



# Tracing protostellar environments with $H_2O$ and CO: from low to high mass with Herschel

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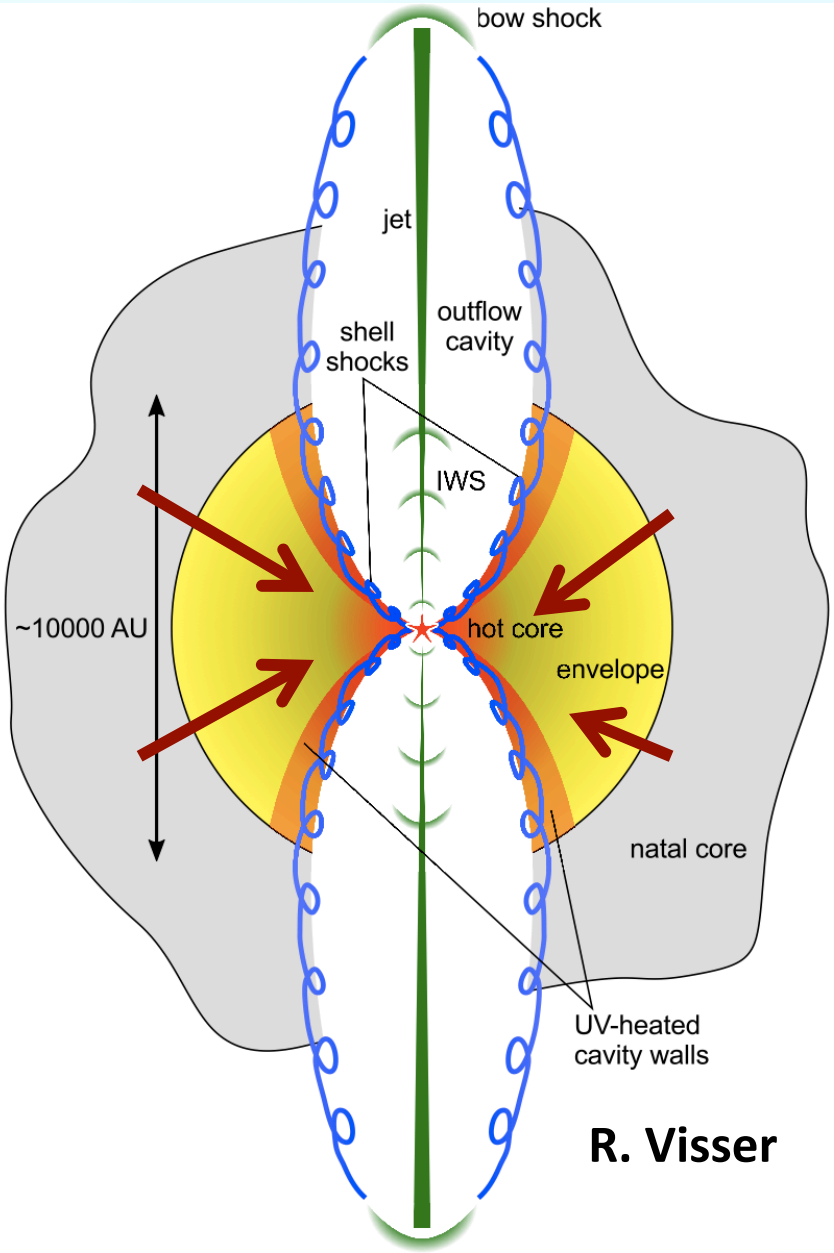
# Motivating questions

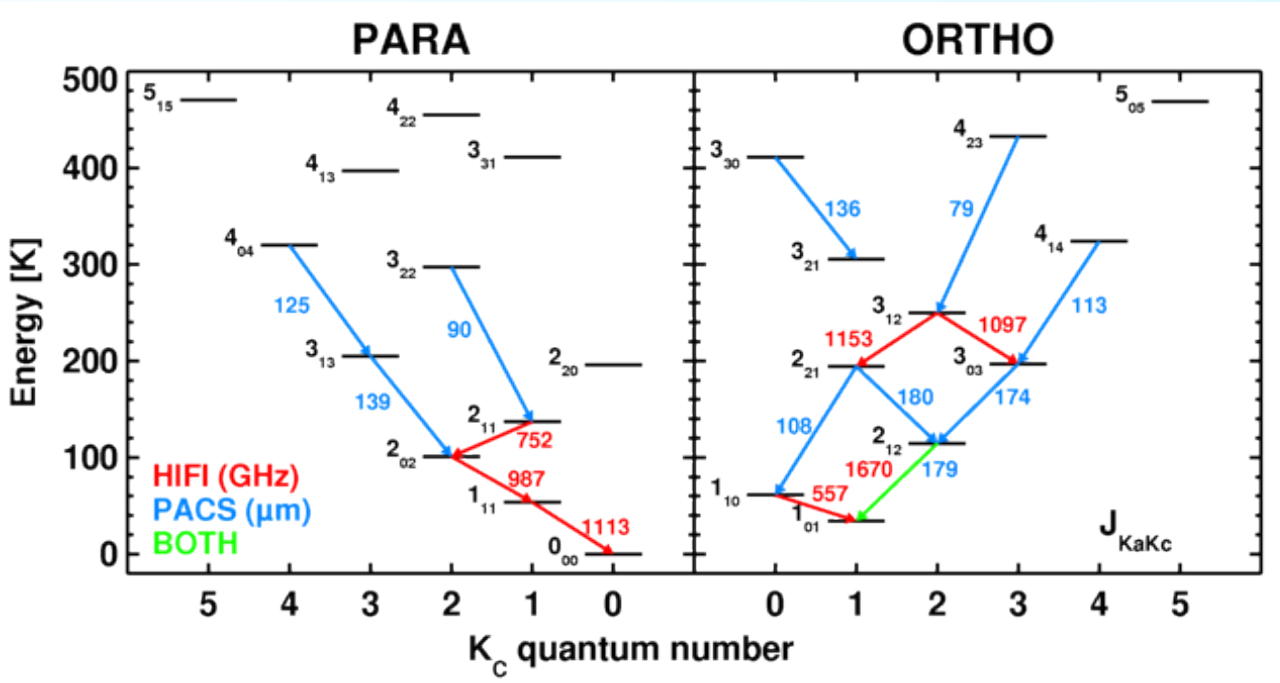
- What physical component(s) do $H_2O$ and CO trace and what are their properties?
- Can we use LM sources as scaled templates for HM sources?
- Does this extend to cluster or extragalactic scales?



# The Data

# WISH: *Water In Star-forming regions with Herschel*

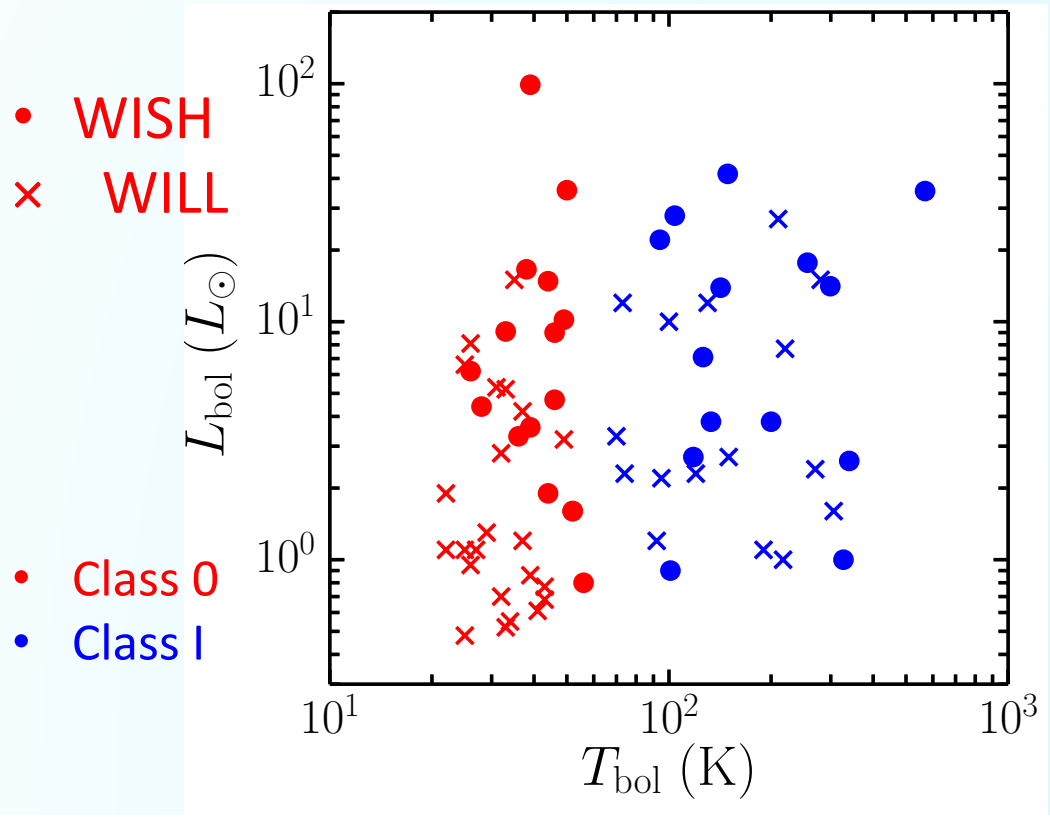
- 425 hrs of Herschel time (van Dishoeck et al., 2011, PASP)
- HIFI spectroscopy & PACS spectral maps of $H_2O$, CO and related molecules




