Water reveals the similarities and differences between low- and high-mass star formation

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Motivating questions

- What physics and physical conditions does H_2O trace in protostars?
- How does the physics probed by H_2O scale with source properties (e.g. L_{bol} and/or M_{env})?
- Can the same physics plausibly explain low and high-mass protostars?
- What can Galactic observations tell us about extragalactic sources?

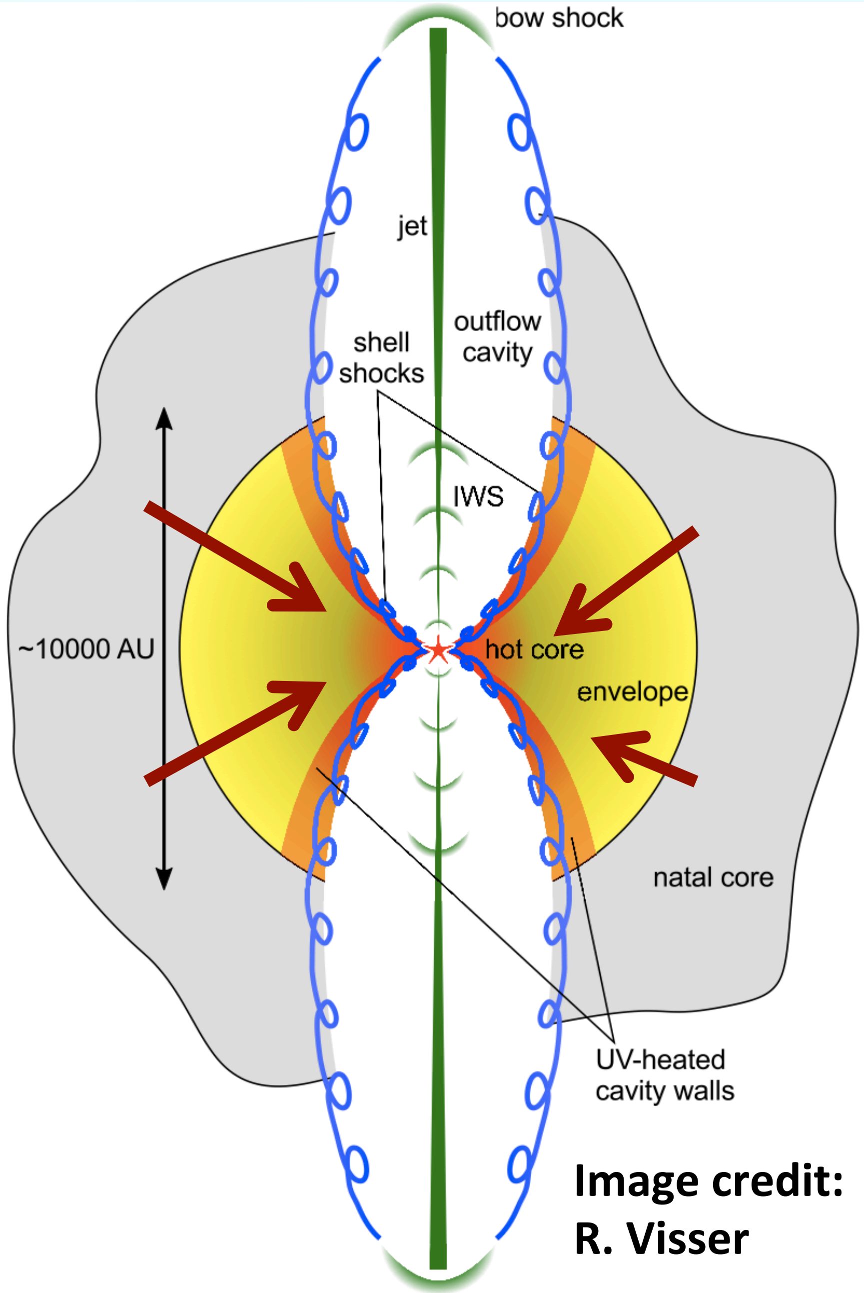


Image credit: R. Visser

Introduction

Low-mass (isolated) star formation

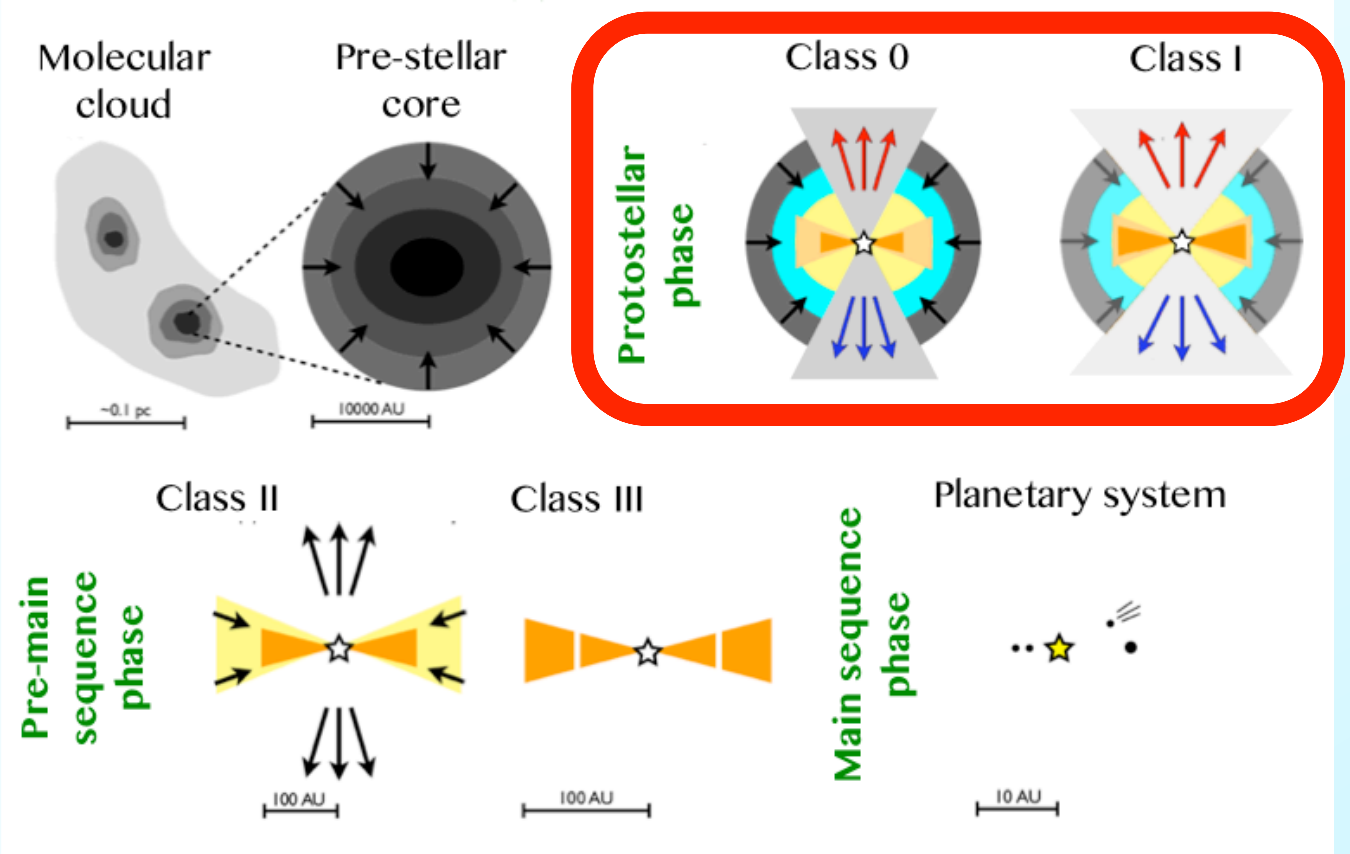
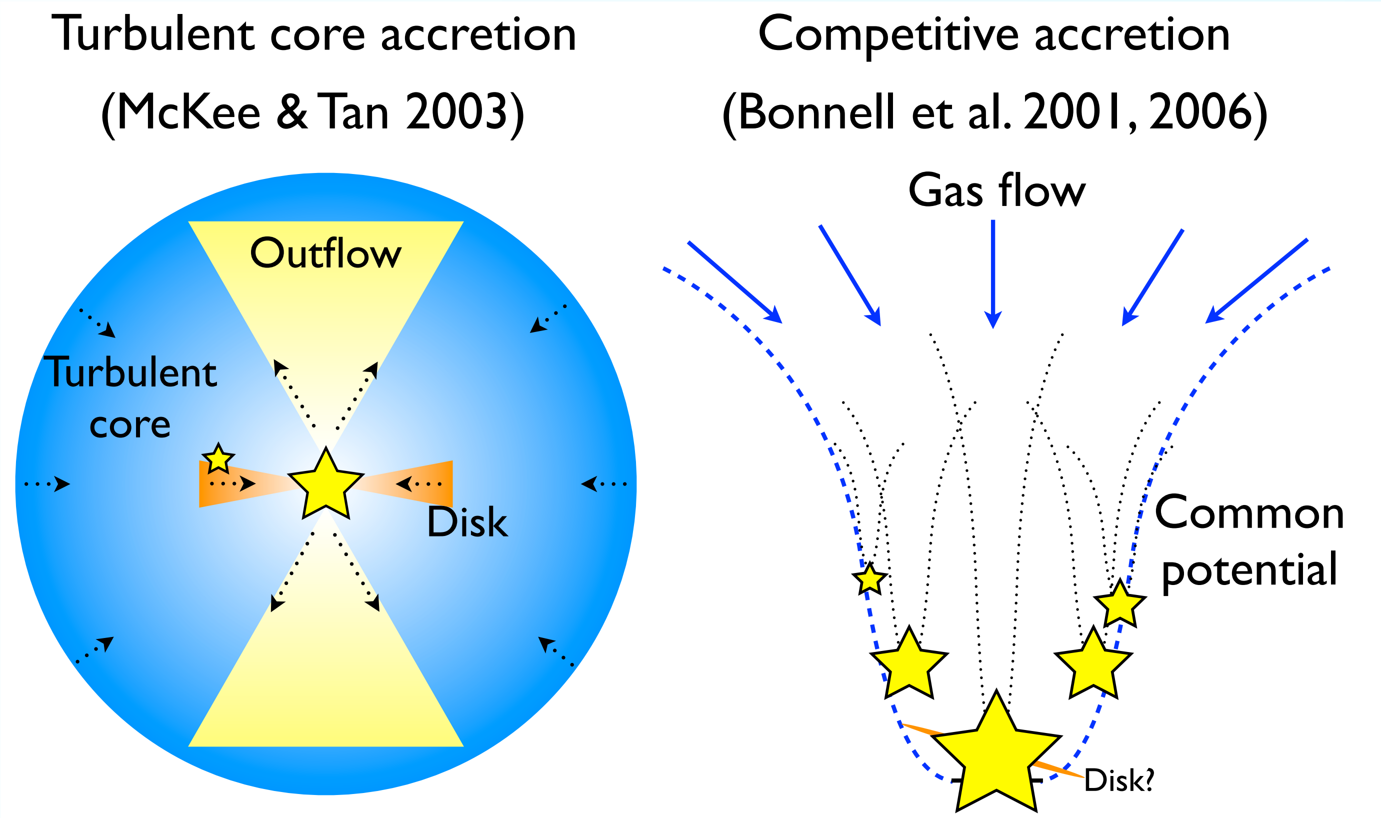


