Towards a universal, predictive star-formation theory:

linking low and high mass star formation

Joseph Mottram

Leiden University

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Irene San José-García

Ewine van Dishoeck

Lars Kristensen

Sylvain Bontemps

Agata Karska

Monika Matuszak

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Outline

- Introduction
- The data
- Low-mass protostars
- From low to high mass
- From the Milky Way to other Galaxies
- Conclusions
- Future prospects

Introduction

Our Goal

- Goal of studying star formation: To understand and predict the properties and dominant physical mechanisms of (proto)stars from initial conditions to main-sequence stars

Low-mass (isolated) star formation

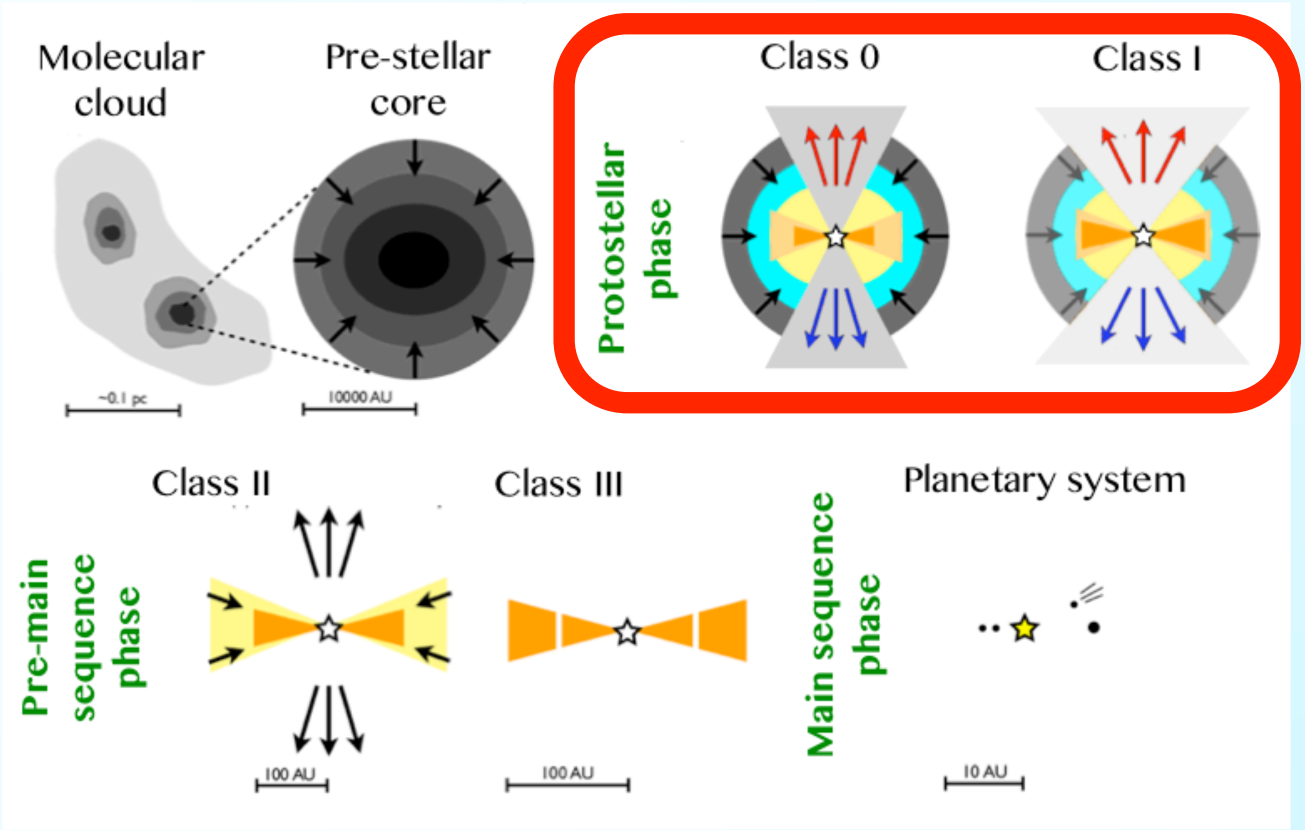
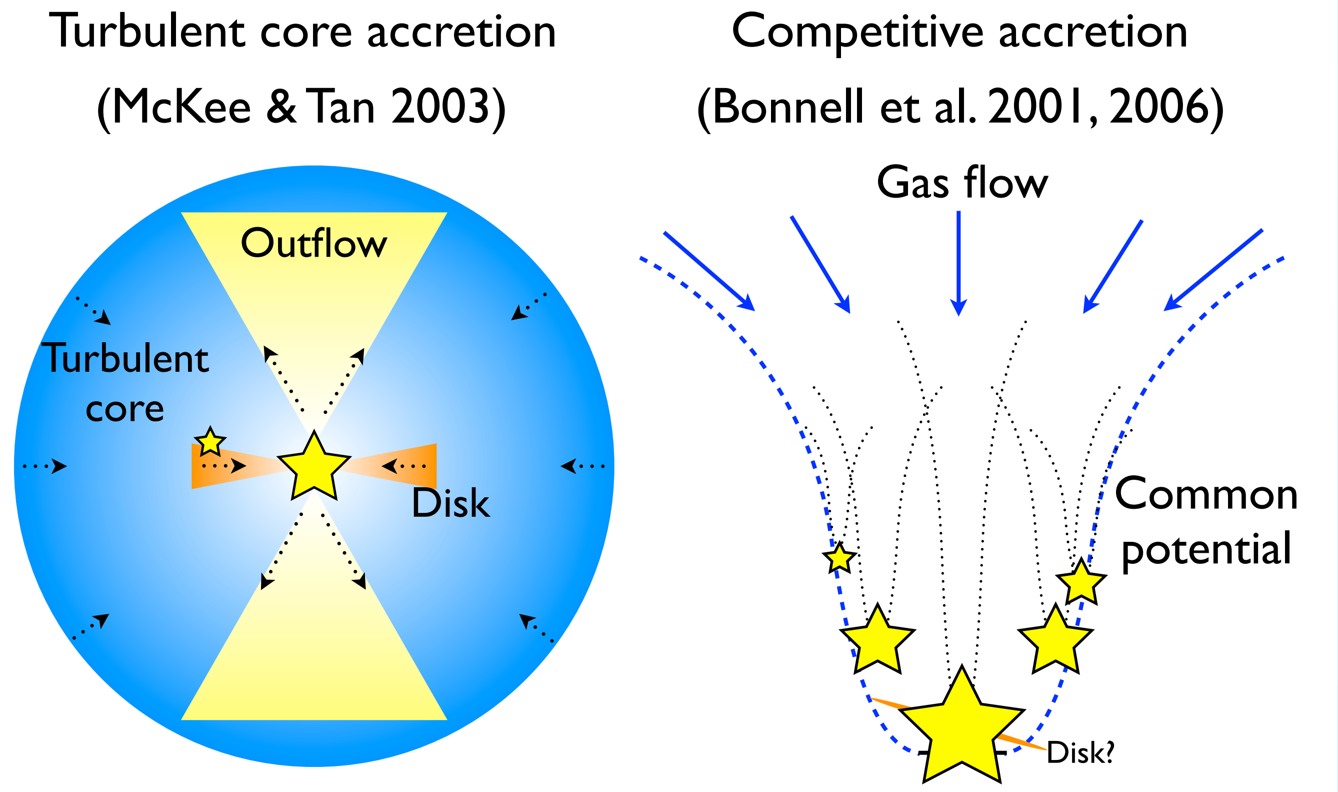