- ~ 80 sources:
  - From 1 $L_\odot$ - $10^5 L_\odot$
  - Prestellar cores to disks

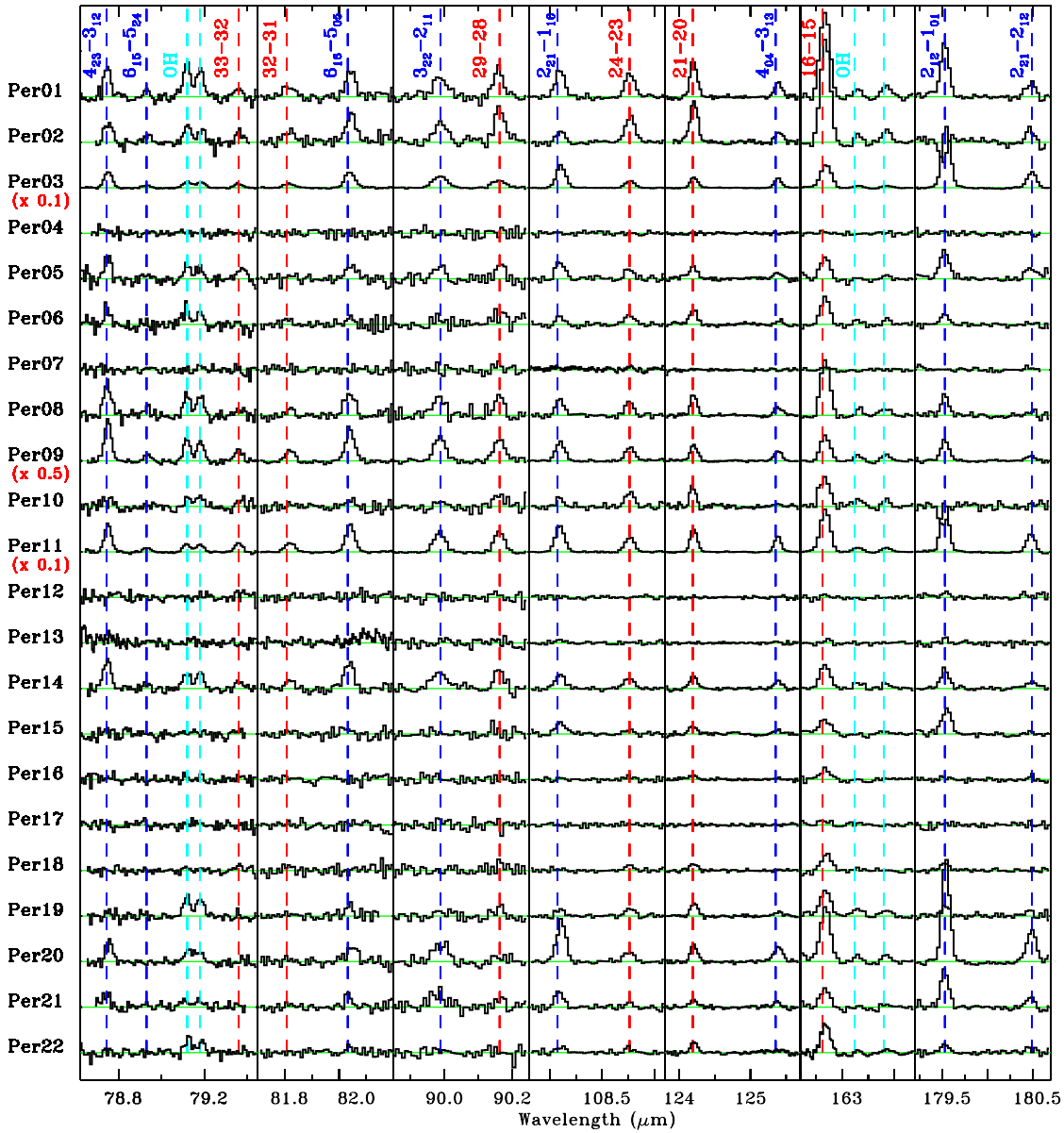
# WILL: *William Herschel Line Legacy*

- OT2 follow-up to WISH-LM of a statistically selected sample (Mottram et al., in prep.)
- ~50 sources selected from Herschel and Spitzer GB surveys using the criteria:



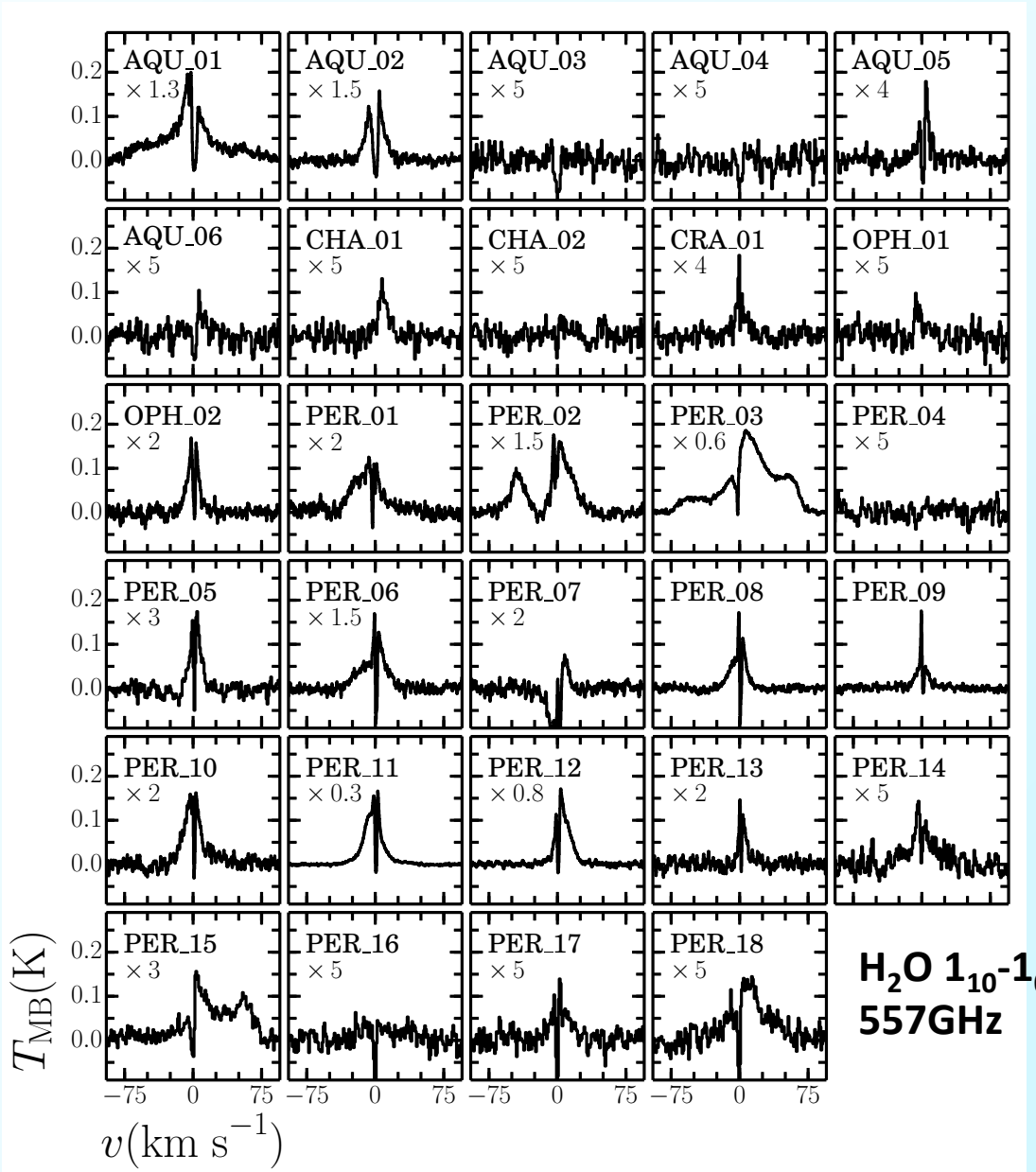

- $\alpha > 0.3$
- $T_{bol} < 300$ K
- $L_{bol} > 0.4\ L_\odot$ for Class 0
- $L_{bol} > 1\ L_\odot$ for Class I
- $\delta < 35°$ for ALMA follow-up
- Vetting with $HCO^+$ where available

# Excellent data quality




**Karska et al., 2014**

# Excellent data quality



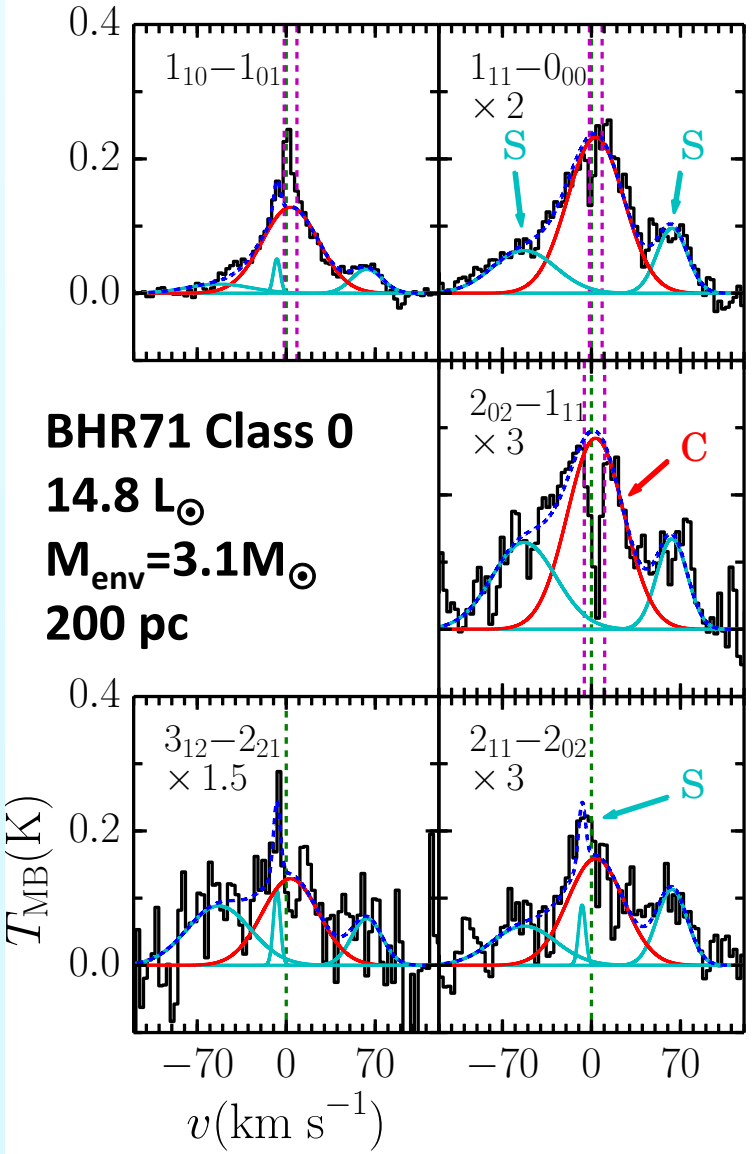

**$H_2O$ $1_{10}$-$1_{01}$ 557GHz**

**Mottram et al., in prep.**

# Low-mass protostars – simplest template of star formation

# Multi-component $H_2O$ line profiles

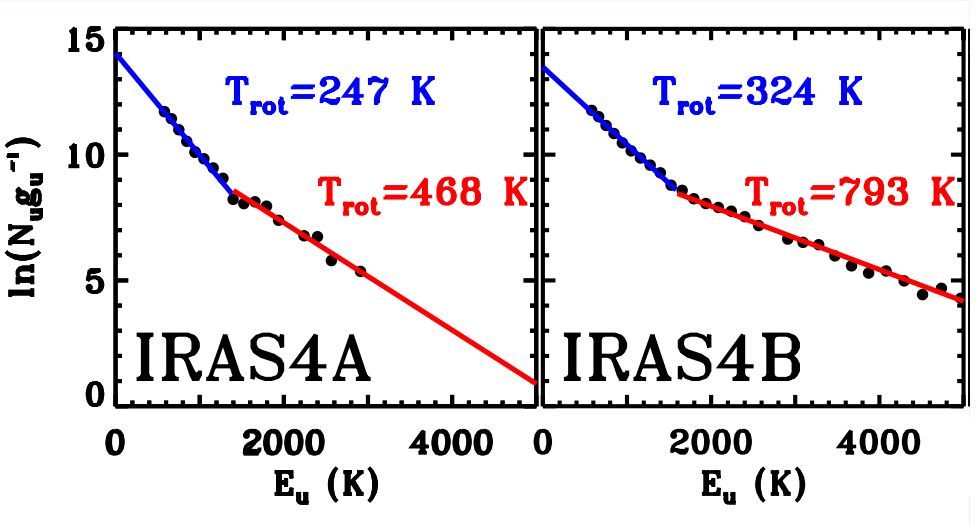
- $H_2O$ line profiles are complex -> trace multiple kinematic components
- Dominated by broad component associated with outflows and shocks
- The FWHM is larger than for low-J CO

