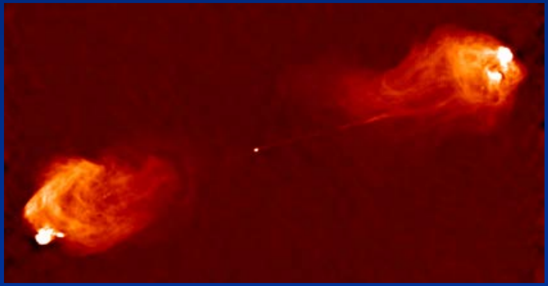
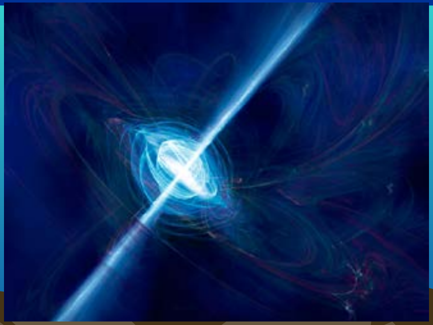
Radio Astronomy

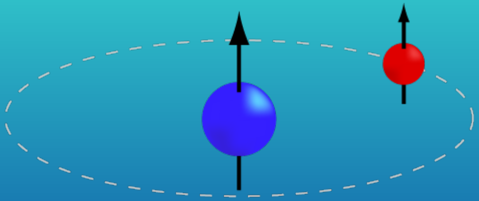
PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

An elective lecture course for the winter term 2012/13 at the Ruperto Carola University Heidelberg







Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Tentative Schedule:
16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer (HB)
11.12. Line radiation (HL)
18.12. Visit to Effelsberg (all)
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Topics for today:

- molecules in space
- rotational transitions
- astro-chemistry
- science examples

Molecules in Space

As mentioned earlier: first molecules found in the optical (CH, CH+, CN) in the 1940s

First radio detections of the molecule OH (hydroxyl) in space in the 18 cm lines in 1963

→ assumption that all interstellar molecules might be just di-atomic

But in 1968: detection of NH_3 (ammonia) and H_2O (water) at around 1.3 cm wavelength

Then in 1969: the organic molecule H_2CO (formaldehyde) is detected at ~ 6 cm

Finally in 1970: the very important molecule CO (carbon monoxide) is detected at 2.7 mm wavelength

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H2	C3 *	c-C3H	C5 *	C5H	C6H	CH3C3N	CH3C4H	CH3C5N	HC9N	c-C6H6 *	HC11N
AlF	C2H	l-C3H	C4H	l-H2C4	CH2CHCN	HC(O)OCH3	CH3CH2CN	(CH3)2CO	CH3C6H	C2H5OCH3 ?	C60 *
AlCl	C2O	C3N	C4Si	C2H4*	CH3C2H	CH3COOH	(CH3)2O	(CH2OH)2	C2H5OCHO	n-C3H7CN	C70 *
C2**	C2S	C3O	l-C3H2	CH3CN	HC5N	C7H	CH3CH2OH	CH3CH2CHO			
CH	CH2	C3S	c-C3H2	CH3NC	CH3CHO	C6H2	HC7N				
CH+	HCN	C2H2*	H2CCN	CH3OH	CH3NH2	CH2OHCHO	C8H				
CN	HCO	NH3	CH4 *	CH3SH	c-C2H4O	l-HC6H *	CH3C(O)NH2				
CO	HCO+	HCCN	HC3N	HC3NH+	H2CCHOH	CH2CHCHO (?)	C8H–				
CO+	HCS+	HCNH+	HC2NC	HC2CHO	C6H–	CH2CCHCN	C3H6				
CP	HOC+	HNCO	HCOOH	NH2CHO		H2NCH2CN					
SiC	H2O	HNCS	H2CNH	C5N							
HCl	H2S	HOCO+	H2C2O	l-HC4H *							
KCl	HNC	H2CO	H2NCN	l-HC4N							
NH	HNO	H2CN	HNC3	c-H2C3O							
NO	MgCN	H2CS	SiH4 *	H2CCNH (?)							
NS	MgNC	H3O+	H2COH+	C5N–							
NaCl	N2H+	c-SiC3	C4H–								
OH	N2O	CH3 *	HC(O)CN								
PN	NaCN	C3N–	HNCNH								
SO	OCS	PH3 ?	CH3O								
SO+	SO2	HCNO									
SiN	c-SiC2	HOCN									
SiO	CO2 *	HSCN									
SiS	NH2	H2O2									
CS	H3+ *	C3H+									
HF	H2D+										
HD	SiCN										
FeO ?	AlNC										
O2	SiNC										
CF+	HCP										
SiH ?	CCP										
PO	AlOH										
AlO	H2O+										
OH+	H2Cl+										
CN–	KCN										
SH+	HO2										
SH	FeCN										
HCl+											

Detected molecules in space (outside of stellar atmospheres): **> 170** (as of 11/2012)

54 molecules also detected in extragalactic systems to date ...

Taken from the CDMS (Cologne Database of Molecular Spectroscopy) http://www.astro.uni-koeln.de/cdms

Line emission from molecules

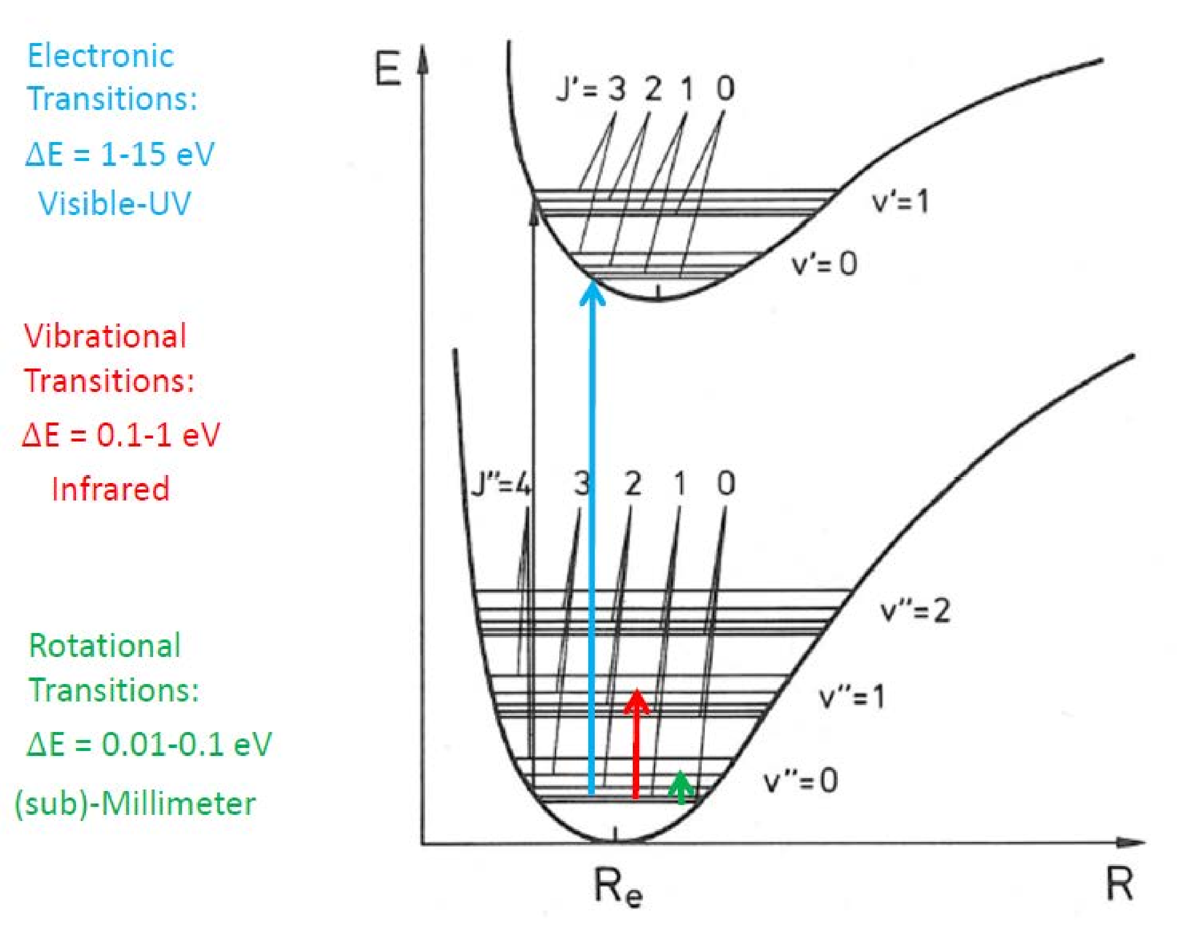
Molecules can exhibit more degrees of freedom and more possibilities of quantised energy levels than simple atoms.

There can be energy transitions due to:

- electronic transitions
- vibrations of different kinds (bending, stretching of molecular bonds)
- molecular rotations
- inversion transitions

All will lead to line emission/absorption of one kind or the other.

