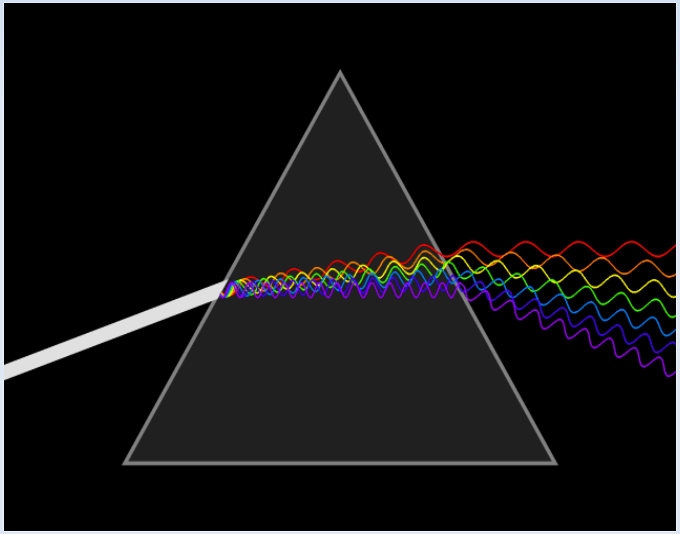
Spectral Line Observing

- Measurement goals
- Spectral line formation processes
- Line Shapes / Doppler effect
- Spectrometers
- Observing techniques
- Calibration
- Data reduction / Data products
- Data visualization



Measurement Goals

- What can we learn from radio spectral lines ?
- We can probe the physical, chemical and dynamical conditions of the interstellar matter (ISM) in the Milky Way and in external galaxies.
- Most ISM gas phases produce spectral lines:
  - Cold: 10 K, dense molecular gas (H_2)
  - Cool: 10^2 K, neutral gas (HI)
  - Warm: 10^4 K, ionized gas (HII)
  - Hot: 10^6 K, low-density ionized (SNR bubbles)

Spectral Lines

Measurement Goals (ctd.)

- Intensities can tell us about:
  - Gas temperature
    - Energy Sources
  - Gas density
    - Gravity / Cloud Criticality
  - Chemical composition
    - Abundances / Evolutionary State
  - Ionization / Magnetic Fields
    - Cloud Support

Measurement Goals (ctd.)

- Frequencies and line widths can be used to derive:
  - Dynamical models
    - Galaxy and Cloud Rotation
    - Cloud Collapse
    - Protostellar Outflows
  - Redshifts
    - Age
    - Distance

Spectroscopy

- Spectroscopy:

  Any measurement of a quantity as a function of either wavelength (λ) or frequency (ν), i.e. also of energy ($E = h\nu$).

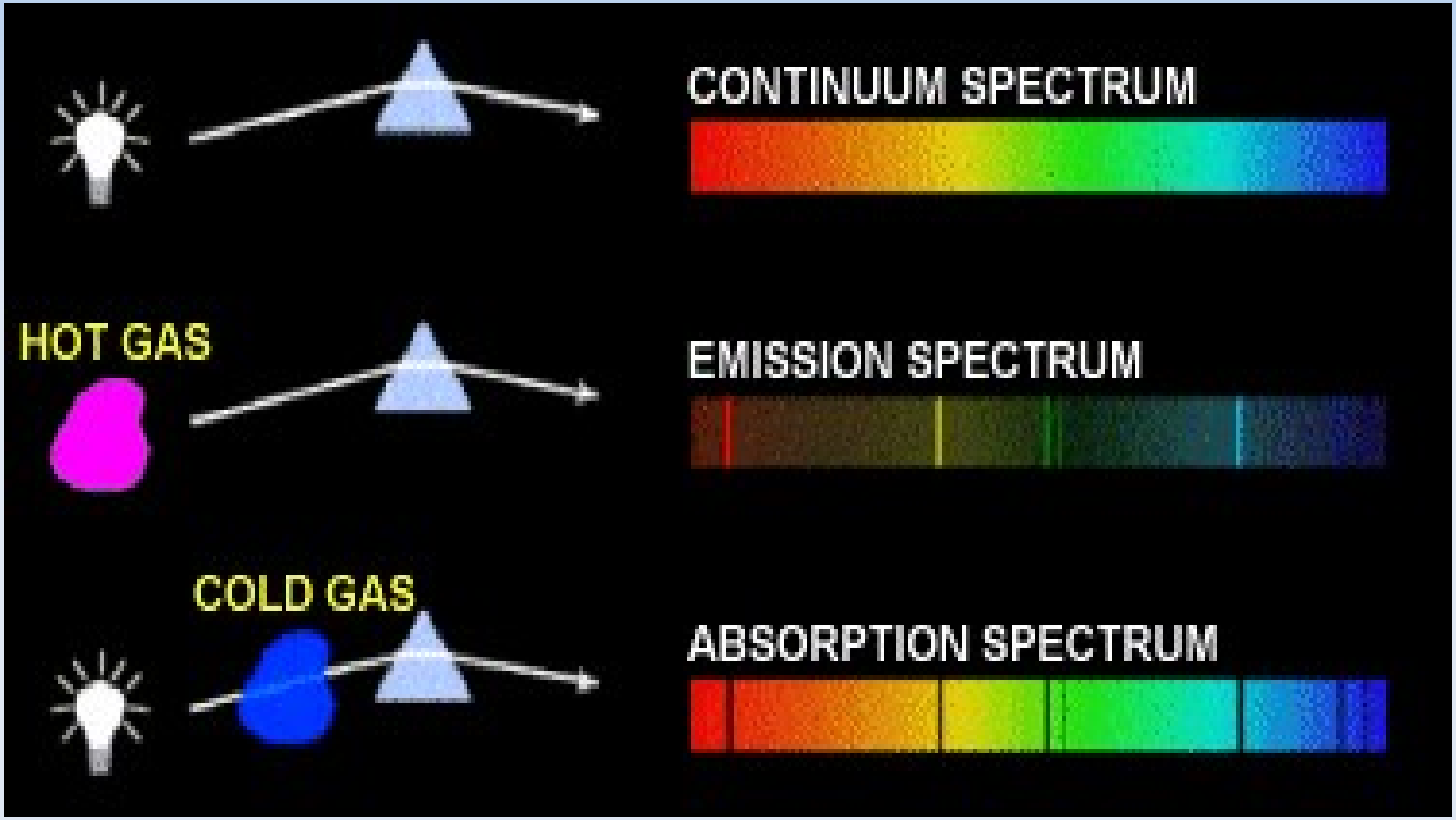
- Spectral Line:

  Result of the interaction between a quantum system and a single photon.

How do spectral lines form ?

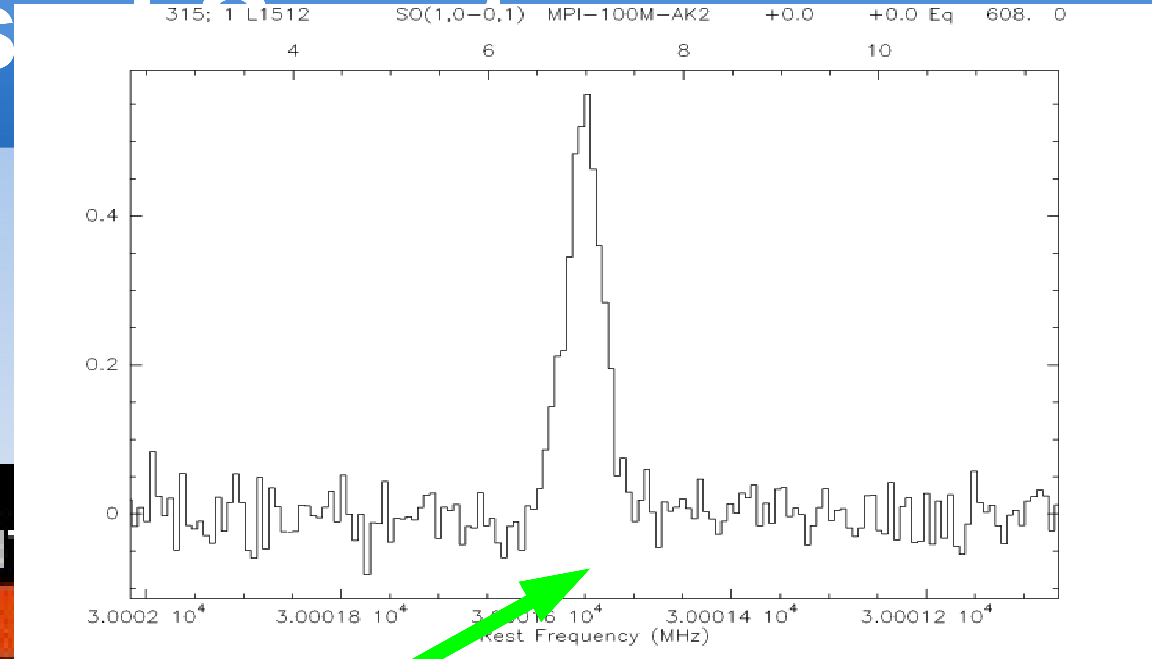
- Quantum systems (atoms or molecules) can change their states only in discrete amounts of energy ΔE
- The transition between these states leads to emission or absorption of light at a single frequency $\nu = \Delta E/h$, the so called rest frequency
- Spectrally this transition is seen as a line

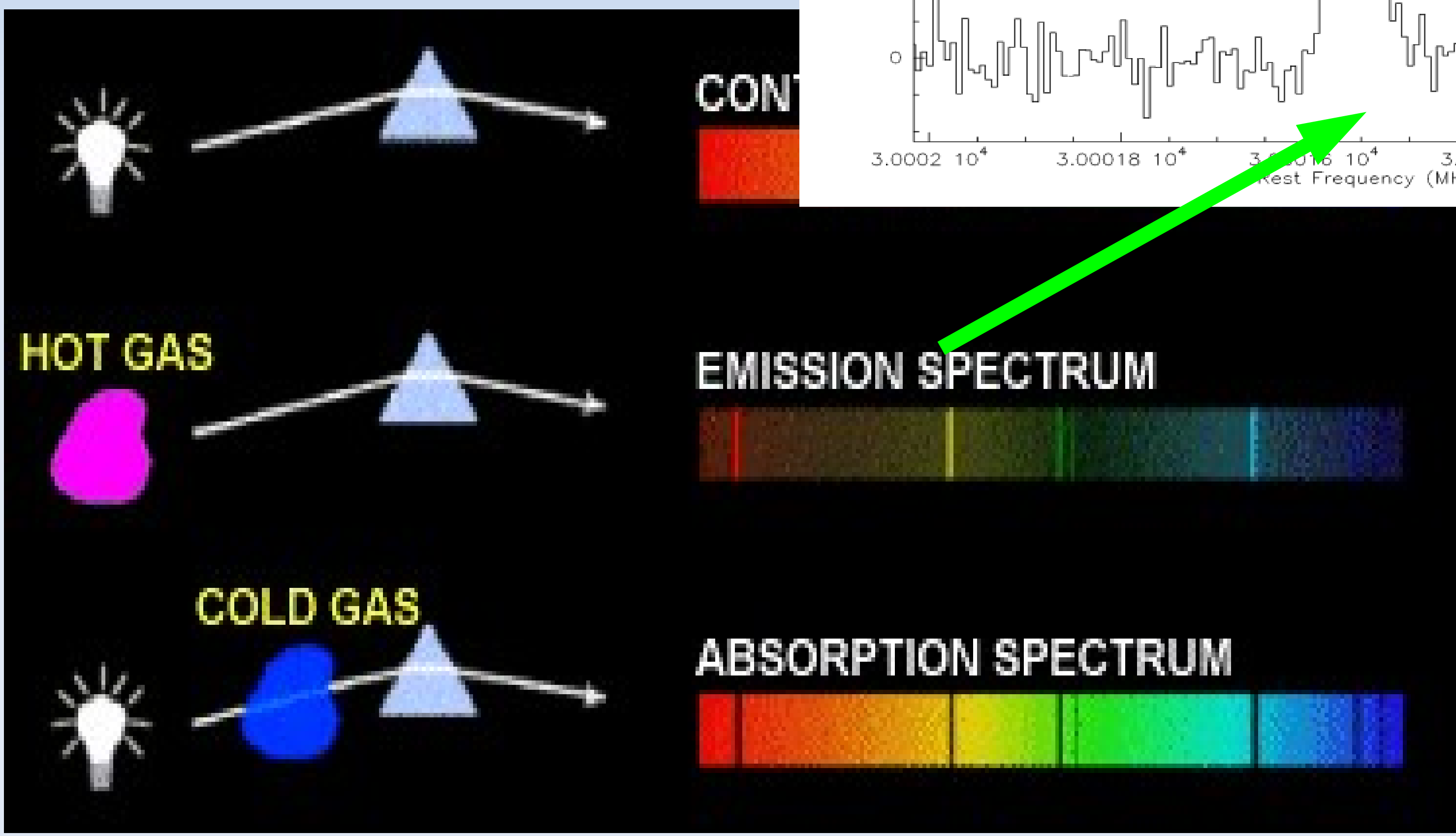
Types of Spectra



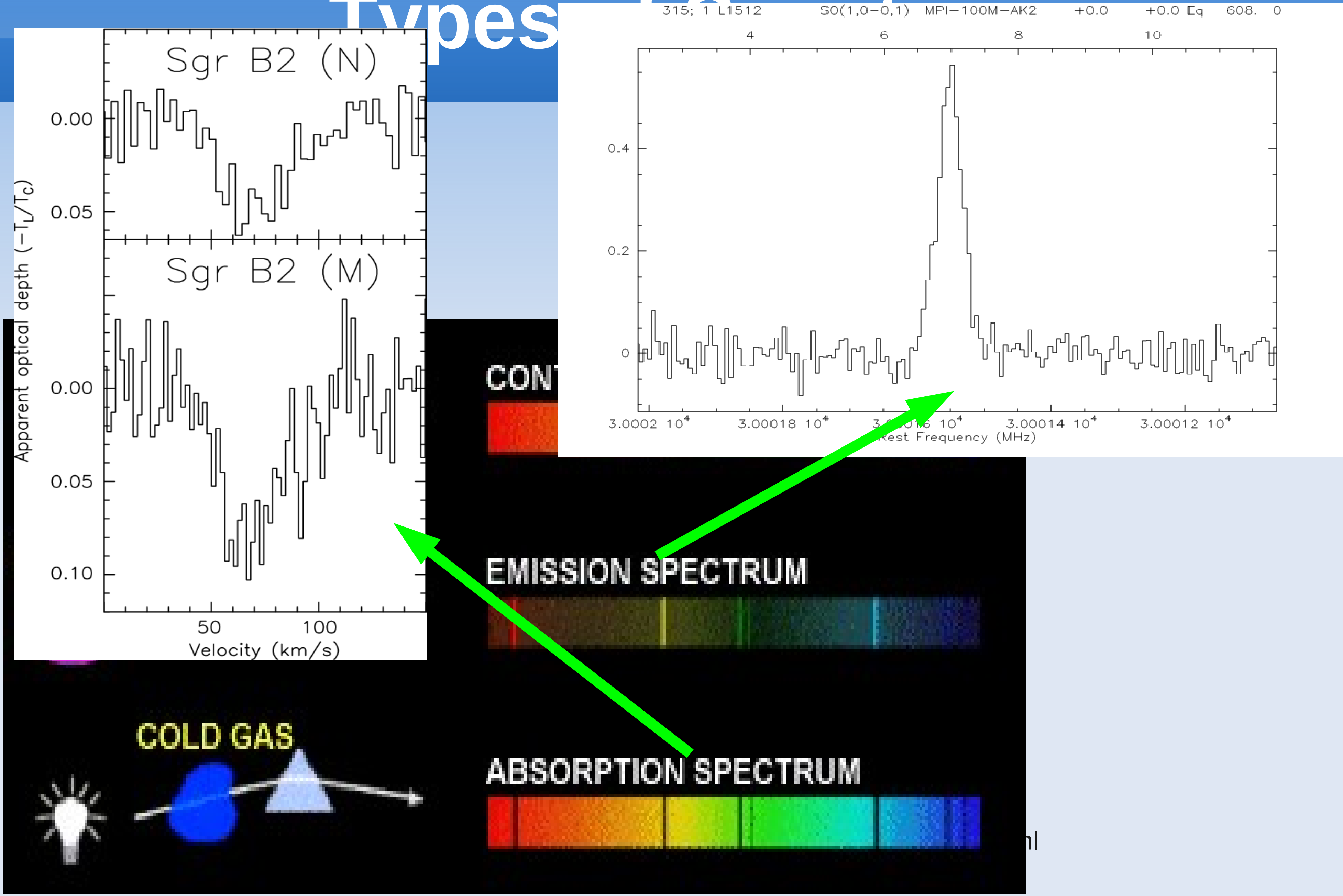
http://www.astro.columbia.edu/~archung/labs/fall2001/lec04_fall01.html

Types


315; 1 L1512
SO(1,0-0,1) MPI-100M-AK2
+0.0
+0.0 Eq
608. 0
4
6
8
10
0.4
0.2
0
3.0002 10^4
3.00018 10^4
3.00014 10^4
3.00012 10^4
Rest Frequency (MHz)


