Prospects for PDR observations

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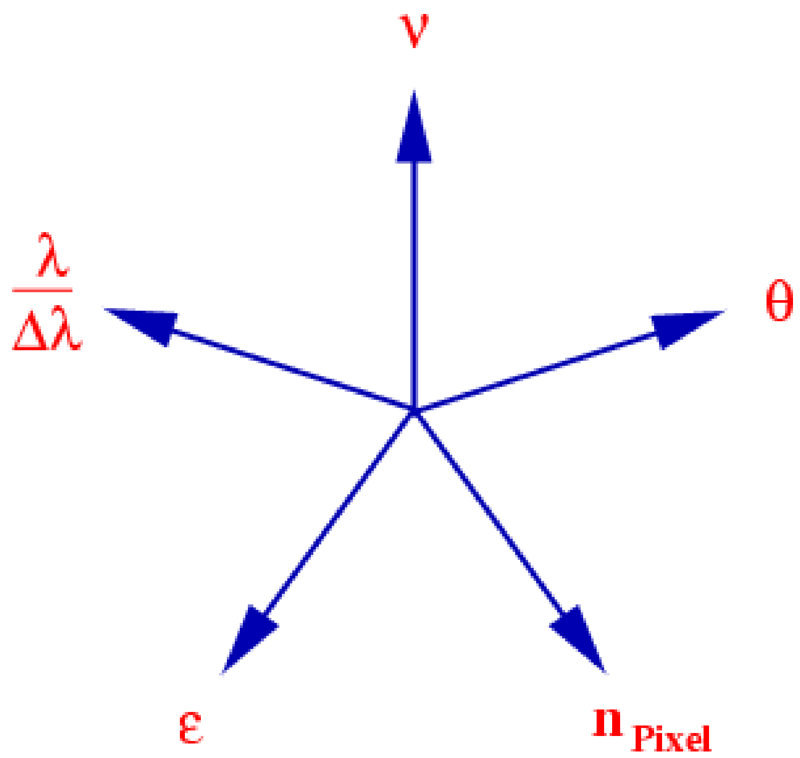
Improvements of the observing technology

Properties of each instrument:



- new frequencies
- higher sensitivity
- better spatial resolution
- better spectral resolution
- arrays

Sensitivity

Spitzer, APEX, HIFI, ALMA, ...

New observations **PDR related questions**

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New observations	**PDR related questions**
faint and diffuse clouds	low density, low χ PDRs

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faint and diffuse clouds	low density, low χ PDRs
absorption lines from PDRs	cool parts, detailed radiative transfer

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faint and diffuse clouds	low density, low χ PDRs
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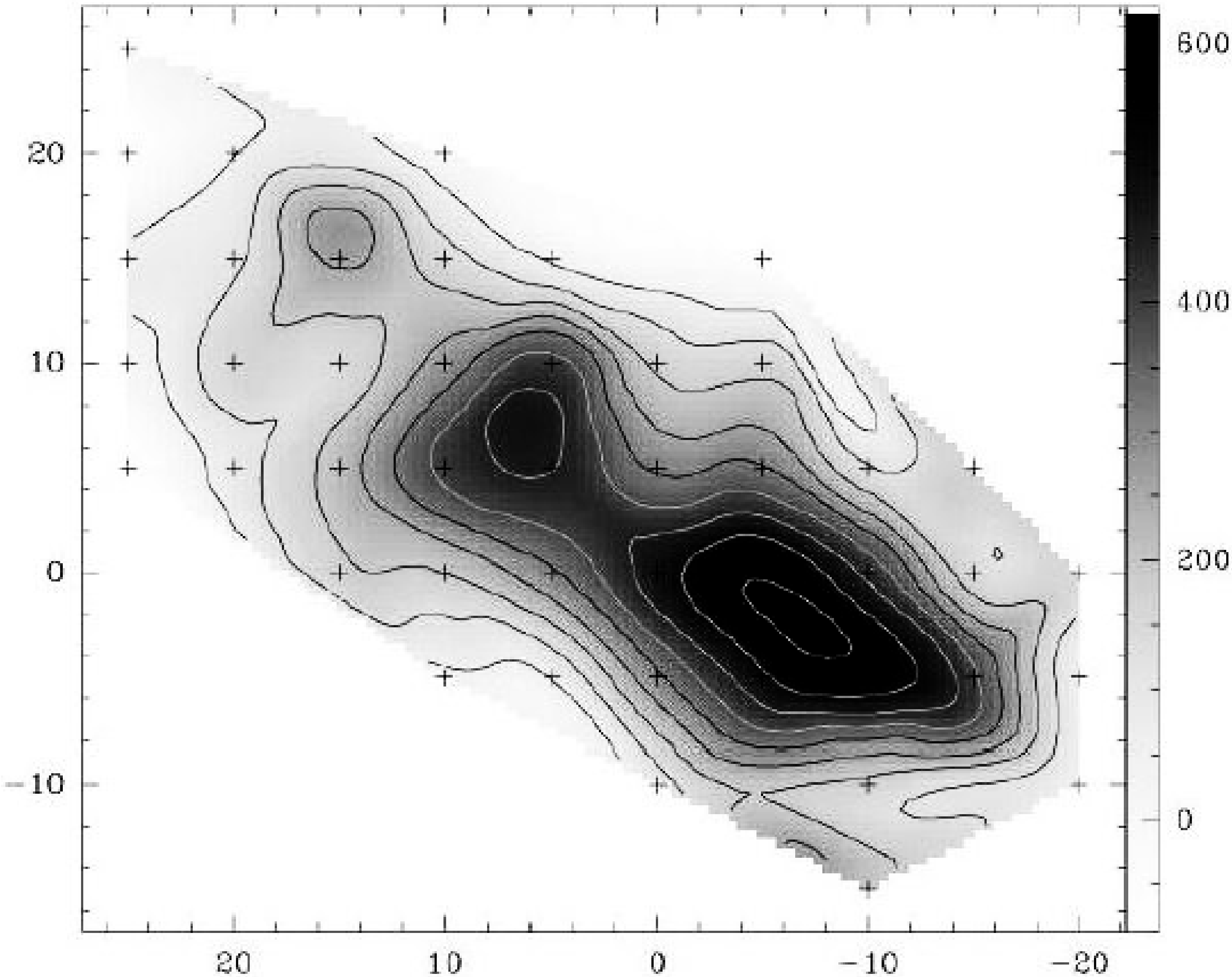
high-redshift galaxies	

