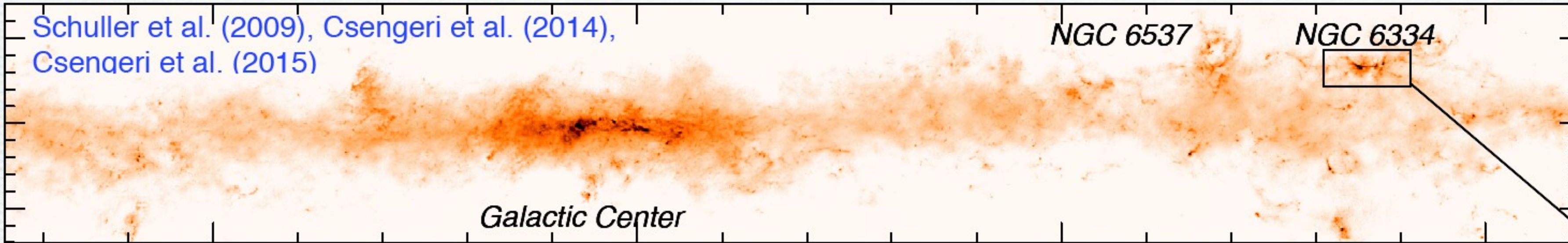
SOFIA follow-ups of high-mass clumps from the ATLASGAL galactic plane survey

Friedrich Wyrowski, Rolf Güsten, Karl Menten,
Helmut Wiesemeyer, Timea Csengeri, Carsten König,
Silvia Leurini & James Urquhart

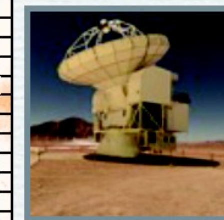
MPIfR Bonn

ATLASGAL: the most sensitive ground based submm survey

APEX Telescope Large Area Survey of the Galaxy: *~ 420 sq. degree of the inner Galaxy*



APEX



870 μm

ℓ < 60° ← → *ℓ > -80°*

1. Continuum

Catalogs:

- compact sources,
  Contreras+2013,
  Csengeri+ 2014,
  Urquhart+ 2014
- filaments
  Li+ *in prep*

Large scale statistics:

- time-scale estimates
  Csengeri+ 2014,
- dense gas fraction
  Csengeri, Weiss+ 2015
- evolutionary stage indicators
  Urquhart+ 2013a,2013b

2. Distances

kinematic
Wienen+ 2012
Wienen+ 2015
Giannetti+ 2015

maser: BesSel
Brunthaler+ 2009

3. Spectroscopy

astro-chemistry
Csengeri+ 2015 (SiO)
Leurini+ 2014 (H_2O)
Giannetti+ 2014 (CO)

4. Young massive clumps

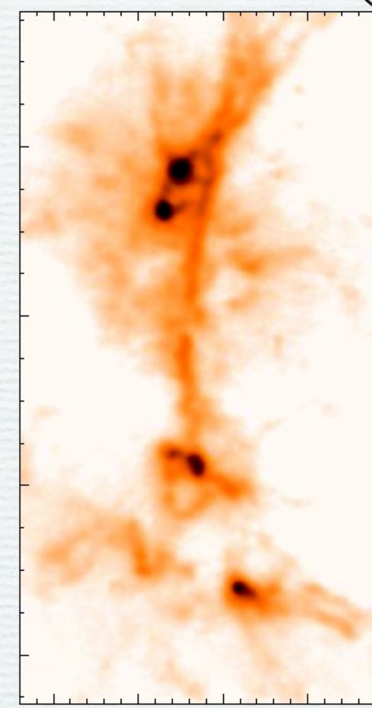
ALMA follow-up
Csengeri+ *in prep*

~ 40 sources

> 400 sources

> 3000 sources

> 10 000 sources



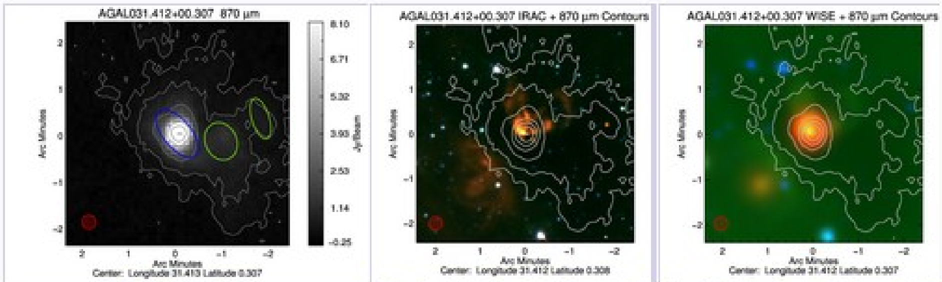
ATLASGAL database: http://atlasgal.mpifr-bonn.mpg.de/

The ATLASGAL Database Server

ATLASGAL CSC Summary Page: AGAL031.412+00.307

Dust Emission Image and Catalogue Parameters

ATLASGAL 870 μm Emission Map (5' x 5')



(fits file) (postscript file) | (3.5μm 4.6μm 5.8μm 8.0μm fits files) (postscript file) | (3.4μm 4.6μm 12μm 22μm fits files) (postscript file)

Notes

The image presented in the left panel is a 5x5 arcmin region extracted from the ATLASGAL tiles and is centred on the position of the peak flux associated with the source. The source size and orientation is shown by the blue ellipse, while the sizes and orientations of any other detected sources located in the field are shown in green. The contours shown in grey start at 3 sigma and increase in steps determined by a dynamic power law (see Thompson et al. 2006 for details). The angular resolution of the ATLASGAL survey is indicated by the hatched red circle shown in the lower left corner. In the middle and right panels we present a three colour mid-infrared image created using the 4.5, 5.8 and 8 μm IRAC band filters extracted from the GLIMPSE Legacy Project, and the 4.6, 12 and 22 μm WISE bands. Contours show the distribution of the dust with respect to the infrared emission (contour levels are the same as shown in the left panel). The white hatched circle shown in the lower left corner of this image again indicates the resolution of the ATLASGAL survey.

CSC Parameters (show GCSC catalogue)

Cat. Id	Source Name	RA	Dec	Size	PA	Eff. Radius[a]	Peak Flux	Integrated Flux	Detection[b]	Notes	V_{LSR}	Catalogue
		(J2000)	(J2000)	('')	(°)	('')	(Jy beam^{-1})	(Jy)	Flag		(km s^{-1})	Reference
10264	AGAL031.412+00.307	18:47:34.27	-01:12:43.0	37 x 18	40	57	22.74	61.68	3	NA	97.6	Contreras et al. (2013)

Useful Links[c]

- Search Simbad Archive
- HEASARC Search of all VizieR Catalogues
- View combined GLIMPSE and MIPSGAL Images using the Space Science Institue GLIMPSE/MIPSGAL VIEWER
- RMS Survey Matches

Footnotes

a) The effective radius is estimated from the geometric mean of the deconvolved major and minor axes and multiplied by a factor of 2.4 that relates the rms size of the emission distribution of the source to its angular radius (Eqn. 6 of Rosolowsky et al. 2010). As the sizes are determined for the emission above 3 times the local background noise the major and minor axes can be smaller than the beam for some of the weaker sources and in these cases a value of -1 is returned for this field.

b) This flag is either zero (no particular problem), or is equal to the sum of one or more number(s) with the following meanings: (1) the object has neighbours, bright and close enough to significantly bias the photometry or bad pixels (more than 10% of the integrated area affected); (2) the object was originally blended with another one; (4) at least one pixel of the object is saturated (or very close to); (8) the object is truncated (too close to an image boundary); (16) object's aperture data are incomplete or corrupted; (32) object's isophotal data are incomplete or corrupted; (64) a memory overflow occurred during deblending; (128) a memory overflow occurred during extraction. For example, a flag value of 10 means that the object was originally blended with another source and that it is truncated because is located too close to the edge of the map.

c) The size of the semi-major axis is used to search for associations with the following links.

Infrared Data

WISE Fluxes

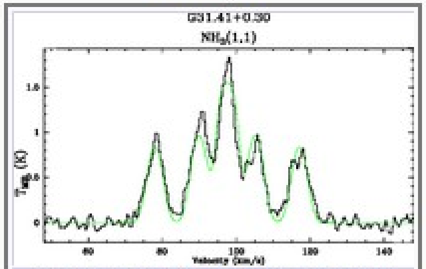
WISE Point Source Position and Fluxes

WISE Name	RA	Dec	Offset	3.4 μm	4.6 μm	12 μm	22 μm	Quality
	(J2000)	(J2000)	('')	(Mag.)	(Mag.)	(Mag.)	(Mag.)	Flags
J184734.26-011240.6	18:47:34.26	-01:12:40.6	2.40	11.3	8.6	3.6	-1.5	0hdh

ATLASGAL Molecular Line Surveys

NH_3 Observations

Ammonia Spectra



NH3 (1,1) emission is shown in black and the fit to the data is overplotted in green.

(Postscript file available)

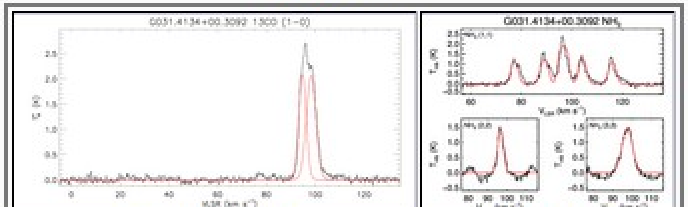
Ammonia Fit Parameters

		Line Transition													
		NH3 (1,1)					NH3 (2,2)				NH3 (3,3)				
Cat. Name	Offset ('')	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	Optical Depth	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	rms (mK)	VLSR (km/s)	T_{mb} (K)	FWHM (km/s)	Reference
G31.41+0.30	18.67	50	97.60	1.50	4.27	3.14	60	97.32	1.04	5.42	50	97.49	1.24	7.31	Wienen et al. 2012

Archival Molecular Line Data

Line Parameters

Observed Spectrum



FCRAO 13CO (J=1-0) fits file | GBT NH3 (1,1) fits file

Fitted Parameters for Observed Molecular Transitions

Id.	Source Name	Line transition	Offset ('')	RMS (K)	VLSR (km/s)	T_a^* (K)	FWHM (km/s)	Telescope	Reference
32	G031.414+00.307	HCO+ (3-2)	4.24	0.06	NA	NA	NA	HHT	
35	G031.414+00.307	N2H+ (3-2)	4.24	0.06	NA	NA	NA	HHT	
34	G031.4134+00.3092	NH3 (1,1)	6.34	0.08	96.3	1.7	2.9	GBT	
6	G031.4134+00.3092	13CO (J=1-0)	8.29	0.05	95.1	2.1	3.6	FCRAO	
8	G031.4134+00.3092	13CO (J=1-0)	8.29	0.05	96.2	0.9	1.5	FCRAO	
7	G031.4134+00.3092	13CO (J=1-0)	8.29	0.05	98.7	2.1	4.6	FCRAO	
4	18449-0115	CS (J=2-1)	13.47	0.10	96.6	1.1	9.1	SEST	
39	G031.414+00.307	NH3 (1,1)	17.57	0.17	96.9	3.8	4.2	GBT	
37	G31.41+0.30	NH3 (1,1)*	18.29	0.05	97.6	1.5	4.3	Effelsberg	

You Tube atlasgal Upload

4:20 / 8:10

Close look at the ATLASGAL image of the plane of the Milky Way

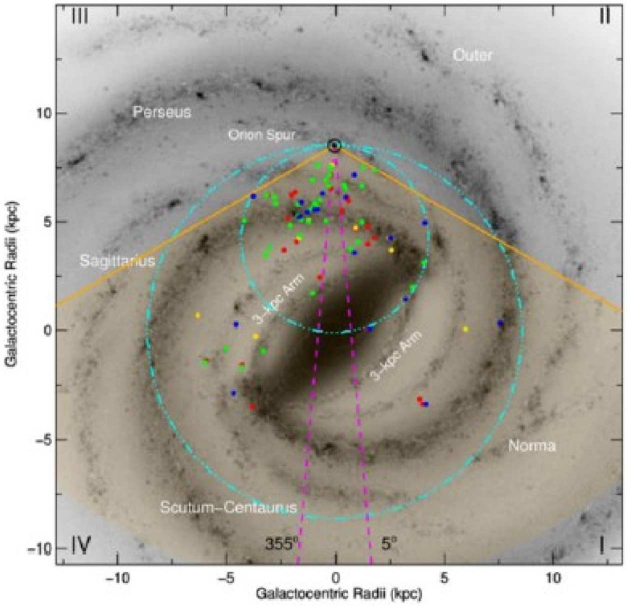
European Southern Observatory (ESO)

Subscribe 13,619

337,212 views

Add to Share ••• More 2,311 31

The TOP100 sample



Selection criteria

- **IRB:** The brightest sources of the survey (excluding the CMZ)
- **RMS:** The brightest sources classified as MYSOs in the RMS survey
- **D8:** The brightest 8 μm-dark sources
- **D24:** The brightest 24 μm-dark sources

The TOP100: Giannetti+2014, König+2015, subm.

- Includes sources in different evolutionary stages
- Is completely characterised in distance
  - Distance disribution is similar in the subsamples
  - $\sim$ 75% within 6 kpc
  - 5 IRDCs ($\sim$ 11%) at the far distance (Giannetti et al. 2015)

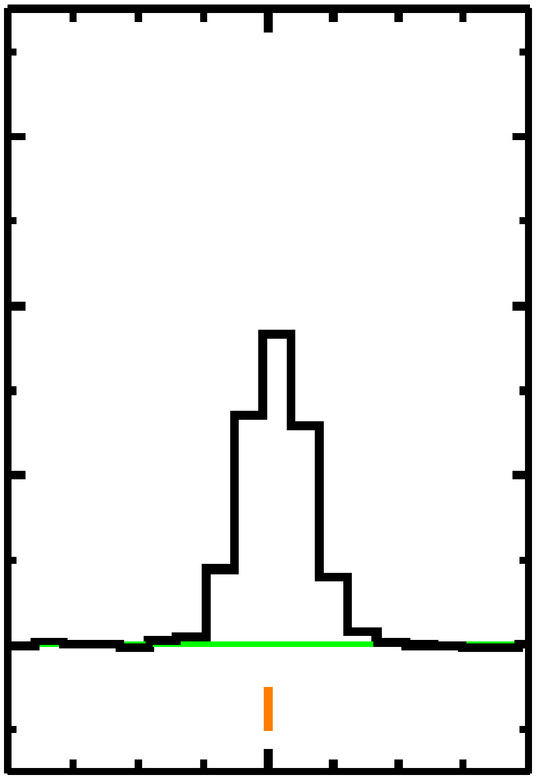
ATLASGAL @ SOFIA

concerted effort on several Thz-unique fronts

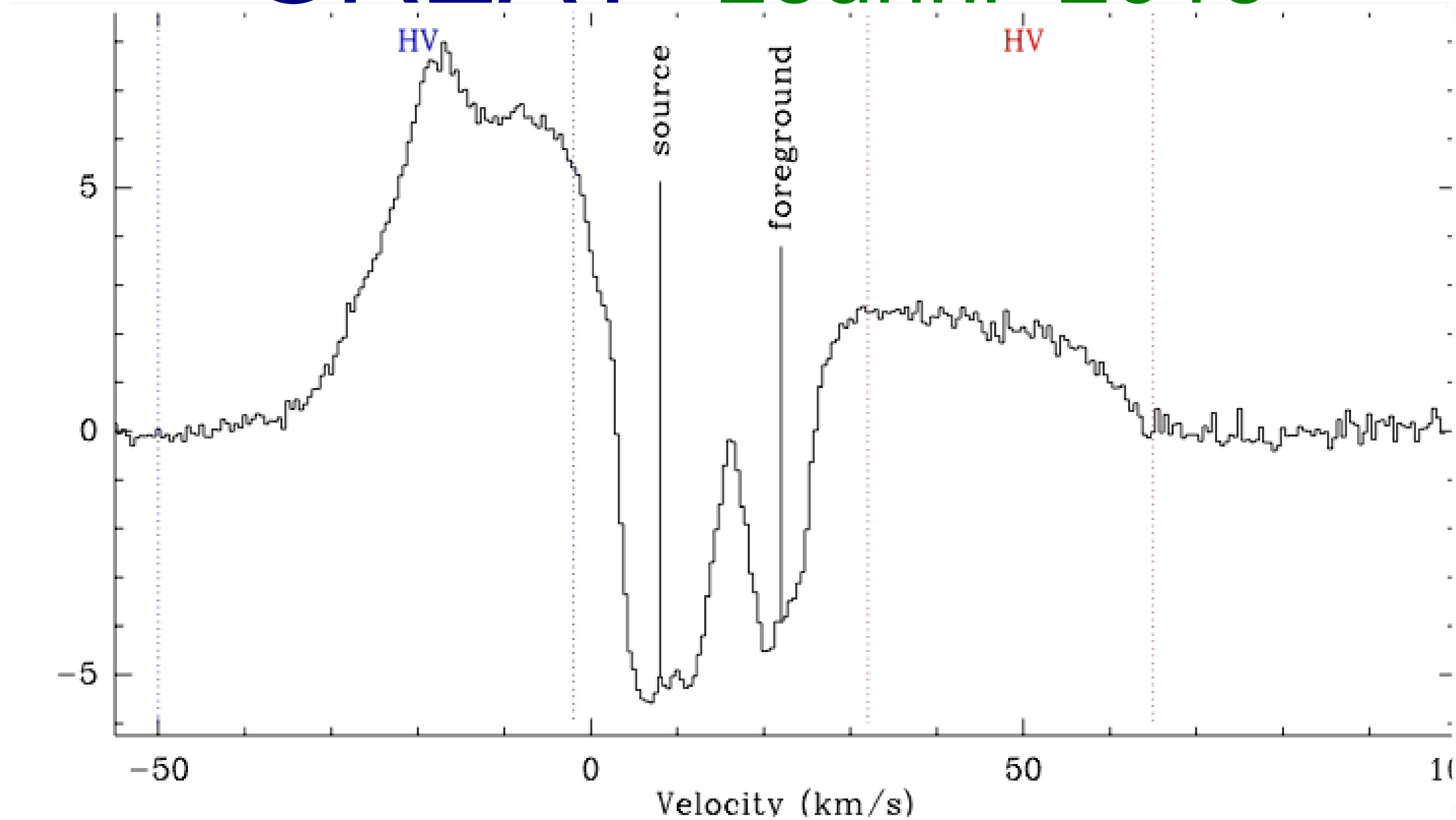
- Plan: on well characterized sample of high-mass clumps in a range of evolutionary stages:
  - Study cooling budget: e.g. OI/CII/OH (H_2O from HIFI)
  - Combine SOFIA high-*J* CO: (11-10)/(16-15) with ground based low/mid-J CO to study CO SEDs
  - Probe infall with ammonia absorption study
- → Ongoing, we are stretching the observations over several semesters

