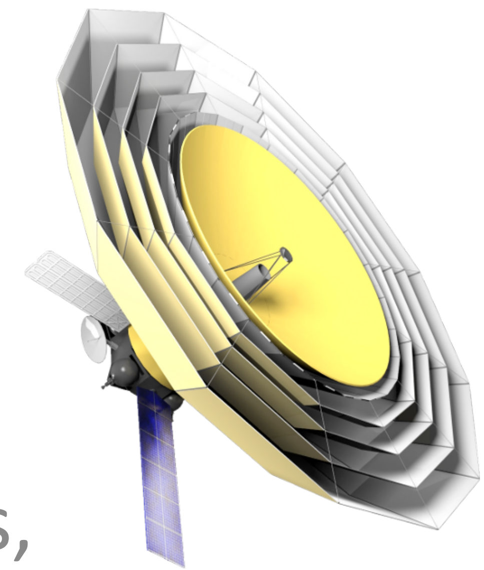
Millimetron in studies of ISM and star formation



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Outline

- Millimetron advantages and preferred targets
- Search for new lines at THz frequencies, important for ISM diagnostics
- Studies of hot cores and outflows by high excitation lines of CO and other molecules
- Surveys of star forming cores at THz frequencies
- ISM in external galaxies

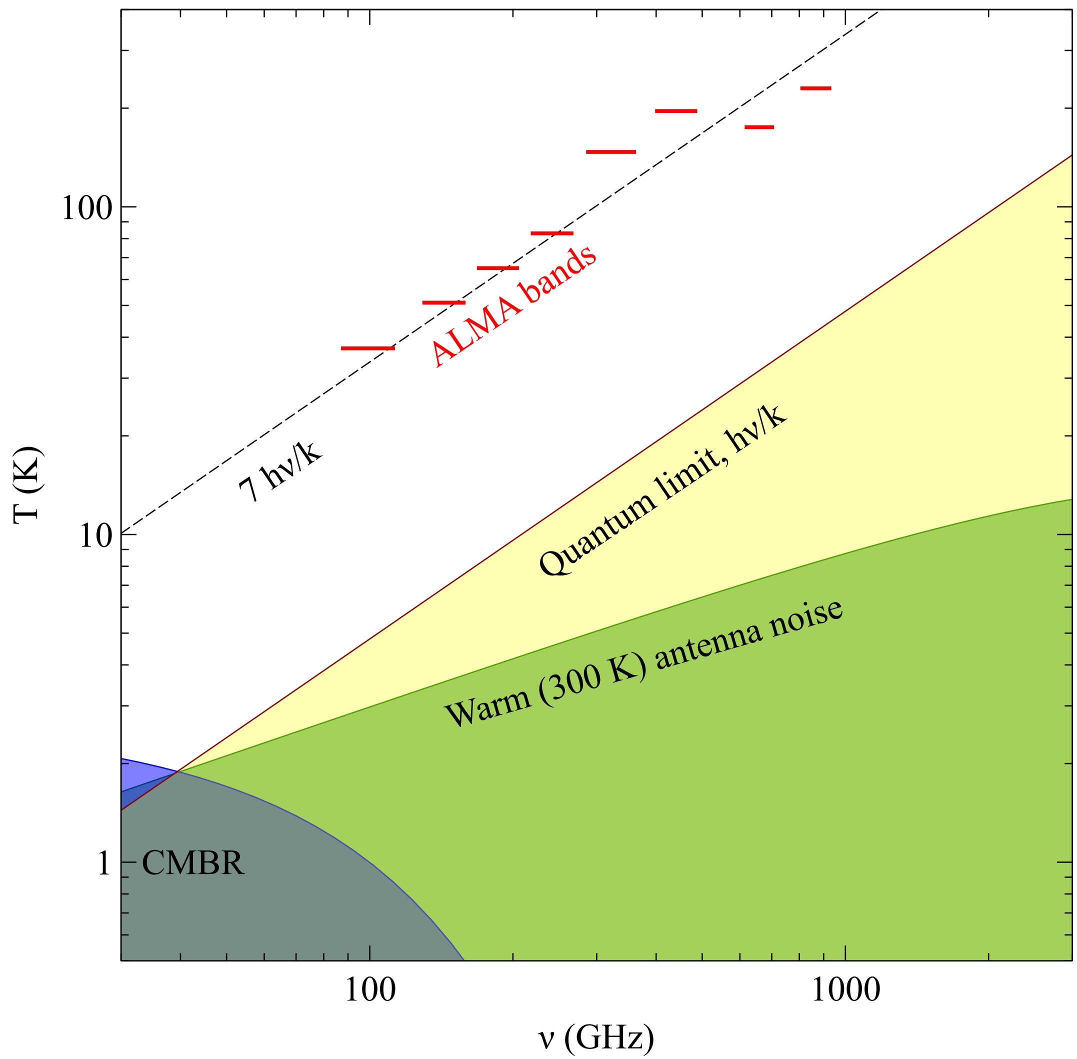
Millimetron advantages

- Antenna is much larger than for other space mm/submm telescopes ➔ higher sensitivity for point sources and higher angular resolution for extended sources.
- Antenna cooling ➔ lower system noise (e.g. in comparison with Herschel) for bolometers (for heterodyne receivers the quantum noise will dominate).
- Frequency range of high resolution spectrometer is more extended than for other mm/submm telescopes ➔ very important for ISM spectroscopy.
- In comparison with ALMA, Millimetron has a much larger field of view ➔ important for studies of extended sources.
- Very high angular resolution in the interferometric mode ➔ possibility to study very compact objects (but they should be very bright).

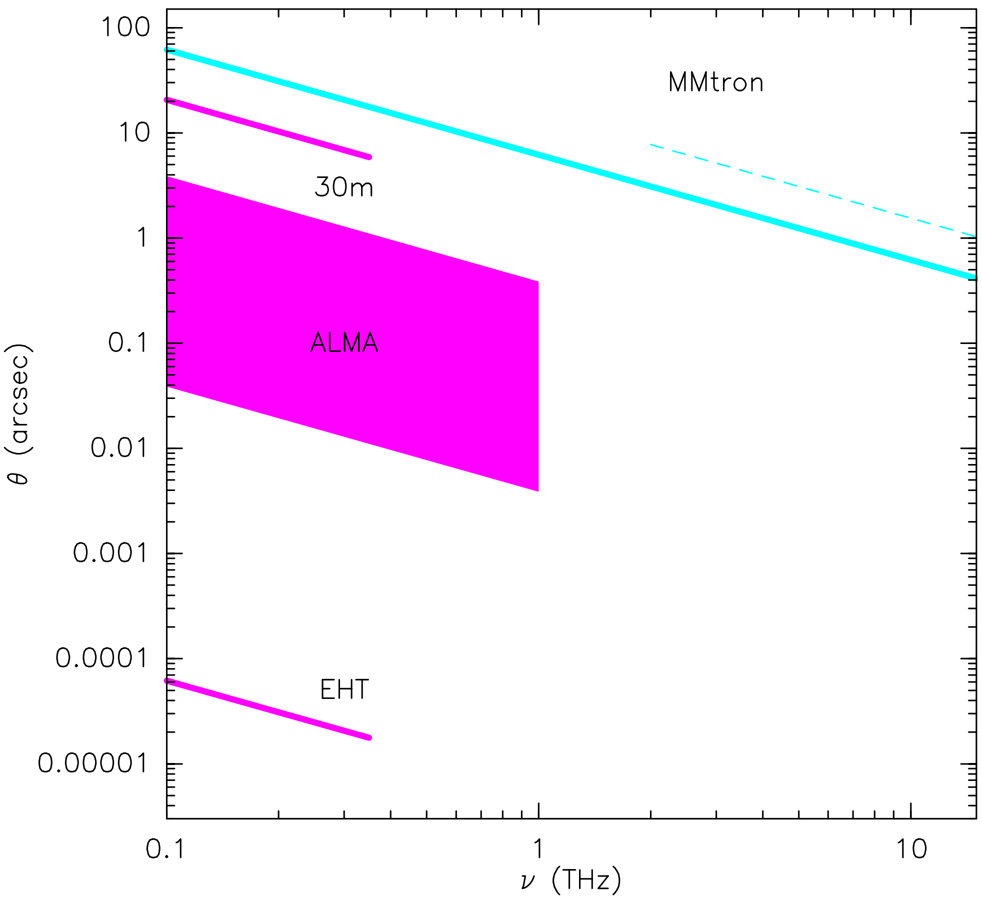
Sensitivity limitations for heterodyne measurements