A combined schematic energy diagram for the electronic, vibrational and rotational transitions



(a) __Electronic__ transitions exist, like in single atoms. Their energy is often in the order of the dissociation energy of the molecules.

(b) __Vibrational__ transitions within the same electronic state, at first approximation behaviour like a harmonic oscillator (equidistant energy levels)

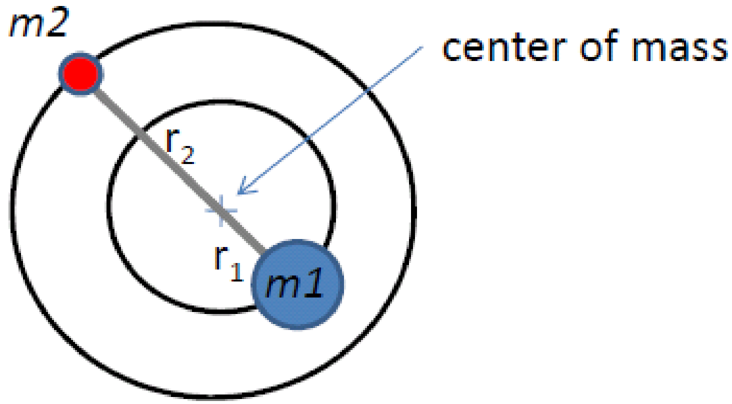
(c) __Rotational__ transitions within the same vibrational level or to a different vibrational level ("roto-vibrational" transitions)

Especially the rotational transitions occur in the (sub-)mm and cm radio regime and give access to cold dense gas!

Rotations: the Rigid Rotor

with quantised angular momentum $L = I\,\omega$

Diatomic or Linear Polyatomic Molecules



Energy levels

rotational quantum number

$$E_r = B\,J(J+1) = L^2 / 2I$$

rotational constant

$$B = \frac{\hbar^2}{2I}$$

Moment of inertia

$$I = \sum_i m_i {r_i}^2$$

$$\boxed{\Delta J = \pm 1}$$

Quantum selection rule

for permitted transitions

Large and heavy molecules have small rotational constants!

Heavy and large molecules have small rotational constants …

→ The rotational transitions with low quantum numbers carry also quite little energies then!

→ Such molecules can therefore have (many) lines at low frequencies ($\nu < 30$ GHz, $\lambda > 1$ cm), while light and small molecules just have transitions in the (sub-)millimeter

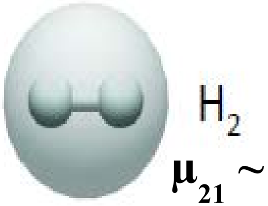
e.g.: HC_7N … J = 1 → 0 at around 1.130 **GHz** ($\lambda \sim 26.6$ **cm**)

HD … J = 1 → 0 at around 2.675 **THz** ($\lambda \sim 112$ **μm**)

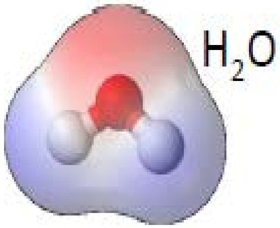
What makes line transitions strong?

1.) The Einstein coefficient has a strong frequency dependence: $A_{21} \sim \nu^3$

2.) Expression for A_{21} can be reformed in order to introduce the transition dipole moment μ_{21}



$\mu_{21} \sim 0$



$\mu_{21} = 1.85$ Debye

Transition dipole moment

$$A_{21} = \frac{2\omega_{21}^3}{3\varepsilon_0 h c^3} \mu_{21}^2$$

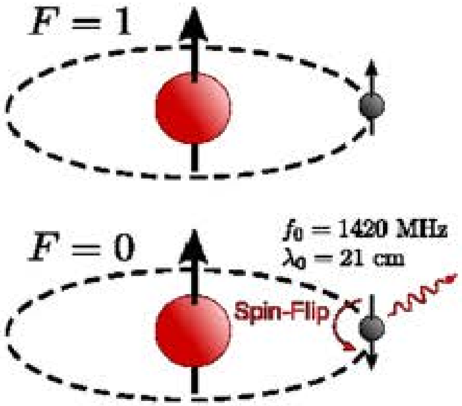
Linear molecules with just the same atoms as constituents in general do not have a permanent electric dipole moment!

→ no purely rotational transitions

Electric Dipole transitions: $\mu_{21} \sim e\, a_0$ (charge times distance/displacement) → $A_{21} \sim e^2 a_0^2$

Dipole moments are measured in Debye [D], molecules with permanent dipole moments typically have 1 – 5 D (1 D = 3.33564 10^{-30} C m)

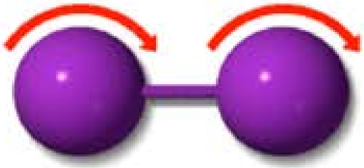
Some remarkable transitions in Hydrogen



21 cm line
Atomic H / electron spin flip

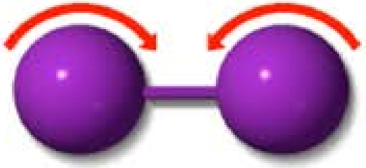
A = 2.9 x 10^{-15} s^{-1}

The most famous line in radio astronomy



Orthohydrogen

Ortho-para transiton in molecular hydrogen
Nuclear spin flip



Parahydrogen

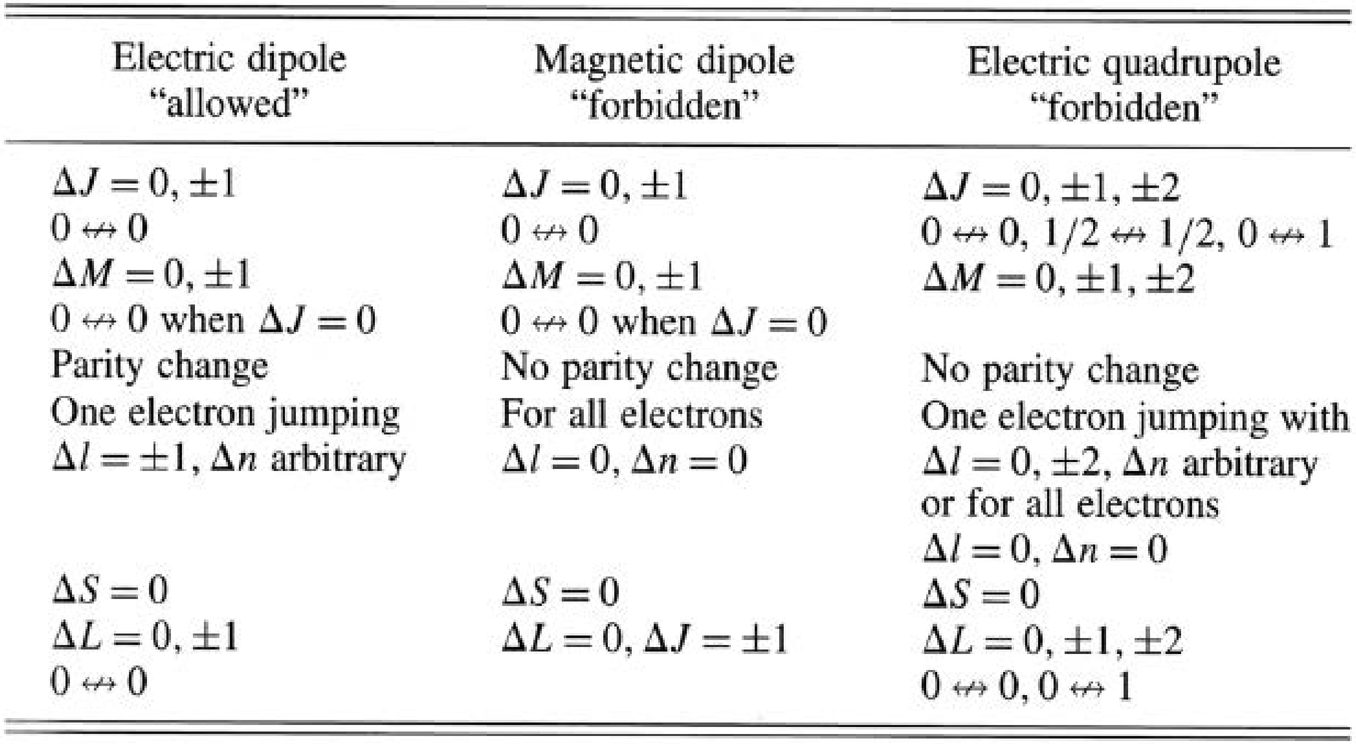
A = 6.2 x 10^{-14} yr^{-1}

Hypothetical … not observed!

