Massive star formation science opportunities with SOFIA

Friedrich Wyrowski, MPIfR Bonn

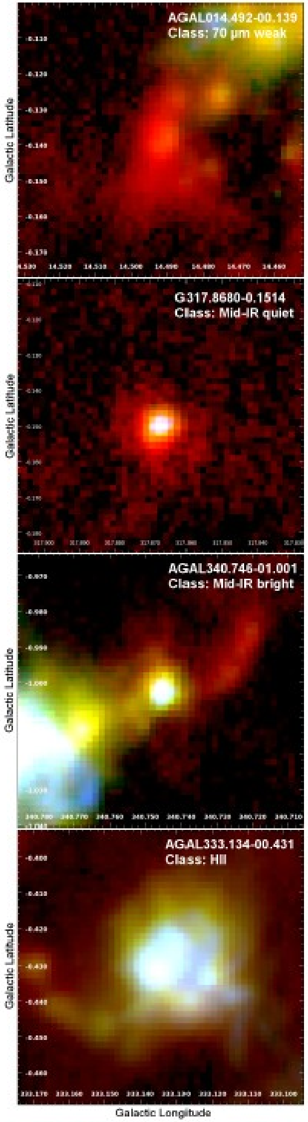
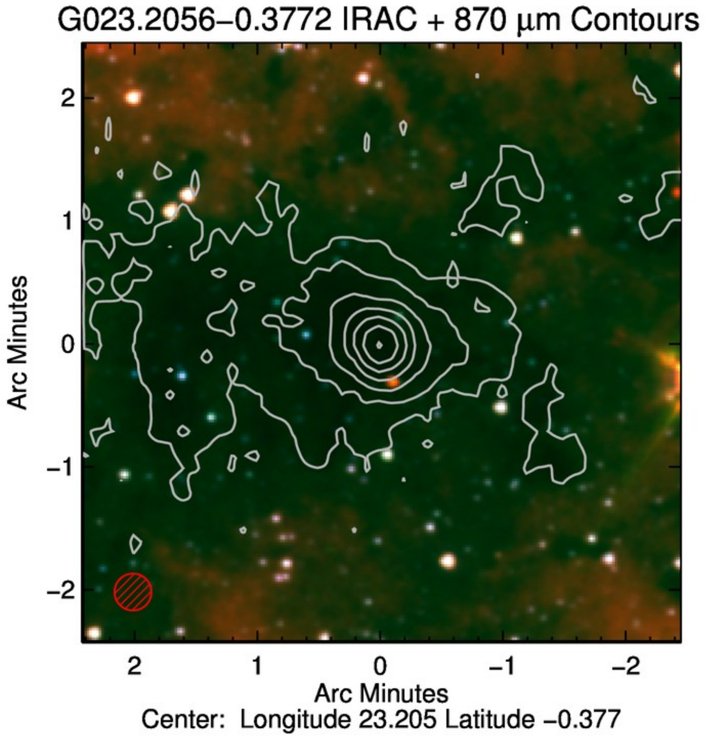


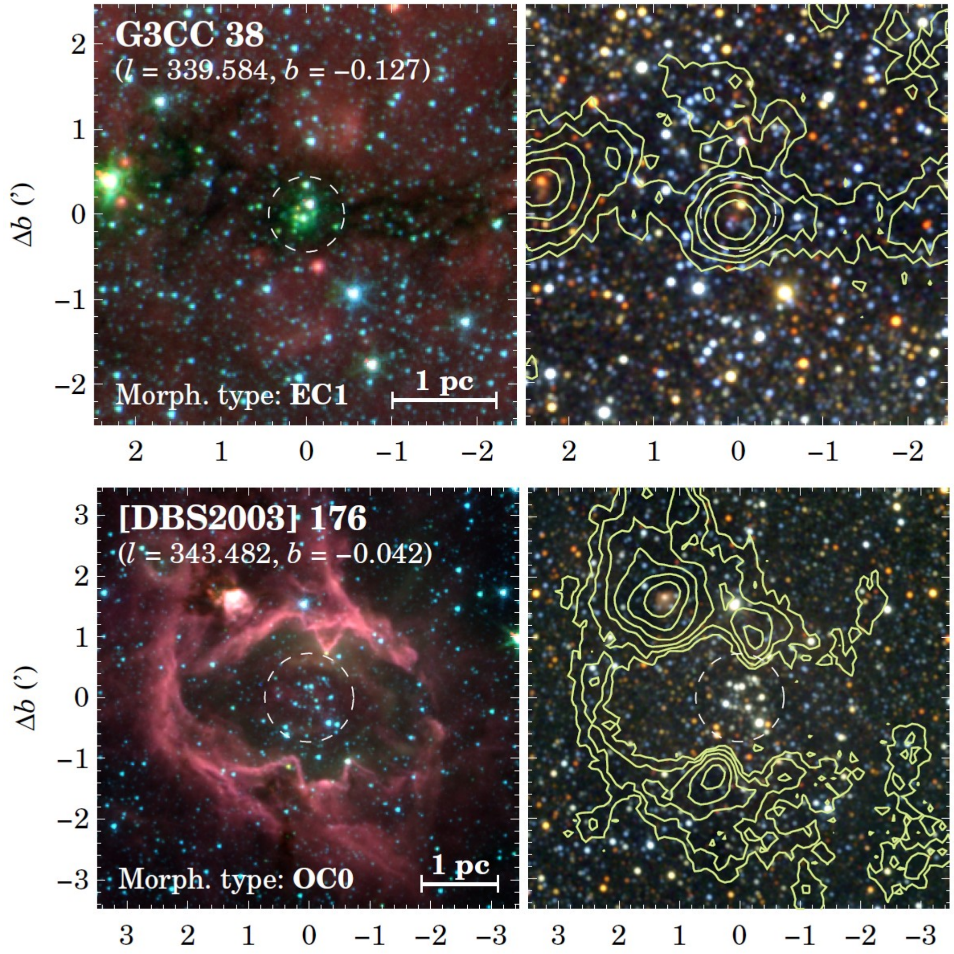
Fig. 2. Three color images of sample sources for each class sorted from youngest (top) to most evolved (bottom). Size: 5'×5'; red: ATLASGAL 870 μm; green: PACS 160 μm; blue: PACS 70 μm.

(High-mass) clump evolution



https://atlasgal.mpifr-bonn.mpg.de

?



Morales+2013

Key MSF questions

Recent reviews: Motte+2018, Rosen+2020

- Fragmentation and mass assembly
- Accretion/Outflows/Jets
- Dynamics of inflow/infall
- Clump cooling
- Timescales
- Feedback processes
- Role of magnetic fields

Current concepts, e.g.

- Turbulent core model (McKee &Tan 2003), monolithic collapse
- Competitive accretion (Bonnell+1998)
- Global hierarchical collapse (Vazquez-Semadeni+2019)

→ Different kinematical signatures

Key MSF questions

- Fragmentation and mass assembly → ALMA/NOEMA
- Accretion/Outflows/Jets → Fischer talk: time variability / SOMA
- Dynamics of inflow/infall
- Clump cooling
- timescales
- Feedback processes → Pabst talk, FEEDBACK
- Role of magnetic fields → Stephens talk, pilot legacy programs

