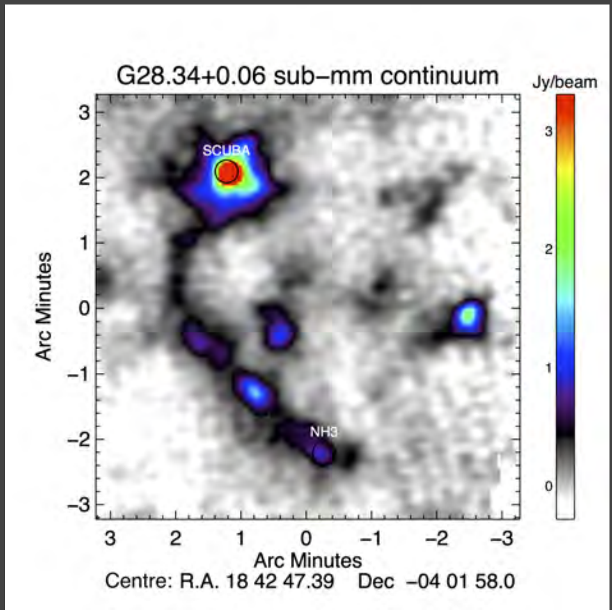
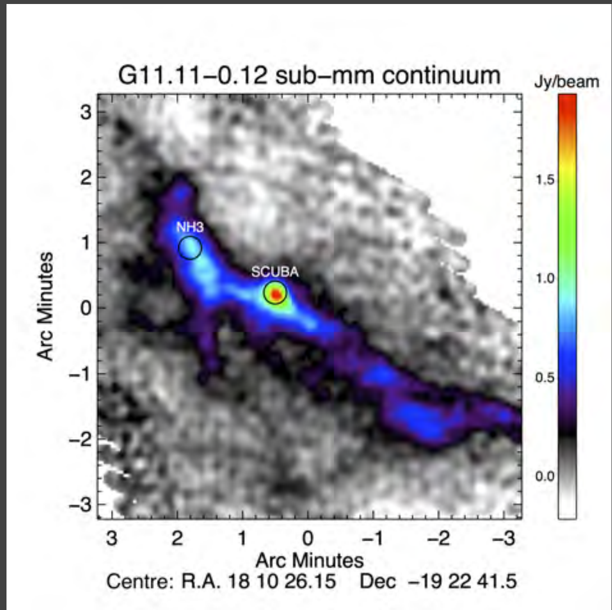
The Water Story in IRDC Clumps





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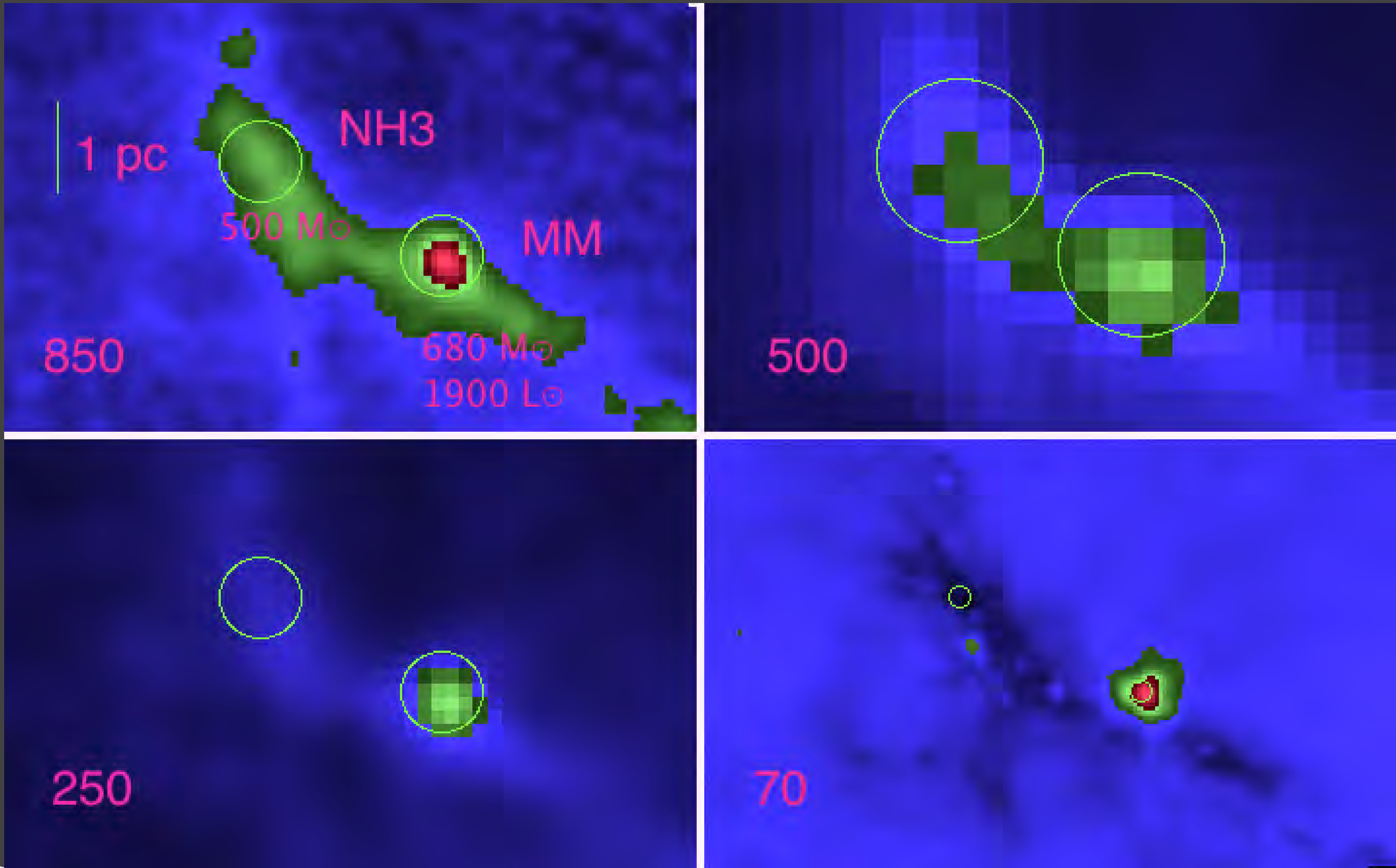
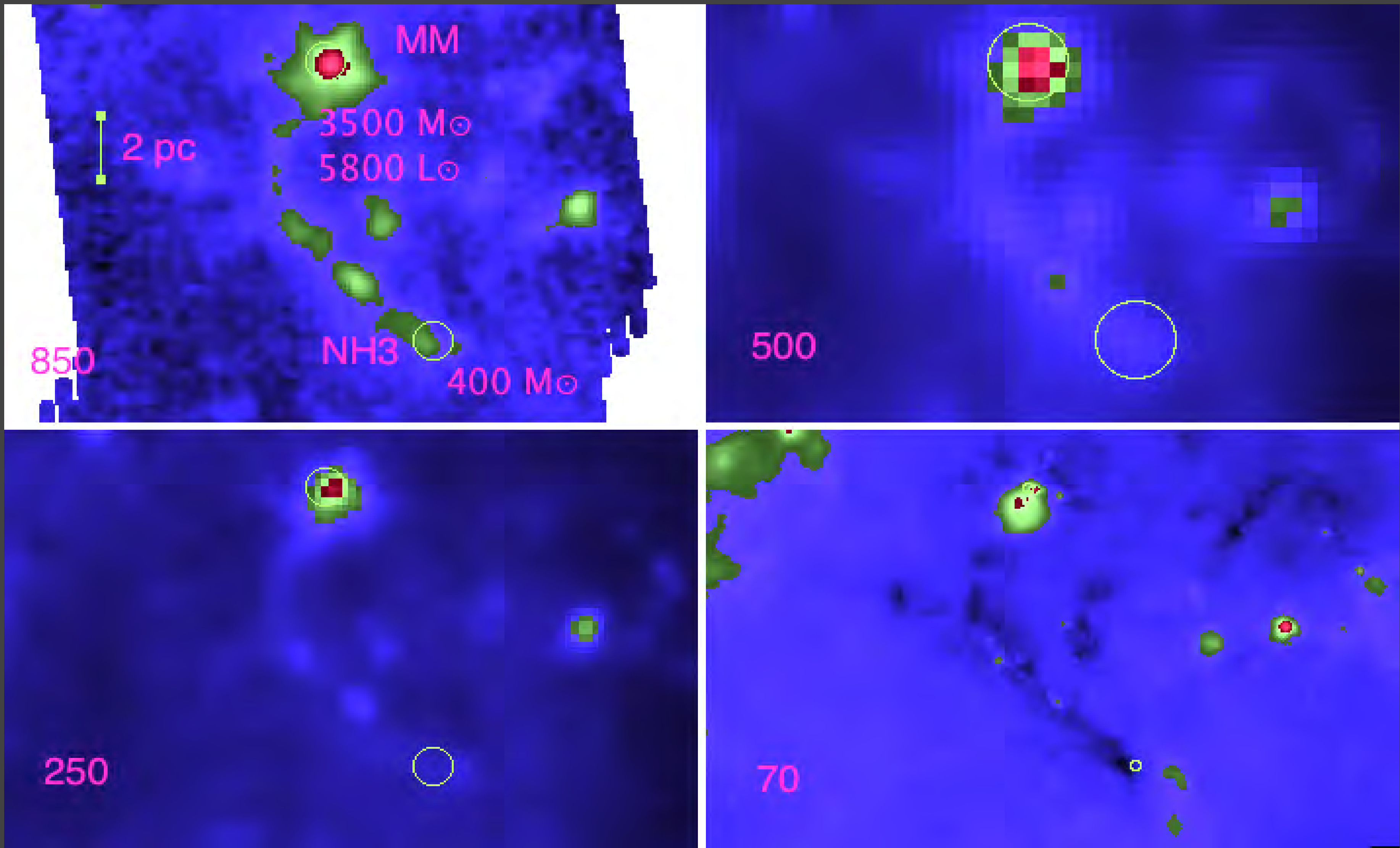
Project Overview