OI teaser: from PACS to GREAT Leurini+2015

G5.89−0.39



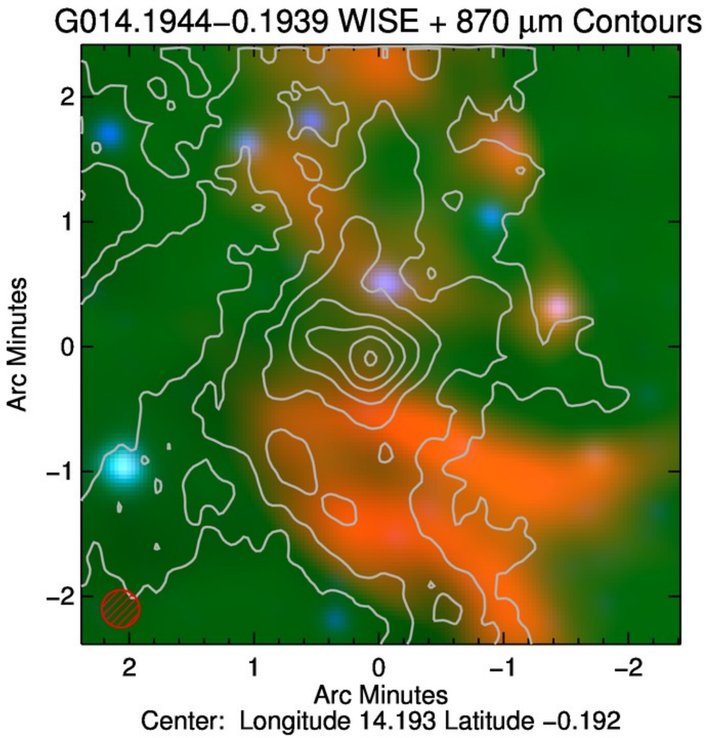
Karska+2013

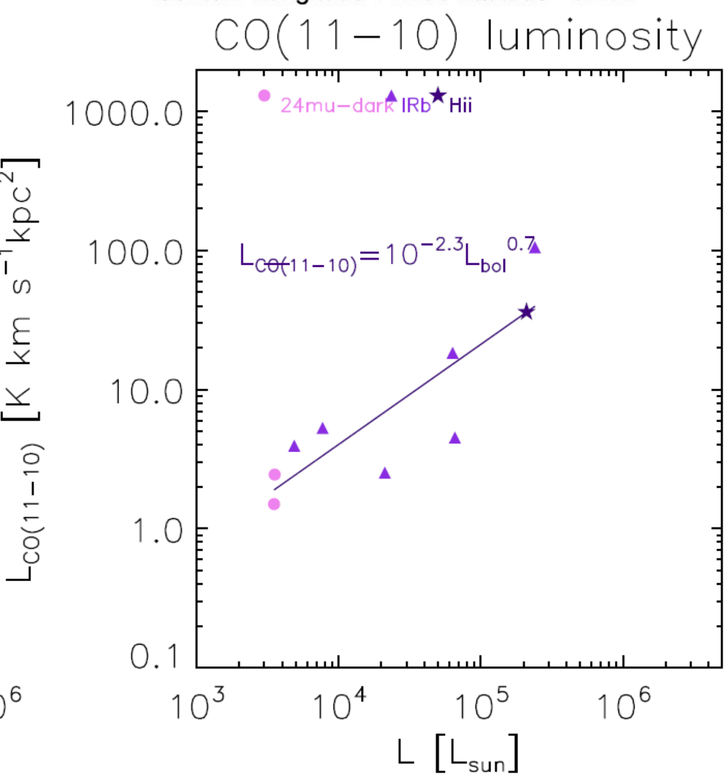


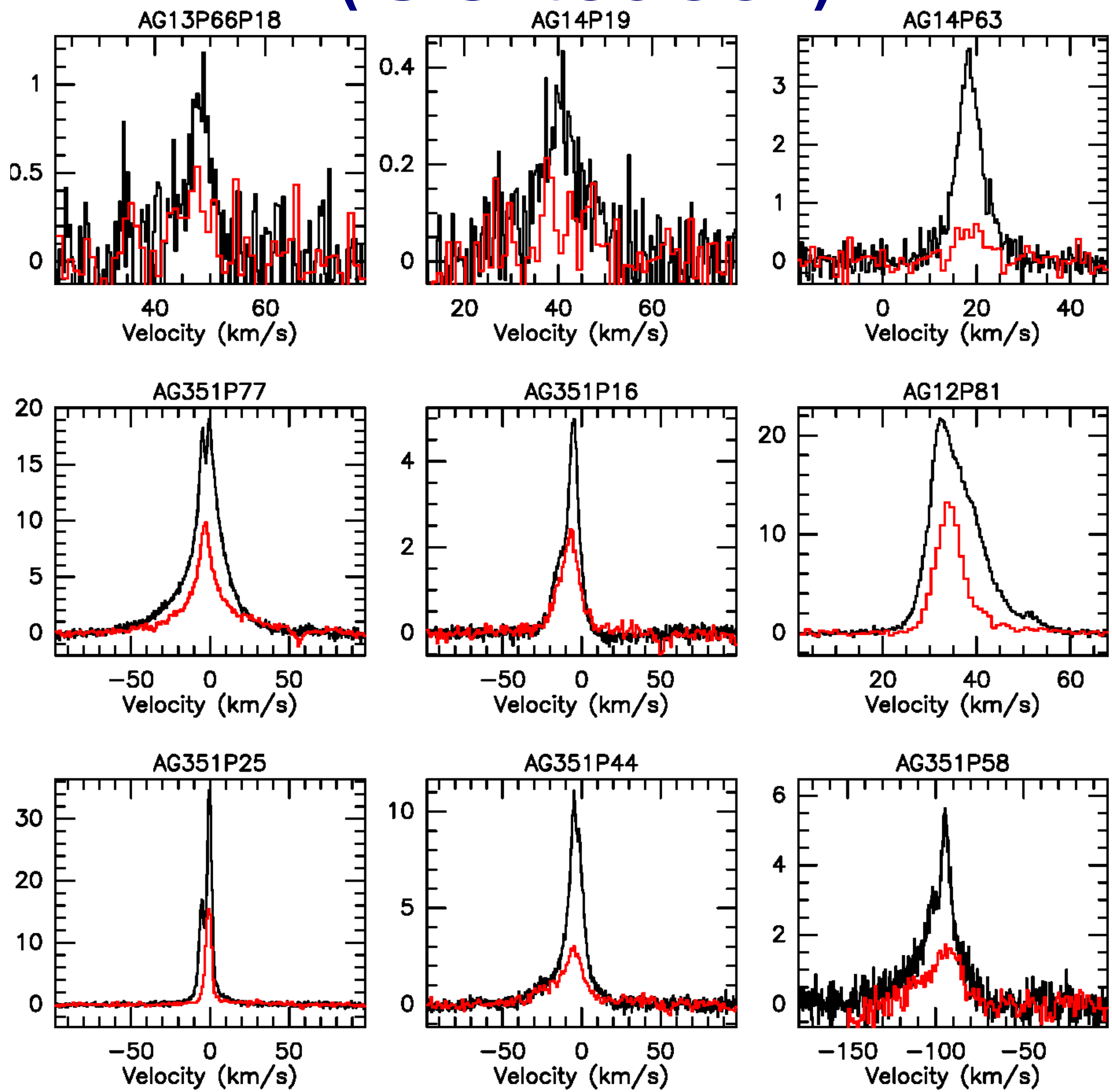
Velocity range	$L_{CO(16-15)}$ ($L_\odot$)	L_{OH}[a] ($L_\odot$)	L_{H_2O}[b] ($L_\odot$)	$L_{OI\,63\,\mu m}$ ($L_\odot$)	L_{CII} ($L_\odot$)	L_{FIRL} ($L_\odot$)
Total profile ([−50, +65] km s^{-1})	0.65	0.44	–	5.7	0.42	7.21
HV-red ([+47, +65] km s^{-1})	–	0.08	0.03	0.9	0.02	1.03
LV-red ([+32, +47] km s^{-1})	0.06	0.13	0.09	1.2	0.06	1.48
Ambient[c] ([−2, +26] km s^{-1})	0.42	0.12	0.08[d]	–	0.1	0.72
HV-blue ([−35, −50] km s^{-1})	–	–	–	0.02	–	0.02
LV-blue ([−35, −2] km s^{-1})	0.17	–	–	5.3	0.2	5.67

SOFIA follow-ups (CO teaser)

11-10 black
16-15 red

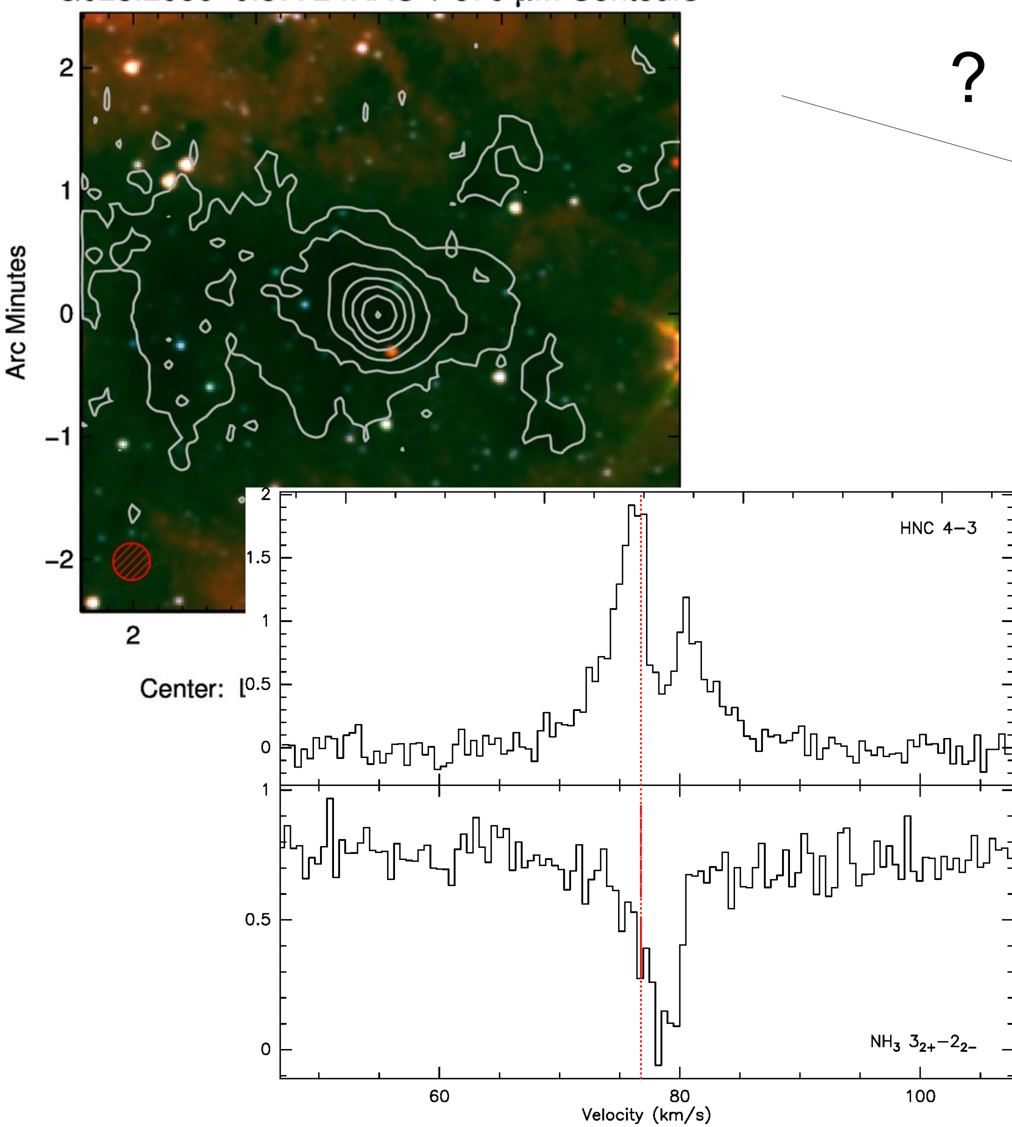




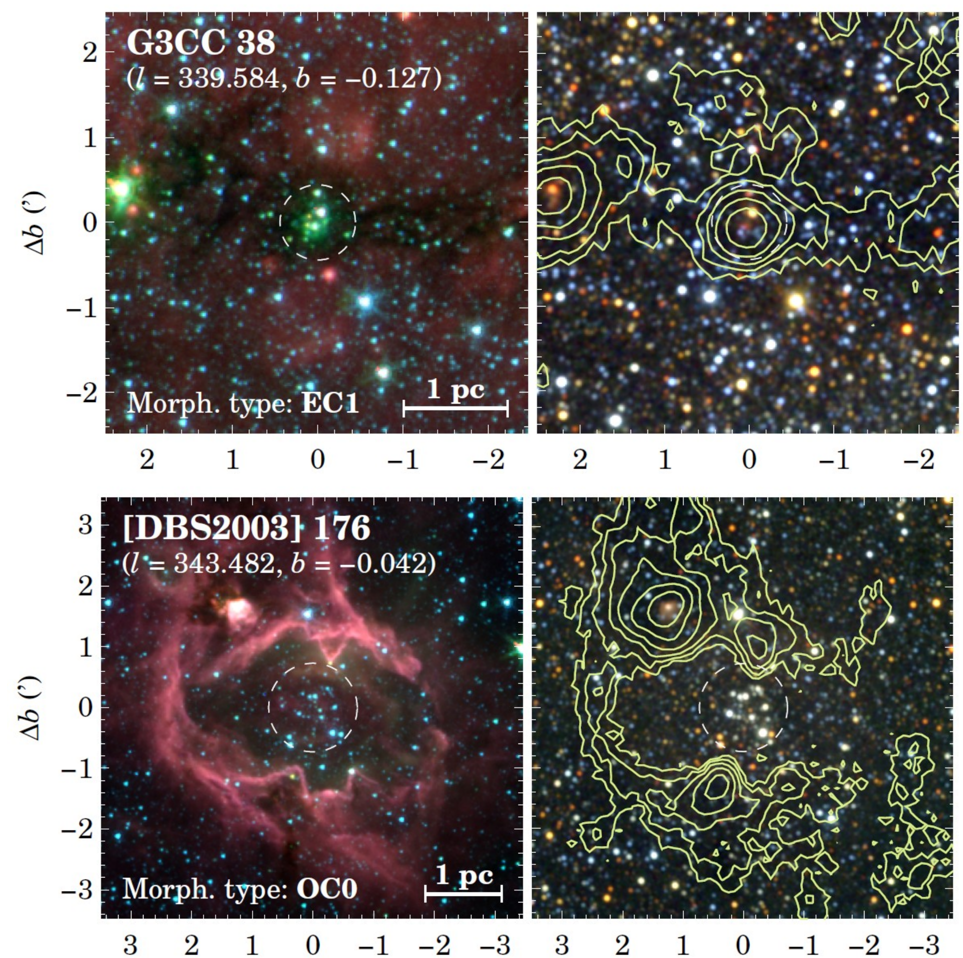


High-mass clump evolution

Infall is a fundamental process in SF!