Image credit: I. San José-García & K.S. Wang

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

Theories of High-mass star formation

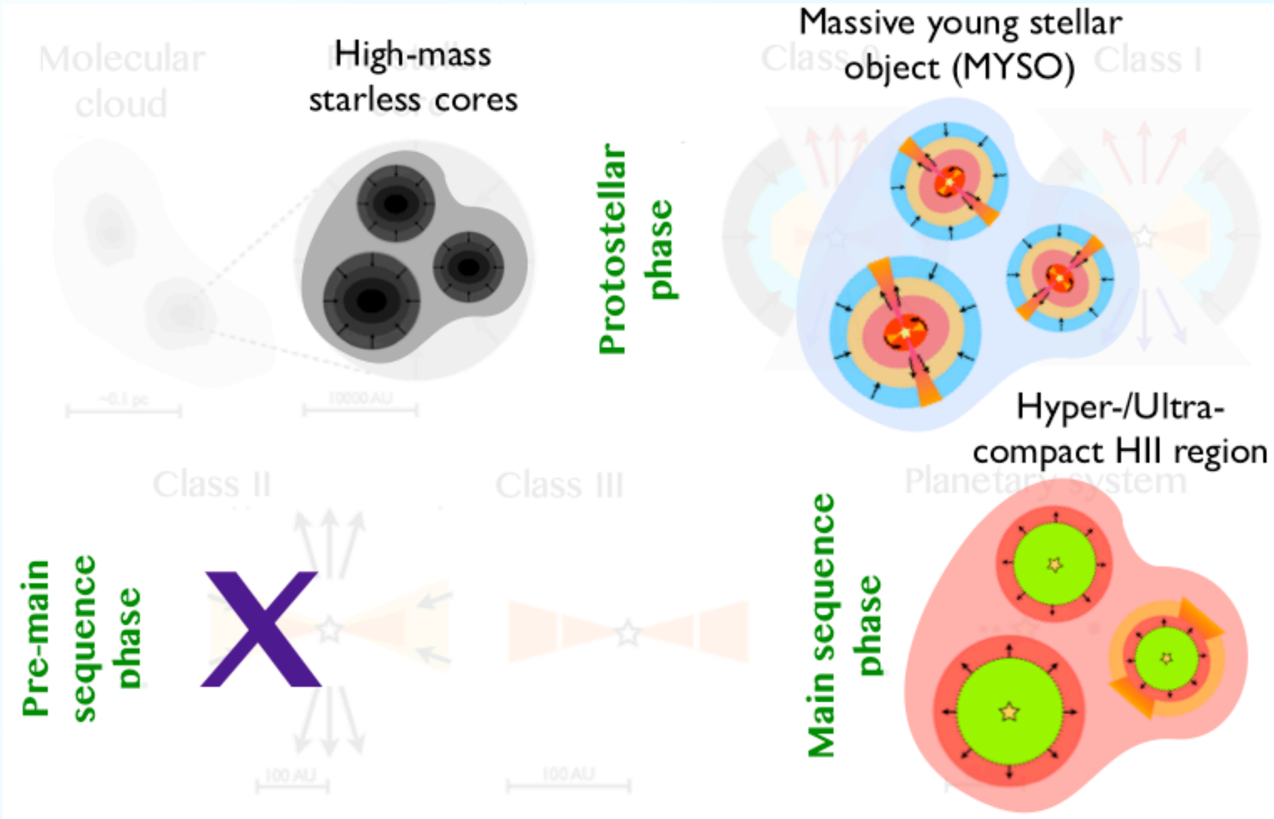


Also fragmentation induced starvation Peters et al., 2010

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

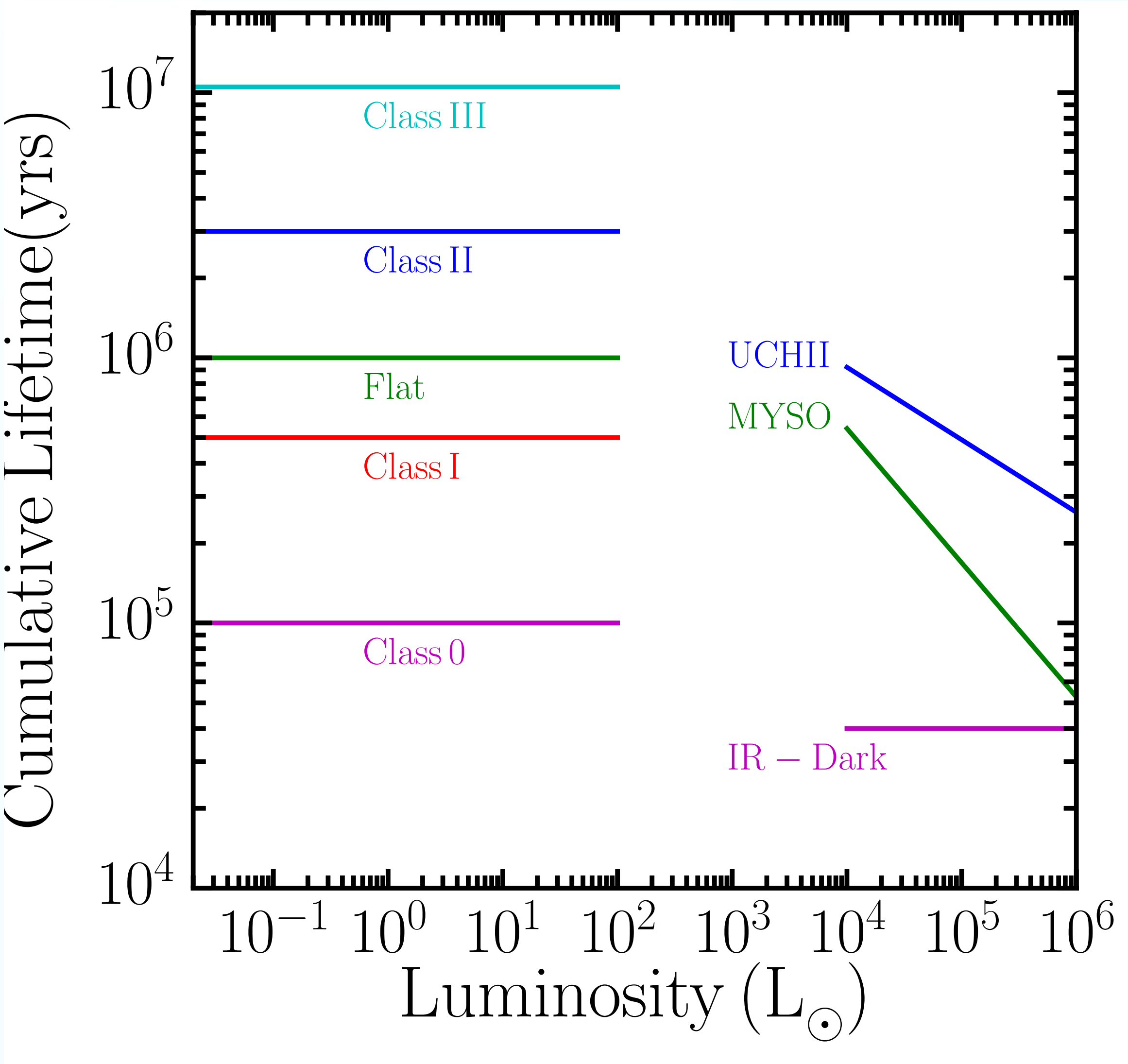


Note: IRDCs and Hot Cores are NOT physically distinct evolutionary stages

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

An aside on comparative timescales



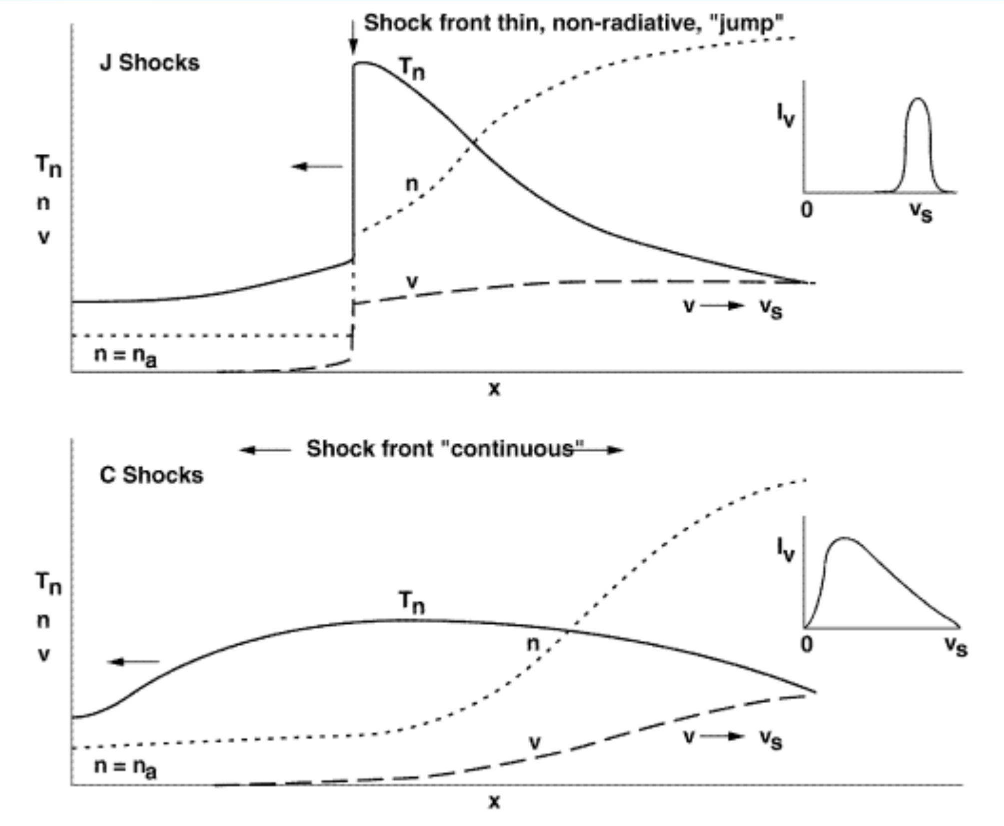
- The timescales for the main accretion phase for low and high-mass star formation are comparable
- The difference is in when the central source reaches the main-sequence

Evans+ 2009

Mottram+ 2011b, Davies+ 2011

Shocks

- Shocks can be continuous (C-Type) or have a jump (J-Type)
- J-shocks shift the emission to some fraction of the shock velocity
- C-shocks have emission from the source velocity to the shock velocity



Hollenbach 1997

Motivating questions

- What physical component(s) do H_2O and CO trace and what are their properties?
- Does the physics scale with L_{bol} and/or M_{env}?
- Can we use LM sources as scaled templates for HM sources?
- Does this extend to cluster or extragalactic scales?