FIR: Roadmap

W3 IRS5

Karska+2013

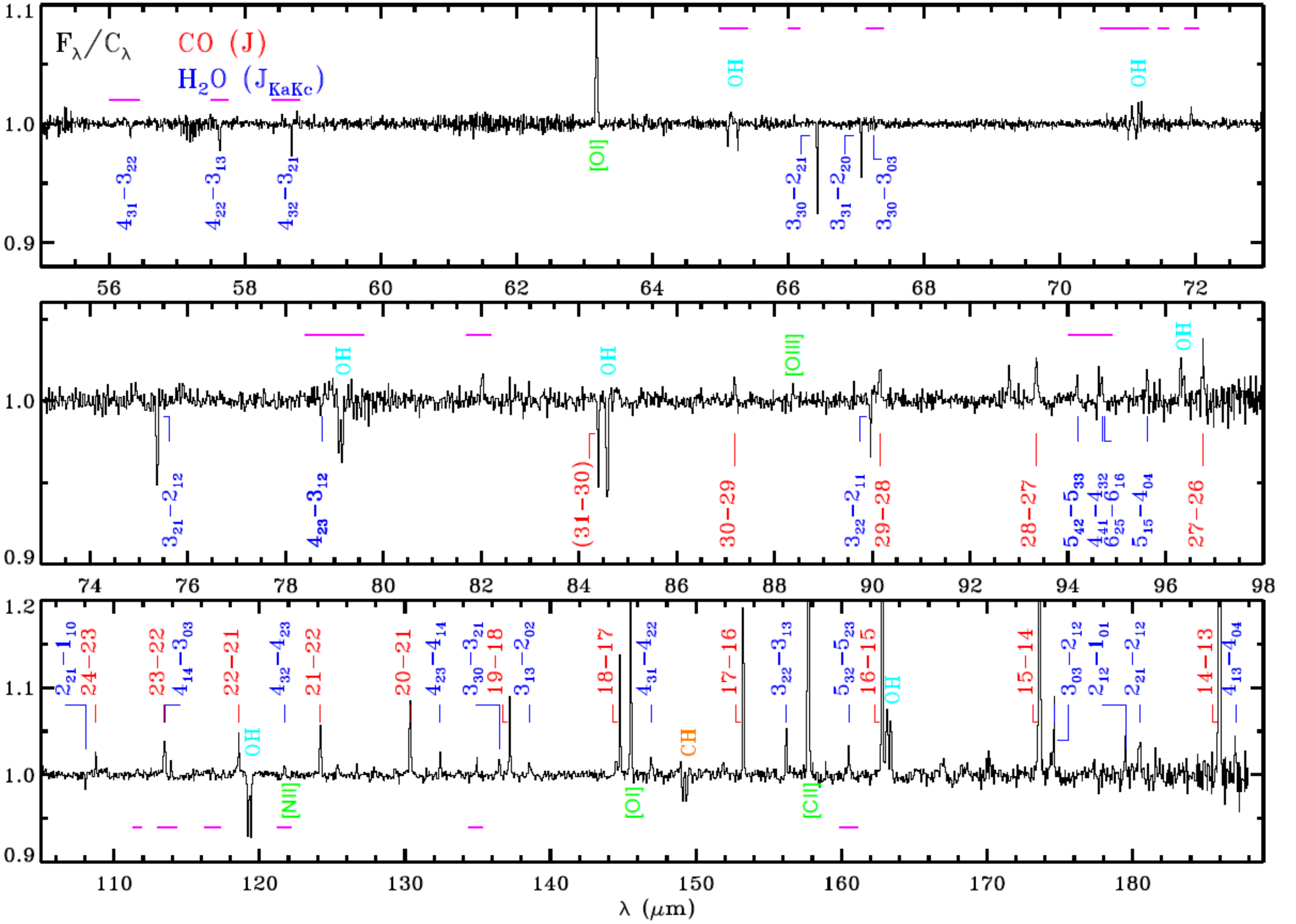


Fig. 1. Herschel-PACS continuum-normalized spectrum of W3 IRS5 at the central position. Lines of CO are shown in red, H_2O in blue, OH in light blue, CH in orange, and atoms and ions in green. Horizontal magenta lines show spectral regions zoomed in Figure C.1.

Unique spectroscopy in the FIR

- Only the FIR offers:
  - Dense cloud cooling: Access to major fine-structure cooling lines
  - Dense cloud kinematics: Access to absorption lines in front of dust
  - Dense cloud excitation: Access to high excitation of abundant and chemically (relatively) stable CO
  - Dense clouds chemistry: Access to hydrides as initial products of ISM chemistry → Neufeld Talk, HyGAL

Velocity resolved spectra crucial for dynamics, kinematics, excitation (optical depth effects)

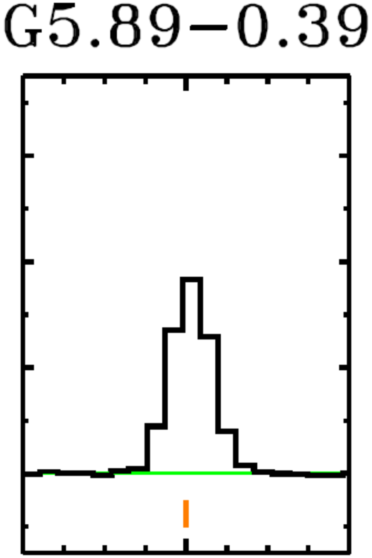
Science case examples

(small selection with strong personal bias)

- Cooling budget separated into different components
- High-J CO to probe excitation/kinematics
- Infall/accretion onto protostars/clusters
- Timescales: chemical clocks

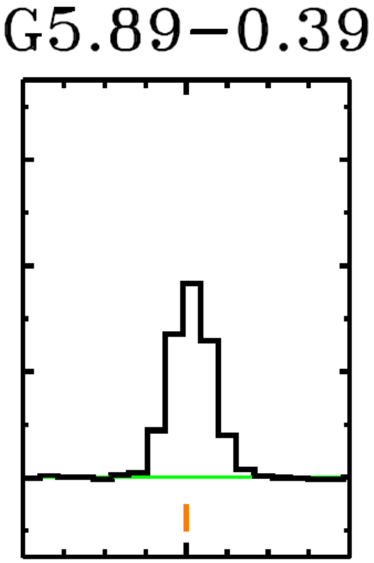
OI: from PACS to GREAT

Leurini+2015



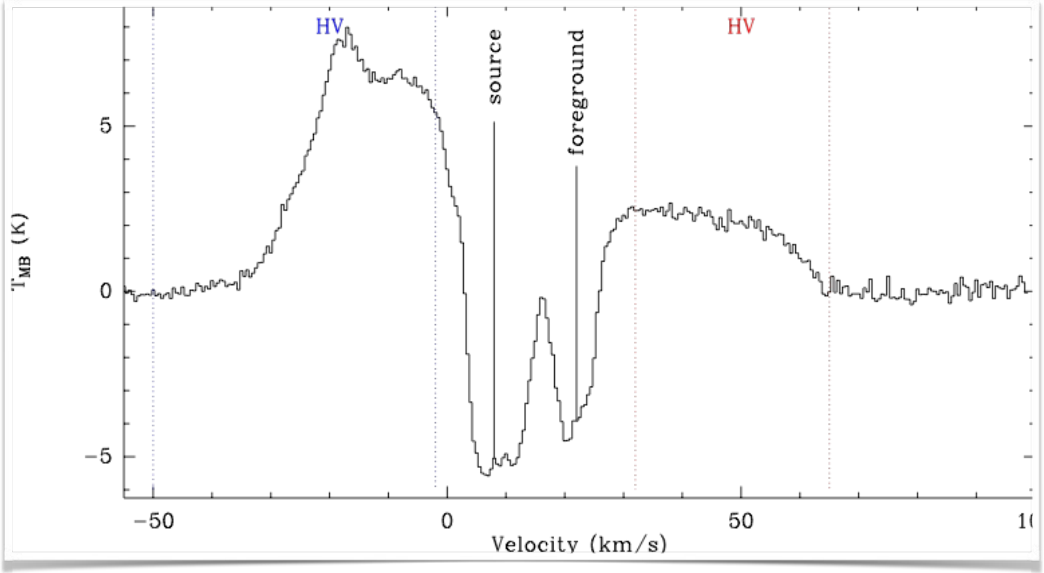
Karska+2013

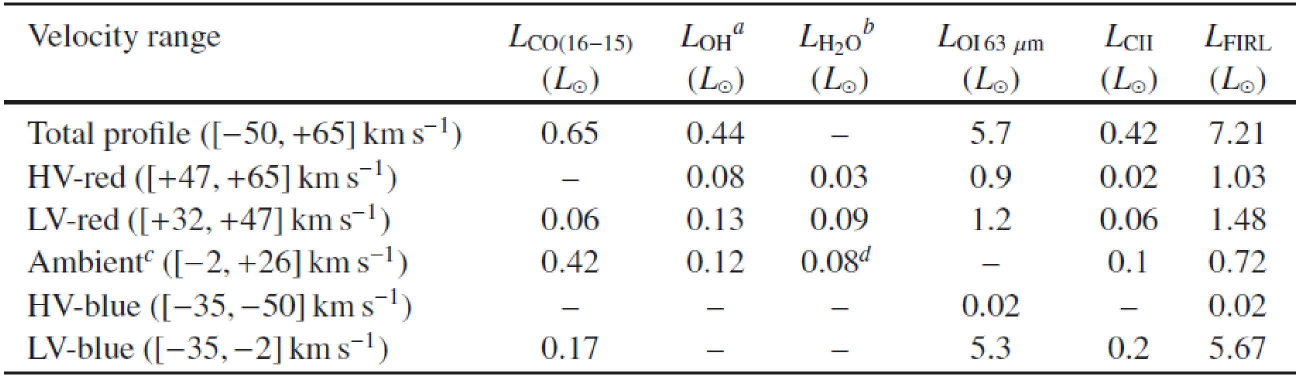
OI: from PACS to GREAT



Karska+2013

Leurini+2015





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

Cooling budget

- OI, CII, CO, OH, (H_2O)
- → Census of cooling in a wide range of conditions
- High spectral resolution mandatory
  - to separate different physical components (e.g. outflow, envelope, different density regimes) and
  - to address optical depths effects
- SOFIA allows already important pathfinder and individual source studies but will for larger statistical samples more sensitivity and spatial coverages are needed.
- Range spectroscopy? Or many lines simultaneously with HIRMES like instrument.
- For dense regions, OI crucial ! For excitation and in cases where OI 63µm is optically thick, OI 145µm necessary (potentially in combination with CII 157µm) → GREAT

CO SLEDs

e.g. HH46 (van Kempen+2010)