?

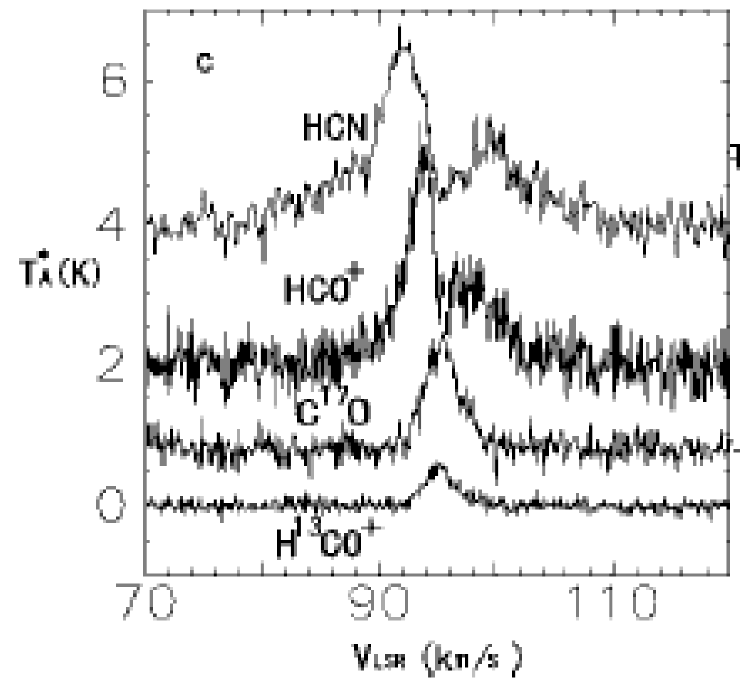


Morales+2013

Evidence for infall (I)

Observe infall asymmetry of optically thick spectral lines in emission:

- HMPOs, Fuller+ 2005: 0.2-1 10^{-3} $M_\odot$/yr
- UCHIIs, Wyrowski+ 2006, Klaassen+2008
- H_2O maser dense clumps, Wu+ 2003: B/R statistics similar to low mass clumps
- Possible earlier stages:
  - G25.38, Wu+ 2005: 3.4 10^{-3} $M_\odot$/yr
  - ISOSS J18339, Birkmann+ 2006
- Some cases with large scale infall → infall strong enough to overcome radiation pressure?



Evans (1999): “path towards salvation”

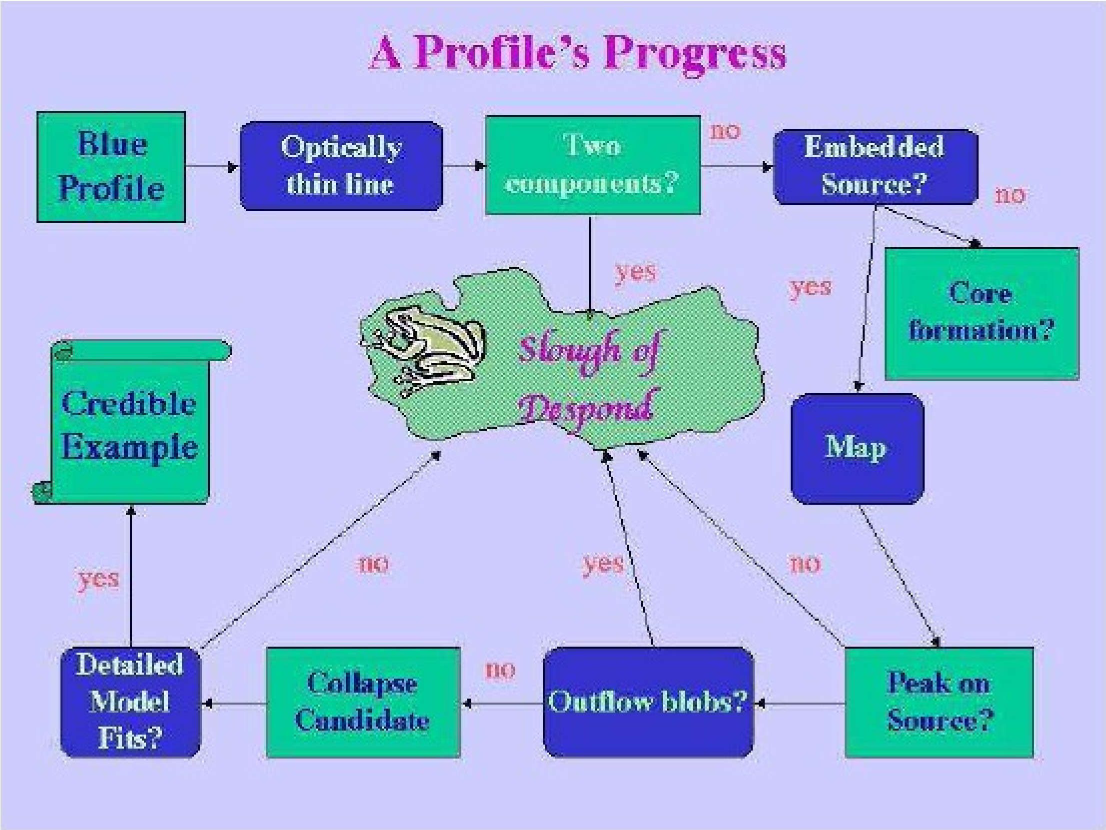


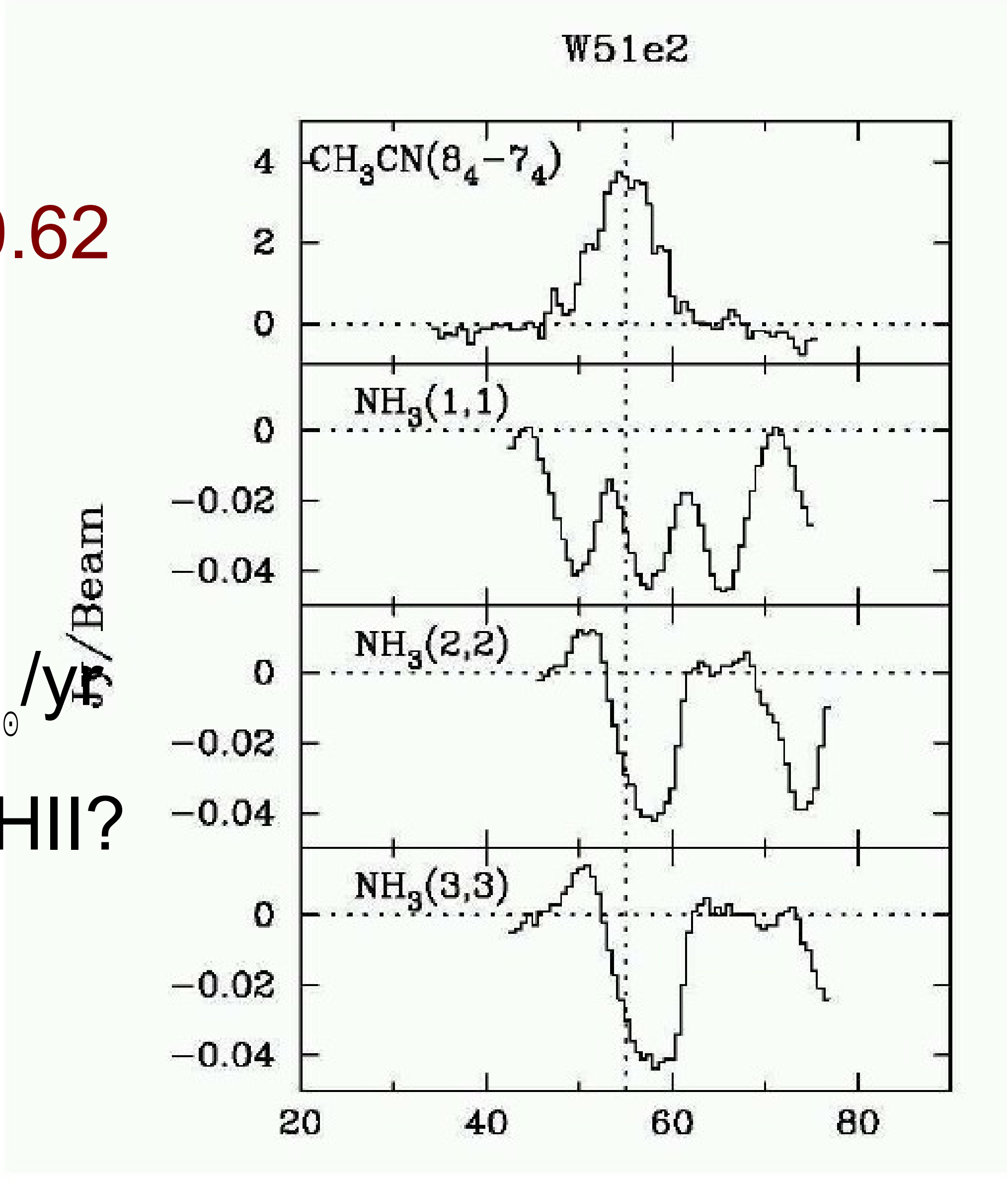
Figure 4. The progress of a blue profile through the many pitfalls on the path toward "salvation," as a credible example of collapse (with apologies to John Bunyan).

And issue of changing abundances not even mentioned ...

Evidence for infall (II)

Observe infall as redshifted absorption in front of strong cm continuum from UCHIIRs:

- Zhang+Ho1997: W51
- Keto++, Sollins+2005: G10.62
- Beltran+2006: G24.78
- Beuther+2009: ATCA southern sources
- → Accretion of up to 10^{-3} $M_\odot$/yr
- Accretion even through UCHII?
- **Only late stage probed :-(**