Examples for Einstein A coefficients – a proxy to the line strength

Type	A_{21} (s^{-1})	Example	λ	A_{21} (s^{-1})
Electric dipole				
UV	10^9	Lyα	121.6 nm	2.4×10^8
Visible	10^7	Hα	656 nm	6×10^6
Vibrational	10^2	CO	4.67 μm	34.0
Rotational	10^{-6}	CS	6.1 mm	1.7×10^{-6}
Forbidden				
Opt. (el. Quadrupole)	1	[OIII]	436.3 nm	1.7
Opt. (magn. Dipole)	10^2	[OIII]	500.7 nm	2×10^2
Hyperfine		HI	21 cm	2.9×10^{-15}

Selection rules



Electric dipole "allowed"	Magnetic dipole "forbidden"	Electric quadrupole "forbidden"
$\Delta J = 0, \pm 1$	$\Delta J = 0, \pm 1$	$\Delta J = 0, \pm 1, \pm 2$
$0 \nleftrightarrow 0$	$0 \nleftrightarrow 0$	$0 \nleftrightarrow 0,\ 1/2 \nleftrightarrow 1/2,\ 0 \nleftrightarrow 1$
$\Delta M = 0, \pm 1$	$\Delta M = 0, \pm 1$	$\Delta M = 0, \pm 1, \pm 2$
$0 \nleftrightarrow 0$ when $\Delta J = 0$	$0 \nleftrightarrow 0$ when $\Delta J = 0$	
Parity change	No parity change	No parity change
One electron jumping	For all electrons	One electron jumping with
$\Delta l = \pm 1$, Δn arbitrary	$\Delta l = 0$, $\Delta n = 0$	$\Delta l = 0, \pm 2$, Δn arbitrary
		or for all electrons
		$\Delta l = 0$, $\Delta n = 0$
$\Delta S = 0$	$\Delta S = 0$	$\Delta S = 0$
$\Delta L = 0, \pm 1$	$\Delta L = 0$, $\Delta J = \pm 1$	$\Delta L = 0, \pm 1, \pm 2$
$0 \nleftrightarrow 0$		$0 \nleftrightarrow 0,\ 0 \nleftrightarrow 1$

Magnetic dipole transitions are proportional to μ_B (Bohr magneton), and are typically $10^4 - 10^5$ times weaker than electric dipole transitions. Electric quadrupole transitions are weaker by a factor of $\sim 10^8$.

Molecular excitation to higher rotational levels:
Collisions vs (spontaneous) radiative decay

We want to have a situation where the radiation signal we receive is a close proxy to the physical conditions in the gas (in order to derive its temperature and/or density)

In LTE the distribution of the rotational levels is governed by the Boltzmann distribution.

But in a too thin gas, there are not enough collisions per time unit to establish this distribution … the spontaneous radiative decay (governed by the Einstein coefficient A_{UL}) is faster.

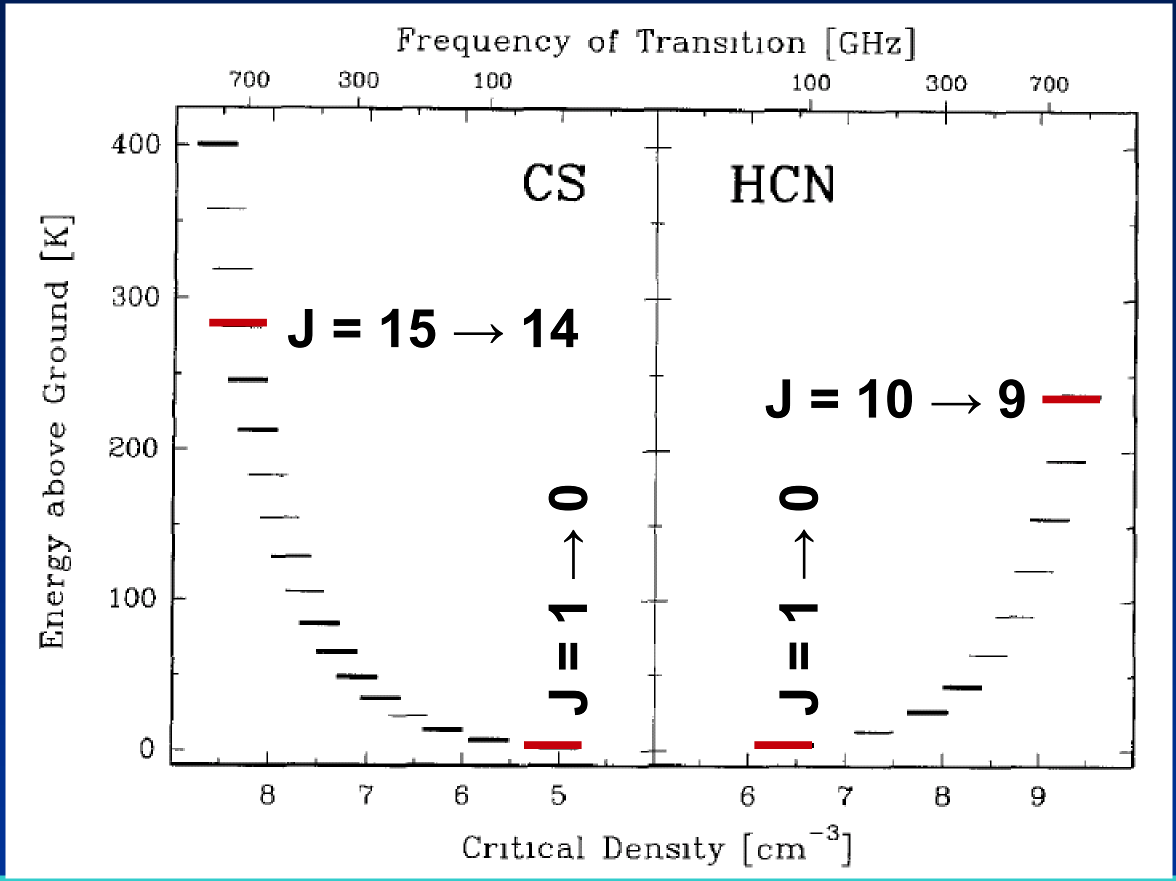
Critical density

$$\boxed{n^* \approx \frac{A_{\mathrm{UL}}}{\langle \sigma v \rangle}}$$

cross section $\sigma \sim 10^{-15}$ cm^{-2}
molecular velocities $v \sim 1$ km/s

At n^*, collisional excitation equals spontaneous radiative decay.

Connection between upper rotational energy levels and critical densities for two dense gas tracers: CS and HCN

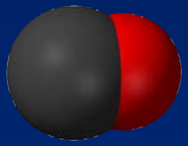


Walmsley & Güsten 1994, Lecture Notes in Physics 439, 164

The upper-level energy (expressed as temperatures: $T = E_{up} / k_B$) over the logarithm of the critical density. Parameter is the rotational quantum number J.

CO as a molecule with special importance for astronomy:

– CO lines are the most important cooling lines for the regime below 100 Kelvin (cooling of the molecular material in order to facilitate gravitational collapse … eventually)



– relatively light, di-atomic, simple rotational spectrum

– low dipole moment (-0.12 Debye) → easily excitable also in thinner molecular gas (1 – 0 transition is in collisional equilibrium already for H_2 densities of less than 10^3 cm^{-3})

– CO is the most abundant molecule after H_2 itself (abundance ~ 10^{-4})

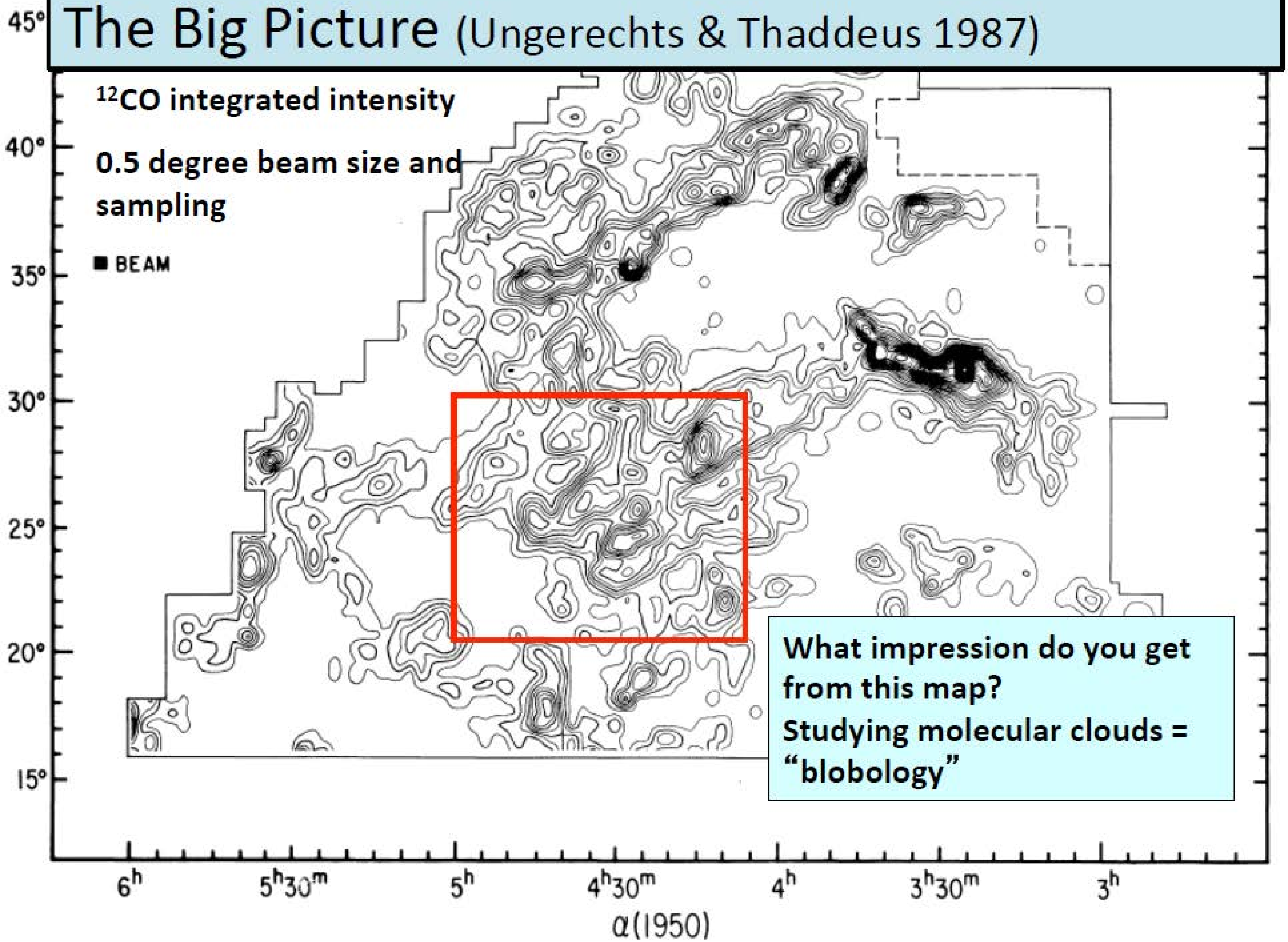
→ Since the bulk of the cold H_2 molecular gas in molecular clouds is not directly accessible (no permanent dipole moment), CO is the best (?) proxy for the total amount of molecular gas in a cloud.