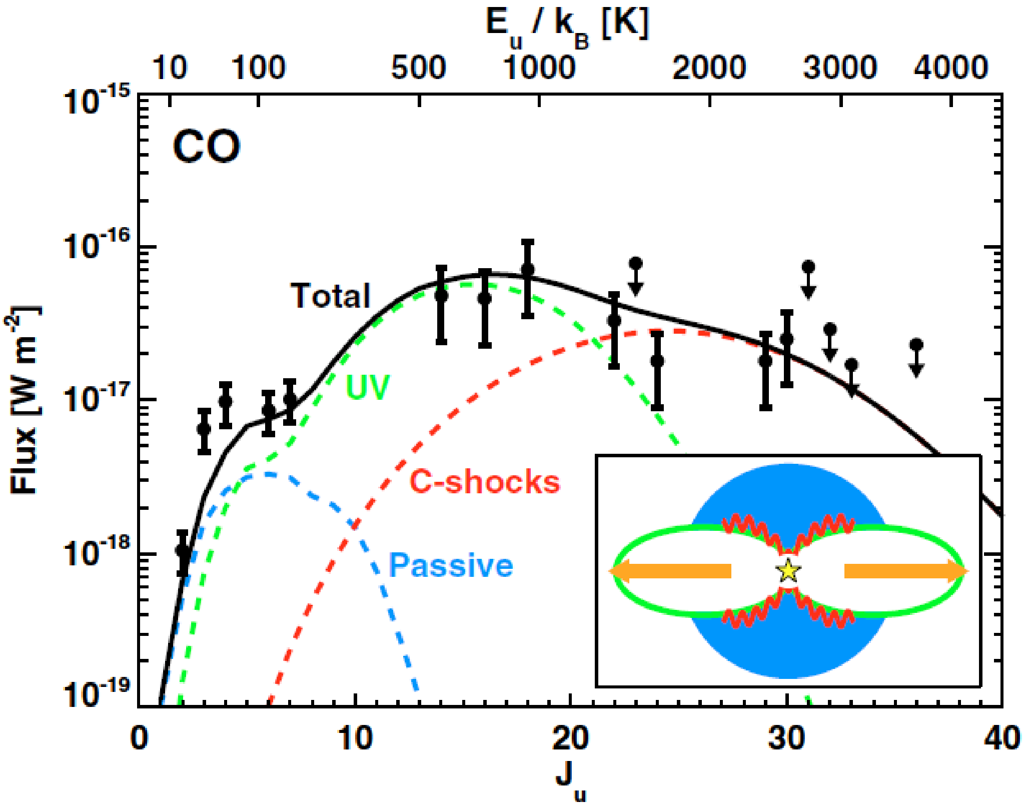
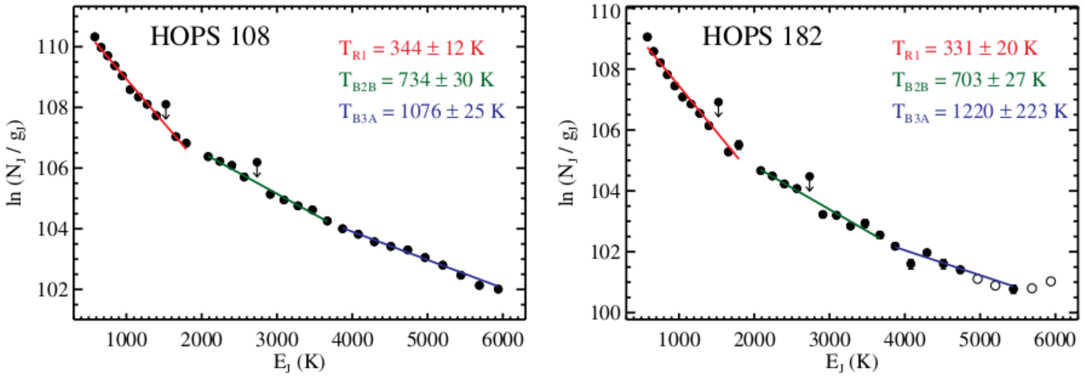
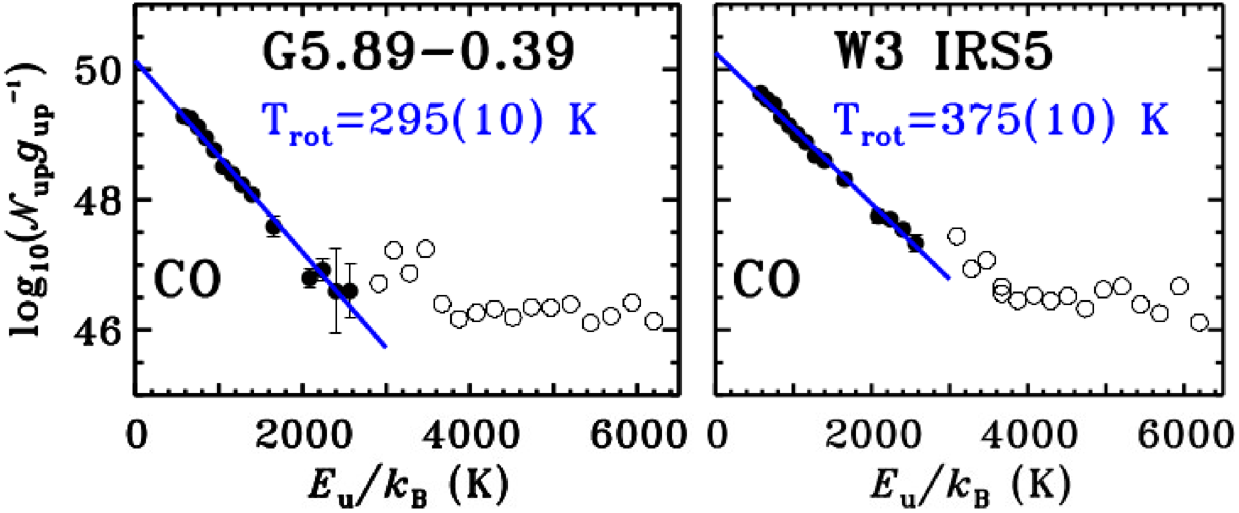


Fig. 2. CO line fluxes observed in the central PACS spaxel ($J_u > 10$) and with APEX ($J_u < 10$). Model fluxes are used to estimate the ratio of flux in a fictive PACS spaxel at the APEX wavelength and the observed APEX flux. Overplotted are predictions from a passively heated envelope (blue), a UV-heated cavity (green), and small-scale shocks in the cavity walls (red). The black line is the sum of the three. A cartoon of the different components is shown in the inset.

Manoj+2013, Karska+2013



A. Karska et al. 2013: Far-infrared molecular lines from Low- to High-Mass Star Forming Regions observed with Herschel

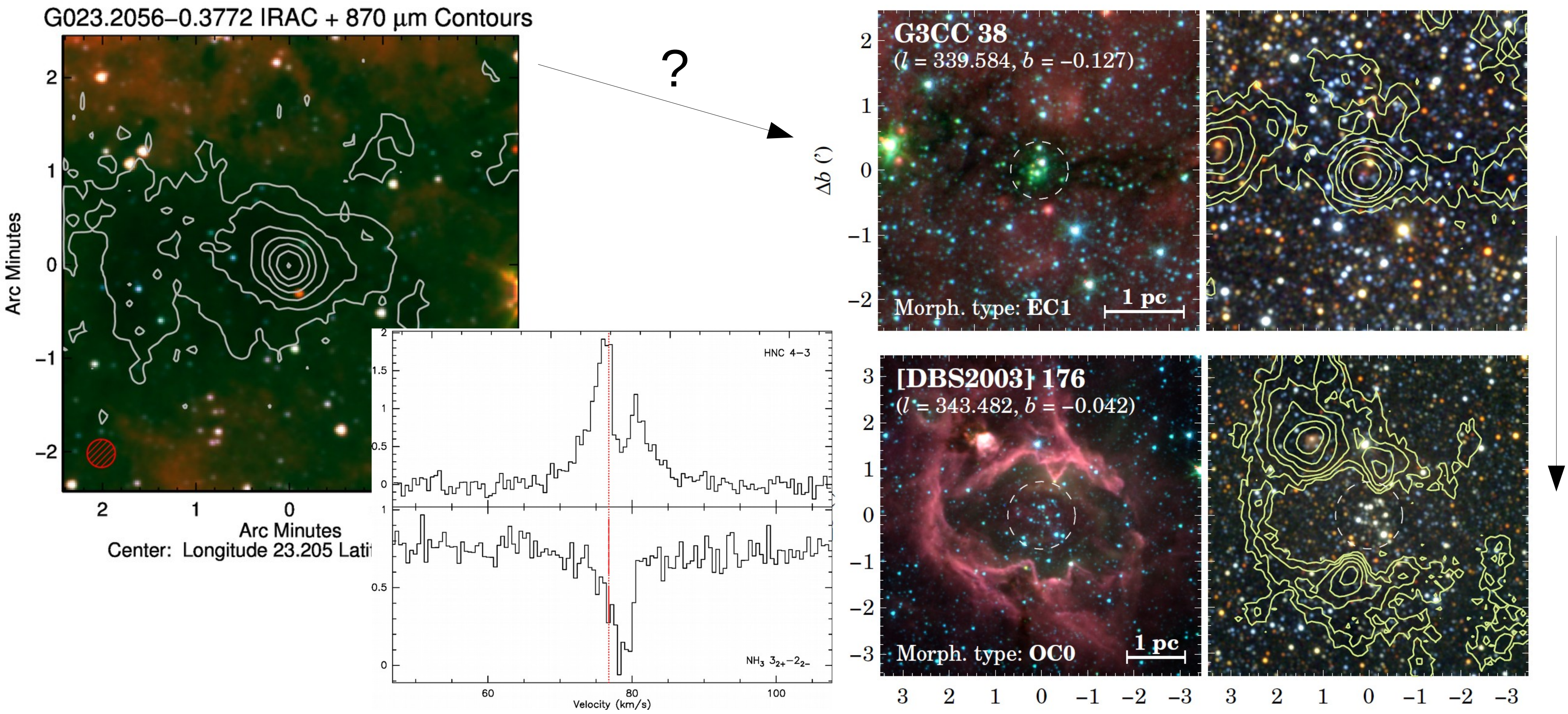


CO SEDs

- CO chemically relative stable in warm gas
- Wide range of excitation can be covered → important cooling contribution
- For Galactic sources, high spectral resolution needed to separated line components arising from different exciting processes
- Again: range spec./many lines simultaneously

(High-mass) clump evolution

Infall is a fundamental process in SF!



Key questions SOFIA can address

- What are the infall speeds? Are free-fall velocities measured or is the infall slowed down?
- Which parts of the clouds take part in the infall? Is the infall local or global?
- What is the velocity profile of the infall?
- What are the corresponding timelines, hence in which evolutionary stages can infall be measured?
- What are the infall rates and can they be converted into accretion rates? Are the accretion rates high enough to overcome radiation pressure?

