Radio and mm astronomy

Wintersemester 2012/2013

Henrik Beuther & Hendrik Linz

16.10	*Introduction & Overview*	*(HL & HB)*
23.10	*Emission mechanisms, physics of radiation*	*(HB)*
30.10	*Telescopes – single-dishs*	*(HL)*
06.11	*Telescopes – interferometers*	*(HB)*
13.11	*Instruments – continuum radiation*	*(HL)*
20.11	*Instruments – line radiation*	*(HB)*
27.11	*Continuous radiation (free-free, synchrotron, dust, CMB)*	*(HL)*
04.12	*Line radiation*	*(HB)*
11.12	*Radiation transfer*	*(HL)*
18.12	*Effelsberg Excursion*	
	Christmas break	
08.01	*Molecules and chemistry*	*(HL)*
15.01	**Physics and kinematics**	**(HB)**
22.01	Applications	(HL)
29.01	Applications	(HB)
05.02	*last week, no lecture*	

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws1213.html
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Topics today

- Physical conditions

- Kinematics of galaxies

- Kinematics in star formtion

Physical conditions : Micro-Level

A medium in thermodynamic eq. can be described by 4 distribution laws:

1.) MAXWELL distribution of the particle velocity contributions (kinetic energy):

$$N(v;T) = 4\pi \left(\frac{m}{2kT} \right)^{3/2} v^2 \exp\left(-\frac{mv^2}{2kT} \right)$$

v : particle velocities

2.) BOLTZMANN distribution of the population numbers of the particle energy levels:

$$\frac{N_o}{N_u} = \frac{g_o}{g_u} \exp\left(-\frac{E_o - E_u}{kT} \right)$$

$E_{o/u}$ → Energies of the upper (o) and lower (u) levels

$g_{o/u}$ → Corresponding statistical weights

3.) PLANCK radiation law (distribution of the photon energies):

$$B_\nu = \frac{2h\nu^3 / c^2}{\exp(h\nu / kT) - 1}$$

ν : photon frequencies

4.) SAHA equation (distribution of the ionisation levels in plasma):

$$\frac{N_{j+1} N_e}{N_j} = \frac{2\, U_{j+1}(T)}{U_j(T)} \left(\frac{2\pi\, m_e\, kT}{h^2} \right)^{3/2} \exp(-\chi_{j,j+1} / kT)$$

N_{j+1}, N_j - Number densities of (j+1)-fold and j-fold ionised particles
N_e - electron density

$\chi_{j,j+1}$ - ionisation energy needed to get from ionisation level j to $j+1$
U_{j+1}, U_j - partition function for both states

Physical conditions : Micro-Level

Are these distribution functions valid in the ISM?
General rule: time scale for processes leading to equilibrium short compared to time scales of disturbing processes

1. Example : collisions between H-atoms: consider T = 100 K, mean velocity v ~ 1 km/s
cross section $\sigma = \pi R_H^2 \sim \pi\,(0.1\ \text{nm})^2$
average time between two collision $\tau_s = (v\,\sigma\,n_H)^{-1}$
with HI density of 1 cm^{-3} we have $\tau_s \sim 1000$ yrs ⟶ short wrt most interstellar processes (except shock fronts)
→ Maxwell distribution valid, introduction of kinetic temperature T_{kin} makes sense!

2. Example : balance for energy level population numbers for ISM:
correction factor to Boltzmann: $\dfrac{1}{1 + (A_{21} / (n\,Q_{21}))}$
Pure Boltzmann only if $(n\,Q_{21}) >> A_{21}$

A_{21} [s^{-1}] Einstein coefficient for spontaneous radiative decay
Q_{21} [$m^3\,s^{-1}$] collision rate
n [m^{-3}] number density

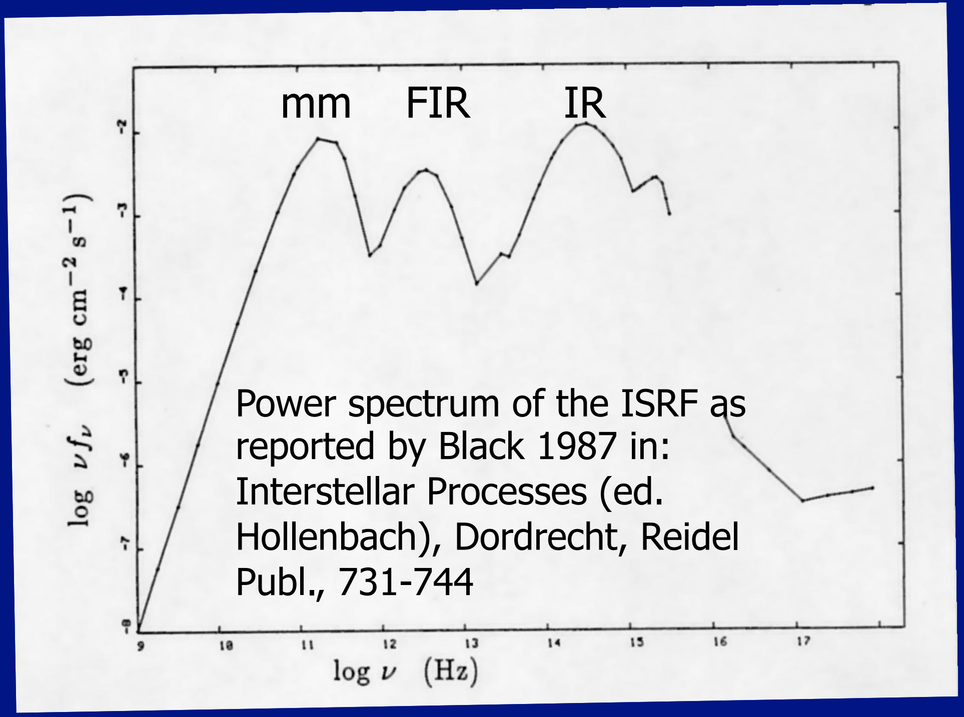
In thin ISM is the collision rate small (see Example 1 above). For permitted transitions ($A_{21} \sim 10^8\ s^{-1}$) the correction factor gets large → almost all particles in ground state. For forbidden transitions ($A_{21} \sim 10^{-2}\ s^{-1}$) the level population approach Boltzmann.

For dense cores: E.g. CO(1-0) at density 10^5cm^{-3}: $A_{21}=7.2\text{x}10^{-8}\text{s}^{-1}$, $Q_{21}=3.3\text{x}10^{-11}\ \text{cm}^3\text{s}^{-1}$
→ $A_{21} / (n\,Q_{21}) \sim 0.02$
→ Boltzmann distribution valid in dense cores!

Physical conditions : Micro-Level

Are these distribution functions valid in the ISM?

3. Example : Interstellar radiation field (ISRF) : sum of emission contributions from all emitting objects (stars, dust, gas) in the nearer and further vicinity of the gas cloud (distance-dependent thinning factor comes into play)



Power spectrum of the ISRF as reported by Black 1987 in: Interstellar Processes (ed. Hollenbach), Dordrecht, Reidel Publ., 731-744

ISRF can not be approximated by a black body (i.e., Planck function not applicable)
ISRF hence far from thermodynamic equilibrium …

<u>However:</u> Dense cores and stars can be fitted relatively well with single or multiple black body functions.

A few important molecules

Mol.	Trans.	Abund.	Crit. Dens. [cm^{-3}]	Comments
H_2	1-0 S(1)	1	$8x10^7$	Shock tracer
CO	J=1-0	$8x10^{-5}$	$3x10^3$	Low-density probe
OH	$^2\Pi_{3/2}$;J=3/2	$3x10^{-7}$	$1x10^0$	Magnetic field probe (Zeeman)
NH_3	J,K=1,1	$2x10^{-8}$	$2x10^4$	Temperature probe
CS	J=2-1	$1x10^{-8}$	$4x10^5$	High-density probe
SiO	J=2-1		$6x10^5$	Outflow shock tracer
H_2O	6_{16}-5_{23}		$1x10^3$	Maser
H_2O	1_{10}-1_{11}	$<7x10^{-8}$	$2x10^7$	Warm gas probe
CH_3OH	7-6	$1x10^{-7}$	$1x10^5$	Dense gas/temperature probe
CH_3CN	19-18	$2x10^{-8}$	$2x10^7$	Temperature probe in Hot Cores

Line broadening

Natural line broadening: Disturbance of molecule by zero-point vibrations of electromagnetic field (or from thermal electromagnetic field)

$d\nu = 32\pi^3\nu^3 \mu^2/(3hc^3)$ (μ: Dipole moment)

For CO(1-0) at 20K → $d\nu \sim 3.5\text{x}10^{-8}$ or $dv \sim 9\text{x}10^{-14}$ km/s

→ Negligable!