- Goal:
  - Determine the physical, dynamical and chemical structure of massive clumps in earliest stages of high-mass star formation.
  - Clarify the water story in outflow and infall components
- Context:
  - Clumps in IRDCs are dense, cold and massive.
  - Sites of ongoing or yet to occur massive star formation
- Method:
  - Observe and model water lines in 2 clumps in 2 IRDCs
    - bright sub-mm positions or strong NH_3 peak positions.
  - Identify trends in line properties between clumps
  - Consistent molecular line modeling using Ratran (Hogerheijde and van der Tak, 2000 A&A 262, 697)

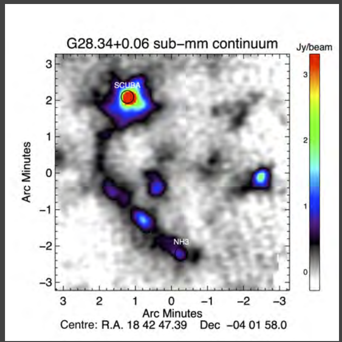
G11.11 positions



G28.34 positions

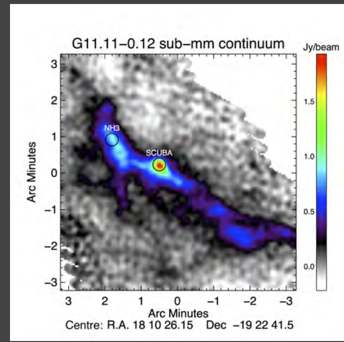


Targets/Transitions/Continuum



IRDCs G28.34+0.06 & G11.11-0.12

- Strong NH_3 peaks (Pillai et al. 2006)
- Strong sub-mm peaks



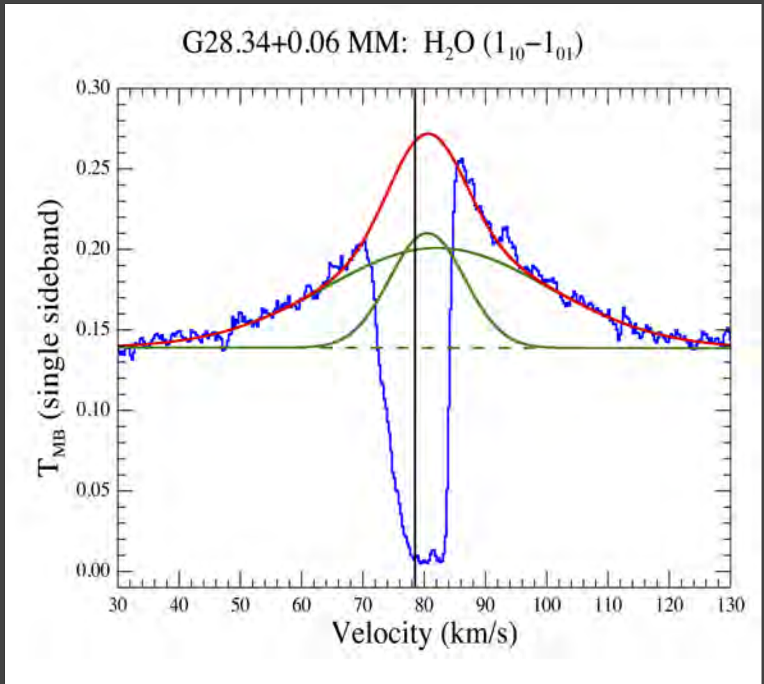
Herschel/HIFI
(557 GHz)
o-H_2O (1_{10}-1_{01})
N_2H^+ (6-5)
o-$H_2^{18}O$ (1_{10}-1_{01})