CONT
HOT GAS
EMISSION SPECTRUM
COLD GAS
ABSORPTION SPECTRUM

Types



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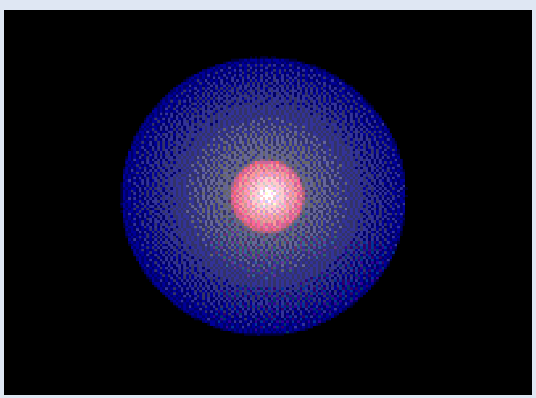
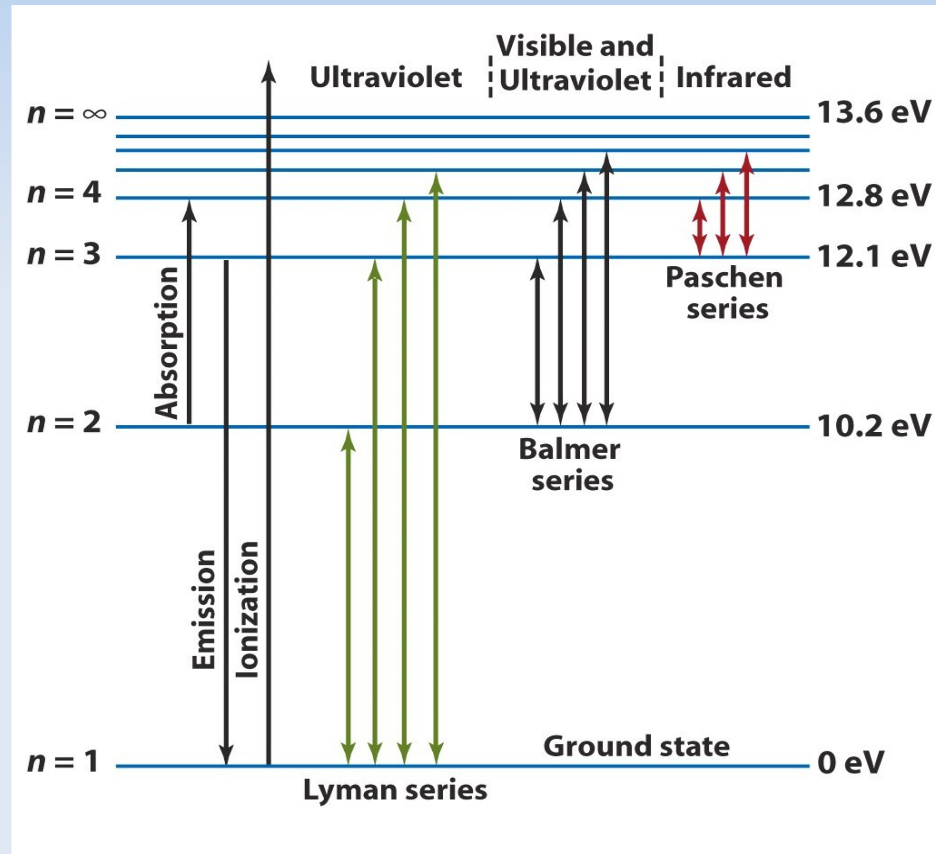
Atomic Lines I

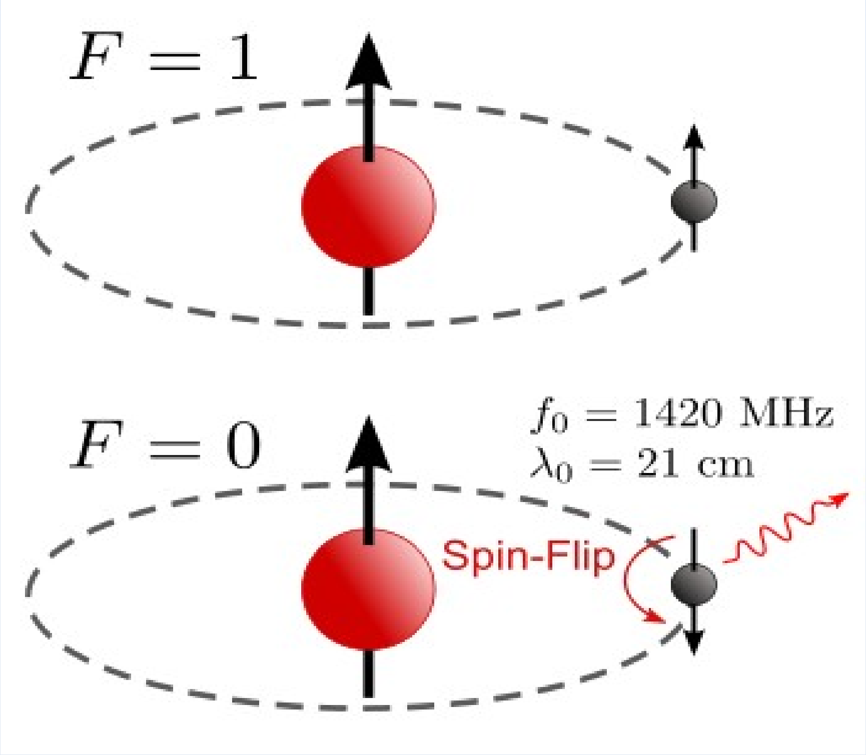
- Electronic transitions (e.g. recombination lines (H<n>α, etc.))





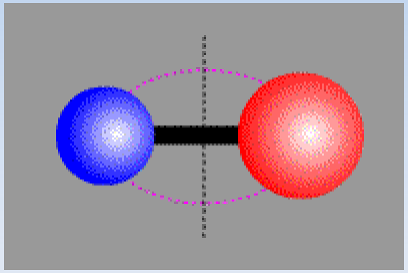
Atomic Lines II

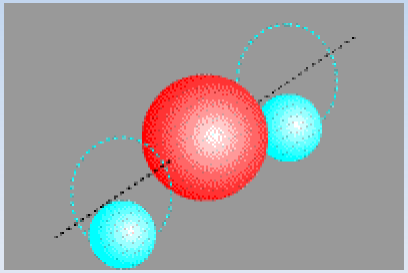
- Hyperfine splitting / spin flips (e.g. HI 21 cm line → separate talk on Tuesday)



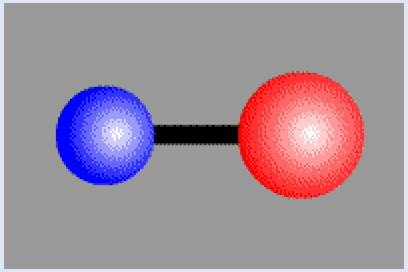
Molecular Lines I

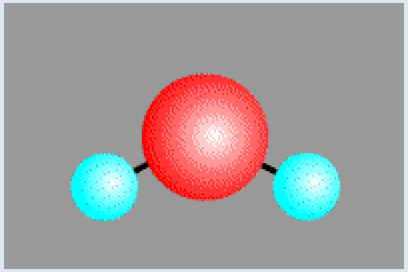
- Electronic transitions (rather in VIS / UV)
- Rotational transitions (needs dipole, so no H_2 !)





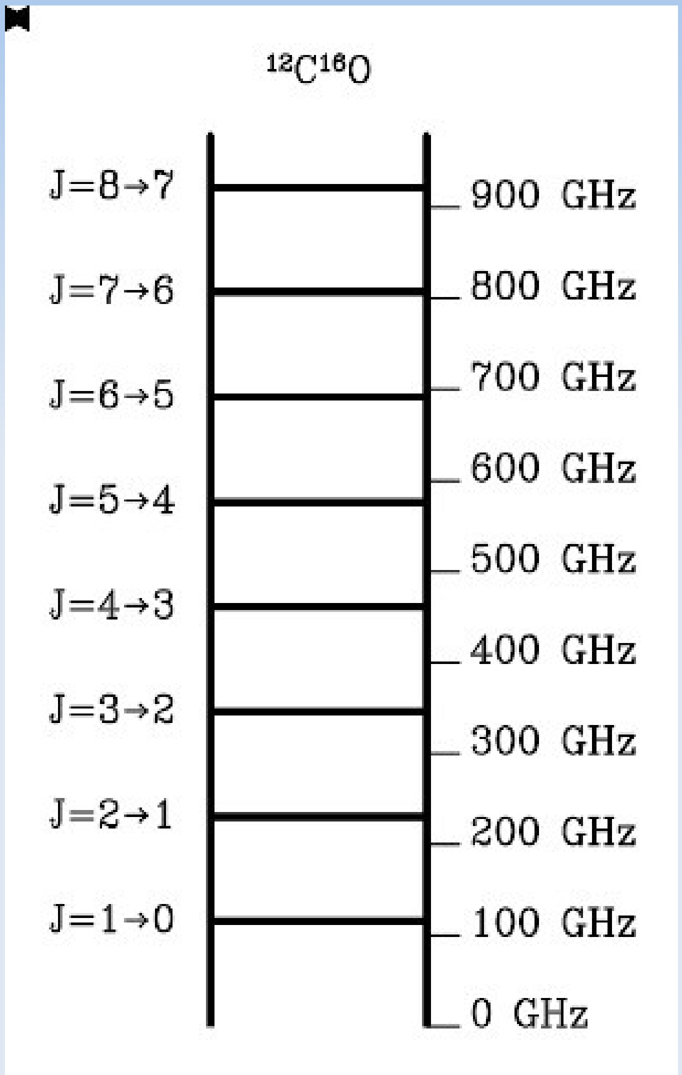
- Vibrational transitions

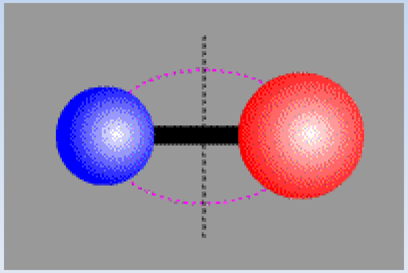


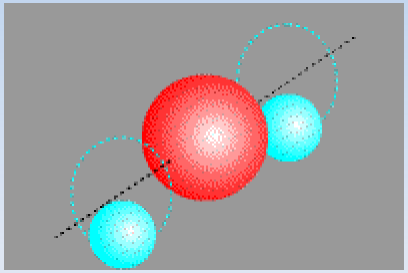


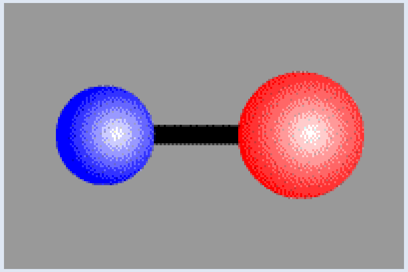
Animations: http://www.shokabo.co.jp/sp_e/optical/labo/opt_line/opt_line.htm

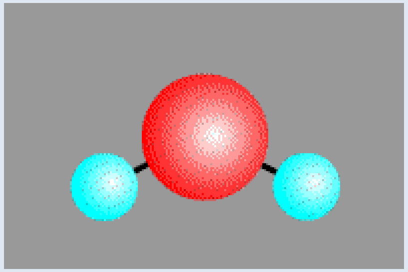
Molecular Lines I











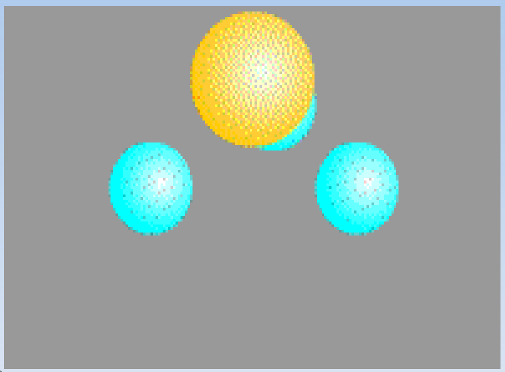
Animations: http://www.shokabo.co.jp/sp_e/optical/labo/opt_line/opt_line.htm