Image credit: I. San José-García & K.S. Wang

- General observational scheme around for some time (Lada & Wilking 1984, André 1993)
- Stellar properties set in Class 0/I main accretion phase

Theories of High-mass star formation



Also fragmentation induced starvation Peters+ 2010

Image credit: K.S. Wang

- Main difference is what the mass reservoir is and how this evolves over time
- Essentially isolated vs. highly clustered

High-mass star formation

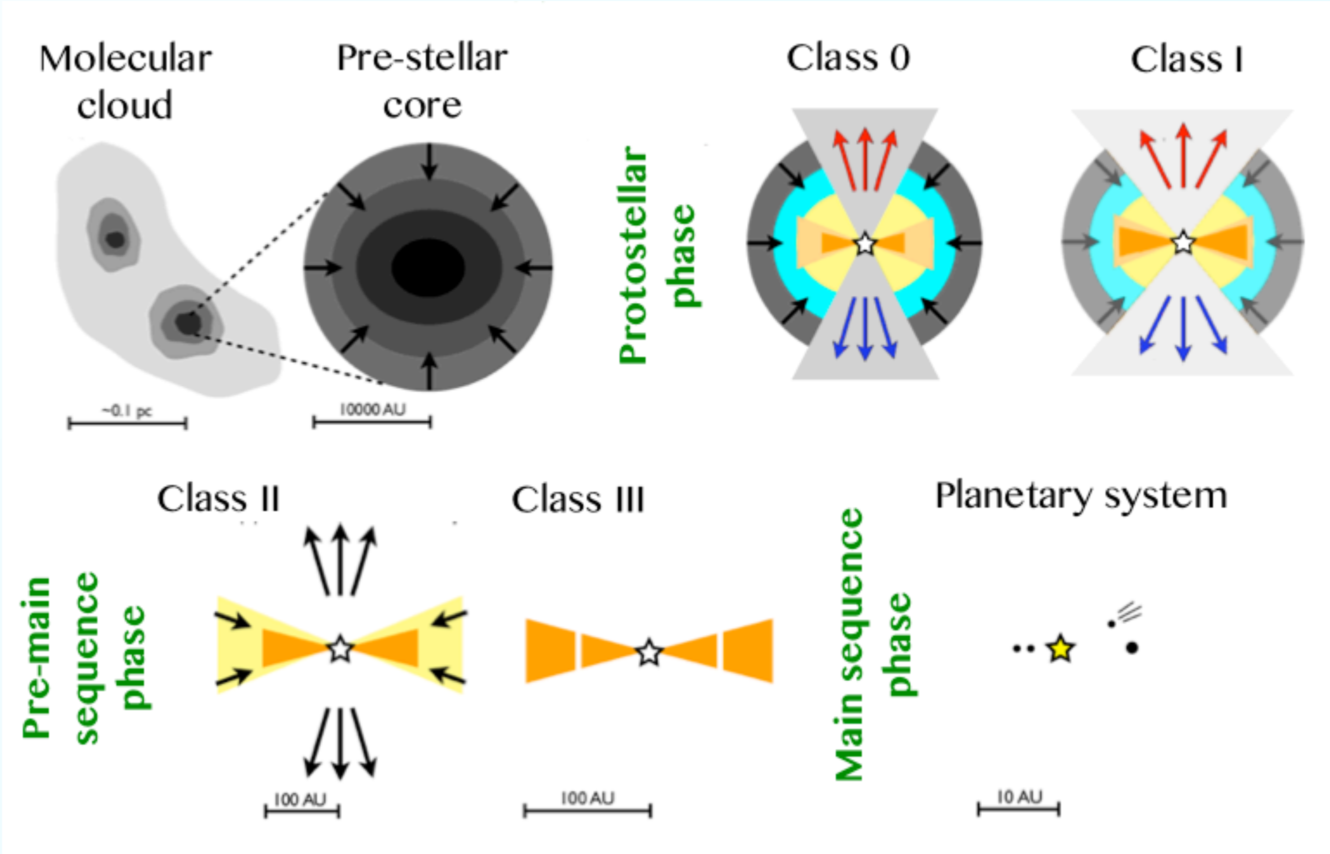


Image credit: I. San José-García & K.S. Wang

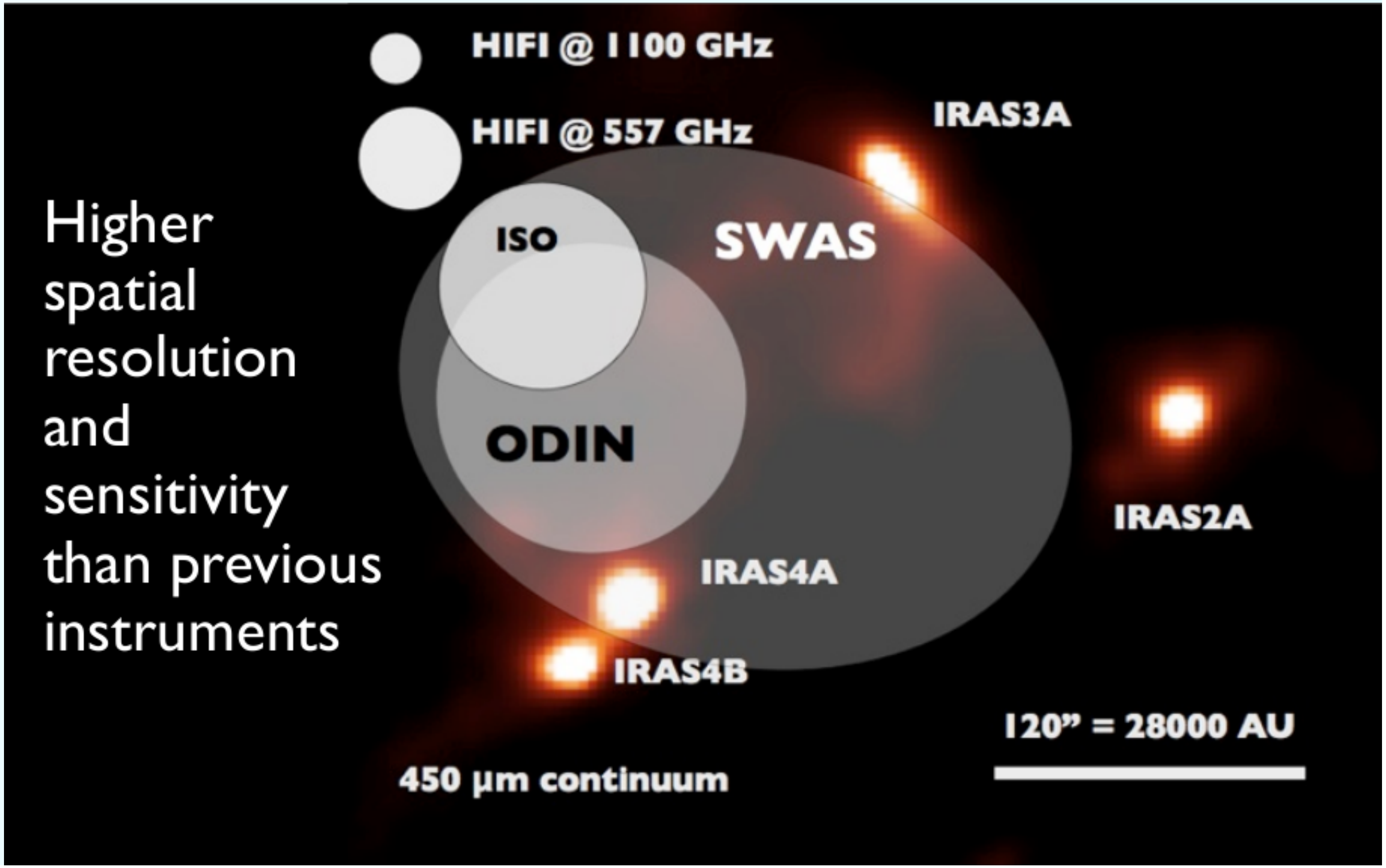
- Main differences for HM observational scheme