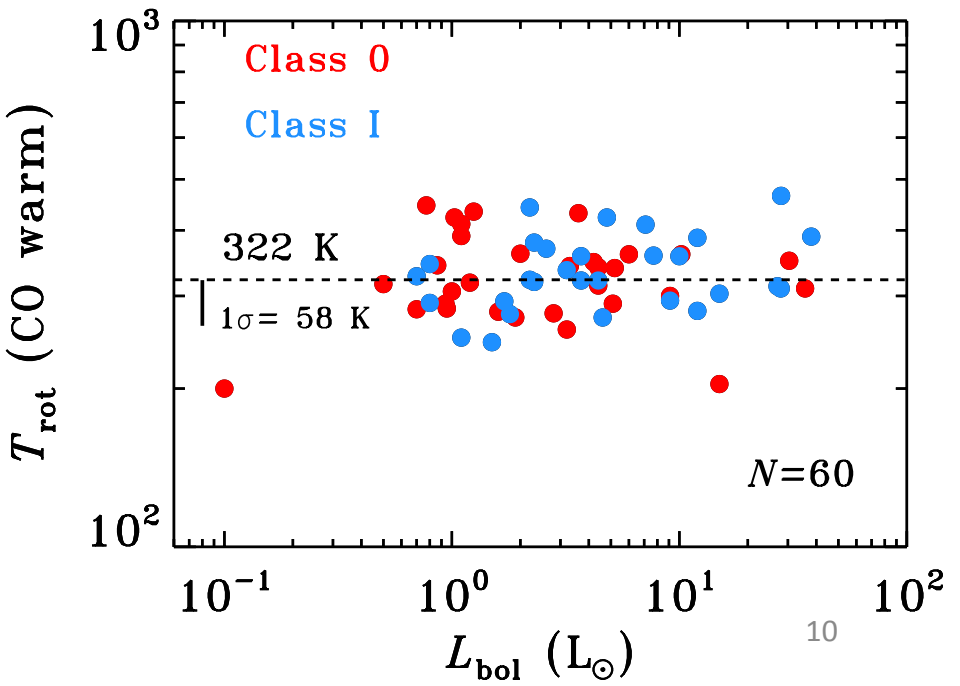



**Kristensen et al., 2012, Mottram et al., 2013, 2014**

# Multi-component CO rotational diagram

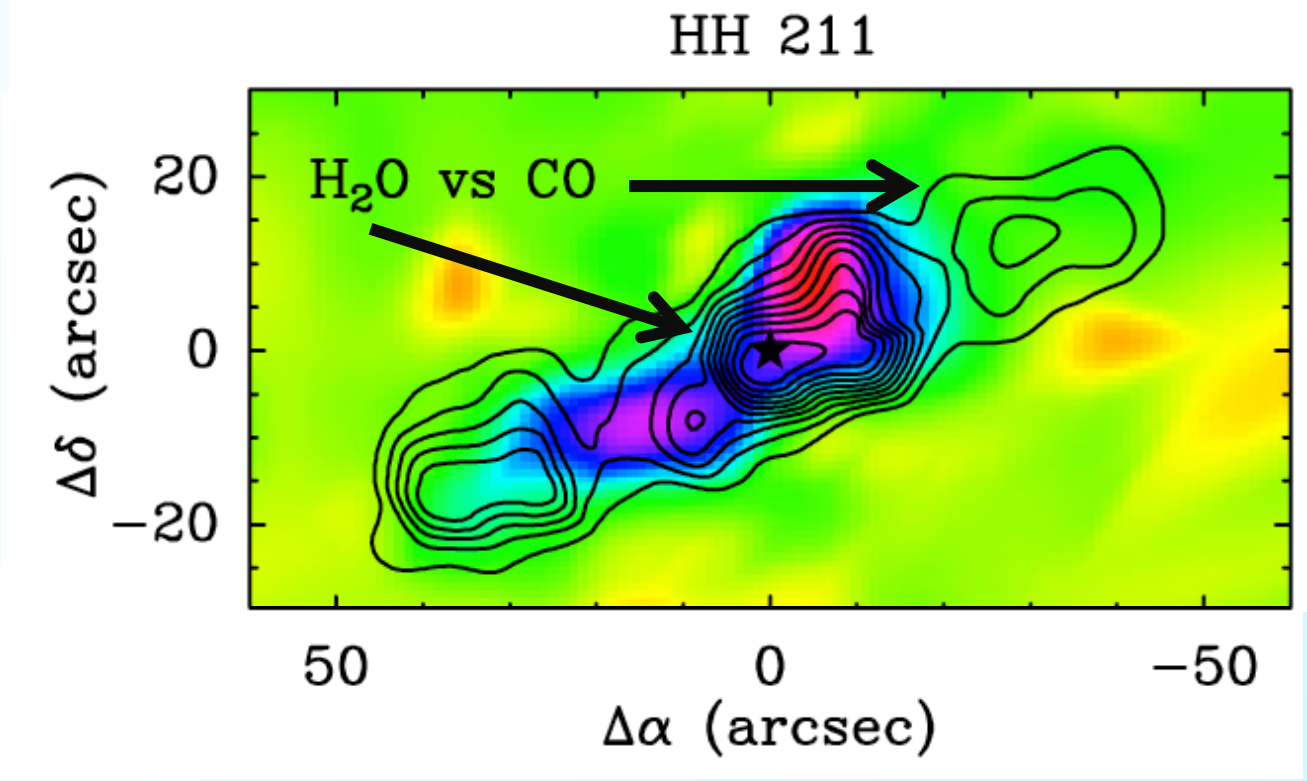
- CO rotational diagrams from PACS show a warm (~300K) mid-J and sometimes also a hot (~750K) high-J component
- Temperatures similar for all sources




**Karska et al., 2013, 2014b**
**see also Green et al., 2013, Manoj et al., 2013**

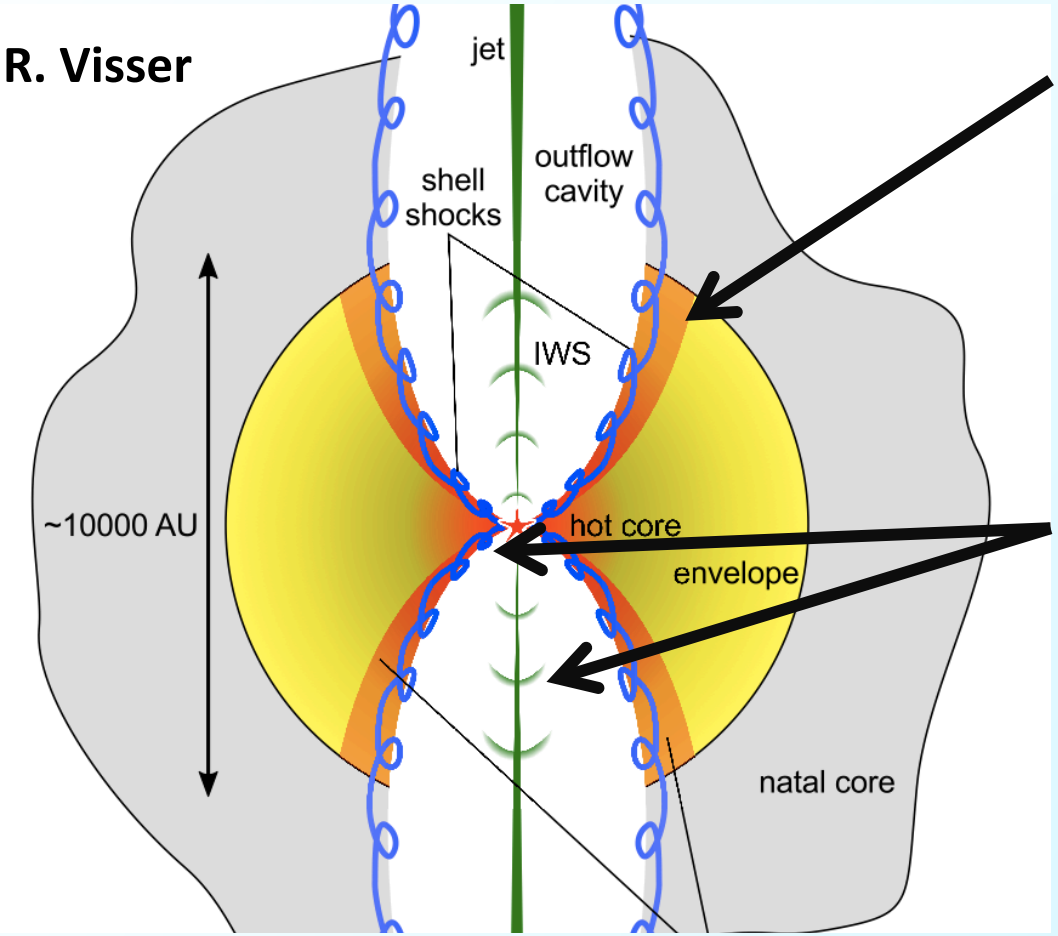
# Spatial extent of water




**Tafalla et al., 2013, Karska et al., in prep.**

- Water and low-J CO trace different spatial regions within the outflow
- Water limited to central PACS spaxel in bulk of sources; few show extended emission.