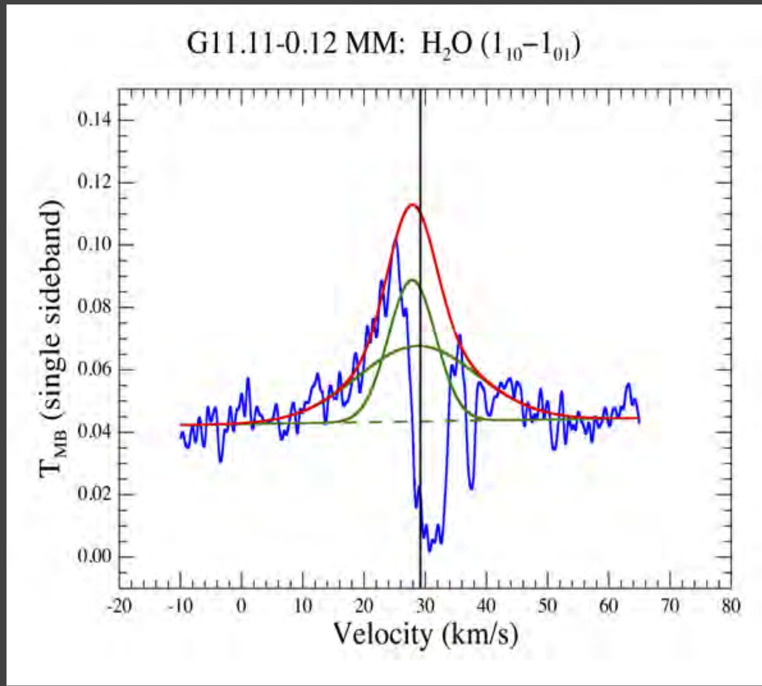
APEX
(330-800 GHz)
$C^{17}O$ (3-2)
CO (4-3), (7-6)
$C^{34}S$ (7-6)
N_2H^+ (3-2)
CH_3OH (7_K-6_K)

PACS/SPIRE/SCUBA
70, 100, 160
250, 350, 500
450, 850

Water Emission

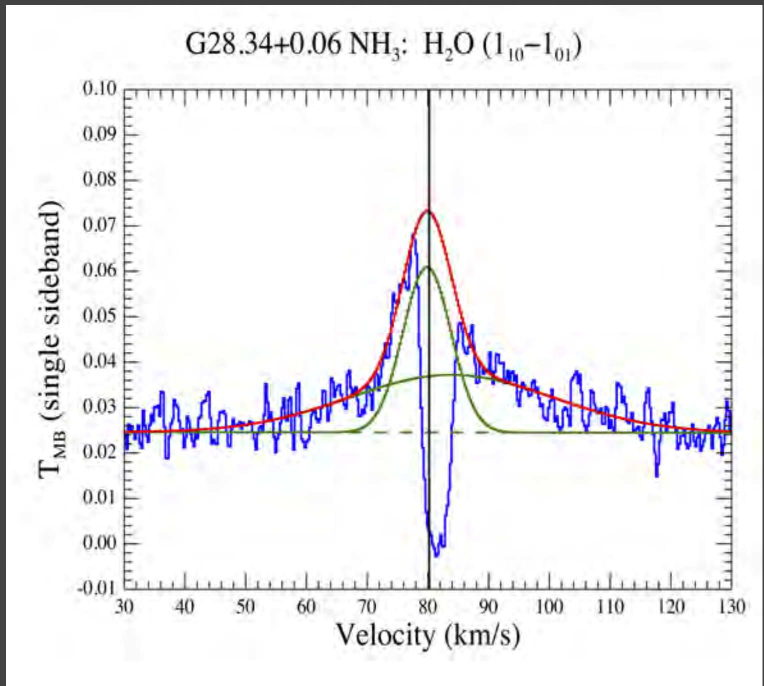
- All MM peak positions display outflows in H_2O

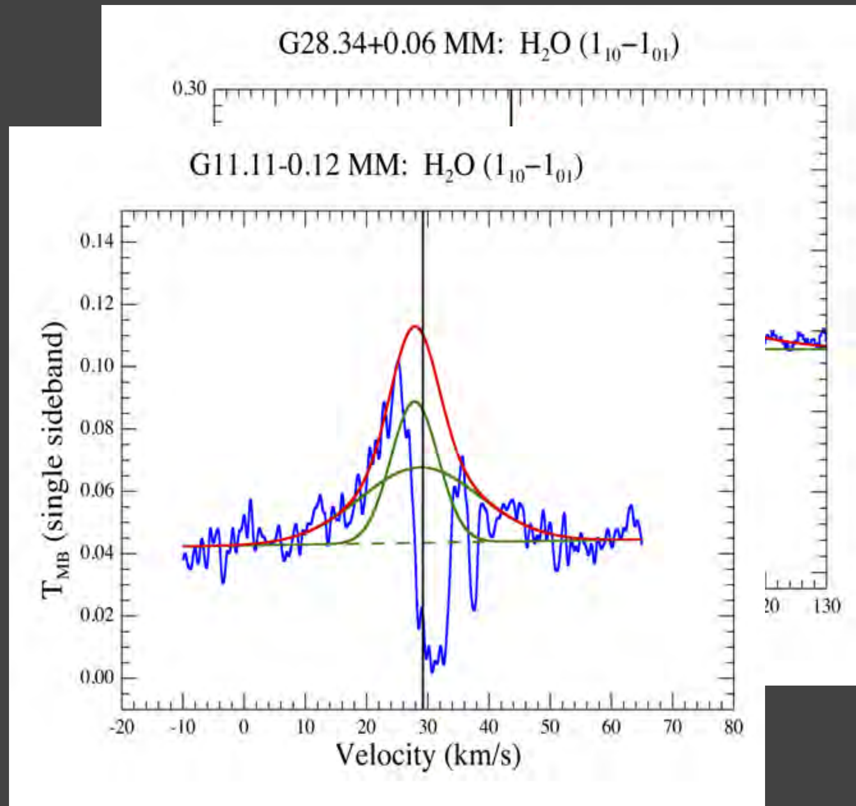




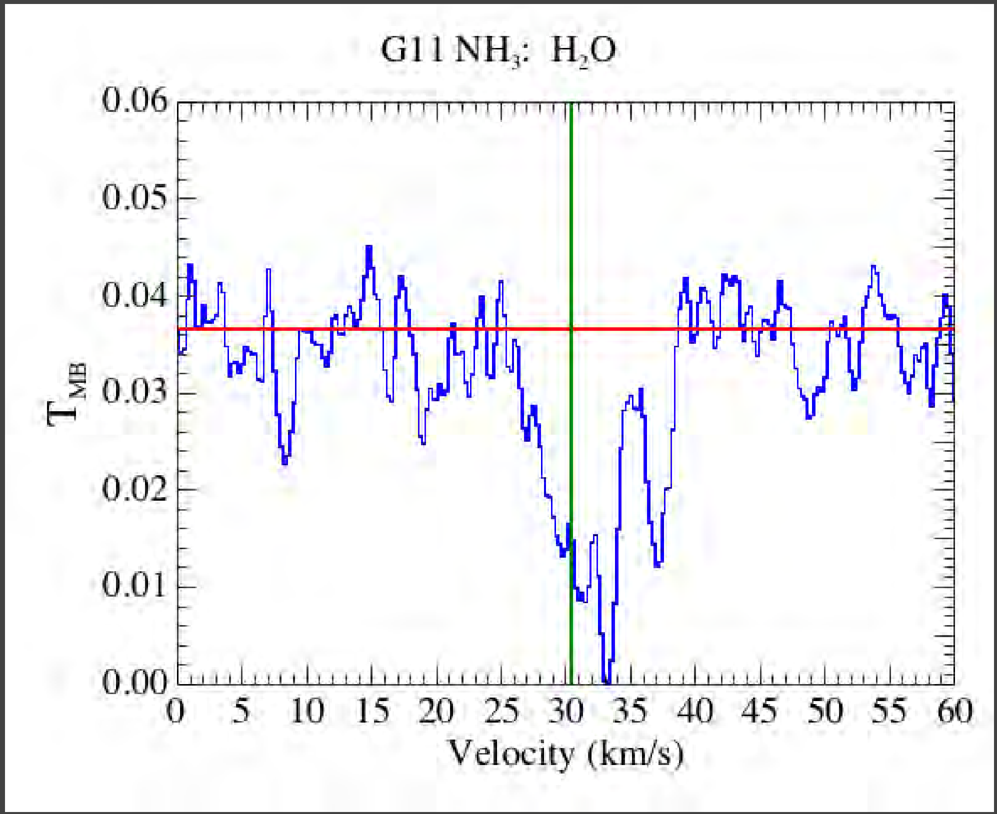
Water Emission

- All MM peak positions display outflows in H_2O
- The G28 NH_3 position also shows evidence of outflow