  - no PMS phase
  - Higher radiation field & UV, particularly later
- Masers evolve and overlap but are not unique or complete

The data

Herschel HIFI/PACS surveys of low, intermediate and high mass YSOs

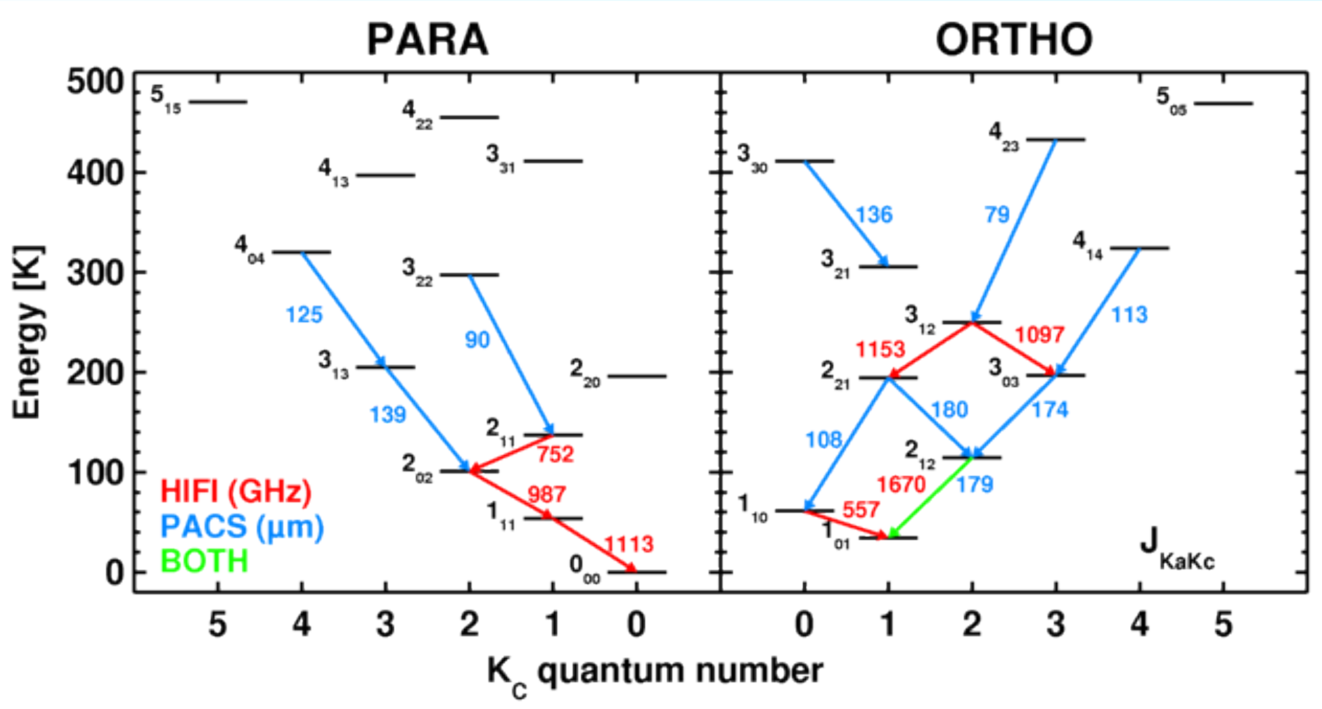
Standing on the shoulders of giants

- Herschel has enabled the detailed exploration and progress on the questions/hints raised by SWAS and ODIN



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

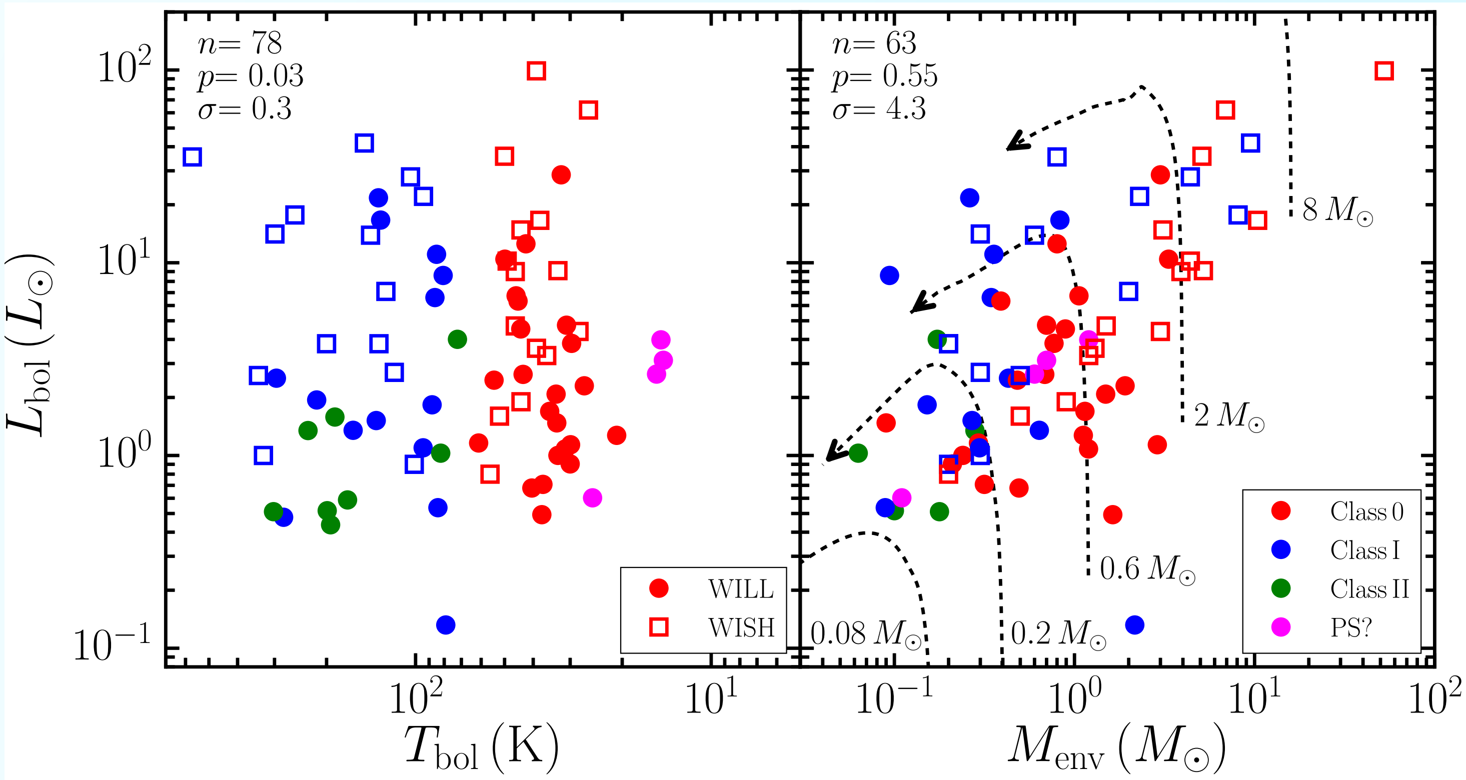
- 425 hrs of Herschel time (van Dishoeck+, 2011, PASP)
- HIFI spectroscopy & PACS spectral maps of H_2O, CO and related molecules