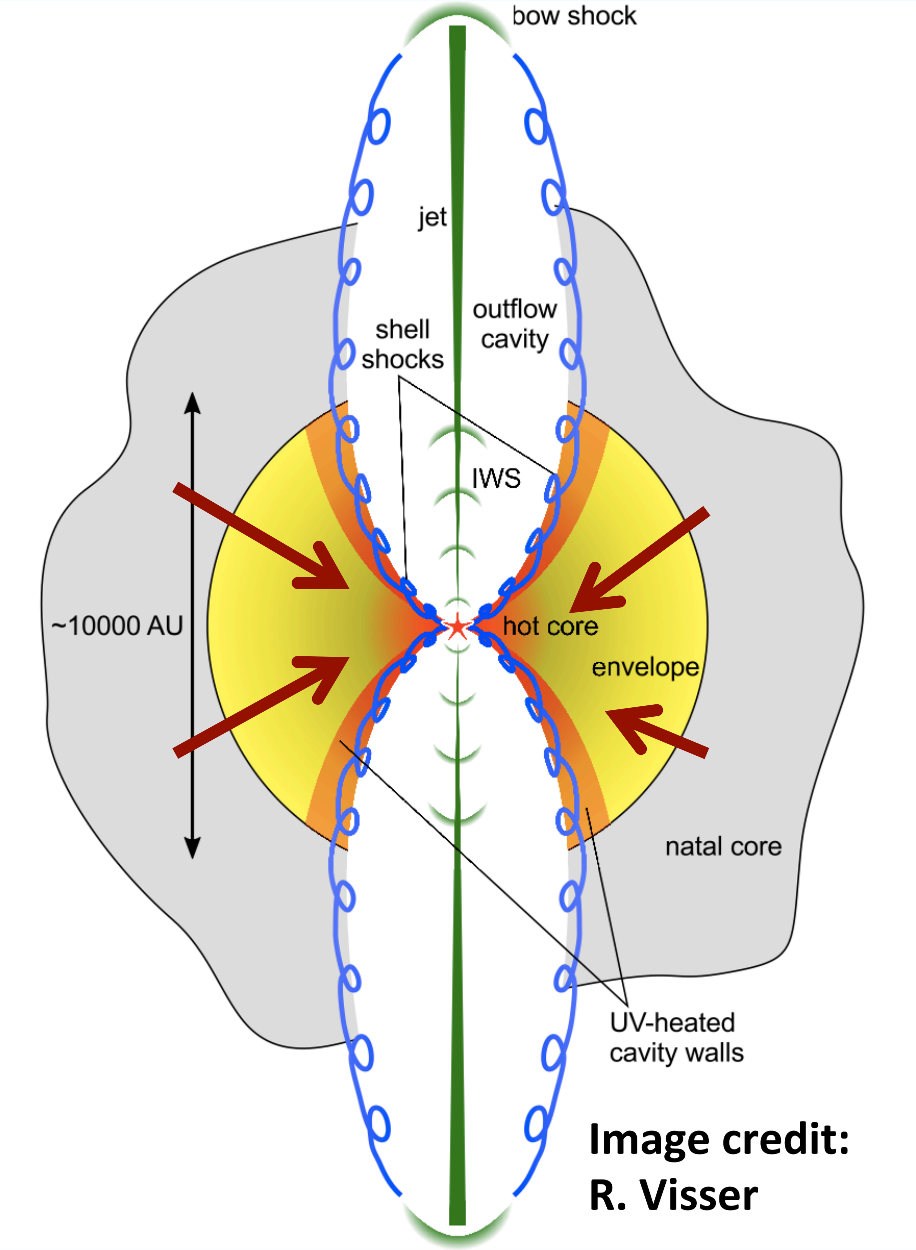


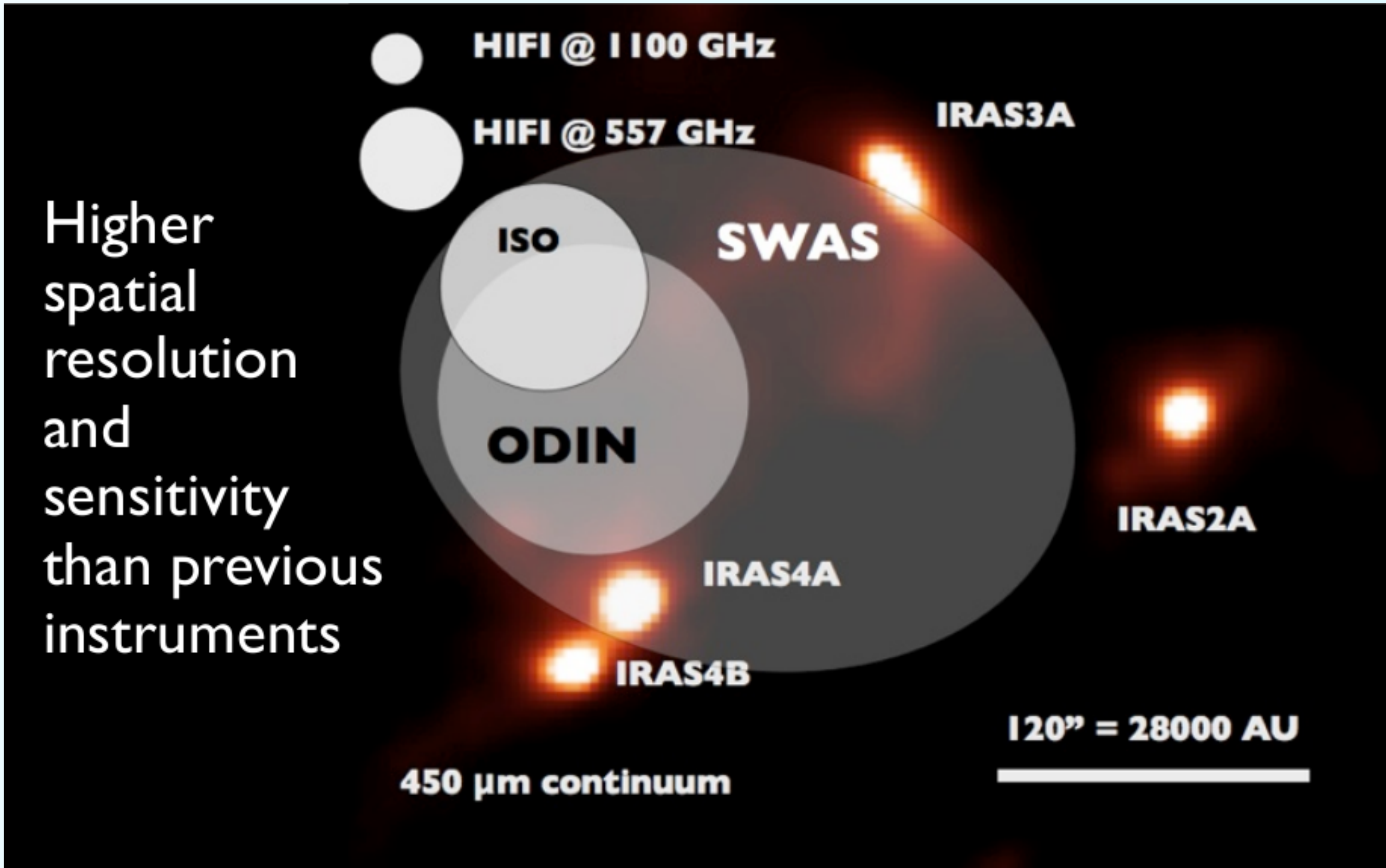
Image credit: R. Visser

The data

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

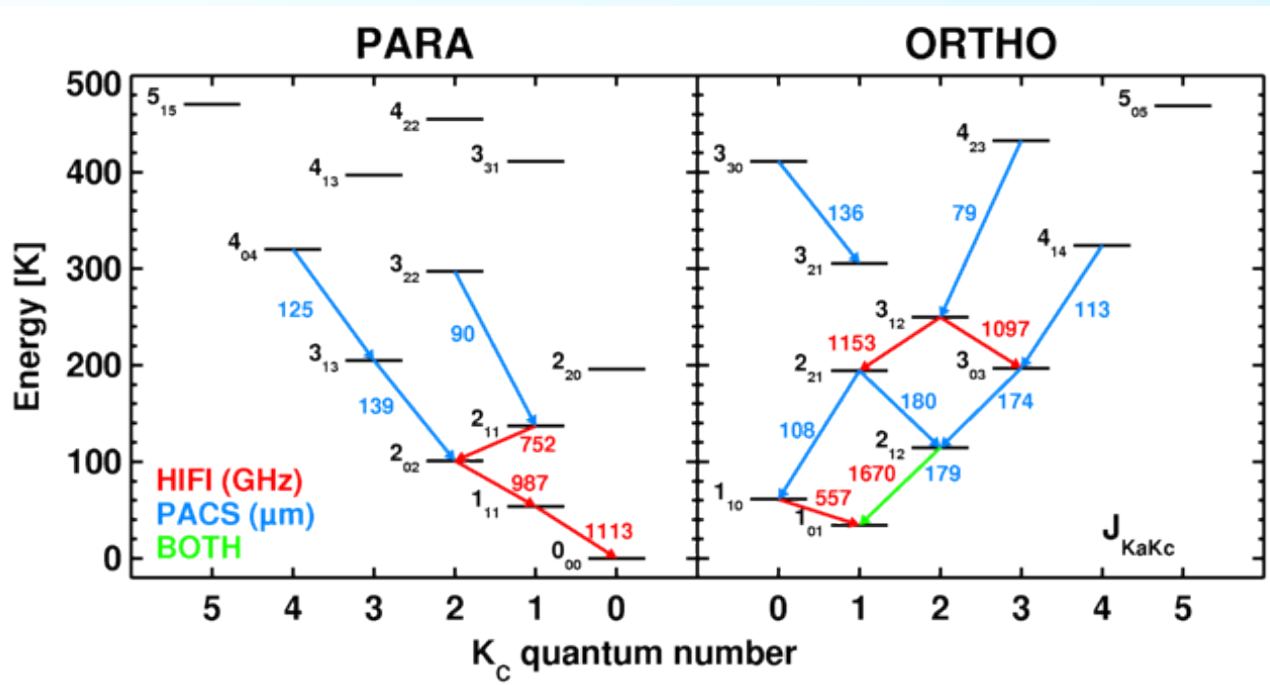
Standing on the shoulders of giants

- Herschel has enabled the detailed exploration and resolution of questions/hints raised by SWAS and ODIN



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

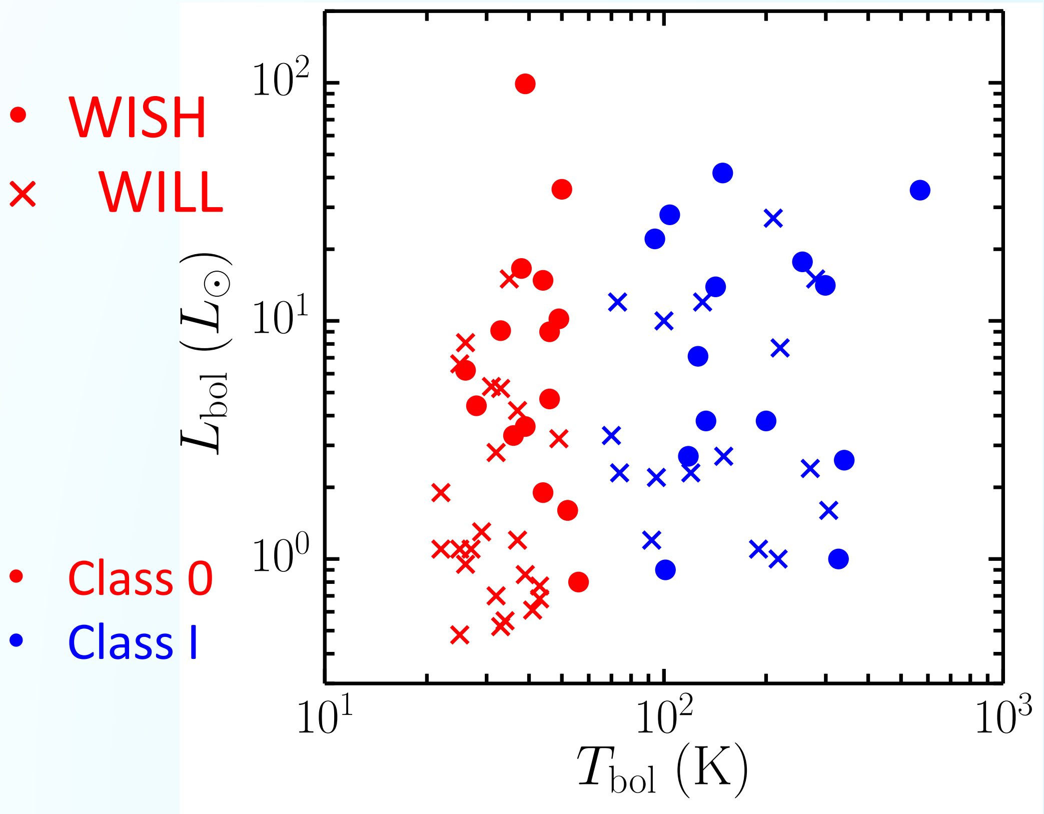
- 425 hrs of Herschel time (van Dishoeck et al., 2011, PASP)
- HIFI spectroscopy & PACS spectral maps of H_2O, CO and related molecules