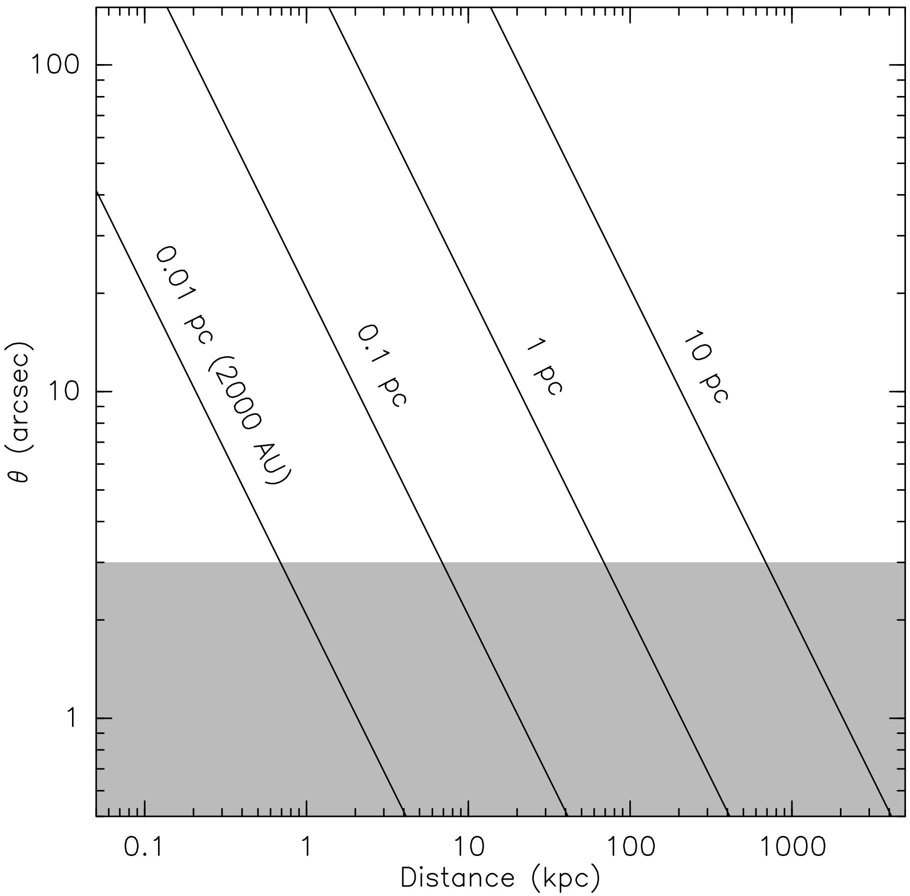
Minimum noise temperature ("quantum limit")

$$T_{\min} \sim \frac{h\nu}{k}$$



Angular resolution





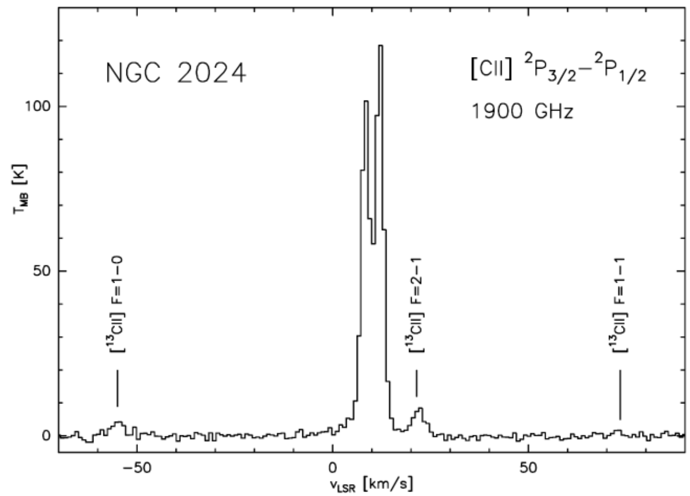
Targets

- Cold low mass clumps
- Low brightness objects
- Dense “hot” regions with the emission peak at very high frequencies (“hot cores”, post-shock gas, etc.)
- Diffuse ISM
- Submillimeter masers
- ISM in external galaxies

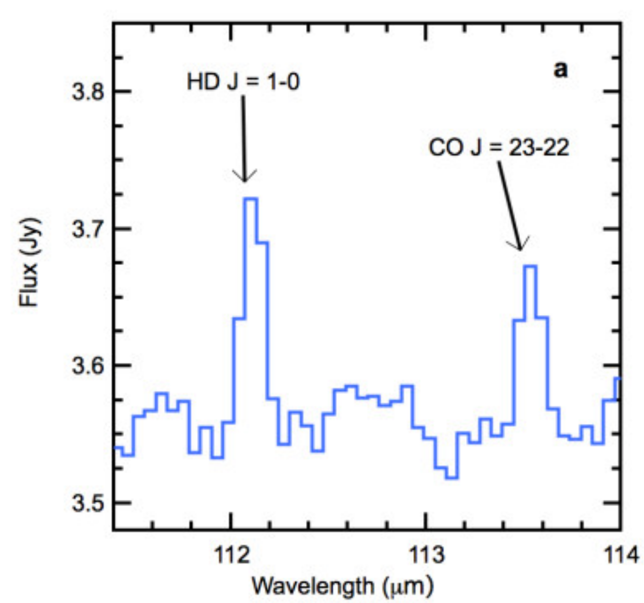
Some important submillimeter atomic and molecular transitions

Line	Wavelength (μm)	Ionisation Potentials[a] (eV)
OIII	51.800	35.12-54.94
NIII	57.317	29.60-47.45
OI	63.184	— 13.62
OIII	88.356	35.12-54.94
NII	121.898	14.53-29.60
OI	145.525	— 13.62
CII	157.741	11.26-24.38
NII	205.178	14.53-29.60

Molecule	Frequencies (GHz)
HD	2675, 5332
HF	1232, 2463
H_2O	1113, 1670, 2774, 2969,…
HeH^+	2010, 4009



Graf et al. (2012) using GREAT instrument on SOFIA.



HD J = 1 − 0 spectrum in TW Hya measured by Herschel/PACS (Bergin et al. 2013)

Some important lines

- In Herschel [CII] 158 μm survey a large amount of "dark" warm molecular hydrogen was found in diffuse clouds (Langer et al. 2010, Velusamy et al. 2010).
- HD J=1-0 (112 μm). HD is an important tracer of molecular gas. Can be excited in a relatively warm medium. Observations of absorption lines can be interesting (a bright background continuum source is needed).
- HeH^+ J=1-0 (149 μm). Can trace different from other molecules ISM environments. Available models (e.g., Roberge & Dalgarno 1982; Cecchi-Pestellini & Dalgarno 1993) predict a rather large HeH^+ abundance in vicinity of extreme UV and X-ray sources. Expected in early Universe.

$$He^+ + H \rightarrow HeH^+ + h\nu$$

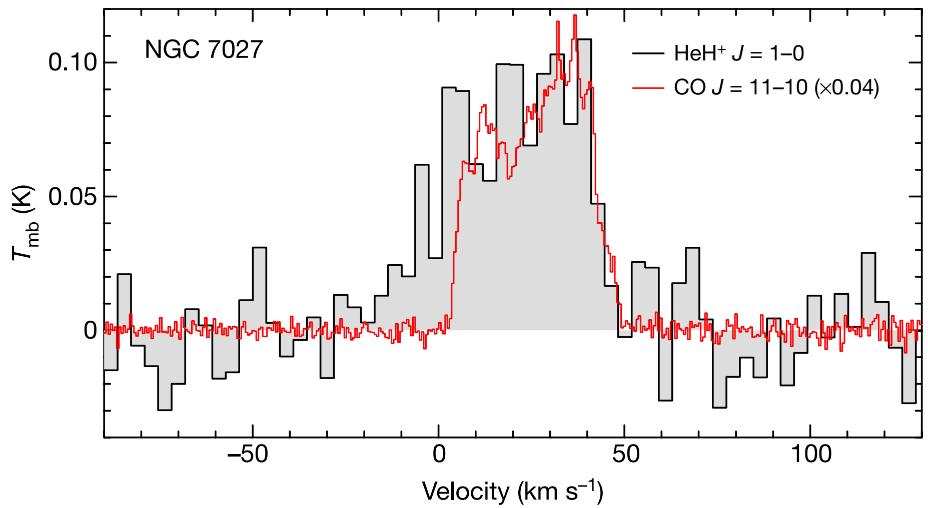
HeH^+ as a new tracer of the ISM

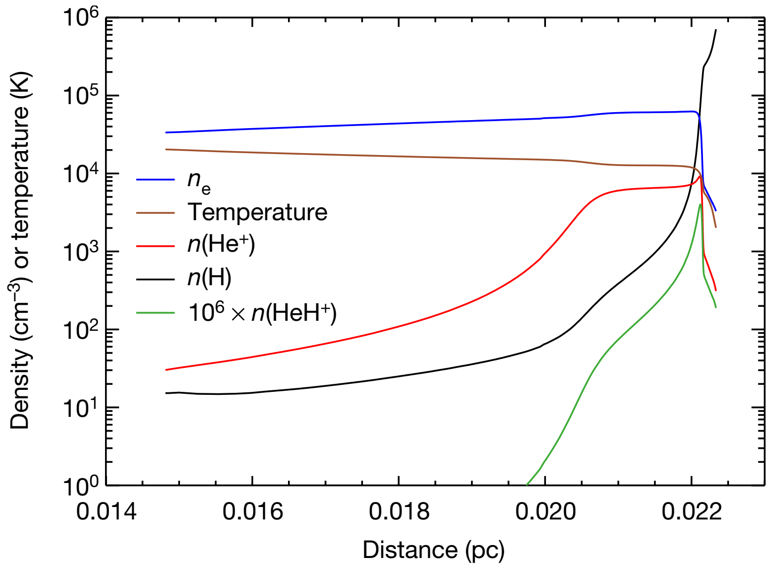
- Neutral helium atoms formed the Universe's first molecular bond in the helium hydride ion HeH^+ through radiative association with protons.
- Its observations are impossible from the ground since the lowest rotational transition is at 2 THz.
- J=2-1 observations (at 4 THz)?