# Origin of the emission



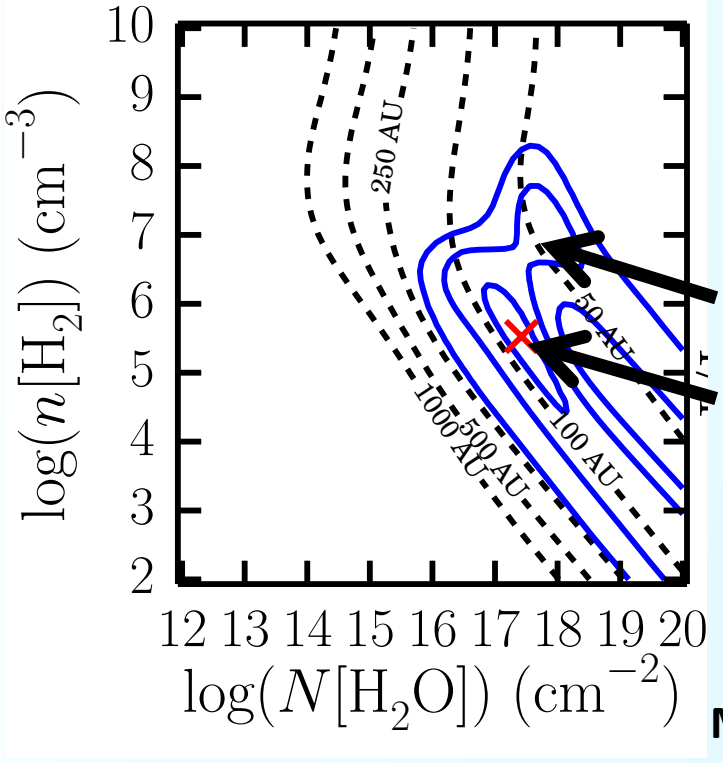

**Mottram et al., 2014**

**building on Kristensen et al., 2012, 2013, Karska et al., 2013**

- Cavity shock
  - C-shock along outflow cavity wall (central $H_2O$, warm mid-J CO)
  - Dominates $H_2O$ integrated intensity
  - $T_{gas}$~300 K
- Spot Shocks
  - J-shock internal to jet and at point of first impact on cavity wall (offset/EHV $H_2O$, hot high-J CO)
  - $T_{gas}$~750 K

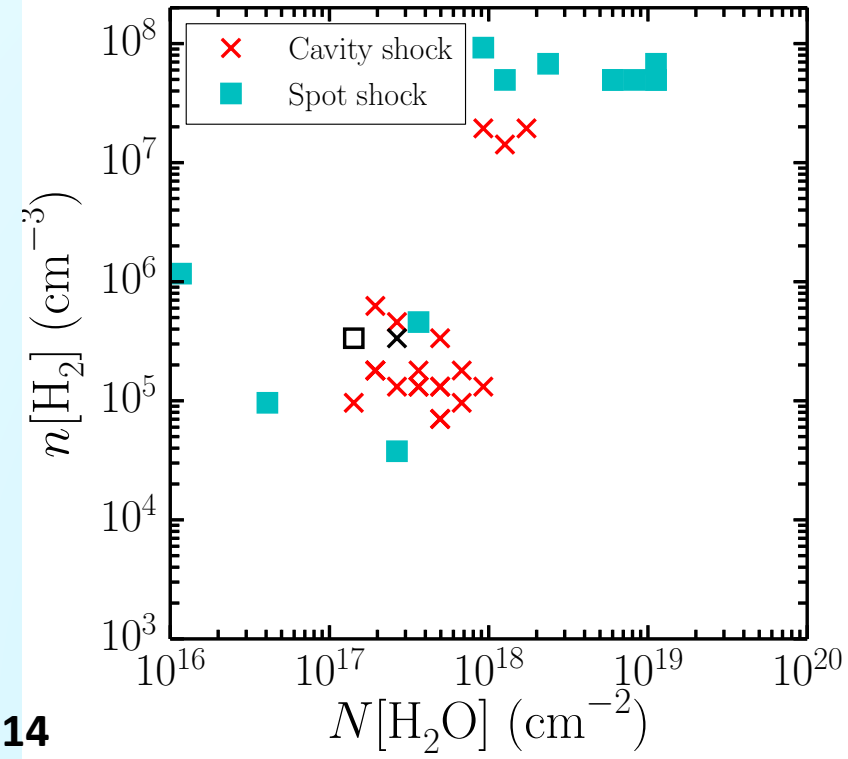
# Water excitation

- Lines are optically thick but effectively thin
- Emitting region sizes are small, of order 10-200AU
- n= $10^5$-$10^8$ $cm^{-3}$, N=$10^{16}$-$10^{18}$ $cm^{-2}$
- Radiative pumping ruled out



