al. (in preparation)
Leurini et al. (in preparation)
Daniel et al (in preparation)

Abundances and dynamics results (3)



Same behavior for W43MM1

Highly supersonic turbulence, increasing with radius

⟹ while not in clear disagreement with the competitive accretion scenario, this **behaviour is predicted by the turbulent core model** *(Krumholz & Bonnel 2009)*

Abundances and dynamics results (4)

Water | **Accretion**

Object	χ_{out} 10^{-8}	χ_{in} 10^{-5}	M_{H_2O} $[10^{-4}\ M_\odot]$	M_{H_2O} $[10^{-7}\ M_{env}]$	M_{inner} $[\%\ M_{total}]$	V_{inf} $[\mathrm{km\,s^{-1}}]$	$L_{tot}/(c.v_{inf})$ $[M_\odot\ \mathrm{yr}^{-1}]$	$\dot{M}_{acc}$ $[M_\odot\ \mathrm{yr}^{-1}]$	L_{acc} $[10^3\ L_\odot]$
NGC 6334I(N)	2.3	0.4	8.8	2.3	3.6	−0.7	5.4×10^{-5}	$5.2{-}5.6\times10^{-4}$	3.1–3.3
W43-MM1	6.7	14	1100	146	97.2	−2.9	1.6×10^{-4}	$3{-}4\times10^{-2}$	30
DR21(OH)	14	0.5	7.7	16.3	11.8	−1.5	1.7×10^{-4}	$9.6{-}11\times10^{-5}$	0.58–0.66
IRAS 16272	4.7	0.17	1.3	0.6	43.8	−0.2	$2.\times10^{-3}$	$6.3{-}6.8\times10^{-5}$	0.38–0.41
IRAS 05358	8.8	1.3	1.1	7.7	26.7	+3.0	N/A	N/A	N/A

⇒ **Accretion rates high enough to overcome the strong radiation pressure for W43-MM1, NGC6334I(N), but not for the other sources** (note that we here probe infall in the envelope and not accretion onto the protostar).

⟹ **Mid-IR quiet: accretion rates ≈ 10^{-5}-10^{-4}** (higher for W43MM1) **>> free-fall accretion rate**

In agreement with turbulent core model and compatible with the competitive accretion model, as predicted by gravito-turbulent fragmentation models (Schmeja & Klessen 2004).

Models based on gravitational collapse of massive magnetized molecular cloud cores (e.g., Banerjee & Pudritz 2007) through disk-driven outflows and high accretion rates that can exceed 10^{-3} M⊙/yr.

No infall in the more evolved objects (except G327-0.6)

Why do the inner envelopes appear to be so dry (1)?

Except for W43-MM1, inner water abundances are below the predicted high water inner abundance value from Fraser et al. (2001)

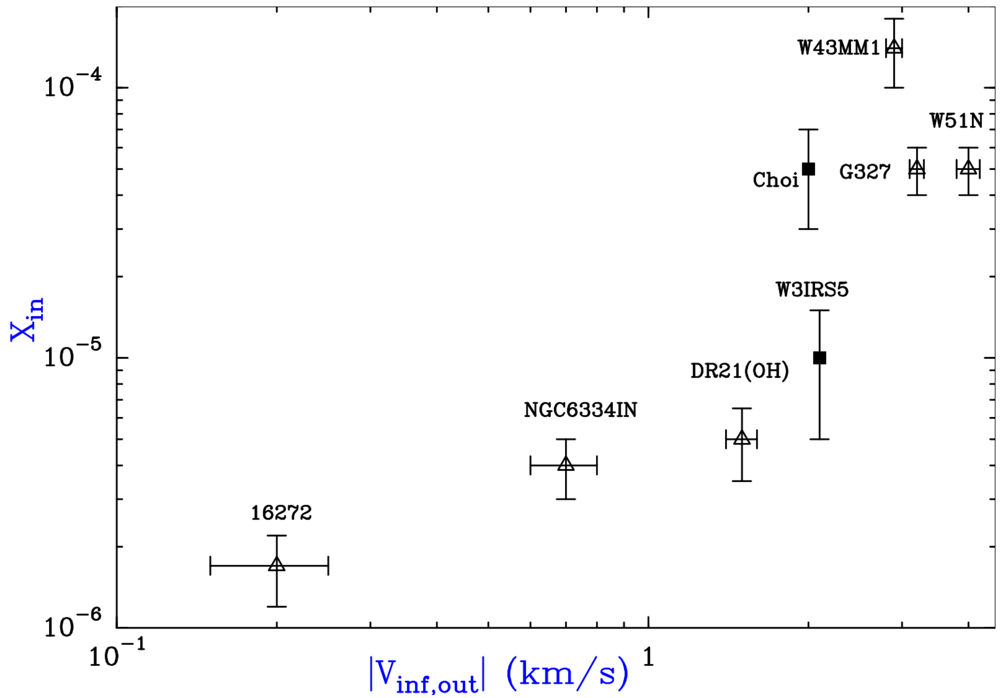
$\Longrightarrow$ Why?