$$\mathrm{He}^{+} + \mathrm{H} \rightarrow \mathrm{HeH}^{+} + h\nu$$

$$\mathrm{HeH}^{+} + e^{-} \rightarrow \mathrm{He} + \mathrm{H}$$

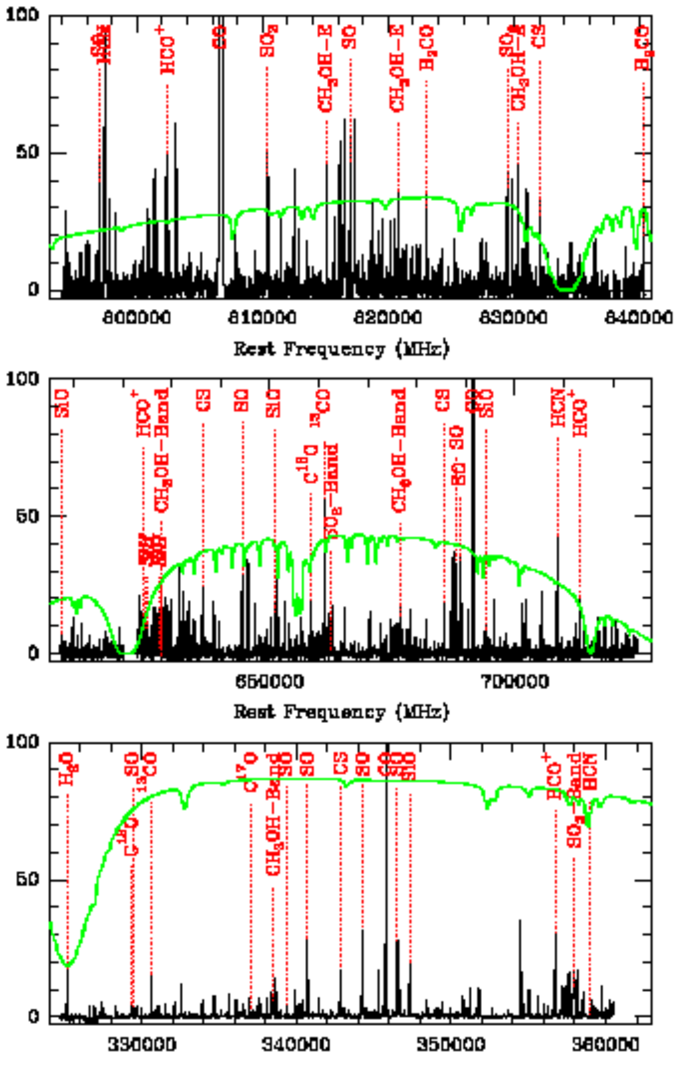
$$\mathrm{HeH}^{+} + \mathrm{H} \rightarrow \mathrm{H}_2^{+} + \mathrm{He}$$