The next four slides are taken from a review talk

Given by Paul Goldsmith

During the 2012 EPOS conference at Schloss Ringberg

Molecular Cloud Structure: Perseus + Taurus - The Big Picture (Ungerechts & Thaddeus 1987)



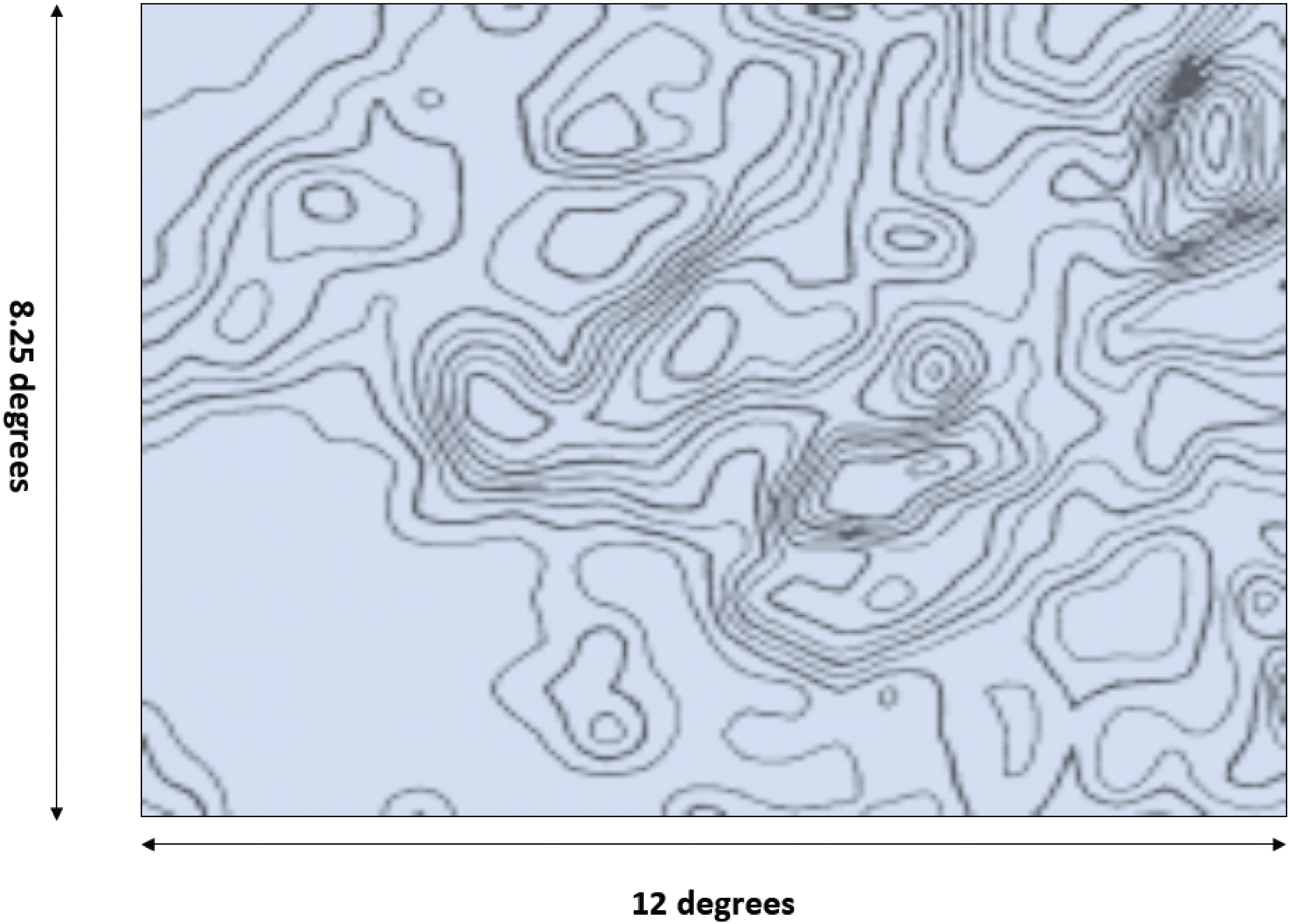
^{12}CO integrated intensity

0.5 degree beam size and sampling

What impression do you get from this map?
Studying molecular clouds = "blobology"

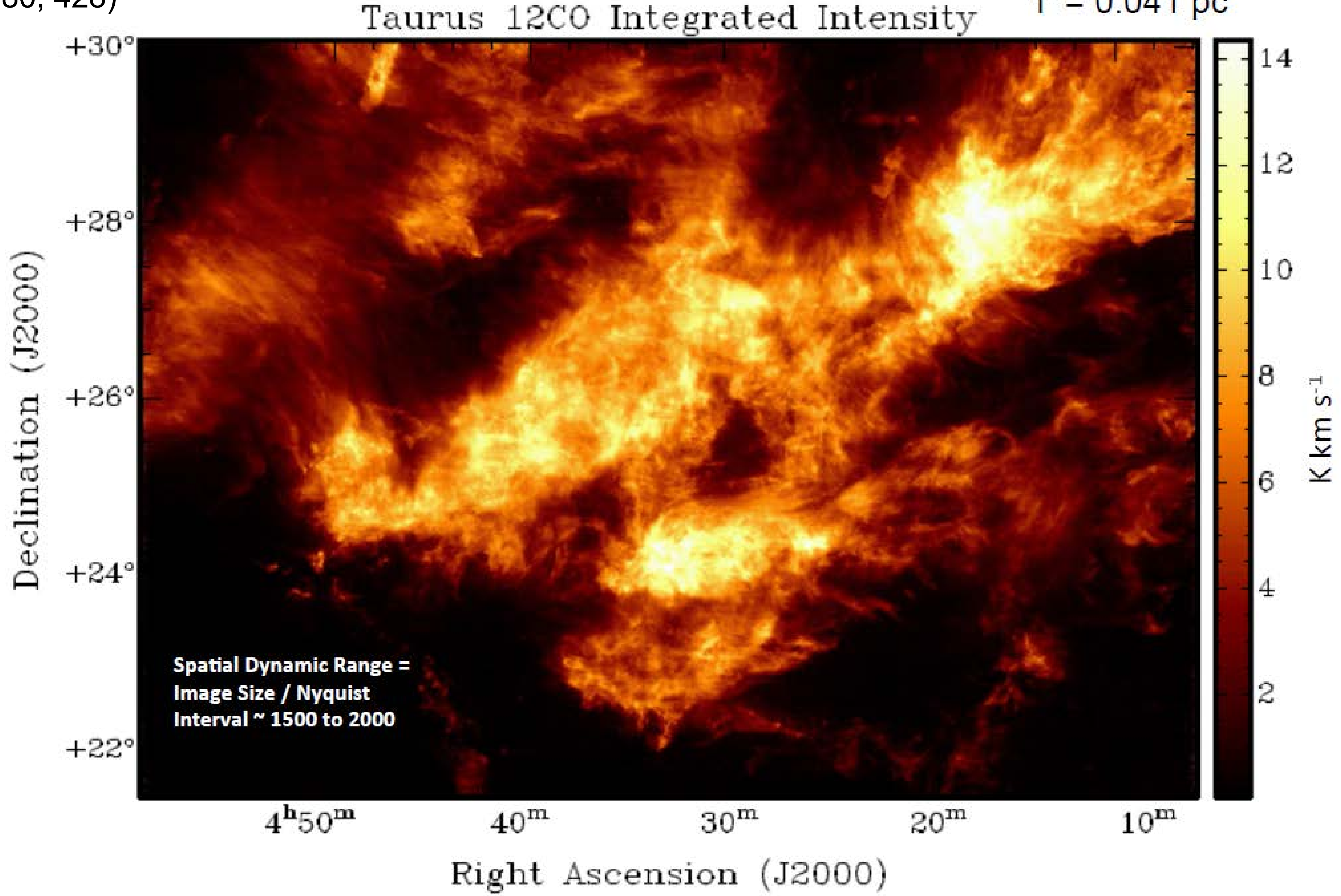
Back then done with a 1.2 m radio telescope at Columbia Univ.