Search for infall

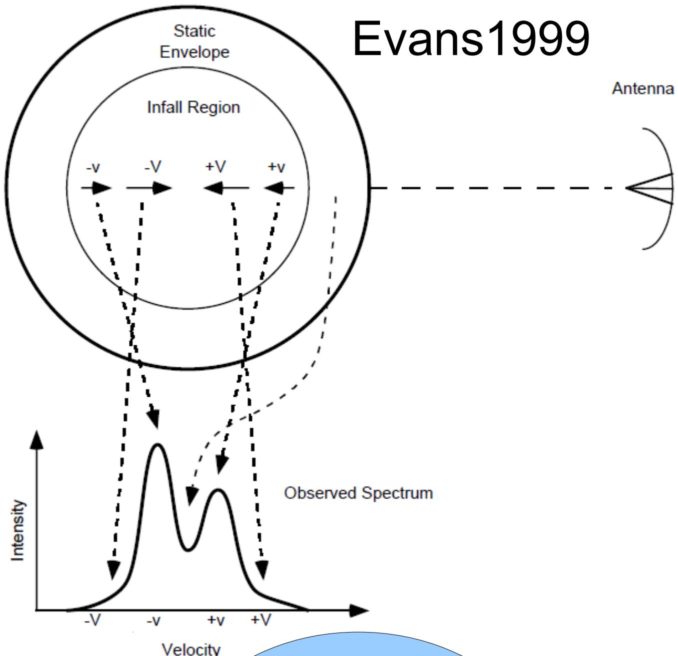
I: Blue-skewed profiles

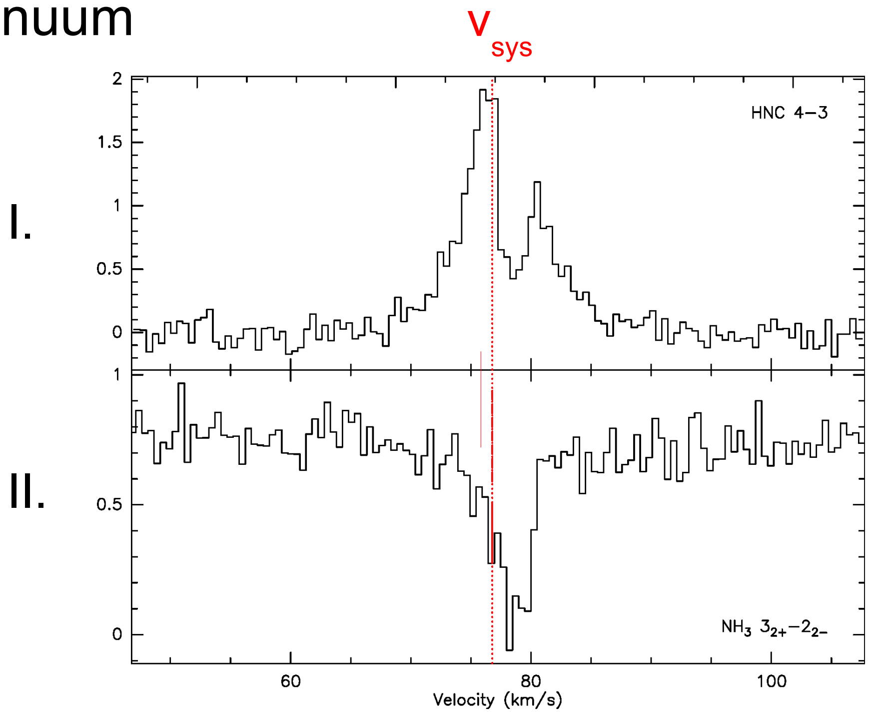
Needs excitation gradient, right tau

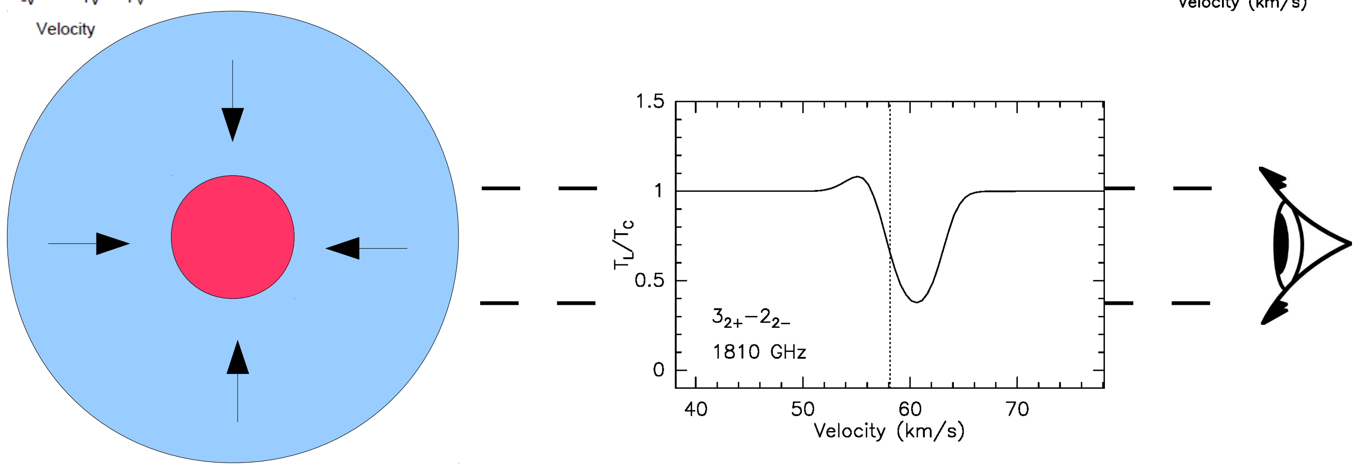
II: red-shifted absorption

Needs high critical density, central continuum

Evans1999







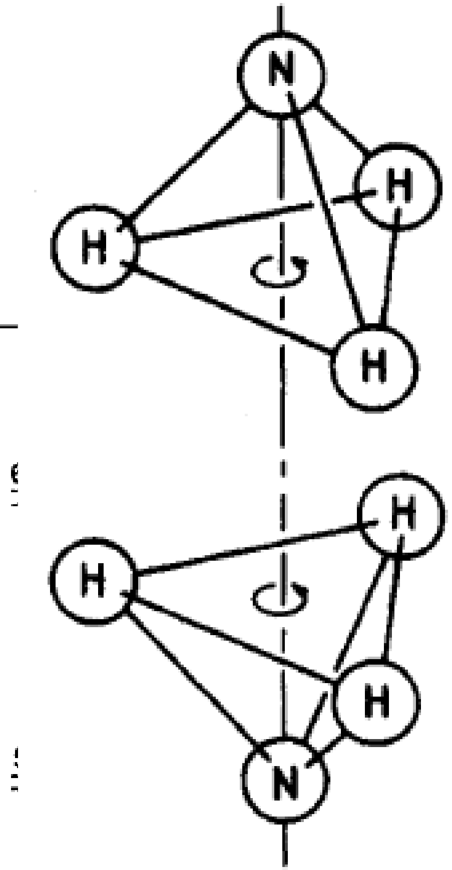
Science objective

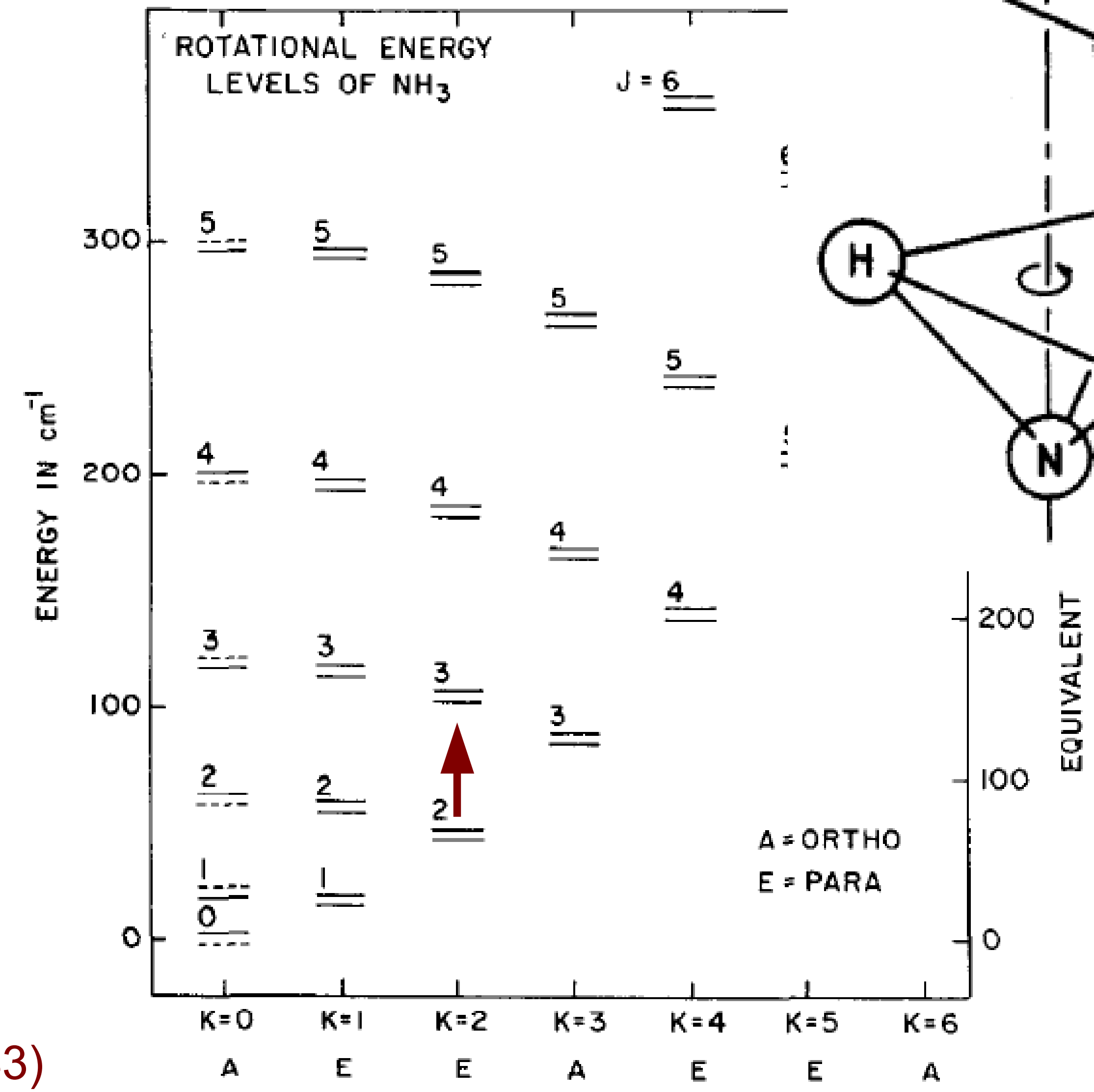
Ammonia as a probe of infall in HMSF regions

- New approach: study rotational transition
- Explore absorption of THz lines in front of dust continuum as new tool *(previously only studies in the cm towards evolved stages, HII regions)*
- Determine infall rates on LOS (pencil beam)
- Probe ammonia abundance in envelope
- Study infall through the evolution of high-mass clumps using ATLASGAL as target finder
- Reminder: clump-scale infall towards (proto-) cluster

Ammonia

- cm: Inversion lines
- FIR: Rotational lines
- overabundant in hot cores, apparently no depletion in cold sources





From Ho & Townes (1983)

Figure 1 Energy level diagram of rotation-inversion states. *J* is the total angular-momentum quantum number, and *K* is the projected angular momentum along the molecular axis.

DETECTION OF INTERSTELLAR NH_3 IN THE FAR-INFRARED: WARM AND DENSE GAS IN ORION-KL

C. H. TOWNES, R. GENZEL, AND DAN M. WATSON
Department of Physics, University of California, Berkeley

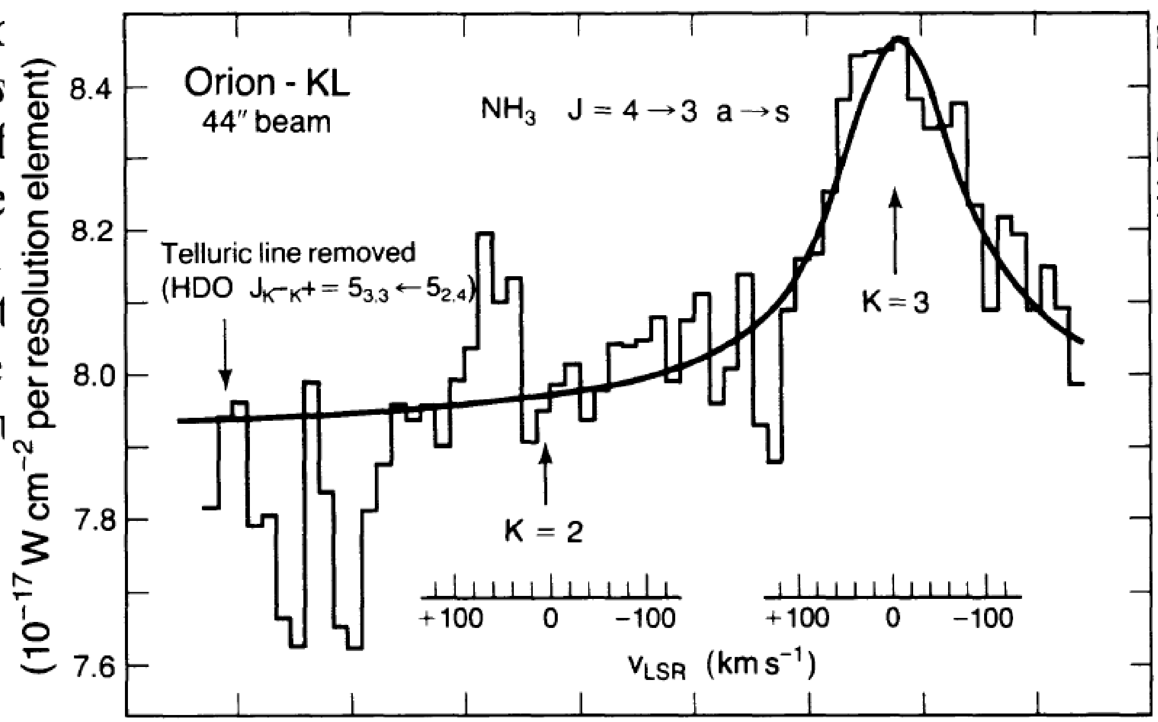
AND

J. W. V. STOREY
Anglo-Australian Observatory

Received 1982 December 28; accepted 1983 February 18

ABSTRACT

We report the detection of the $(J, K) = a(4, 3) \rightarrow s(3, 3)$ rotation-inversion transition of ammonia at 124.6 μm toward the center of the Orion-KL region. The line is in emission and has a FWHM ≥ 30 km s^{-1}. The far-IR ammonia line emission probably comes mainly from the "hot core," a compact regi … radio inversion lines of NH_3. The $a(4, 3) \rightarrow s$ … it is seen in emission, radiative excitation of … thin the source can be ruled out. Radiative e … I_3 also seems unlikely. Hence, the (4, 3) level … core region is warmer than the dust. Since t … $\sim 10^7$ cm^{-3} are high enough to explain the … IRc2 may account for the high gas temperatu…

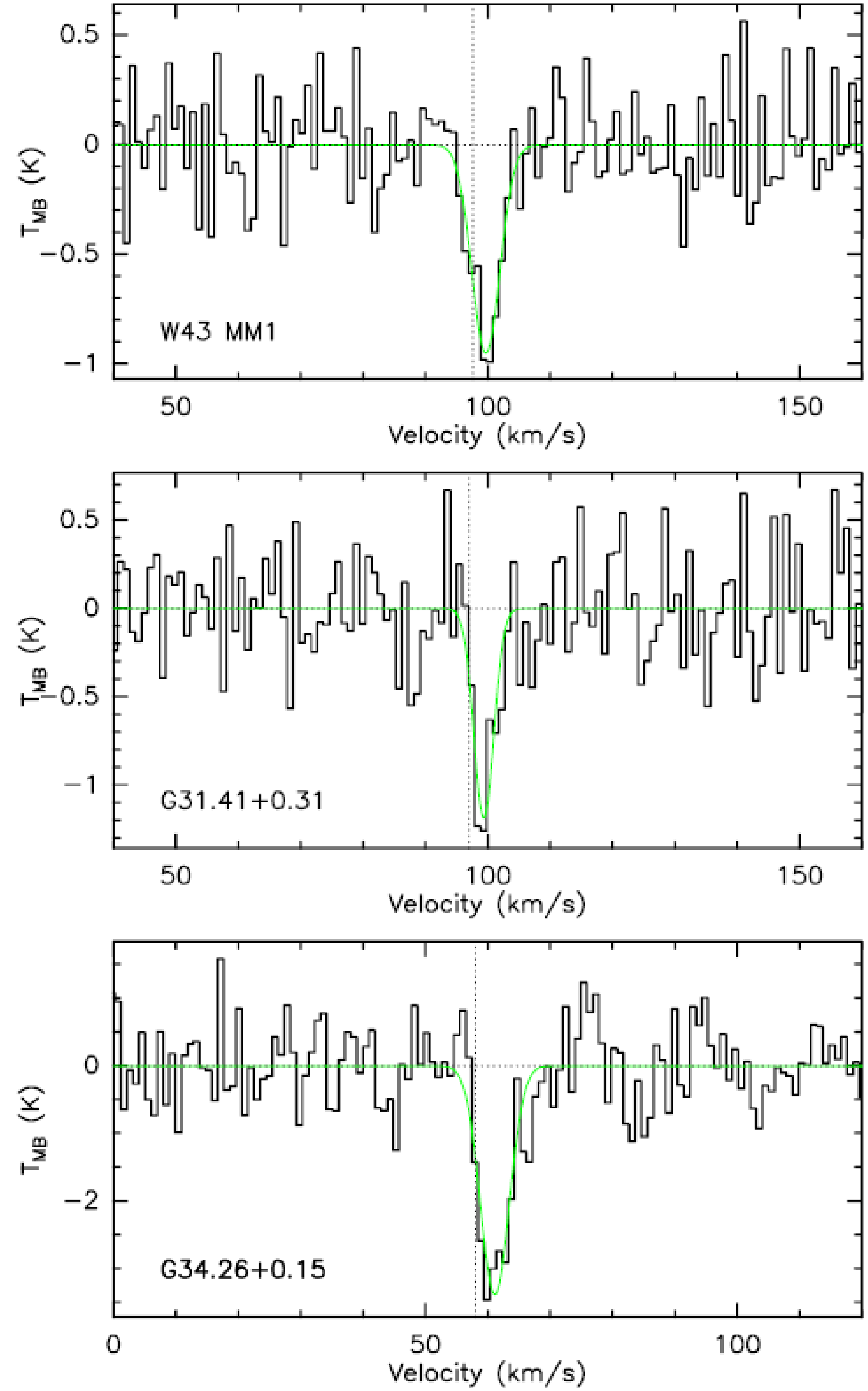


The story so far:
Ammonia@1.8THz
Wyrowski+2012

- 3 absorption line detections in science verification
- All redshifted with respect to v_sys
- **τ** ~ 1

Table 2. Line parameters from Gaussian fits to the NH_3 lines. Nominal fit errors are given in brackets. In addition, the velocity of $C^{17}O$ (3–2) lines observed with the APEX telescope are given.

Source	T_{peak} (K)	Δv (km s^{-1})	$V_{LSR}^{NH_3}$ (km s^{-1})	$V_{LSR}^{C^{17}O}$ (km s^{-1})
W43-MM1	−0.96 (0.22)	5.3 (0.8)	99.7 (0.4)	97.65 (0.06)
G31.41+0.31	−1.18 (0.29)	3.7 (0.8)	99.4 (0.4)	97.02 (0.04)
G34.26+0.15	−3.38 (0.56)	5.5 (0.6)	61.2 (0.3)	58.12 (0.03)



ig. 2. NH_3 spectra of the observed sources. Results of Gaussian fits o the line are overlaid in green. The systemic velocities of the sources, letermined using $C^{17}O$ (3–2) are shown with dotted lines.