G11 NH_3: Absorption only



Results of line observations: Dynamic Structures

- Widths and centroids of various species expose different components (Shipman et al. 2014 A&A 570, A51)

Component	Properties	Tracer
Quiescent outer Envelope	ΔV < 3km/s at systemic	$H_2{}^{18}O$, N_2H^+, $C^{17}O$
Envelope	ΔV 3-7 km/s at systemic	CH_3OH, $C^{34}S$, CCH
Outflow	ΔV > 7 km/s at systemic	H_2O emission
Infall	ΔV 3-7 km/s red shifted	H_2O absorption

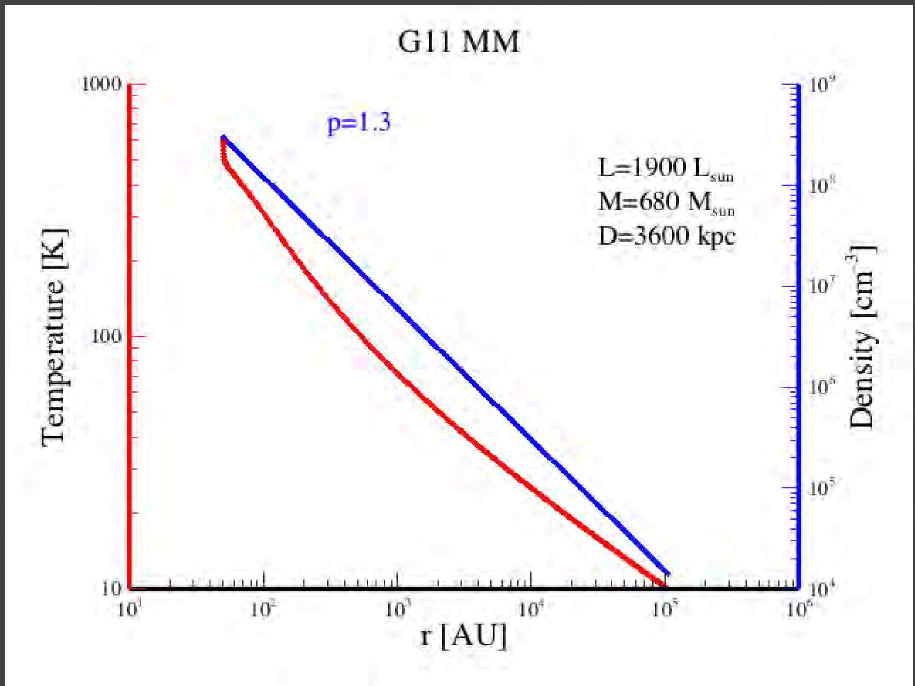
- Only MM peaks show CH_3OH
  - RADEX modeling suggests high density and temperature

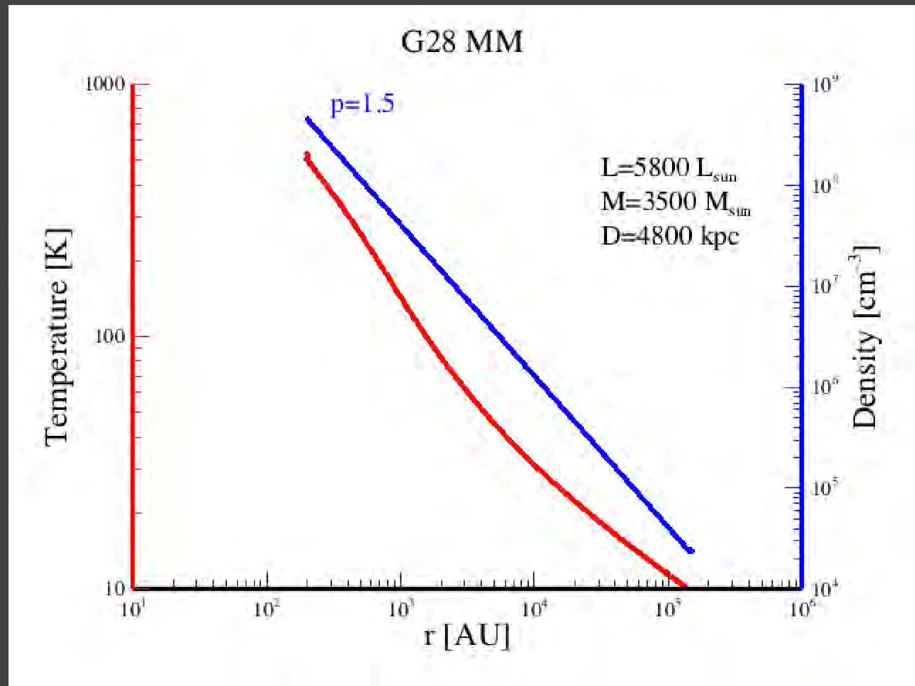
Proposed Evolution Ordering

Clump	Main Features	Stage
G28.34 MM	Broadest outflow, multiple methanol transitions, water infall	Most Advanced
G11.11 MM	Outflow and methanol transitions, water infall	Advanced
G28.34 NH_3	Outflow, no methanol, water infall	Young
G11.11 NH_3	Only water infall	Youngest: High Mass Prestellar Core

Structure Modelling

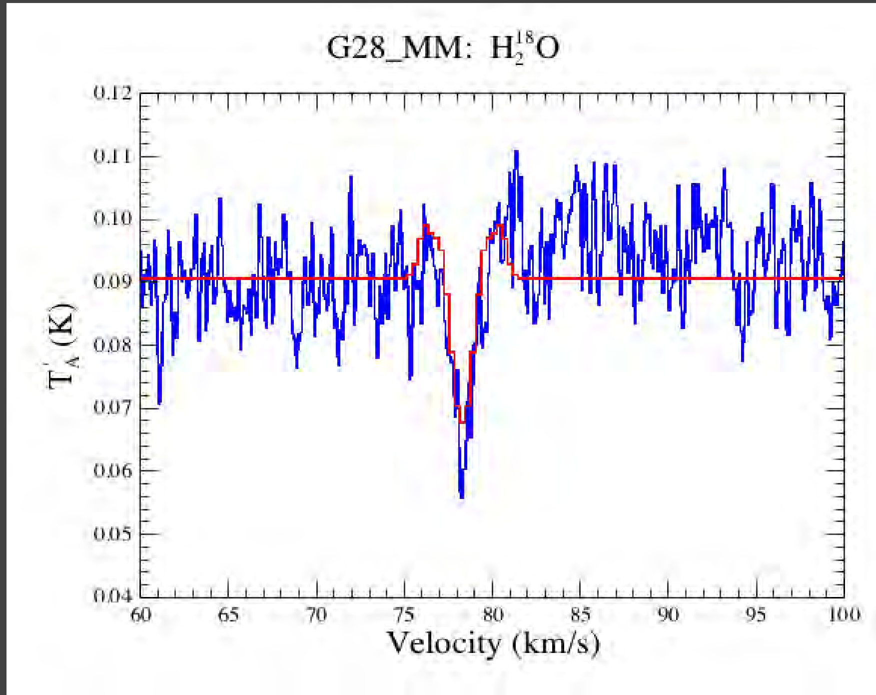
- 1 D spherical model of temperature and density