Zoom into the previous map ...



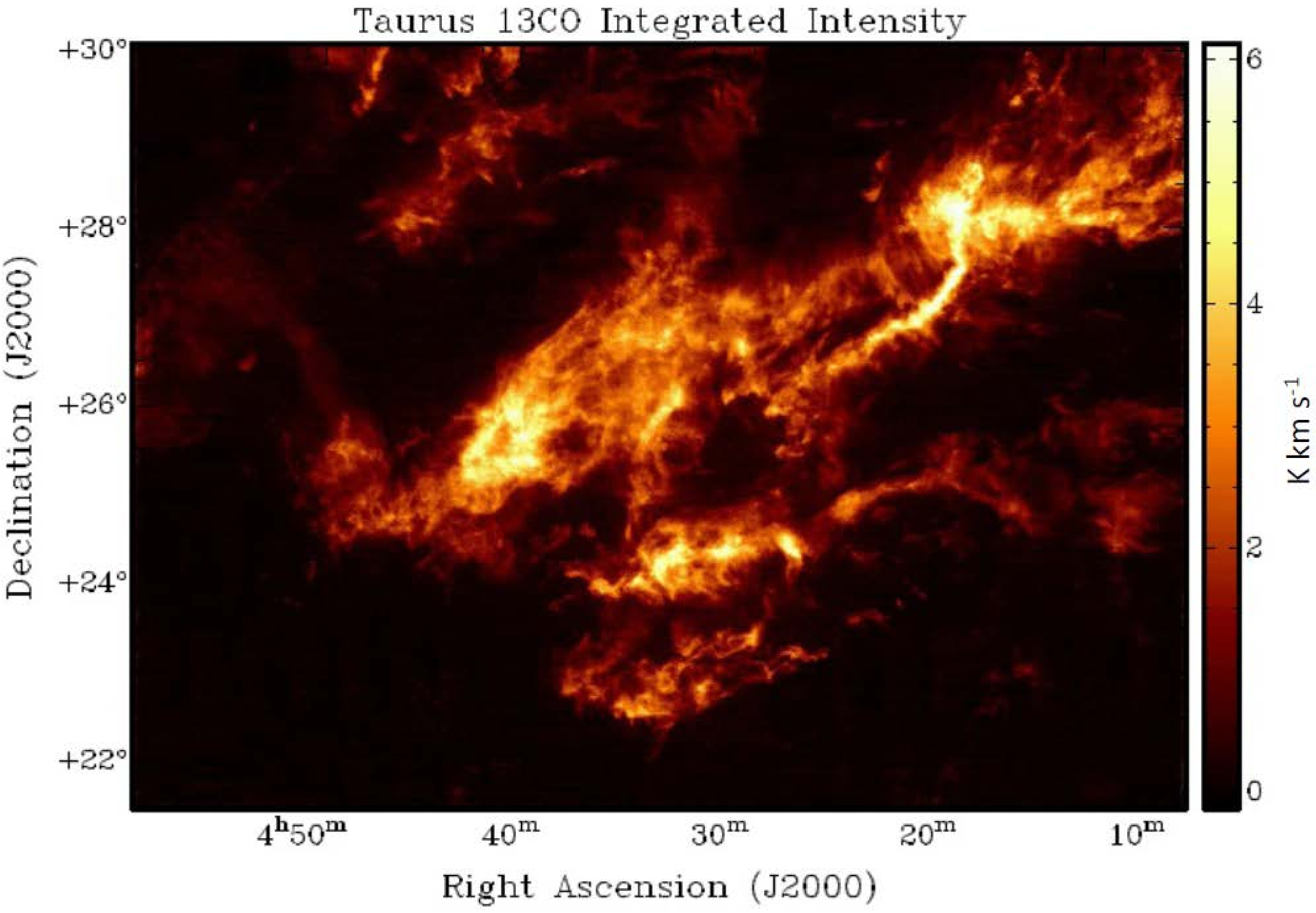
Done 20 years later with a 13.7 m radio telescope + line receiver array (32 “pixels”) in on-the-fly scanning mode (Goldsmith et al. 2008, ApJ 680, 428)

Distance = 140 pc
1° = 2.4 pc
1’ = 0.041 pc

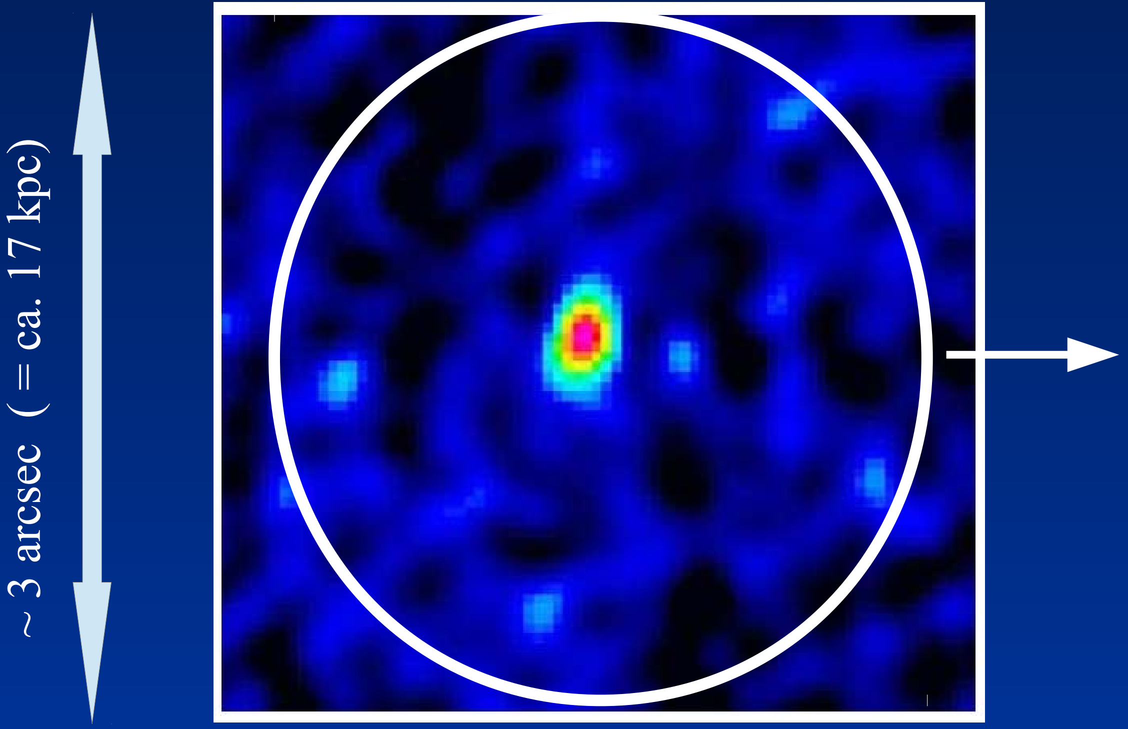


Spatial Dynamic Range = Image Size / Nyquist Interval ~ 1500 to 2000

Paradigm change in molecular cloud structure : From Blobology to Filamentology!



Molecular gas at early times of galaxy evolution (< 1 Gyr after the Big Bang). Even back then there was a co-evolution of the star-formation process in the host galaxy (traced by the CO) and the central black hole (evident as the action associated with the central quasar).



Equivalent to our Sun orbit around Our Galactic Center

Fabian Walter et al. 2004, ApJ 615, L17

The CO(3 – 2) radiation associated with the quasar *J1148+5251*. The rest frequency is around 346 GHz. Due to the large redshift of z = 6.42, this line is shifted to much lower frequencies (46.61 GHz) accessible with the VLA.

Astro-Chemistry

Molecular line measurements as observational basis to study the chemistry in the interstellar medium

→ interesting in itself in order to study rare molecules in conditions that are not common on earth (low pressures, densities and temperatures)

→ chemistry as additional tool to constrain physical processes, especially relevant for star formation research

  → mixing of gas, (in)homogeneity, spatial differentiation
  → energetics (embedded heating sources)
  → influence of shocks

Astro-Chemistry: What happens?