Molecular Lines II

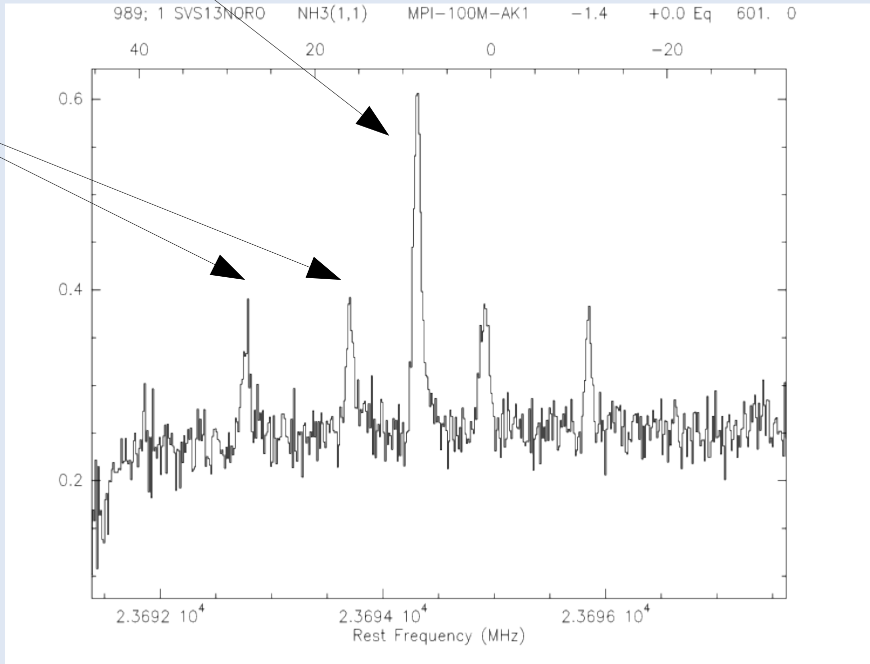
- Inversion

  Here: Nitrogen tunnels through double well potential

- Hyperfine splitting

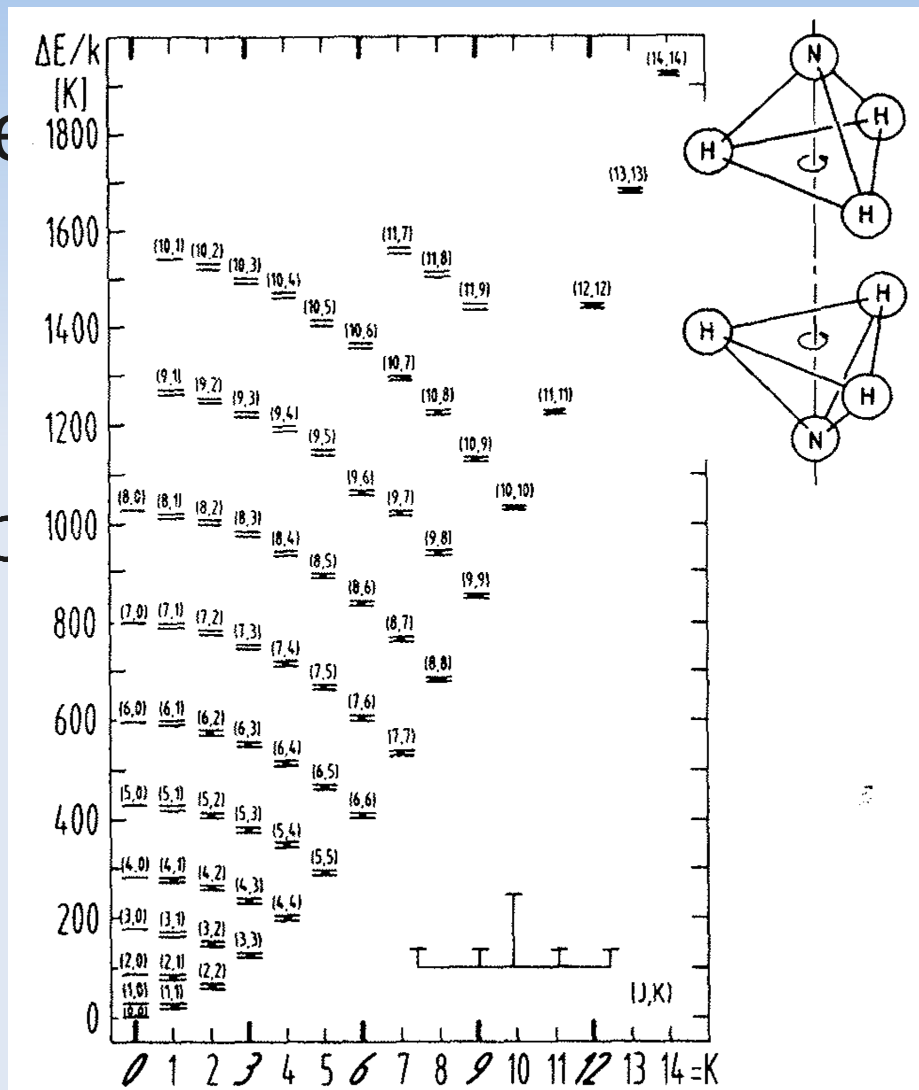


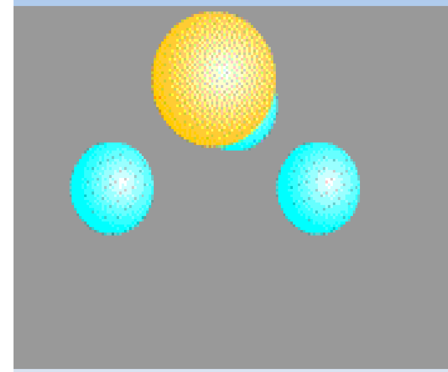
NH_3



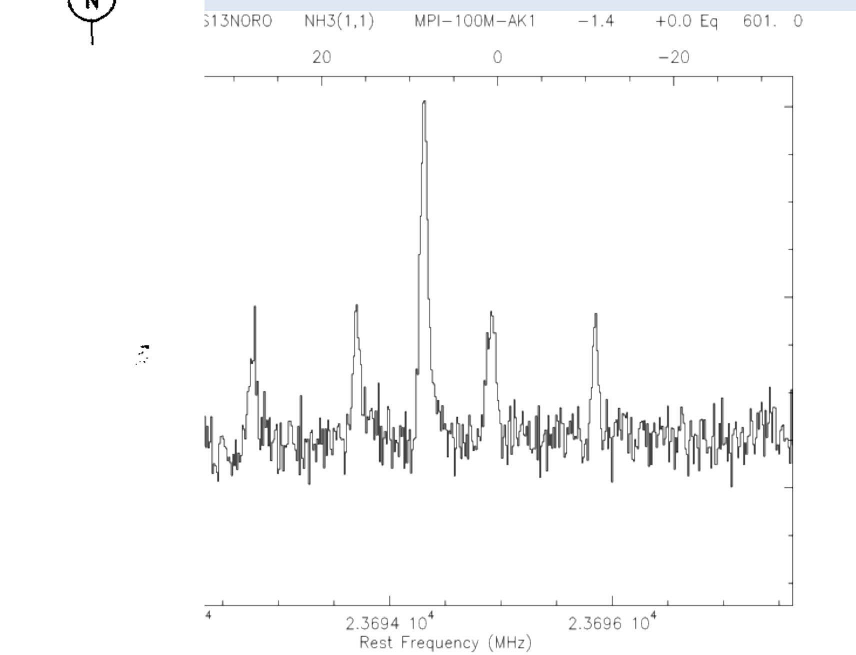
Molecular Lines II

- Inve
- Hyp



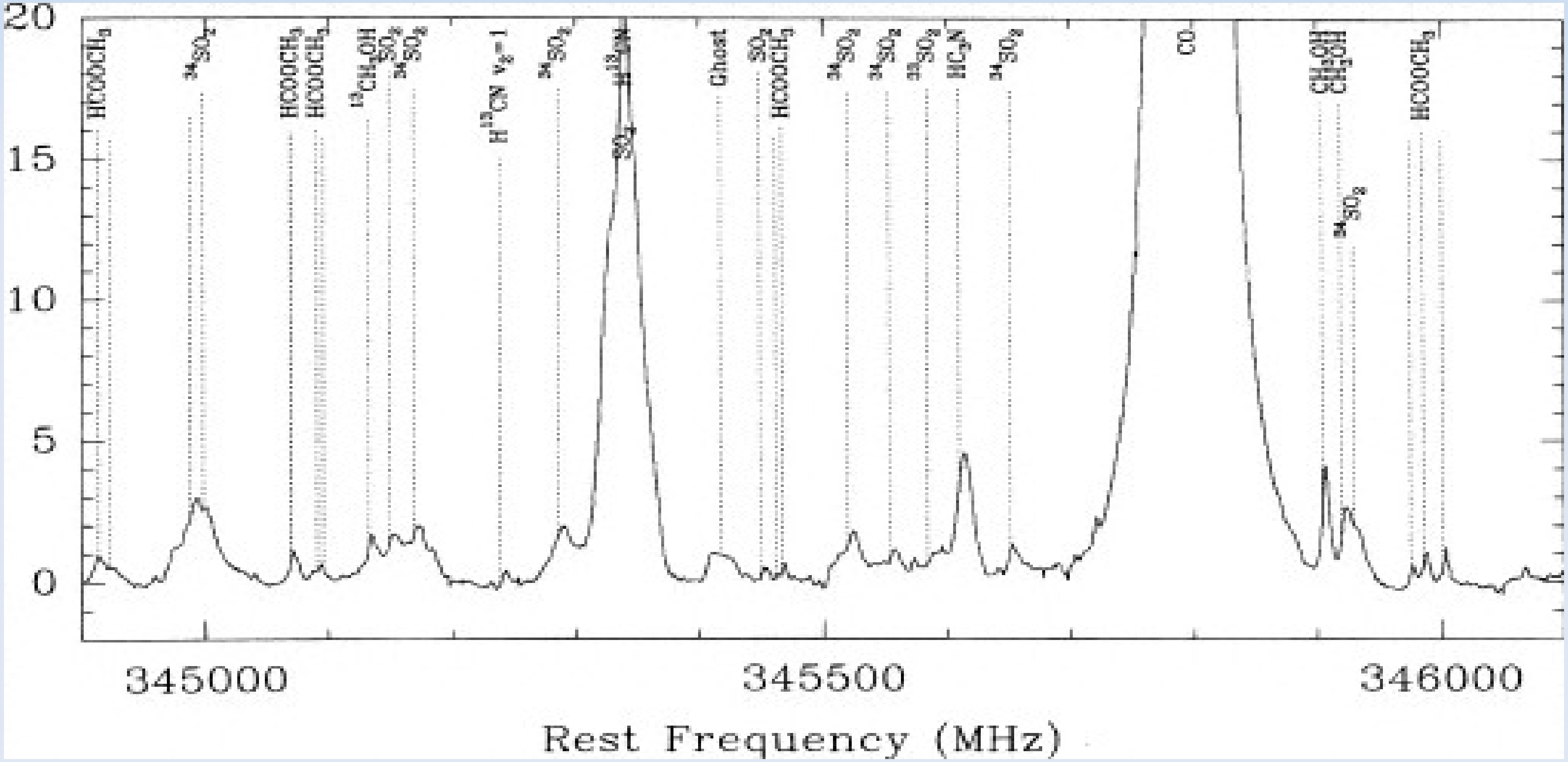


NH_3



Interstellar Fingerprints

- Set of all possible lines of an atom or molecule is its personal “fingerprint”



Schilke et al. ApJS 108:301–337, 1997

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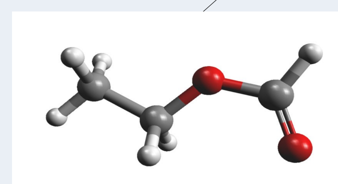
Interstellar Molecular Zoo

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	13 atoms
H_2	C_3*	c-C_3H	C_5*	C_5H	C_6H 2008	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	C_6H_6* (?)	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN 2008	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$?	
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO 2009	n-C_3H_7CN 2009	
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	H_2C_6	HC_7N				
CH^+	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	CH_4*	CH_3SH	c-C_2H_4O	l-HC_6H* (?)	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO		H_2NCH_2CN 2008					
SiC	H_2O	HNCS	H_2CNH	C_5N							
HCl	H_2S	$HOCO^+$ 2008	H_2C_2O	l-HC_4H* (?)							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4*	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^- 2008							
NaCl	N_2H^+	c-SiC_3	C_4H^- 2008								
OH	N_2O	CH_3*	$HC(O)CN$ 2008								
PN	NaCN	C_3N^- 2008									
SO	OCS	PH_3 ? 2008									
SO^+	SO_2	HCNO 2009									
SiN	c-SiC_2	HOCN 2010									
SiO	CO_2*	HSCN 2009									
SiS	NH_2										
CS	H_3^+*										
HF	H_2D^+, HD_2^+										
HD	SiCN										
FeO ?	AlNC										
O_2	SiNC										
CF^+	HCP										
SiH ?	CCP 2008										
PO	AlOH 2010										
AlO 2009	H_2O^+ 2010										
OH^+ 2010											
CN^- 2010											

www.cdms.de 08/2010

Interstellar Molecular Zoo

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	13 atoms
H_2	C_3^*	c-C_3H	C_5^*	C_5H	C_6H 2008	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	$C_6H_6^*$ (?)	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN 2008	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	$C_2H_5OCH_3$?	
AlCl	C_2O	C_3N	C_4Si	$C_2H_4^*$	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO 2009	n-C_3H_7CN 2009	
C_2^{**}	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO			
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	H_2C_6	HC_7N				
CH^+	HCN	$C_2H_2^*$	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	CH_4^*	CH_3SH	c-C_2H_4O	l-HC_6H^* (?)	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO		H_2NCH_2CN 2008					
SiC	H_2O	HNCS	H_2CNH	C_5N							
HCl	H_2S	$HOCO^+$ 2008	H_2C_2O	l-HC_4H^* (?)							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4^*	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^- 2008							
NaCl	N_2H^+	c-SiC_3	C_4H^- 2008								
OH	N_2O	CH_3^*	$HC(O)CN$ 2008								
PN	NaCN	C_3N^- 2008									
SO	OCS	PH_3 ? 2008									
SO^+	SO_2	HCNO 2009									
SiN	c-SiC_2	HOCN 2010									
SiO	CO_2^*	HSCN 2009									
SiS	NH_2										
CS	H_3^{+*}										
HF	H_2D^+, HD_2^+										
HD	SiCN										
FeO ?	AlNC										
O_2	SiNC										
CF^+	HCP										
SiH ?	CCP 2008										
PO	AlOH 2010										
AlO 2009	H_2O^+ 2010										
OH^+ 2010											
CN^- 2010											
35	33	23	18	16	9	10	9	4	3	3	1



Ethyl formate

Belloche et al. A&A, 499, 215, 2009

Total of 164 and counting !

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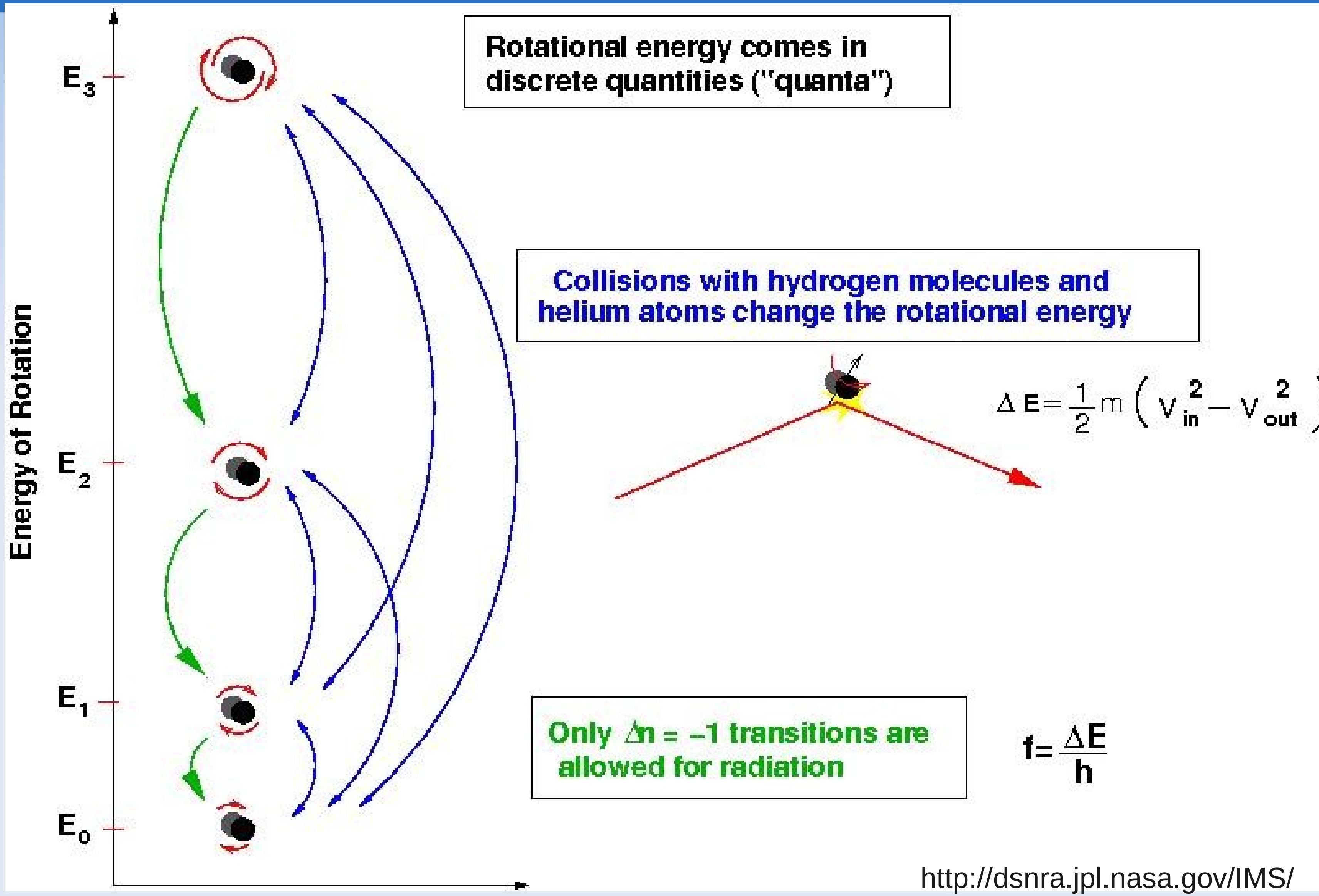
Spectral Line Excitation

- Near HII regions radiatively via UV fields
- In cold molecular clouds via CMB but predominantly via collisions with H_2
- In case of a level inversion one gets a maser (→ see also special maser talk tomorrow)

Collisional Excitation



http://dsnra.jpl.nasa.gov/IMS/

Maser Molecules

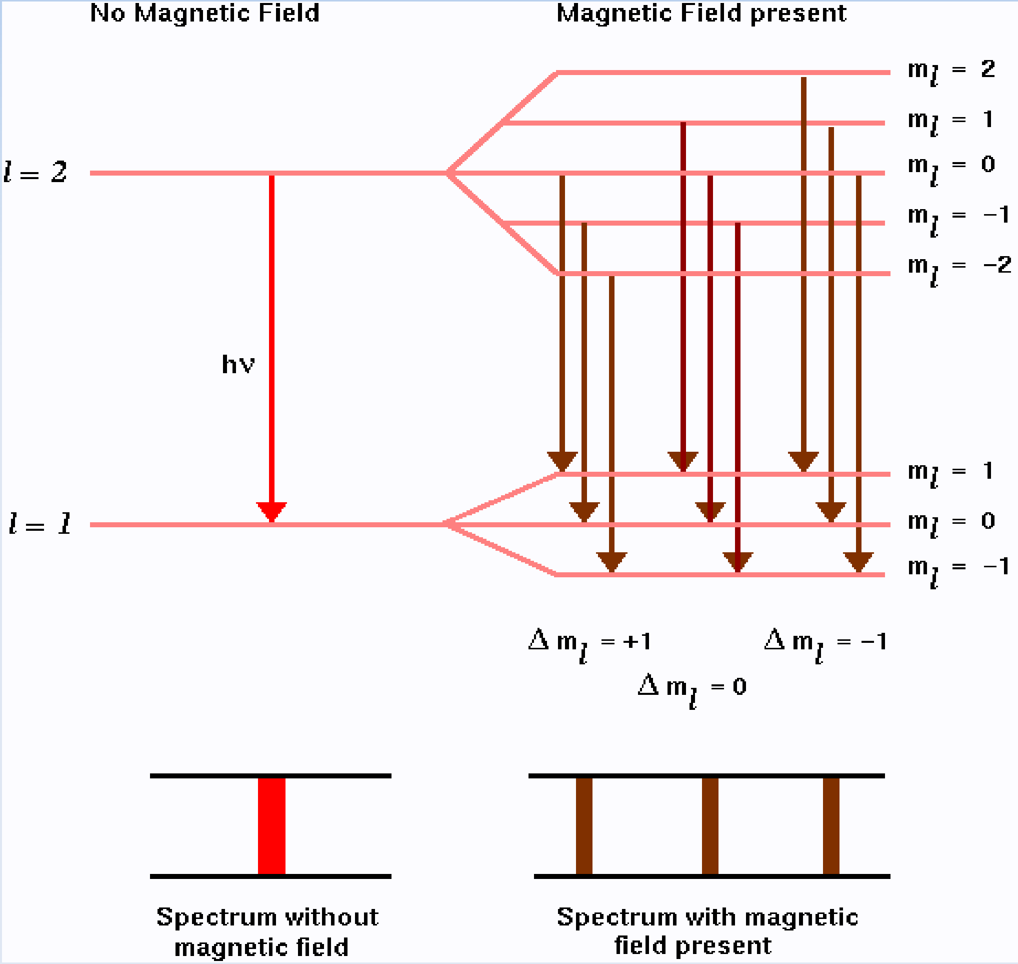
Molecules that exhibit maser action in celestial objects			
molecule	name	frequency (GHz)	characteristics*
OH	hydroxyl	1.612	O, M
	"	1.667	O, M
	"	1.720	O
H_2CO		4.829	O
CH_3OH	methanol	12.178	O
SiS	silicon sulfide	18.155	C
H_2O	water	22.235	O, M
NH_3	ammonia	23.870	O
SiO	silicon oxide	43.122	M, S, O
	"	86.243	M, S
HCN	hydrogen cyanide	89.087	C

*O means that the maser emission is frequently found in star-forming regions; M, in M stars; S, in S stars; C, in carbon stars

http://www.daviddarling.info/encyclopedia/I/interstellar_maser.html

Zeeman Effect

- Degenerate energy levels split up if an external magnetic field is applied
- This leads to additional transitions and allows to measure the magnetic field



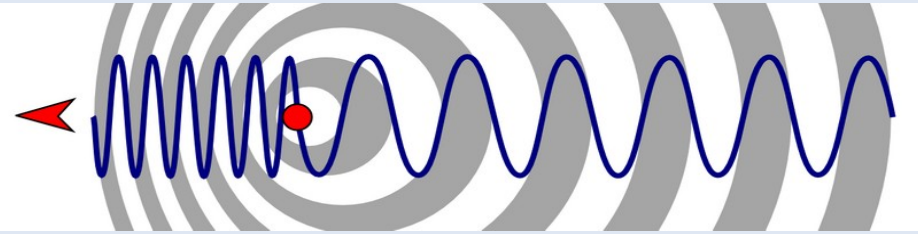
Kingshuk Majumdar (2000)