Infall in star forming regions

- New approach:
  - Employ absorption of THz lines in front of dust continuum as more straightforward tool *(previously only studies in the cm towards evolved stages, HII regions and mm/submm blue-skewed selfabsorption)*
- Determine infall rates on LOS
- Probe abundances in envelope
- Study infall through the evolution of star forming clumps

Search for infall

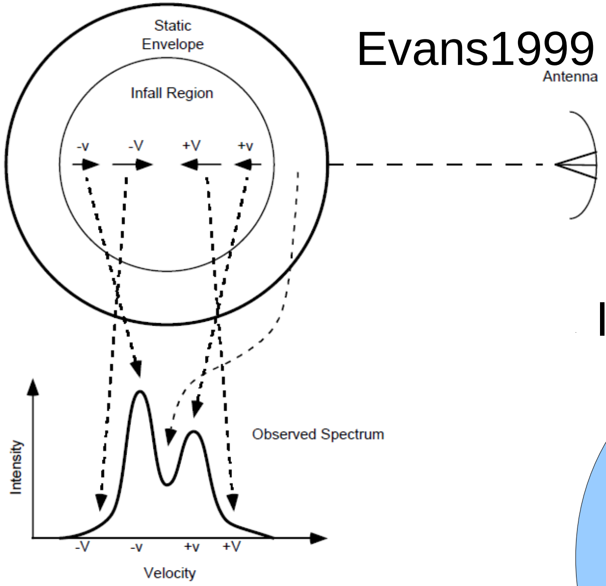
I: Blue-skewed profiles

Needs excitation gradient, right tau

II: red-shifted absorption

Needs high critical density, central continuum

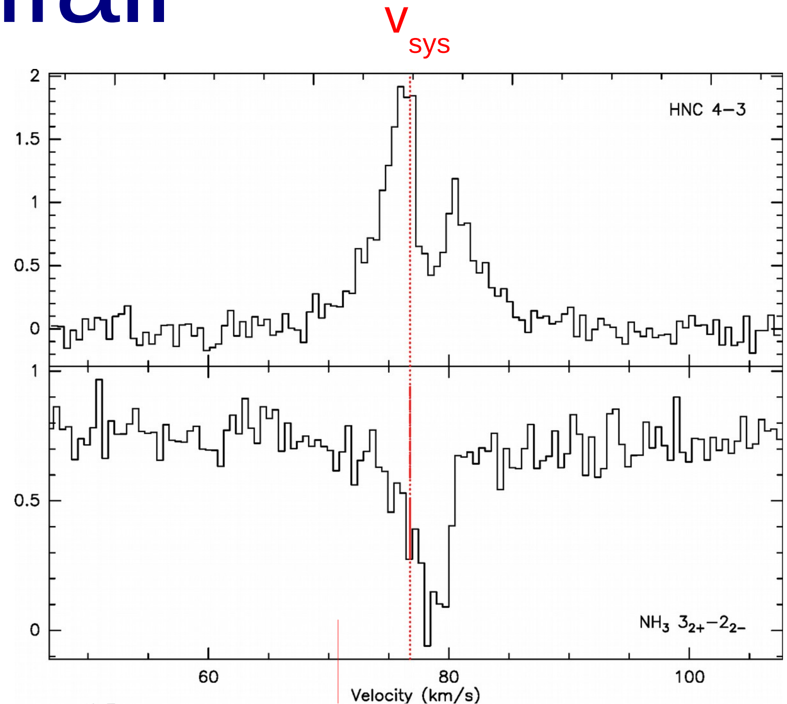
I.



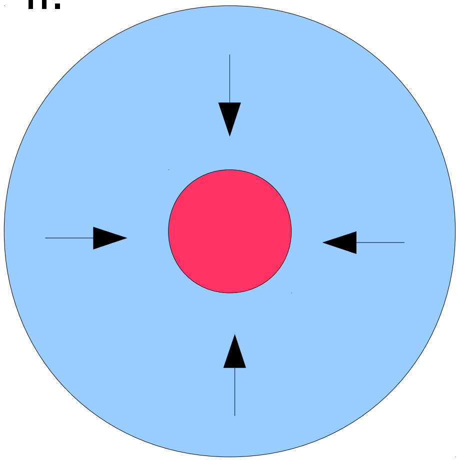
Evans1999

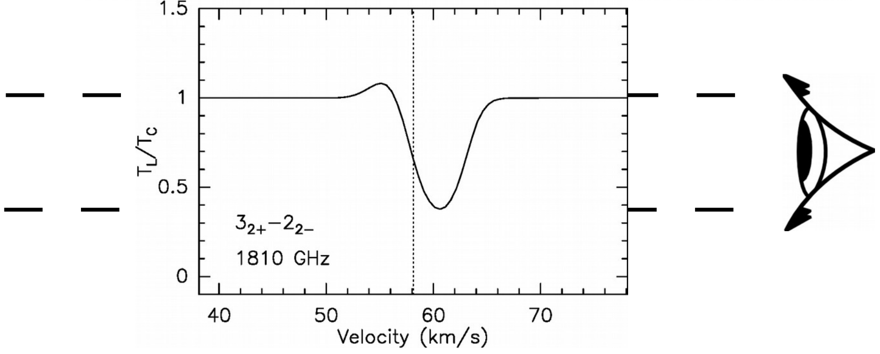
I.

II.



II.





Ammonia

- cm: Inversion lines
- FIR: Rotational lines, high n_{crit}
- overabundant in hot cores, apparently no depletion in cold sources

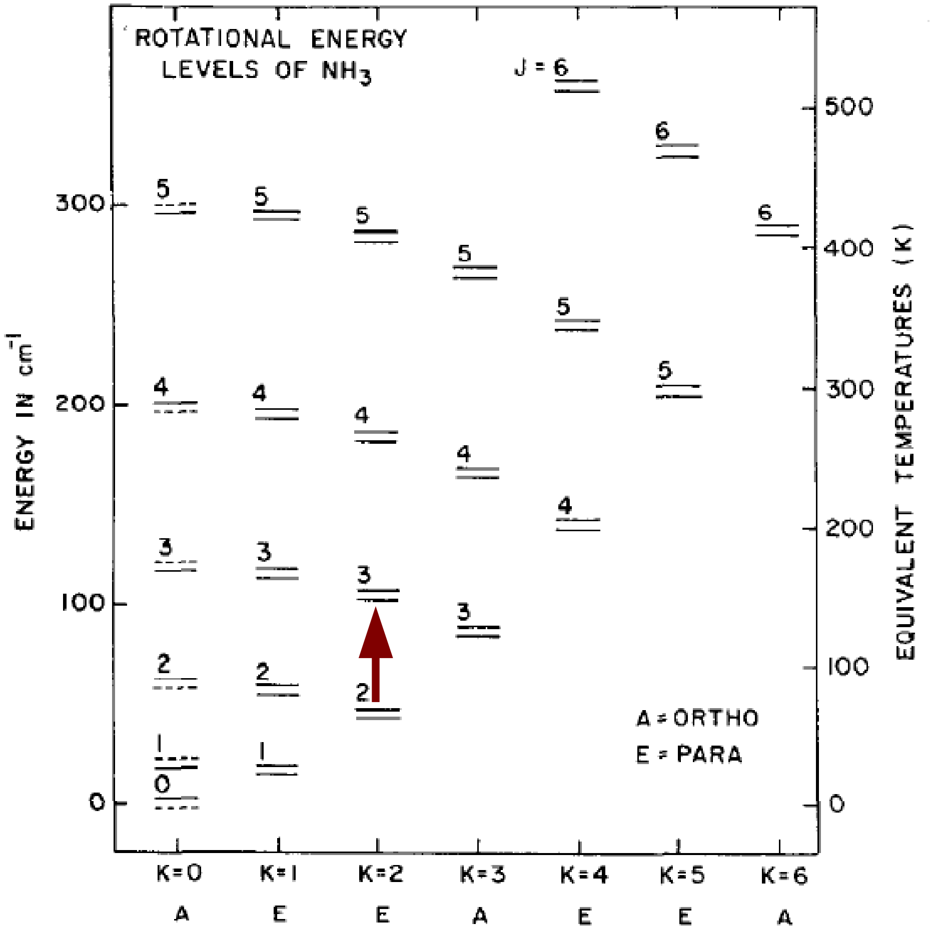
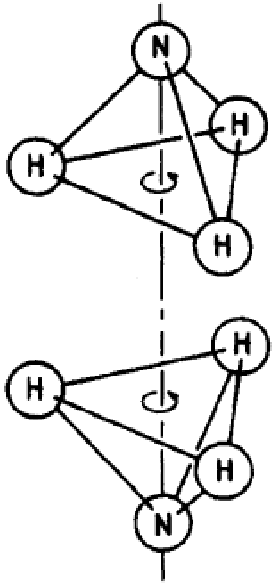


Figure 1 Energy level diagram of rotation-inversion states. *J* is the total angular-momentum quantum number, and *K* is the projected angular momentum along the molecular axis.