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

WILL: *William Herschel Line Legacy*

- OT2 HIFI & PACS 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

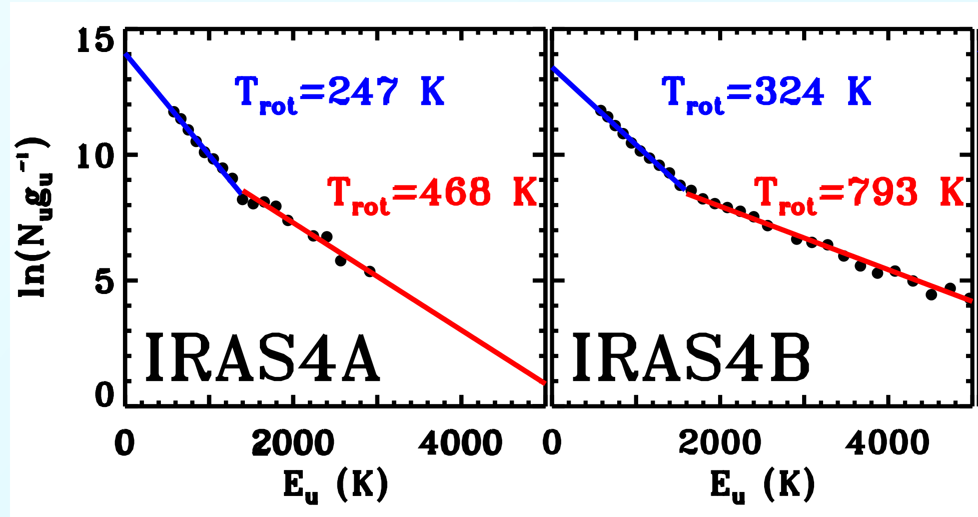
HIFI Cygnus-X Survey

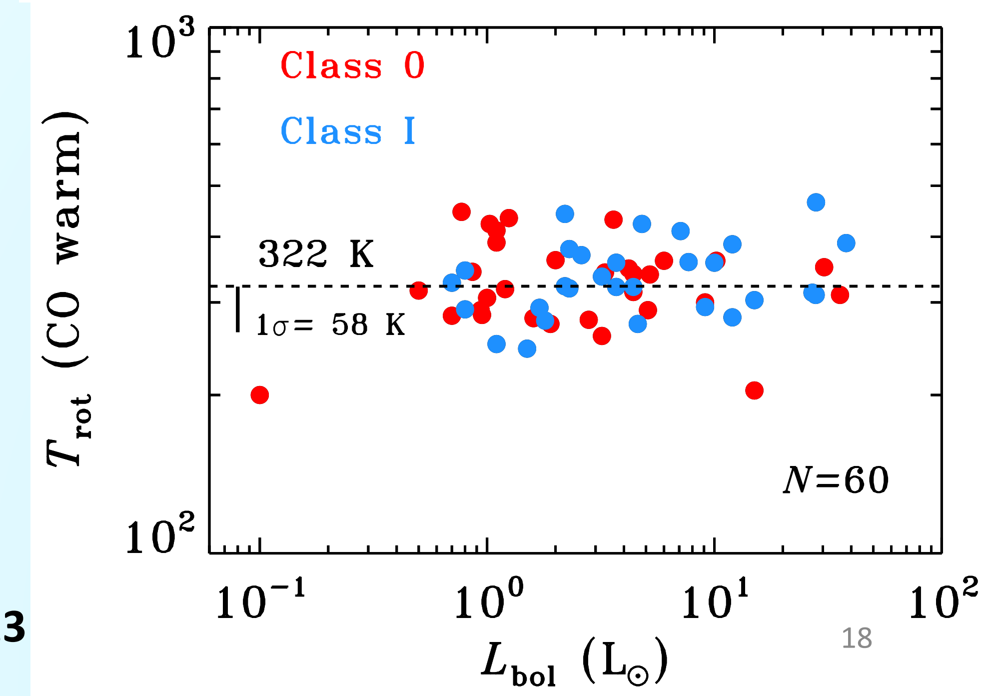
- Targeted the 86 most luminous protostars in the Cygnus-X star forming region with HIFI (PI: S. Bontemps)
- Span $L_{bol} \sim 10^2$-10^3 $L_\odot$
- Mix of Class 0 and I low and intermediate mass YSOs

Low-mass protostars – simplest template of star formation

Multi-component PACS CO rotational diagram

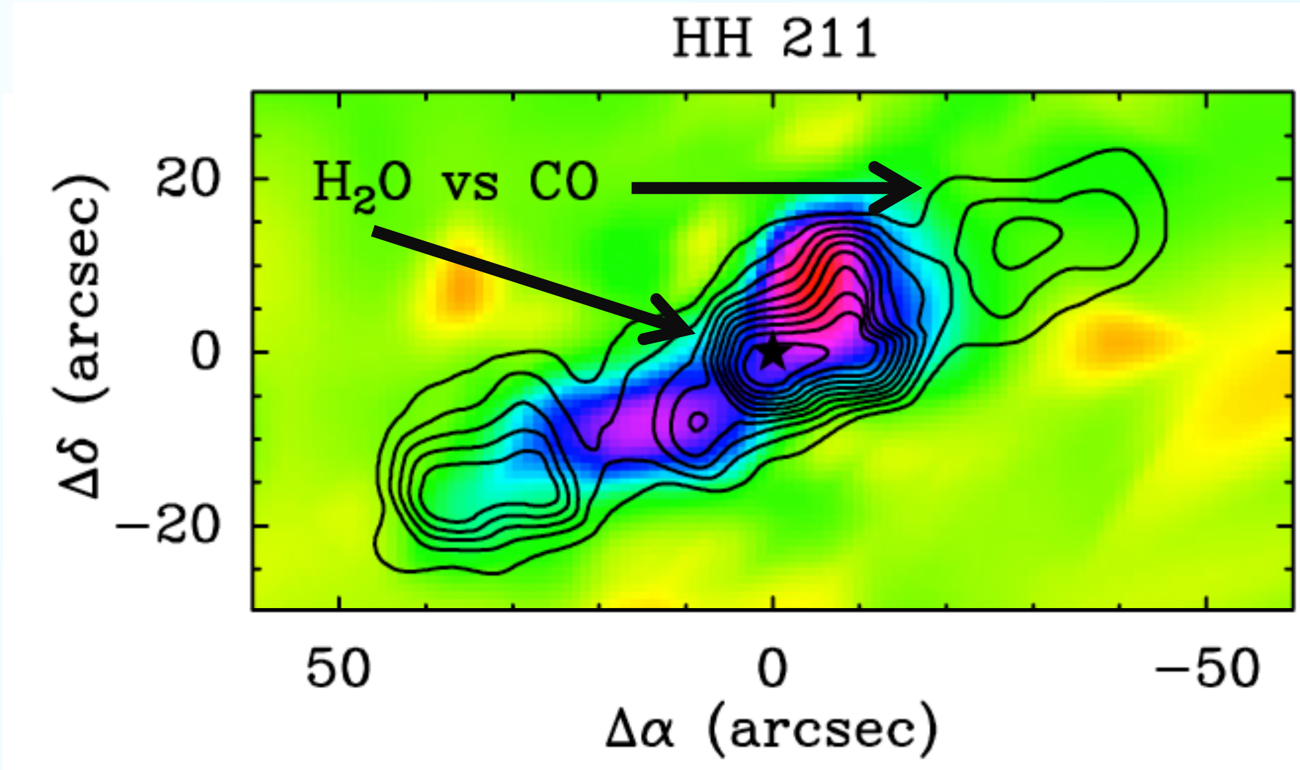
- CO rotational diagrams from PACS show a warm (~300K) mid-J and sometimes also a hot (~750K) high-J component
- Temperatures similar for all sources





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

Spatial extent of water

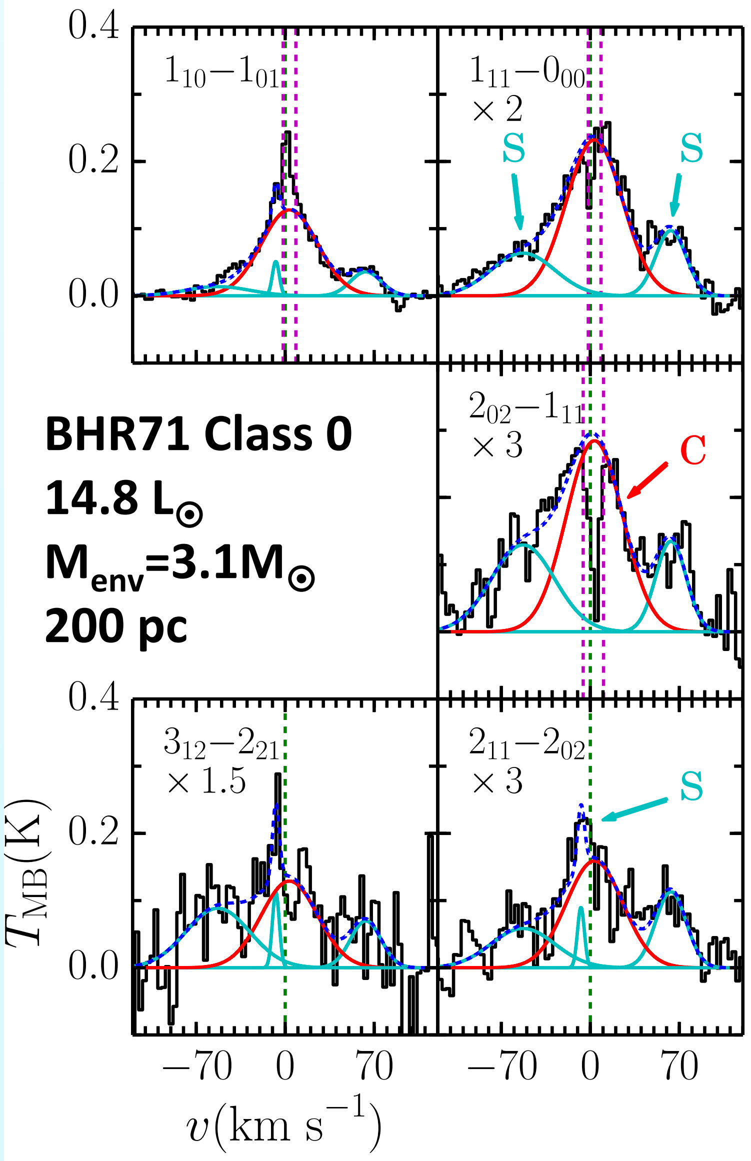


Tafalla et al., 2013, Karska et al., in prep.

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

Multi-component H_2O line profiles

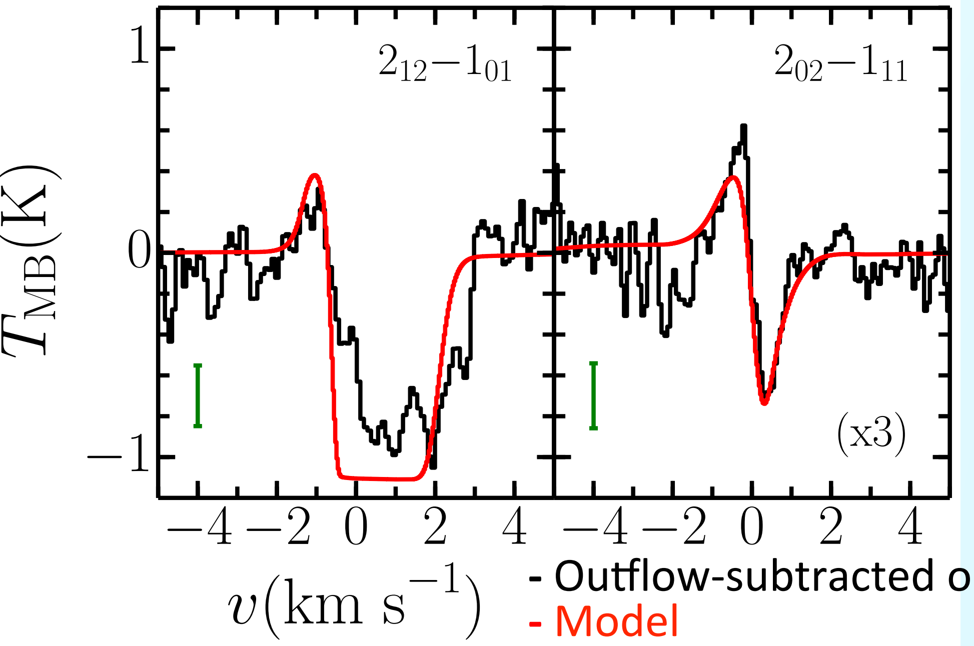
- H_2O line profiles are complex -> trace multiple kinematic components
- Dominated by broad component associated with outflows and shocks
- Different from ground-based line profiles => probing new parts of the protostellar system