Galaxies as PDRs



Extended CO 7-6 in M82 observed with the HHT (Mao et al. 2000)

Sensitivity

Spitzer, APEX, HIFI, ALMA, ...

New observations	**PDR related questions**
faint and diffuse clouds	low density, low χ PDRs
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high-redshift galaxies	interpretation of whole galaxies as PDRs

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faint and diffuse clouds	low density, low χ PDRs
absorption lines from PDRs	cool parts, detailed radiative transfer
high-redshift galaxies	interpretation of whole galaxies as PDRs

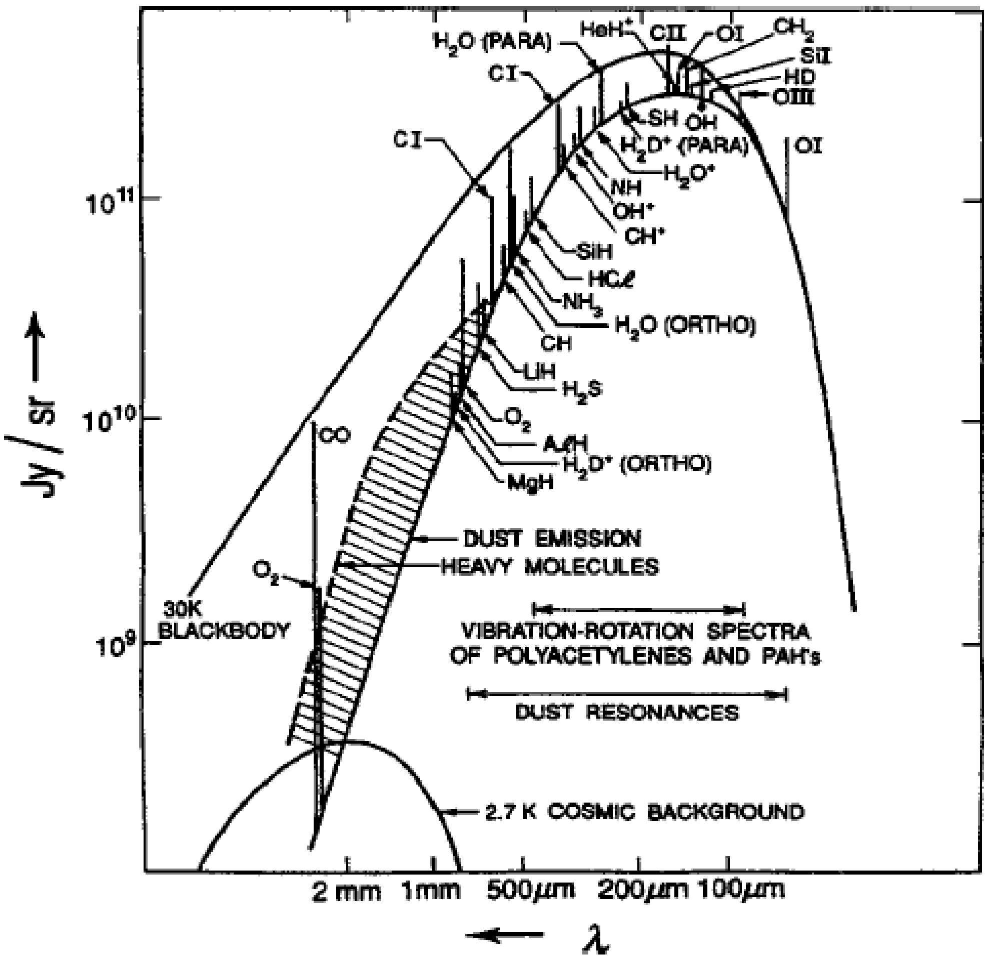
☞ We have to provide knowledge on the “average Galactic PDRs”, not just the bright ones which are mainly observed until now.