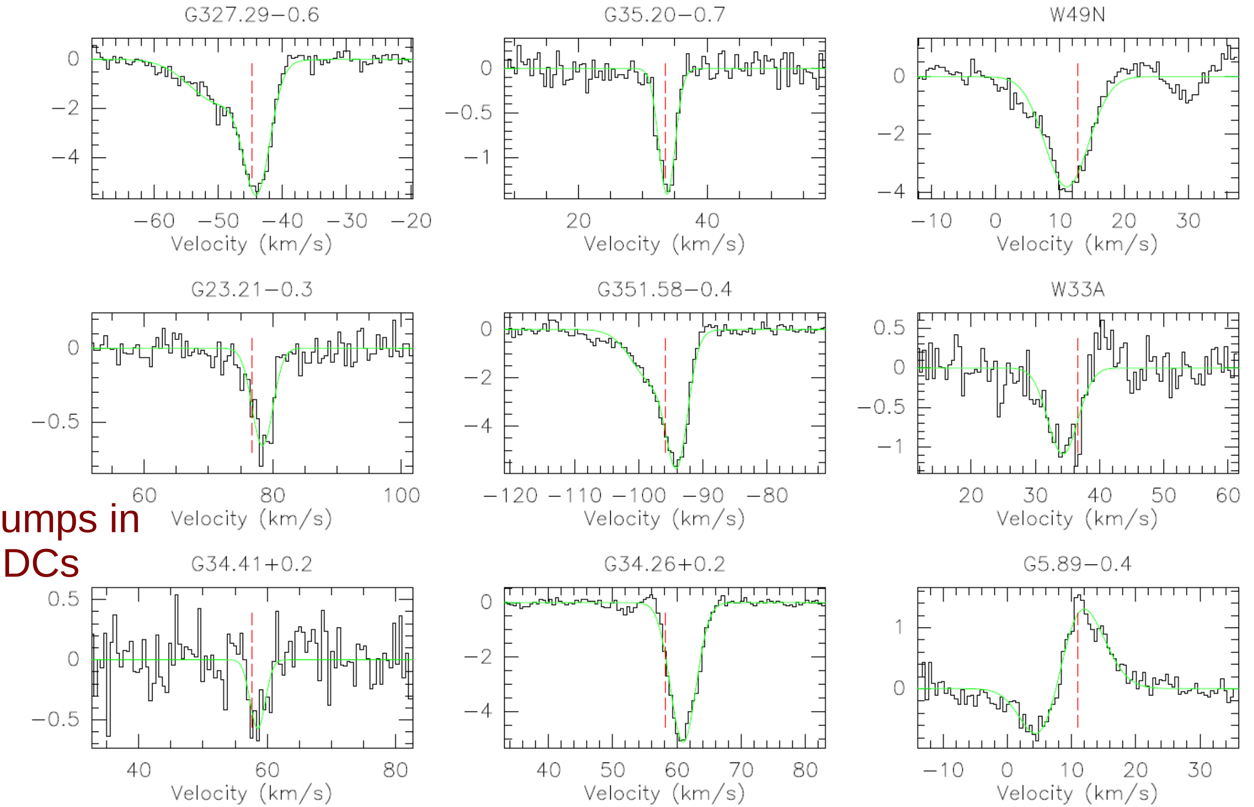
SOFIA results: Wyrowski+2012,2016

New data from 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



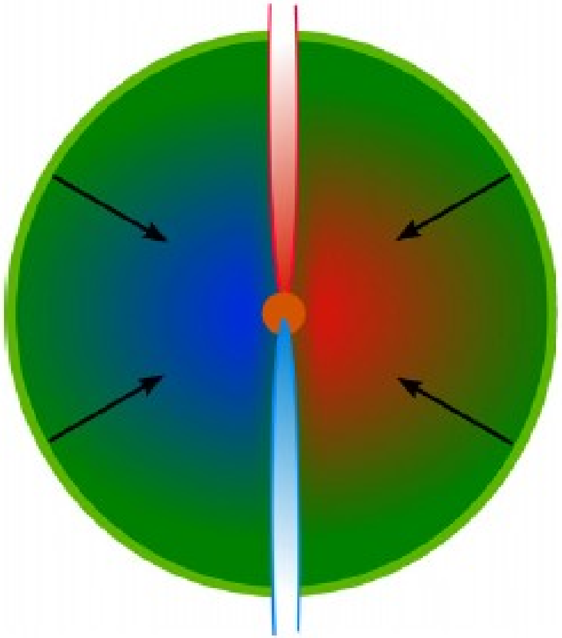
Clumps in IRDCs

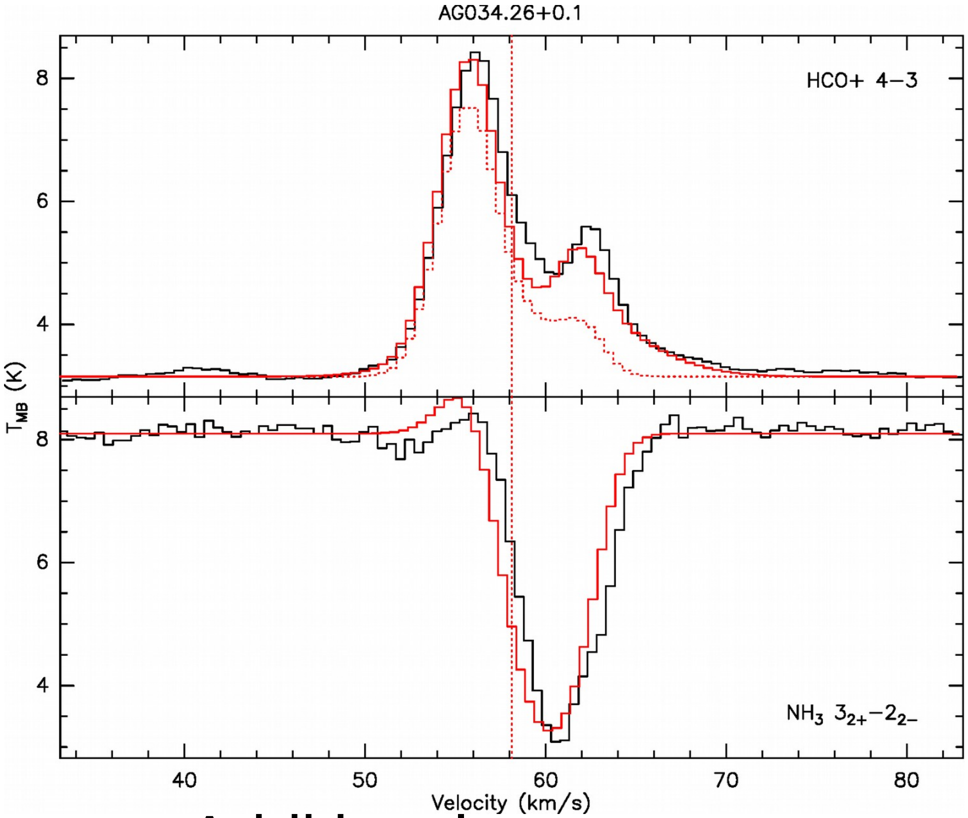
Fig. 2. NH_3 $3_{2+} - 2_{2-}$ spectra of the observed sources. Results of Gaussian fits to the line profiles are overlaid in green. The systemic velocities of the sources, determined using $C^{17}O$ (3–2), are shown with dotted lines. W49N shows in addition at 30 km/s the NH_3 $3_{1+} - 2_{1-}$ from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

Modeling: RATRAN + Outflow component

HCO^+ usually probing additional outflow component

→ RATRAN modification of Mottram+2013



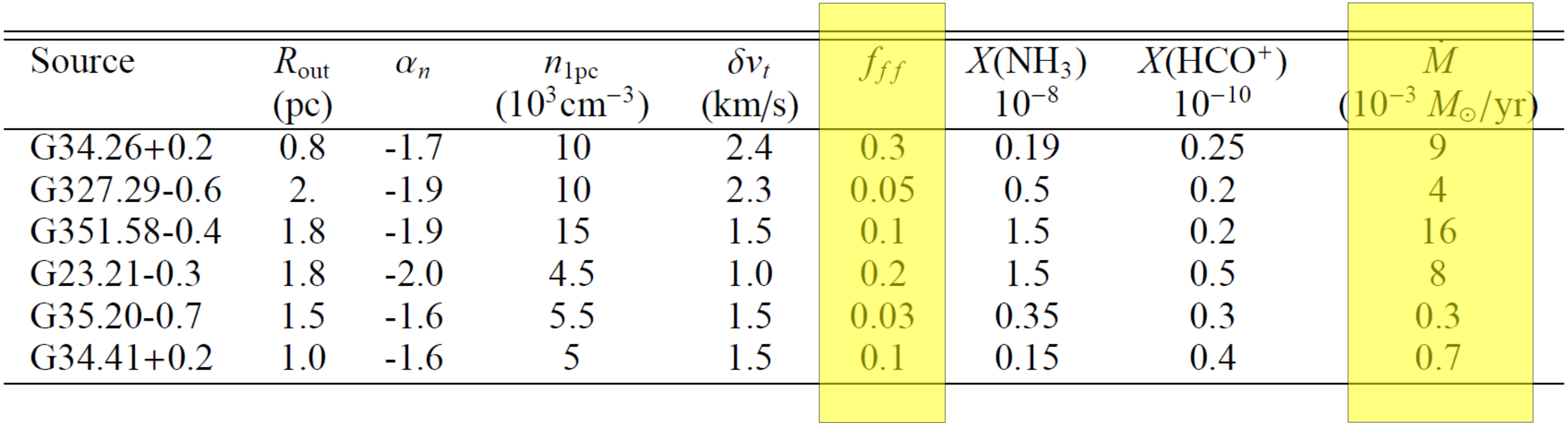


Additional parameter:

- outflow widths/strength
- HCO^+ abundance

Modeling results

Wyrowski+2016



Source	R_{out} (pc)	α_n	$n_{1\mathrm{pc}}$ ($10^3\mathrm{cm}^{-3}$)	δv_t (km/s)	f_{ff}	$X(\mathrm{NH_3})$ 10^{-8}	$X(\mathrm{HCO^+})$ 10^{-10}	$\dot{M}$ ($10^{-3}\ M_\odot/\mathrm{yr}$)
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 %. Clump scale probed. To further constrain models, → measure larger spatial range