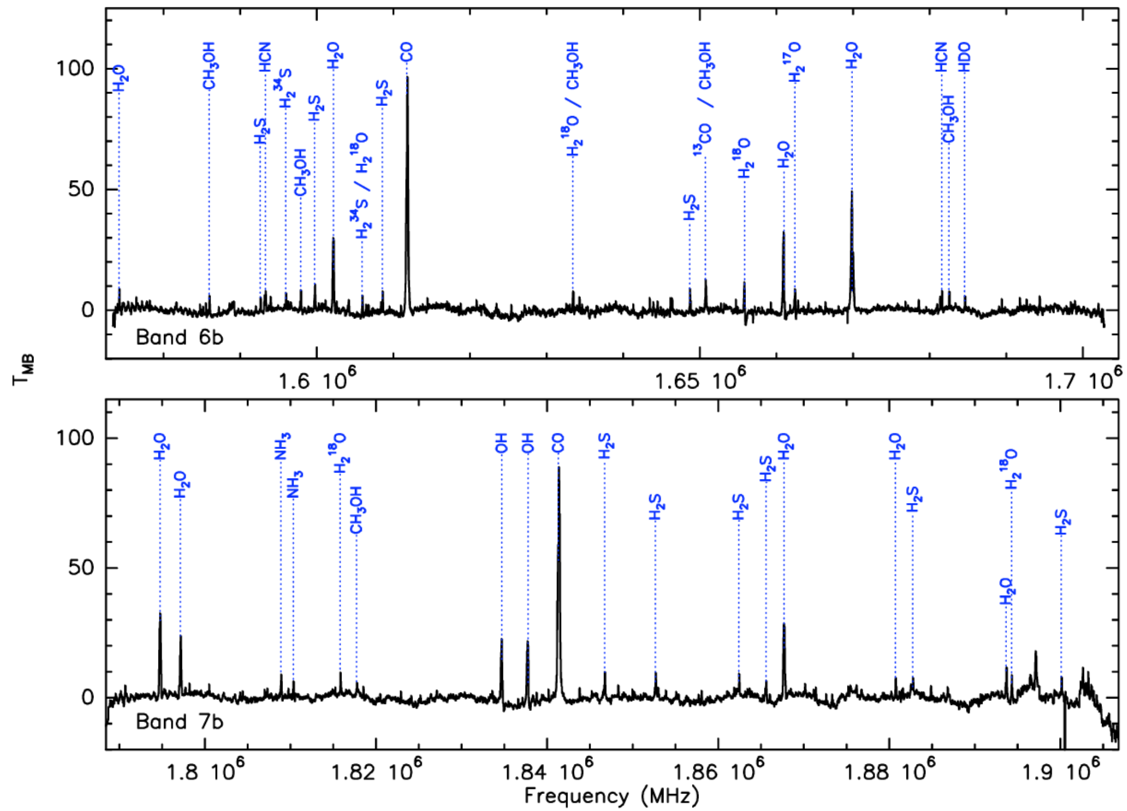




Güsten et al. 2019

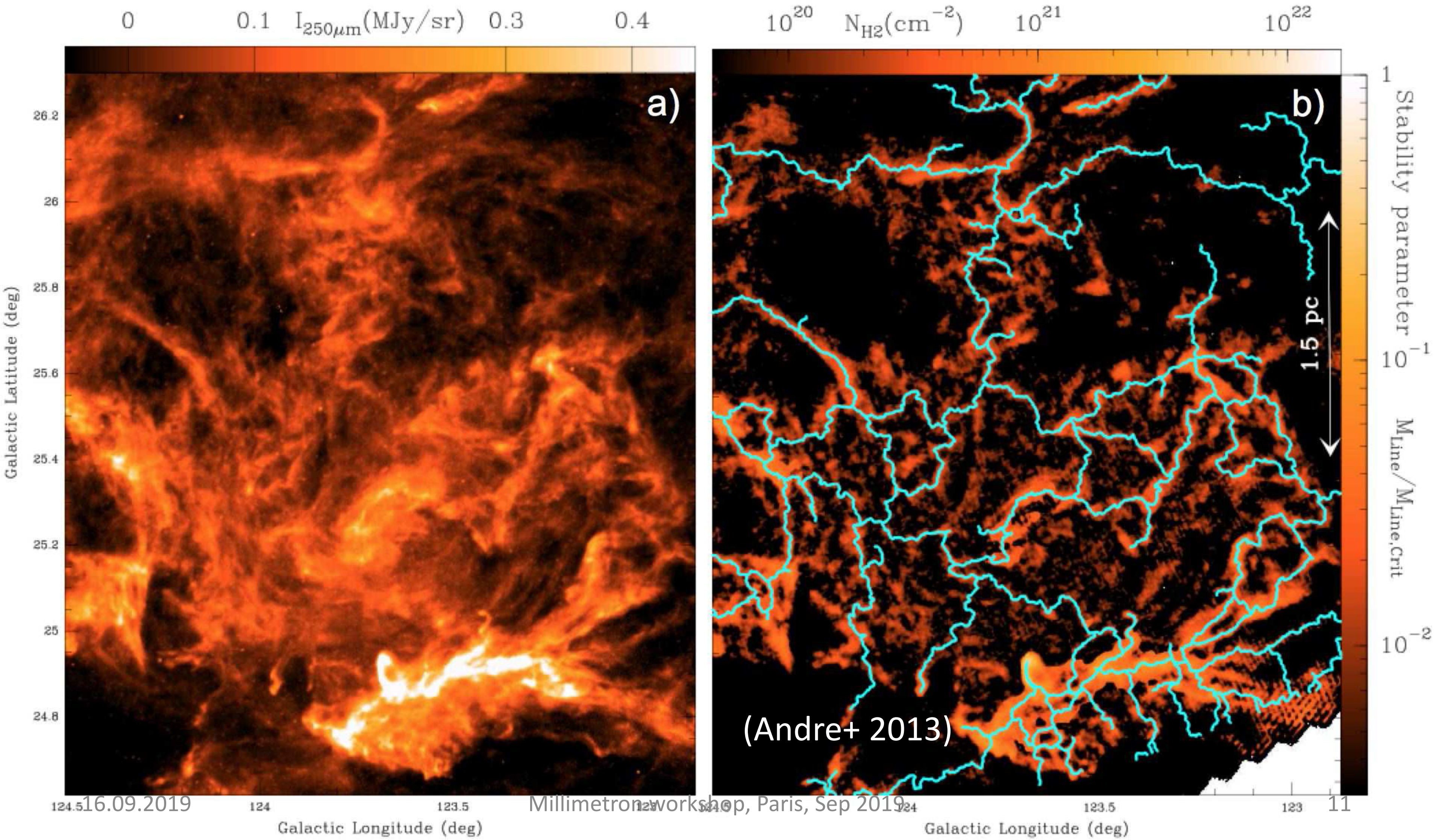
Spectral line surveys



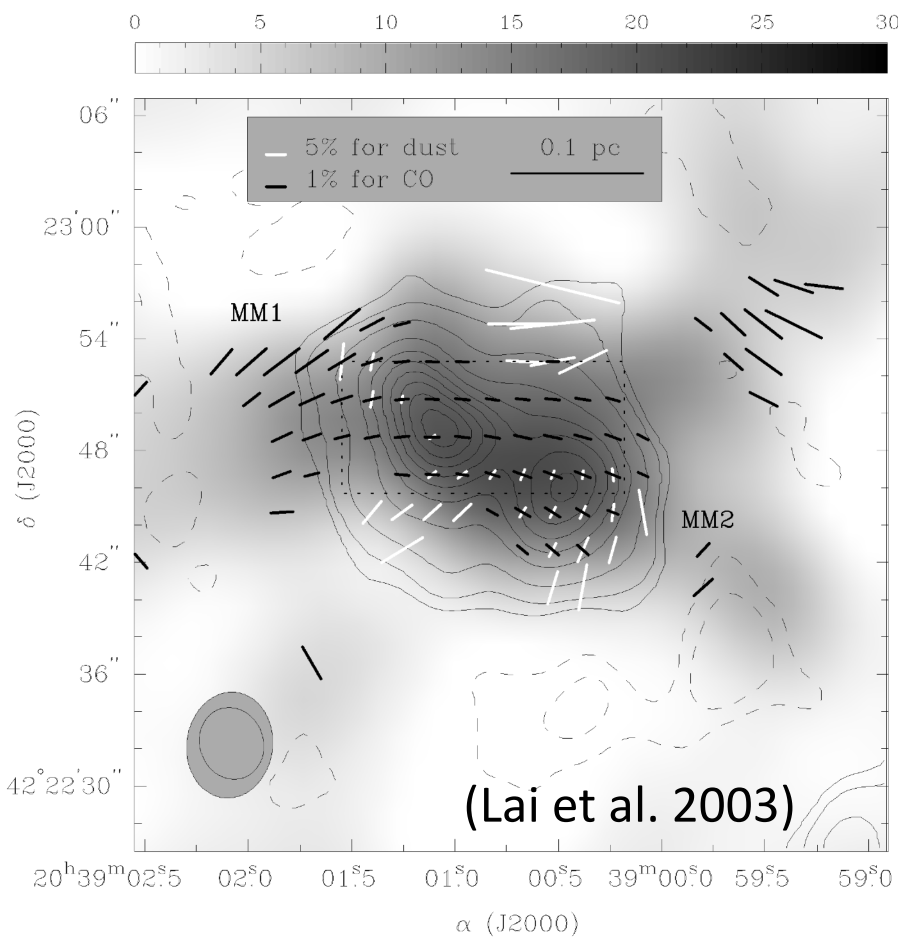


Left panel: ground-based Orion KL spectral surveys: 794-840 GHz (Comito et al. 2005), 600-720 GHz (Schilke et al. 2001) and 325-360 GHz (Schilke et al. 1997). Right panel: THz Orion KL spectrum from Herschel (Crockett et al. 2010).

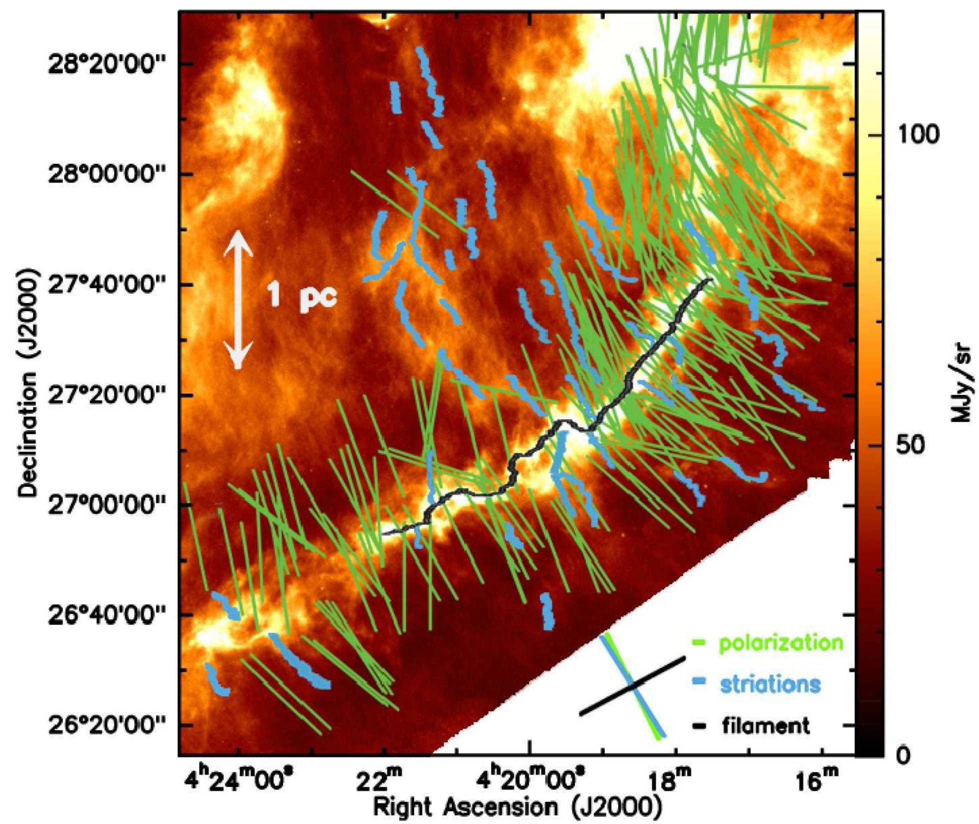
Interstellar filaments



Polarization of dust and molecular emission



(Lai et al. 2003)

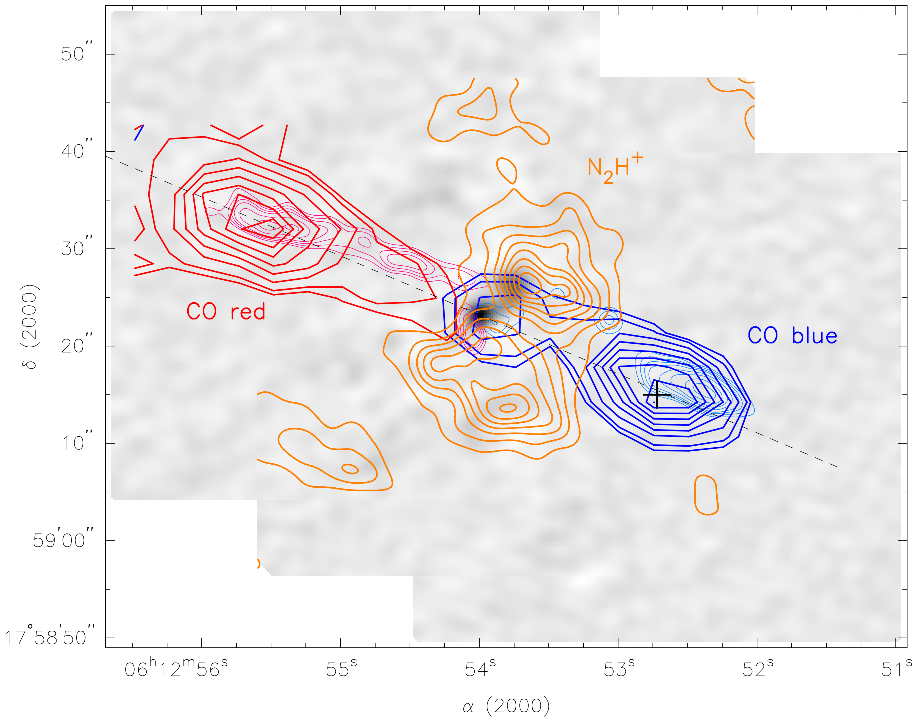


(Andre et al. 2013)