Optical Depth Effects

- Depending on the density and temperature spectral line emission can be optically thin or thick
- In the case of optical depth $\tau \ll 1$, one can look through a cloud and determine column densities and internal dynamics
- For $\tau \gg 1$, one can see only the surface of an object. Using radiative transfer one can calculate the cloud temperature

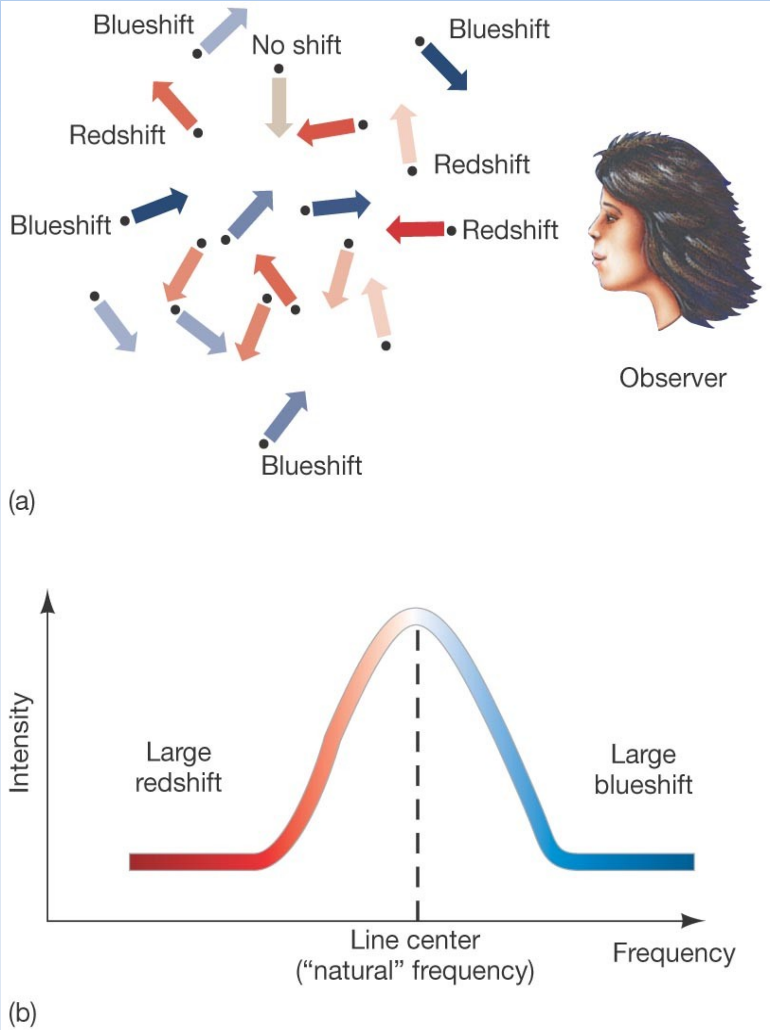
Line Profile Shape

- Ideal line should be infinitely sharp because there is a fixed energy difference $\Delta E = h\nu_0$
- Energy uncertainty causes a small broadening, the “natural line width”
- Thermal motion of emitters leads to Doppler shifted line frequencies



Thermal Broadening

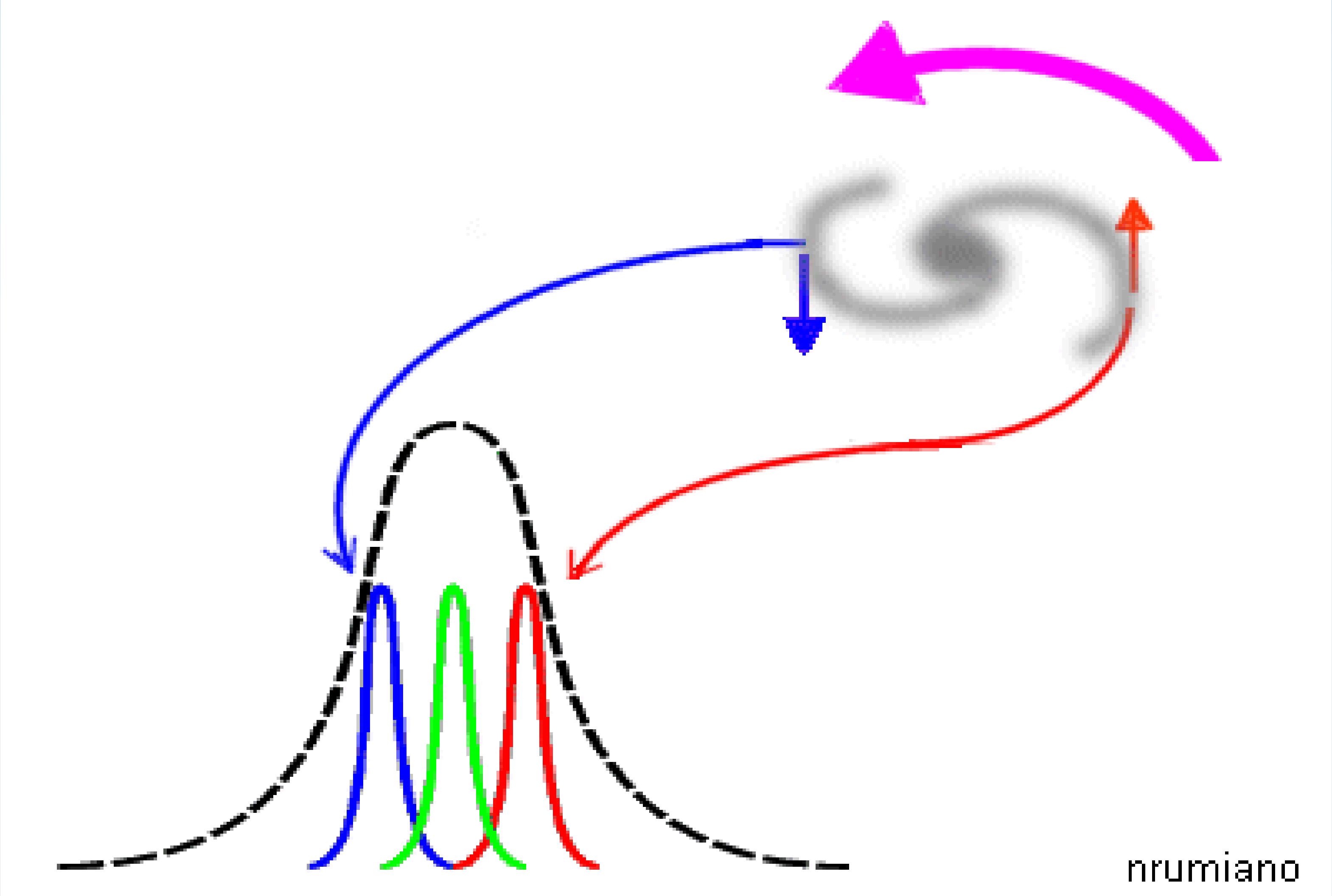
- Considering statistical ensembles one can derive a Gaussian shape for the broadened line
- Only the line-of-sight, i.e. the radial component adds to this effect



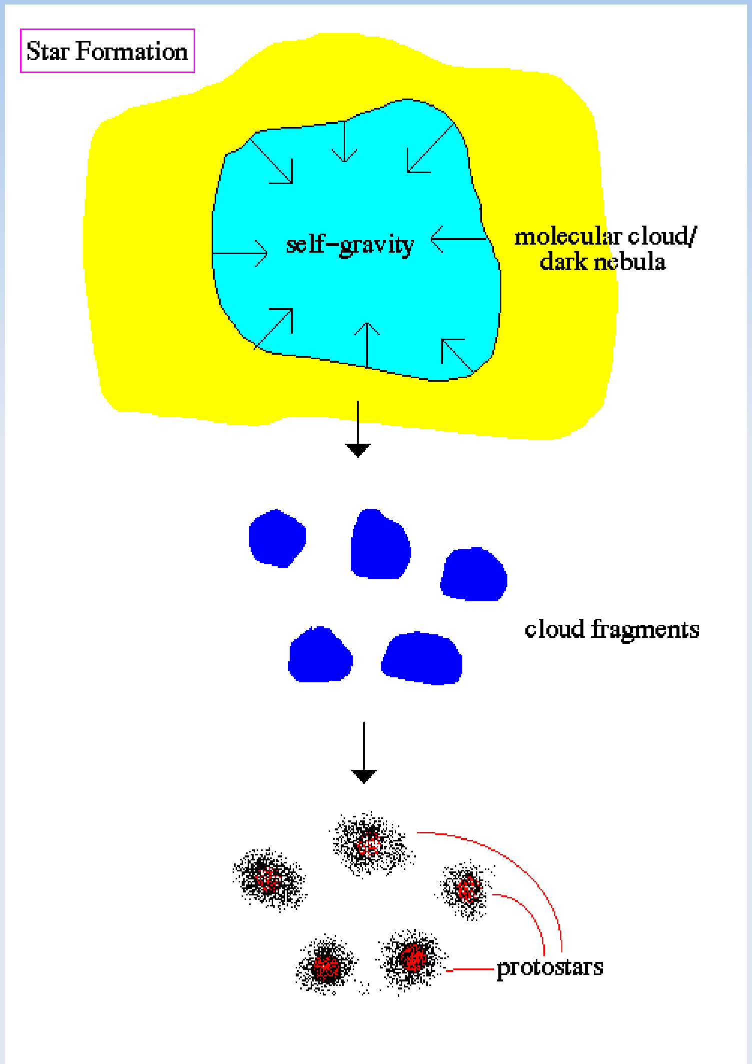
Radial Velocity

- Larger Doppler shifts can occur due to several effects:
  - Galactic rotation
  - Dynamical processes in molecular clouds and stars
  - Expansion of the universe (redshift can be so large that submm lines are shifted to cm wavelengths !)
- Each type of shift creates typical line profile shapes
- We often use radial Doppler velocity as x-axis