Wavelength coverage

SOFIA, HIFI, ...

New observations	**PDR related questions**
lines and continuum quasi-simultaneously	

The full FIR spectrum "at one shot"



Schematic view of the spectrum of M82 (Phillips & Keene 1992).

We get simultaneously:

- molecular rotational lines
- atomic fine structure lines
- spectral energy distribution of the continuum
- dust features in the continuum

☞ Line and continuum interpretation has to go hand in hand.

Wavelength coverage

SOFIA, HIFI, ...

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lines and continuum quasi-simultaneously	

Wavelength coverage

SOFIA, HIFI, ...

New observations	**PDR related questions**
lines and continuum quasi-simultaneously	interplay with continuum (FIR pumping, PAH excitation, ice destruction ...)
	all major PDR cooling lines

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SOFIA, HIFI, ...

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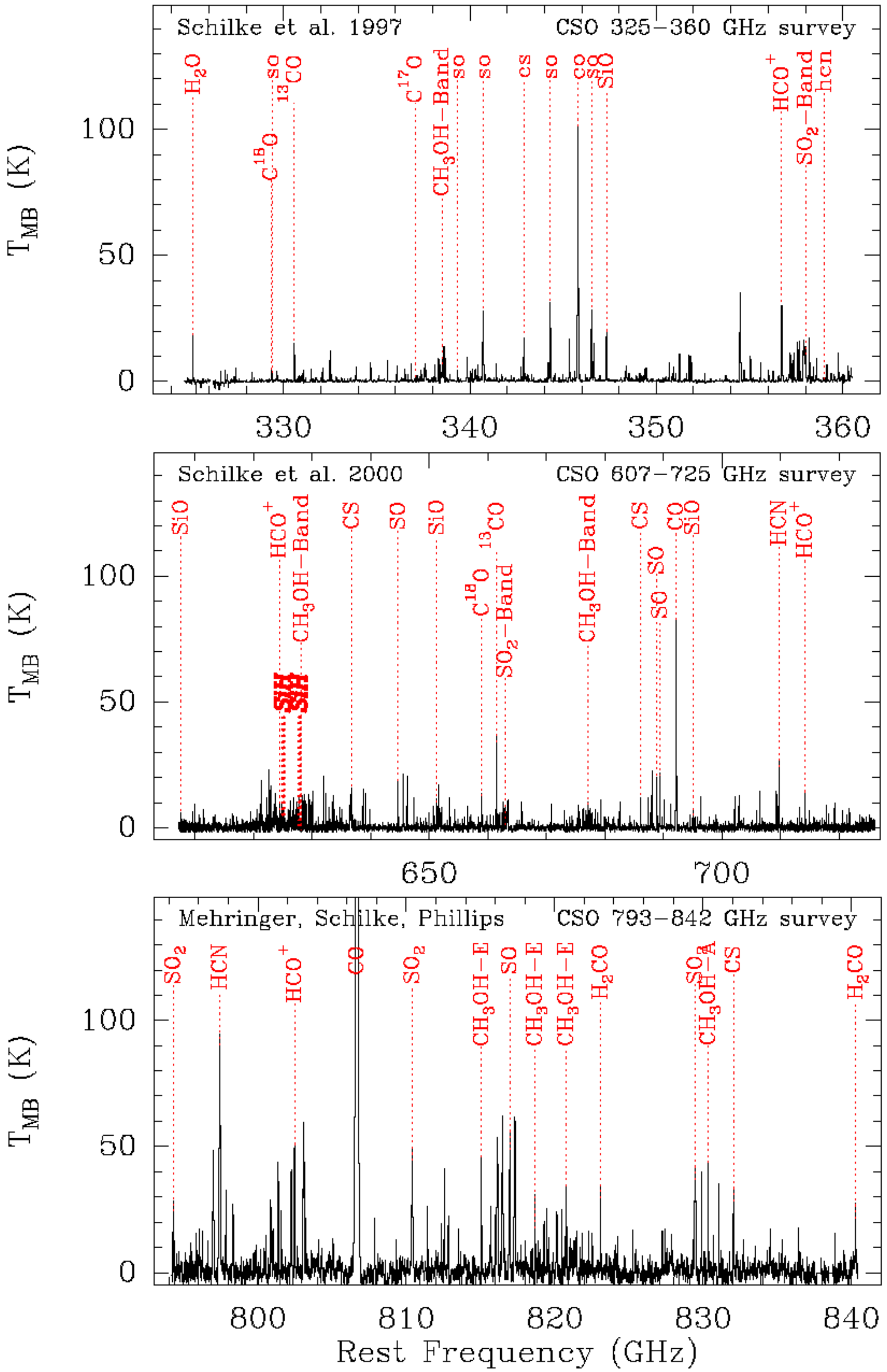
full frequency surveys	