Polarization measurements help to study magnetic field in star forming regions

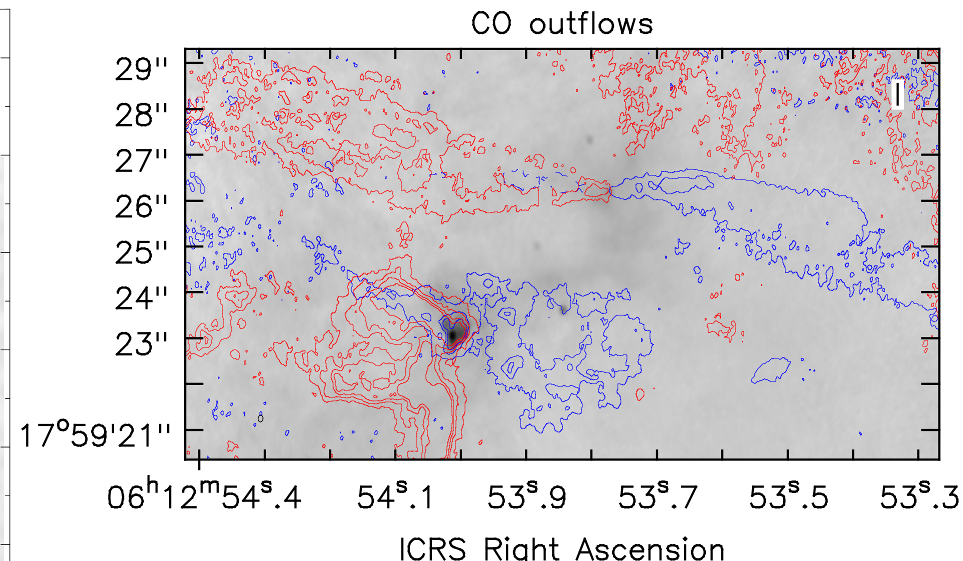
CO outflows in S255IR

SMA+30m

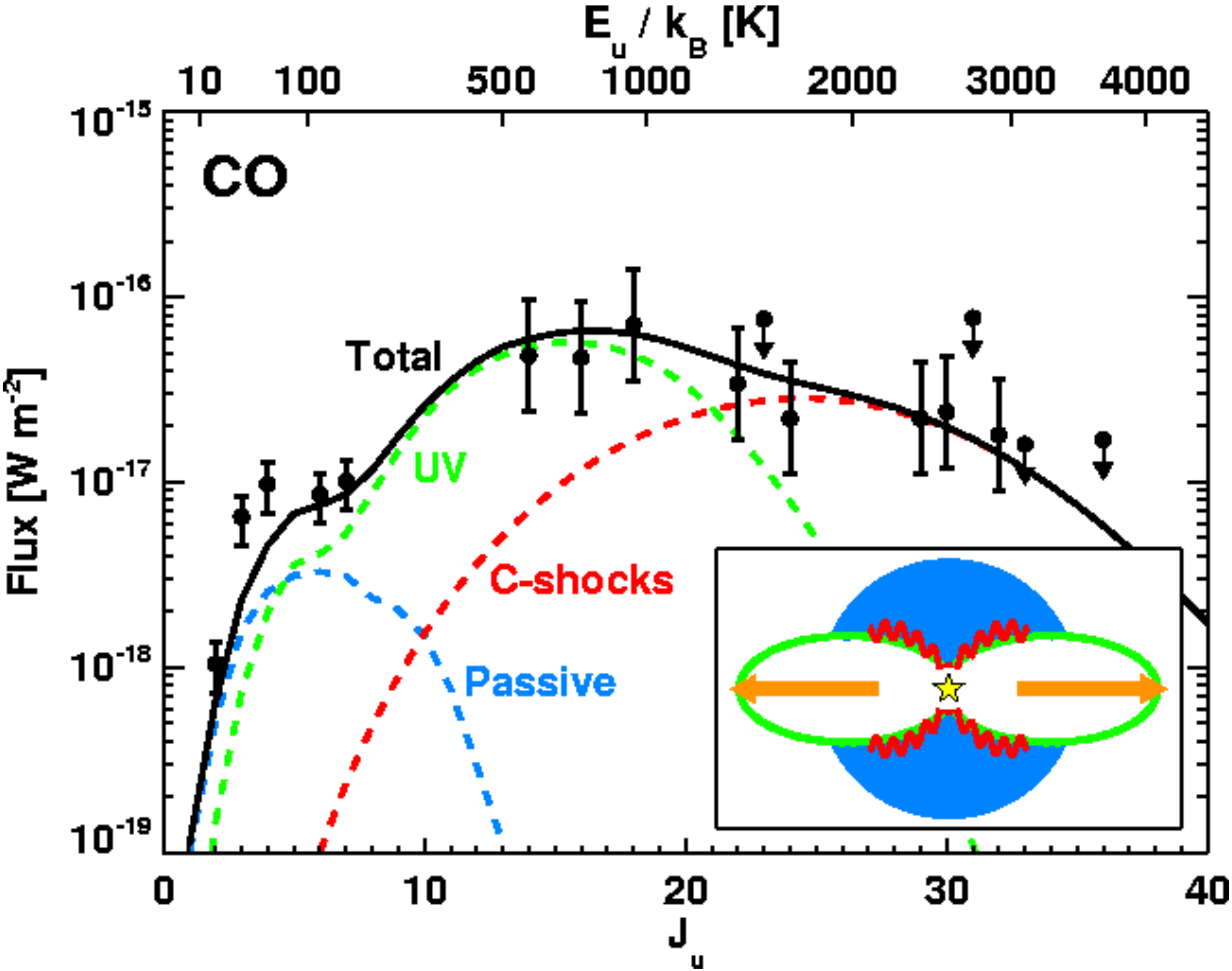


Zinchenko et al. 2015

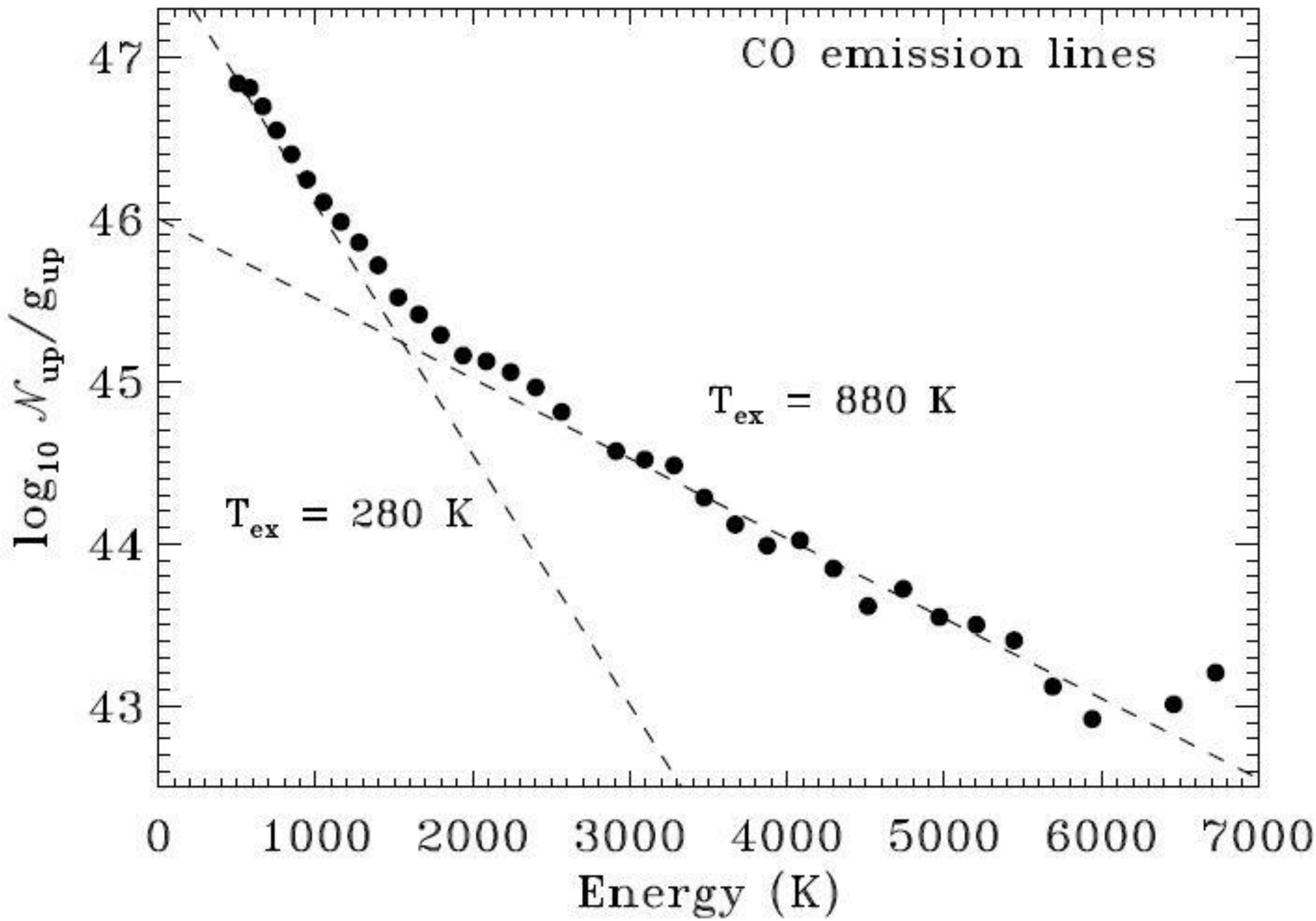
ALMA



Zinchenko et al. 2018

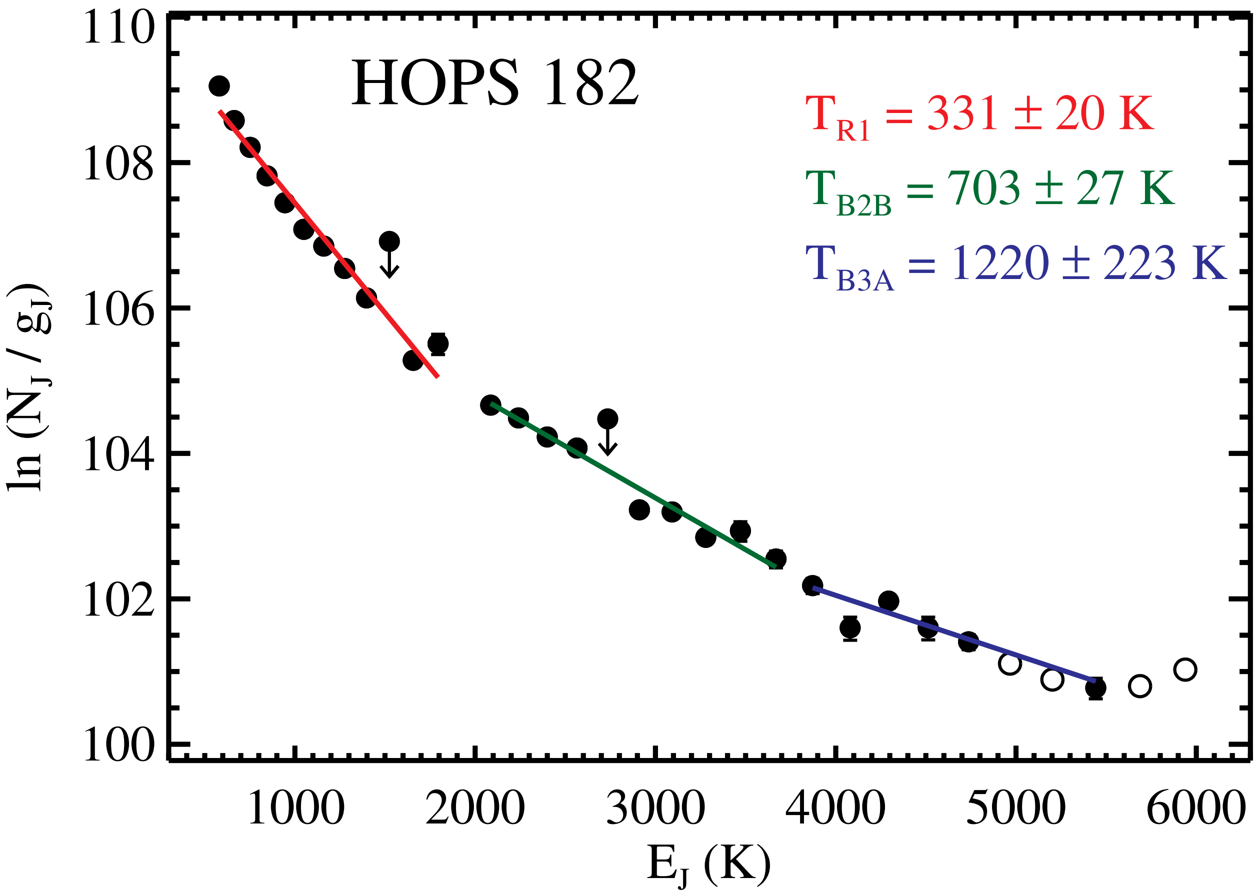


E. van Dishoeck at OSSF14



Herczeg et al. 2012

Studies of hot cores and outflows by high excitation lines of CO and other molecules