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

Constraining infall on cloud to envelope scales

- 1-D non-LTE modeling including simple chemistry allows best constraints to date for infall in protostellar envelopes (10,000 to 3,000 AU scales)
- Can discriminate between cloud-scale motions (2/7) and infall in envelopes (5/7)



- Mass infall rate in NGC1333-IRAS4A 2×10^{-4} $M_\odot\ yr^{-1}$ and

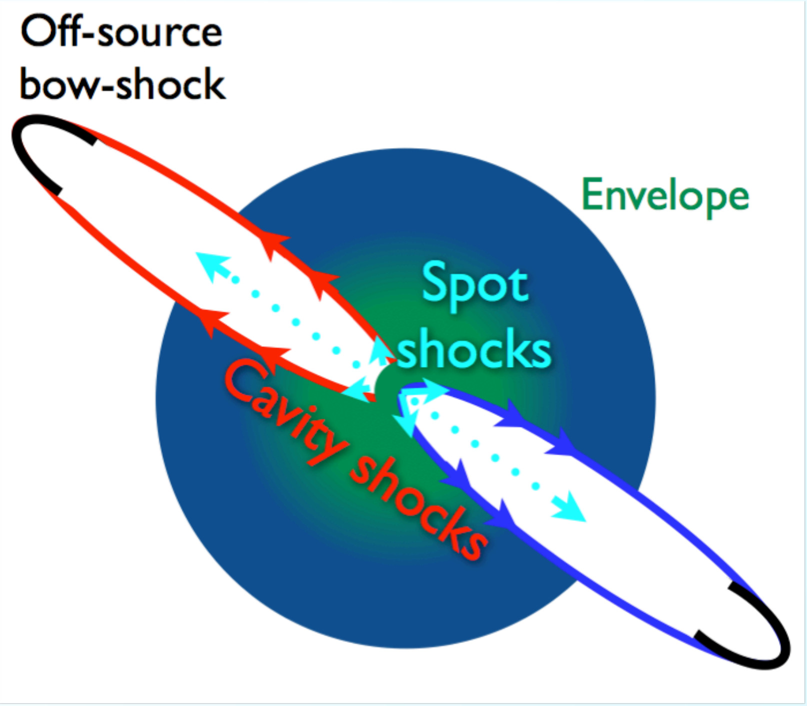
$$\dot{M}_{\inf} >> \dot{M}_{acc} + \dot{M}_{out}$$

Mottram et al., 2013

See also Schmalzl et al., 2014 for H_2O chemistry and O budget

Component classification

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



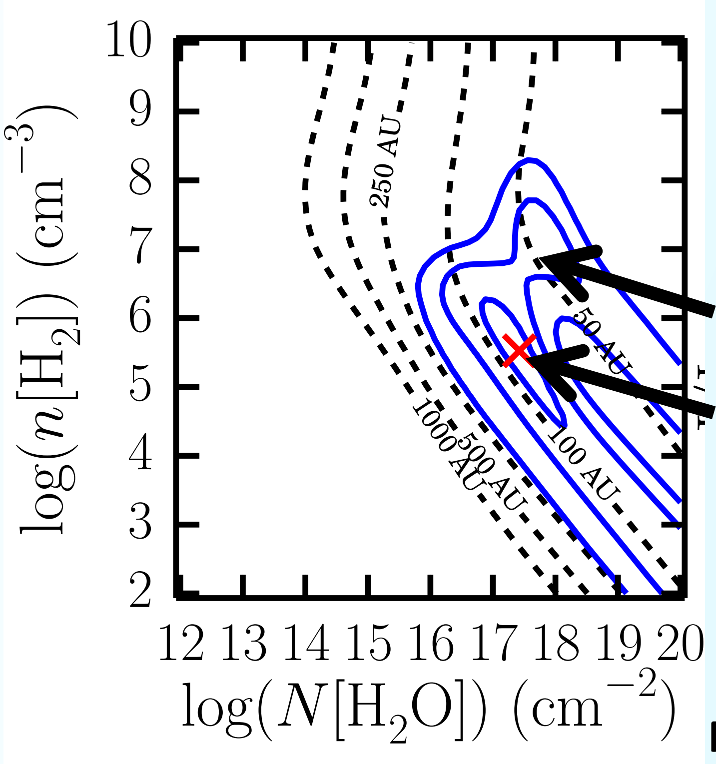
  - Spot Shock: offset from source velocity -> J-shock at base of outflow or in jet shock, T_{gas}~750 K
  - Envelope: narrow, sometimes IPC/ RPC

Mottram et al., 2014

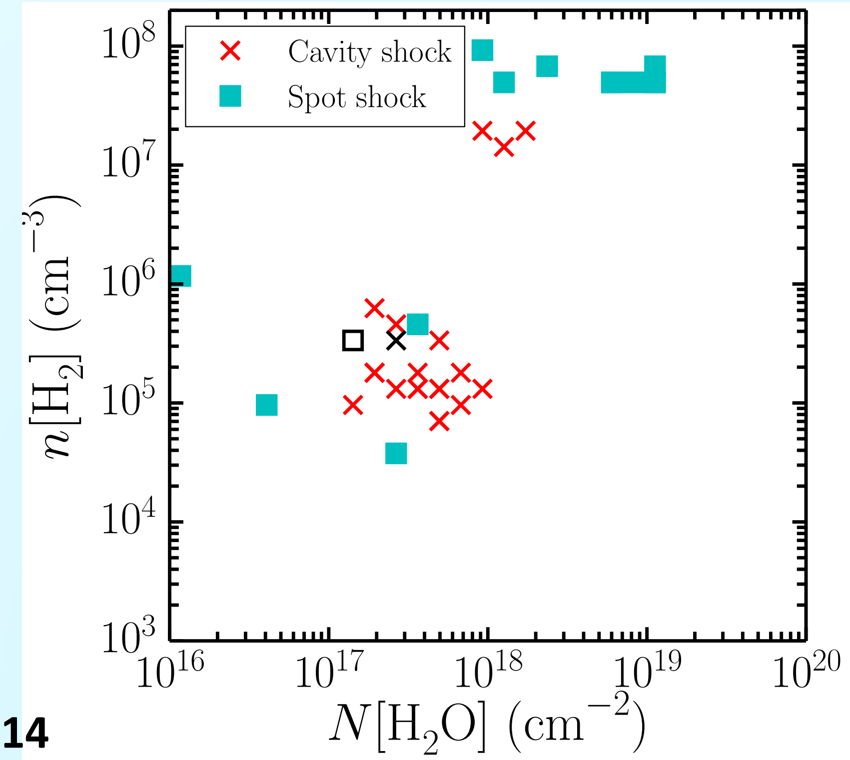
building on Kristensen et al., 2012, 2013, Karska et al., 2013

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



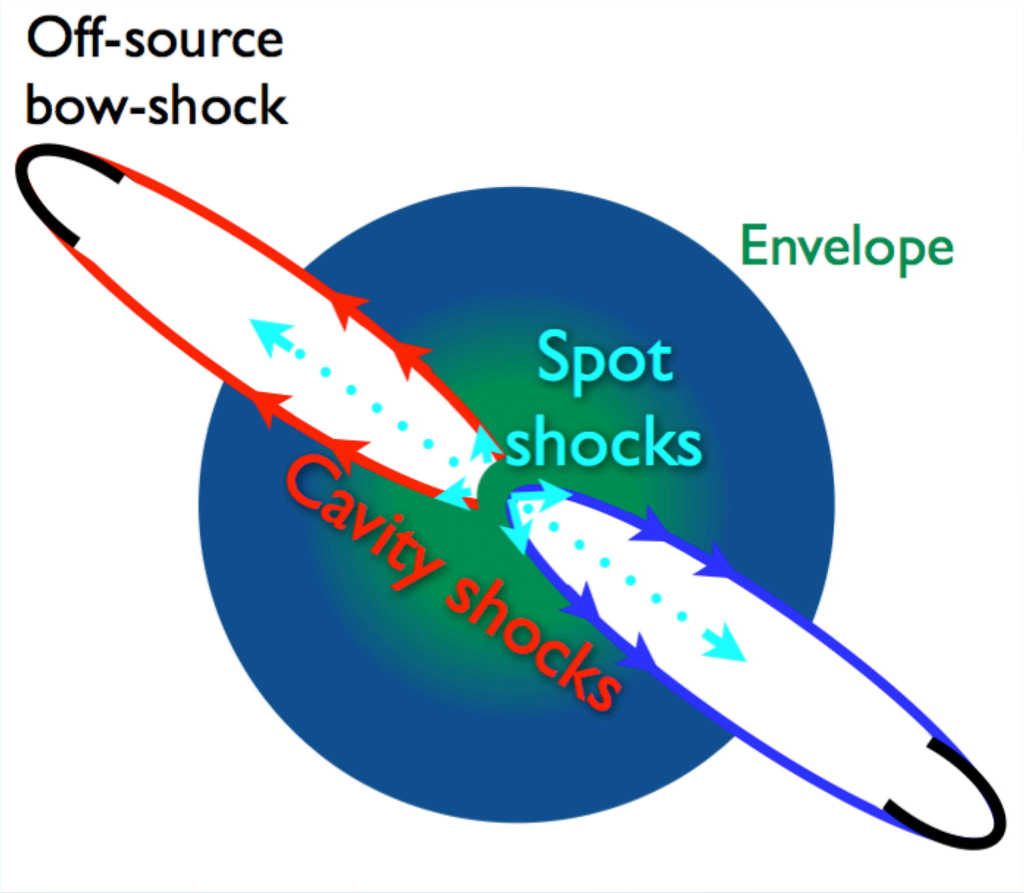
Two solutions: marginally and fully sub-thermal