Early theoretical investigations: at typical densities, neutral-neutral reactions are too slow to produce appreciable amounts of new molecules in less than 10^6 years

Solution: Ion-molecule chemistry with reaction rates a thousand times faster than neutral-neutral reactions (for these space conditions) (→ ionisation in interiors of molecular cloud cores well, shielded against UV radiation, comes mainly from Cosmic Rays)

Central is the molecule H_3^+ as a focal point in any chemical network:

e.g.: $H_3^+ + CO \rightarrow HCO^+ + H_2$

Destruction can come from recombination with electrons:

$H_3^+ + e^- \rightarrow H_2 + H$

$HCO^+ + e^- \rightarrow H + CO$

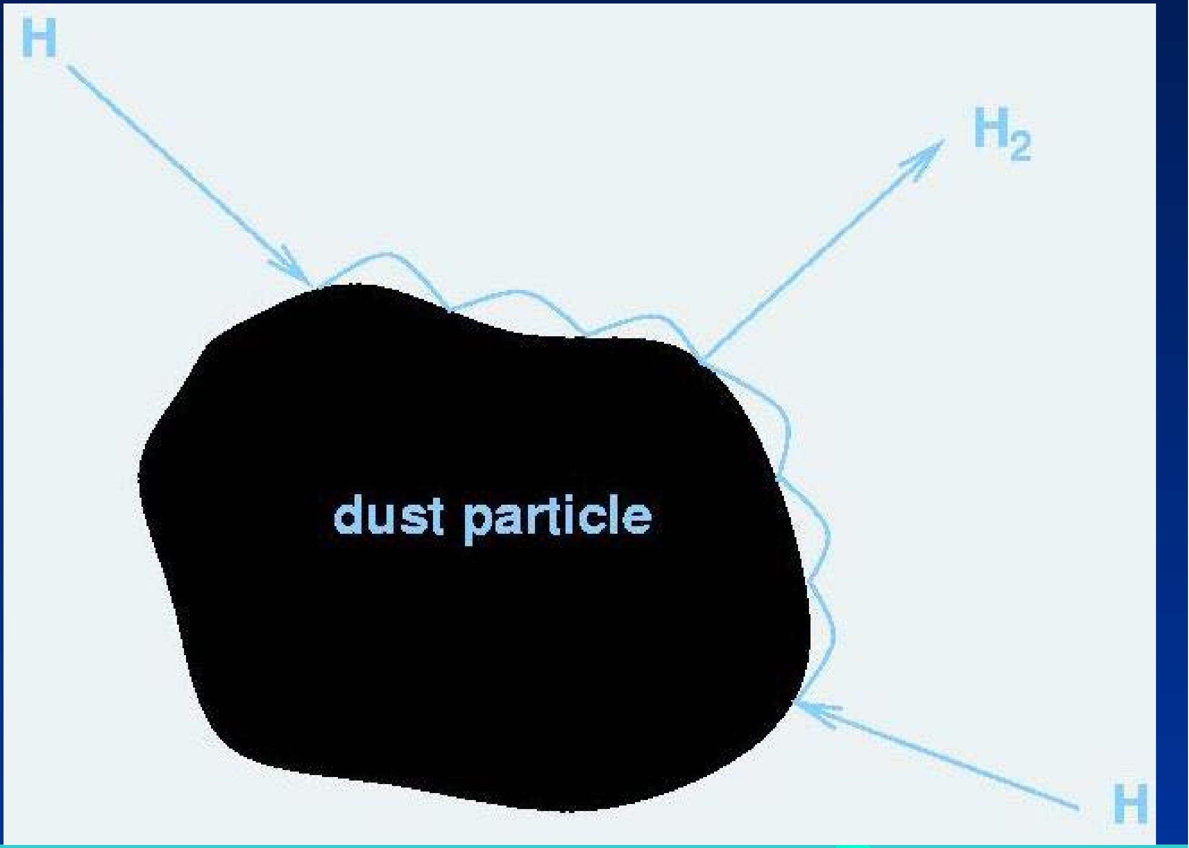
However, for the production of H_3^+ one needs H_2.

Astro-Chemistry: the importance of dust grains

H_2 forms on dust grain surfaces!

Thermal hopping of accreted H atoms on the grain surfaces until a reaction partner is met.

Also other more complex molecules like CH_3OH (methanol) can be formed on grain surfaces if the conditions are sufficiently cold so that potential constituents of the final products freeze out from the gas phase onto the grains.



Astro-Chemistry: complex processes of accretion and desorption

Until recently, the situation seemed clear:

Cold conditions : many species on dust grains (formation yes, but no way back to the gas phase → not accessible via rotational gas phase transitions)

Warming up: central heating source (e.g., a protostar with a strong far—infrared radiation field) heats the grains clearly above 20 K
→ thermal desorption of the surface species into the gas phase
→ extreme objects: “Hot Molecular Cores” (HMCs) with gas temperatures of 100 – 300 K: drastic release of surface species and subsequent intense chemical reactions lead to very rich chemistry (complex molecules, saturated, methanol! and higher alcohols)

Astro-Chemistry: complex processes of accretion and desorption

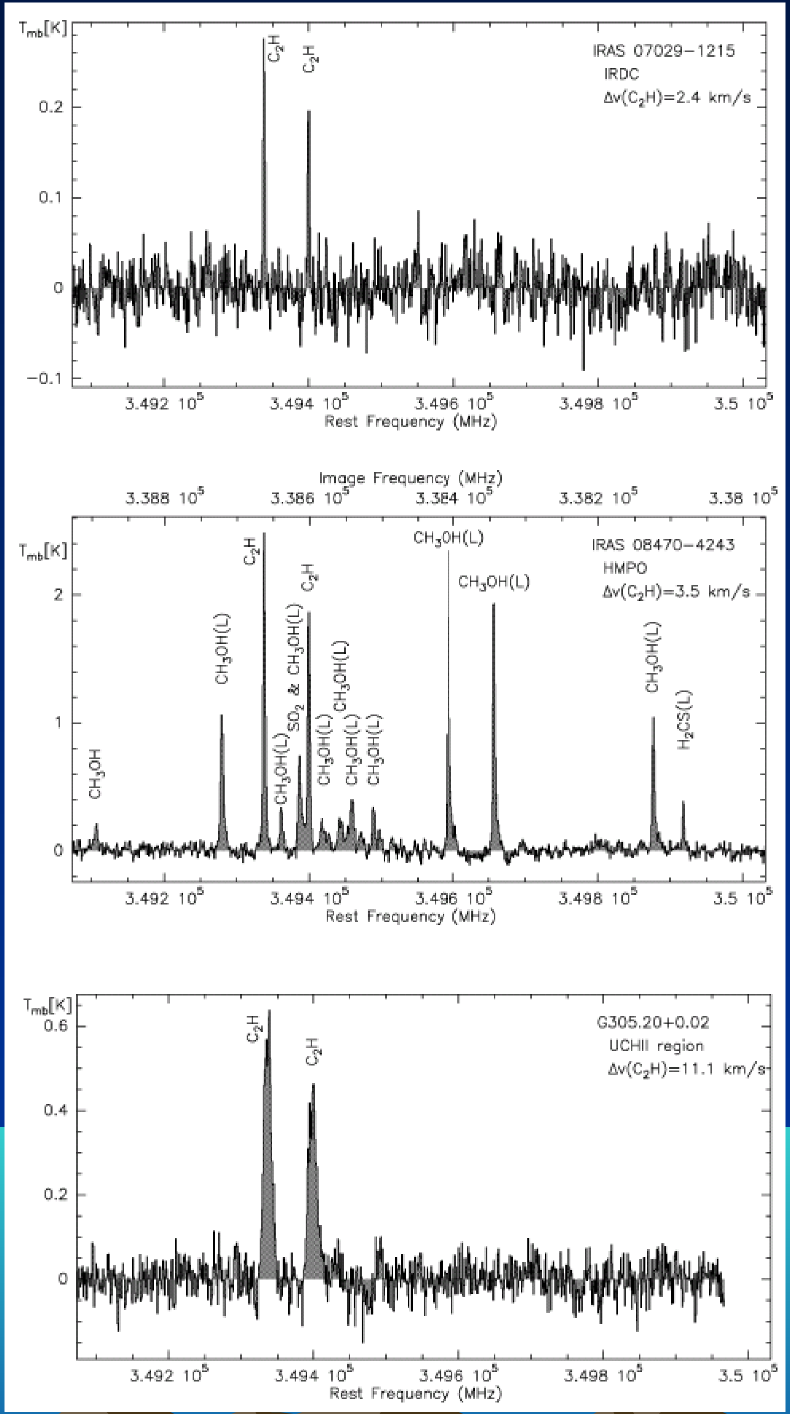
New observations of cold cores (10 – 20 K):

complex species and methanol detected in the gas phase (although the grains are not warm enough to provide normal thermal desorption)

One idea : “reactive desorption” → some grain surface reactions are slightly exothermic → reaction energy is one route to provide sufficient thrust for molecule desorption

See: Garrod, Wakelam, & Herbst 2007, A&A 467, 1103

Chemical diversity in star-forming regions (I)