- ~ 80 sources:
  - From 1 $L_\odot$ - $10^5 L_\odot$
  - Prestellar cores to disks
  - 29 Class 0/Is

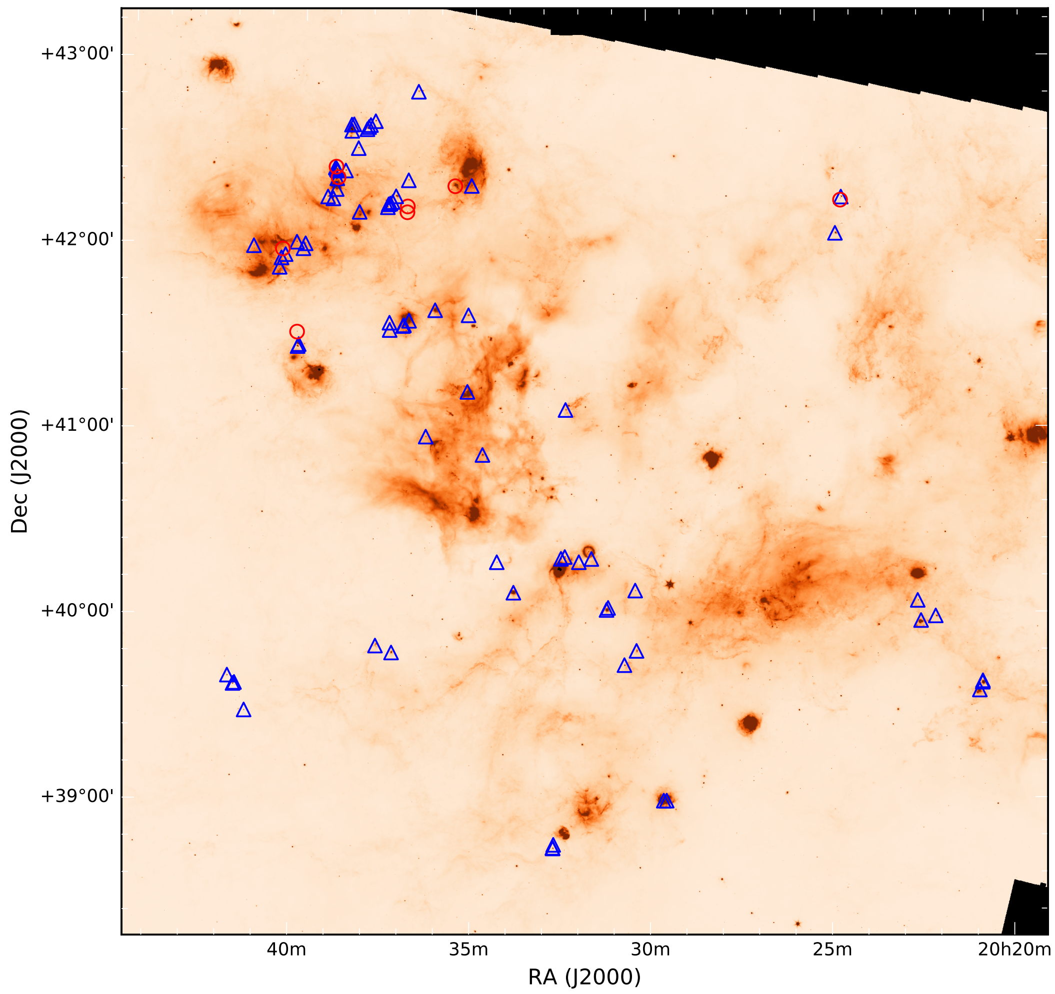
WILL: *William Herschel Line Legacy*

- OT2 HIFI & PACS follow-up to WISH-LM of a statistically selected sample (Mottram+ subm.)
- ~50 low-mass sources selected from Herschel and Spitzer GB surveys. Follow-up confirms most as Class 0/I



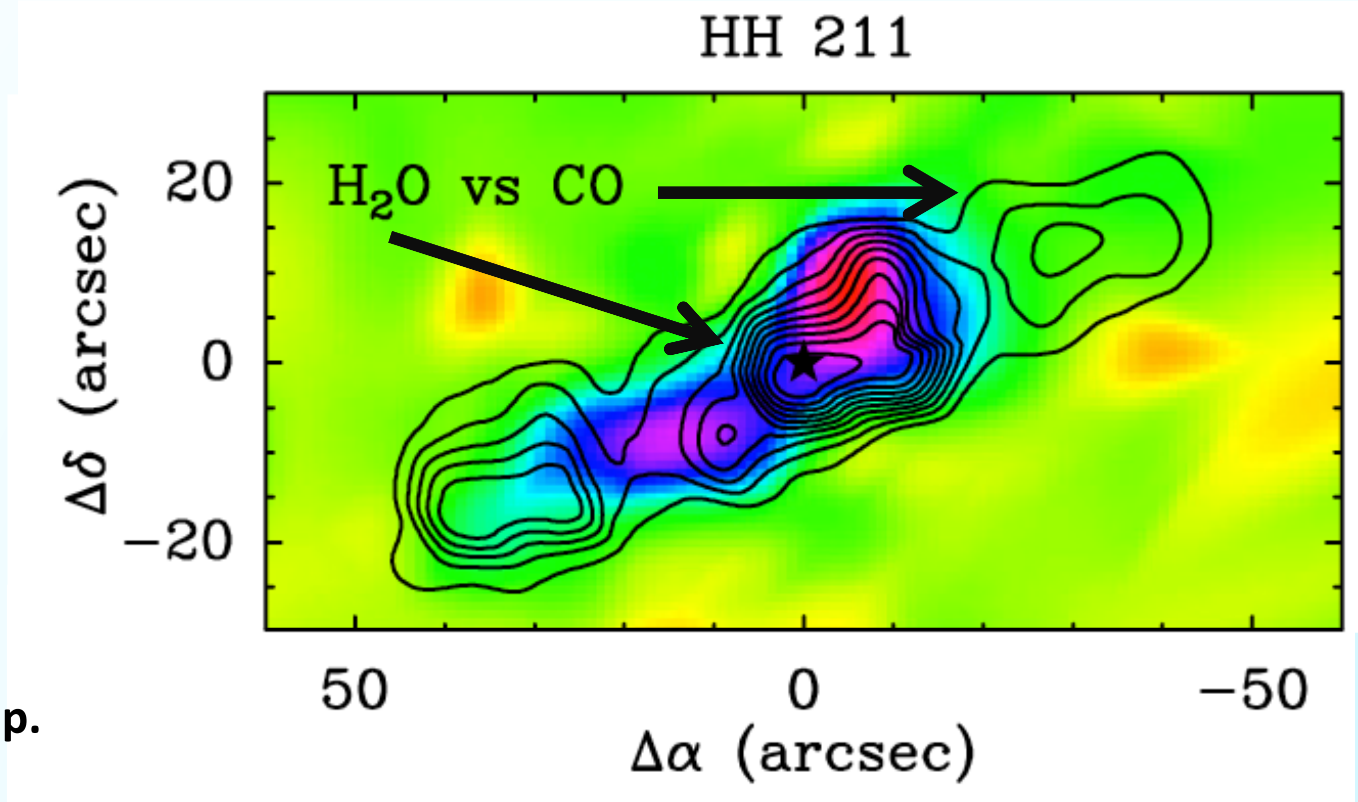
HIFI Cygnus-X Survey

- Targeted the 86 most luminous protostars in the Cygnus-X star forming region with HIFI (PI: S. Bontemps)
- Span $L_{bol} \sim 10^2\text{-}10^3\ L_{\odot}$
- Mix of Class 0 and I low and intermediate mass YSOs