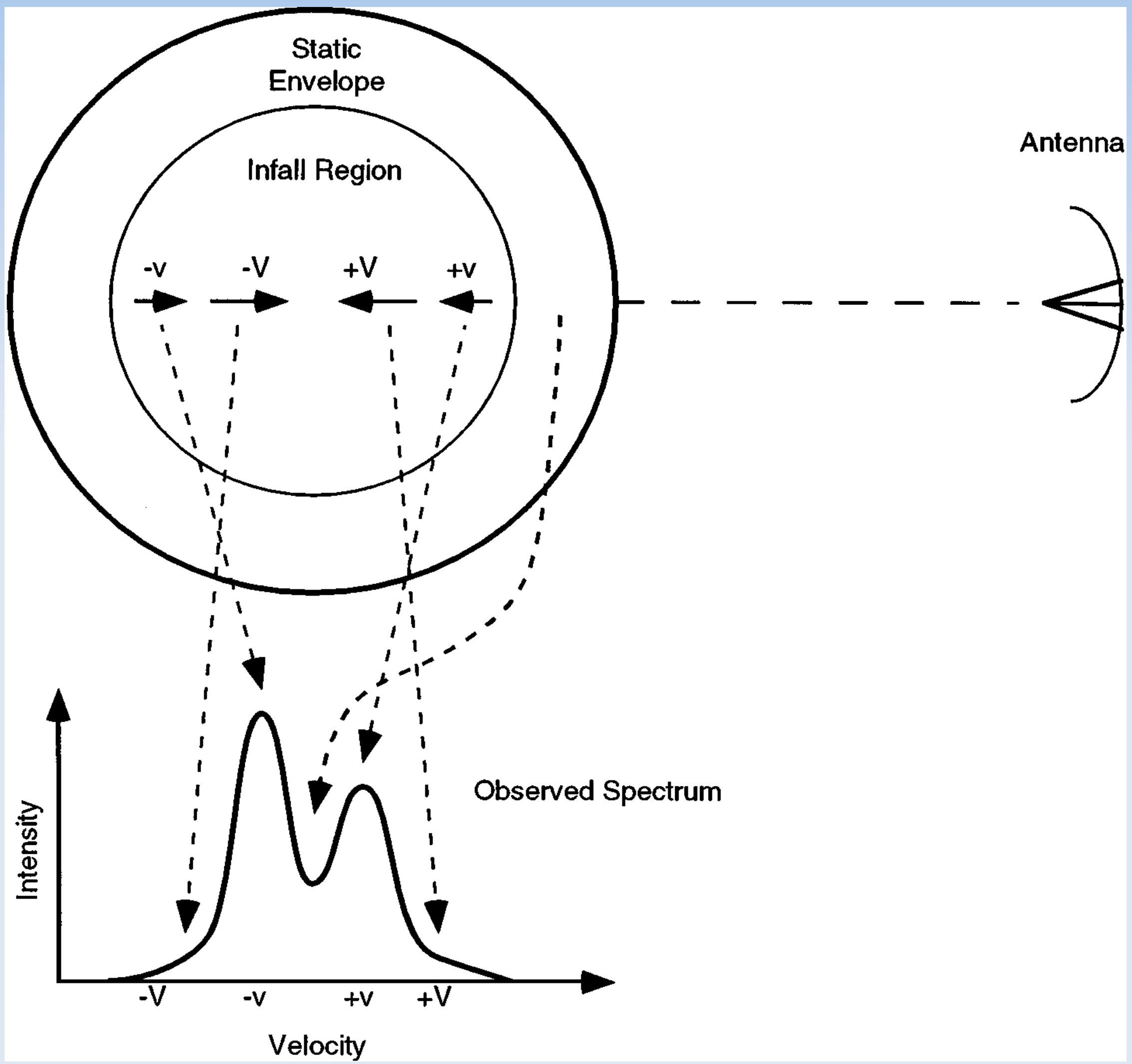
Dynamics: Rotation



Dynamics: Cloud Collapse

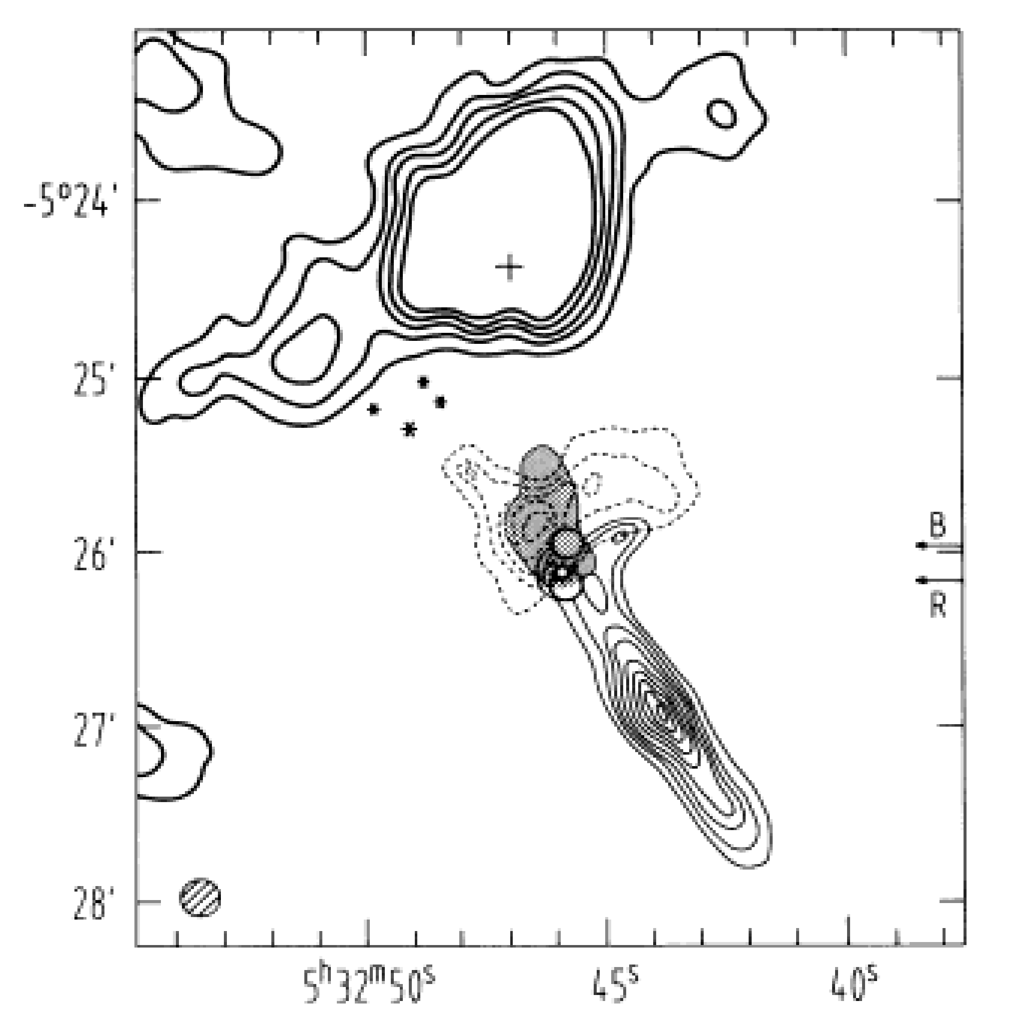


http://www.oglethorpe.edu/faculty/~m_rulison

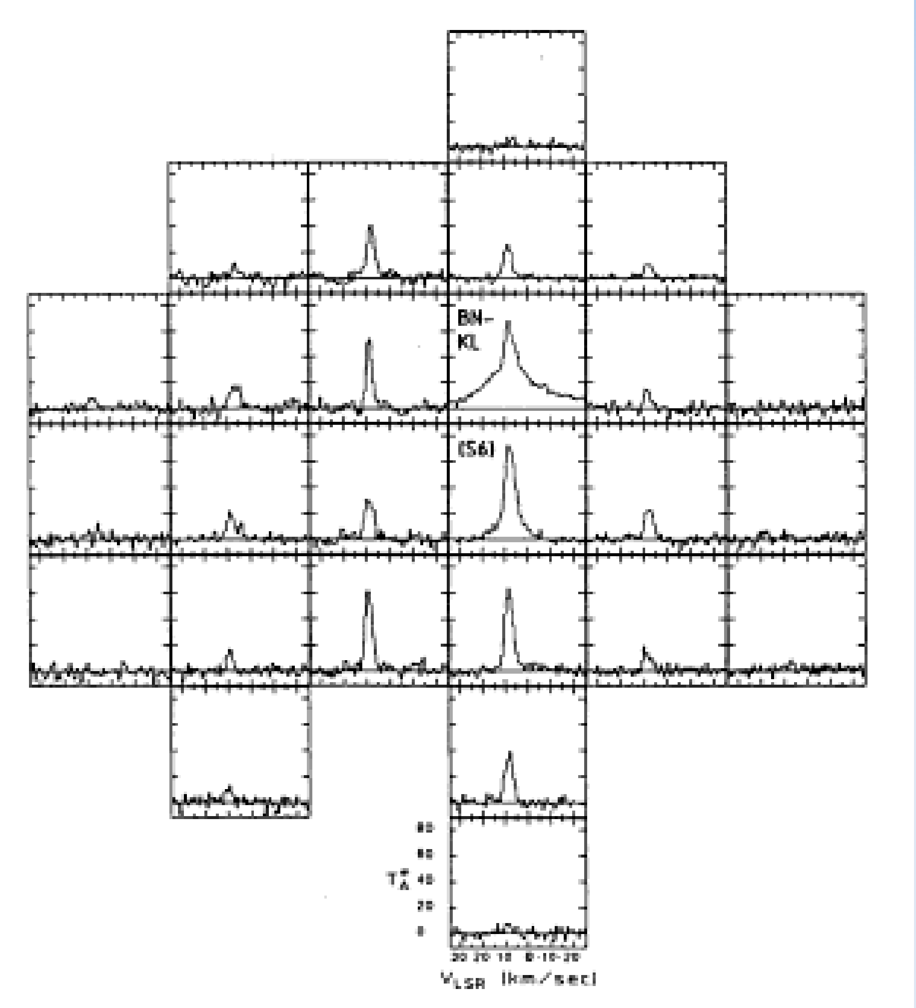


Neal J. Evans II, ARAA, 37, 311, 1999

Dynamics: Outflows



Schmid-Burgk et al. ApJ 362L, 25, 1990



Schmid-Burgk et al. LIACo, 29, 193, 1990

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für Radioastronomie

Spectral Instruments

- What does one need to observe radio astronomical spectral lines ?
  - Heterodyne frontend (→ special talk)
  - Usually a down-converter from observing frequencies to a “low” (0-4 GHz) intermediate frequency (IF) band
  - Spectrometers to analyze the signal

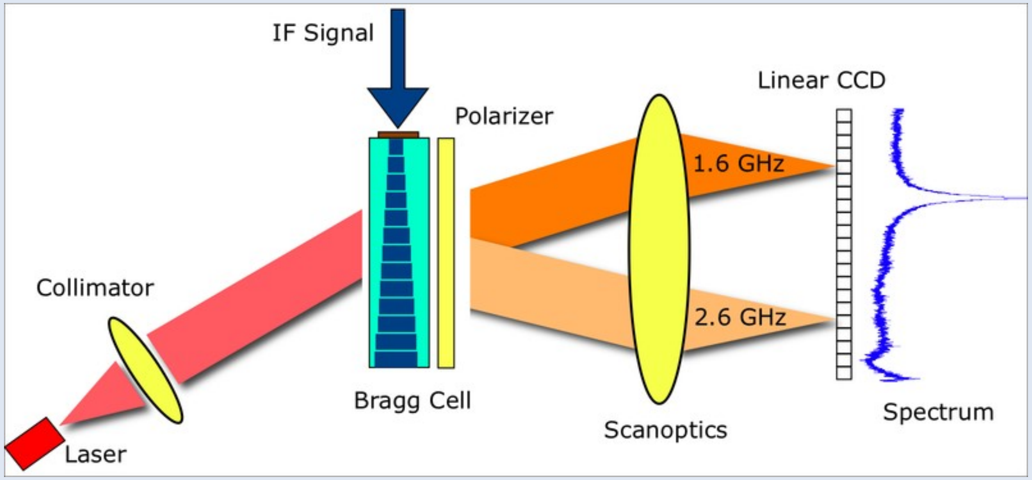
↳ Will concentrate on spectrometers here

Spectrometers

- Spectrometers measure the frontend signal in many frequency bins across the available bandwidth
- There are several techniques:
  - Filter banks: Series of analog filters; complex electronics
  - Auto-correlators: Special purpose computers; correlation function of time series signals; low number of bits

Spectrometers (ctd.)

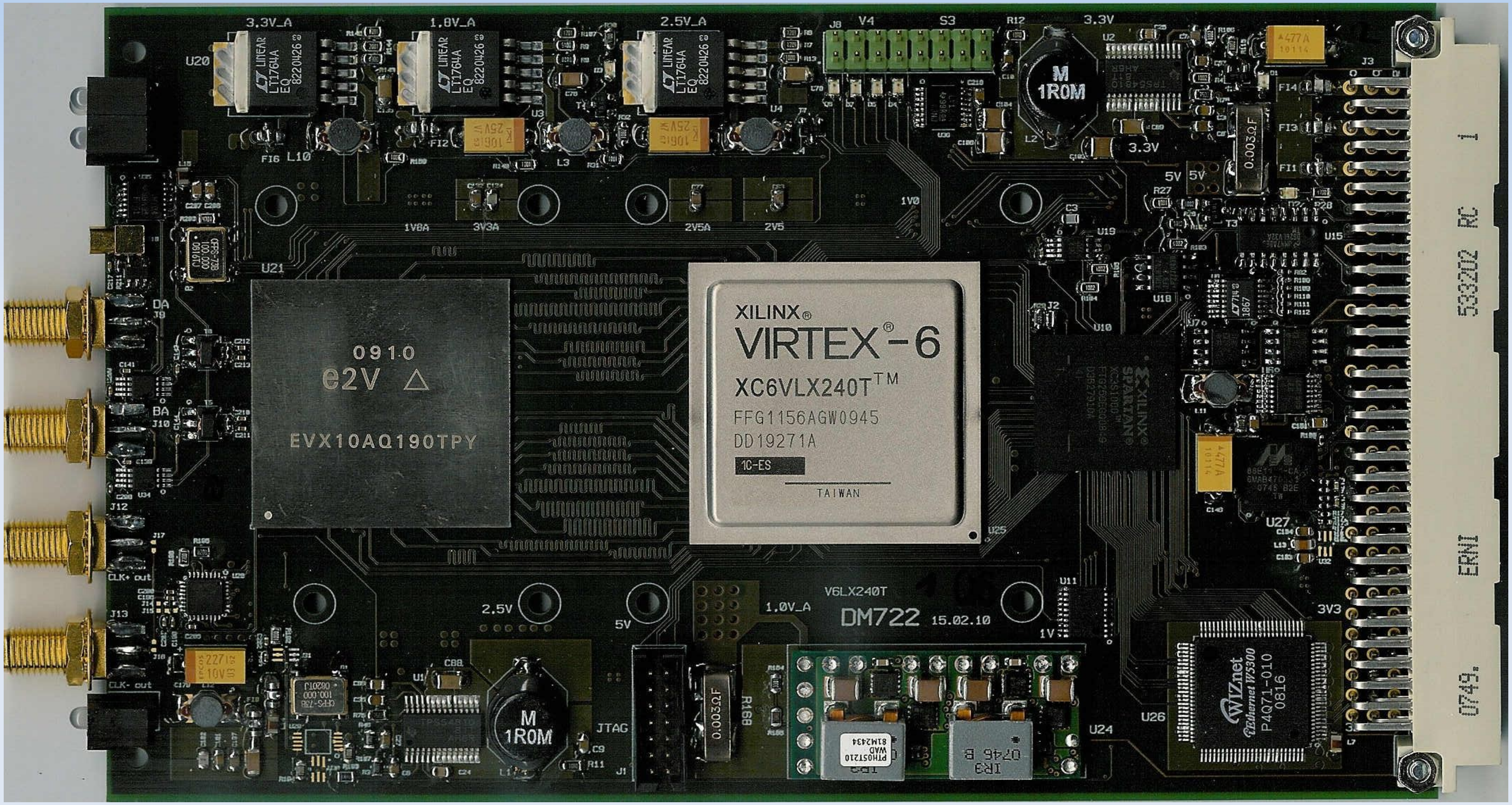
- More spectrometer types
  - Acousto-optical spectrometers (AOS): Diffraction of laser light at ultrasonic waves in a Bragg crystal; delicate optical setup



  - Fast Fourier Transform Spectrometers: High speed ADCs and FPGAs → Development at the MPIfR

Fast Fourier Transform Spectrometer

XFFTS: 2.5 GHz bandwidth / 32768 channels (ENBW 88.5 kHz)

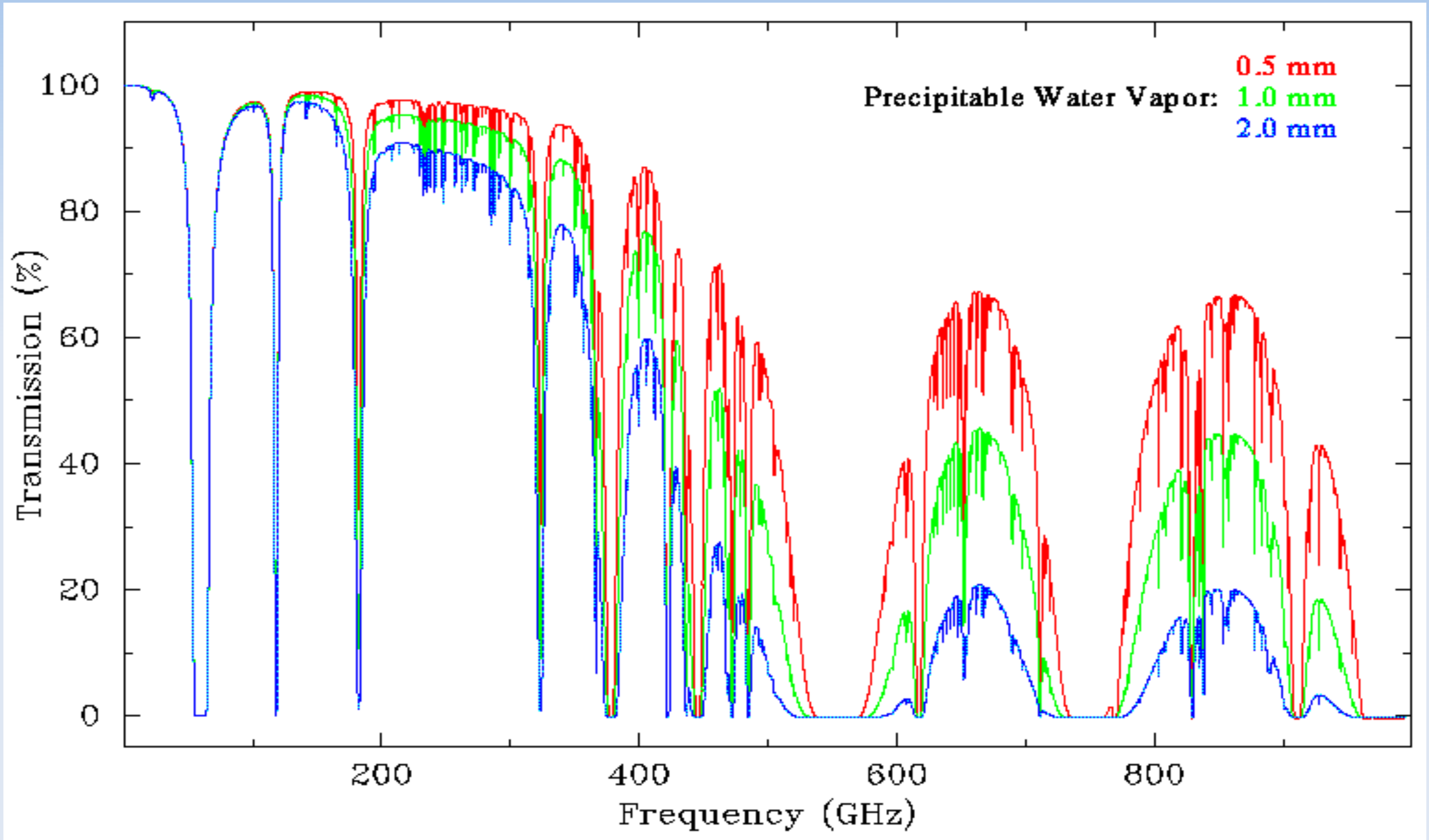


E2V 5 GS/s 10-bit ADC, XILINX Virtex-6 LX240T
[40 nm, 1.0 volt core voltage, >240‘000 logic cells, 768 DSP48 slices]

Observations

- Source signal is partially absorbed by the earth atmosphere
- The atmosphere also radiates itself and thus contributes to the signal

Atmospheric Transmission



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Observations

- Source signal is partially absorbed by the earth atmosphere
- The atmosphere also radiates itself and thus contributes to the signal
- The telescope beam picks up ground spillover
- Receiver etc. add a signal too
- Direct measurement therefore yields

$$C_{on} = C_{source} e^{-\tau A} + C_{atm}(1-e^{-\tau A}) + C_{spillover} + C_{rec}$$

On-Off Technique

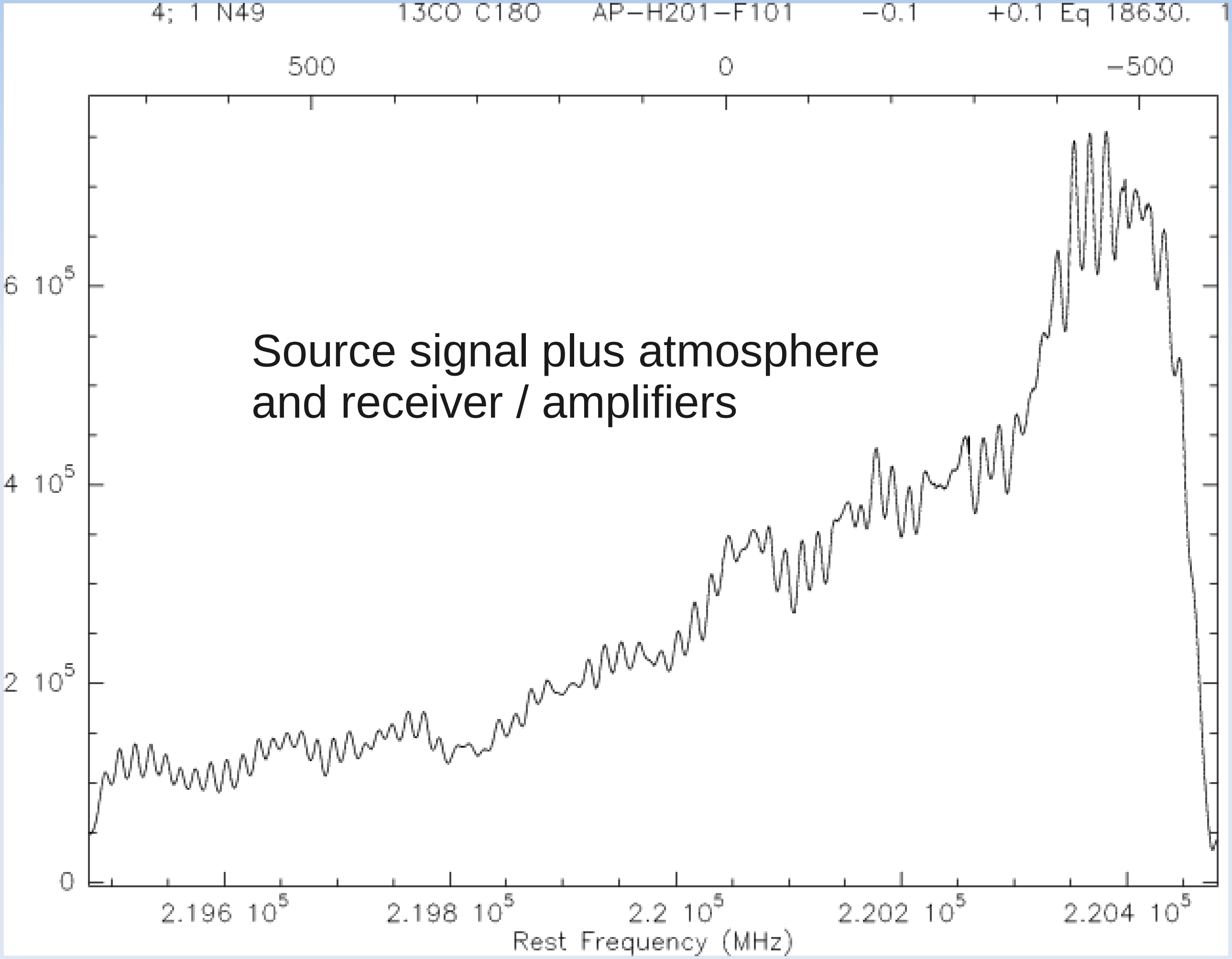
- To remove the atmospheric and instrumental emissions one observes the target and then a position on sky without astronomical emission