G34: comparison to VLA absorption

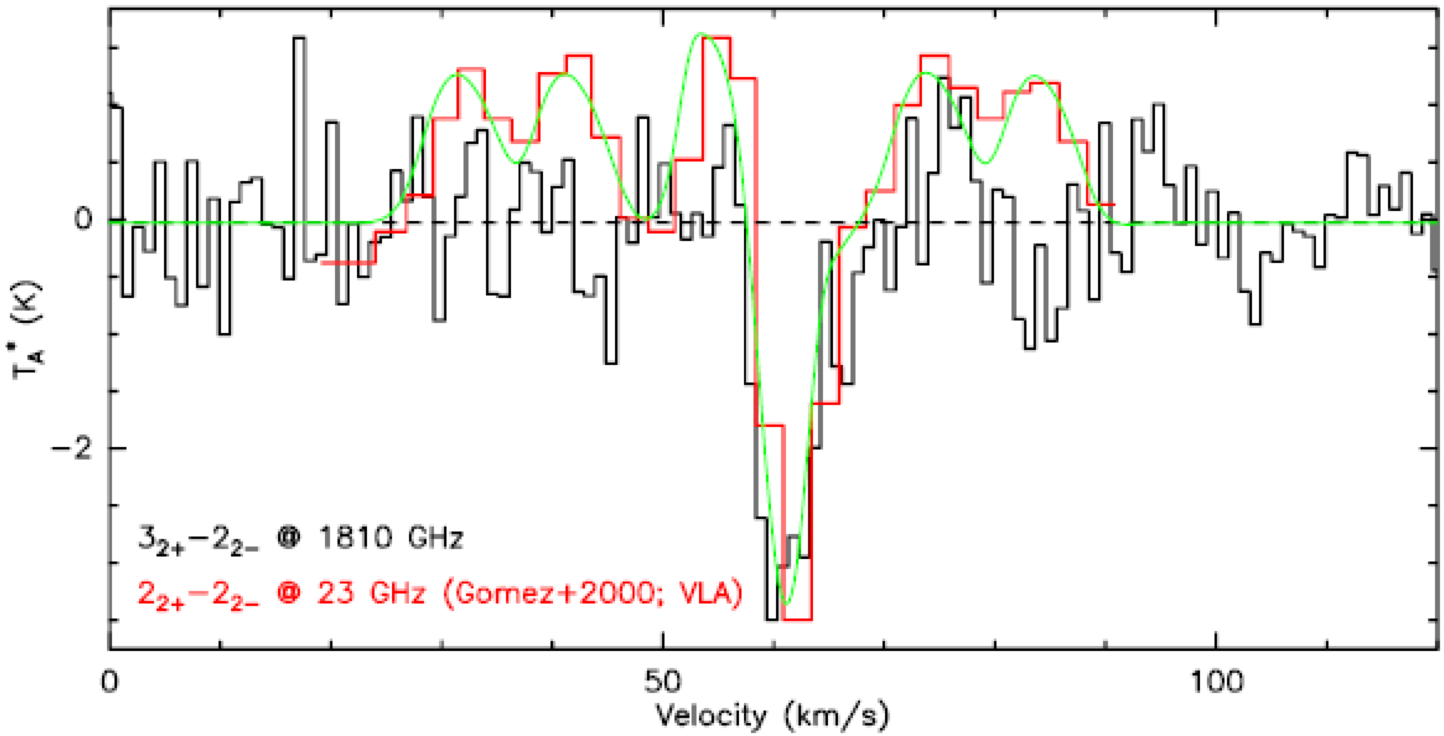


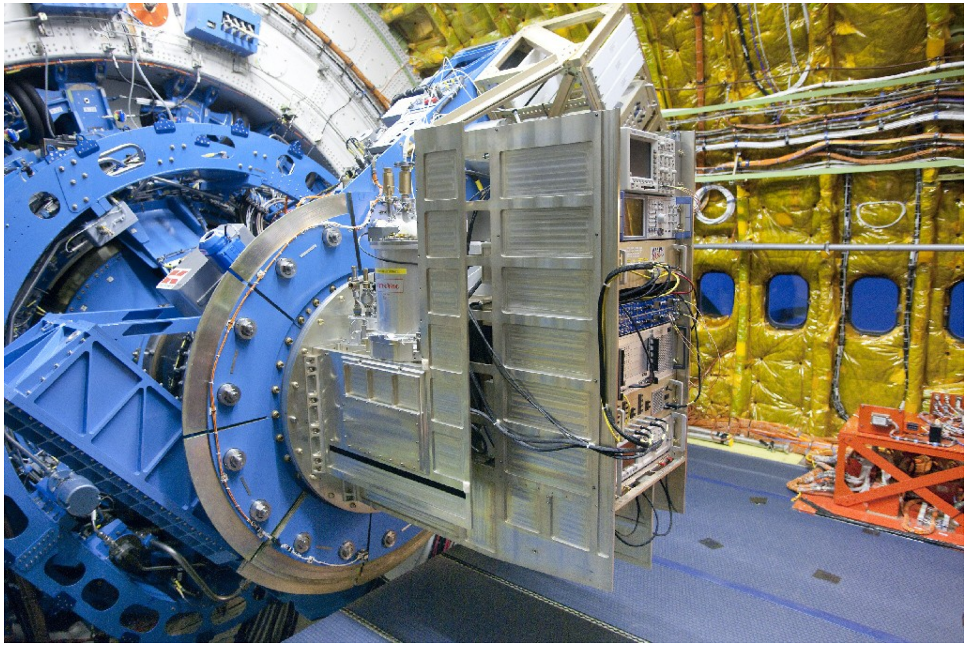
Fig. 3. G34.26+0.15 SOFIA NH_3 spectrum compared with the VLA NH_3 (2,2) spectrum taken from Gómez et al. (2000) which was integrated over the region which shows absorption. A two-component hyperfine fit to the (2,2) spectrum is shown in green.

Infall Results

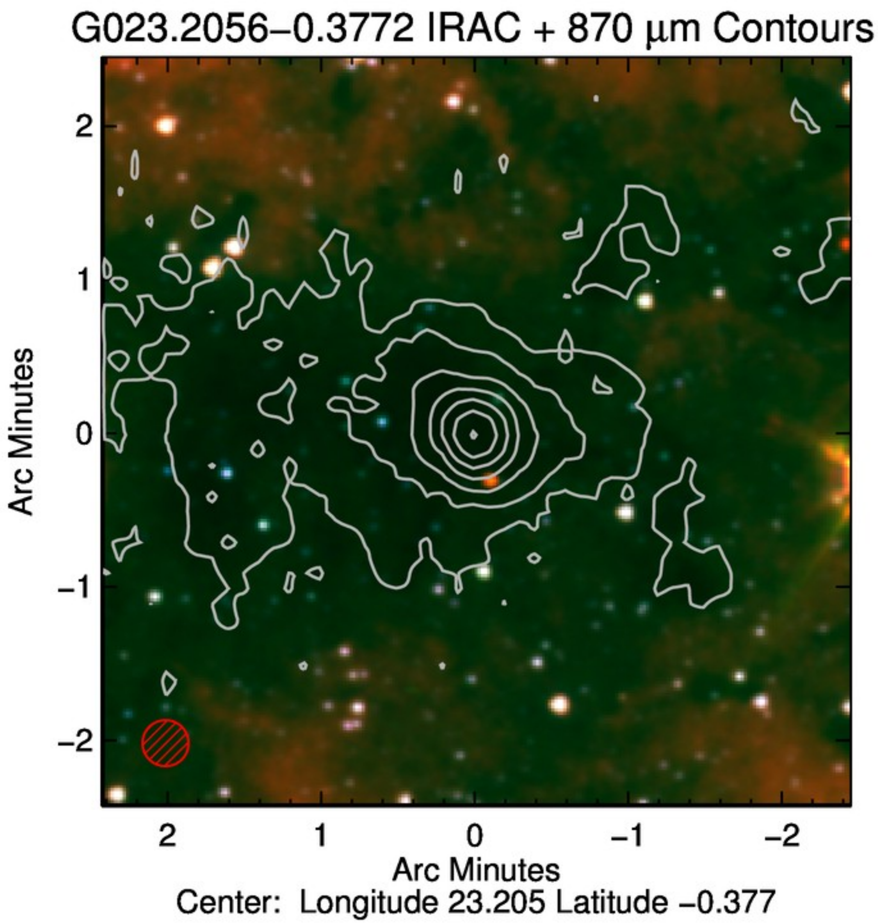
- 3 clear detections of Ammonia line-of-sight infall consistent with results from cm-absorption and/or blue-skewed emission profiles
- More direct probe of infall that can be extended to earlier stages of SF without cm background continuum and cases where other species are depleted
- Infall rates of 3-10 x 10^{-3} $M_{\odot}$/yr (if spherical)
- Next step: extend to more sources and stages, in particular earlier ones

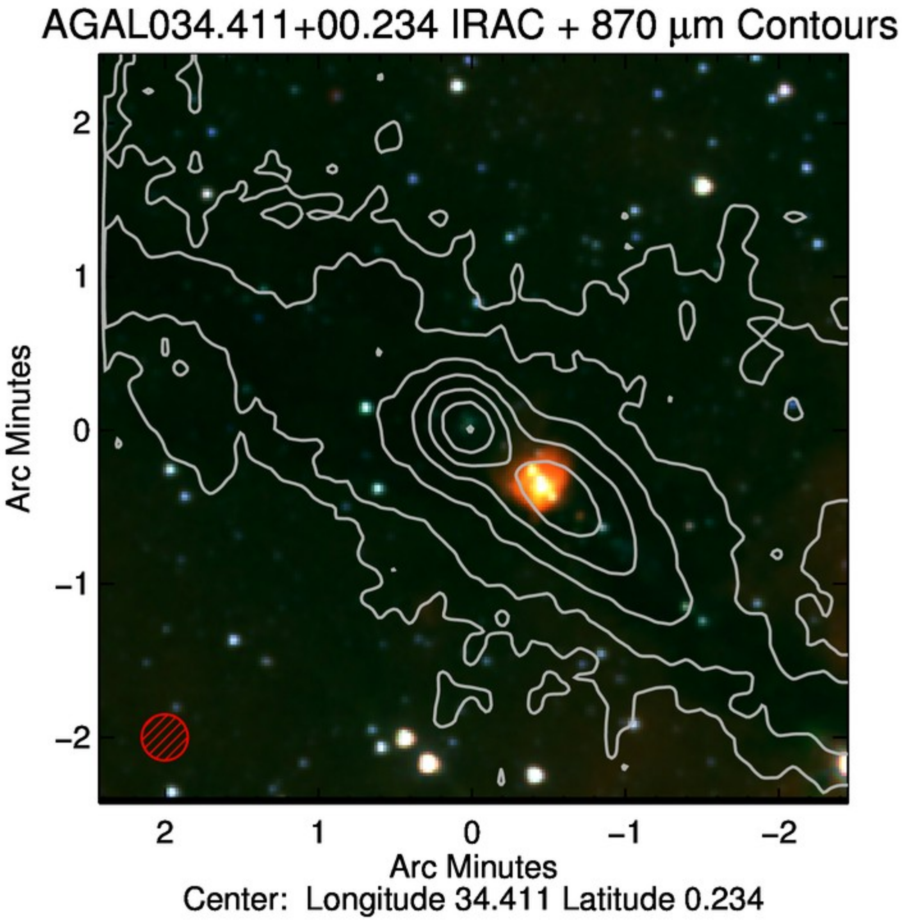
SOFIA Observations

- GT and cycle 1 science flights
- GREAT:
  - L1, various lines
  - NH_3 3_{2+}-2_{2-} 1810.379 GHz LSB
  - AFFTS/XFFTS:1.5/2.5 GHz
  - Chopped observations of 9 sources
  - 16” beam size



Cycle I: a) continuation to Infrared dark clouds

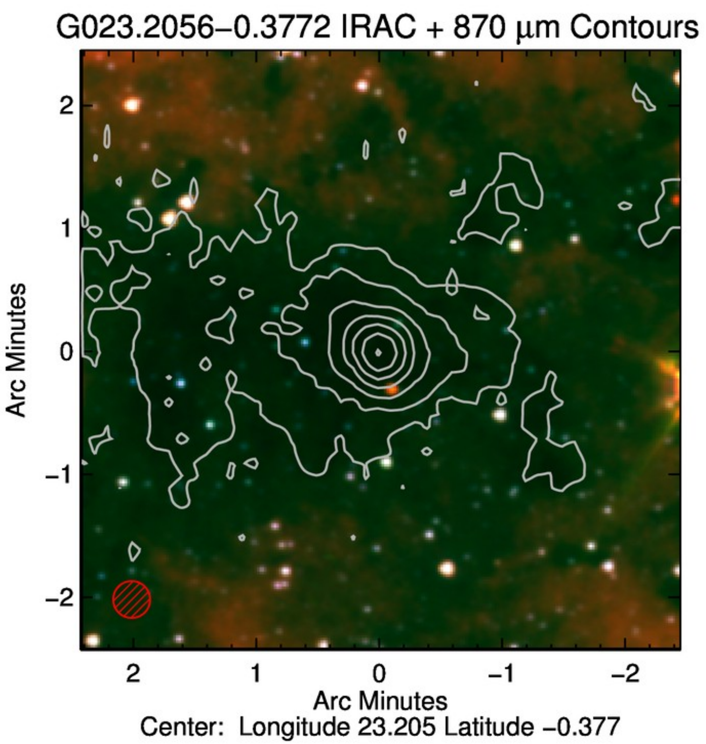


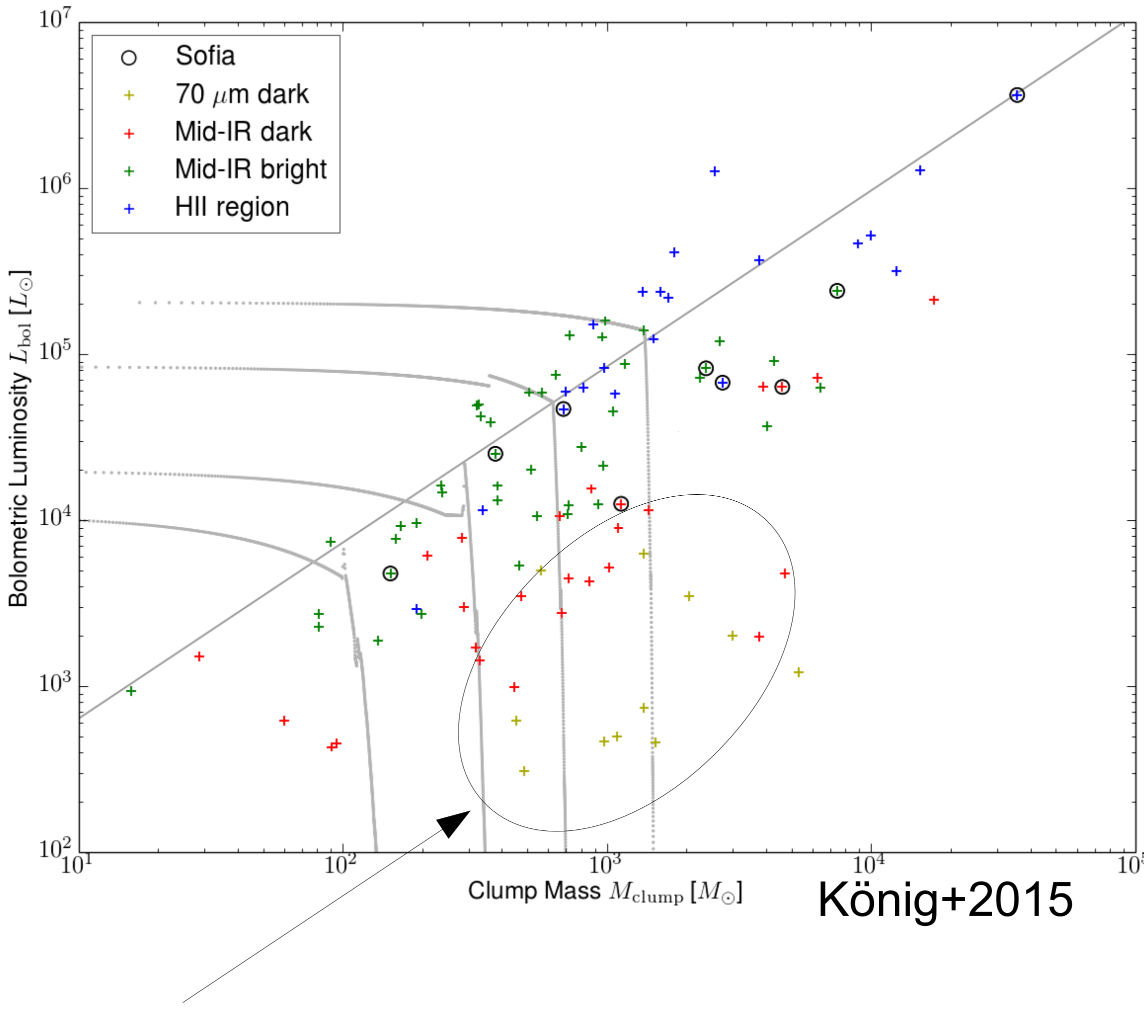


Cycle I: b) filling in further stages:

- G35.20-0.74: submm brightest, northern massive young stellar object, fulfilling Lumsden+ MSX color criteria
- G327.3/G351.58: hot cores/ultracompact HII regions with high luminosity (up to $2 \times 10^5 L_\odot$)
- PRISMAS sources, hence bright in cm & submm: G5.89/W33A/W49