- Do we probe deep enough? *Yes!* Thanks to some high-excitation lines, i.e. $5_{24}-4_{31}$, $3_{12}-3_{03}$, or the $H^{18}O$ 3_{13}-2_{20} line at 203.3916 GHz (E_{up} = 204 K).
- Is our model guilty? *Could be*…Simplified 1D-model. Visser et al. (2013) showed that in low-mass objects the spherical geometry is not valid on the spatial scale of the hot core and might lead to underestimate the inner water abundance $\Longrightarrow$ LIME!!
- Dynamical reasons? *No correlation* is found between χ_{in} and the turbulent velocity or outflow.

But the higher the infall or expansion velocity, the higher the inner abundance

$\Longrightarrow$ Larger infall or expansion velocities generate shocks that will sputter water out of the dust grain mantles.

Nevertheless, according to Neufeld et al. (2014), shock velocities of ~20−25 km/s are necessary to release water from ice mantles…



Why do the inner envelopes appear to be so dry (2)?

- other explanation: **photodissociation through protostellar UV photons** is more efficient than expected and thus not completely outrun by the O→H2O conversion.

but no known difference in terms of FUV internal field among our sample. For some reasons (e.g., self-shielding due to the thickness of the inner region), water photodissociation can be more efficient in IRAS 16272 than in W43-MM1, for instance.

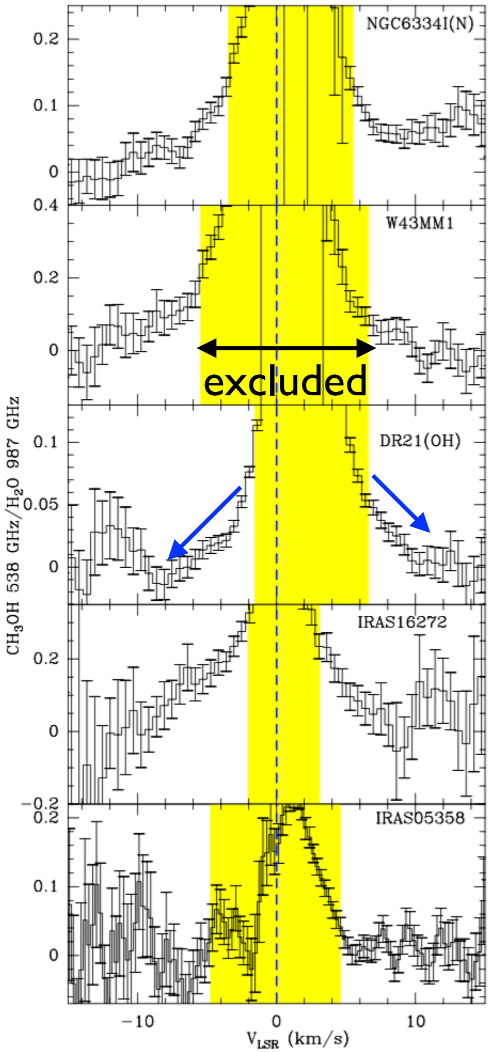
⟹ ***Observing good FUV irradiation tracers*** such as OH^+ or CH^+, or the product of the water photodissociation, OH, might help to constrain this scenario.

Methanol and the formation route of water at higher velocities

Line ratio of CH3OH/water as a function of the velocity in the line wings

⟹ to **differentiate between two potential formation routes of H2O** (Suutarinen et al. 2014):

gas-phase synthesis versus a sputtered origin in the outflow



CH3OH $5_{1,5}-4_{0,4}$ *A*+−*A*+ over p-H2O $2_{02}-1_{11}$

We compare CH3OH and water lines whose upper energy levels are similar. All transitions assumed to fill the beam. We do not consider a range of velocities around the line center, where the significant optical depth in the water lines increases the line ratio much more than physical processes would. Considering the high critical densities of water transitions, we assume effectively thin emission away from this central line region.