$$C_{off} = C_{atm}(1-e^{-\tau A}) + C_{spillover} + C_{rec}$$

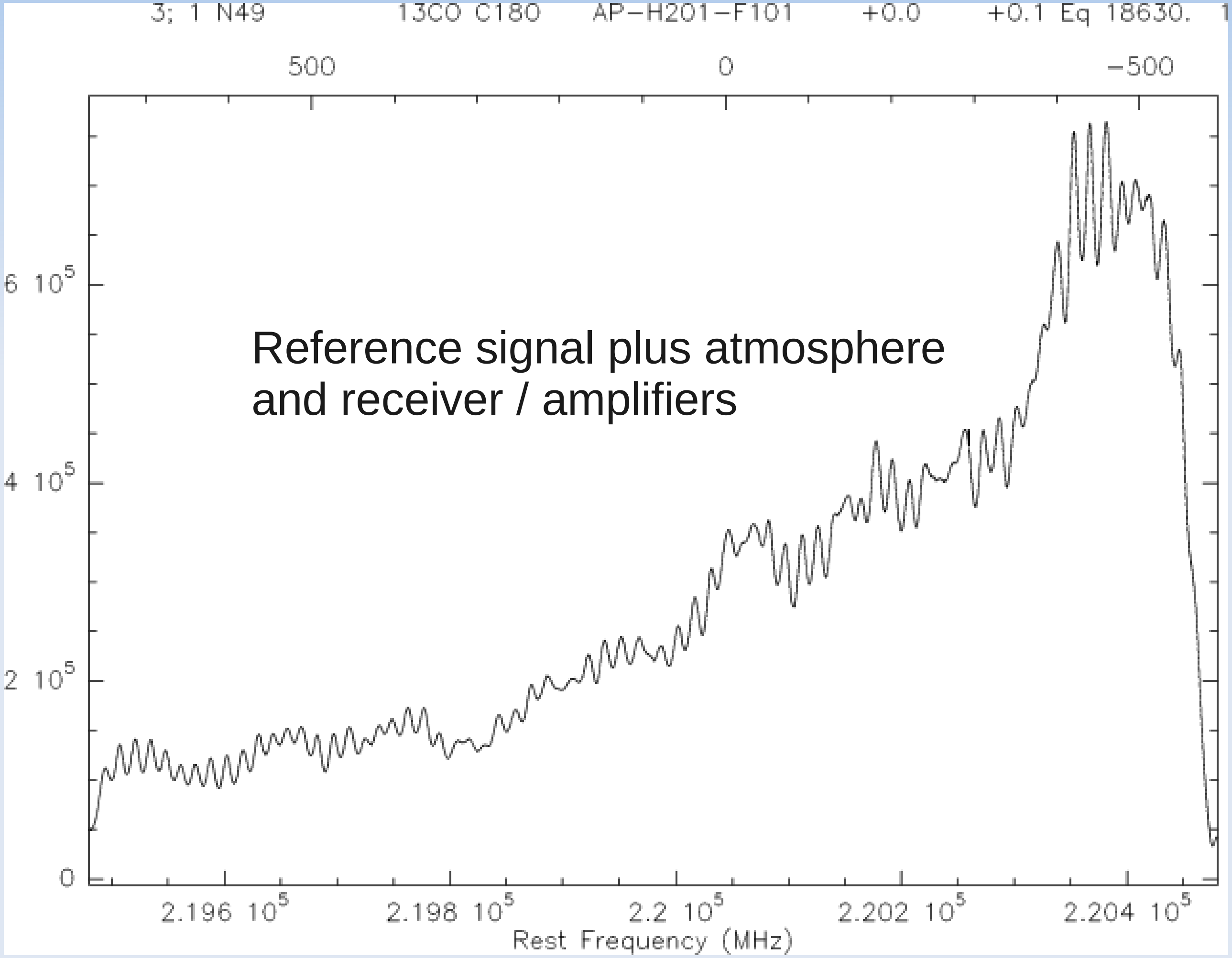
- The difference of the two measurements contains only the source signal (still weakened by atmospheric absorption):

$$C_{on} - C_{off} = C_{source} e^{-\tau A}$$

On-Off Technique



On-Off Technique



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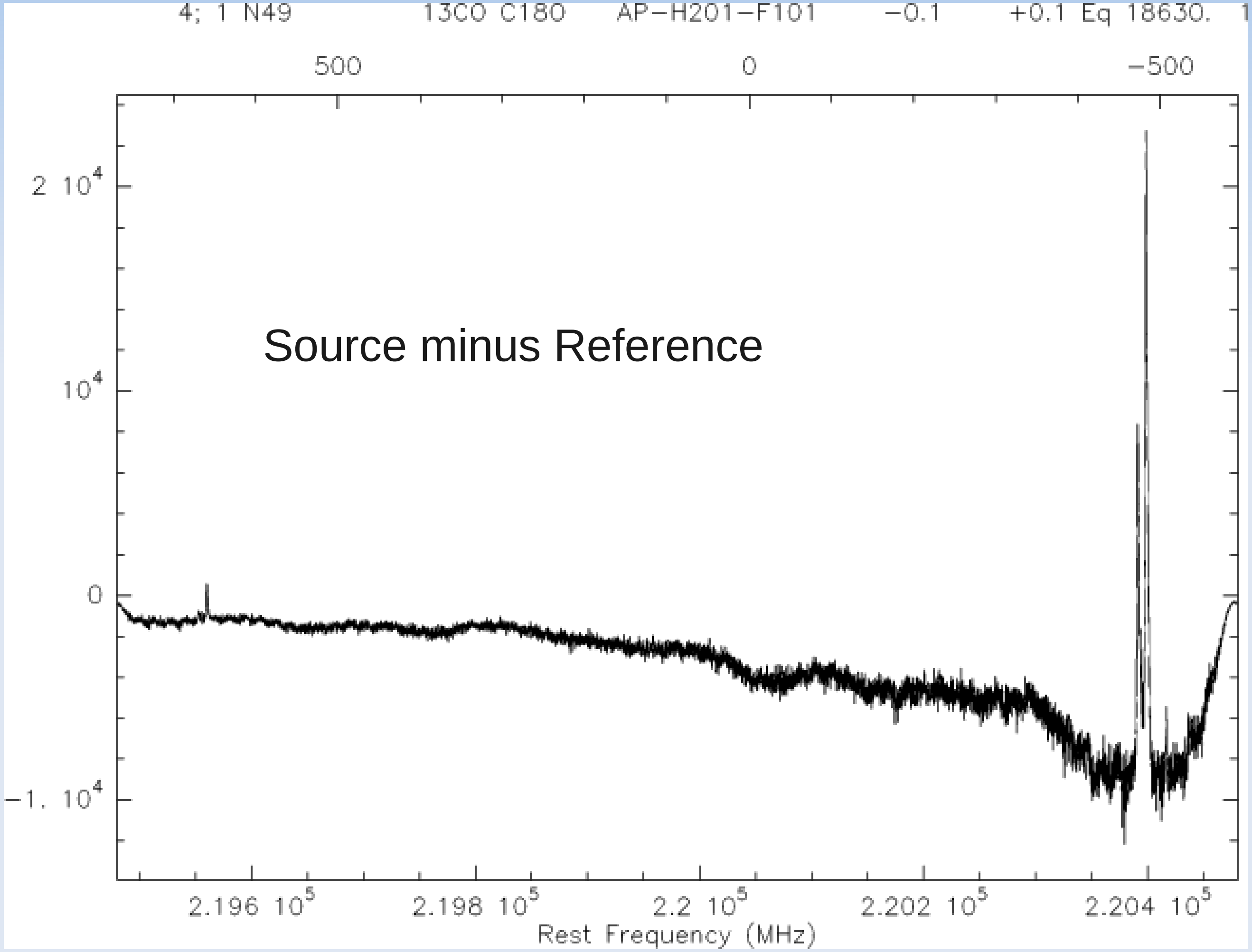
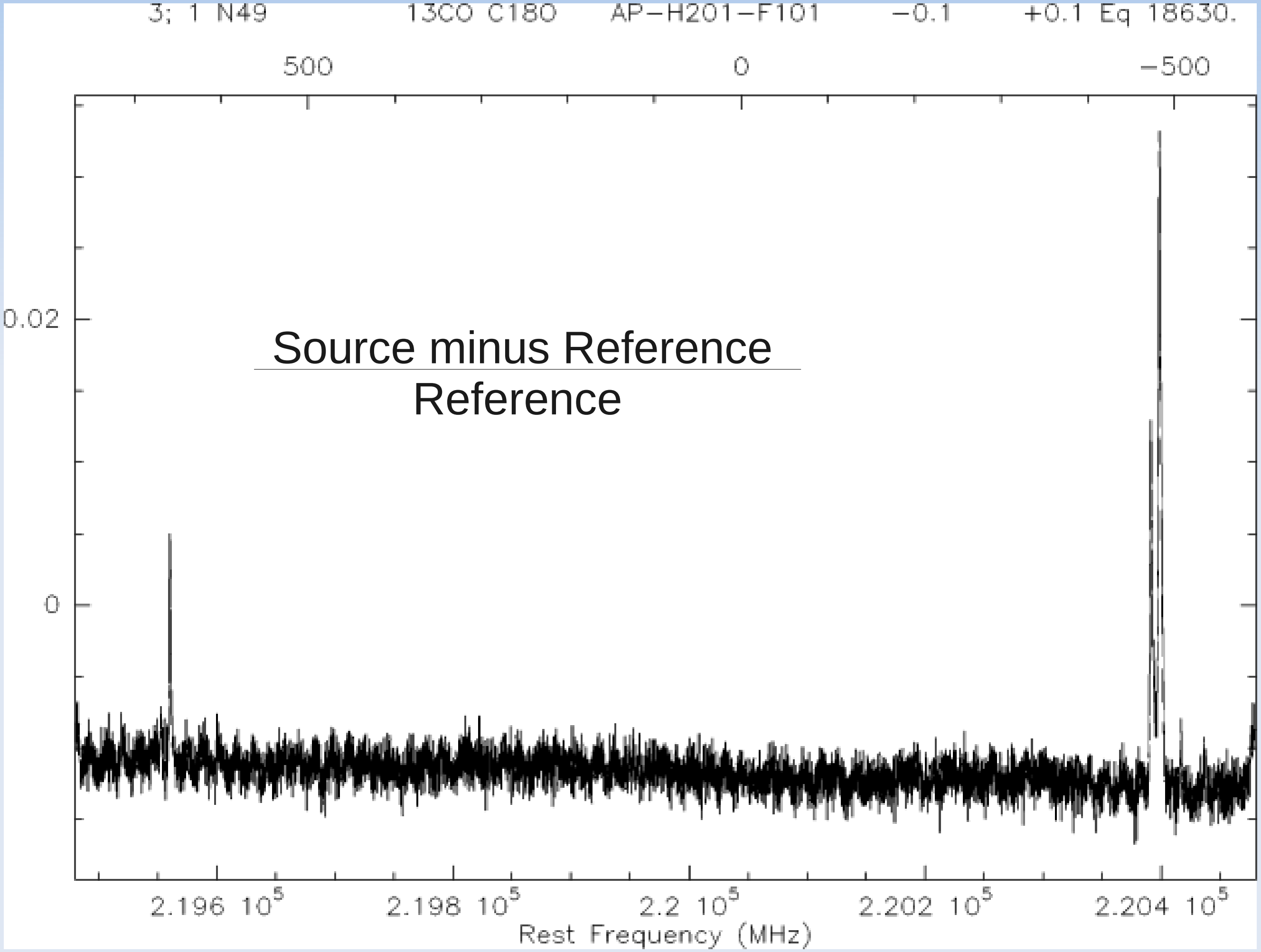
On-Off Technique



On-Off Technique



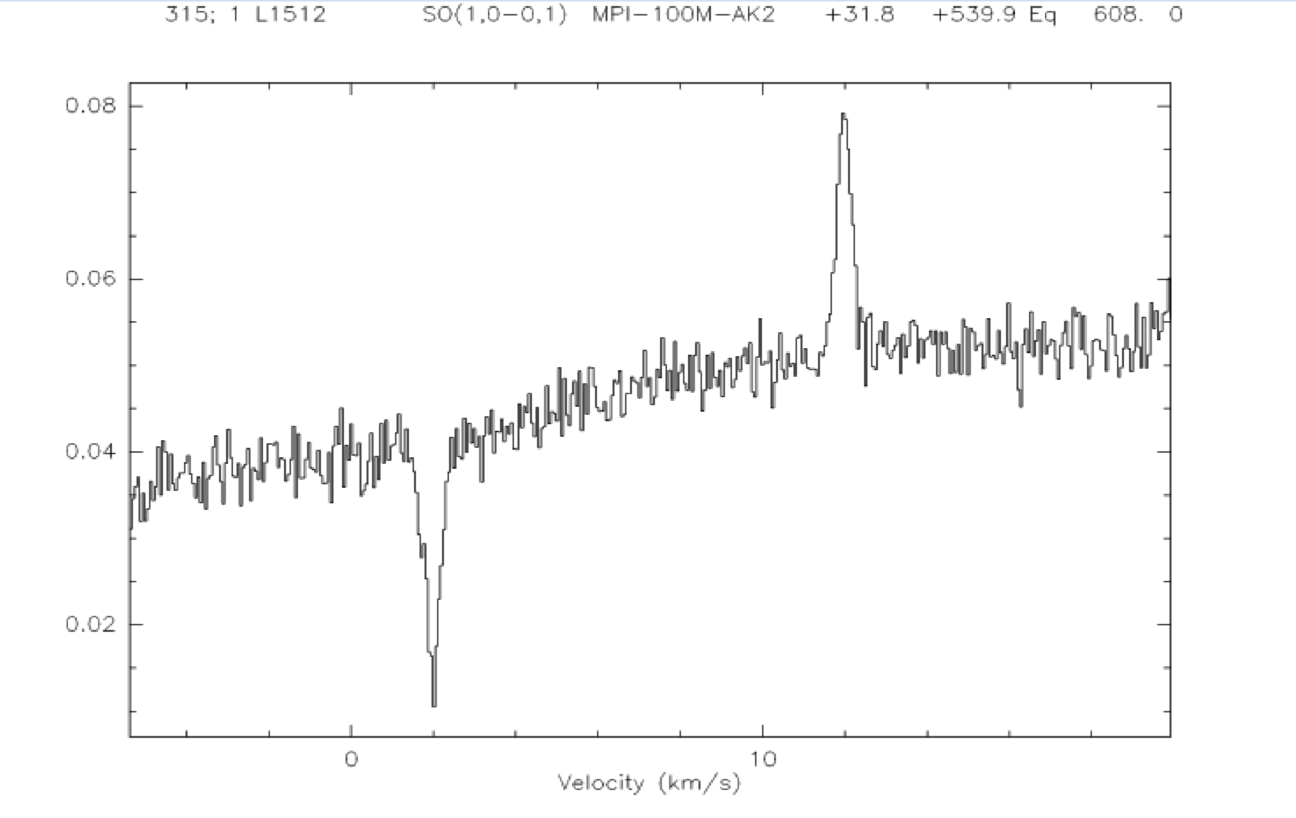
$$\frac{\text{Source minus Reference}}{\text{Reference}}$$

On-Off Alternatives

- On-Off measurements can be taken by moving the telescope between two positions.
- If the source is small, then one can use horn or wobbler switching which is faster. This helps if the atmospheric emission varies quickly.
- One can also measure the “off” at a slightly shifted frequency but pointing to the source. This doubles the actual “on” time and reduces telescope movements.