Search for the complete chemical inventory



First systematic frequency surveys in the submm (Orion KL, Schilke et al. 2002)

Wavelength coverage

SOFIA, HIFI, ...

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full frequency surveys	huge chemical network

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hydrides in their ground state
(CH, NH, NH^+, NH_3, OH^+, H_3O^+, H_2O)

Table 2: Line candidates for HIFI observations to trace the chemical and physical structure of PDRs and shocks

molecule	transition	frequency [GHz]	lower level energy [K]	$\kappa_{\rm LTE,rel}$ [km/s cm^2] at 10 K	at 50 K	at 100 K	at 300 K	bonus line	comments
CII	$^2P_{3/2} - ^2P_{1/2}$	1900.545	0	$7.5\,10^{-18}$	$4.8\,10^{-18}$	$2.5\,10^{-18}$	$8.0\,10^{-19}$		
CH	$^2\Pi_{3/2}\ 1,2^- - {}^2\Pi_{1/2}\ 1,1^+$	536.761	0	$2.2\,10^{-14}$	$3.8\,10^{-15}$	$1.2\,10^{-15}$	$1.5\,10^{-16}$		$^2\Pi_{3/2}\ 1,1^- - {}^2\Pi_{1/2}\ 1,1^-$ and $^2\Pi_{3/2}\ 1,1^- - {}^2\Pi_{1/2}\ 1,0^+$ only 20 MHz apart
	$^2\Pi_{5/2}\ 2,3^- - {}^2\Pi_{3/2}\ 1,2^+$	1656.961	26	$8.8\,10^{-15}$	$2.1\,10^{-14}$	$1.1\,10^{-14}$	$1.9\,10^{-15}$	✓	blended with $^2\Pi_{5/2}\ 2,2^- - {}^2\Pi_{3/2}\ 1,2^+$ and $^2\Pi_{5/2}\ 2,2^- - {}^2\Pi_{3/2}\ 1,1^+$, simultaneously with $H_3O^+\ 1_{1,1} - 1_{1,0}$
CH^+	1-0	835.07	0	$1.2\,10^{-13}$	$2.4\,10^{-14}$	$7.7\,10^{-15}$	$1.0\,10^{-15}$		
	2-1	1669.16	40	$4.3\,10^{-15}$	$3.1\,10^{-14}$	$1.7\,10^{-14}$	$3.3\,10^{-15}$		
NH	$^3\Sigma^-\ 1,1/2 - 0,1/2$	974.479	0	$6.5\,10^{-14}$	$1.6\,10^{-14}$	$5.5\,10^{-15}$	$3.9\,10^{-16}$	✓	blended with $^3\Sigma^-\ 1,3/2-0,1/2$, $^3\Sigma^-\ 1,3/2 - 0,3/2$, lines between 974.531 and 974.607 GHz simultaneously, $H_2O\ 2_{0,2} - 1_{1,1}$ in upper sideband
NH+	$^2\Pi_{1/2c}\ 3/2,5/2,3 - 1/2,3/2,2$	1012.524	0	$4.7\,10^{-16}$	$7.2\,10^{-15}$	$4.0\,10^{-15}$	$7.5\,10^{-16}$		blended $^2\Pi_{1/2c}\ 3/2,3/2,2 - 1/2,1/2,1$; four other transitions only 30–50 MHz apart
NH_3	$1_0 - 0_0$	572.498	0.5	$1.7\,10^{-13}$	$1.1\,10^{-14}$	$2.3\,10^{-15}$	$1.7\,10^{-16}$		
	$2_1 - 1_1$	1168.452	24	$1.3\,10^{-14}$	$8.4\,10^{-15}$	$2.5\,10^{-15}$	$2.3\,10^{-16}$		