From Beuther et al. 2008, ApJ 675, L33

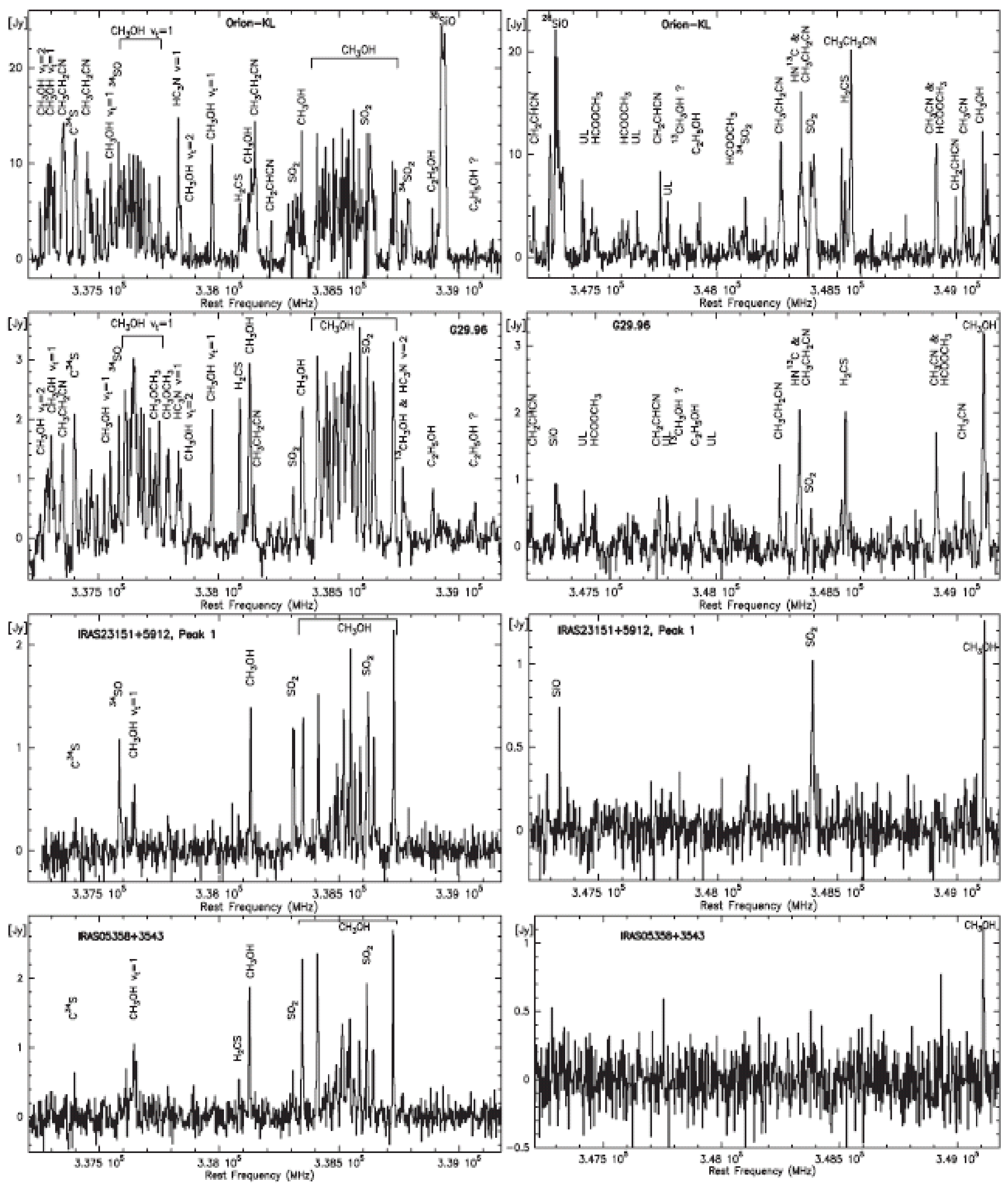
An infrared-Dark Cloud (IRDC), Cold (< 20 K), mostly simple chemistry (but with some surprises …), narrow lines

A High-Mass Protostellar Object (HMPO), elevated temperature (30 – 50 K), more complex chemistry, many methanol lines

An ultracompact HII region (UCHIIR), central massive star has ignited, hot gas, dominating ionised gas component with > 8000 K destroys most molecules, the remaining ones show broad lines

Time and chemical evolution

From: Beuther et al. 2009, AJ 137, 406



Chemical diversity in star-Forming regions (II): The true molecular line factories are Hot Cores!

Hot Core: Orion KL

Hot Core: G29.96-0.02

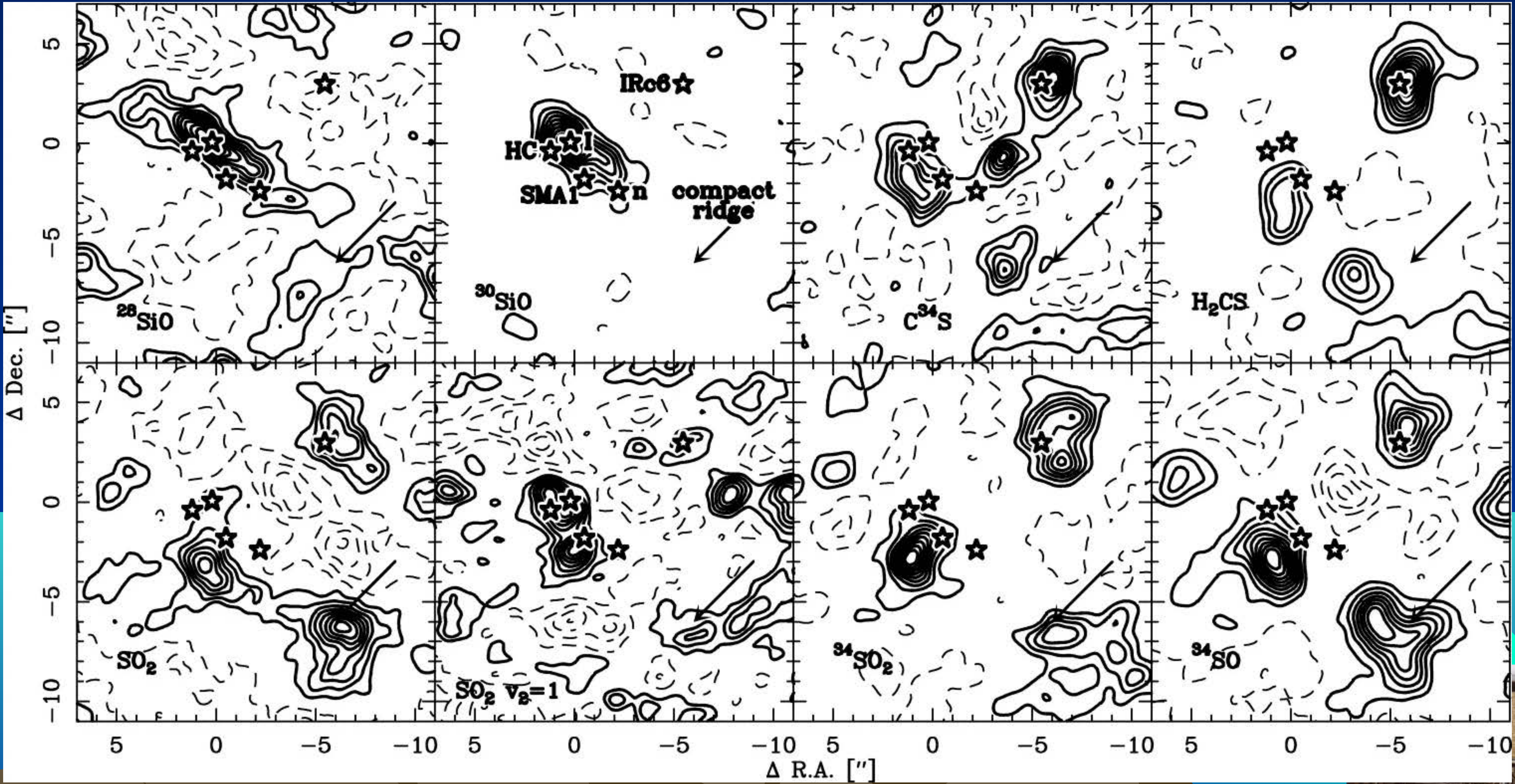
Not (yet) a hot core:
IRAS 23151+5912

Not (yet) a hot core:
IRAS 05358+3543

The advantage of spatially resolved imaging spectroscopy via modern interferometers with broad immediate spectral bandpasses (SMA, PdBI, ALMA):

Chemical differentiation on small scales can be revealed!