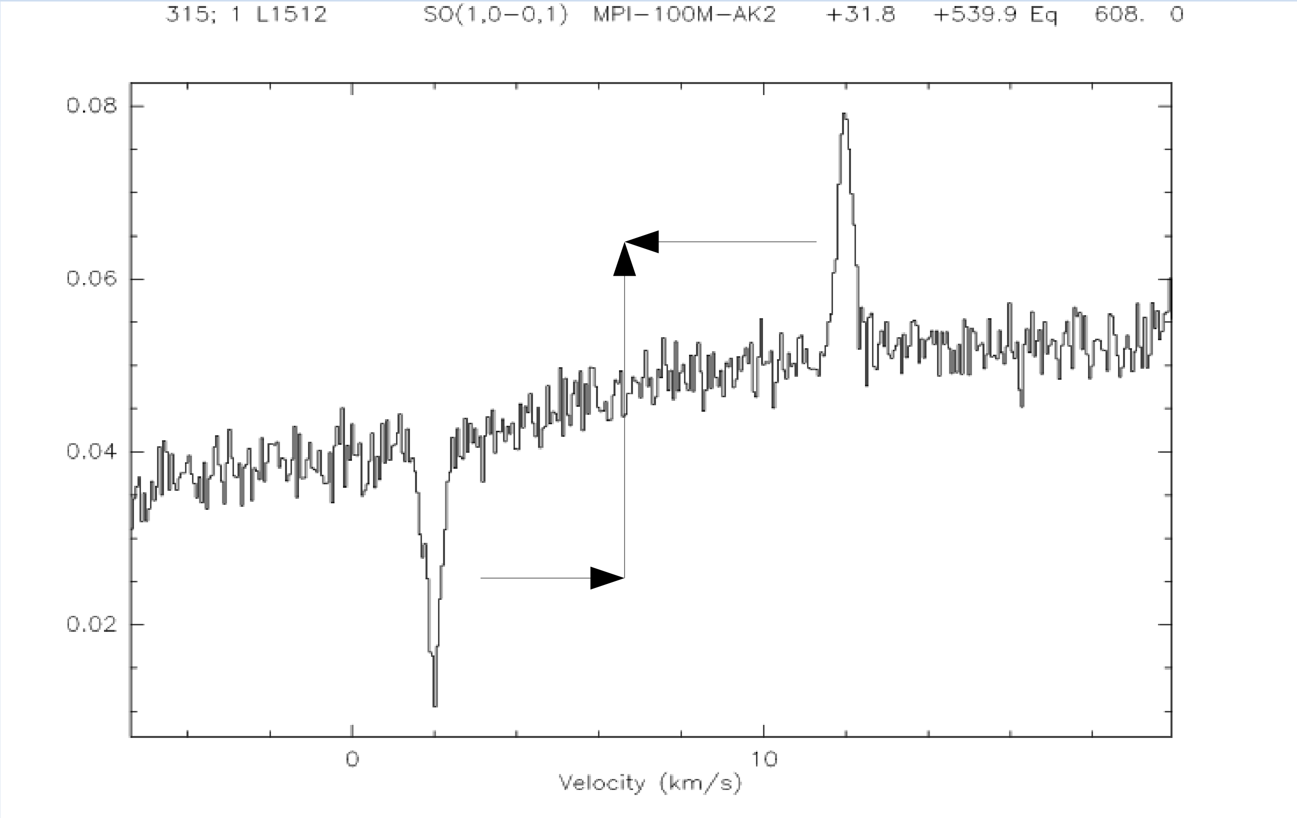
Frequency Switching

- Reference at a slightly different frequency but same position on the target



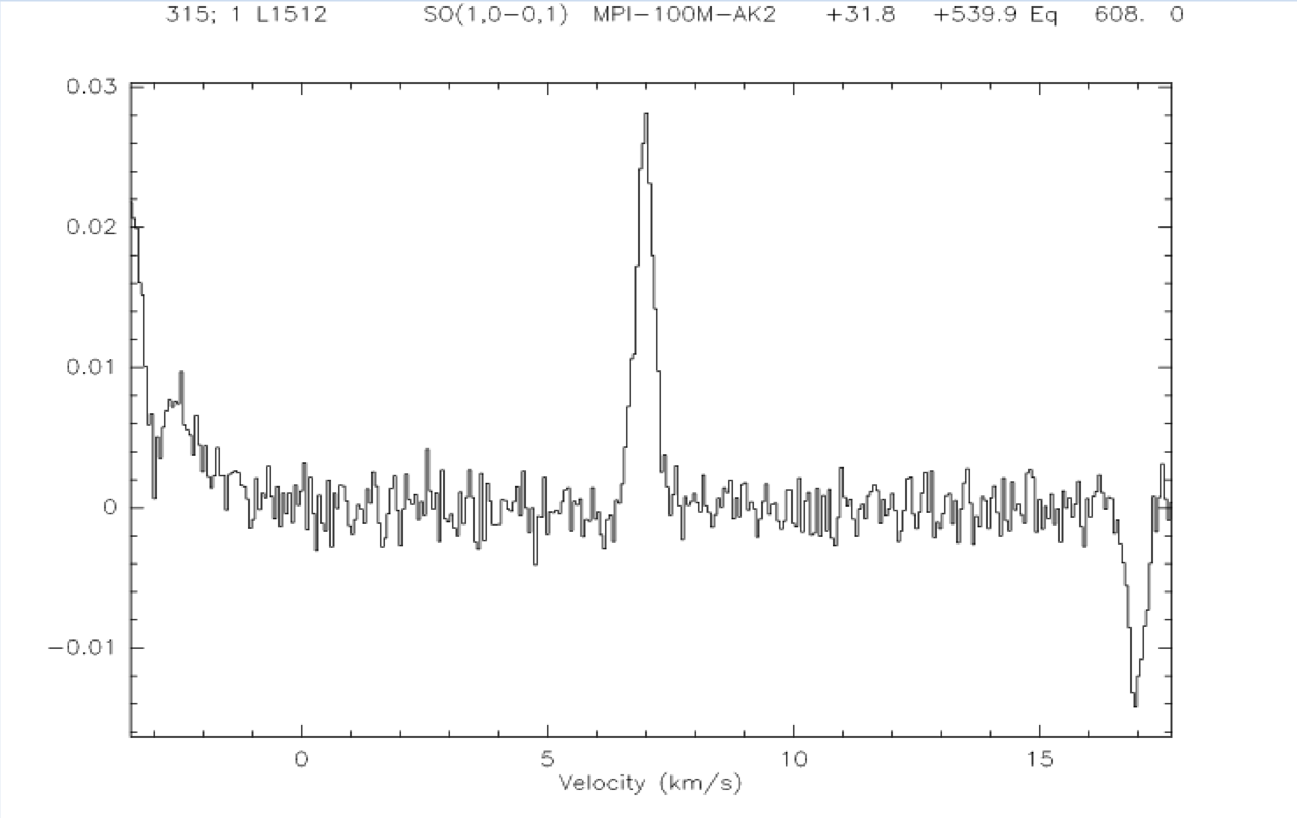
Frequency Switching

- Reference at a slightly different frequency but same position on the target



Frequency Switching

- Reference at a slightly different frequency but same position on the target



Observing Patterns

- Most radio receivers are still single pixel or small multi-beam systems
- To cover an extended source area one must observe several spatial offset positions
- Typical patterns are
  - (Rectangular) rasters with half beam spacing
  - (Rectangular) “On-The-Fly” rasters
  - Advanced figures like spirals, Lissajous figures, Rotating bow ties, etc.

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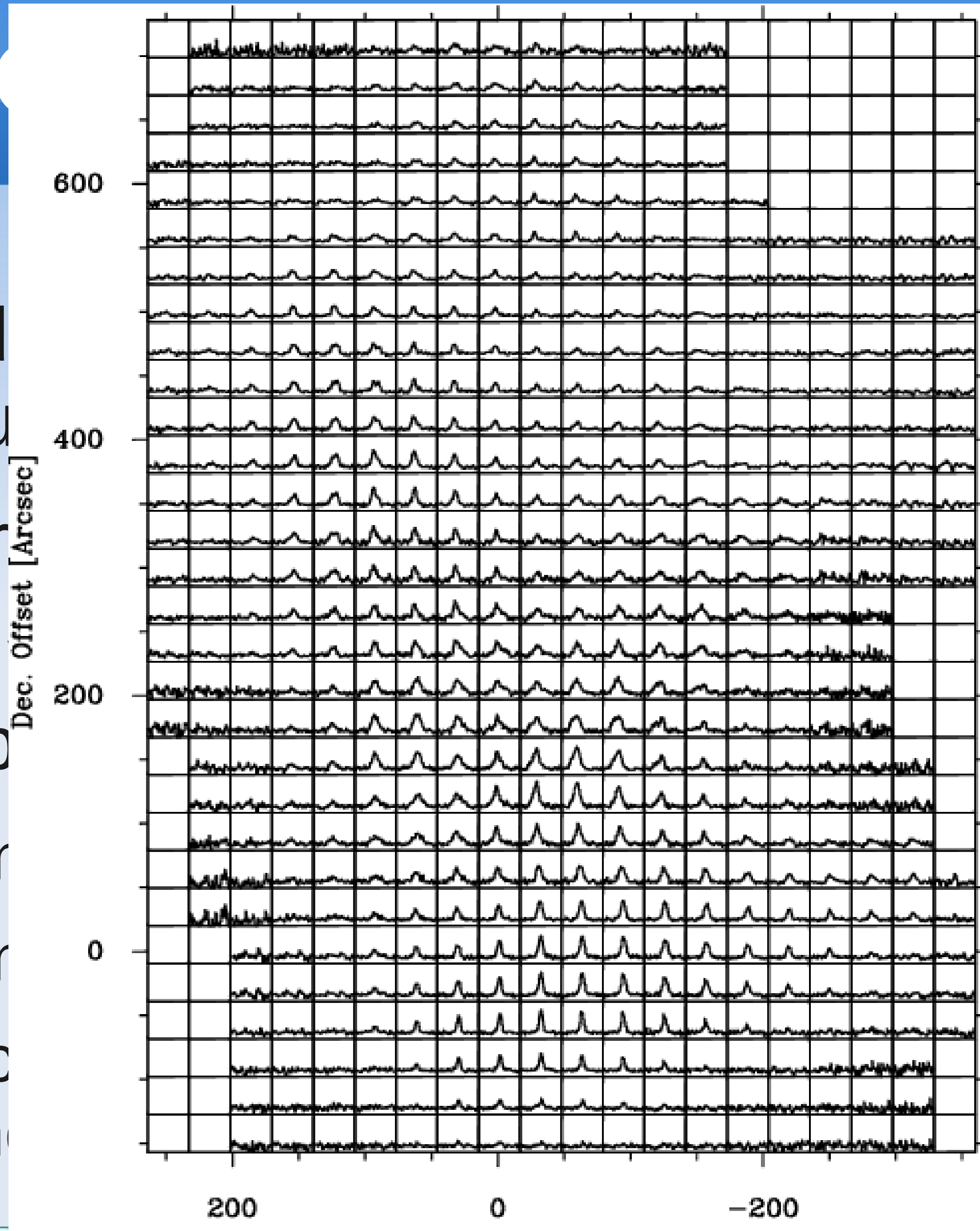


L1512, SO 1-0, 100m

Calibration

- The measurements in arbitrary counts need to be calibrated to physical units
- For spectral lines one usually uses the “Antenna Temperature” scale
- The receiver system is calibrated against “hot” (usually ambient temperature) and “cold” (usually LN_2 @ 77 K) black bodies
- In cm wave receivers one uses a noise diode that was hot/cold calibrated in the lab

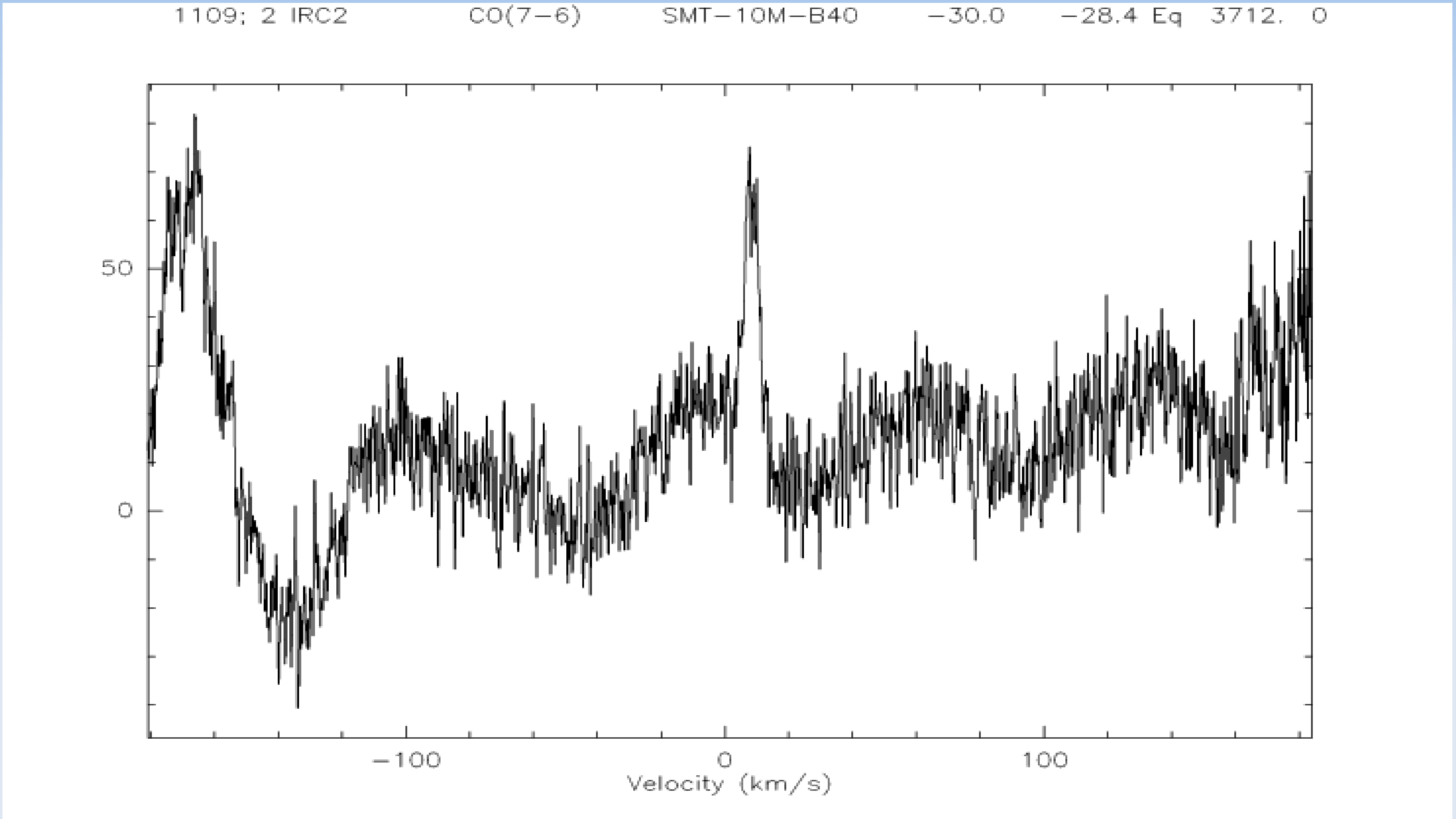
Calibration (ctd.)

- The absorption of astronomical signals needs to be corrected too:
  - Scaling according to measurements of secondary calibrator sources
  - Sky measurements and atmospheric models can be used to derive τ
  - More details in the calibration talk on Thursday

Data reduction

- Atmospheric and instrumental instabilities lead to spectral baseline artifacts

Data reduction



Data reduction

- Atmospheric and instrumental instabilities lead to spectral baseline artifacts
- Techniques to process spectral line data include:
  - Spectral baseline fits using polynomials
  - FFT analysis to remove sinusoidal components due to standing waves
  - Flagging of very bad data
- Caveat: Must be very careful not to alter the line emission, esp. for broad lines

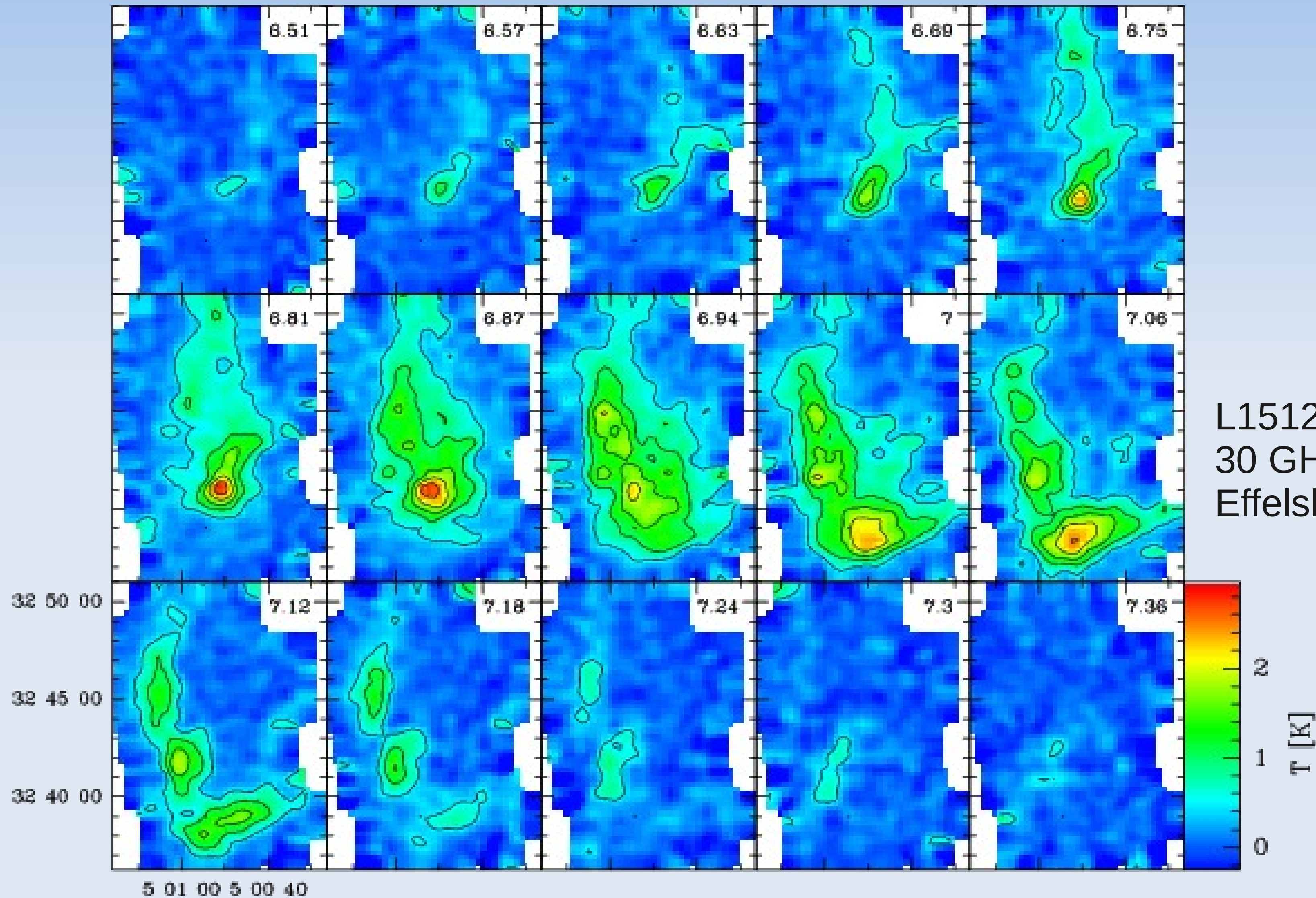
Data Products

- Primary data products are calibrated spectra
- For mapping projects the spatially distributed spectra are interpolated onto a regular grid to make 3D data cubes with two spatial and one spectral axis
- ALMA Pipeline Heuristics development (led by MPIfR) attempts to provide automatic data reduction (also applicable to Effelsberg data)