OH^+	$^3\Sigma^-\ 1,2,5/2 - 0,1,3/2$	971.804	0	$3.2\,10^{-13}$	$8.1\,10^{-14}$	$2.7\,10^{-14}$	$3.6\,10^{-15}$	✓	blended with $^3\Sigma^-\ 1,2,3/2 - 0,1,1/2$; $^3\Sigma^-\ 1,2,3/2 - 0,1,3/2$ only 15 MHz apart, simultaneously with NH
H_3O^+	$1_{1,1} - 1_{1,0}$	1655.814	0	$6.5\,10^{-14}$	$1.7\,10^{-14}$	$4.4\,10^{-15}$	$3.5\,10^{-16}$		$2_{2,1} - 2_{2,0}$ simultaneously at 1657.236 GHz
	$0_{0,1} - 1_{0,0}$	984.697	7	$4.1\,10^{-14}$	$1.5\,10^{-14}$	$3.8\,10^{-15}$	$2.8\,10^{-16}$	✓	simultaneously with $H_2O\ 2_{0,2} - 1_{1,1}$
p-H_2O	$1_{1,1} - 0_{0,0}$	1113.343	0	$4.2\,10^{-13}$	$8.6\,10^{-14}$	$2.0\,10^{-14}$	$1.6\,10^{-15}$		
	$2_{0,2} - 1_{1,1}$	987.927	53	$1.5\,10^{-15}$	$2.1\,10^{-14}$	$8.2\,10^{-15}$	$9.0\,10^{-16}$		
	$2_{1,1} - 2_{0,2}$	752.033	101	$3.6\,10^{-17}$	$1.9\,10^{-14}$	$1.1\,10^{-14}$	$1.6\,10^{-15}$		
o-H_2O	$1_{1,0} - 1_{0,1}$	556.936	0	$1.9\,10^{-13}$	$4.2\,10^{-14}$	$1.2\,10^{-14}$	$1.1\,10^{-15}$	✓	$NH_3\ 1_0 - 0_0$ in the upper sideband
	$2_{1,2} - 1_{0,1}$	1669.905	0	$2.0\,10^{-13}$	$8.0\,10^{-14}$	$2.9\,10^{-14}$	$3.0\,10^{-15}$	✓	simultaneously with $CH^+\ 2-1$
	$3_{0,3} - 2_{1,2}$	1716.770	114	$7.7\,10^{-17}$	$1.9\,10^{-14}$	$1.5\,10^{-14}$	$2.8\,10^{-15}$		
HDO	$1_{1,1} - 0_{0,0}$	893.639	0	$2.7\,10^{-13}$	$2.1\,10^{-14}$	$4.6\,10^{-15}$	$3.4\,10^{-16}$		
$H_2{}^{18}O$	$1_{1,1} - 0_{0,0}$	1101.698	0	$4.2\,10^{-13}$	$8.5\,10^{-14}$	$2.0\,10^{-14}$	$1.6\,10^{-15}$	✓	$H_2O\ 1_{1,1} - 0_{0,0}$ in the upper sideband
OH	$2\Pi_{1/2}\ 3/2 - 1/2$	1834.747	181	$6.5\,10^{-22}$	$9.6\,10^{-16}$	$2.9\,10^{-15}$	$1.5\,10^{-15}$	✓	CO 16-15 in the upper sideband
CO	10-9	1151.985	249	$5.8\,10^{-26}$	$3.7\,10^{-18}$	$1.4\,10^{-17}$	$1.0\,10^{-17}$		
	16-15	1841.345	663	$3.2\,10^{-32}$	$1.8\,10^{-21}$	$4.9\,10^{-19}$	$5.9\,10^{-18}$		
^{13}CO	10-9	1101.350	238	$1.7\,10^{-25}$	$4.3\,10^{-18}$	$1.5\,10^{-17}$	$9.6\,10^{-18}$	✓	$H_2O\ 1_{1,1} - 0_{0,0}$ in the upper sideband
	15-14	1650.768	555	$7.5\,10^{-31}$	$1.4\,10^{-20}$	$1.2\,10^{-18}$	$7.0\,10^{-18}$	✓	$H_3O^+\ 1_{1,1} - 1_{1,0}$ in the upper sideband