Low-mass protostars – `simplest’ template of star formation

Spatial extent of water

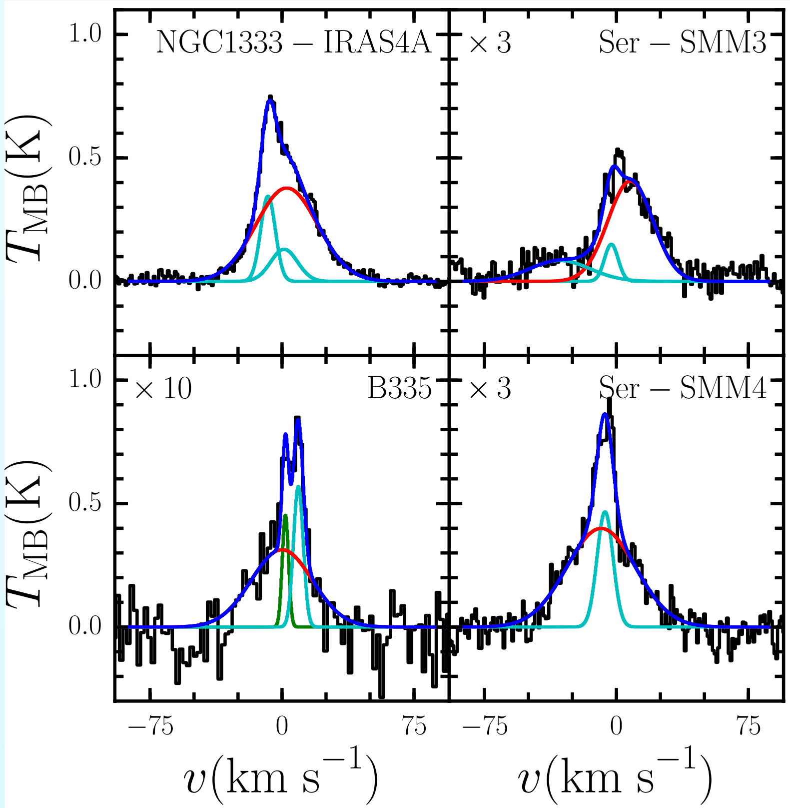


Tafalla+ 2013, Karska+ in prep.

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

Multi-component H_2O line profiles

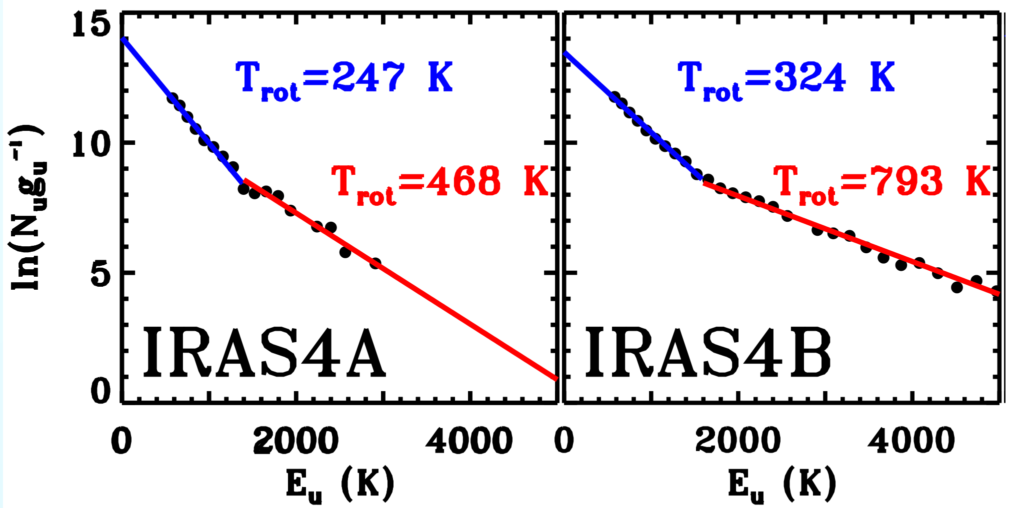
- H_2O line profiles are complex -> trace multiple kinematic components
- Dominated by broad component associated with outflows and shocks
- Different from ground-based line profiles -> probing new parts of the protostellar system
- Line shape similar between H_2O transitions -> tracing same gas

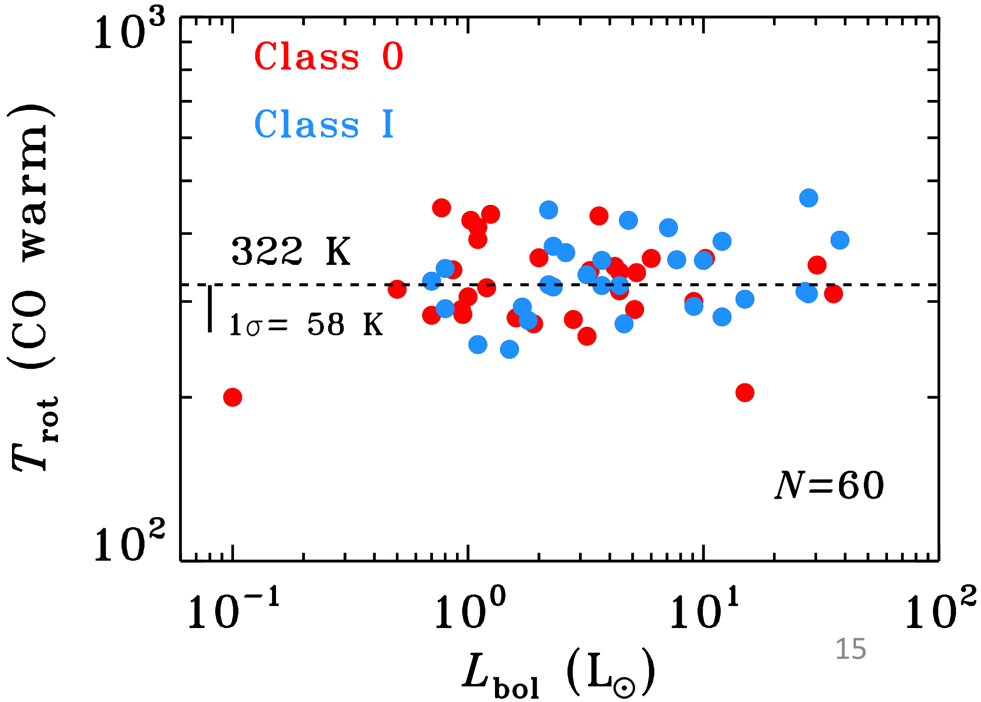


Kristensen+ 2012, Mottram+ 2013, 2014

Multi-component PACS CO rotational diagram

- H_2O insensitive to temperature - get from high-*J* CO
- 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

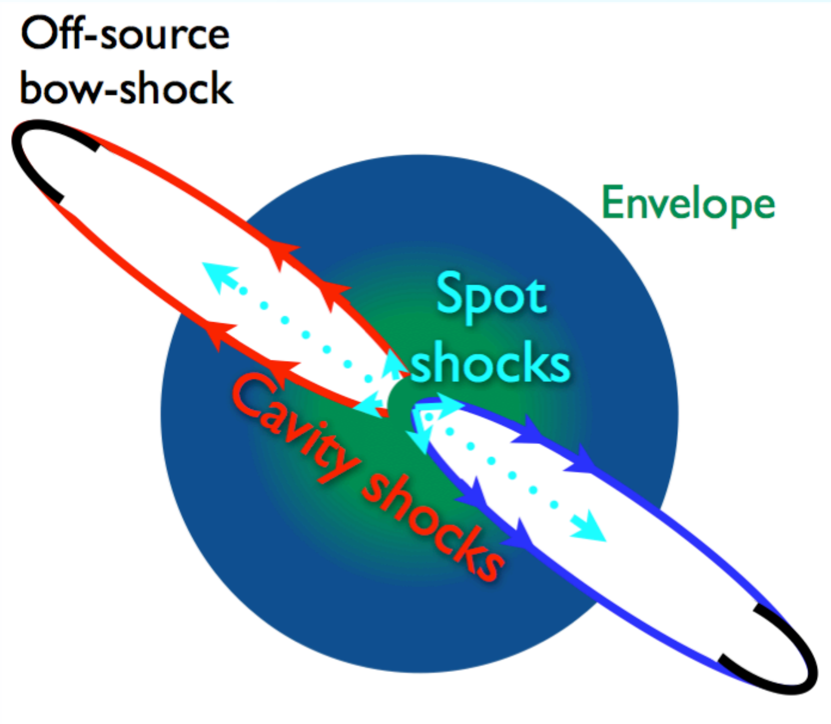




Karska+ 2013, 2014b & in prep.
see also Green+ 2013, Manoj+ 2013

Physical components traced by H_2O

- Three categories: Envelope, Cavity Shock and Spot Shock
  - Cavity Shock: broad, centred at source velocity -> C-shock in outflow cavity wall, T_{gas}~300 K