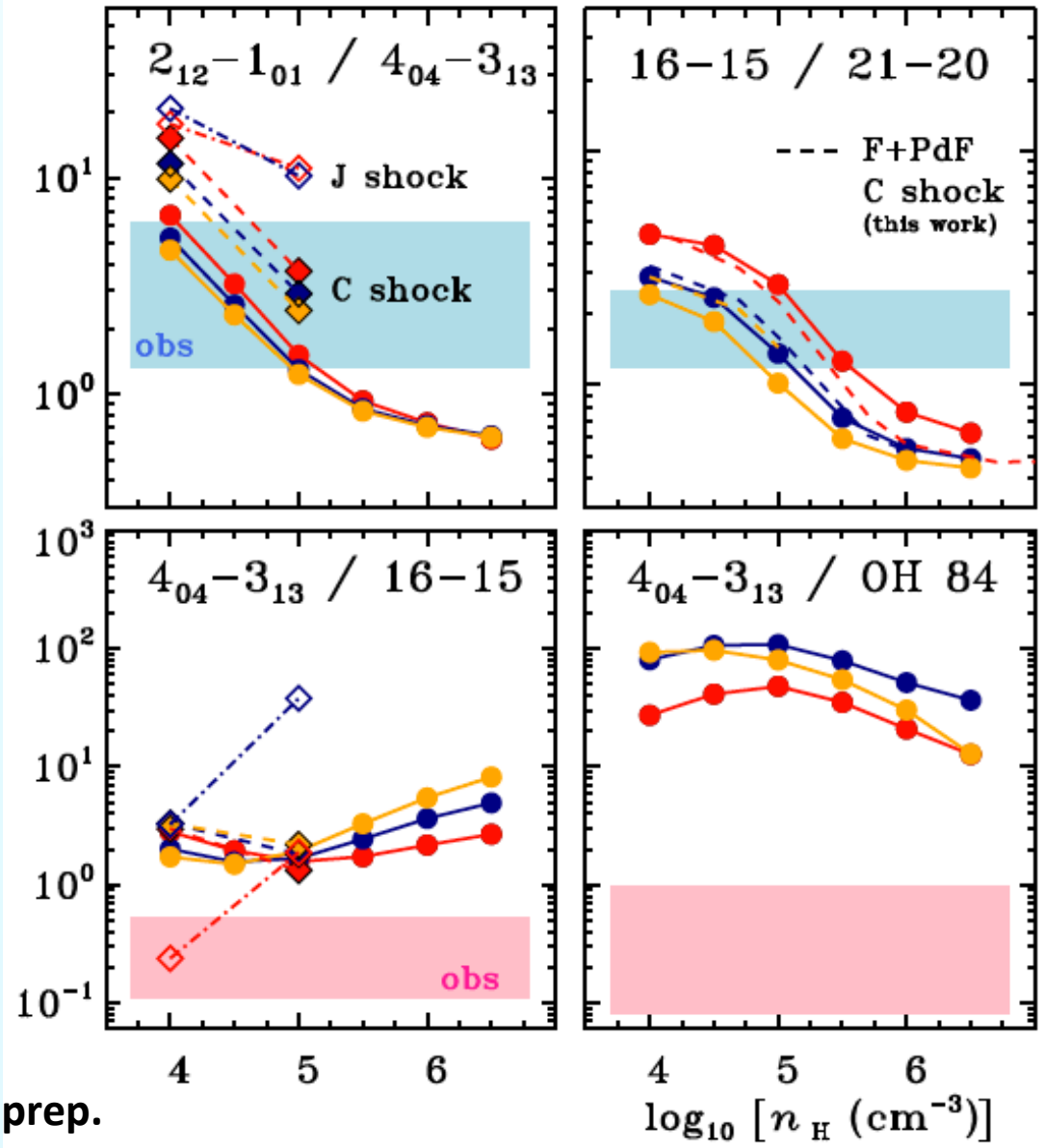

Two solutions: marginally and fully sub-thermal

Mottram et al., 2014



# Need for UV irradiation

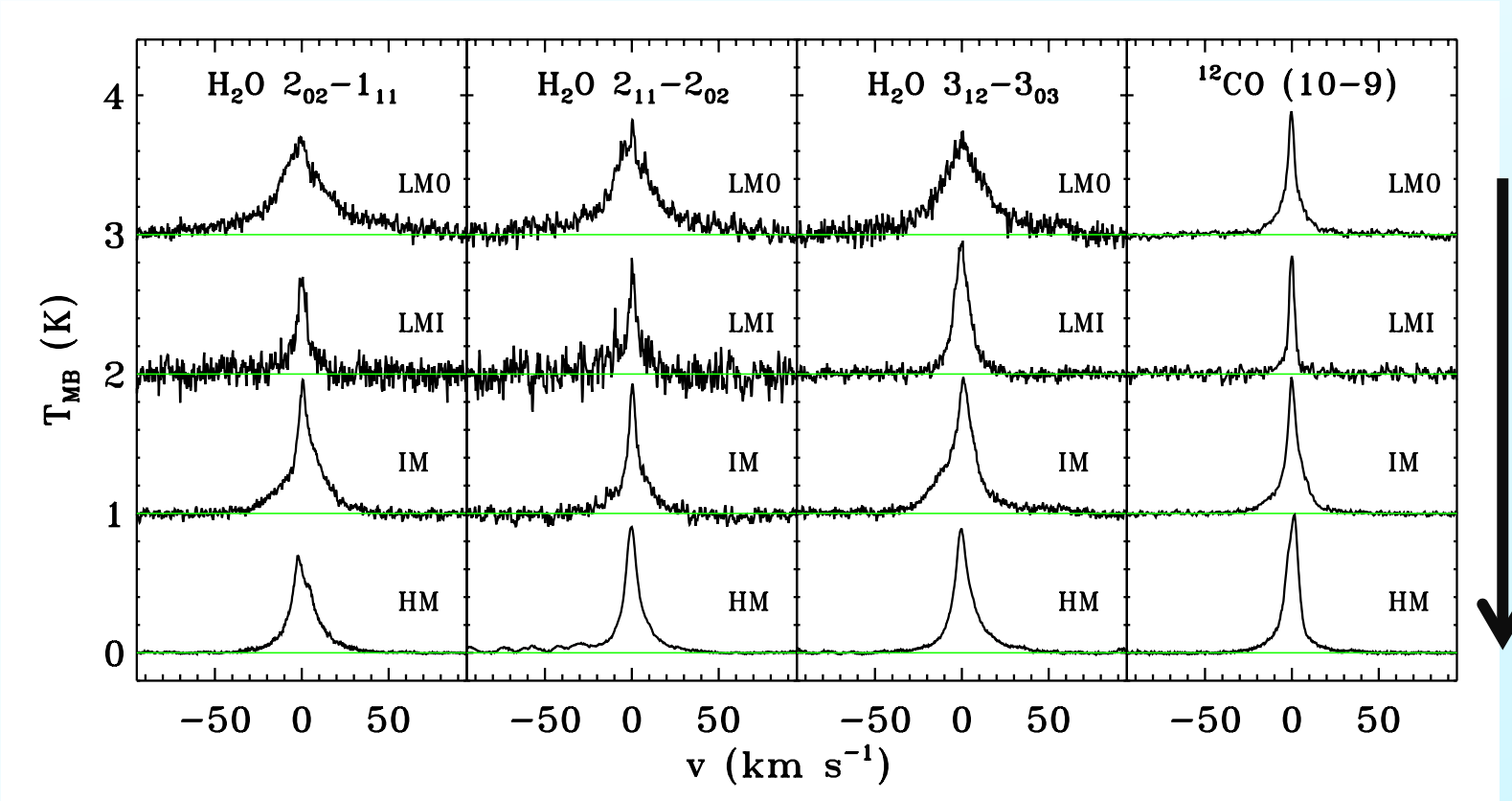
- Good agreement with shock models for single species PACS ratios
- Poor fit for inter-species ratios e.g. $CO/H_2O$ -> too much $H_2O$ in models
- $H_2O/CO$ 16-15 from HIFI finds $X(H_2O)\sim10^{-5}$




**Karska et al., 2014, Kirstensen et al., in prep.**

# From low to high mass – does it all just scale?

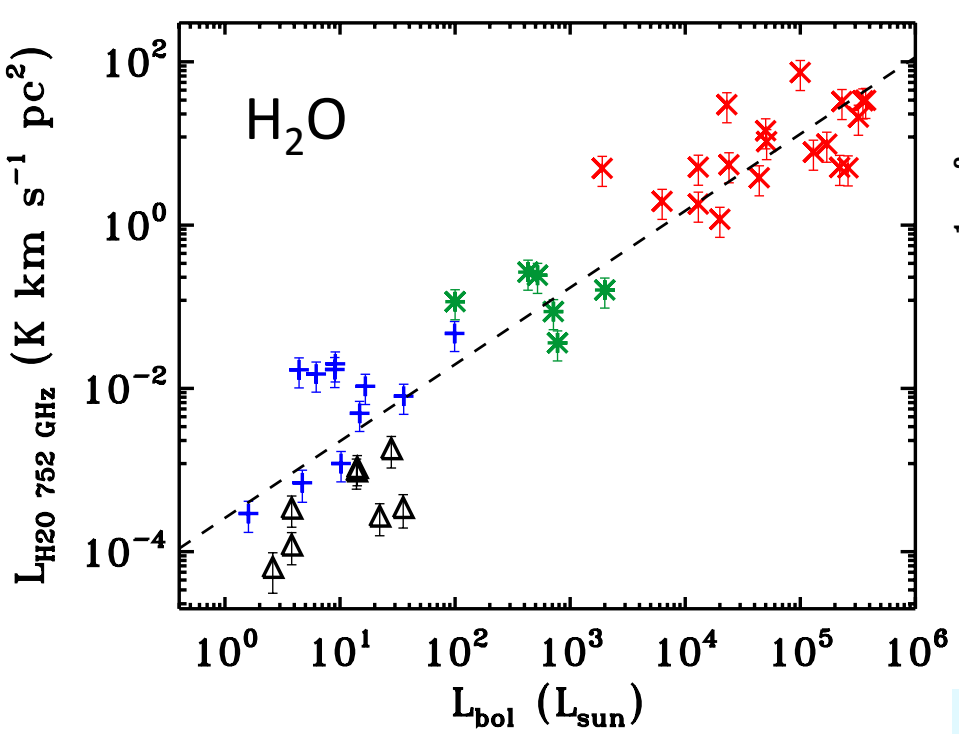
# Line profiles over probed L range

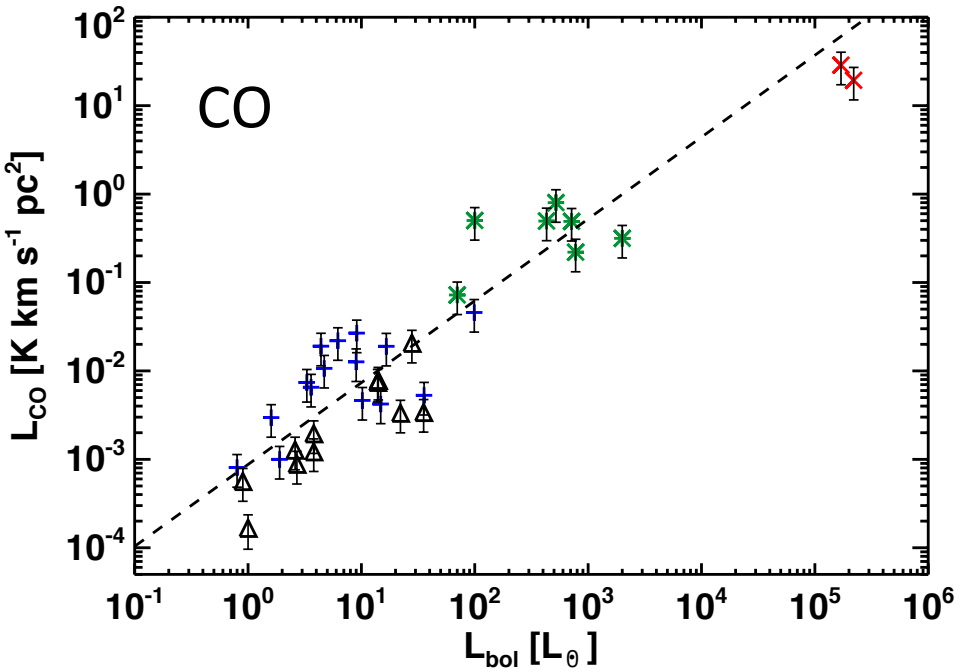



- Profiles similar between Class 0, intermediate and high-mass WISH sources
- Still dominated by cavity-shock component