Uncertainties in hydride intensities

Species	Freq. [GHz]	Relative Abundance at (0,0)	T_B † [K] at (0,0)
CII	1900.545	1.0E-05	6.5E+01 (3.6E+1)
CH	536.761	1.5E-09	2.0E+00
CH	1656.961	1.5E-09	6.9E+00
CH^+	835.070	9.3E-13	2.5E-03 (1.6E-1)
CH^+	1669.160	9.3E-13	8.0E-03 (2.3E-2)
NH	974.479	5.6E-10	2.2E+00
NH^+	1012.524	2.2E-13	4.5E-04
NH_3	572.498	4.3E-11	2.1E-01
NH_3	1168.452	4.3E-11	4.3E-03
OH^+s	971.804	5.7E-13	5.5E-03
H_3O^+	1655.814	1.0E-10	1.4E-02
H_3O^+	984.697	1.0E-10	4.8E-02
H_2O	1113.343	2.2E-07	1.6E+00 (2.0E-1)
H_2O	987.927	2.2E-07	1.8E+00 (2.8E-2)
H_2O	752.033	2.2E-07	1.6E-01
H_2O	556.936	2.2E-07	5.4E+00 (1.0E+0)
H_2O	1669.905	2.2E-07	3.8E-01
HDO	893.639	1.3E-12	1.1E-02
$H_2^{18}O$	1101.698	2.0E-10	1.5E+00
CO(10-9)	1151.985	2.6E-04	1.4E+01 (2.1E+0)
CO(15-14)	1726.603	2.6E-04	9.2E+00 (4.8E-4)
13CO(10-9)	1101.350	3.8E-06	4.0E+00
13CO(15-14)	1650.768	3.8E-06	3.0E-01
OH	2509.988	4.0E-10	1.4E-02
OH	2514.316	4.0E-10	1.4E-02
O	4745.804	1.4E-04	3.8E+00 (1.5E+2)
O	2060.068	1.4E-04	2.4E+00 (5.6E+1)

Line estimates for S106 from two different PDR codes (Meudon & KOSMA) obtained with similar input parameters.

Wavelength coverage

SOFIA, HIFI, ...

New observations	**PDR related questions**
lines and continuum quasi-simultaneously	interplay with continuum (FIR pumping, PAH excitation, ice destruction ...) all major PDR cooling lines
full frequency surveys	huge chemical network

hydrides in their ground state
(CH, NH, NH^+, NH_3, OH^+, H_3O^+, H_2O)

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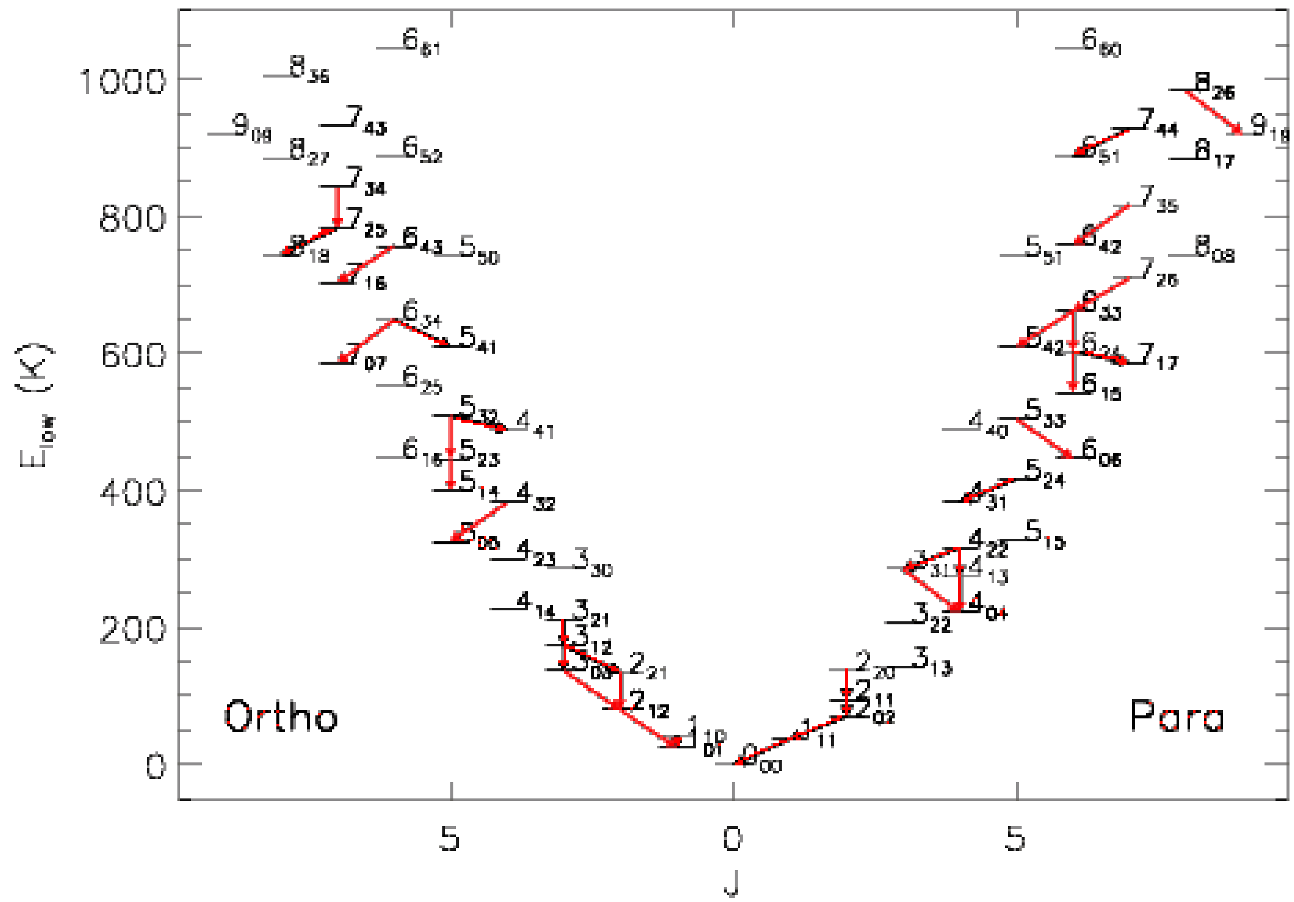
the water ladder	