New SOFIA results: sample



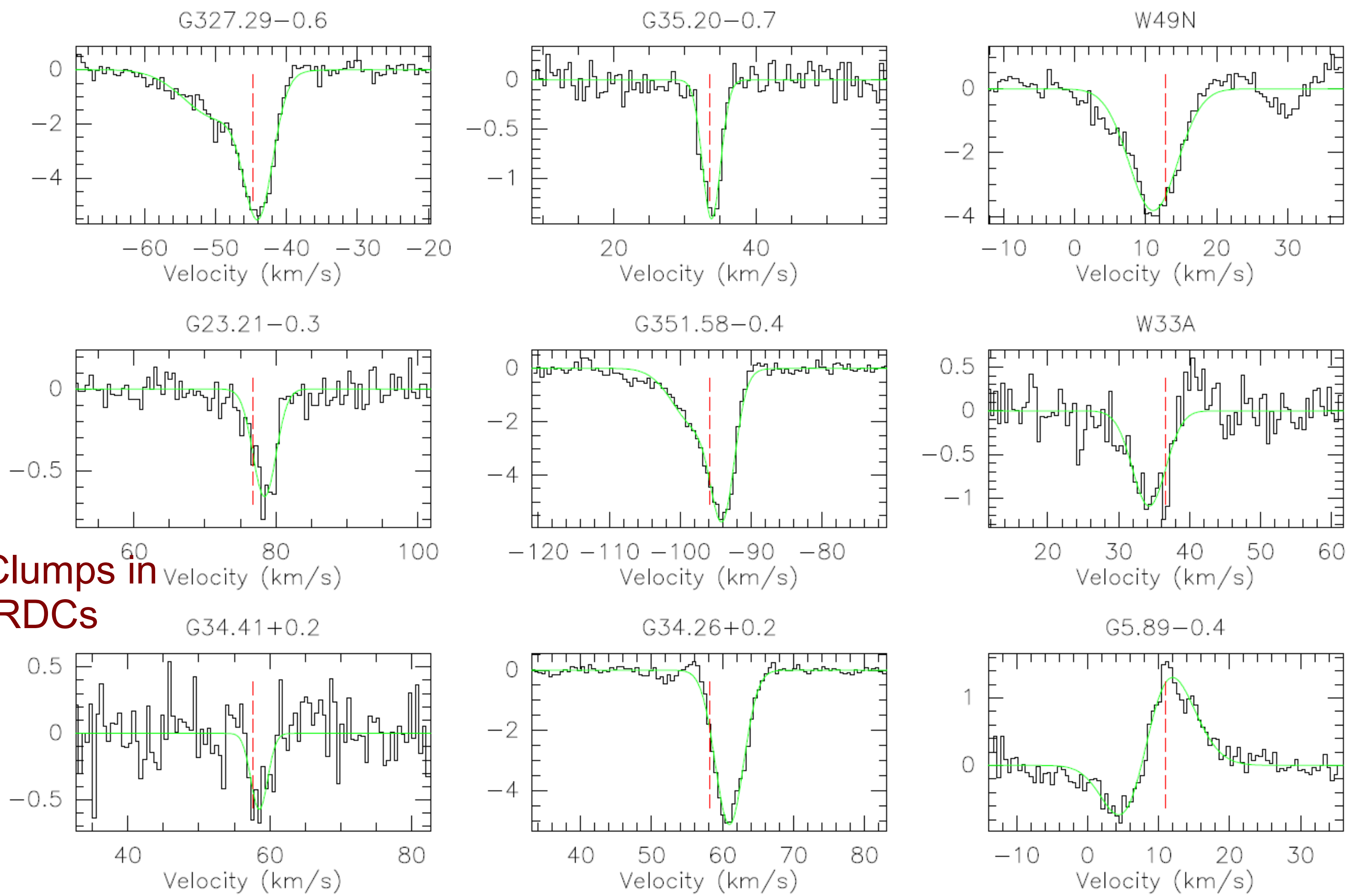


König+2015

No/too weak SOFIA 1.8THz continuum ! → 572 GHz

New SOFIA results: Wyrowski+2016

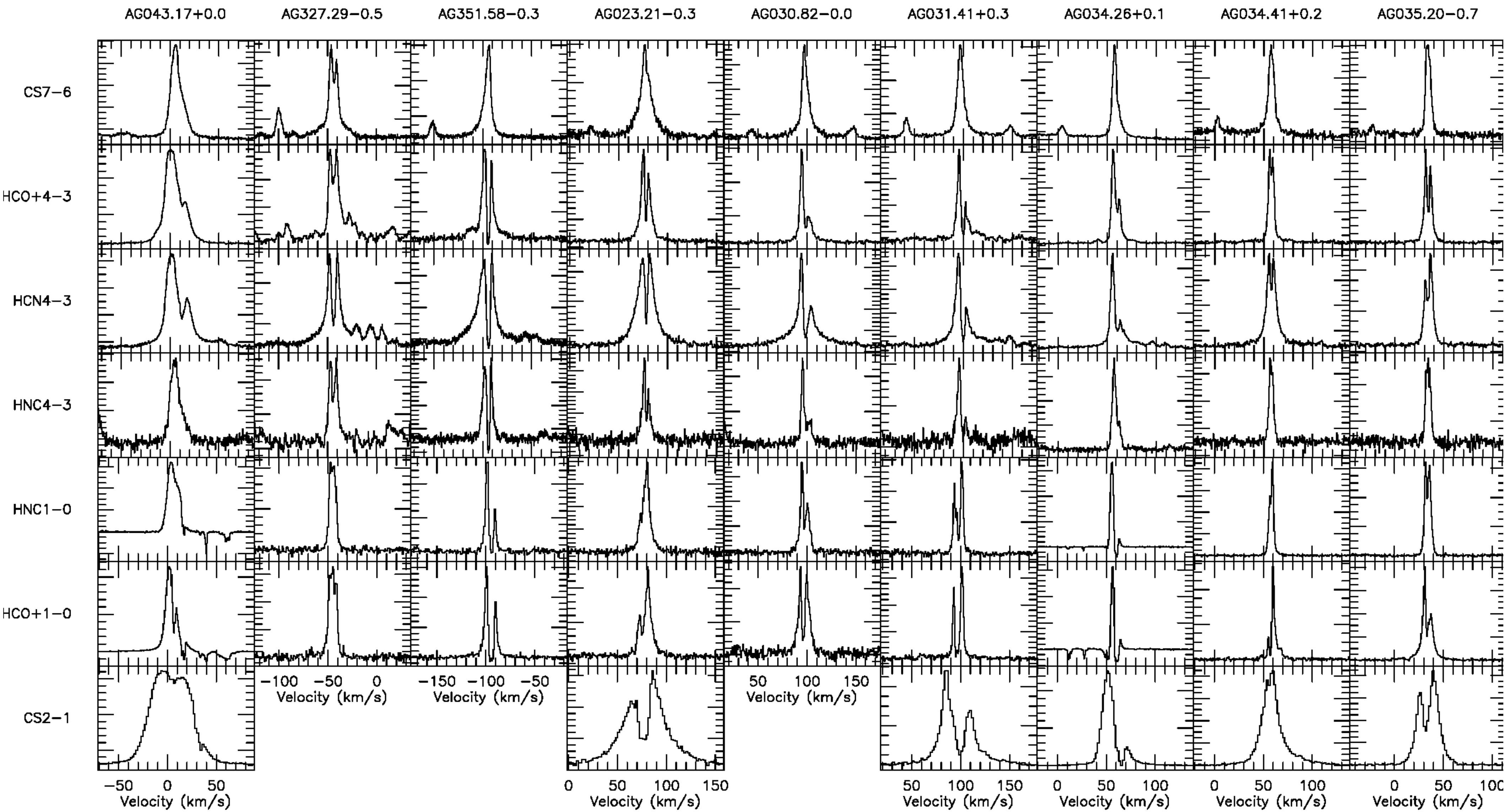
- 5 new redshifted absorption with shifts of 0.2 – 1.6 km/s with respect to $C^{17}O$
- 1 source dominated by outflow (G5.89), several blue wings
- 2 sources with blue shifted absorption



Clumps in IRDCs

Fig. 2. NH_3 $3_{2+} - 2_{2-}$ spectra of the observed sources. Results of Gaussian fits to the line profiles are overlaid in green. The systemic velocities of the sources, determined using $C^{17}O$ (3–2), are shown with dotted lines. W49N shows in addition at 30 km/s the NH_3 $3_{1+} - 2_{1-}$ from the other sideband.

Complementary ground based data

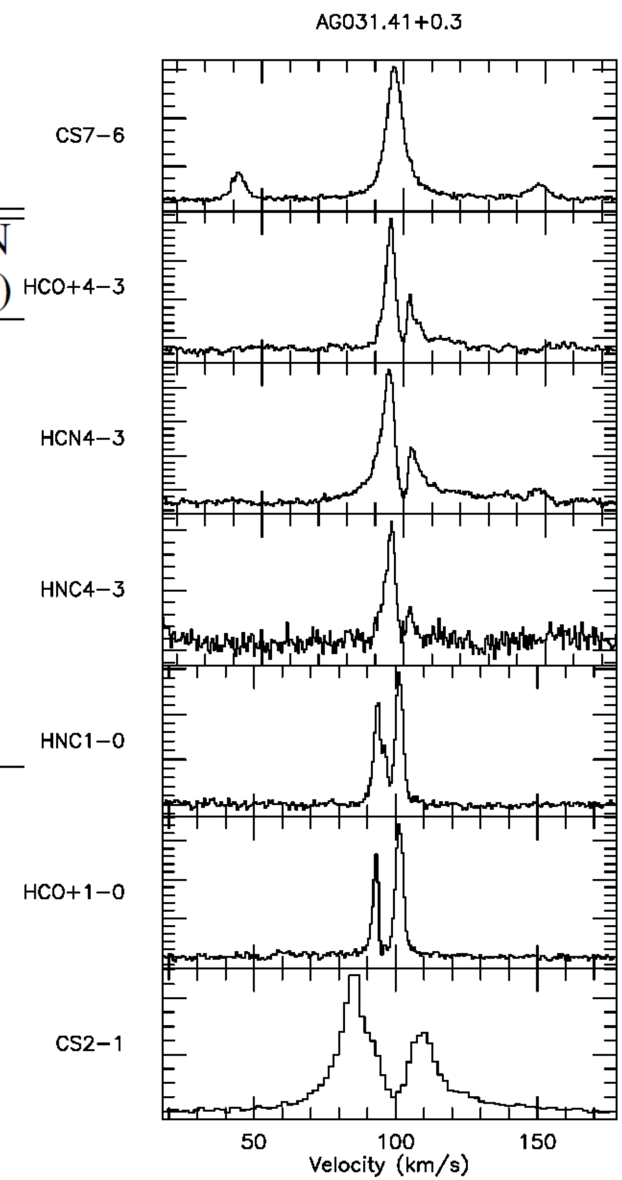


How consistent are different probes ?

Source	NH_3	HCO^+ (1–0)	HCO^+ (4–3)	HNC (1–0)	HNC (4–3)	CS (2–1)	CS (7–6)	HCN (4–3)
G327.29-0.6	+	0	0	0	0		+	0
G351.58-0.4	++	++	+	++	-		-	0
G23.21-0.3	++	- -	++	-	++	- -	0	0
G34.41+0.2	+	- -	+	- -	0	0	0	+
G35.20-0.7	+	++	+	0	0	- -	0	- -
G31.41+0.3	++	- -	++	- -	++	++	0	++
G34.26+0.2	++	++	++	++	++	++	+	++
G30.82-0.0	++	+	++	++	++		0	++
W49N	-	++	+	+	+	0	+	++

→ Ammonia and HCO^+ (4-3) show best correspondence

- HCO^+ enhanced in outflows but probable less than CS/HCN
- HNC, tau too small?

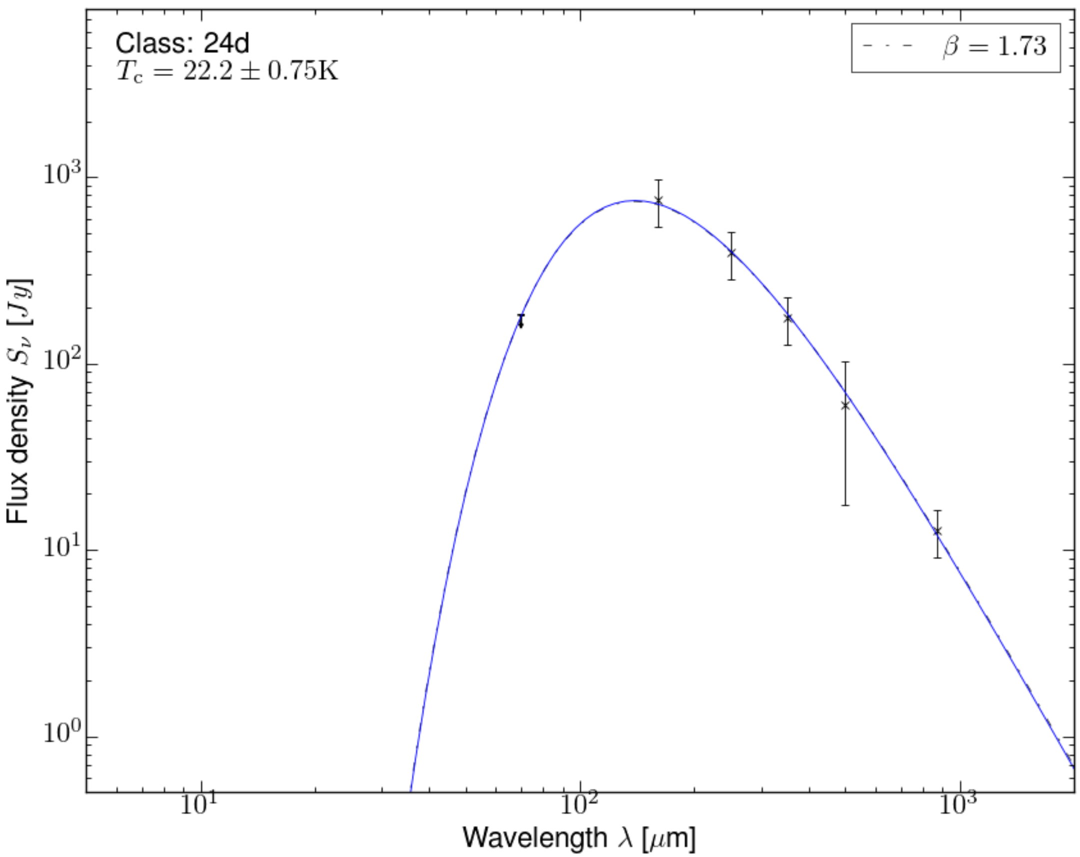


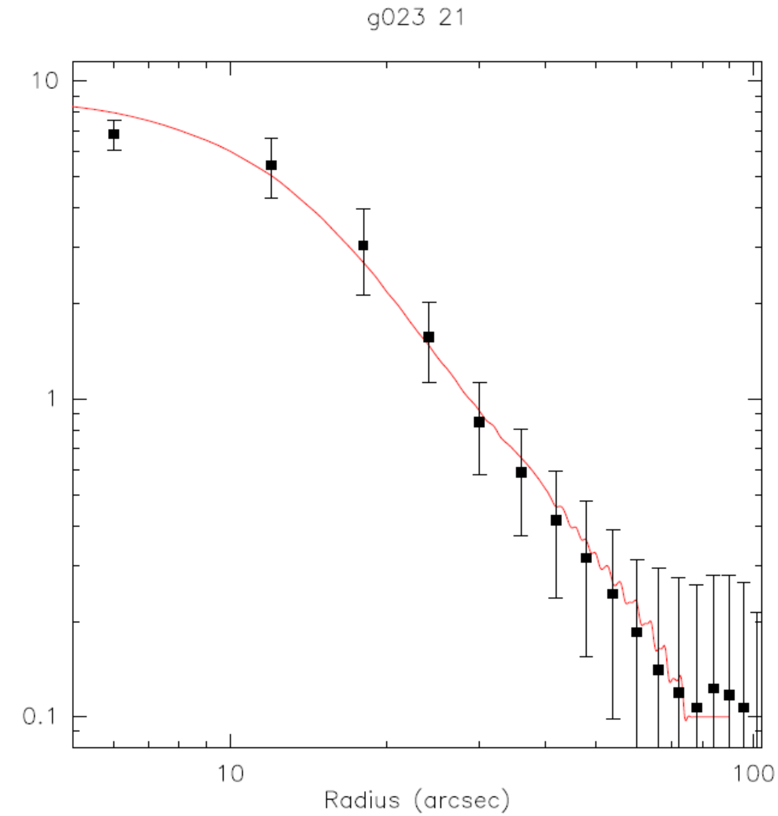
Reversal of infall?

Modeling I

Radial structure and SEDs

König+2016, subm.





Example of constraining the radial physical structure with the f the ATLASGAL submm dust continuum radial profiles.