Pressure broadening: Arises from collisions between molecules. Complex quantum-mechanical problem for intermolecular forces. At densities of star-forming regions for molecular lines negligable (different for recombination lines).

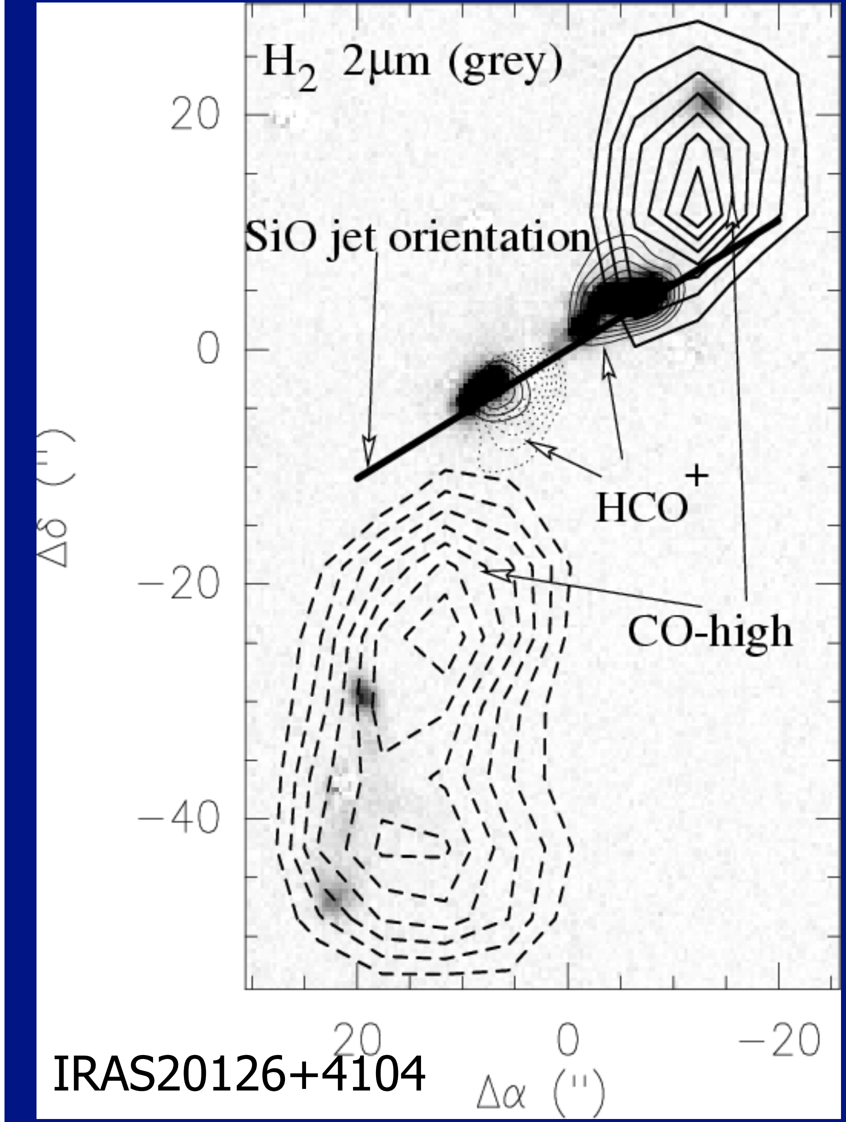
Thermal line broadening: Thermal motions of gas cause doppler broadening:

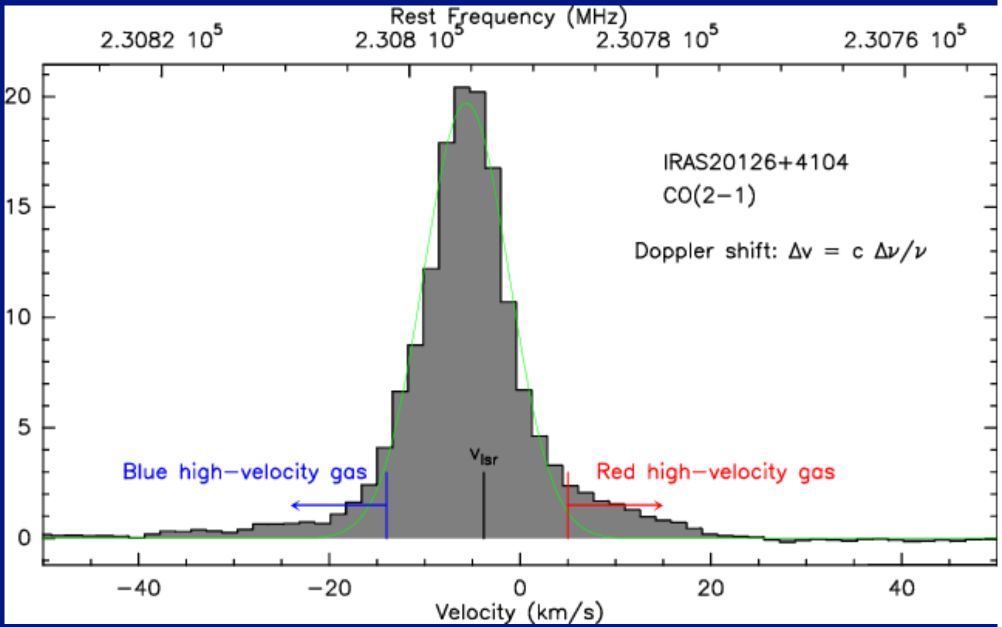
$dv = \text{sqrt}(8\ln 2\ kT/m_{mol})$

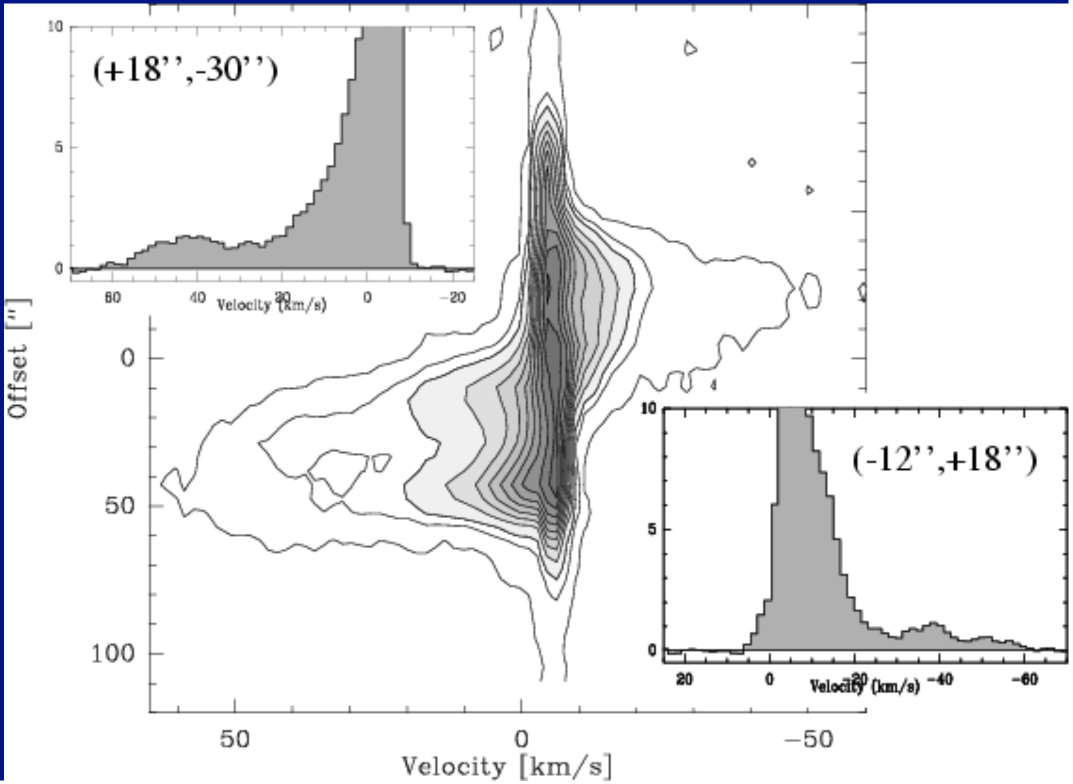
$dv(NH_3@30K) \sim 0.28$ km/s

Other physical effects: Line broadening due to outflow motions, rotation …

Molecular outflows

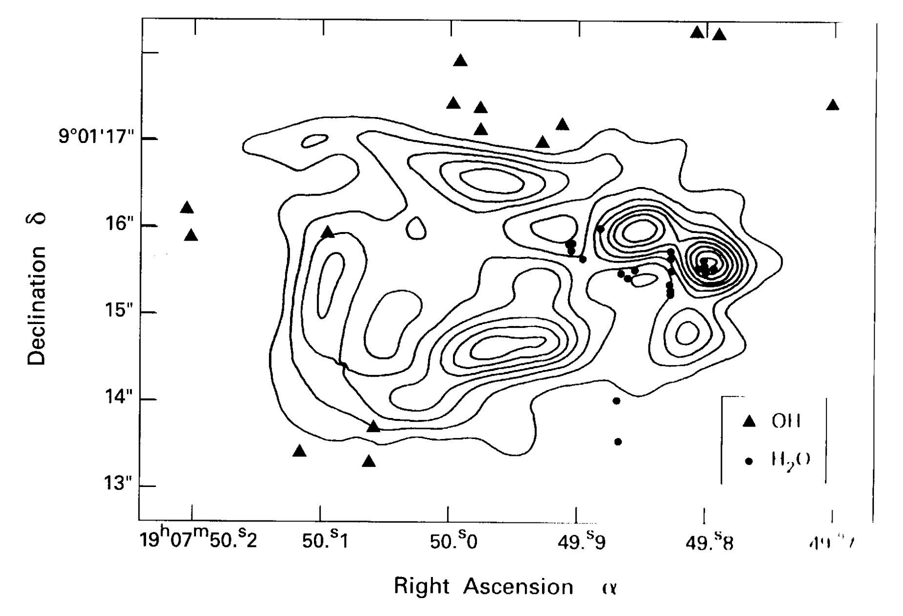


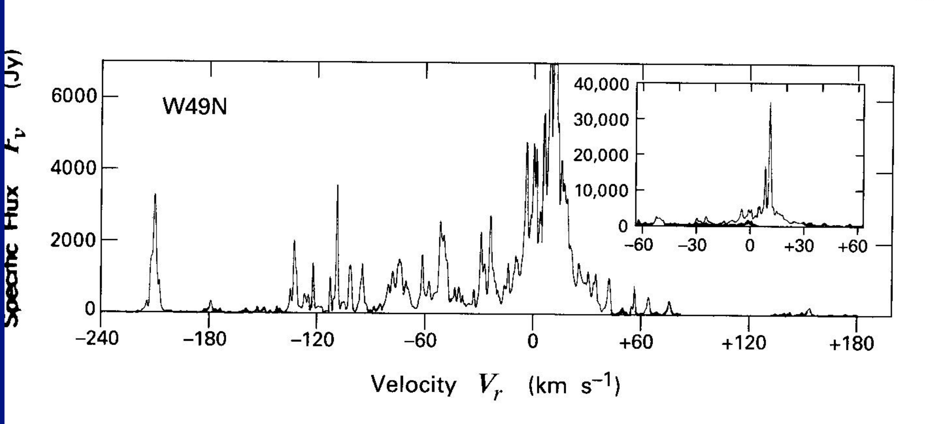


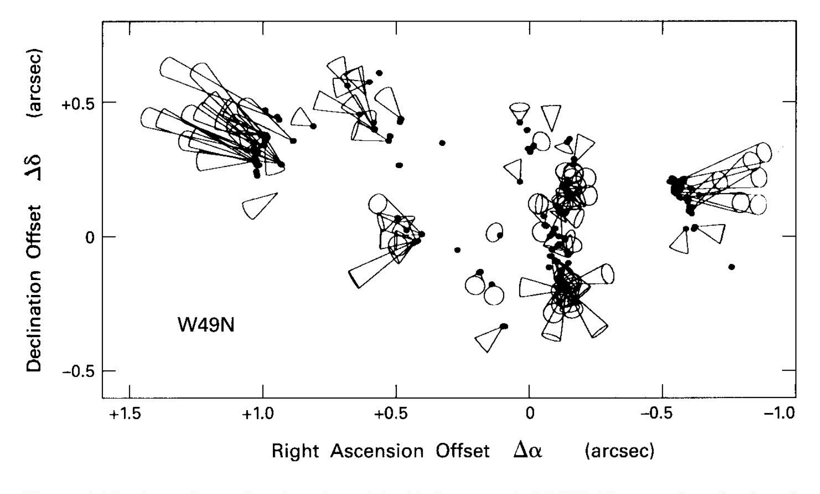


Lebron et al. 2006

Molecular Masers I



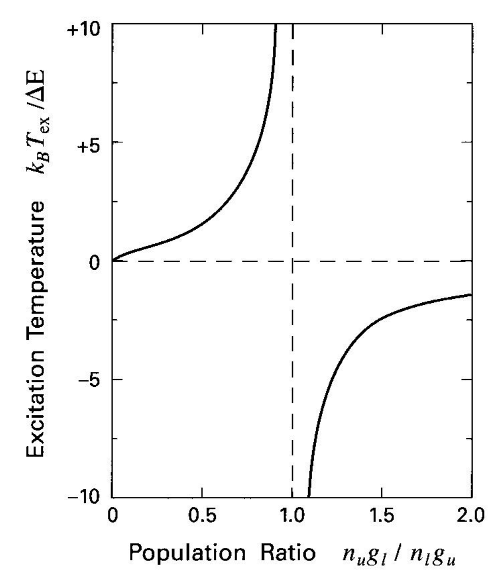




- In the Rayleigh-Jeans limit, brightness temperature T and intensity I relate like $T = c^2/2k\nu^2 I$ with $I=F/\Omega$ (Ω: solid angle). With the small spot diameters (of the order some AU), this implies brightness temperatures as high as 10^{15}K, far in excess of any thermal temperature --> no thermal equilibrium and no Boltzmann distribution.
- Narrow line-width
- Potential broad velocity distribution.
- They allow to study proper motions.

Molecular Masers II

- The excitation temperature was defined as: $n_u/n_l = g_u/g_l \exp(-h\nu/kT_{ex})$.
- For maser activity, population inversion is required, i.e., $n_u/g_u > n_l/g_l$.
  --> This implies negative excitation temperatures for maser activity.
- In thermal conditions at a few 100K, for typical microwave lines
  $E_{line} = h\nu/k < T_{kin} \sim T_{ex}$ --> $n_u/g_u \sim n_l/g_l$
  --> Only a relatively small shift is required in get population inversion



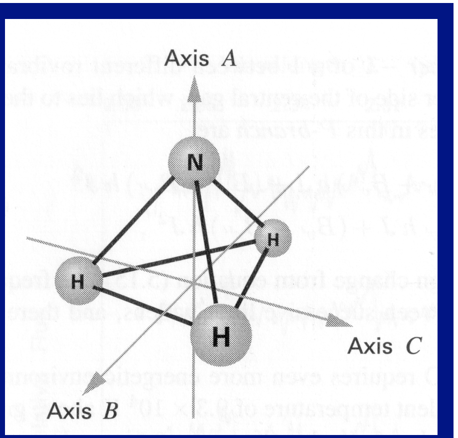
$$T_{ex}/E_{line} = -1/\ln(n_u g_l/n_l g_u)$$

With rising T_{ex} the level populations are approaching each other, and then one has only to “overcome the border”.

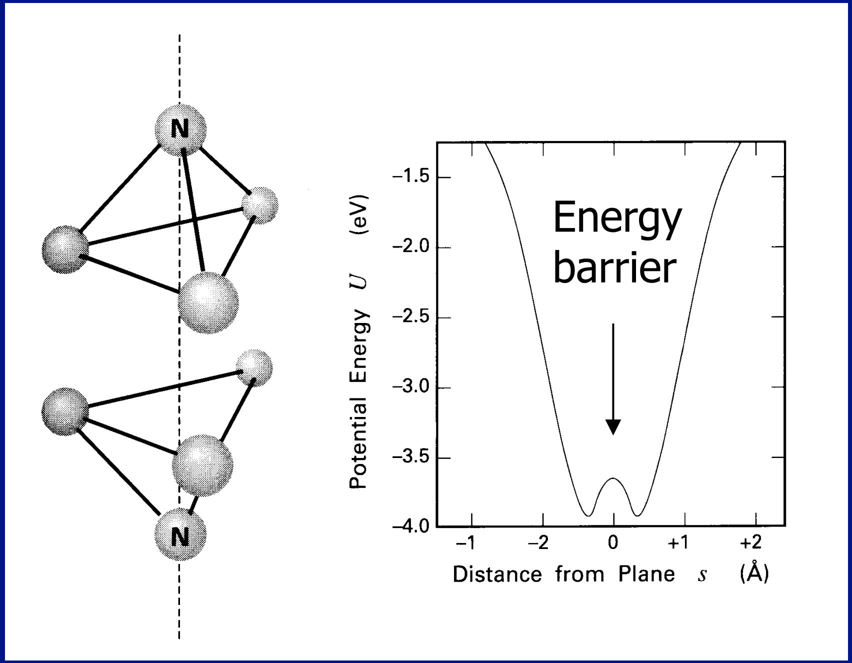
Different proposed pumping mechanisms, e.g.:
- Collisional pumping in J- and C-shocks of protostellar jets for H_2O masers.
- Radiative pumping at shock fronts between UCHII regions and ambient clouds.