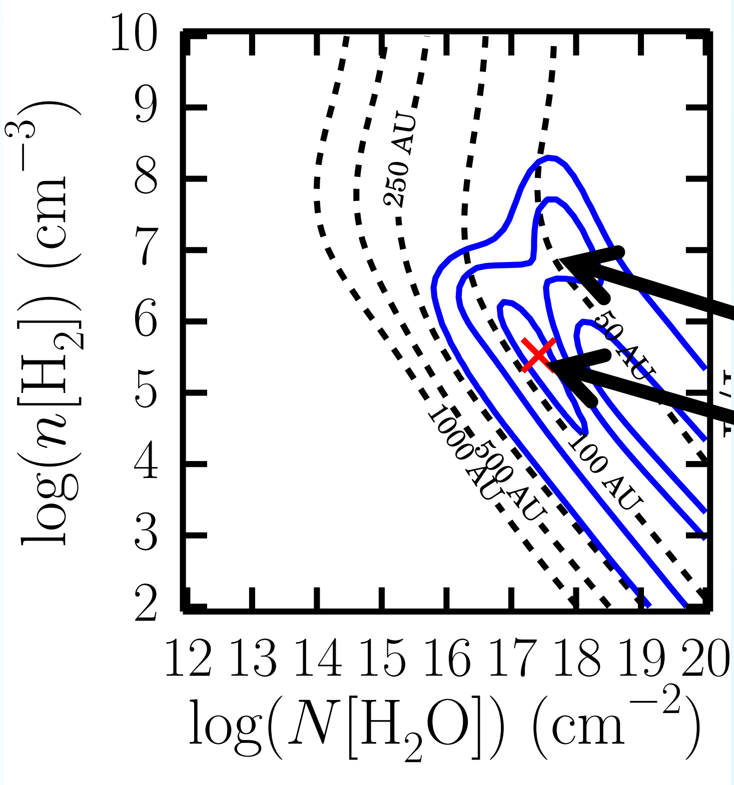
  - Spot Shock: offset from source velocity -> J-shock at base of outflow or in jet shock, T_{gas}~750 K
- Envelope: narrow, sometimes IPC/RPC

Mottram+ 2014

building on Kristensen+ 2012, 2013, Karska+ 2013

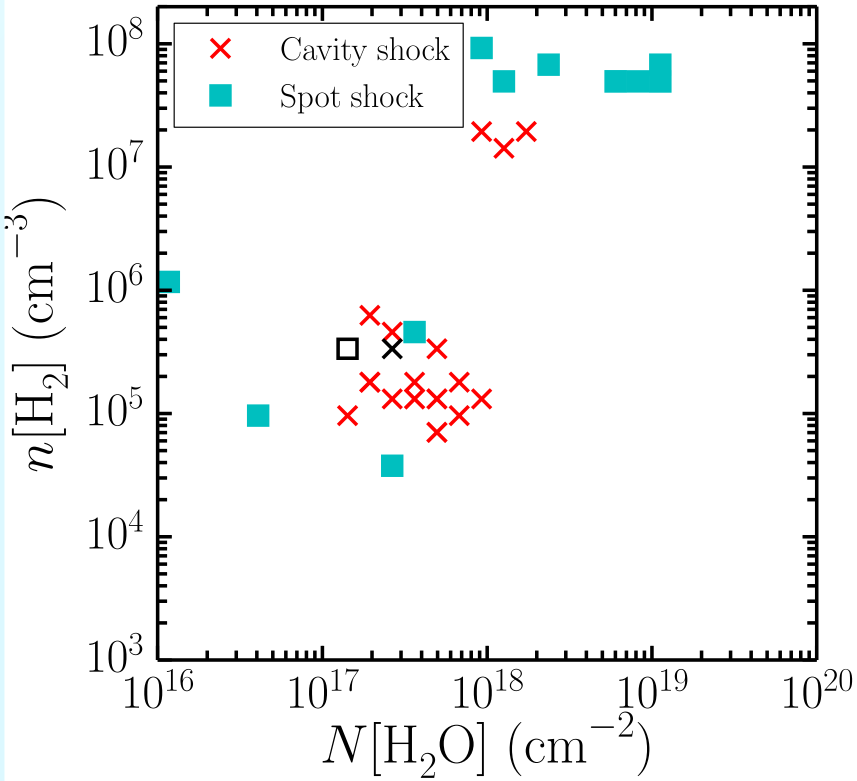
Water excitation

- 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



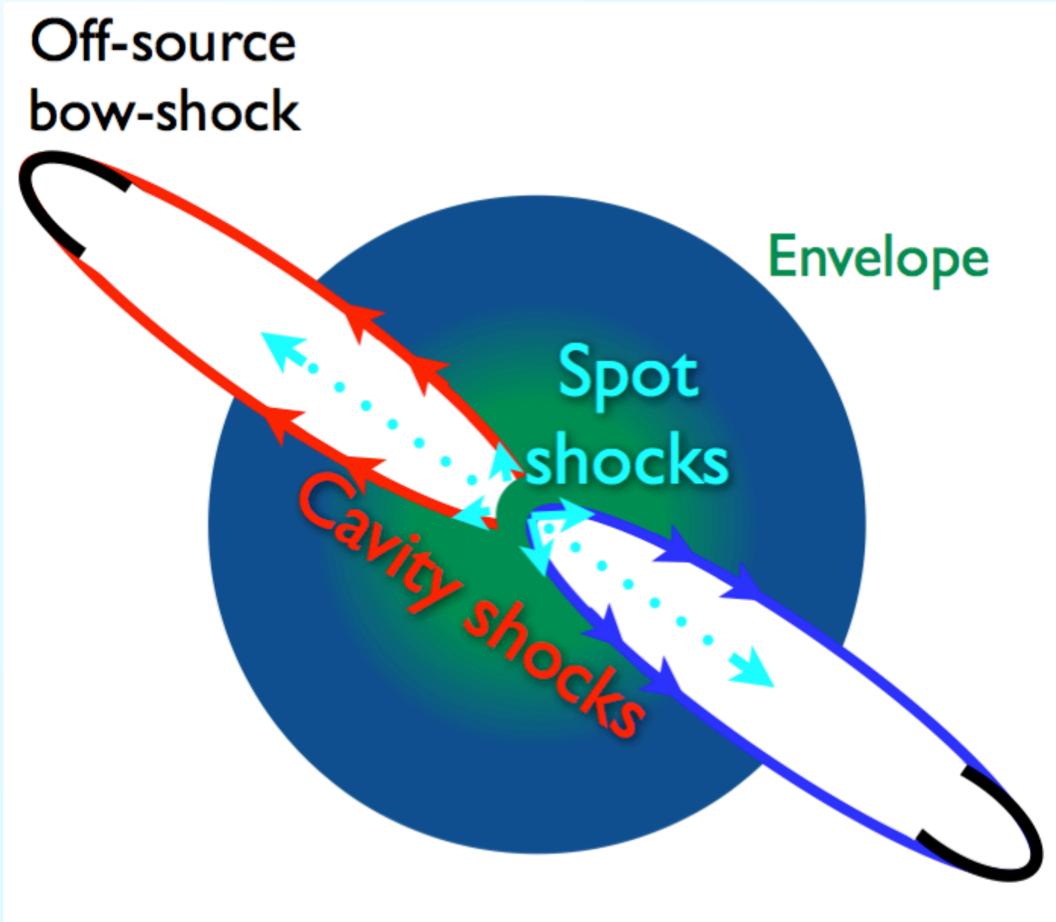
Two solutions: marginally and fully sub-thermal