Example: SMA interferometry at around 345 GHz for the famous Orion KL region (Beuther et al. 2005, ApJ 632, 355)

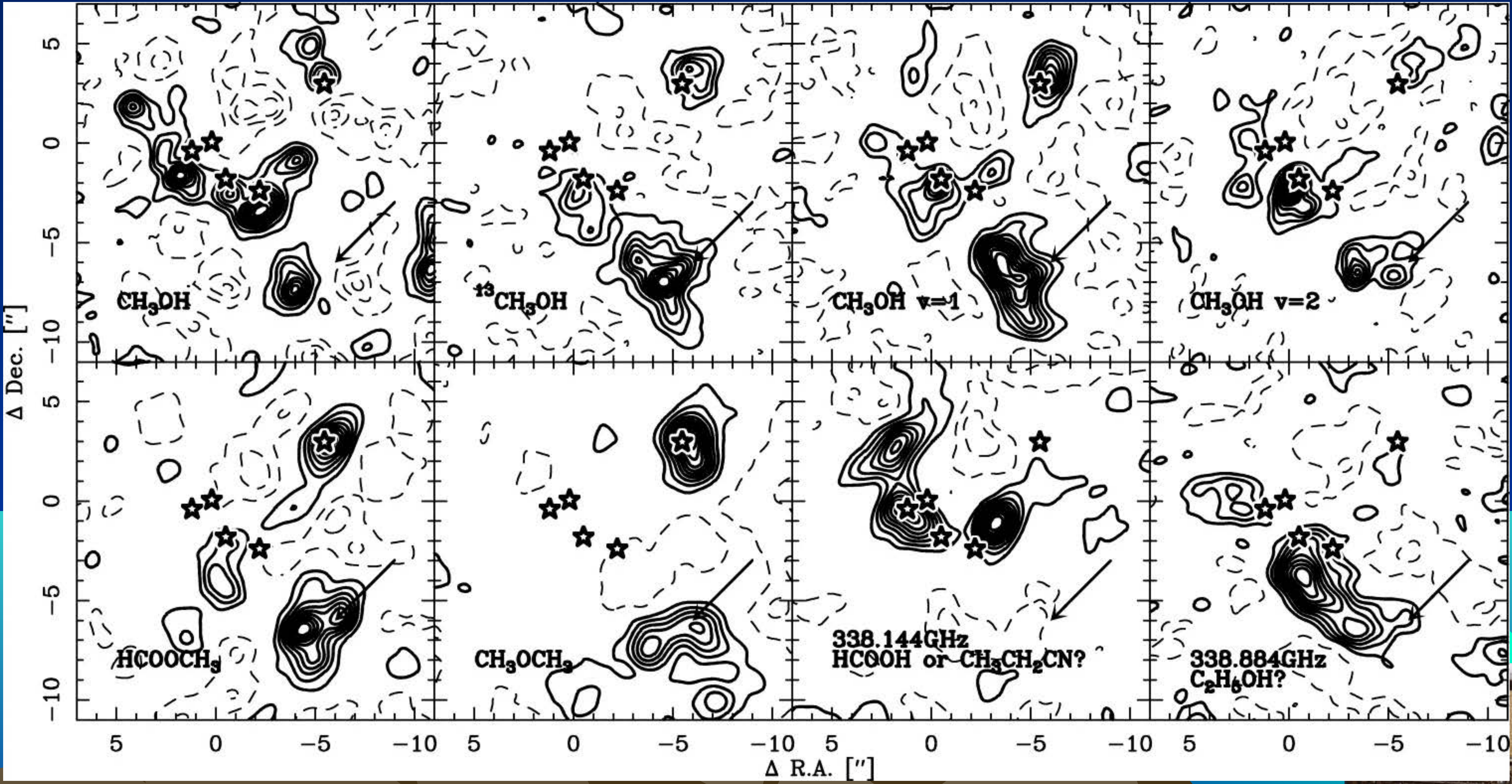


Sulfur-bearing molecules

The advantage of spatially resolved imaging spectroscopy via modern interferometers with broad immediate spectral bandpasses (SMA, PdBI, ALMA):

Chemical differentiation on small scales can be revealed!

Example: SMA interferometry at around 345 GHz for the famous
Orion KL region (Beuther et al. 2005, ApJ 632, 355)

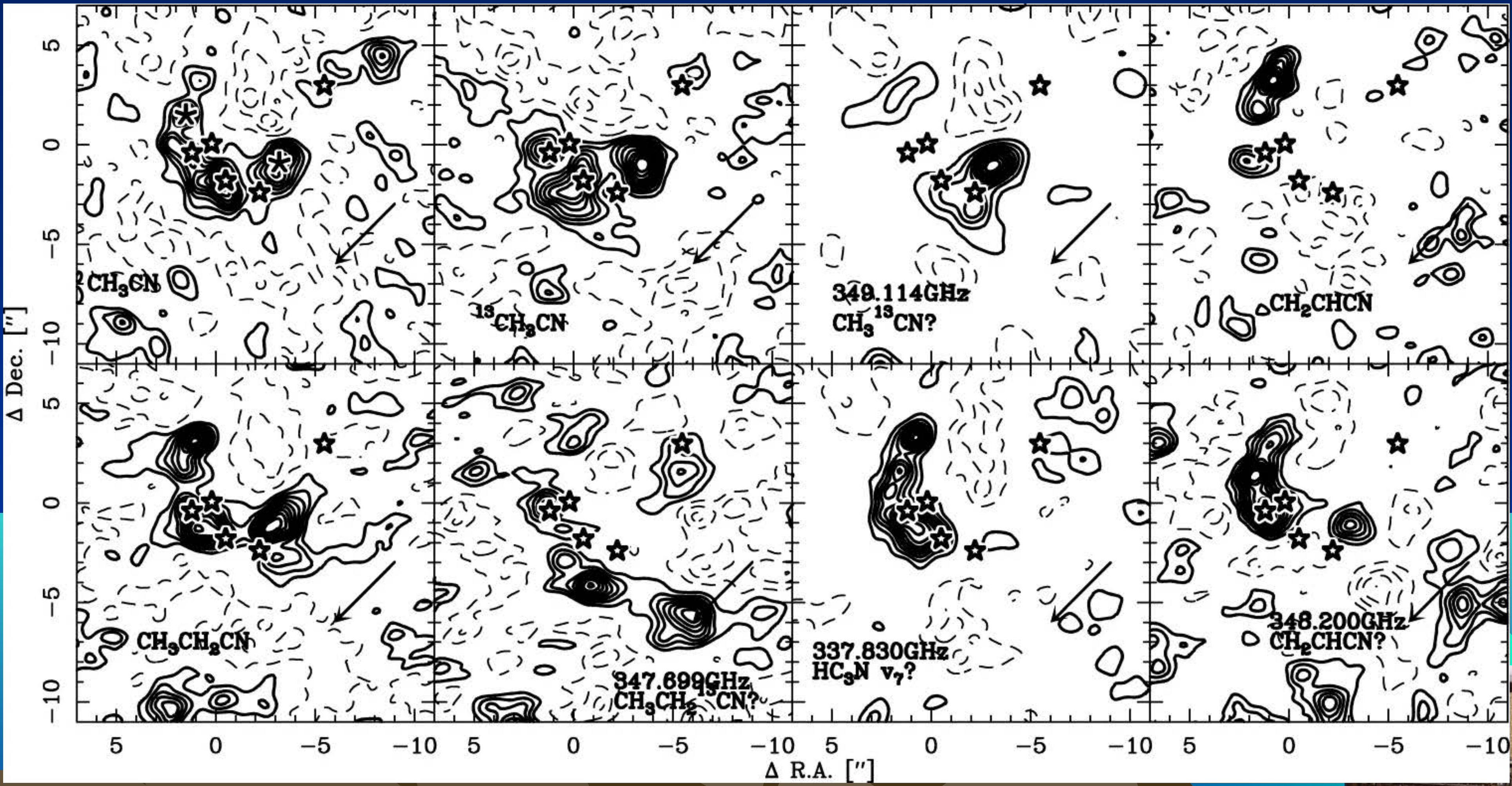


Oxygen-bearing molecules

The advantage of spatially resolved imaging spectroscopy via modern interferometers with broad immediate spectral bandpasses (SMA, PdBI, ALMA):

Chemical differentiation on small scales can be revealed!

Example: SMA interferometry at around 345 GHz for the famous Orion KL region (Beuther et al. 2005, ApJ 632, 355)



Nitrogen-bearing molecules

Radio Astronomy

PD Dr. Henrik Beuther and Dr. Hendrik Linz

MPIA Heidelberg

Scripts at : http://www.mpia.de/homes/beuther/lecture_ws1213.html

<u>Tentative Schedule:</u>

16.10. Introduction and overview (HL & HB)
23.10. Emission mechanisms, physics of radiation (HB)
30.10. Telescopes – single-dish (HL)
06.11. Telescopes – interferometers (HB)
13.11. Instruments – continuum detection (HL)
20.11. Instruments – line detection (HB)
27.11. Continuous radiation (free-free, synchrotron, dust) (HL)
04.12. Radiation transfer (HL)
11.12. Line radiation (HL)
18.12. Visiting the Effelsberg Telescope (all)
08.01. Molecules and chemistry (HL)
15.01. Physics and kinematics (HB)
22.01. Applications (HL)
29.01. Applications (HB)
05.02. Exam week