Spectral Data Visualization

- Usually display maps as false color images and contour plots
- Frequency axis allows for additional analysis, e.g. via so called channel maps or via position-velocity plots
- Since we have a data *cube*, one can apply 3D rendering techniques but one must be careful interpreting the graphs because of the frequency axis

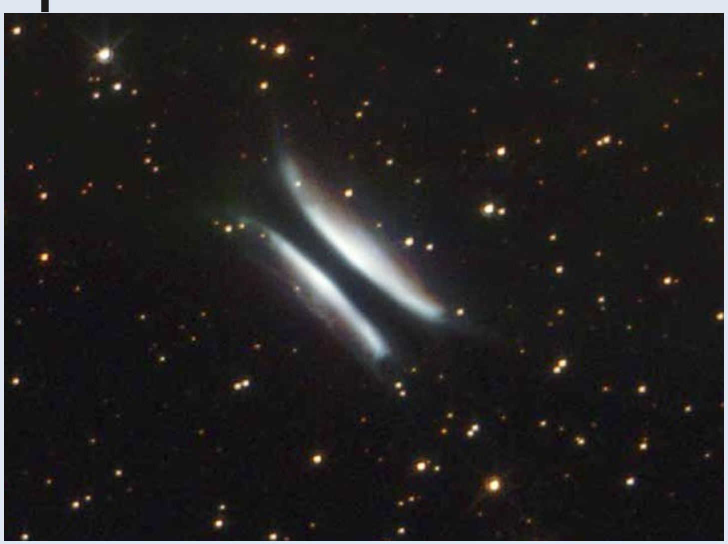
Channel Maps



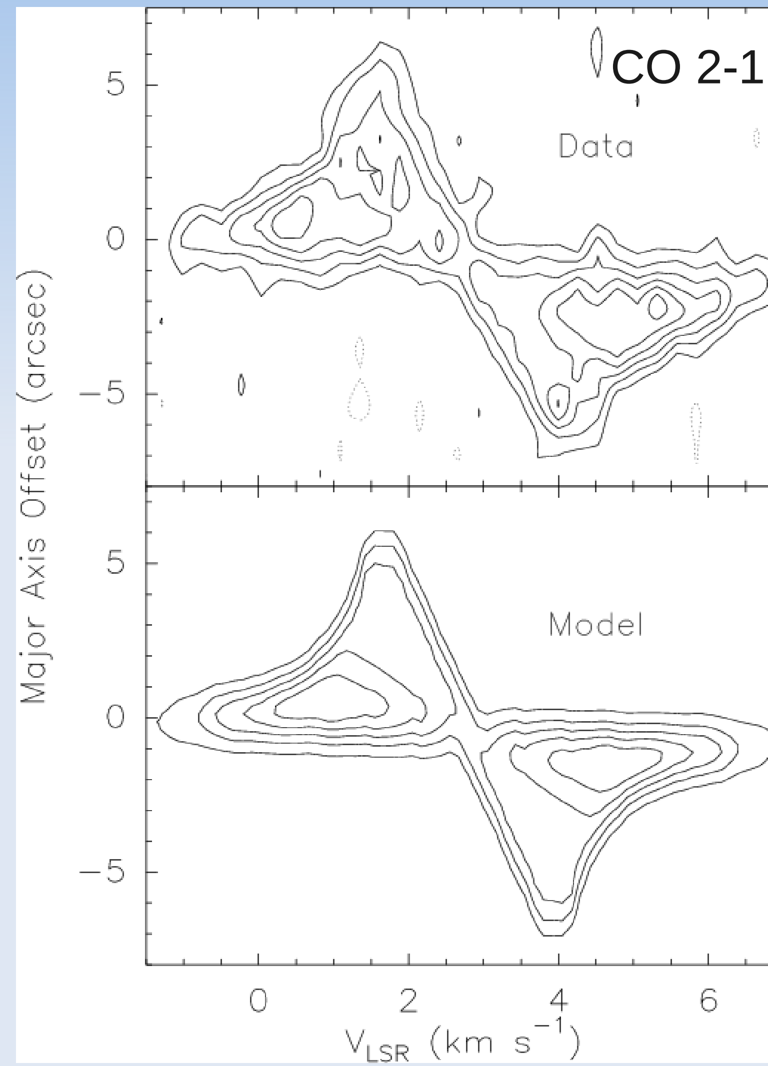
L1512, SO 1-0
30 GHz
Effelsberg 100m

Position Velocity Plots

- Plot spatial axis against velocity to study cloud dynamics, e.g. Keplerian rotation



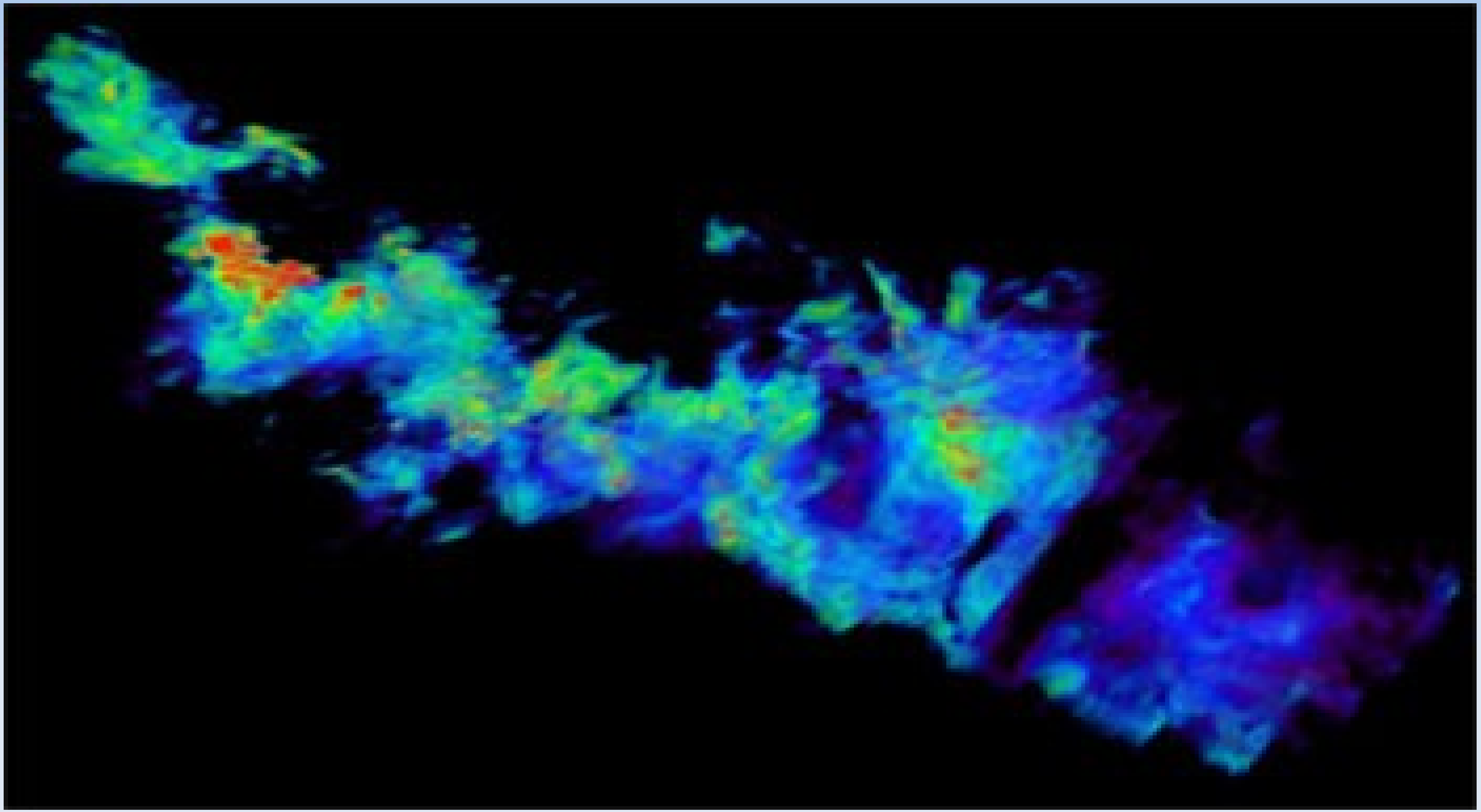
A. Gomez, CTIO, NOAO, HST, NASA



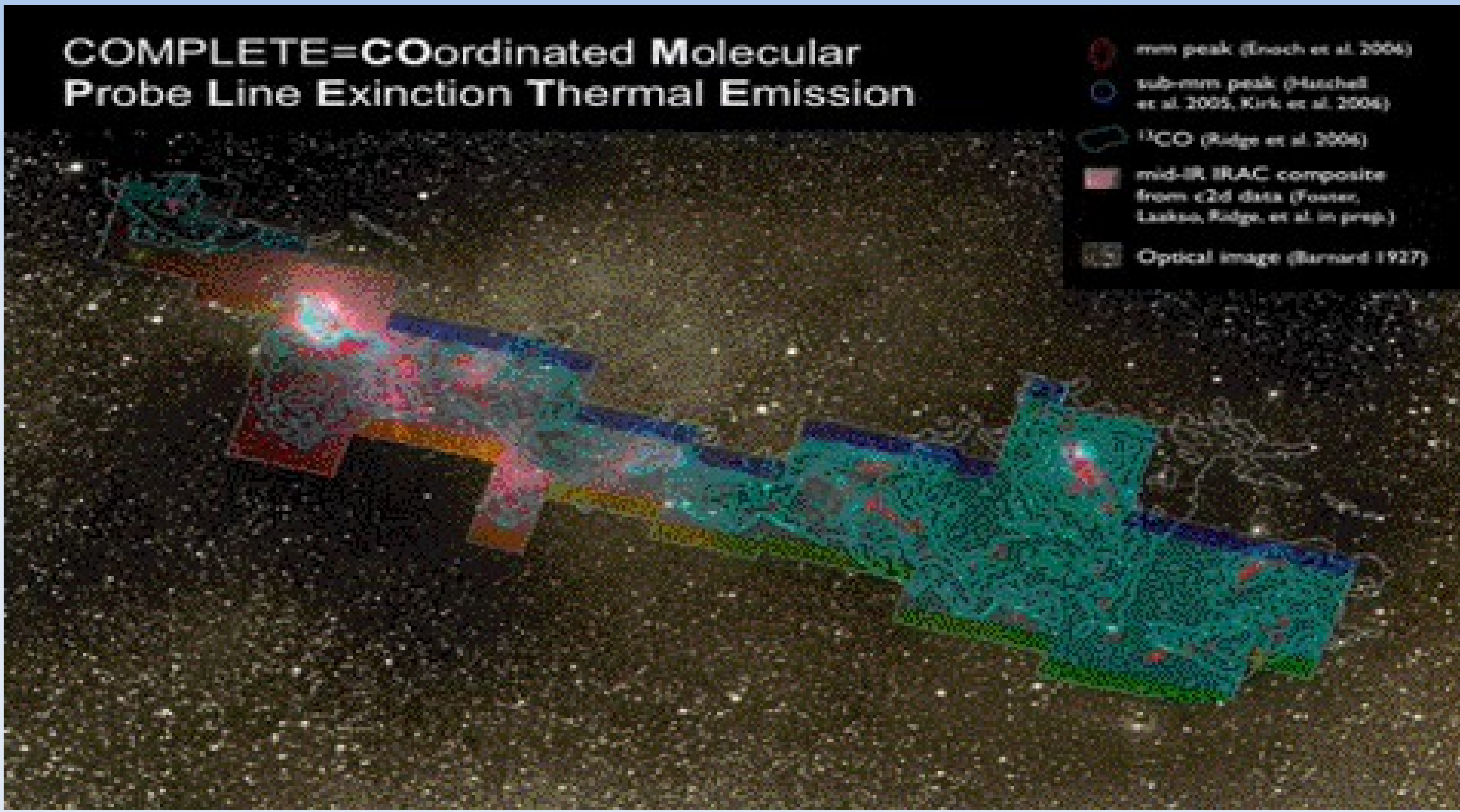
Bujarrabal et al. A&A 483, 839-845, 2008

Gomez's Hamburger (IRAS 18059-3211)

3D Rendering



3D Rendering



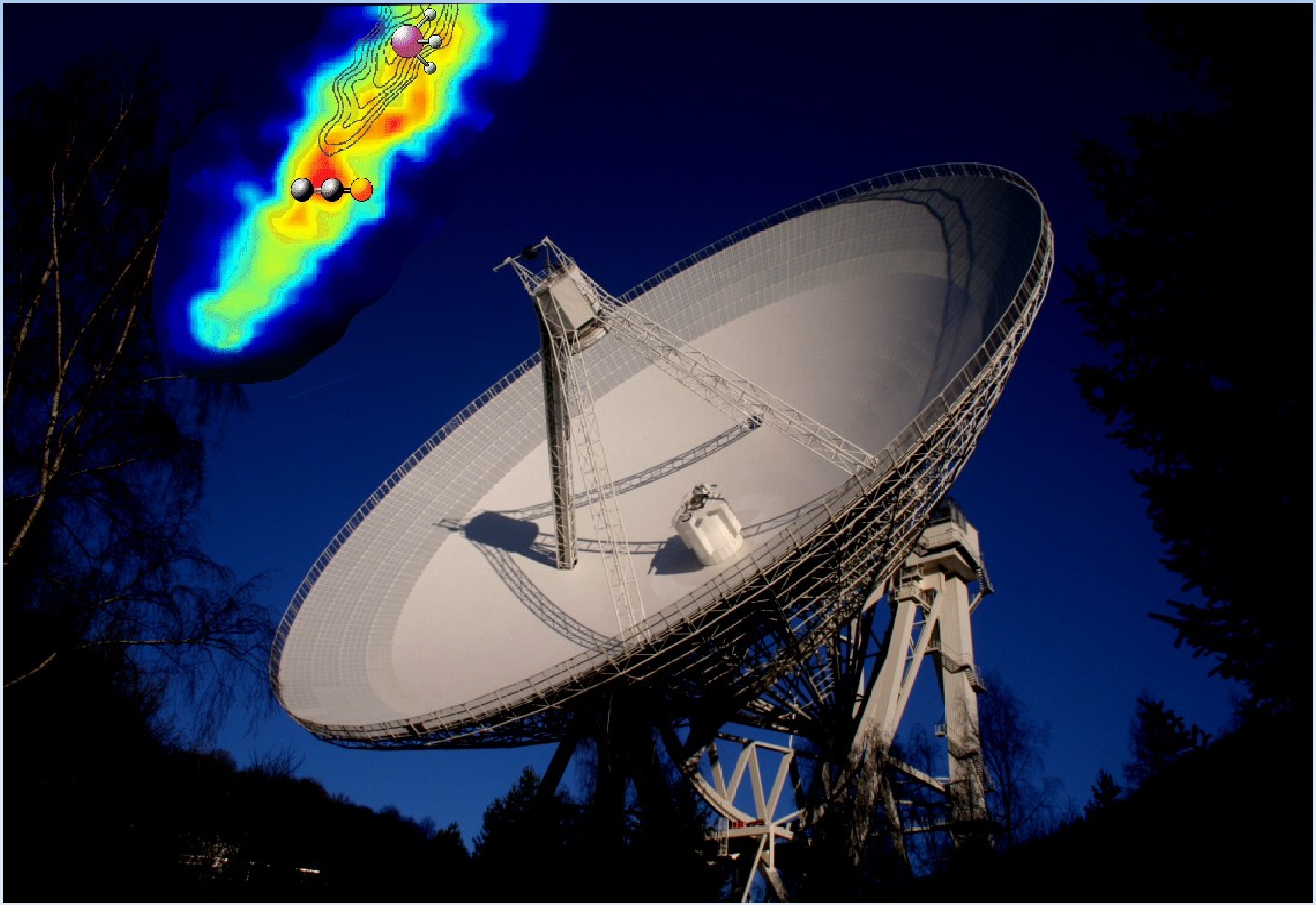
Deriving Physical Parameters

- Spectra and data cubes of several transitions are used in conjunction with models to derive physical parameter of the ISM:
  - Optically thin lines (involving isotopologues) to calculate column and volume densities
  - Line Ratios are modeled with chemical networks and radiative transfer programs
  - Spectral signatures of dynamical processes are fitted against the data
  - And many more ...

Summary

- Spectral lines provide a wealth of information about the interstellar medium
- Different atomic and molecular processes generate numerous spectral lines in the cm to submm wavelength range
- More than 160 molecules detected in space
- Physical, chemical and dynamical state of interstellar medium can be studied using spectral lines

Happy Observing !



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Thermal Line Broadening

Since the thermal velocities are non-relativistic, the Doppler shift in the angular frequency is given by the simple form

$$\omega = \omega_0\left(1 \pm \frac{v}{c}\right)$$

ω_0 = frequency for an atom at rest

From the Boltzmann distribution, the number of atoms with velocity v in the direction of the observed light is given by

$$n(v)dv = N\sqrt{\frac{m_0}{2\pi kT}}\, e^{-m_0 v^2/2kT}\, dv$$

N = total number of atoms

m_0 = atomic mass

The distribution of radiation around the center frequency is then given by

$$I(\omega) = I_0 \exp\left[\frac{-m_0 c^2(\omega_0 - \omega)^2}{2kT\omega_0^2}\right]$$

http://hyperphysics.phy-astr.gsu.edu/hbase/atomic/broaden.html

Antenna Temperature

Antenna temperature is a measure of signal strength in radio astronomy. It is defined as the temperature of a black-body enclosure which, if completely surrounding a radio telescope, would produce the same signal power as the source under observation. Antenna temperature is a property of the source, not of the antenna itself.

$$T_A = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{\pi} R(\theta,\phi) T(\theta,\phi) \sin\theta d\theta d\phi$$

R(Θ,Φ) is the antenna pattern.