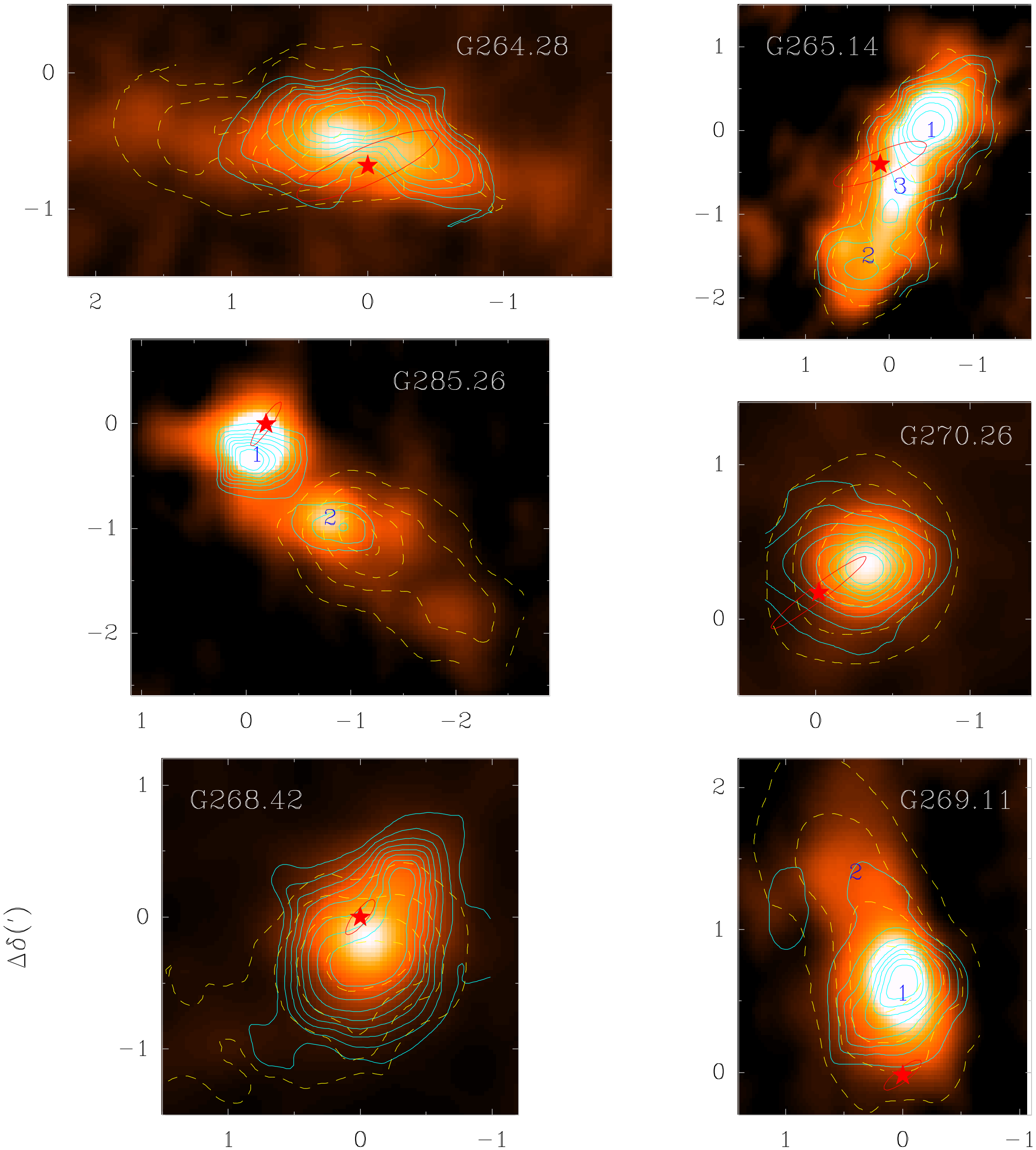


Manoj et al. (2013)

Surveys of star forming cores

- Provide statistical information on physical properties of star forming cores.
- Chemical variations.
- Search for prestellar massive cores.

Observations in the new frequency band can better constrain core properties.



Examples of dense cores in regions of high mass star formation

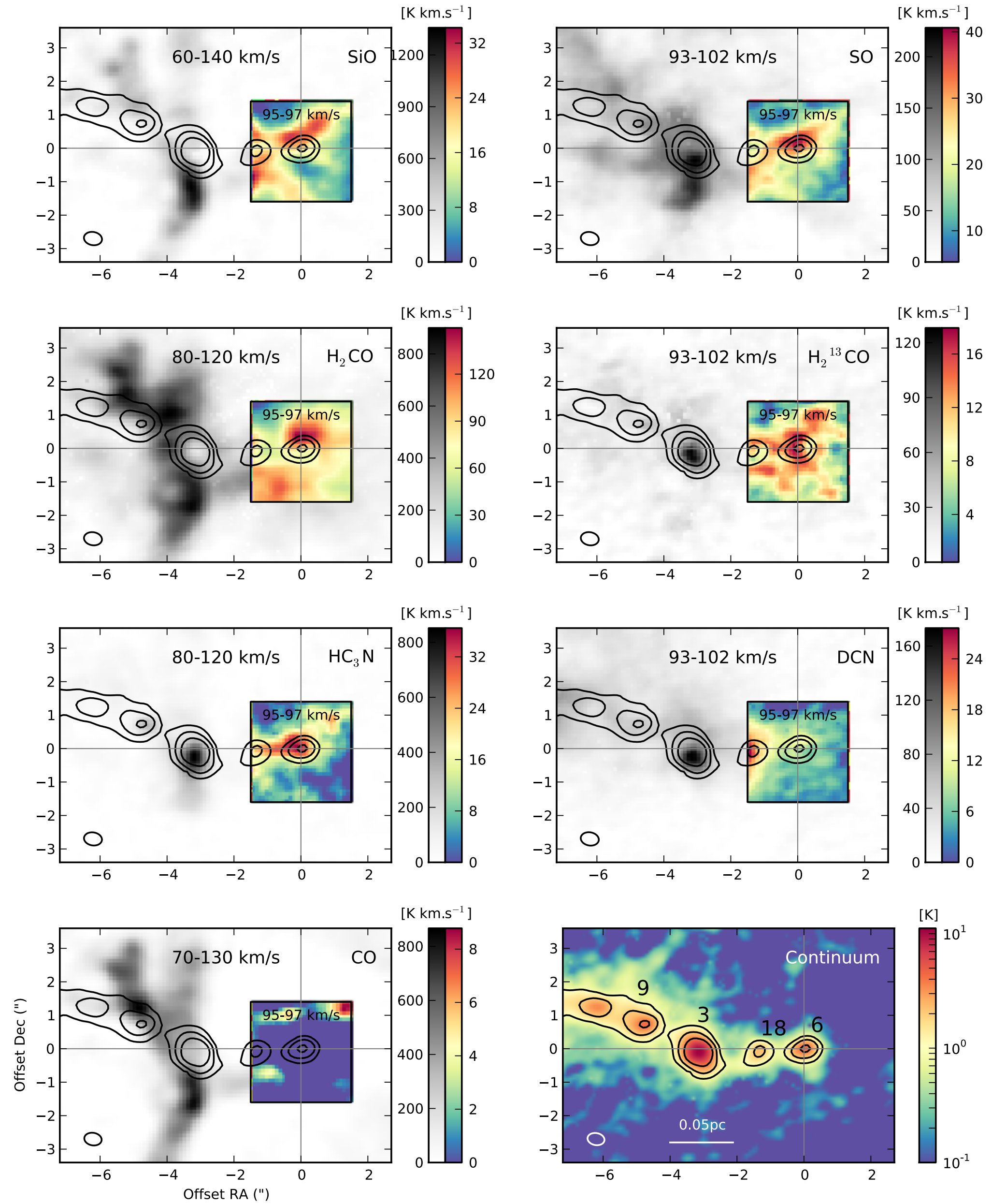
Color maps show dust continuum emission at 1.2 mm, blue contours indicate CS J=5-4 emission and yellow dashed contours correspond to N_2H^+ J=1-0 emission.

(Pirogov, Zinchenko, Caselli, Johansson, 2007)

Internal structure?
Chemical variations?
Evolution stage?