**San Jose-Garcia et al., in prep.**

# Line luminosities scales with L



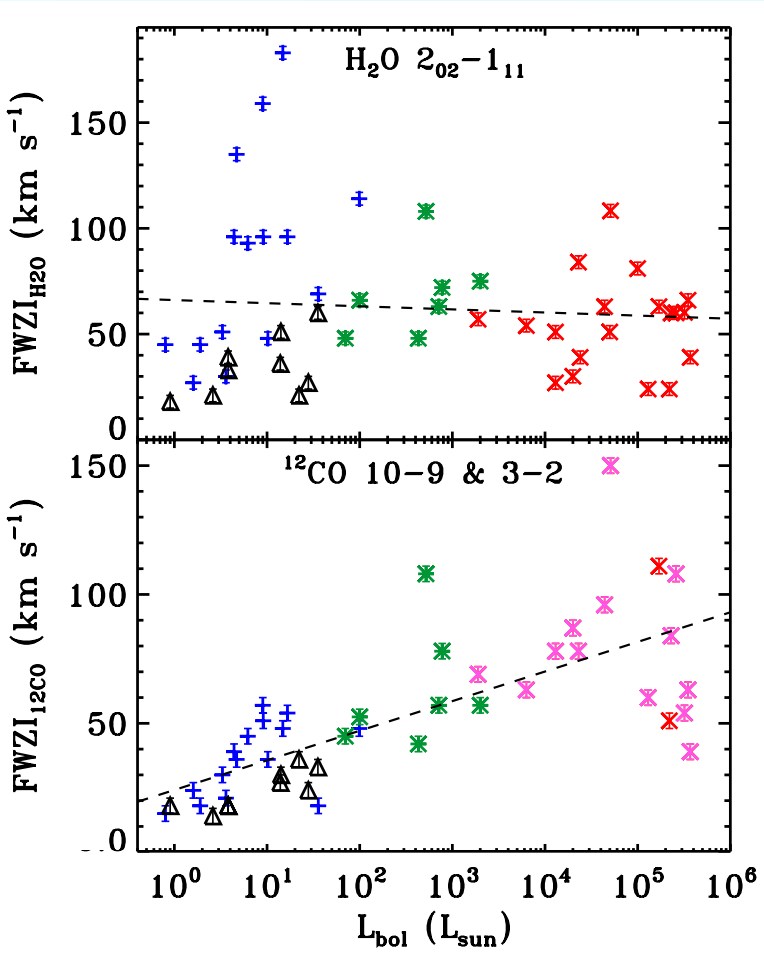




- Integrated intensity of water and CO scale linearly with $L_{bol}$
- Warm PACS CO component also seen in HM sources with similar $T_{rot}$

**San Jose-Garcia et al., 2013 & in prep., Karska et al., 2014 & in prep.**

# $H_2O$ vs. $^{12}CO$

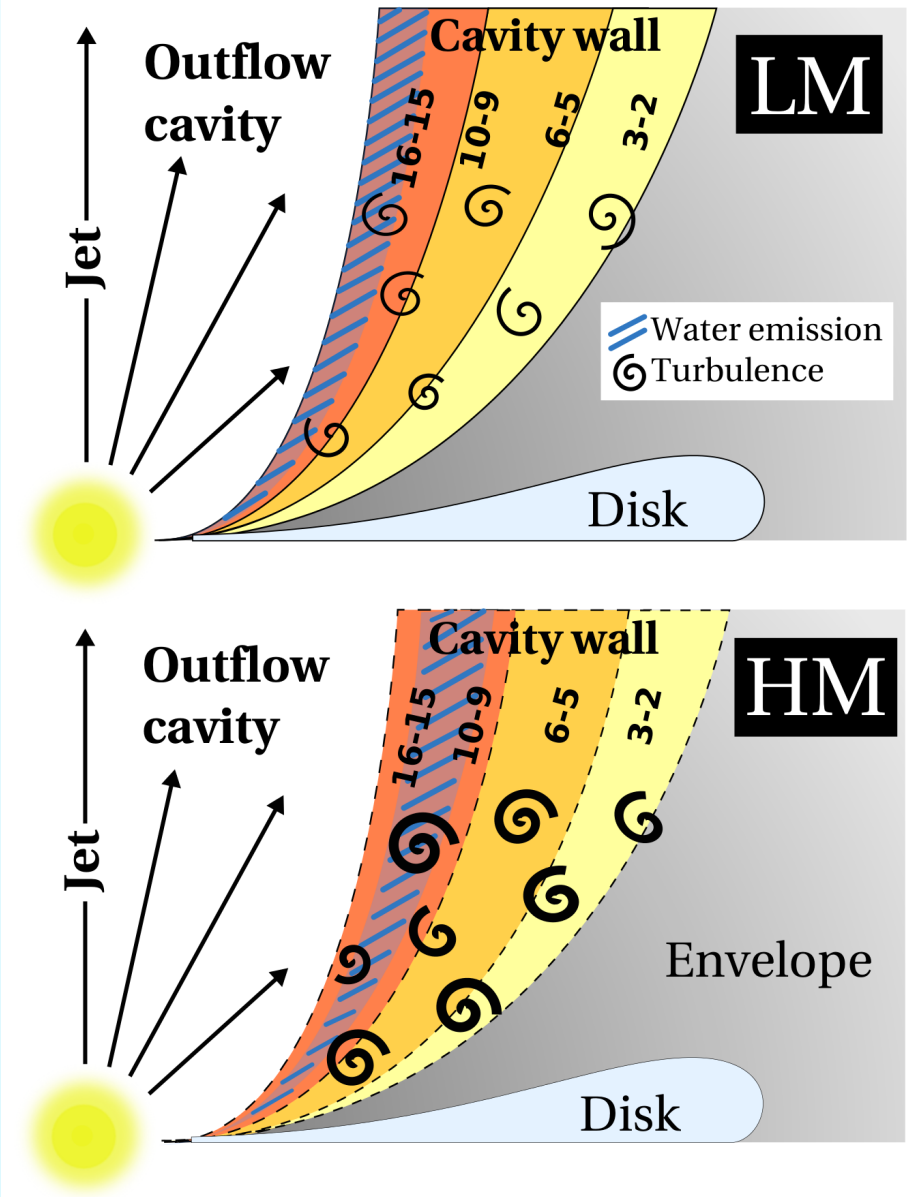
- The FWZI (and FWHM) of $H_2O$ lines doesn't vary with $L_{bol}$
- They increase with $L_{bol}$ for CO
- Therefore the relationship between $H_2O$ and $^{12}CO$ changes with $L_{bol}$
- Also seen when comparing line ratios of $H_2O$ with $^{12}CO$ J=10-9 and 16-15 as a function of velocity