→ Luminosity → temperature structure

→ density structure

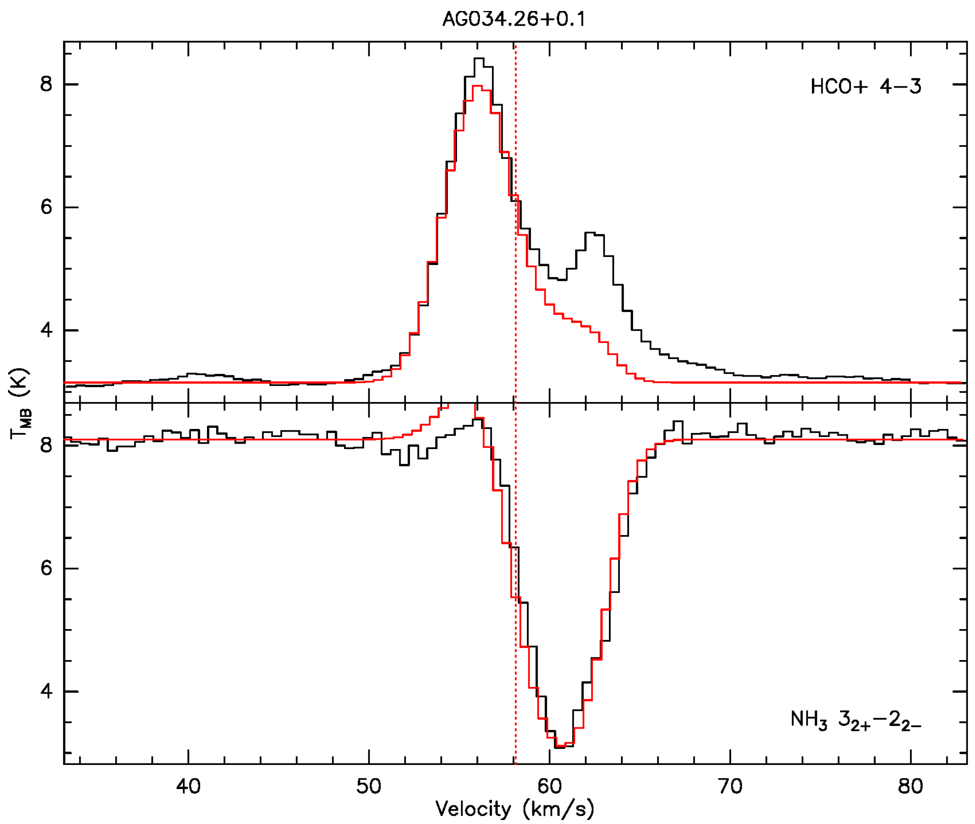
Modeling II

- Fit dust continuum (ATLASGAL) with density power law ($n \sim r^{-\alpha}$, α=1.5 – 2.2)
- Temperature structure dictated by inner heating source (luminosities known from SED fits, König+2016)
- → Adjust ammonia abundance and velocity structure in spherical RATRAN models
- Velocity structure: as fraction of free-fall

- Modeling of NH_3 and HCO^+ simultaneously as consistency check

New modeling

After adjusting HCO^+ abundance, wing missing, no redshifted peak

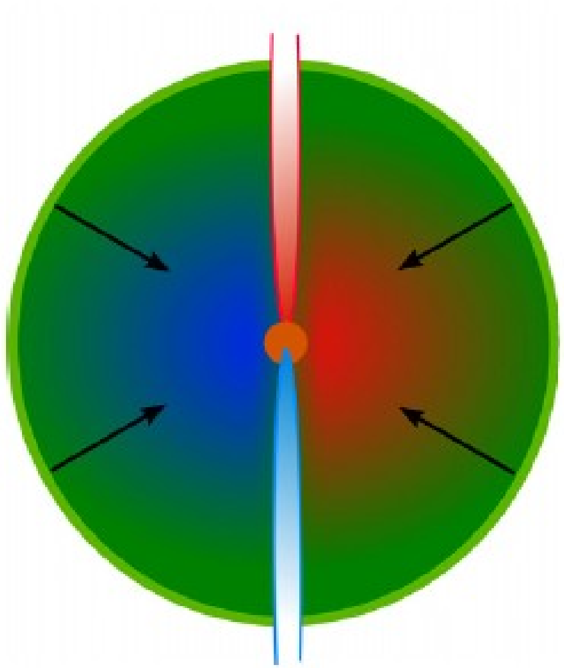


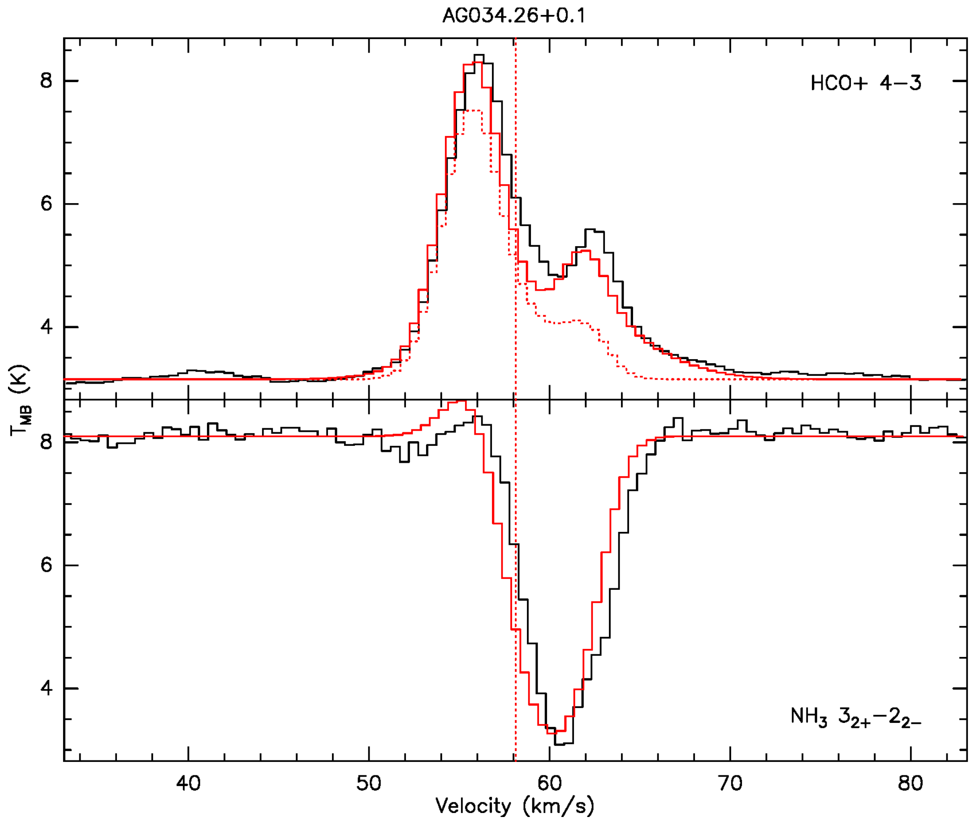
Additional parameter:

- HCO^+ abundance

New modeling
Outflow component

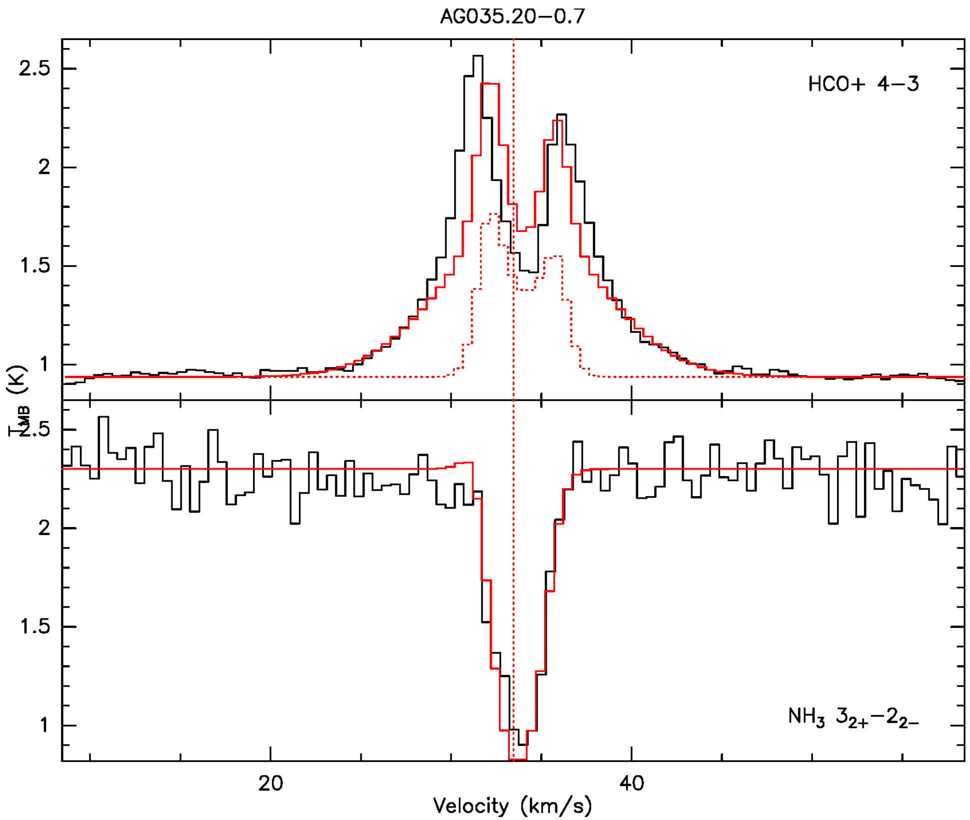
HCO$^+$ usually probing additional outflow component
→ RATRAN modification of Mottram+2013



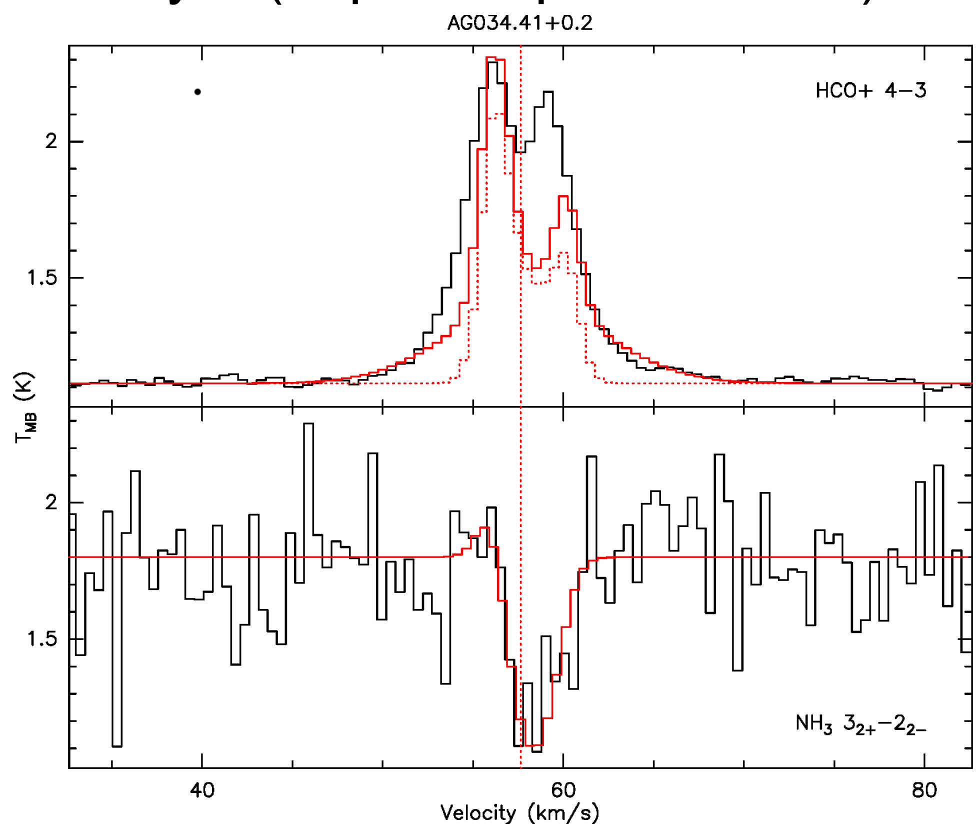


Additional parameter:
- outflow widths/strength
- HCO$^+$ abundance

New modeling: Outflow component



But many cases do not work with this simple geometry. Complicated outflows? Additional low density outer layer (Lopez-Sepulcre+2010)?



Also this clump shows consistent results!

→ Disentangling outflow/inflow difficult in emission case. For absorption, affects only blue part.

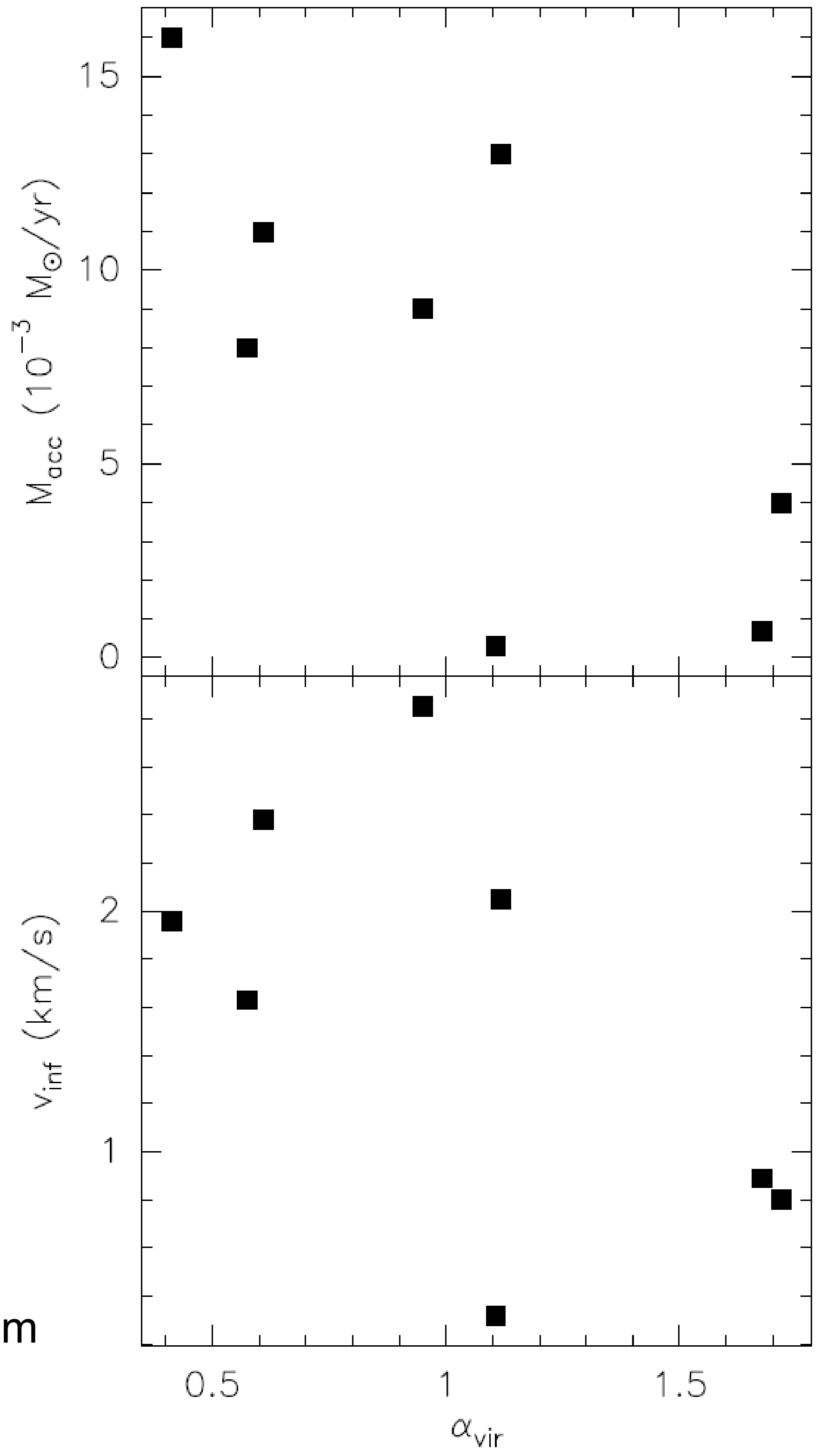
Modeling results

Source	R_{out} (pc)	α_n	n_{1pc} ($10^3 cm^{-3}$)	δv_t (km/s)	f_{ff}	$X(NH_3)$ 10^{-8}	$X(HCO^+)$ 10^{-10}	$\dot{M}$ (10^{-3} $M_\odot$/yr)
G34.26+0.2	0.8	-1.7	10	2.4	0.3	0.19	0.25	9
G327.29-0.6	2.	-1.9	10	2.3	0.05	0.5	0.2	4
G351.58-0.4	1.8	-1.9	15	1.5	0.1	1.5	0.2	16
G23.21-0.3	1.8	-2.0	4.5	1.0	0.2	1.5	0.5	8
G35.20-0.7	1.5	-1.6	5.5	1.5	0.03	0.35	0.3	0.3
G34.41+0.2	1.0	-1.6	5	1.5	0.1	0.15	0.4	0.7

- Modeling of sources results in infall with fractions of free-fall of 3 – 30 %. The ammonia abundances are in the range of 0.15 – 1.5 x 10^{-8}.

Any dependences on the virial parameter or evolution?