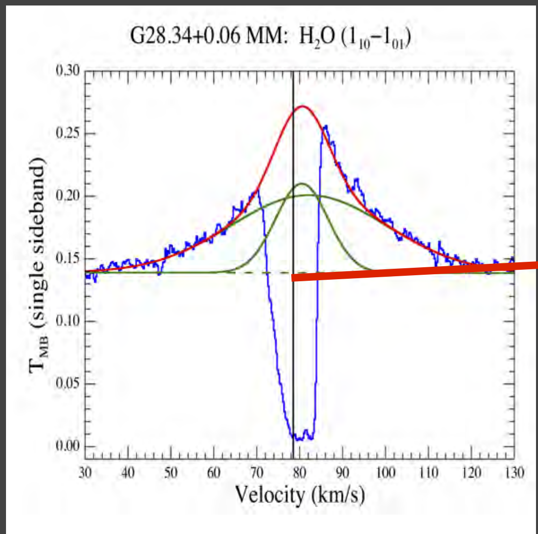
Water absorption: initial results from $H_2^{18}O$

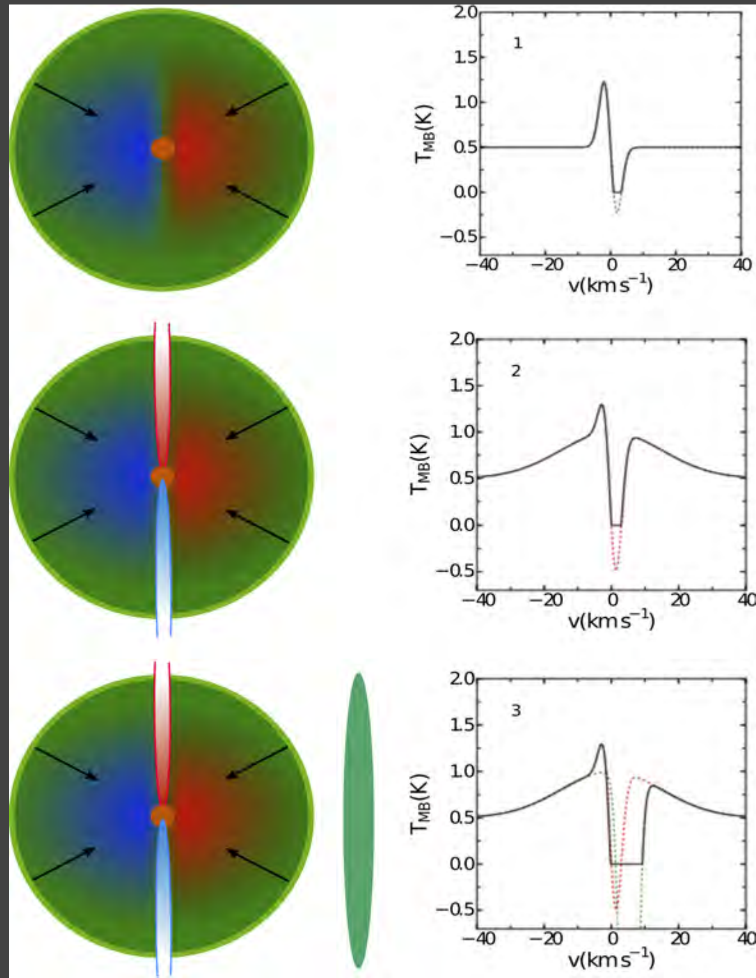
- Best model:
    - decreasing abundance interior to clump
    - similar to low mass protostars (Mottram et al., 2013, A&A, 558 A126)
    - contrary to more advanced high mass protostars) (Choi et al 2014, A&A Accepted)



The water story for G28 MM: Initial Results

- H_2O: Red shifted 100% absorption
  - Note: $H_2{}^{18}O$ *does not display infall*
- Best model is for a "foreground" cloud
  - Foreground wrt clump dust emission model.
  - Part of the collapsing GMC?