Water



HIFI will observe a lot of low-level water transitions

☞ We will have the chance to actually understand the chemistry and excitation of water.

Wavelength coverage

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the water ladder	chemistry and cooling by water

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the water ladder	chemistry and cooling by water

☞ Think big! We have to put everything together in the models as we will get everything together in the observations.

Spectral resolution

SOFIA, HIFI, ALMA...

New observations	**PDR related questions**
velocity profile of cooling lines	evaporation of PDRs transport pattern of species (Decamp & Le Bourlot) expansion of HII shells turbulent flows (Gerin et al.)

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SOFIA, HIFI, ALMA...

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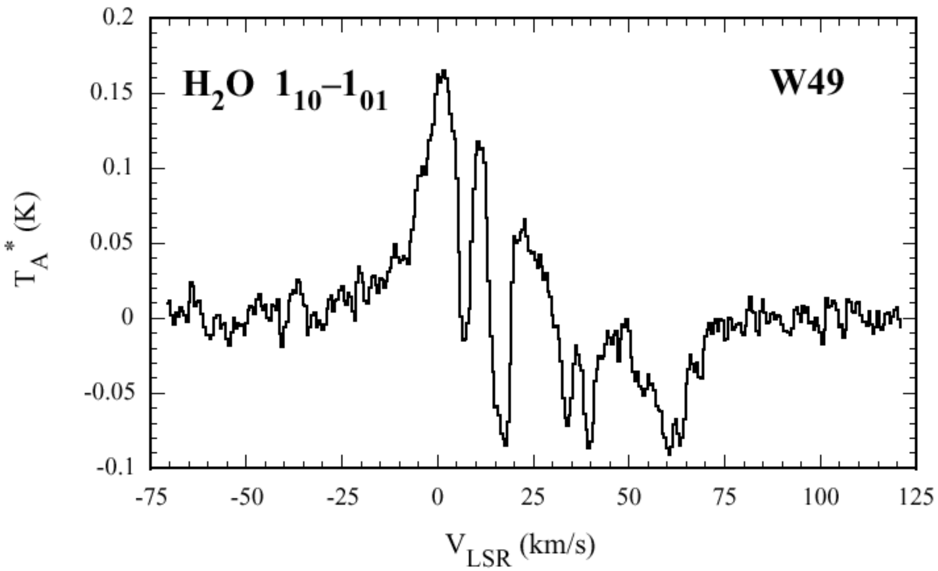
self absorption pattern in the lines	

PDR profiles



SWAS spectrum of the ortho-water ground state transition in W49

☞ Combining the observation of many lines and the profiles only allows to extract the excitation structure along the line of sight.

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SOFIA, HIFI, ALMA...

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☞ Time dependent models will be essential.