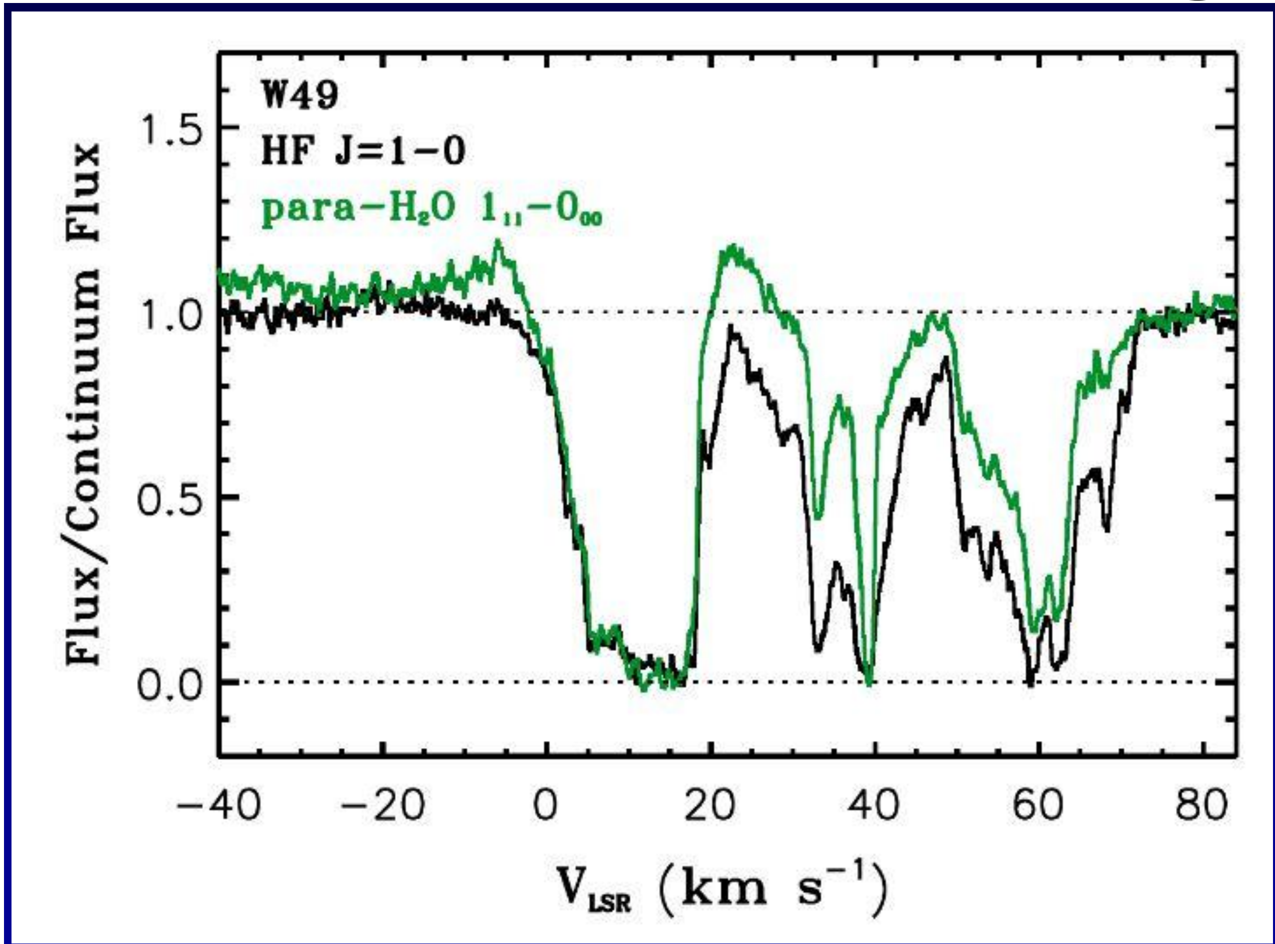
Search for prestellar massive cores

- Only a few high-mass pre-stellar cores (~30 $M_\odot$ for a radius of ~0.03 pc) have been reported.
- The expected flux density at 300 μm for such core at the distance of 10 kpc is ~ 100 mJy.
- Millimetron will be able to easily detect such objects across the Milky Way galaxy.



Molet et al. (2019)

Diffuse interstellar gas



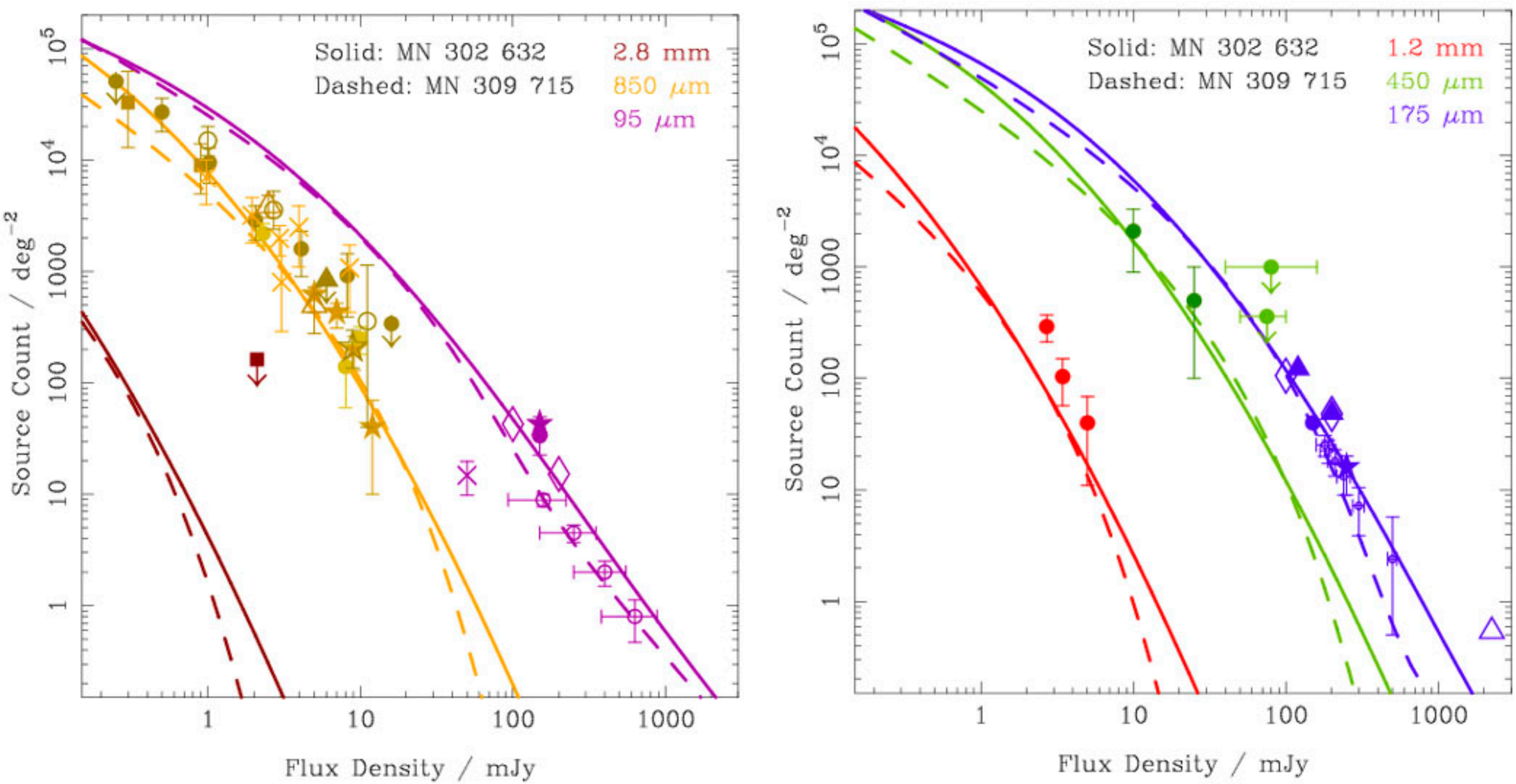
Water
o/p=3

Neufeld et al. 2010,
Sonnetrucker et al. 2010
Godard et al. 2012
Emprechtinger et al. 2012
Flagey et al. 2013

Strong background sources are required.

At T_{sys} ~ 1000 K, ΔV ~ 1 km/s and Δt ~ 1 h ΔS ~ 1 Jy

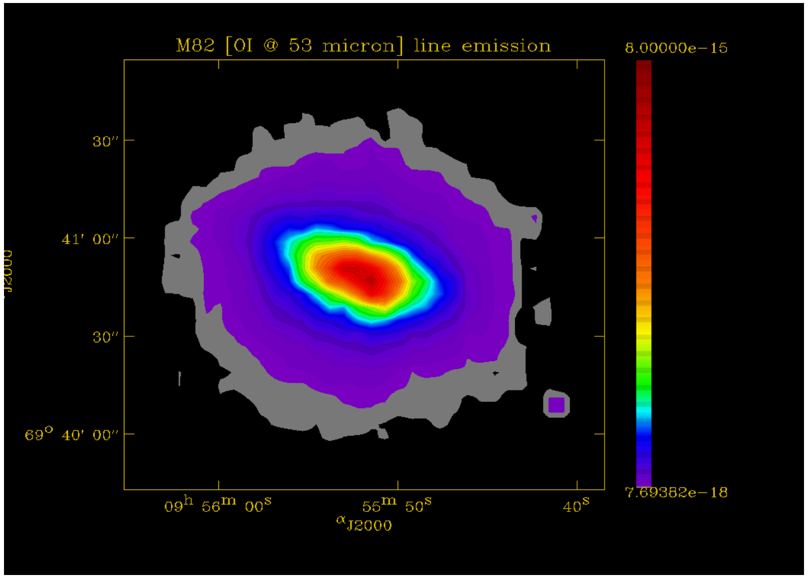
Source counts

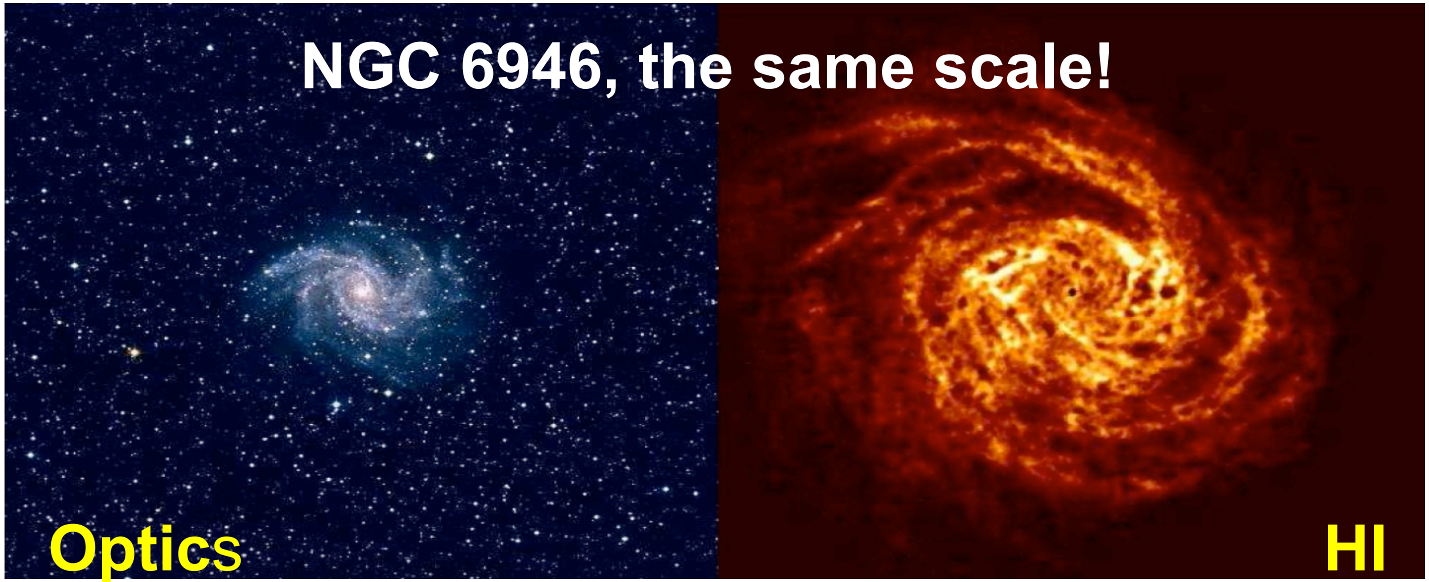


Blain et al. 2002

ISM in external galaxies

Map of M82 in the [OI] 63μ line obtained with Herschel-PACS (Contursi et al. 2010).