**San Jose-Garcia et al., in prep.**

# $H_2O$ vs. CO – explanation(s)

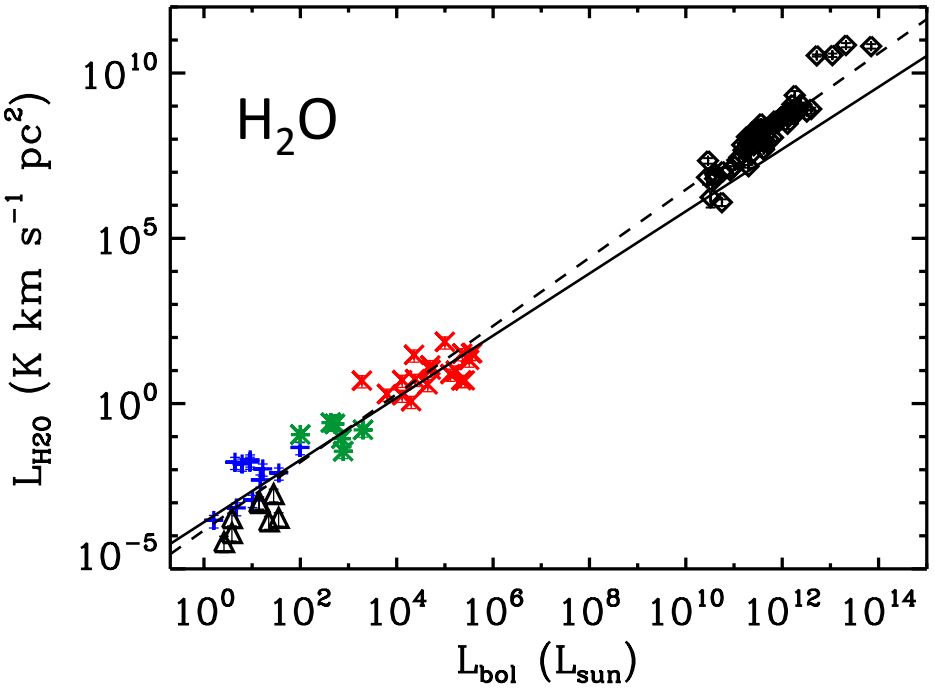
- Two scenarios to explain this:
  - 1: Higher UV in HM sources destroys water closer to the cavity but releases more water further in
  - 2: Higher turbulence caused by the outflow leads to mixing of material deeper into the cavity wall
- Taken together, outflows seem to scale with $L_{bol}$

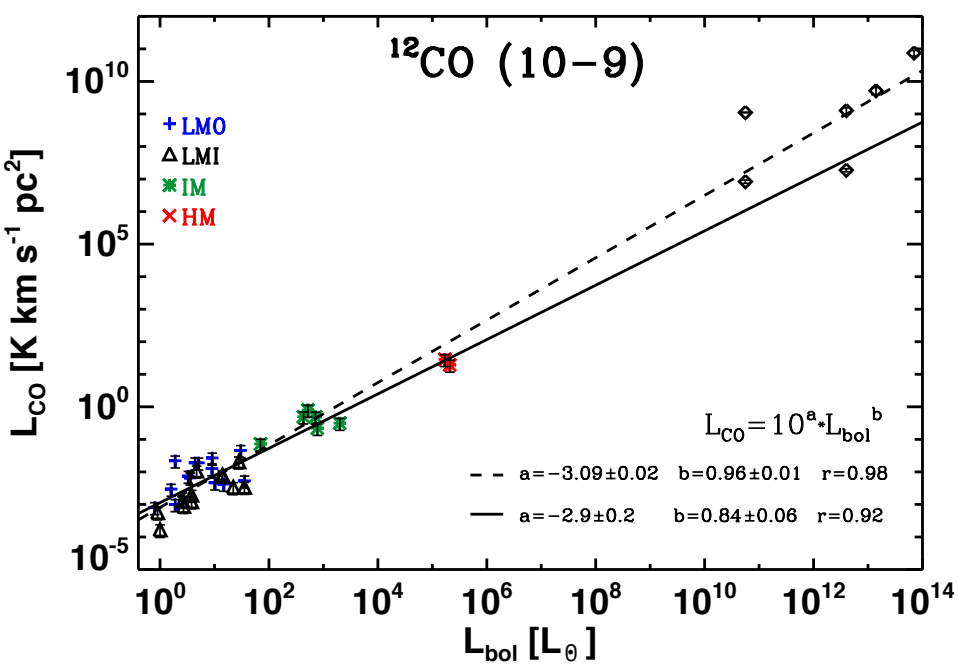



**San Jose-Garcia et al., in prep.**

# From the Milky Way to other Galaxies

# Can we keep on scaling up?



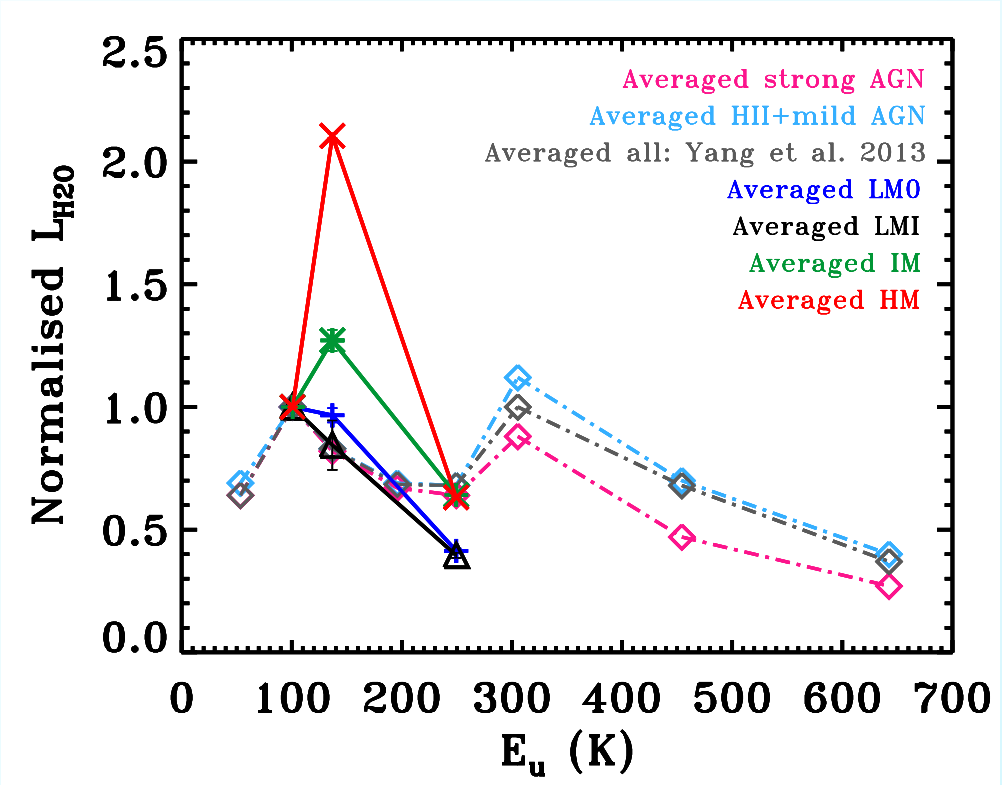




**Extragalactic data from Yang et al., 2013, van der Werf et al., 2010, Spinoglio et al., 2012, Kamenetzky et al. 2012; Meijerink et al. 2013**

- $H_2O$ and CO intensity seem to continue to scale with $L_{bol}$ to extragalactic scales
- Combination of LM and HM sources in beam?

**San Jose-Garcia et al., 2013 & in prep., Kristensen & Bergin, in prep.**

# What about excitation?




- Extragalactic water line-ratios more similar to LM than HM over common energy range
- Hot CO from protostars in extragalactic sources too?

**San Jose-Garcia et al. in prep.**

# Conclusions

# Conclusions

- Water and warm (~300K, mid-J) CO are dominated by the compact cavity shock in both LM and HM sources
- Integrated intensity scales linearly with $L_{bol}$
- Excitation of warm CO consistent between LM and HM, $H_2O$ under investigation
- After accounting for details, LM can be scaled up to HM (at least for the outflow physics we are probing)
- LM and HM sources provide templates which may be able explain observed extragalactic emission

More details and papers can be found at http://www.strw.leidenuniv.nl/WISH/


Thank you for your attention.

Any questions?