Spatial resolution

ALMA

New observations	**PDR related questions**
complex, clumpy, turbulent structure at mas scale	neither plane-parallel nor spherical PDRs merging turbulence models with PDR models

Spatial resolution

ALMA

New observations

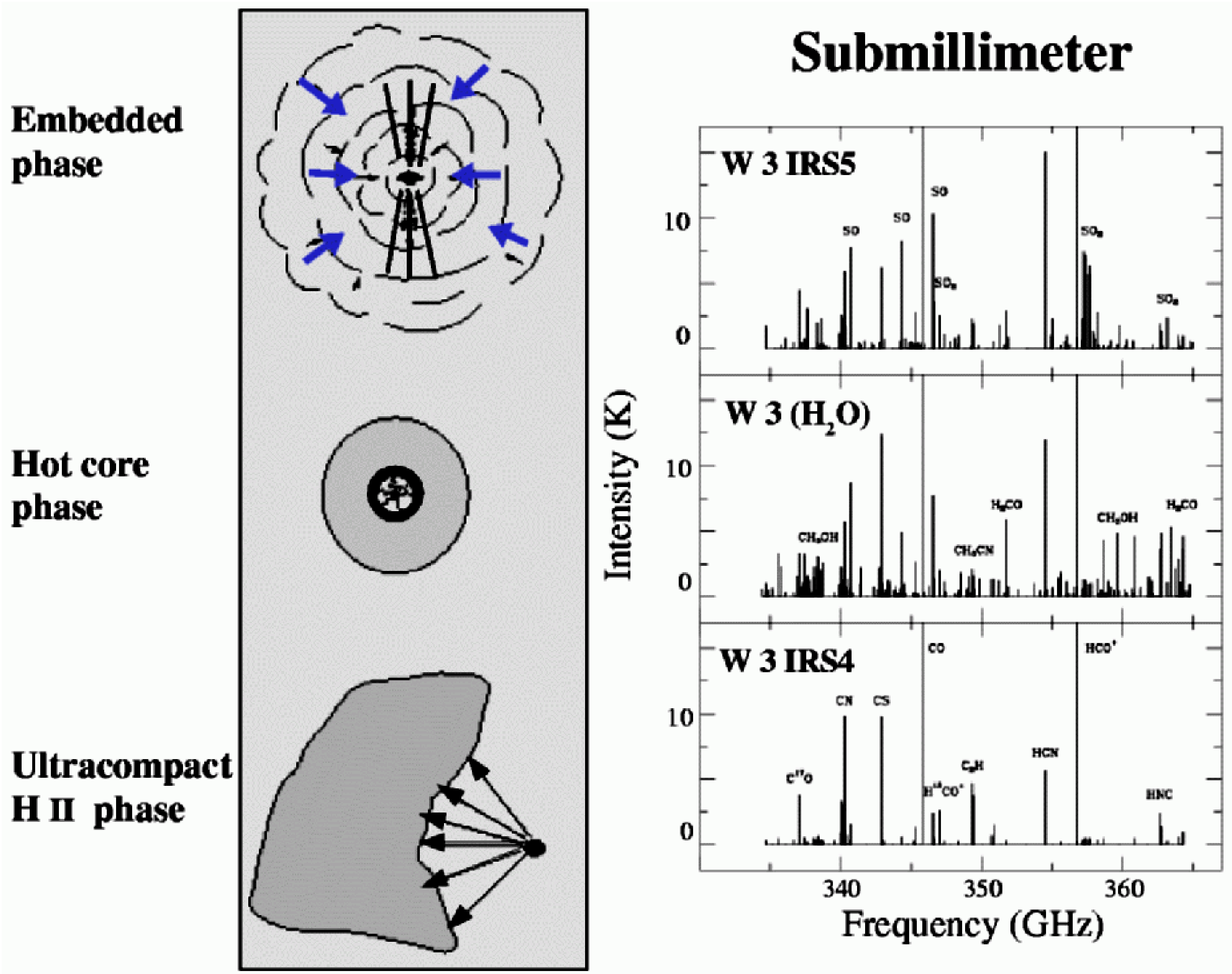
complex, clumpy, turbulent structure at mas scale

resolution dependent pattern of species

PDR related questions

neither plane-parallel nor spherical PDRs
merging turbulence models with PDR models

Chemistry and resolution



The chemical structure is time dependent and changes at different spatial scales on different time scales (Helmich 1998).

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resolution dependent pattern of species	nested-scales chemistry

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☞ We will need 3-D PDR codes.

Conclusion

The modelling progress has to be accelerated to catch up with the upcoming observational prospects.

We need the bundled effort – as started here – to achieve this acceleration.