Herschel G34.26 results

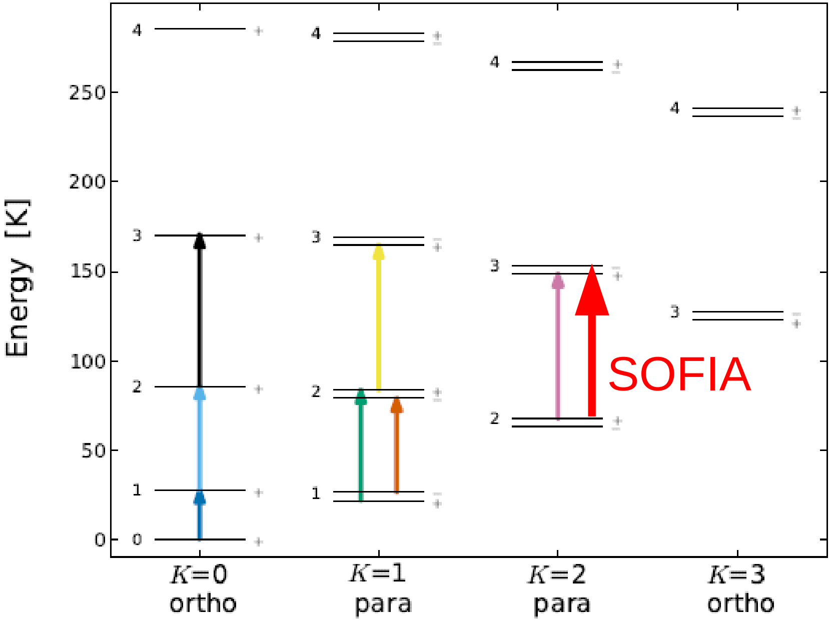
Hajigholi+2015

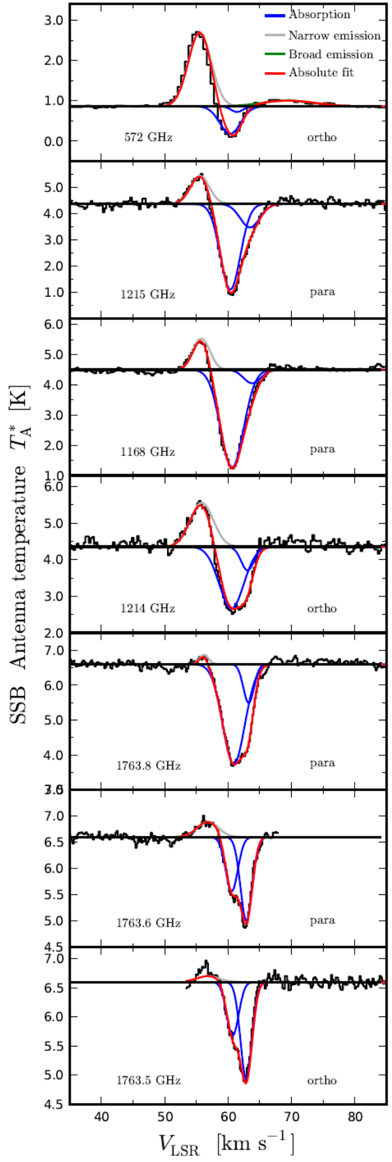
Different excitation traces different v

- → infall accelerating towards inner part of clump

Future SOFIA opportunities:

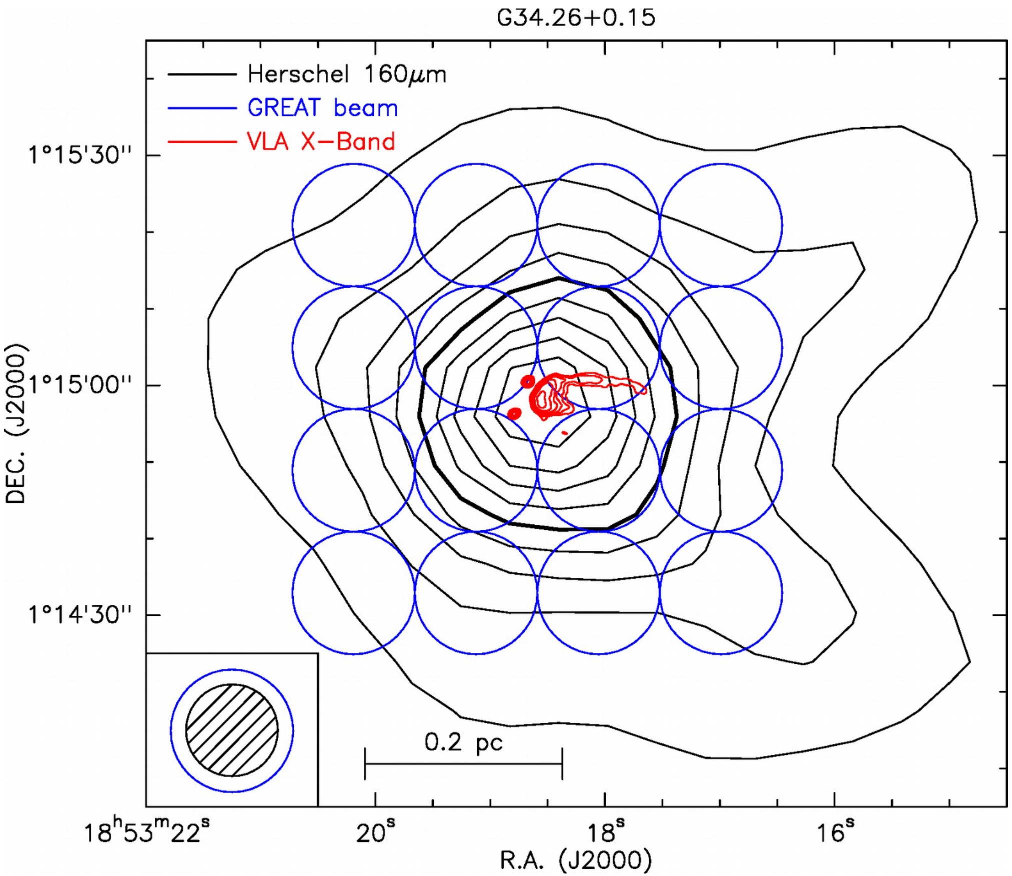
- GS 572 GHz @ 90% transmission (4GREAT)
- 1214 GHz (201-100, 211-110) @ 65%
- 2355 GHz (4-3 lines) @ 63%





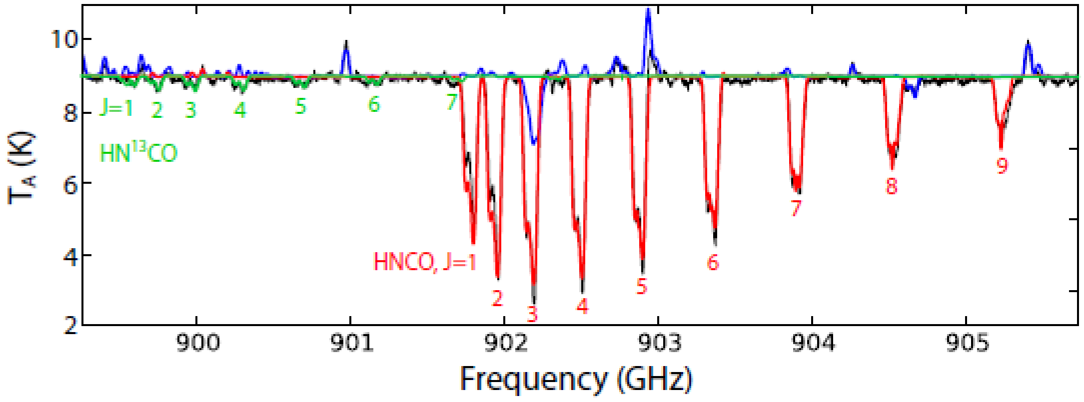
Search for large scale infall

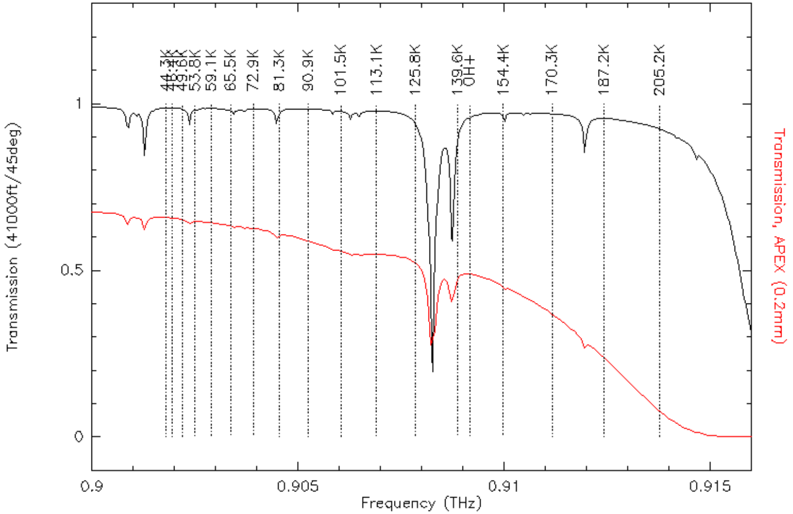
- Extended dust continuum, ~0.5pc
- Infall localized or global ?
- Infer 3D velocity pattern.
- Search for velocity gradients, rotation?