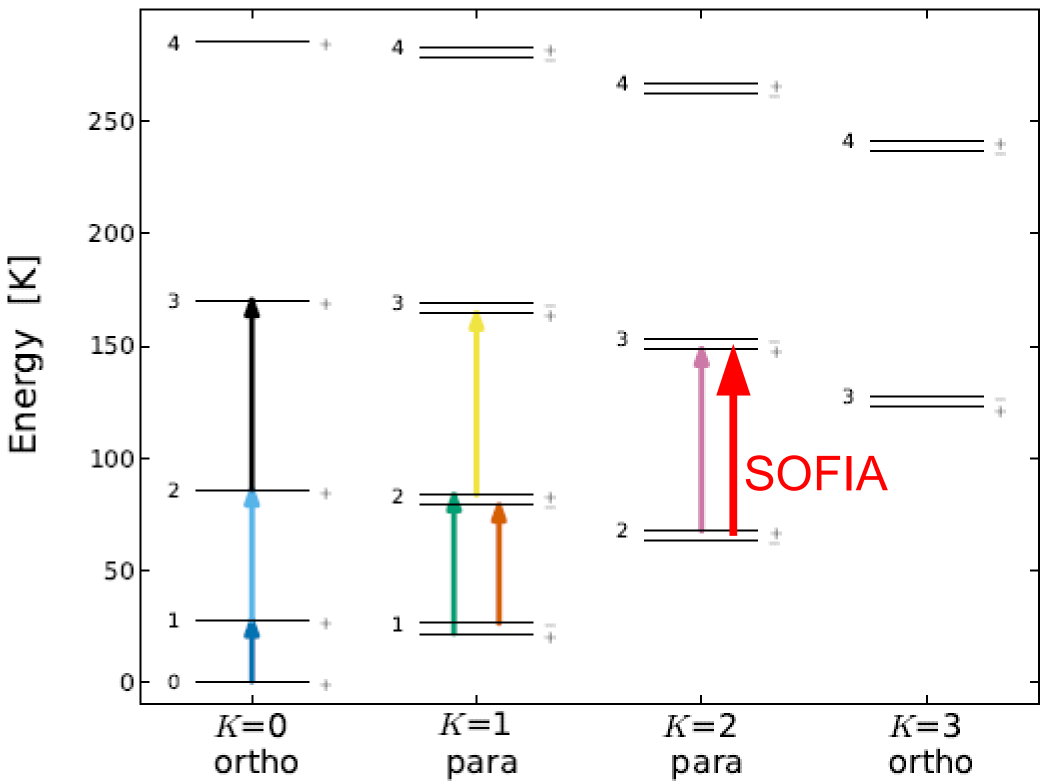
- alpha_vir<1 should indicate unstable clump
- → slight trend
- No L/M trend (so far) but high L/M sources, either infall stopped or undetectable
- → extend L/M range and statistics

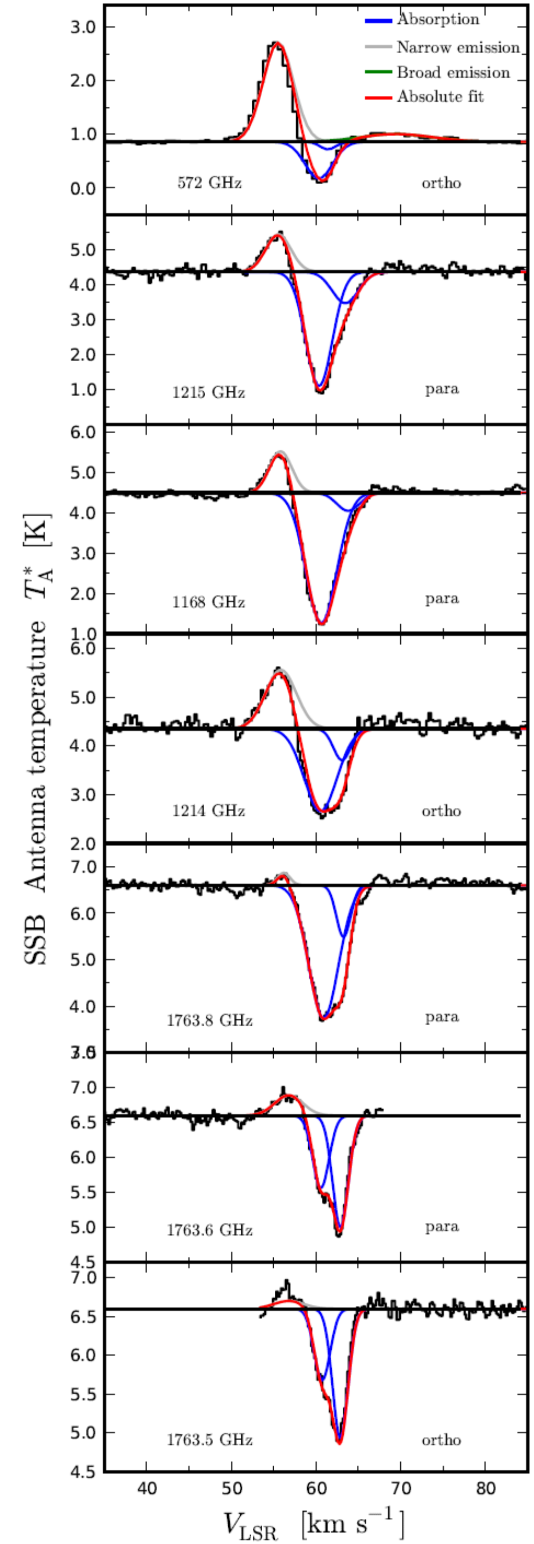


Virial parameters from Giannetti+2014

Herschel G34.26 results

Hajigholi+2015

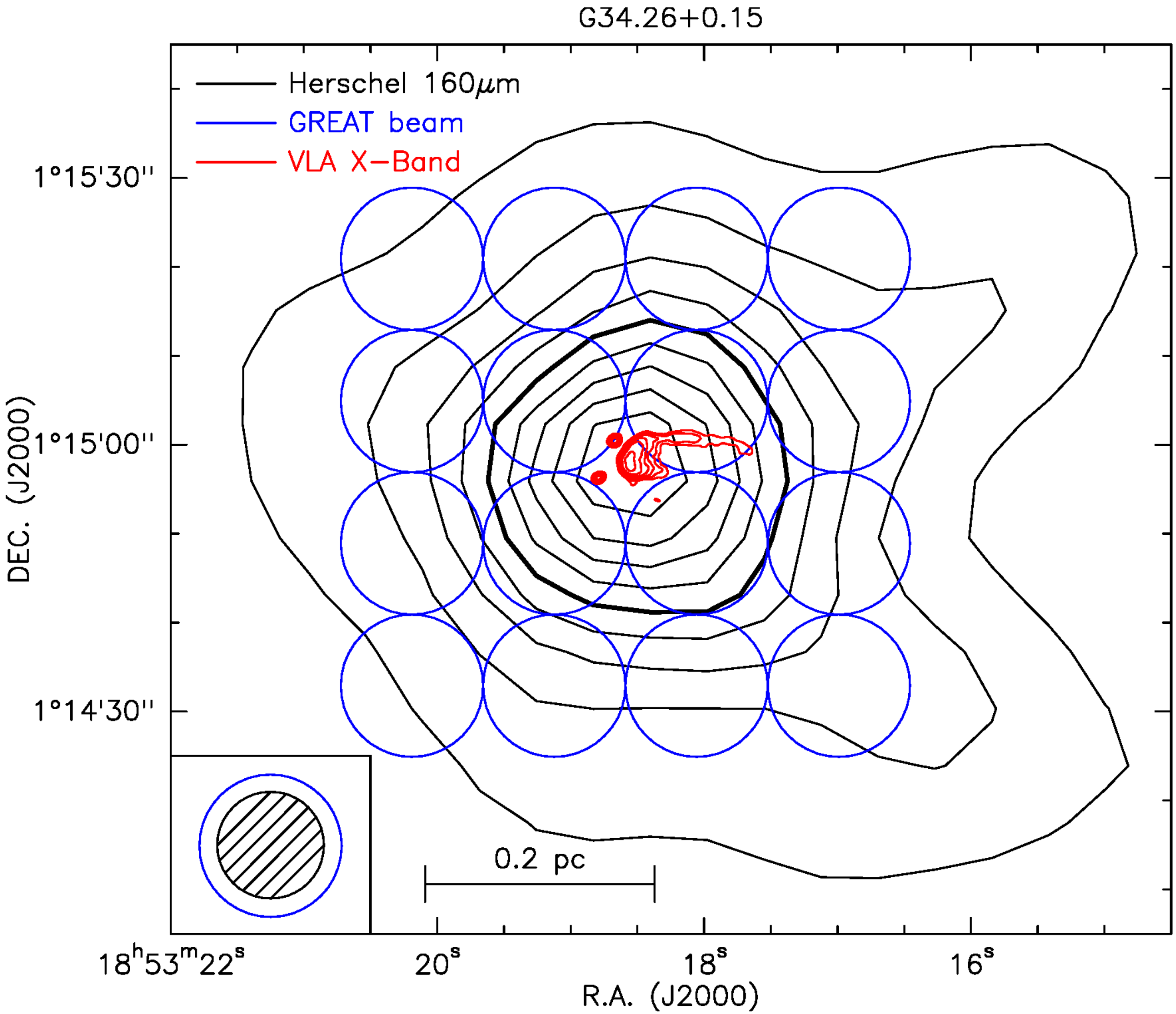




- Different excitation traces different v
- SOFIA opportunities:
  - GS 572 GHz @ 90% transmission
  - 1214 GHz (201-100, 211-110) @ 65%
  - 2355 GHz (4-3 lines) @ 63%

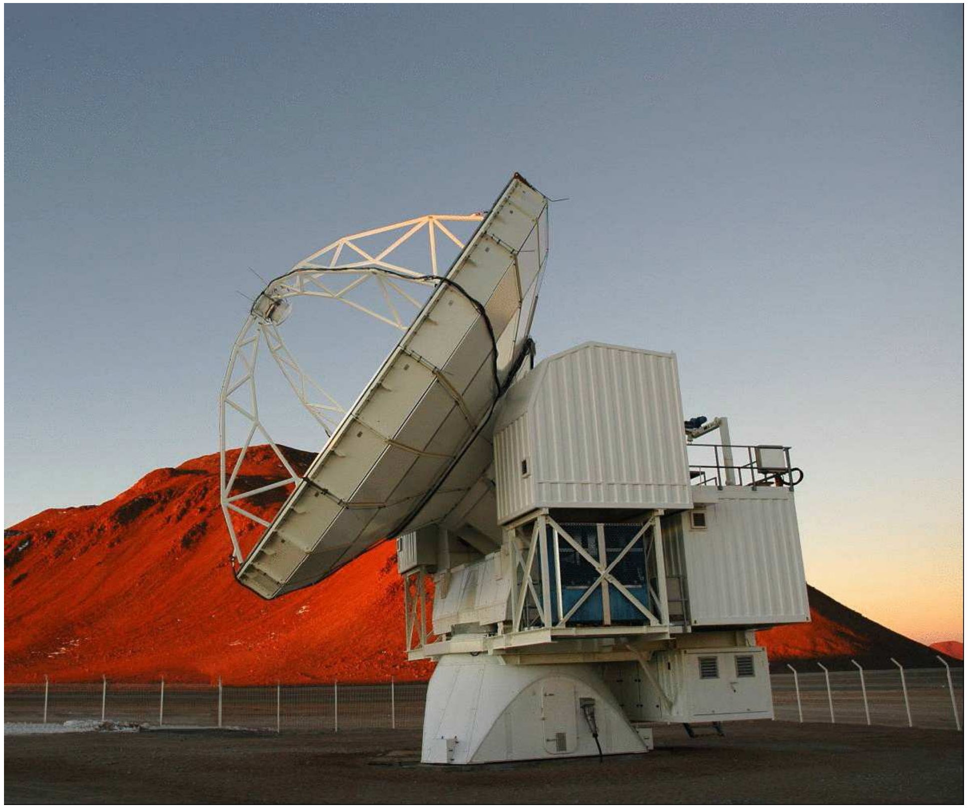
Probing large scale infall

- Extended dust continuum, ~0.5pc
- Infall localized or global ?
- Infer 3D velocity pattern.
- Search for velocity gradients, rotation?



APEX-SOFIA synergies

- Mid vs. High J CO
- Blue-skewed self-absorbed high density probes vs. red-shifted absorption studies
- CO/CI cooling vs. CII/OI
- Complex molecules vs. hydrides
- Similar beamsizes in APEX submm windows and with SOFIA THz RX
- Imaging: CHAMP+/LASMA vs. upGREAT



Summary & Outlook

- Infall on clump scales ubiquitous through wide range of evolutionary stages
- Ammonia and HCO^+ (4-3) show best correspondence but HCO^+ stronger affected by outflows
- Continue filling in stages (populating the M-L diagram), improve statistics
- Study infall across clumps (continuum extended)
- Add additional lines to cover larger excitation range (new single pixel RXs)

Ringberg Workshop on Spectroscopy with the Stratospheric Observatory For Infrared Astronomy (SOFIA)

15-18 March 2015 *Schloss Ringberg*

Next Workshop March 5-8, 2017 !

Potential future SOFIA ammonia lines:

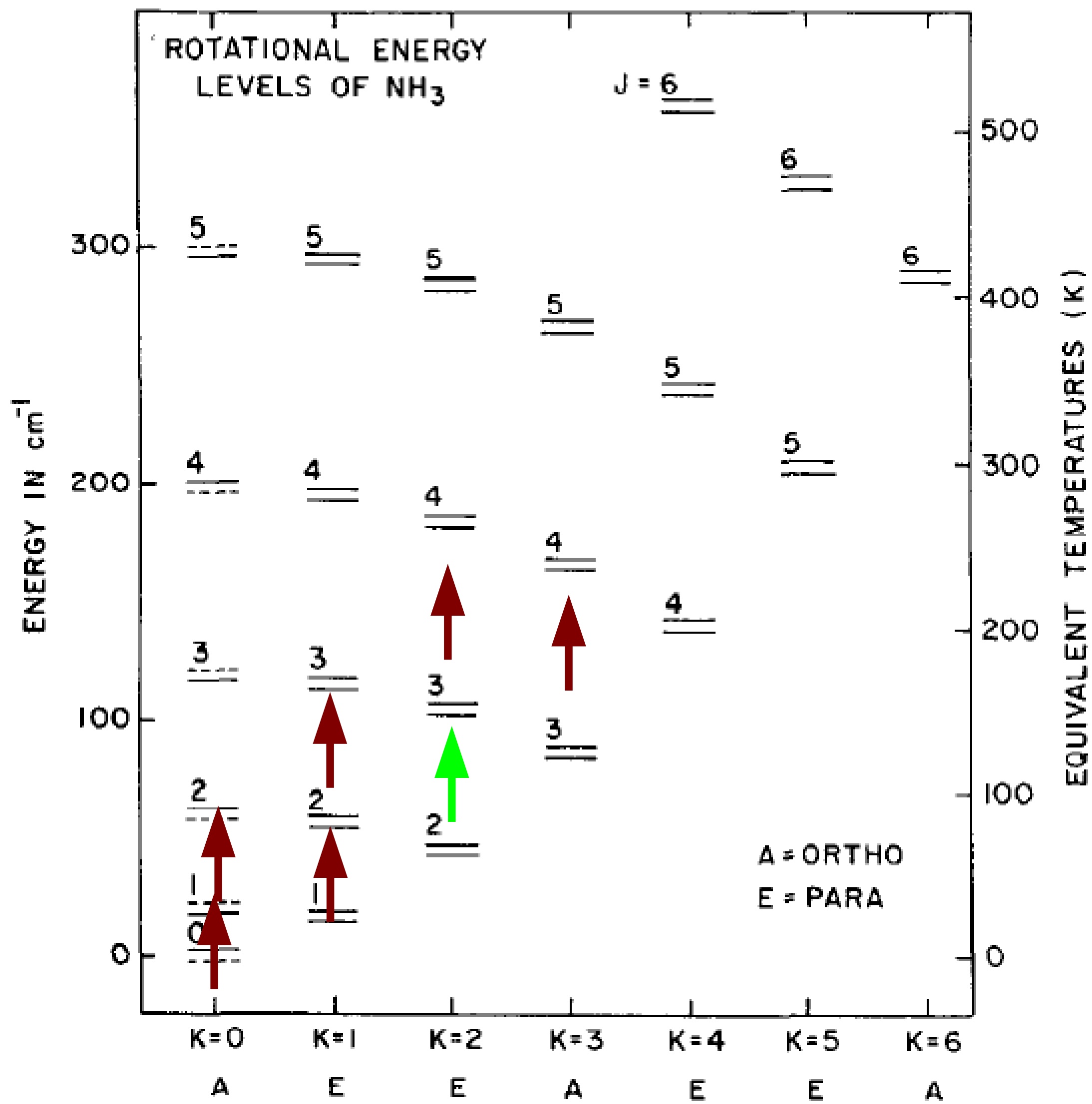


Figure 1 Energy level diagram of rotation-inversion states. *J* is the total angular-momentum quantum number, and *K* is the projected angular momentum along the molecular axis.

+ new Effelsberg K-Band RX !