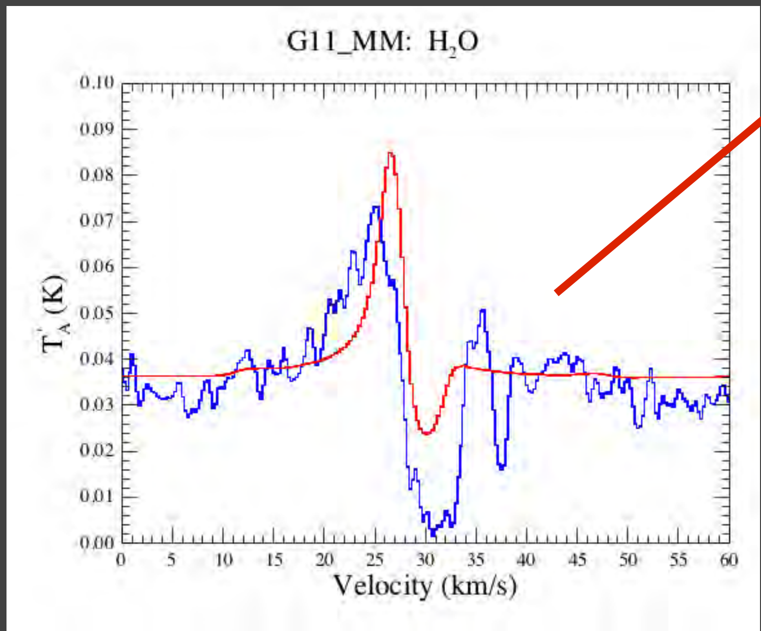


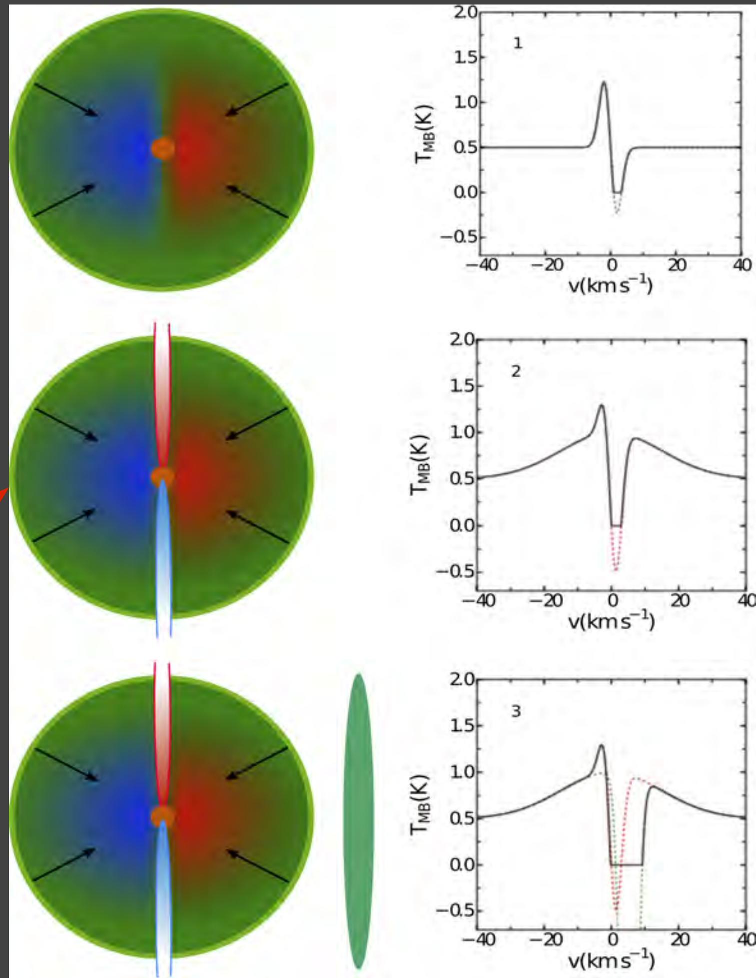


Mottram et al., 2013, A&A, 558 A126

The water story for G11 MM

- Red shifted 100% absorption
- No $H_2^{18}O$ detected: upper limit
- Initial results
  - Infall may reproduce both
    - The red shifted absorption and the "blue" emission





Conclusions

- We place the clumps into an evolutionary order
  - G28.34 MM: Most advanced
  - G11.11 MM: Advanced
  - G28.34 NH_3: Early stage
  - G11.11 NH_3: Earliest stage a High Mass Starless Core
- Modeling water lines imposes further constraints structure and dynamics
  - G28.34 MM $H_2{}^{18}O$ must decrease in abundance deeper in envelope
  - G28.34 MM has outflow plus an infalling foreground cloud
  - G11.11 either Inverse P-Cygni and/or outflow with infalling foreground
- Structure models needed for NH_3 clumps.

Thanks!

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Infall Rates

Table 8. Mass infall rates at densities from 10^5 to 10^7 cm^{-3}

Core	V_{inf}	R [pc]	10^5	10^6	10^7
G28-NH_3	2.0	0.05 [a]	3.6×10^{-4}	3.6×10^{-3}	3.6×10^{-2}
G28-MM	0.35	0.1 [a]	2.5×10^{-4}	2.5×10^{-3}	2.5×10^{-2}
G11-NH_3	0.8	0.04[b]	9.2×10^{-5}	9.2×10^{-4}	9.2×10^{-3}
G11-MM	1.15	0.04 [c]	1.3×10^{-4}	1.3×10^{-3}	1.3×10^{-2}

Notes. Infall velocity in km s^{-1}, Radius of compact cores from interferometric observations in pc, Mass infall rate in $M_\odot$/yr.
[a] Chen et al. (2010) [b] Core size assumed same a G11-MM
[c] Gómez et al. (2011)

- Range of Densities
- Sizes of cores from interferometric observations

- 10^{-4} to 10^{-2} Msun/yr

(Shipman et al. 2014 A&A 570, A51)

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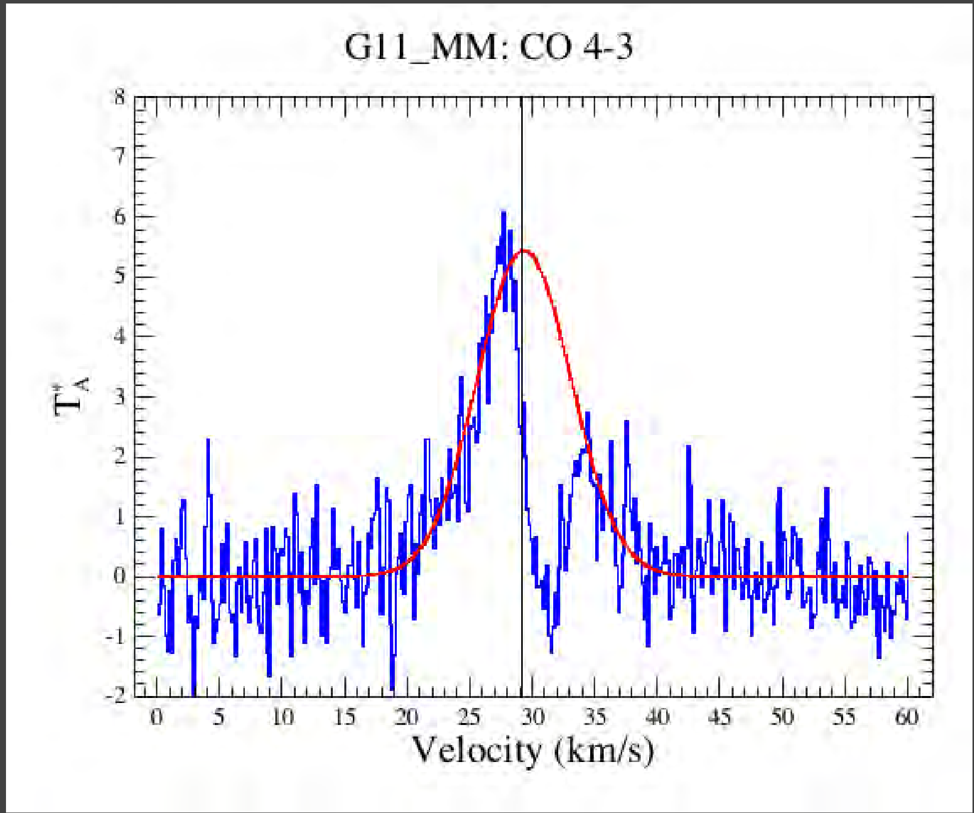
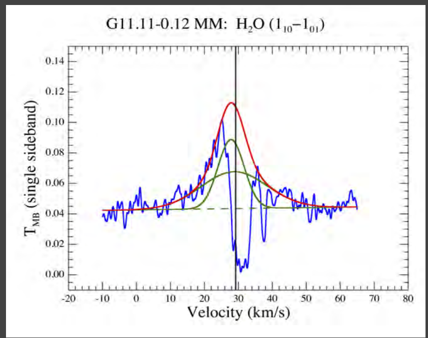
Next Steps