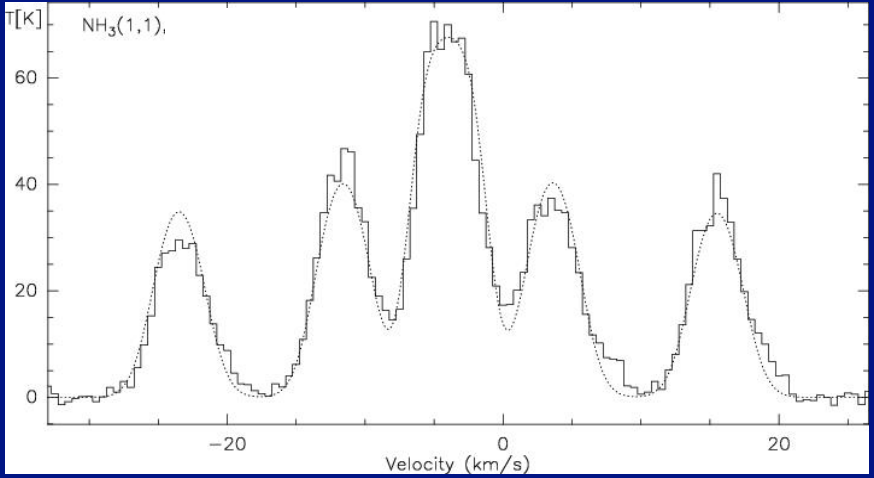
In both cases, very high densities and temperatures are required.

Ammonia (NH_3)

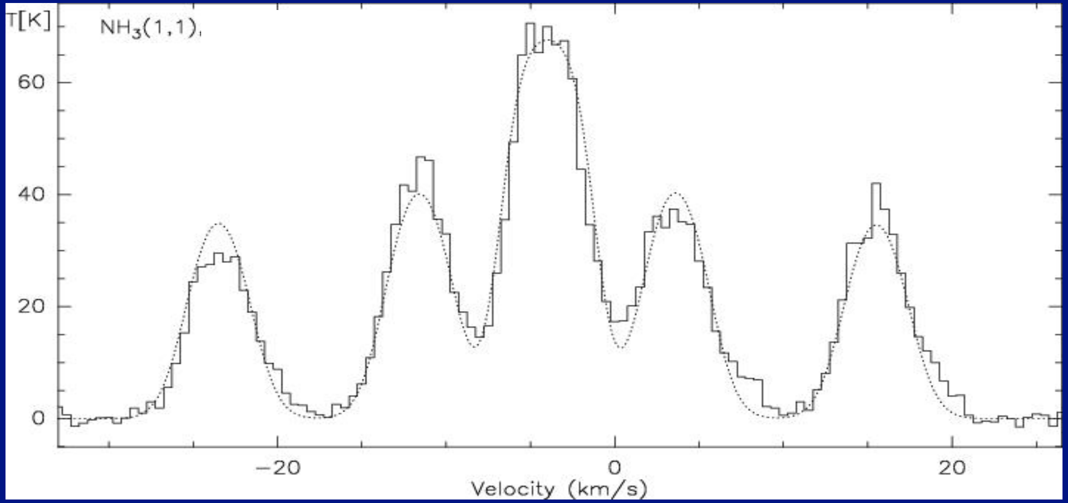


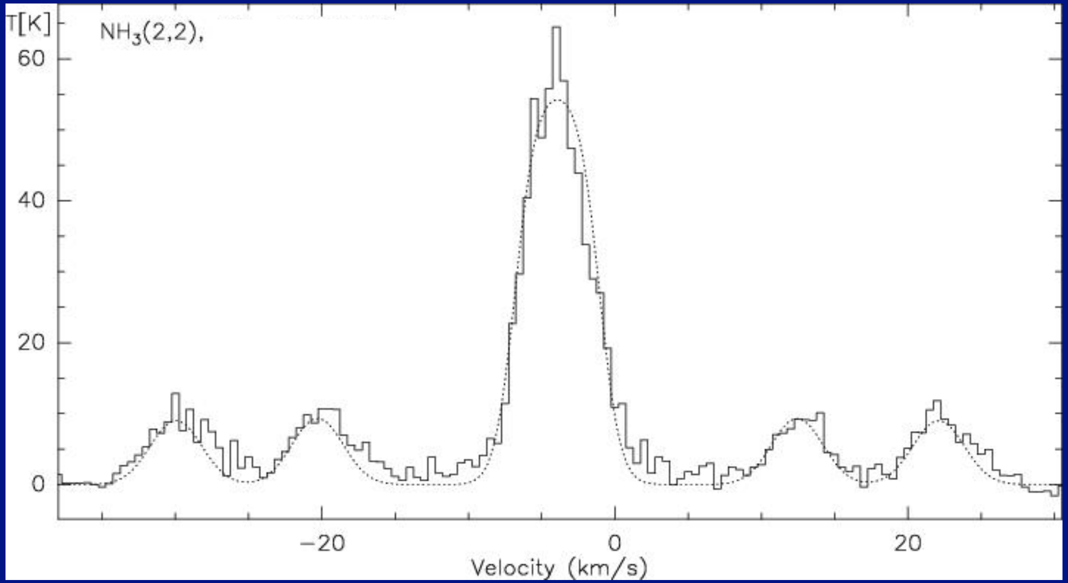
- Formed through gas-phase reactions.
- Symmetric-top molecule
- However, useful rot. transitions only at very high freq.
- Most useful transitions are the inversion transitions around 25GHz. --> tunneling energy barrier
- Additional effects (non-spherical charge distribution, quadr. mom., magn. interaction between spins) causes further hyperfine splitting.