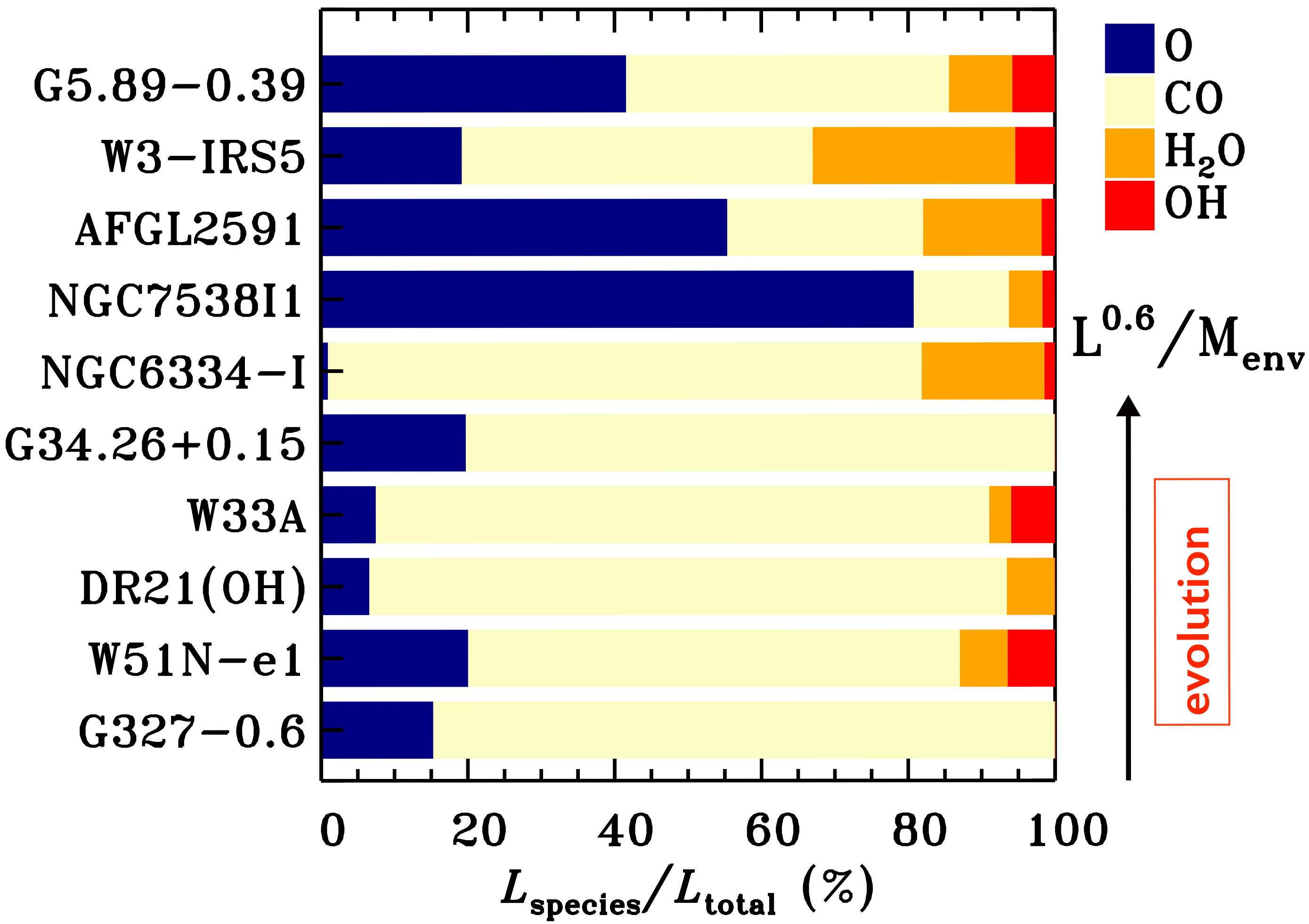
Except for IRAS 05358 (no wing), **the ratio drops as a function of velocity in both wings**

⟹ suggests a **dominant gas-phase synthesis of H_2O from shocked material** because methanol is produced on grain surfaces.

⟹ high-velocity water must be formed in the gas-phase from shocked material, i.e. it is not created solely through grain mantle evaporation.

Evolution of far-IR gas cooling (PACS)

Karska, Herpin et al. (2014)



- CO dominates the cooling of young objects (median ~75%)
- [OI] increases for the more evolved sources (~20%)
- H_2O and OH - minor contribution (<1%)

Conclusions

• **highly supersonic turbulence, tends to increase with radius**

• **high accretion rate in mid-IR quiet HMPOs**

⟹ ***high enough in some sources to overcome the radiation pressure***

• **water abundance: $\chi_{out} \approx$ few 10^{-8}, $\chi_{in} = 10^{-6}$-10^{-4}**, lower than expected from ice evaporation

• **H_2O have a minor contribution in the cooling** ⟹ ***water is not the key***, but help.

• Photodissociation of water from the UV internal photons more efficient than expected??, or our simple spherical envelope model underestimates the inner water abundance.

• **the higher the infall (or expansion velocity), the higher the inner abundance**

⟹ **shocks that sputter water from the ice mantles of dust grains in the inner region?**

• **At high velocities, water must be formed in the gas phase from shocked material,** i.e. not created solely through grain mantle evaporation.

Thanks for your attention !

see poster by Matuszak et al.

Thanks CNES for its financial support