Potential probes of infall for future SOFIA studies

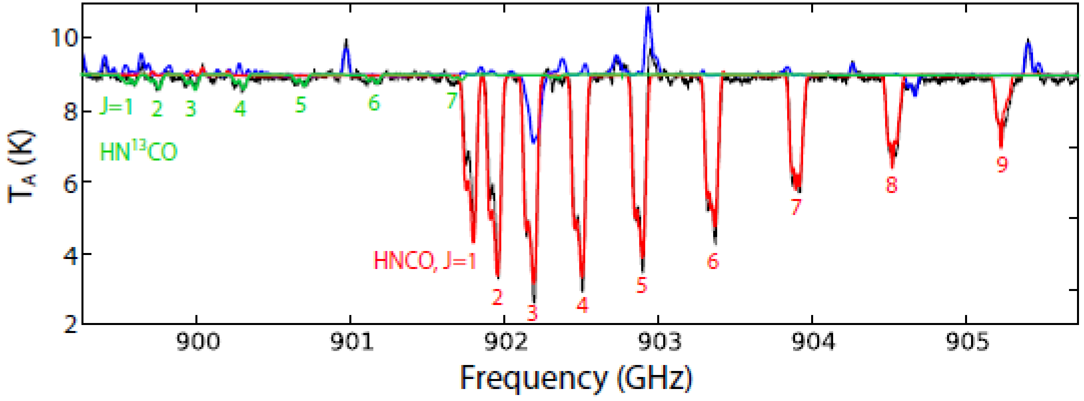
- **HNCO** (range in E)
    - Possible from the ground, but only lower J lines

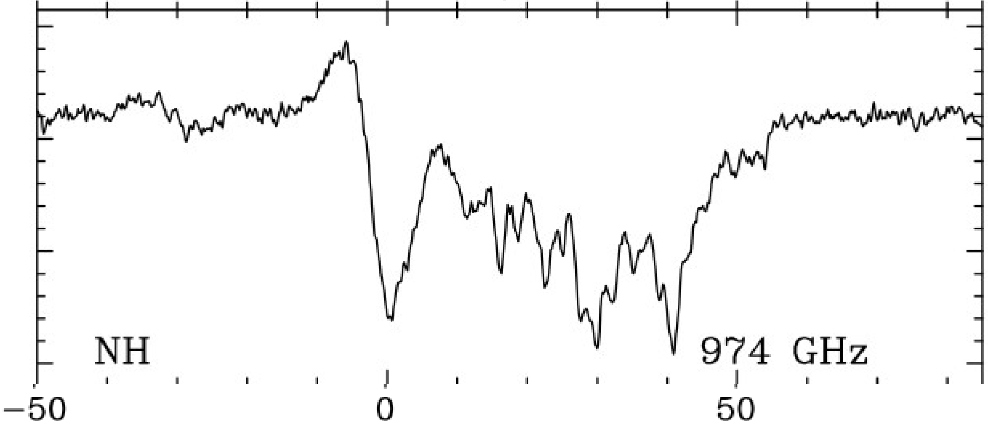

Neill+2014: SgrB2(N) with Herschel/HIFI



Potential probes of infall for future SOFIA studies

- HNCO (range in E)
- NH, NH_2 (HFS)
- H_2O ($H_2^{18}O$), warm gas filter
- H_2S, o/p ratio
- H_2D^+ , OD cold gas
- H_2, 28μm, cold gas

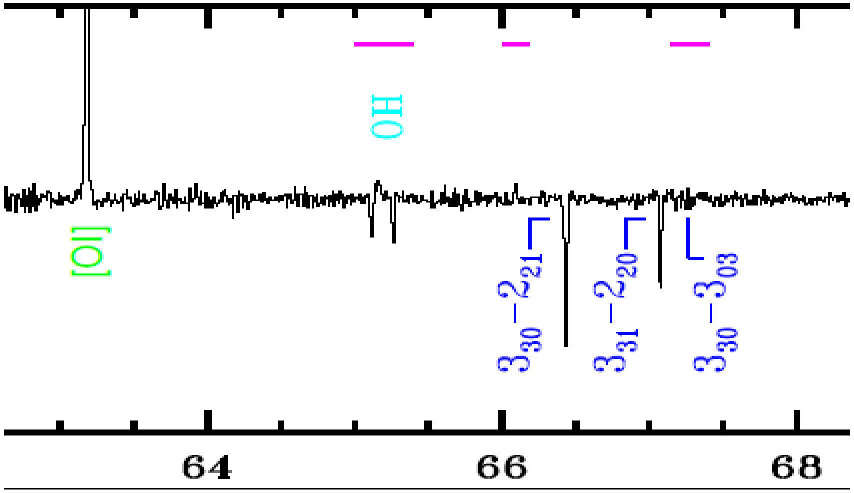

Neill+2014: SgrB2(N) with Herschel/HIFI

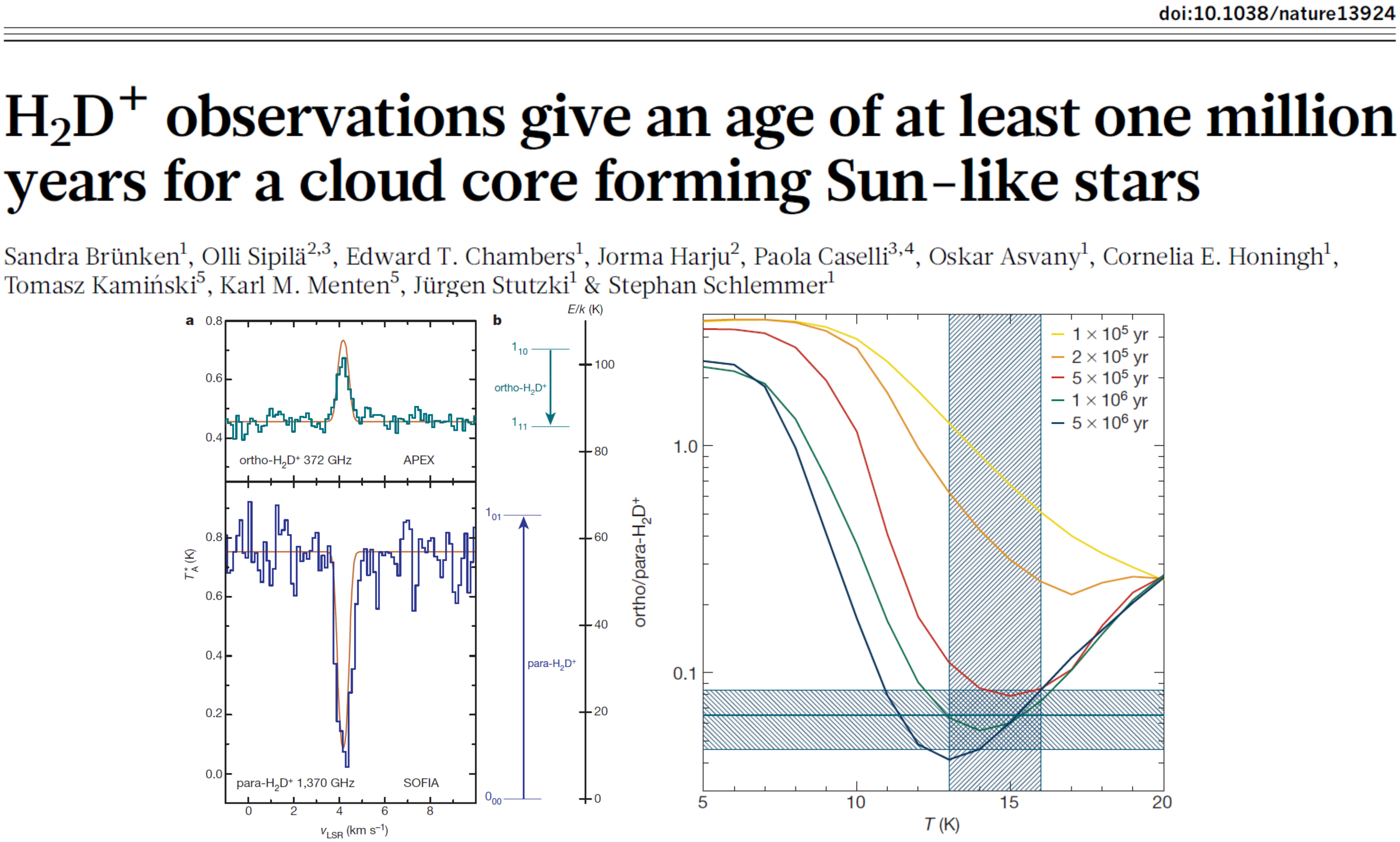

Persson+2012: G10.62, NH with Herschel/HIFI

Karska+2013: W3IRS5

Still lots of discovery space, e.g.:

- OH, 65µm doublet
- Relatively close to OI
- E_lower = 290 K
- PACS: Massive star forming regions




doi:10.1038/nature13924

H_2D^+ observations give an age of at least one million years for a cloud core forming Sun-like stars

Sandra Brünken[1], Olli Sipilä[2,3], Edward T. Chambers[1], Jorma Harju[2], Paola Caselli[3,4], Oskar Asvany[1], Cornelia E. Honingh[1], Tomasz Kamiński[5], Karl M. Menten[5], Jürgen Stutzki[1] & Stephan Schlemmer[1]

Work on HM clumps ongoing. APEX: Giannetti+2019, Modelling e.g. Körtgen+2017.

See also D_2H^+ (Harju+2017)

Probing the circumstellar disk in AFGL2136

Synergies between EXES/TEXES/CRIRES and ALMA

(Indriolo+2020)

- Hot disk emission from clumpy disk structure
- H_2O: 500-800K
- tau(lambda)
- + other molecules (CO, HCN, NH_3,HF, C_2H_2) and unidentified lines