Temperature estimates from NH_3



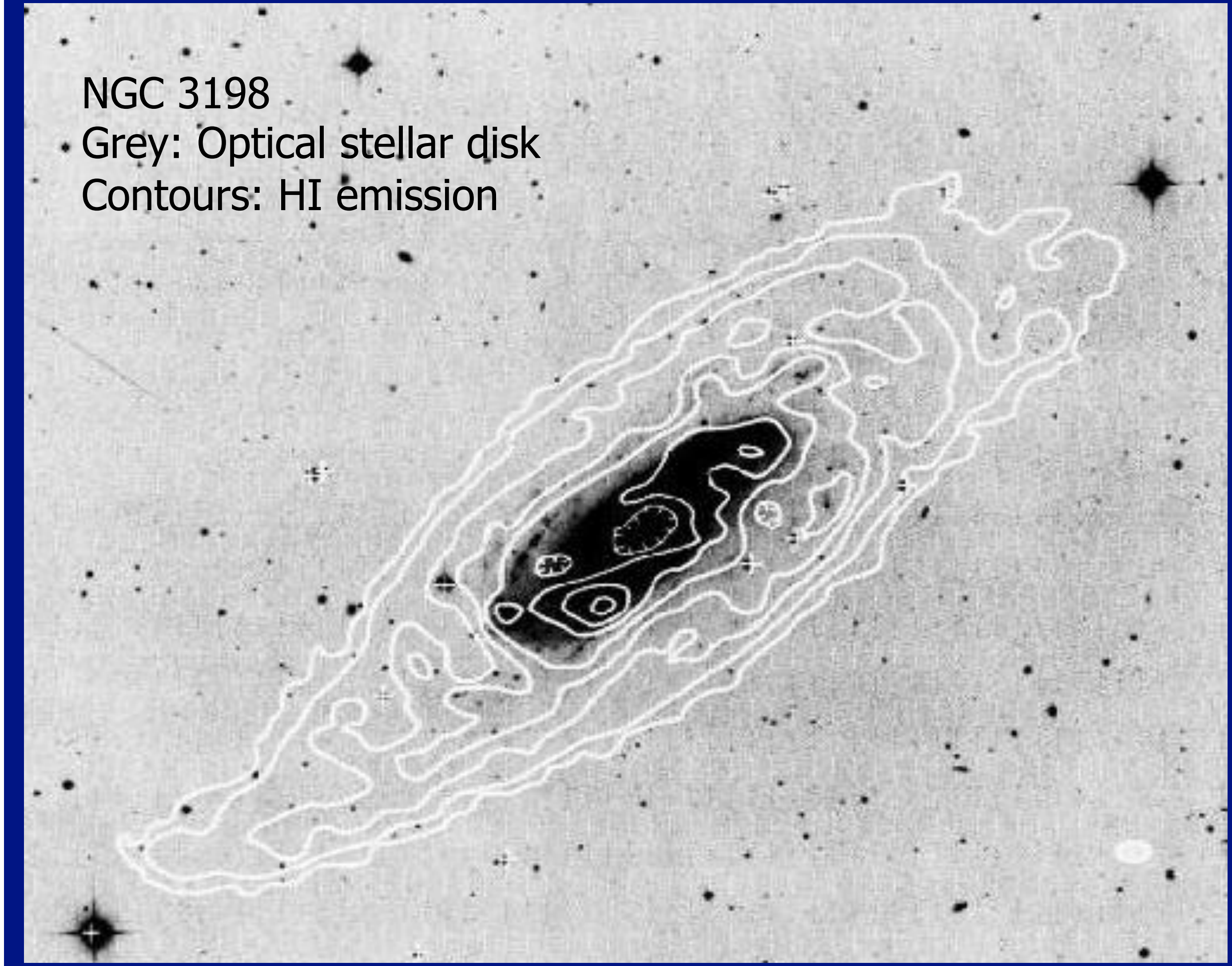


$$T_{kin} = T_{rot}\,(\tau_{11}\;\tau_{22} T_{11} T_{22})$$

Topics today

- Physical conditions
- Kinematics of galaxies
- Kinematics in star formtion

Rotation curves of Galaxies



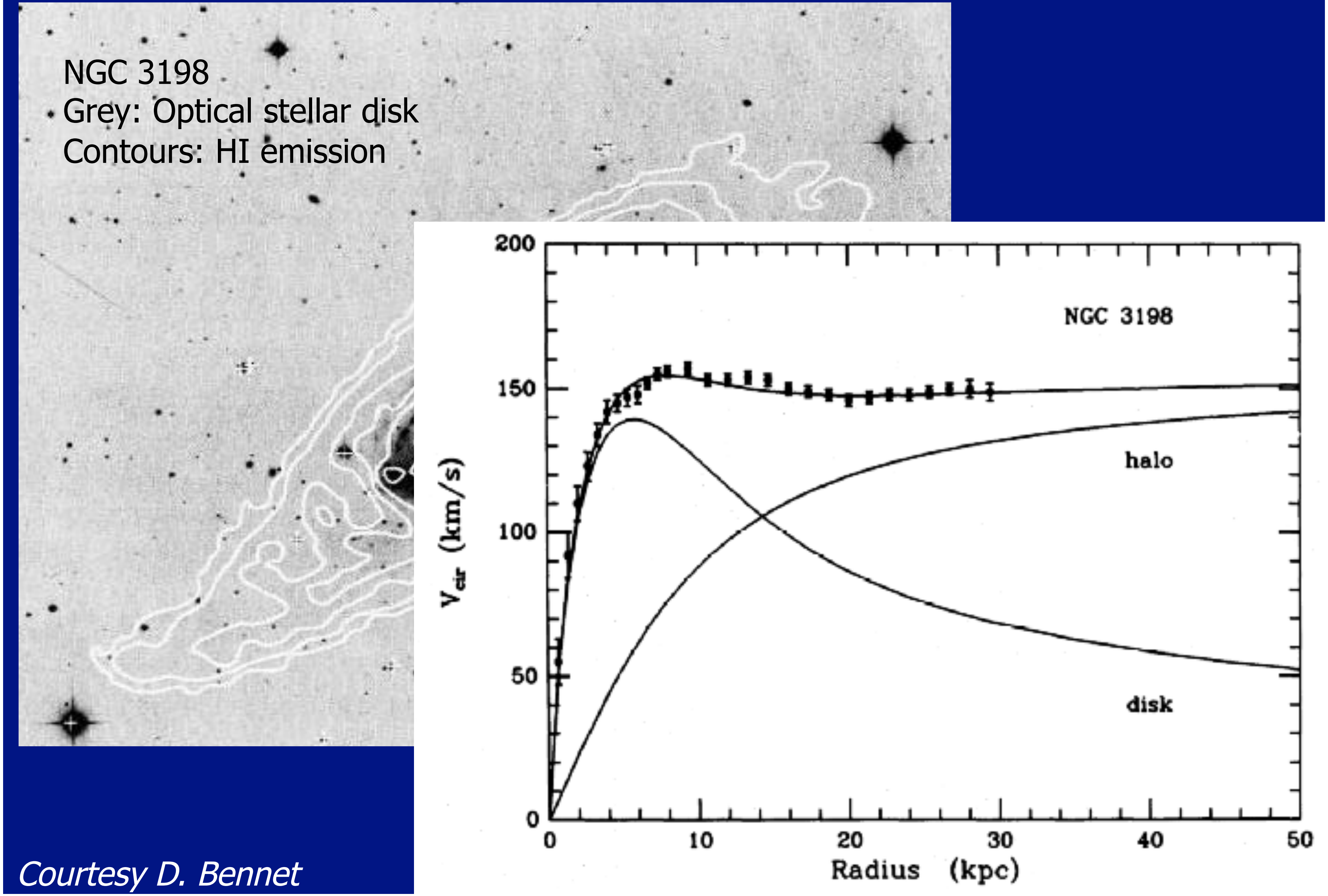
NGC 3198

Grey: Optical stellar disk

Contours: HI emission

Courtesy D. Bennet

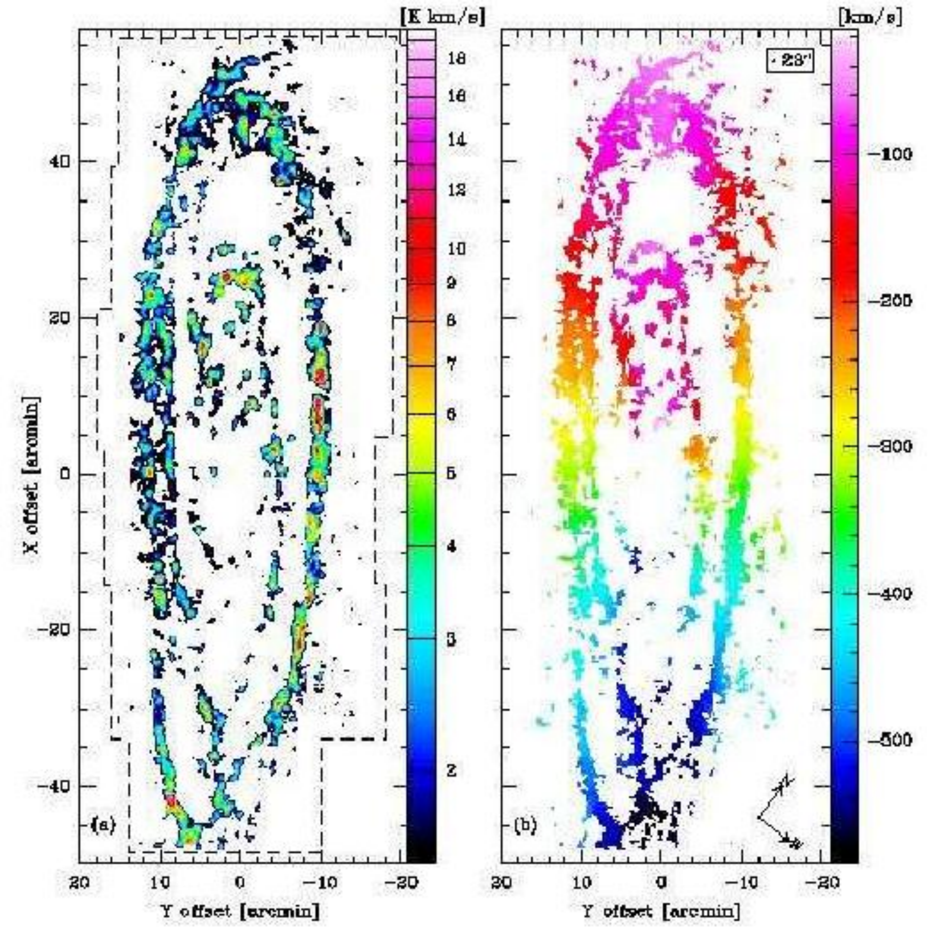
Rotation curves of Galaxies



NGC 3198
Grey: Optical stellar disk
Contours: HI emission

Courtesy D. Bennet

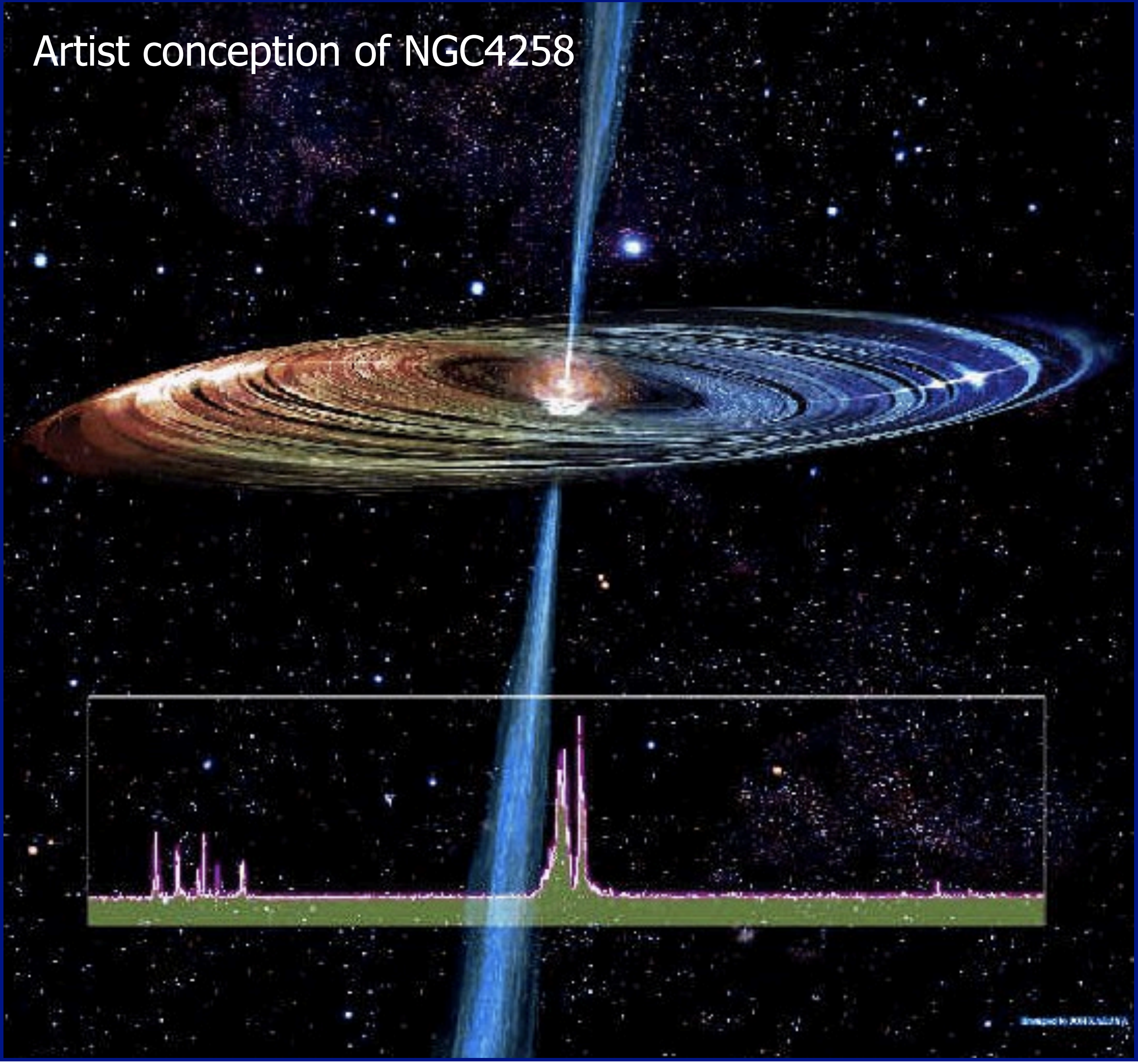
Andromeda



CO(2-1)