Mottram+ 2014



Cavity vs. Spot Shocks

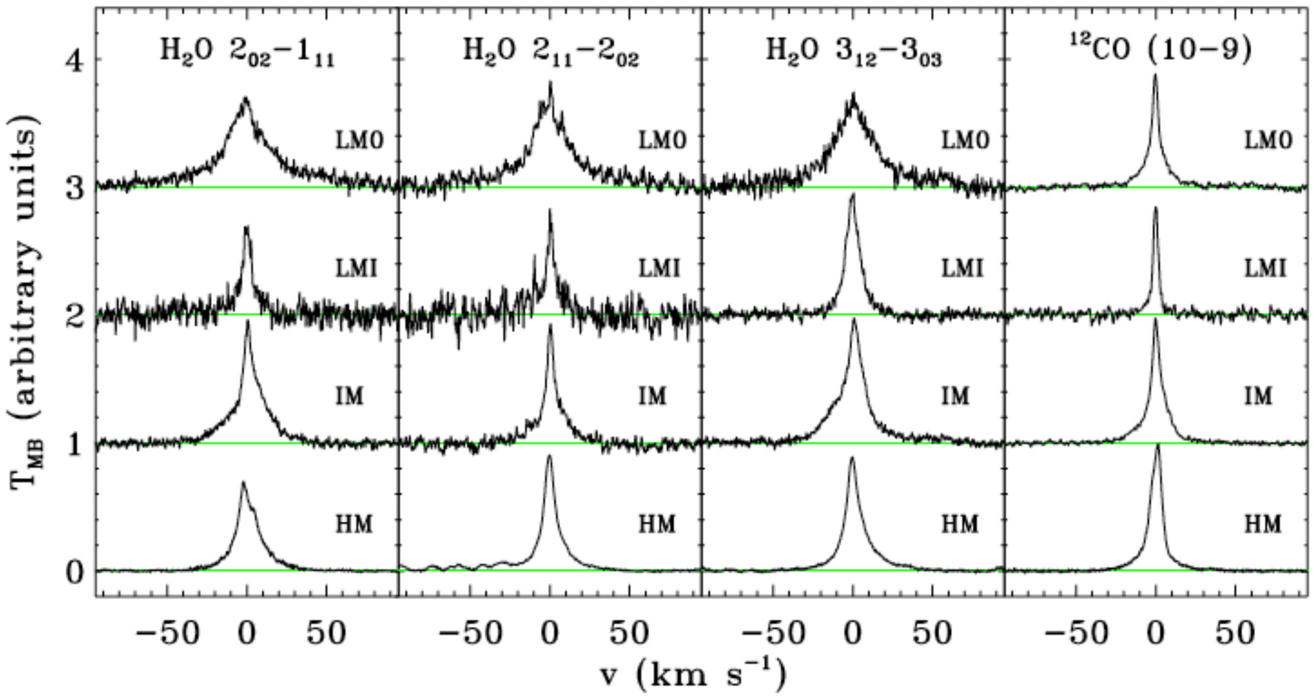
- Transition from spot to cavity shock at outflow base is smooth in n,N
- Small emitting region size suggests cavity shock is a thin (few AU) layer along the outflow wall

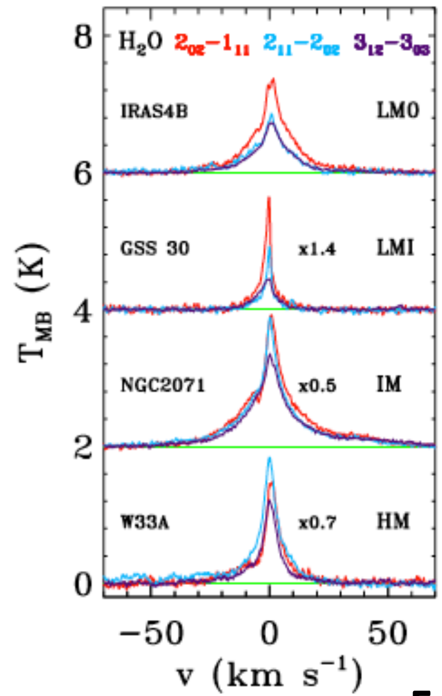


Mottram et al., 2014

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

Line profiles: low to high mass YSOs





Few 1000 AU

Few 10000 AU

Higher L_{bol}

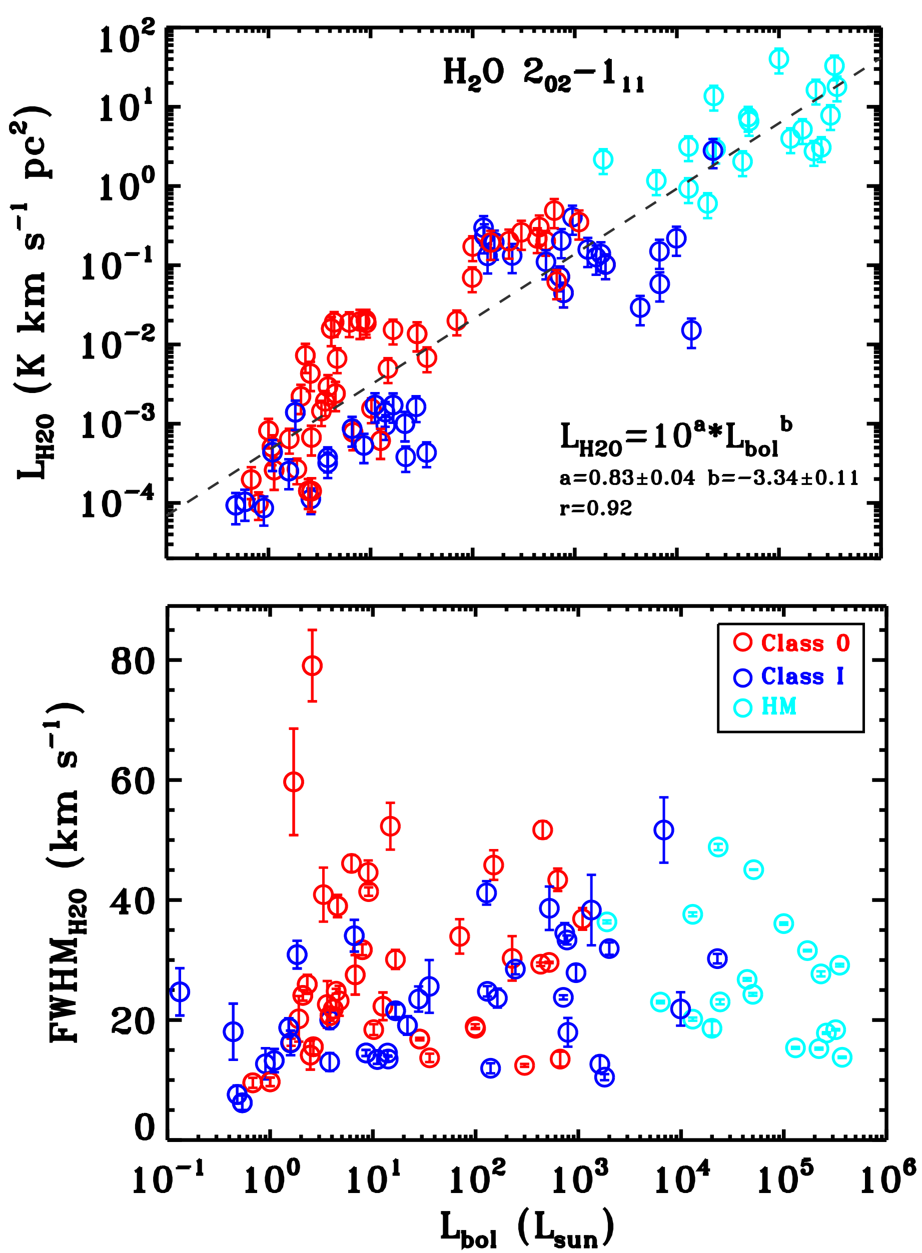
- Dominated by broad outflow-related emission
- H_2O broader than CO but similar between LM and HM
- Same line shape for different transitions