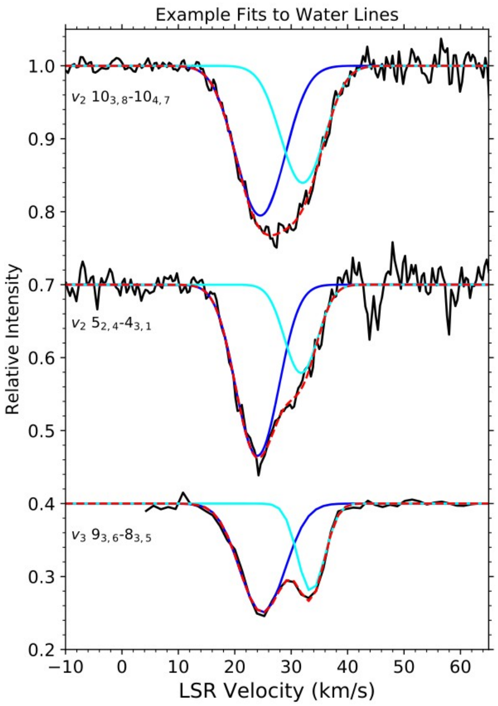
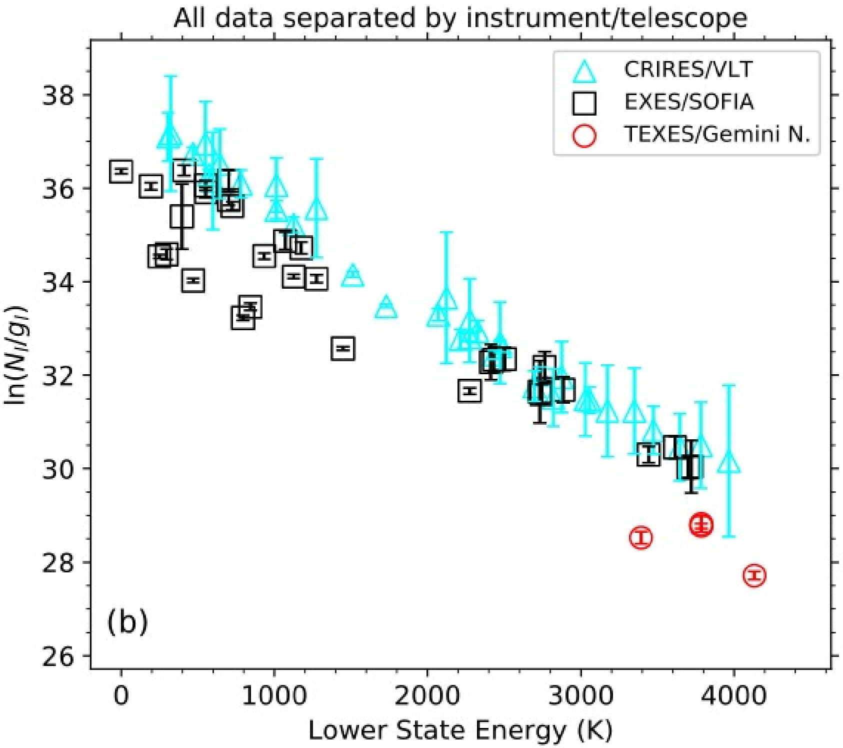
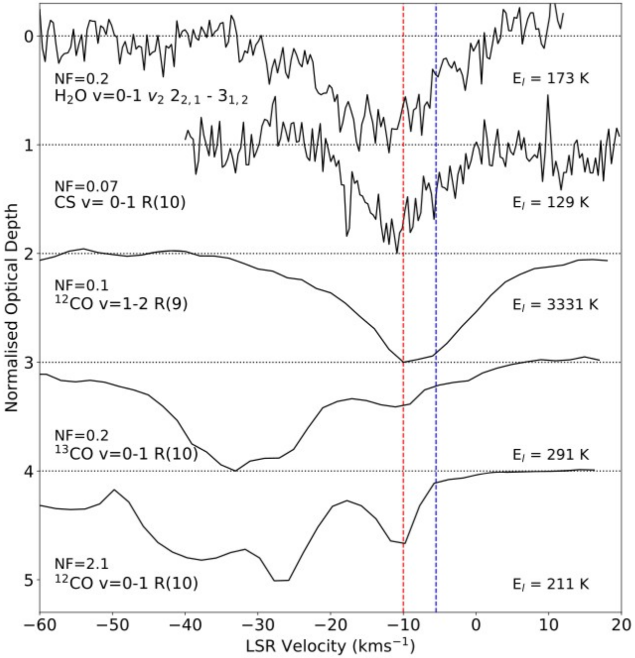


Figure 4. Two-component Gaussian fits to H_2O absorption lines are shown here. The blue and cyan curves mark the components at about 25 km s^{-1} and 33 km s^{-1}, while the red dashed curve is the sum of both components.



EXES rovib. CS (Barr+2017)

- AFGL2591: Base of outflow in hot core (130AU, 0.04”)



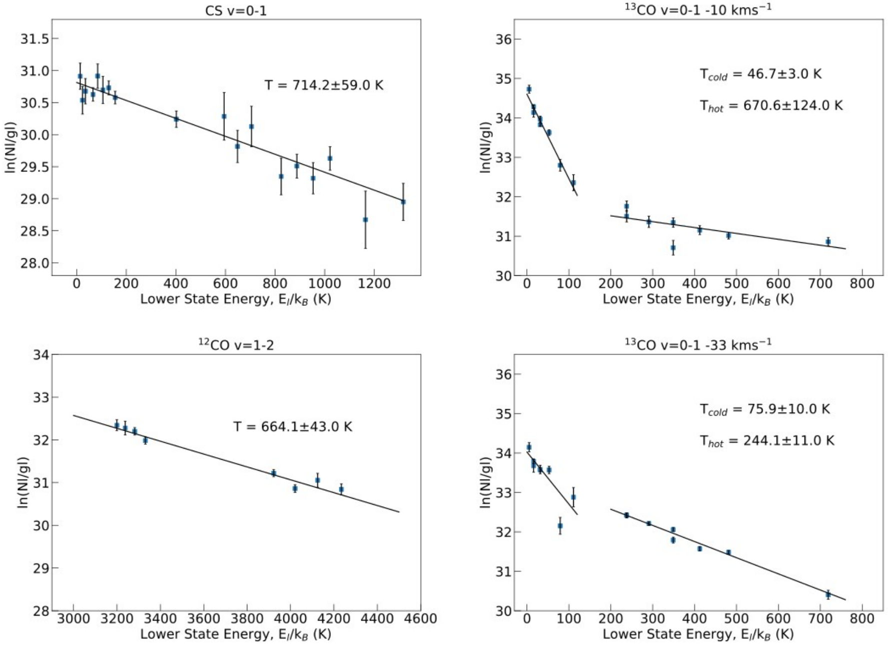
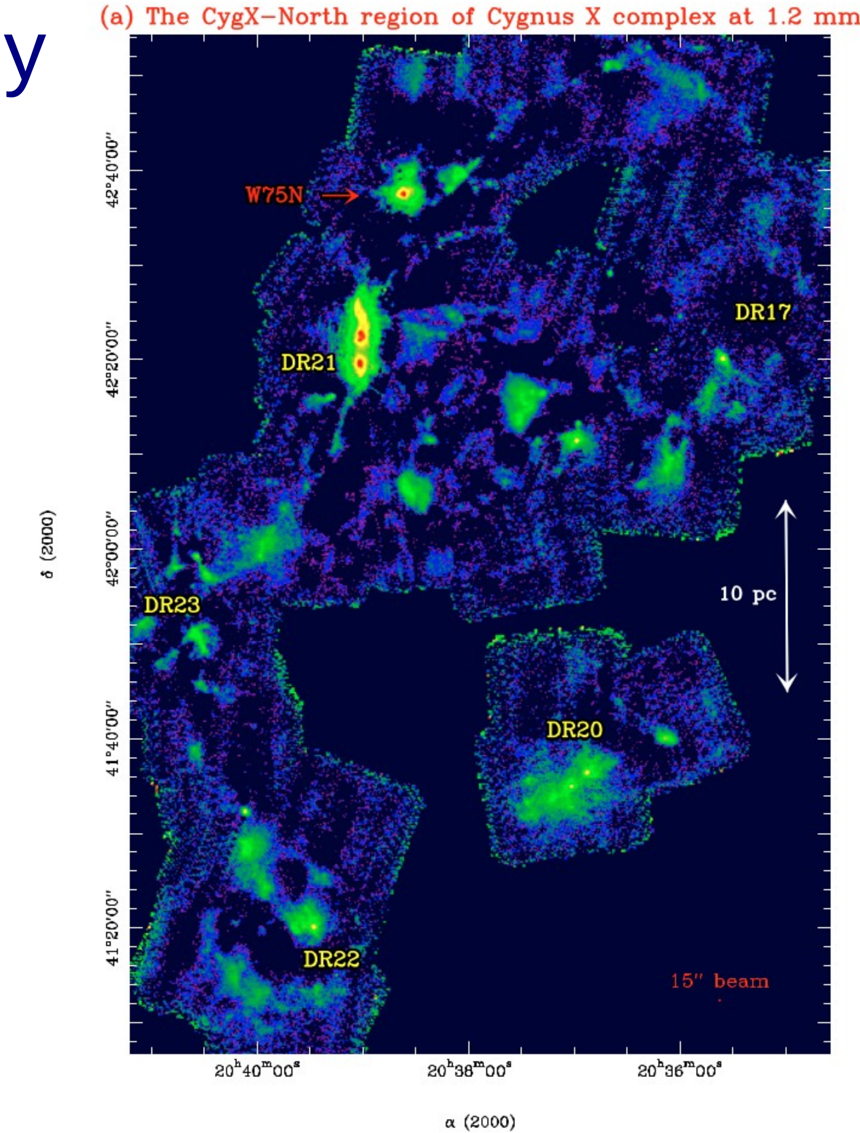


Figure 2. CS and CO rotation diagrams. Temperatures for each species are shown, with two temperature components for ^{13}CO.

Spectroscopy towards statistically significant samples

- GMCs sizes on sky often within sqdeg → no adjustment of flight direction needed
- Increase efficiency for rapid observations of many targets within sqdeg
- e.g.: 40 cores in CygX in HR mode with HIRMES-like instrument in many lines. Also EXES/4GREAT projects would benefit
- While a lot can be learnt from individual sources, large samples allow to average out random traits and facilitate comparison to simulations

F. Motte et al.: High-mass star formation in the Cygnus X complex



(a) The CygX−North region of Cygnus X complex at 1.2 mm

Summary

- HMSF studies with SOFIA, key requirements:
  - High spectral resolution to probe kinematics and deal with optical depths effects
  - Range of lines to probe different scales and evolutionary stages
  - Significant samples to probe large parameter space
- In general
  - increase sensitivity, efficiency
  - Explore new frequency ranges