Optical

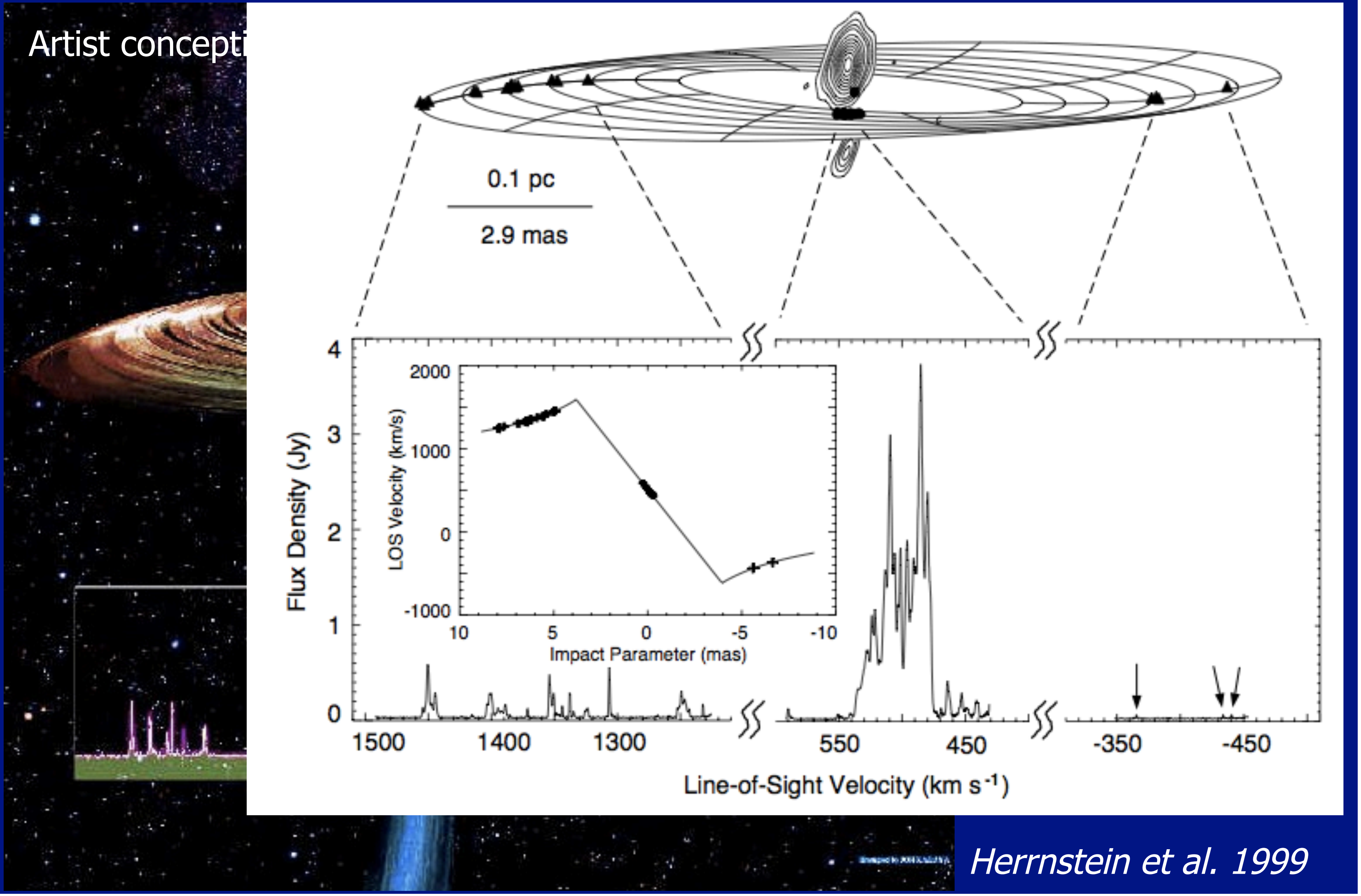
Extragalactic disks



Artist conception of NGC4258

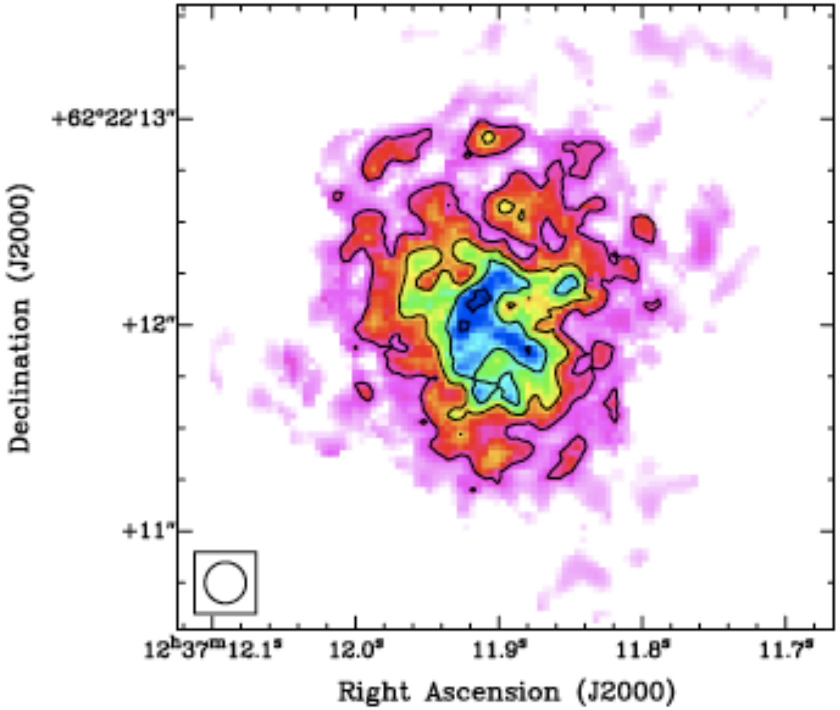
Herrnstein et al. 1999

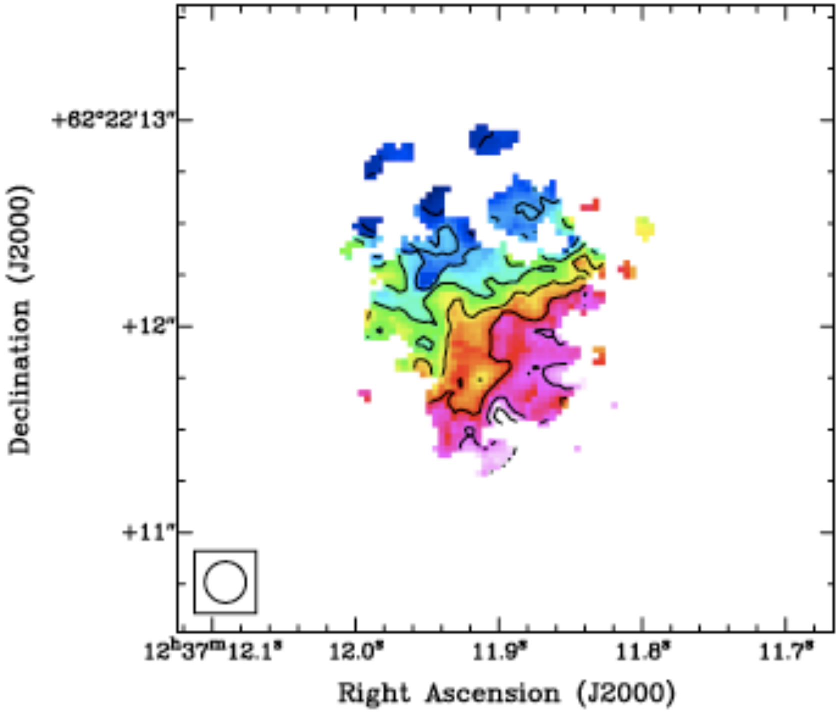
Extragalactic disks


Artist concepti

Herrnstein et al. 1999

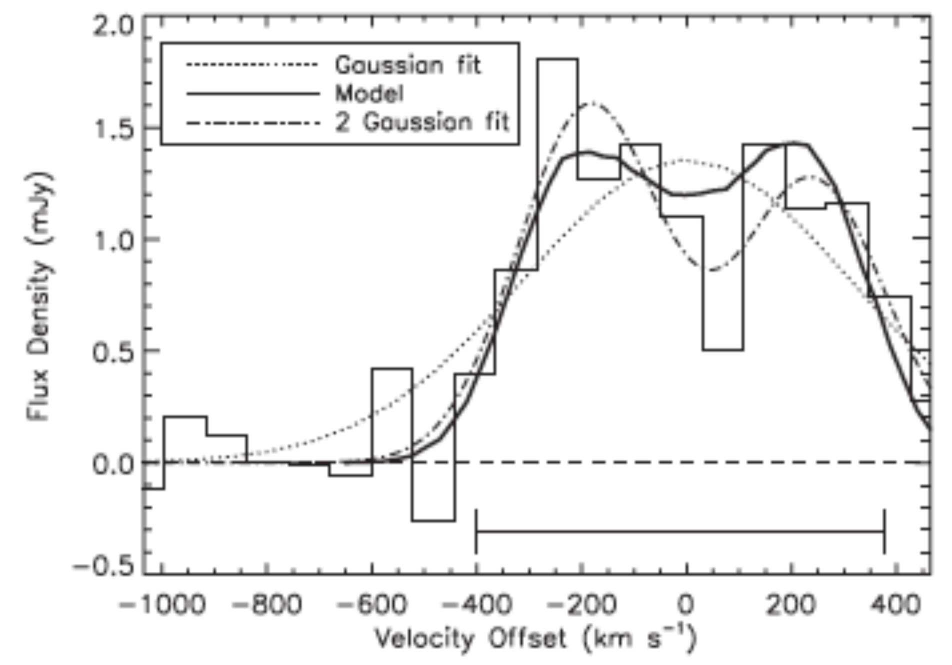
Kinematics at z=4