Mottram et al., 2014

Cavity vs. Spot Shocks

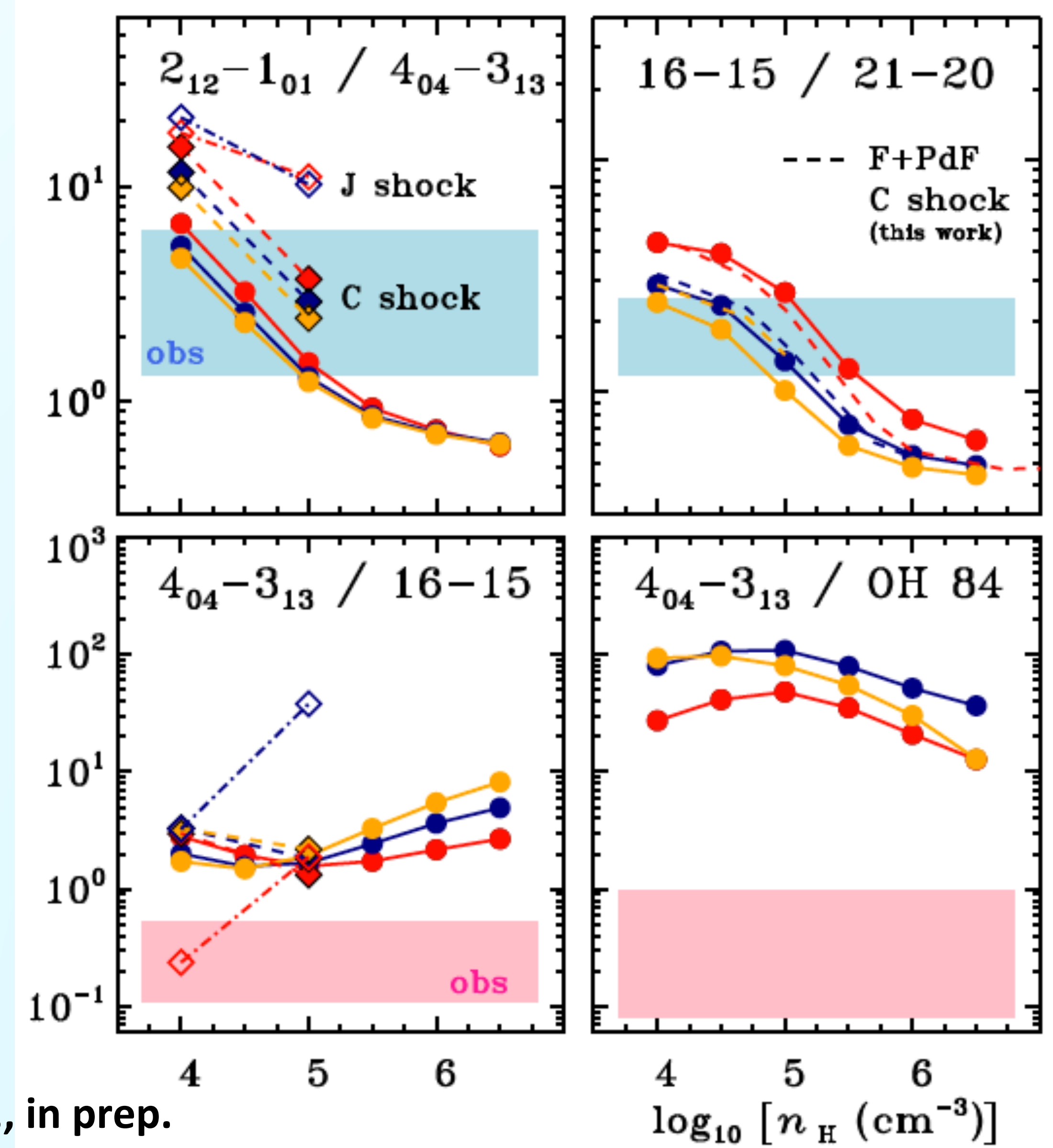
- Transition from spot to cavity shock at outflow base is smooth in *n*,*N*
- Small emitting region size suggests cavity shock is a thin (few AU) layer along the outflow wall



Mottram et al., 2014

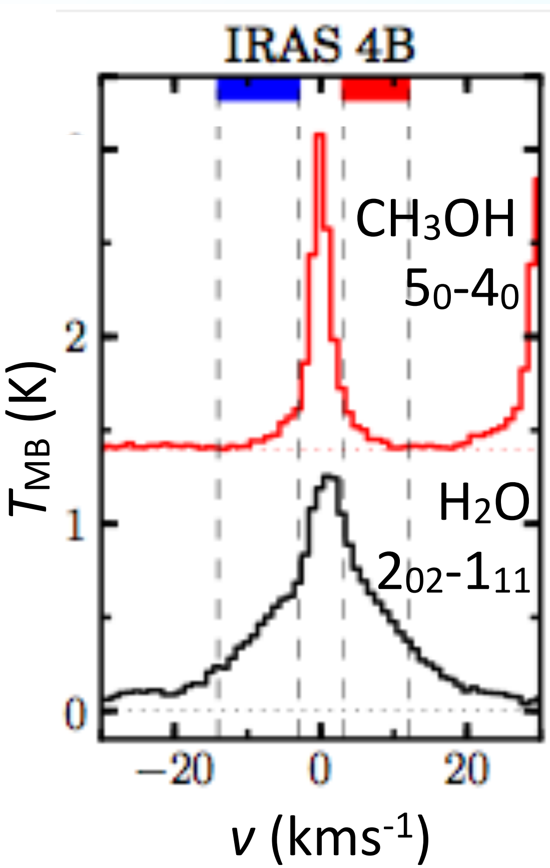
Need for UV irradiation

- 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 $X(H_2O)$~10^{-5}



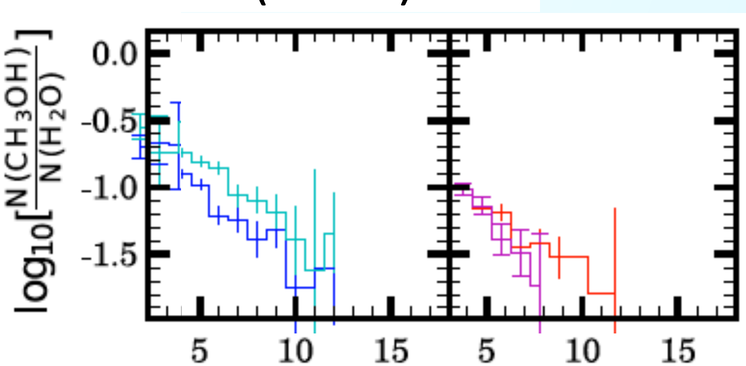
Karska et al., 2014, Kristensen et al., in prep.

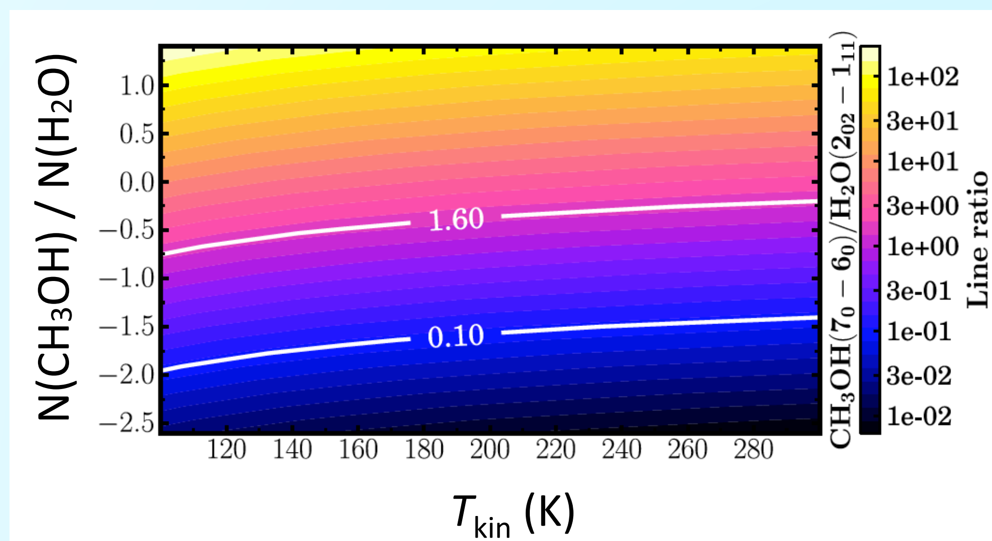
The origin of water in LM outflows



- H_2O can be formed via high-T route or released via sputtering
- CH_3OH can only be released by sputtering
- At low *v*, H_2O is from sputtering, at high *v* gas synthesis