San José-García+ 2016

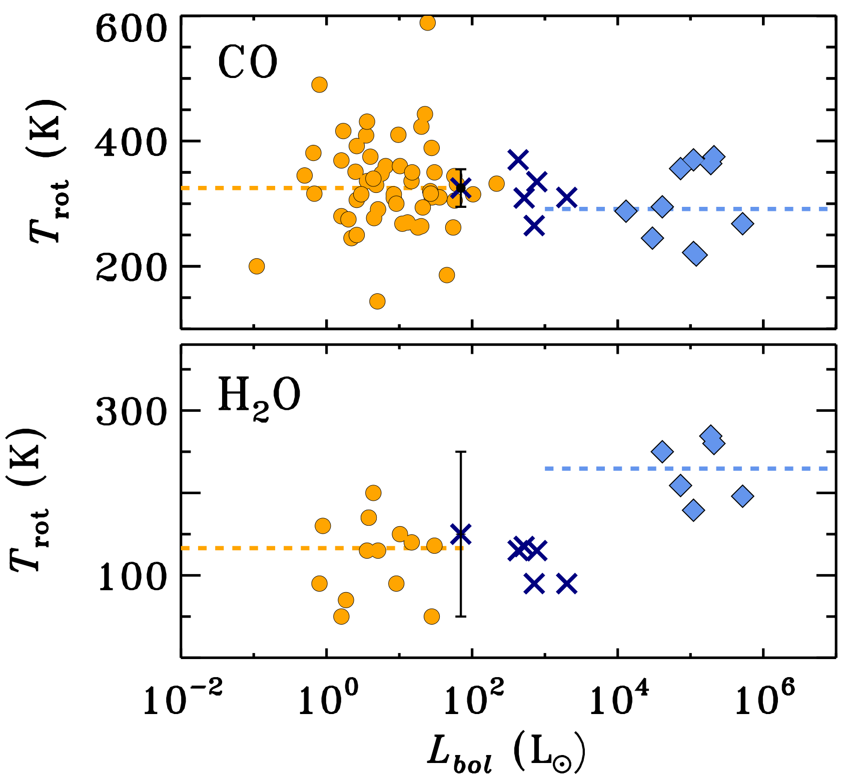
Line luminosities scales with L

- Integrated intensity of water scales with L_{bol}
- Water traces dense warm gas
- Linewidth similar regardless of L_{bol}
- Scatter likely due to intrinsic source properties (e.g. inclination, density), but these don't dominate.

San José-García+ 2016,
Mottram, San José-García+ in prep.



PACS from low to high-mass



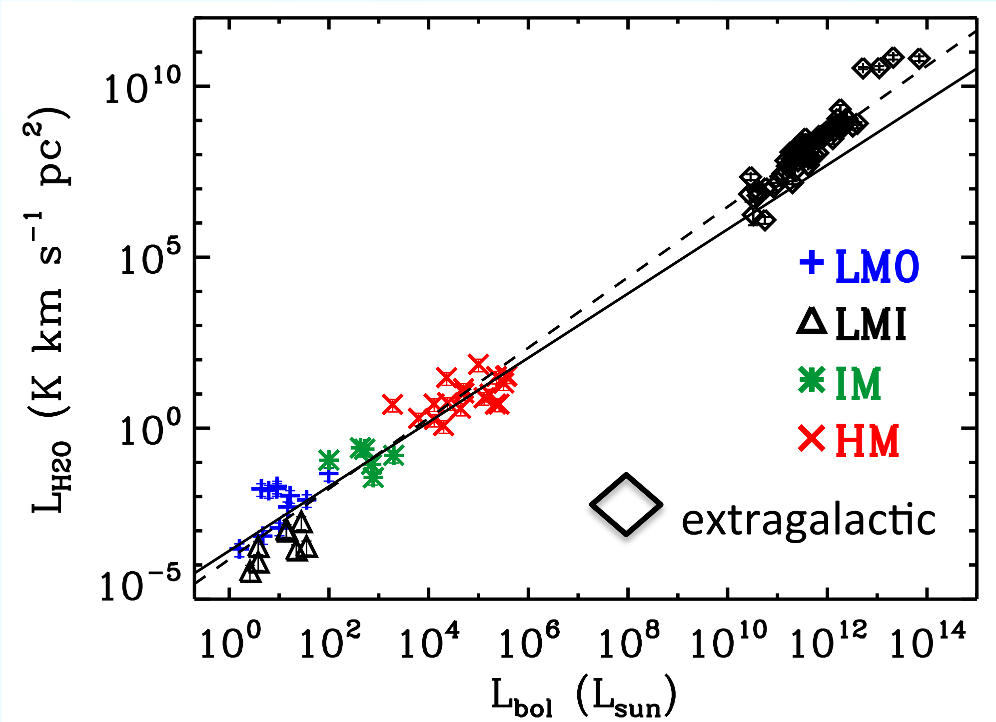
- CO excitation and components the same for low, intermediate and high mass YSOs
- H_2O excitation the same for low and intermediate mass YSOs, also for HIFI radex analysis
- High-mass H_2O T_{rot} higher and HIFI line ratios require radiative pumping for ~half of all sources

Karska+ 2013, 2014, Matuszak+ 2015, San José-García et al., 2016.

From the Milky Way to other Galaxies

Can we keep on scaling up?

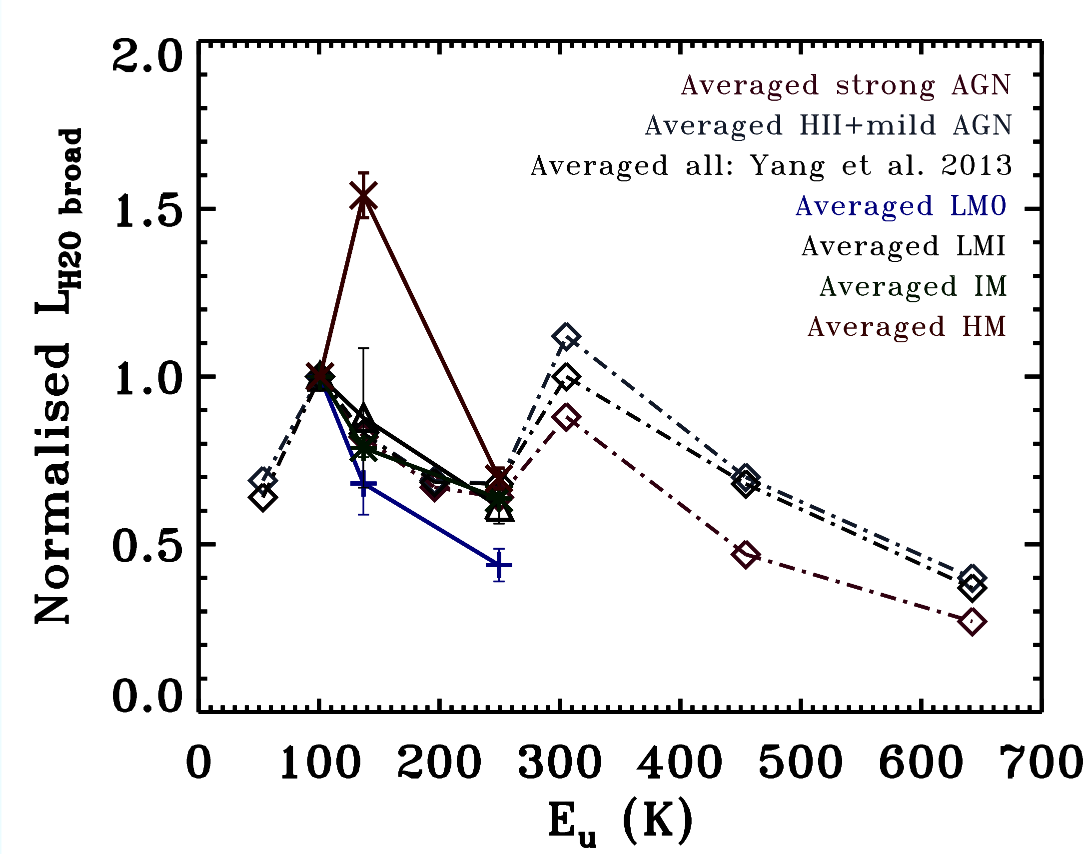
- H_2O intensity continues to scale with L_{bol} to extragalactic scales



San José-García+ 2016.

Extragalactic data from Yang+ 2013, van der Werf+ 2010, Spinoglio+ 2012, Kamenetzky+ 2012, Meijerink+ 2013

What about excitation?



- Extragalactic water line-ratios similar to LM over common energy range
- HM and extragalactic require radiative pumping, but otherwise energetics consistent
- Extragalactic emission could be from a combination of LM and HM sources.

San José-García+ 2016

Conclusions

Conclusions

- Water is dominated by the outflow in both LM and HM sources
- Integrated intensity scales linearly with L_{bol} and has similar line-widths between LM and HM
- Excitation of H_2O similar, except IR pumping is important in some HM sources
- 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?