- GN20 at z=4.05, 1.6Gy after big bang
- CO(2-1) shifted from 235.538 to 46.66GHz

- Rotating disk with
  dynamical mass ~5x10^{11}M$_{sun}$



Hodge et al. 2012

Topics today

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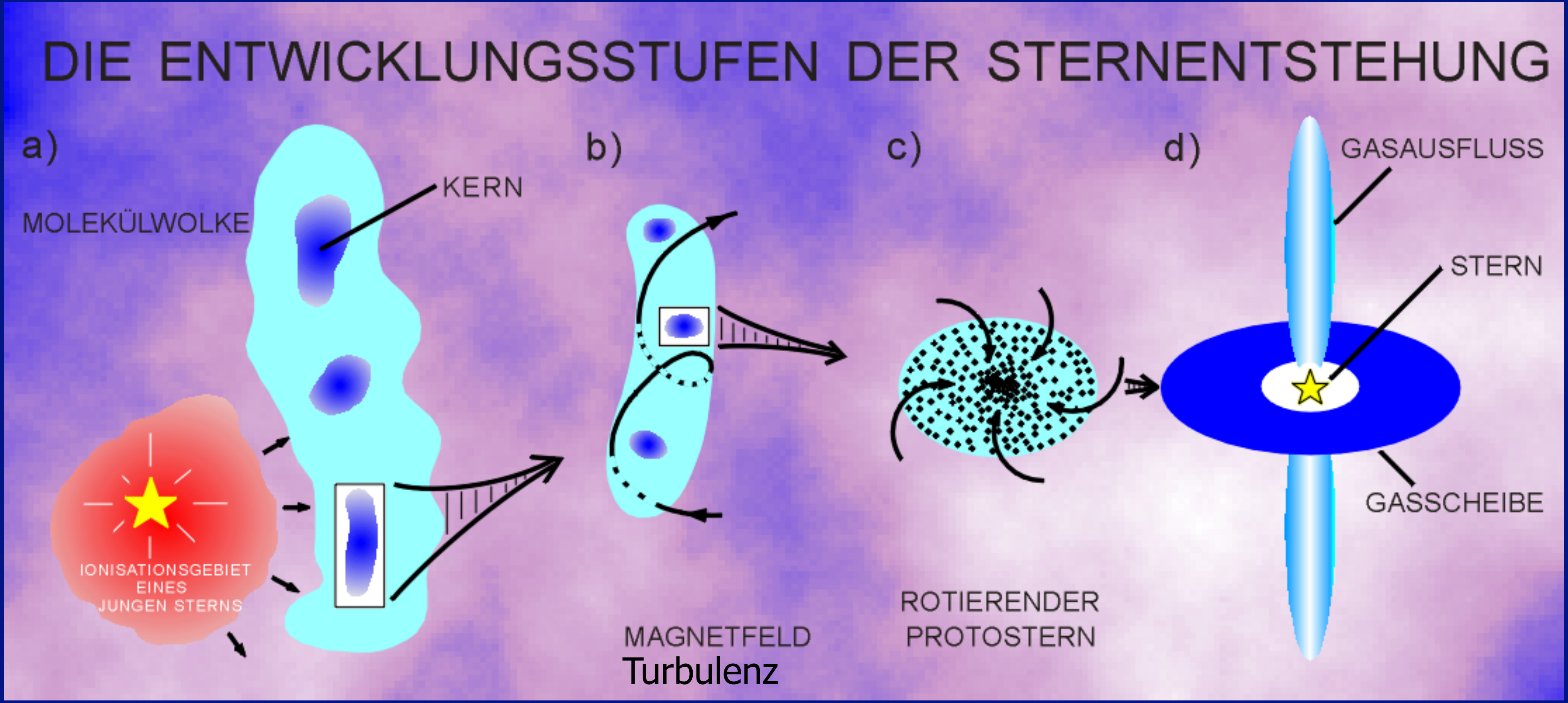
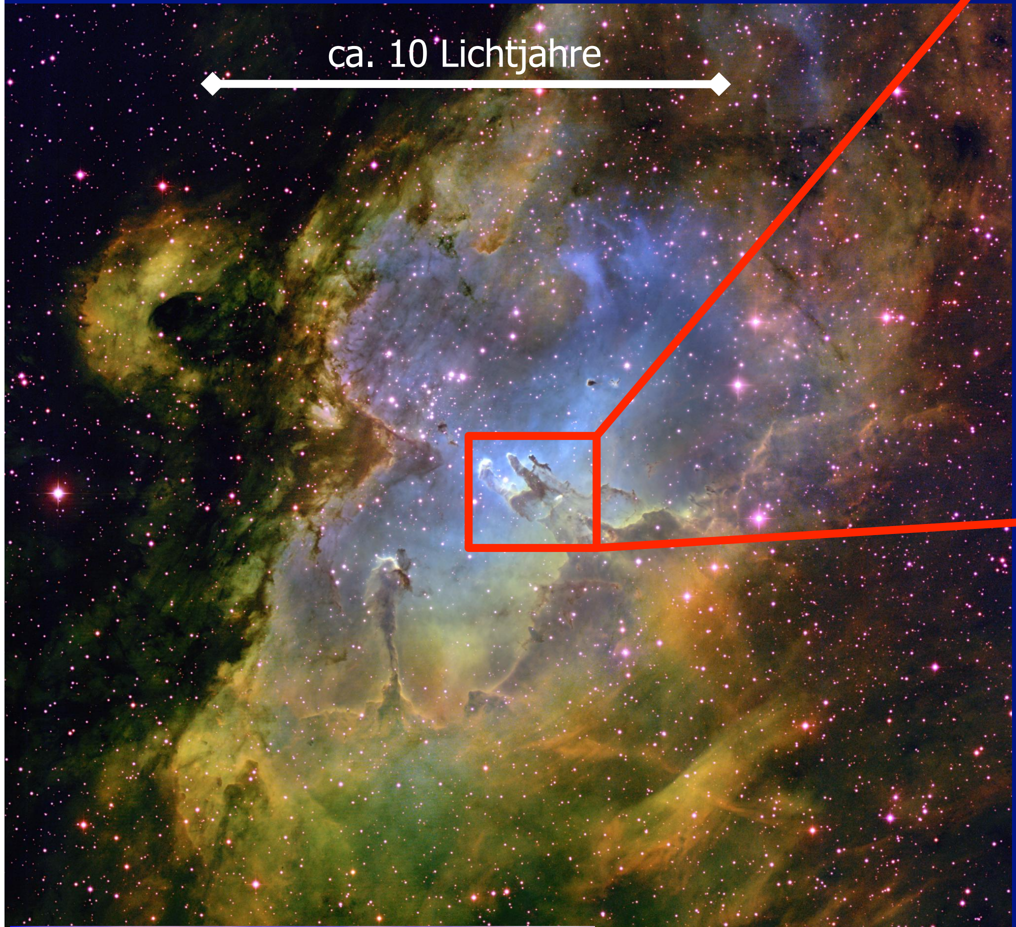
- Kinematics of galaxies
- Kinematics in star formtion