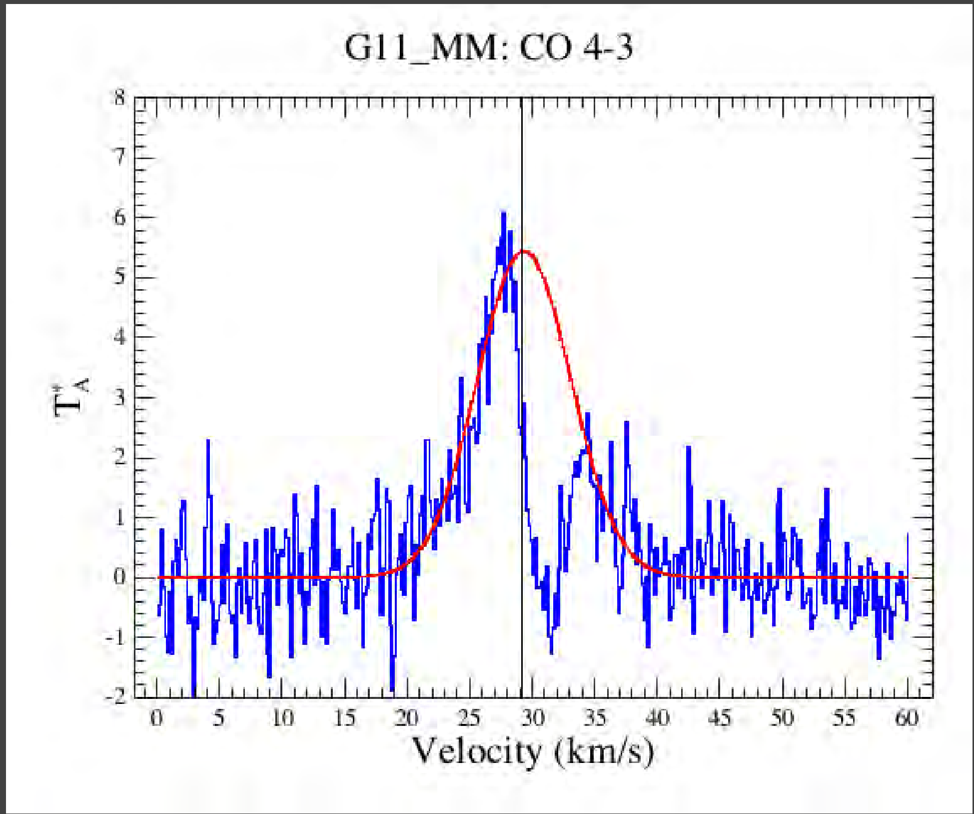
- Modeling the lines constrains the structure and dynamics
- Consistent water story
  - Satisfy both H_2O and $H_2^{18}O$
- CO 4-3
  - redshifted absorption
  - Very similar to H_2O
  - Perhaps "outflows" are a combination of real outflows and infall.





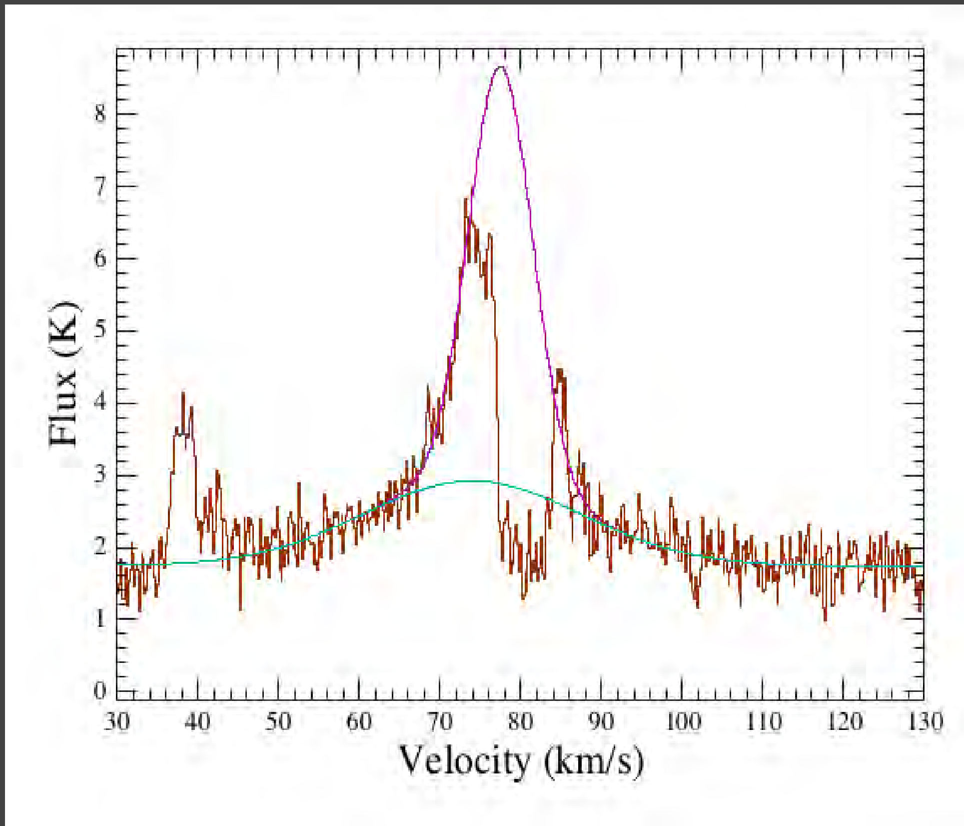
Initial results for G11 MM outflow

- One broad line in CO (4-3):
  - 9.32 km/s, 5.2 K
- CO Column density (Radex 200K and 3e4)
  - $1.7\ 10^{16}\ cm^{-2}$
- $CO/H_2 \sim 10^{-4}$
- H_2O Column density (27.8 km/s, Δv 9.1 km/s)
  - $0.4\ 10^{14}\ cm^{-2}$
- Abundance wrt H_2
  - $2.35\ 10^{-7}$



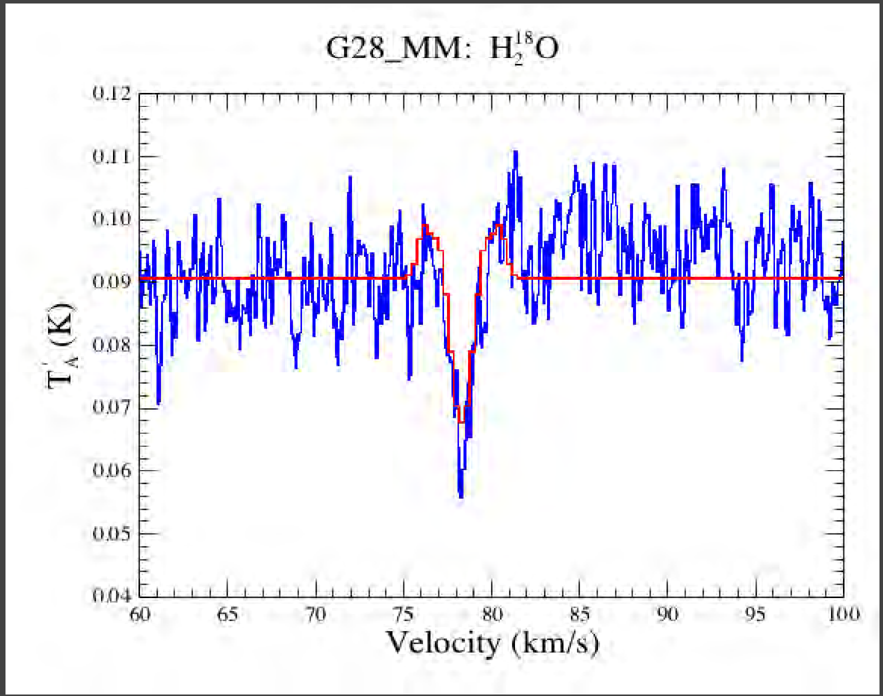
Initial results for G28 MM outflows

- Two broad lines:
  - 32 km/s, 1.2 K
  - 9.4 km/s, 5.8 K
- Radex Column (200K and 3e4)
  - $1.3\ 10^{16}$
  - $1.9\ 10^{16}$
- $CO/H2 \sim 10^{-4}$
- Column H_2O
  - $3\ 10^{14}$
  - $1.1\ 10^{14}$
- Abundance
  - $2.3\ 10^{-6}$
  - $5\ 10^{-7}$