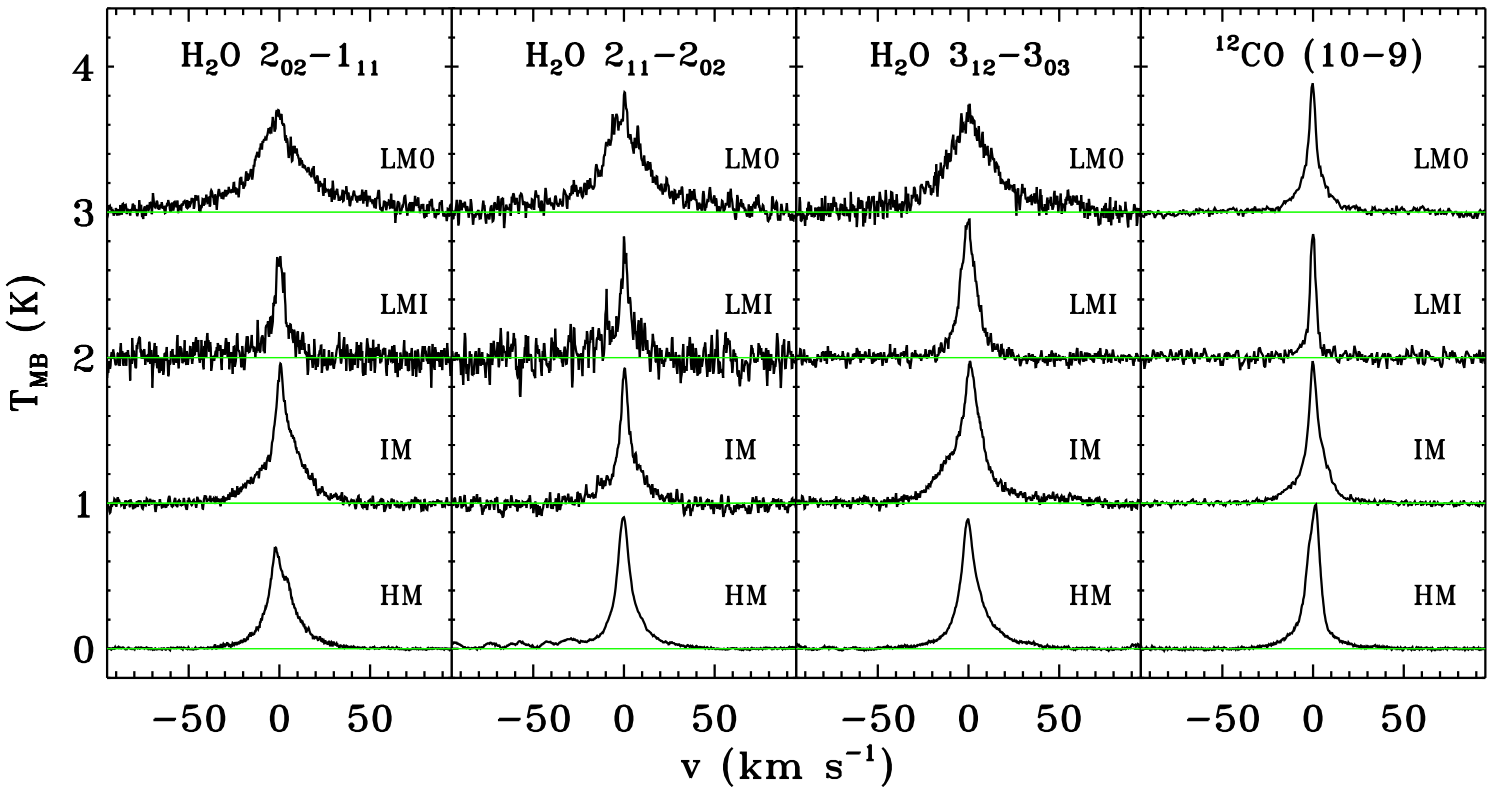
Suutarinen, et al., 2014





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

Line profiles: low to high mass YSOs



Few 1000 AU

Few 10000 AU

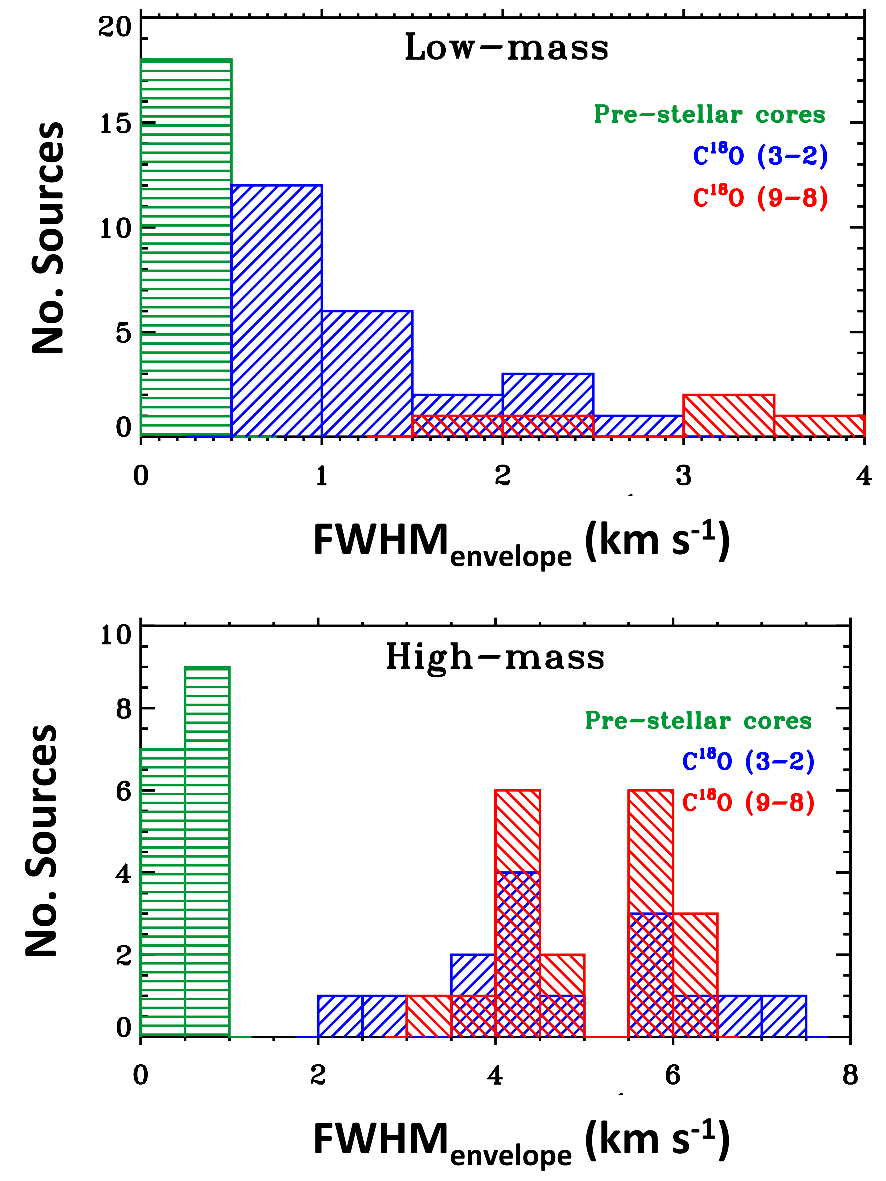
Higher L_{bol}

- Dominated by broad outflow-related emission
- H_2O broader than CO but similar between LM and HM

San José-García et al., subm.

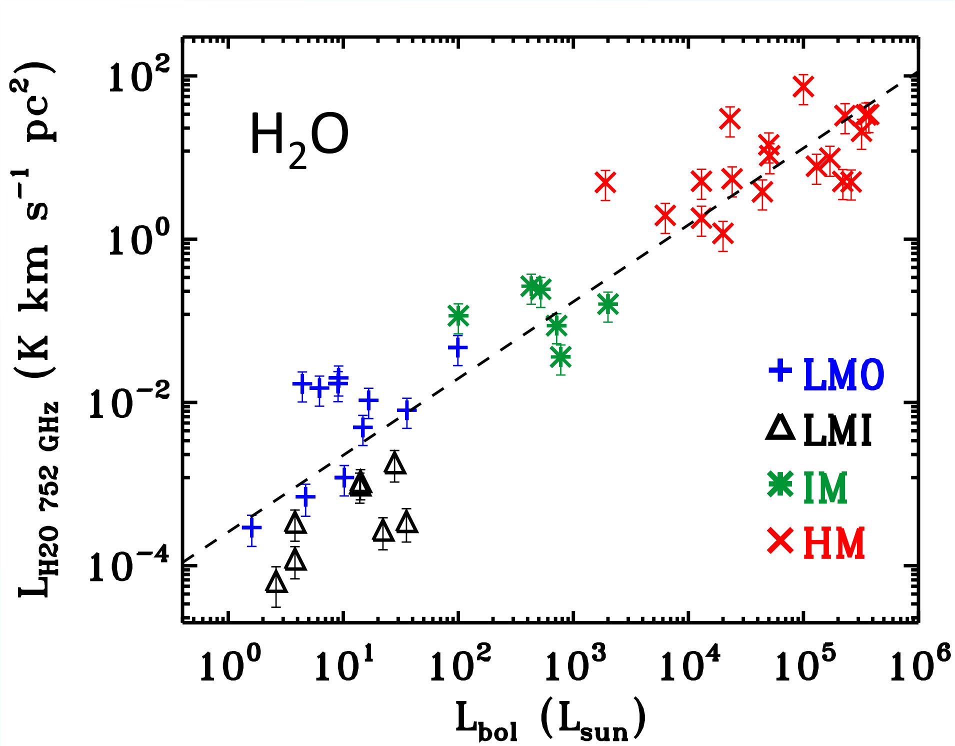
Turbulence in the envelope

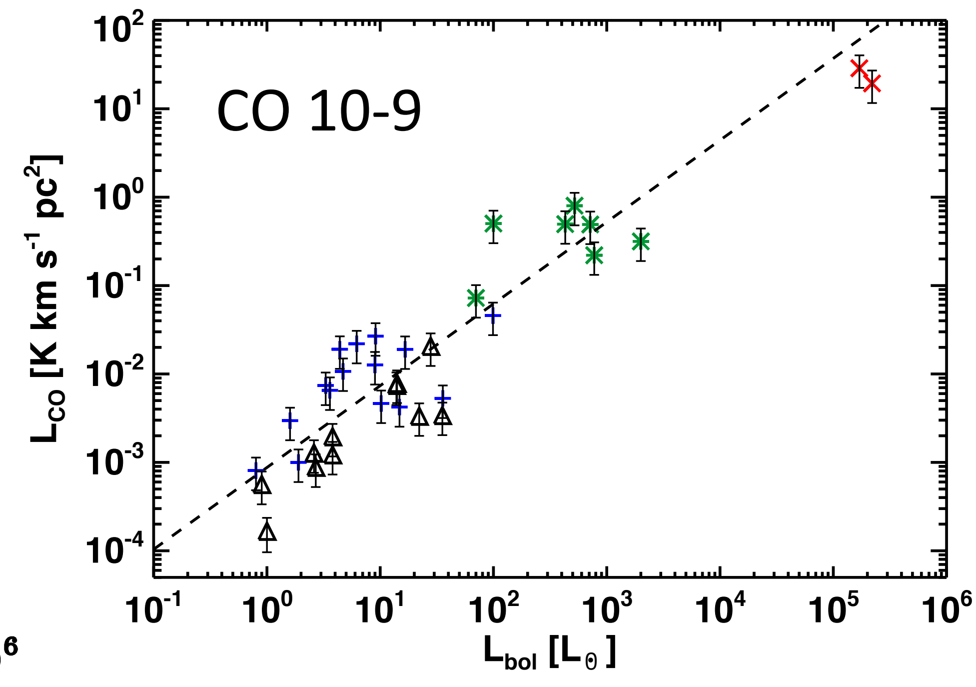
- Turbulence of LM and HM prestellar cores is low
- Turbulence increases between prestellar and protostellar phase for both LM and HM sources
- Turbulence is higher in HM than LM protostars
- This still holds when infall is taken into account



San José-García et al., 2013 & subm.