Submillimeter masers

120 Humphreys

Table 1. H_2O Masers

Freq. (GHz)	Transition J_{k_a,k_c} - J_{k_a,k_c}	Vib. State	Species[1]	E_u/k (K)	CSE[2]	SFR[2]	EXG[2]	Primary Reference
22.235	6_{16} - 5_{23}	G	O	644	Y	Y	Y	Cheung *et al.* (1969)
96.261	4_{40} - 5_{33}	ν_2=1	P	3065	Y			Menten & Melnick (1989)
183.308	3_{13} - 2_{20}	G	P	205	Y	Y	Y	Waters *et al.* (1980)
232.687	5_{50} - 6_{43}	ν_2=1	O	3463	Y			Menten & Melnick (1989)
293.439	6_{61} - 7_{52}	ν_2=1	O	3935	Y			Menten *et al.* (2006)
321.226	10_{29} - 9_{36}	G	O	1862	Y	Y		Menten *et al.* (1990a)
325.153	5_{15} - 4_{22}	G	P	470	Y	Y		Menten *et al.* (1990b
[3]336.228	5_{23} - 6_{16}	ν_2=1	O	2956	Y			Feldman *et al.* (1993)
354.885	17_{412} - 16_{710}	G	O	5782	Y			Feldman *et al.* (1991)
380.194	4_{14} - 3_{21}	G	O	324		Y		Phillips *et al.* (1980)
437.347	7_{53} - 6_{60}	G	P	1525	Y			Melnick *et al.* (1993)
439.151	6_{43} - 5_{50}	G	O	1089	Y	Y		Melnick *et al.* (1993)
470.889	6_{42} - 5_{51}	G	P	1091	Y	Y		Melnick *et al.* (1993)
658.007	1_{10} - 1_{01}	ν_2=1	O	2361	Y			Menten & Young (1995)

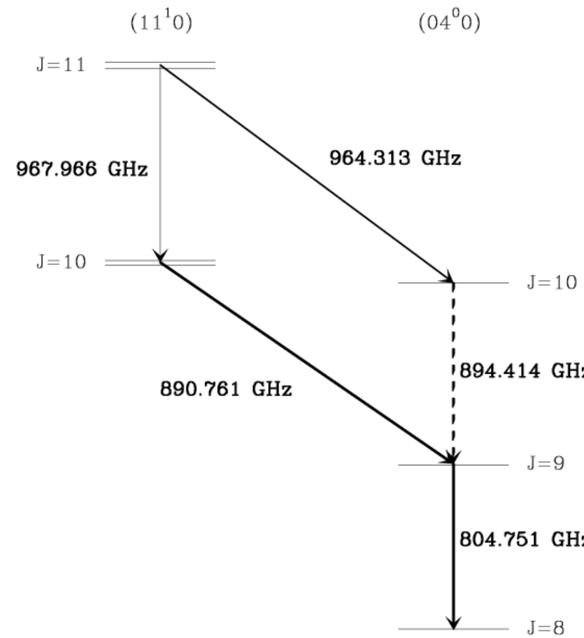
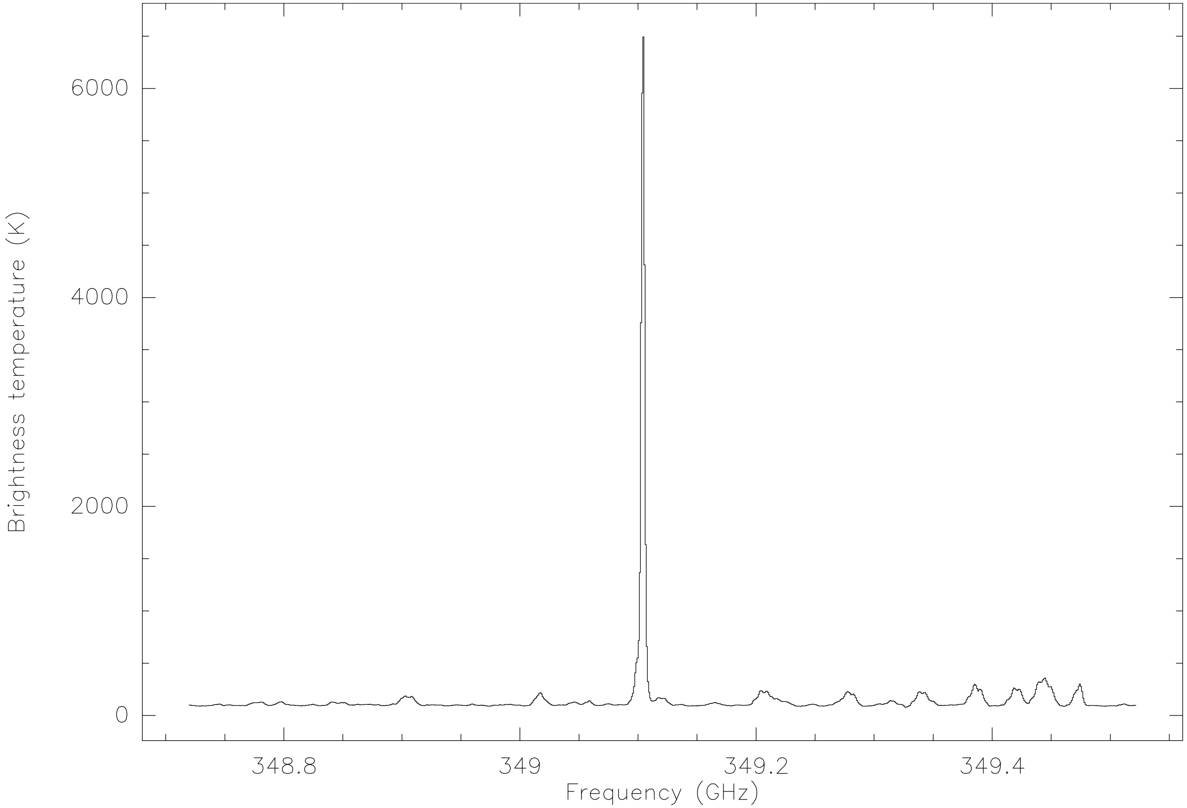
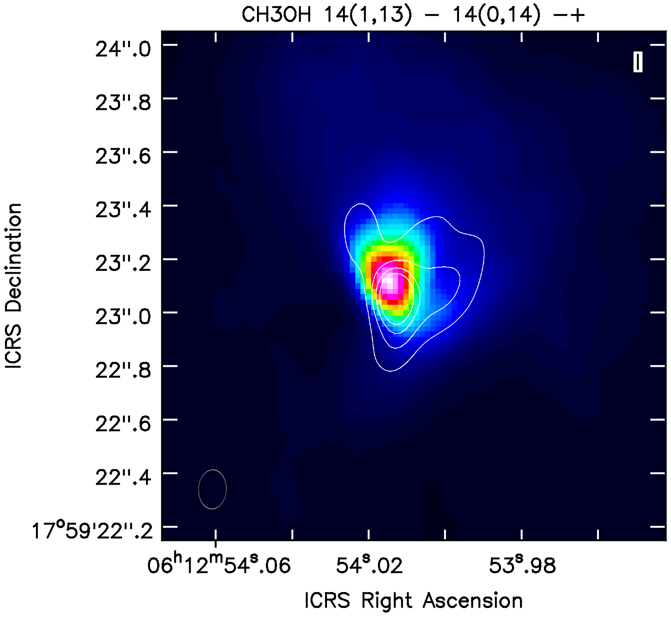


Fig. 1.—Excerpt from the level diagrams of the (11^10) and (04^00) vibrationally excited states of HCN near the Coriolis resonance involving the $J = 8$–12 rotational levels. *Arrows*: Frequencies of prominent laser transitions measured in the laboratory by Hocker & Javan (1967). *Bold arrows*: Lines observed toward IRC +10216. *Dashed arrow*: (04^00), $J = 10$–9 line not detected by us.

Detection of a new methanol maser line with ALMA





Zinchenko, et al. (2017)

Key problems

- General properties of ISM in galaxies
- The earliest stages of star formation
- Mechanisms of (high mass) star formation
- Astrochemistry, spectral surveys

Possible observational programs

- HD surveys
- ^{12}C II and ^{13}C II surveys
- HeH^{+} surveys
- Water in protoplanetary disks and outflows
- High excitation CO and other lines
- Absorption spectroscopy of diffuse clouds
- Magnetic field from polarization measurements

Conclusions

- Millimetron will be a unique instrument for many astrophysical problems, in particular in the field of the ISM and star formation studies.
- The best results can be achieved by combination of the space-borne and ground based facilities.

Thank you for attention!