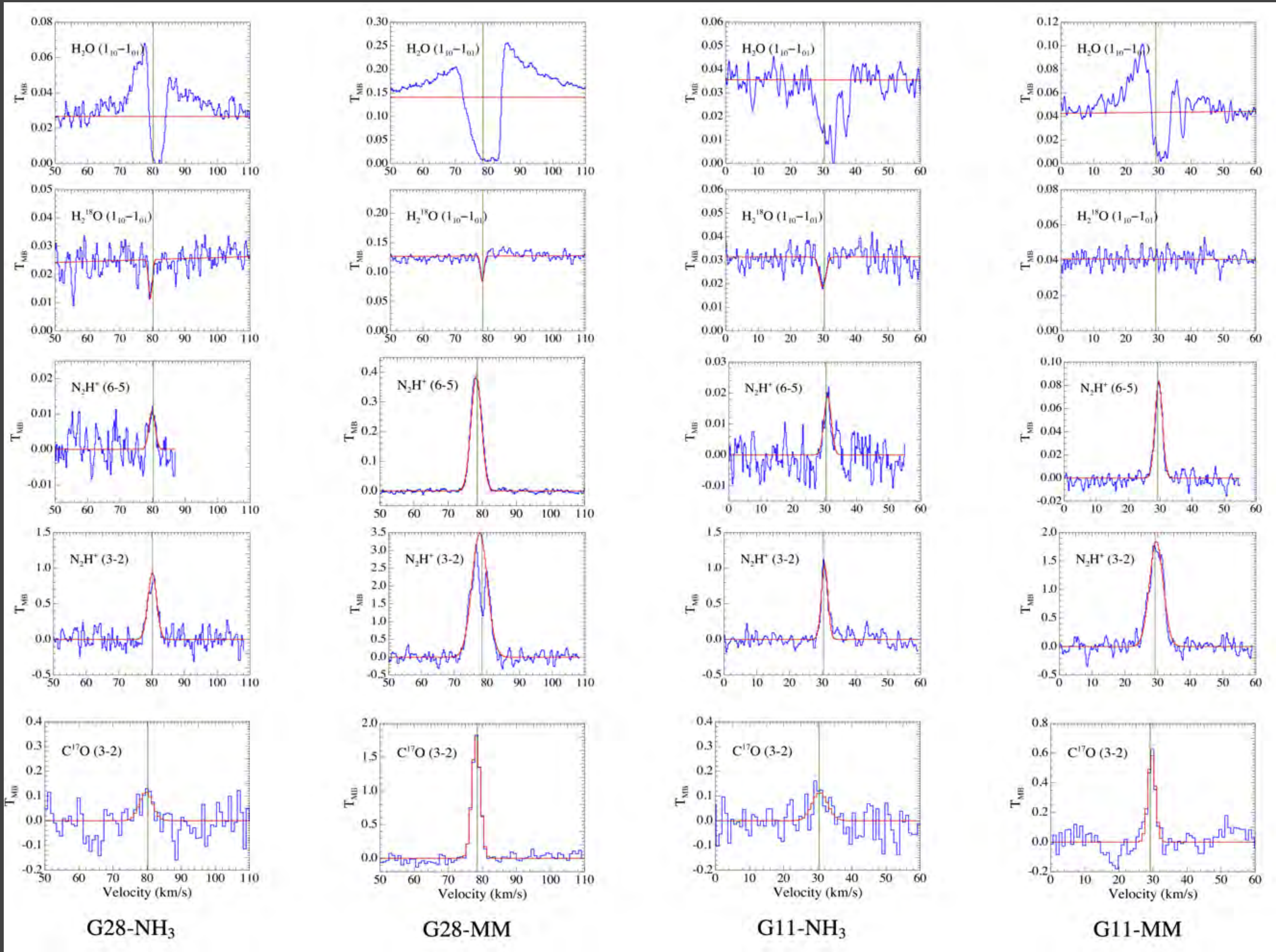
Water Absorption: Initial Results from $H_2{}^{18}O$

- $H_2{}^{18}O$ in absorption narrow at systemic velocity
  - $H_2{}^{18}O$ leads to H_2O abundances (assuming O/^{18}O of 500):
    - G28MM 0.3 10^{-8}
    - G28NH_3 4 10^{-8}
    - G11MM <0.2 10^{-8}
    - G11NH_3 3 10^{-8}
  - Similar to findings of low and high mass protostars



Modeling the absorption suggests decreasing abundance interior to clump (similar to low mass protostars (Mottram et al., 2013, A&A, 558 A126) contrary to more advanced high mass protostars) (Choi et al 2014, A&A Accepted)

Data



- HIFI: o-H_2O (1_{10}-1_{01}), N_2H^+ (6-5), o-$H_2^{18}O$ (1_{10}-1_{01}) (Shipman et al., 2014, A&A 570, A51)
- APEX: $C^{17}O$ (3-2), N_2H^+ (3-2) , not shown CO (4-3), CO (7-6), $C^{34}S$ (7-6), CH_3OH (7_K-6_K)

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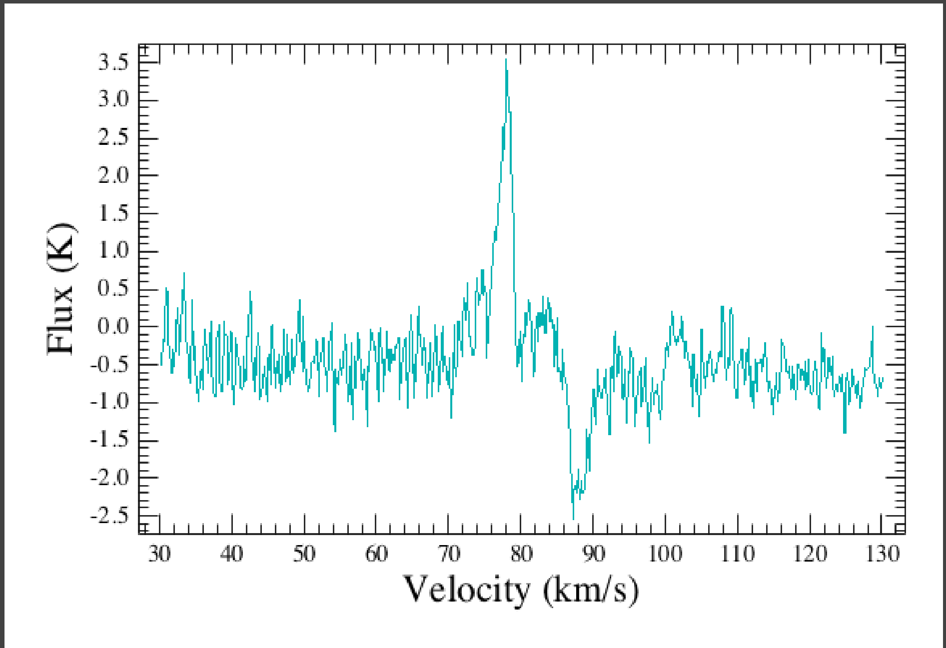
CO (4-3) of G28 clumps

G28 NH_3



G28 MM