Line luminosities scales with L



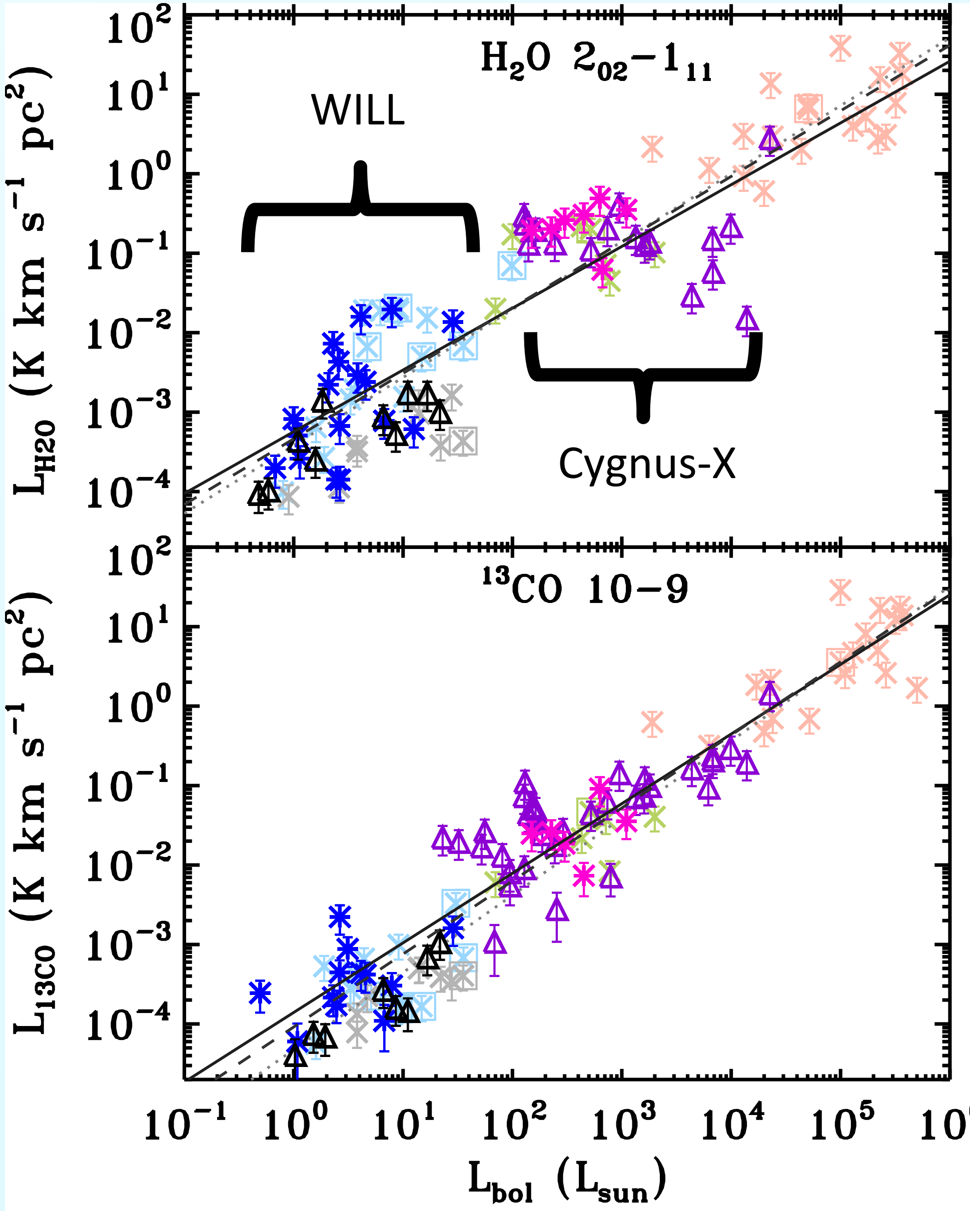


- Integrated intensity of water and high-*J* CO scale linearly with L_{bol} – tracing dense gas
- HM scaled up LM

San José-García et al., 2013 & subm.

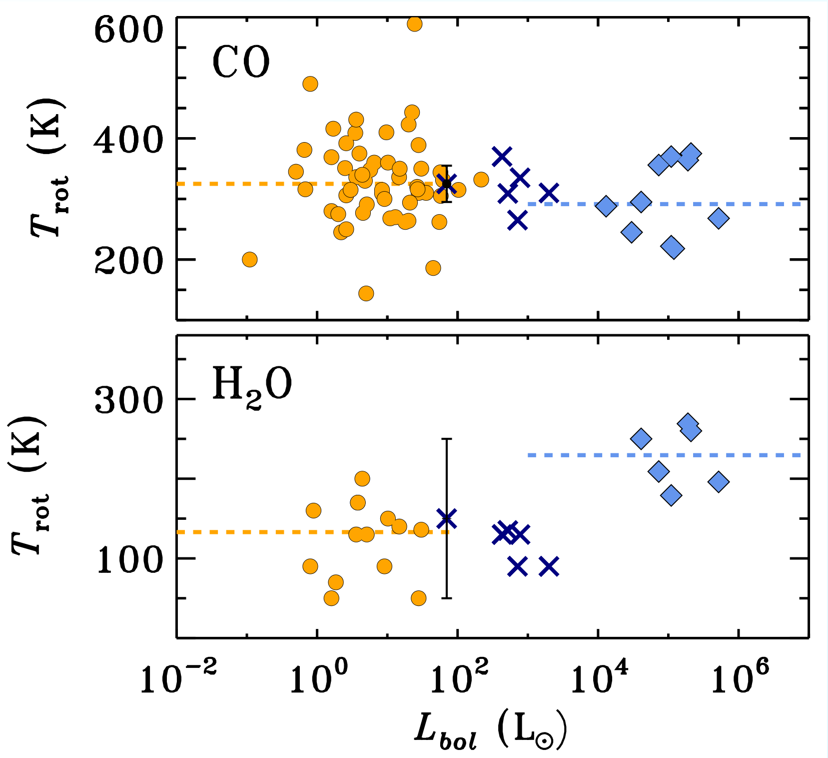
Line luminosities scales with L

- Holds when larger, statistically selected samples are included.
- Scatter likely due to intrinsic source properties (e.g. inclination, density), but these don't dominate.



San José-García et al., in prep.

PACS from low to high-mass

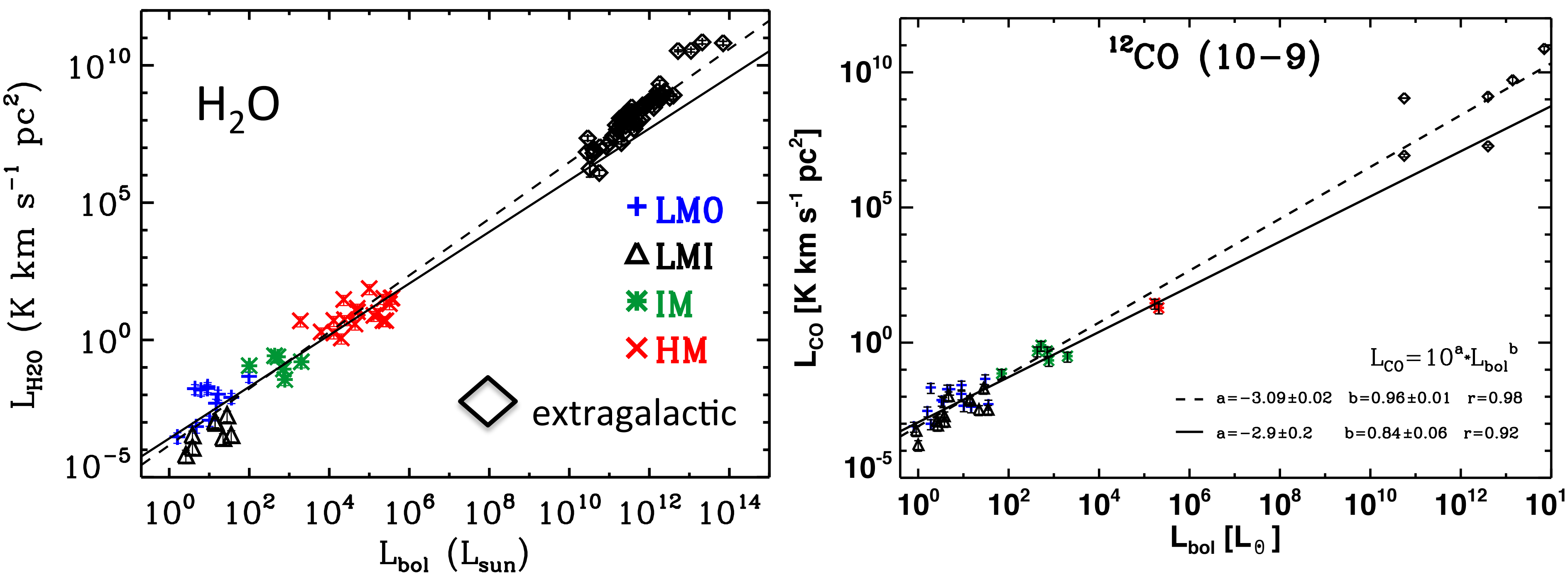


- CO excitation and components the same for low, intermediate and high mass YSOs
- H_2O excitation the same for low and intermediate mass YSOs, also for HIFI radex analysis
- High-mass H_2O T_{rot} higher and HIFI line ratios require radiative pumping

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

From the Milky Way to other Galaxies

Can we keep on scaling up?

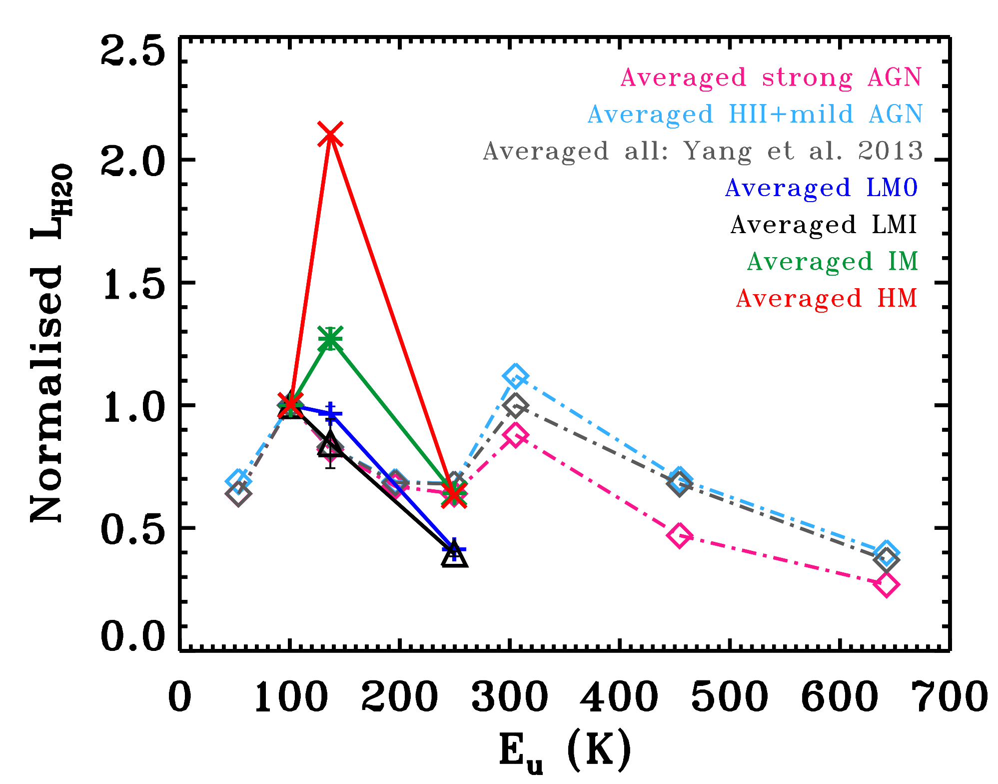


San José-García et al., 2013 & subm.

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

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

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 et al. subm.

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 requires IR pumping in the latter
- 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

Future prospects
Star Formation: The Next Generation

New questions and their observational requirements

- Where are the spot shocks really located?
  - Interferometric observations of proxies (see Lars' Talk)
- Where is the missing O in protostellar outflows?
  - Pilot study with SOFIA for spectrally resolved observations of 63 micron [OI] line (successful proposal PI Kristensen)
- Are trends between low and high mass sources fundamental or due to observational effects?
  - ALMA observations will allow analysis on same spatial scales as for LM sources, though not in H_2O or high-J CO (Cycle 3 proposal submitted, PI Mottram)
- What fraction of water emission is associated with star formation vs. the central black hole in external galaxies?
  - Redshift probably not enough for galaxies close enough to be resolved -> Herschel interferometer is space with heterodyne ability down to 60 microns!