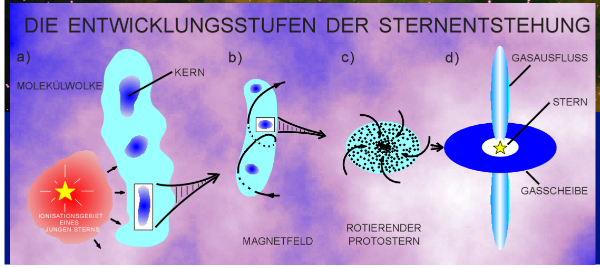
Sternentstehungsparadigma

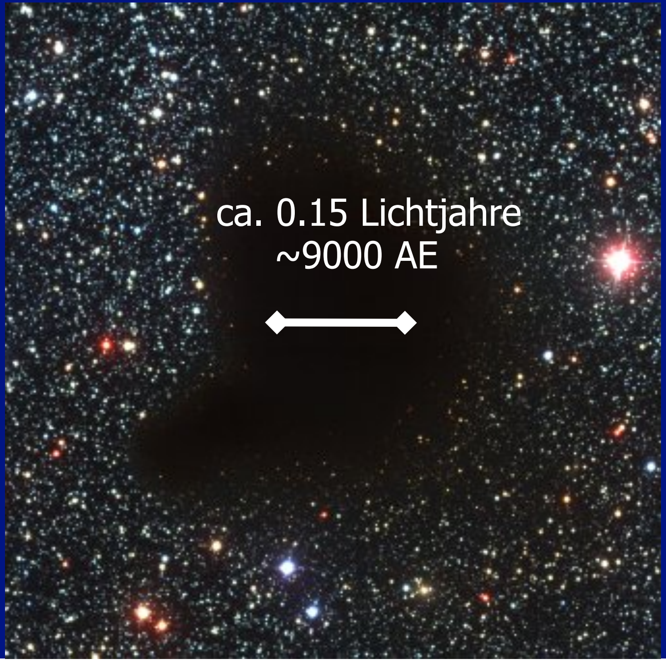


Time scales: Main accretion phase ~500 000 years
Pre-main-sequence evolution ~2e6 years

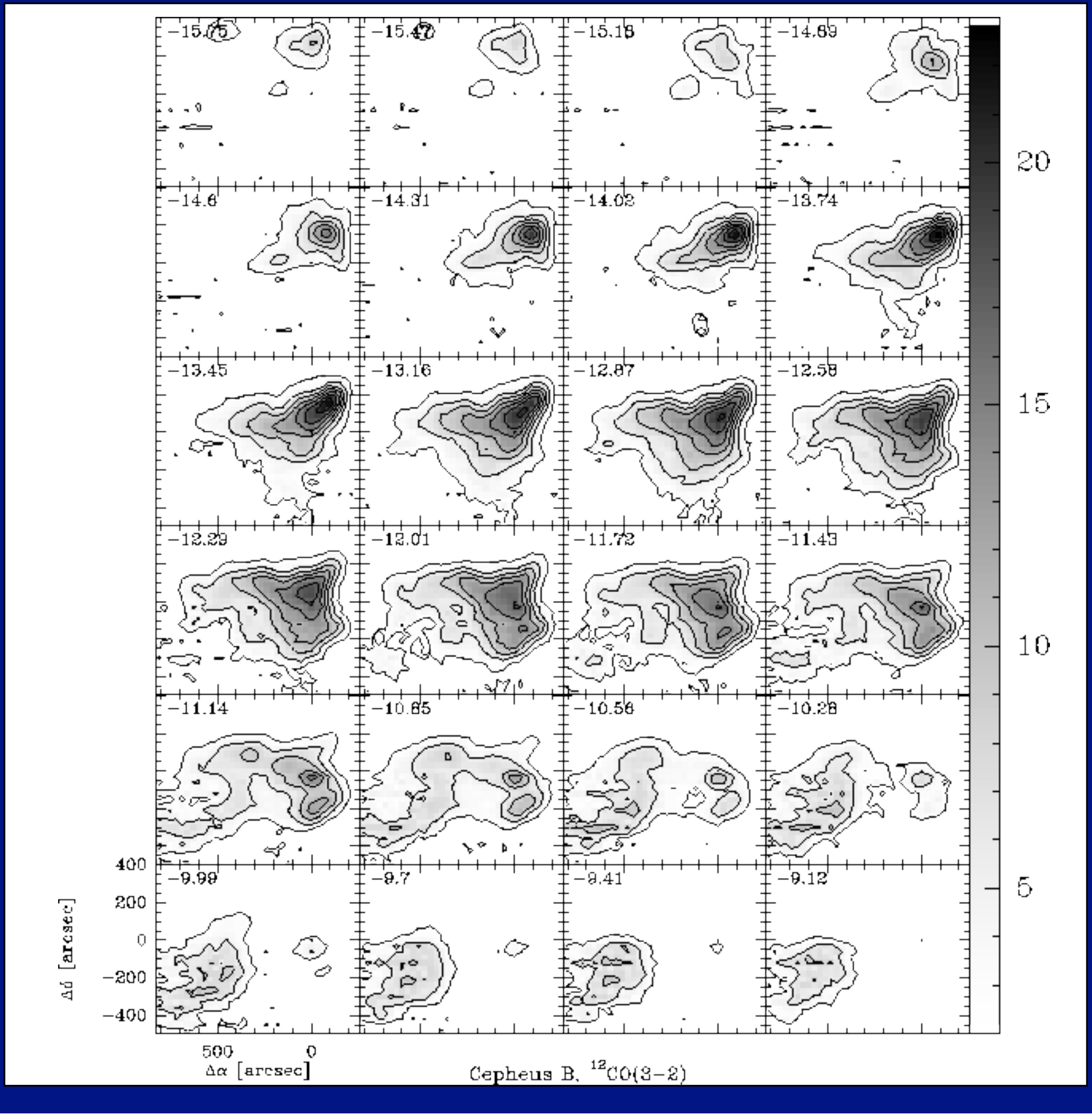
Molekülwolkenskalen



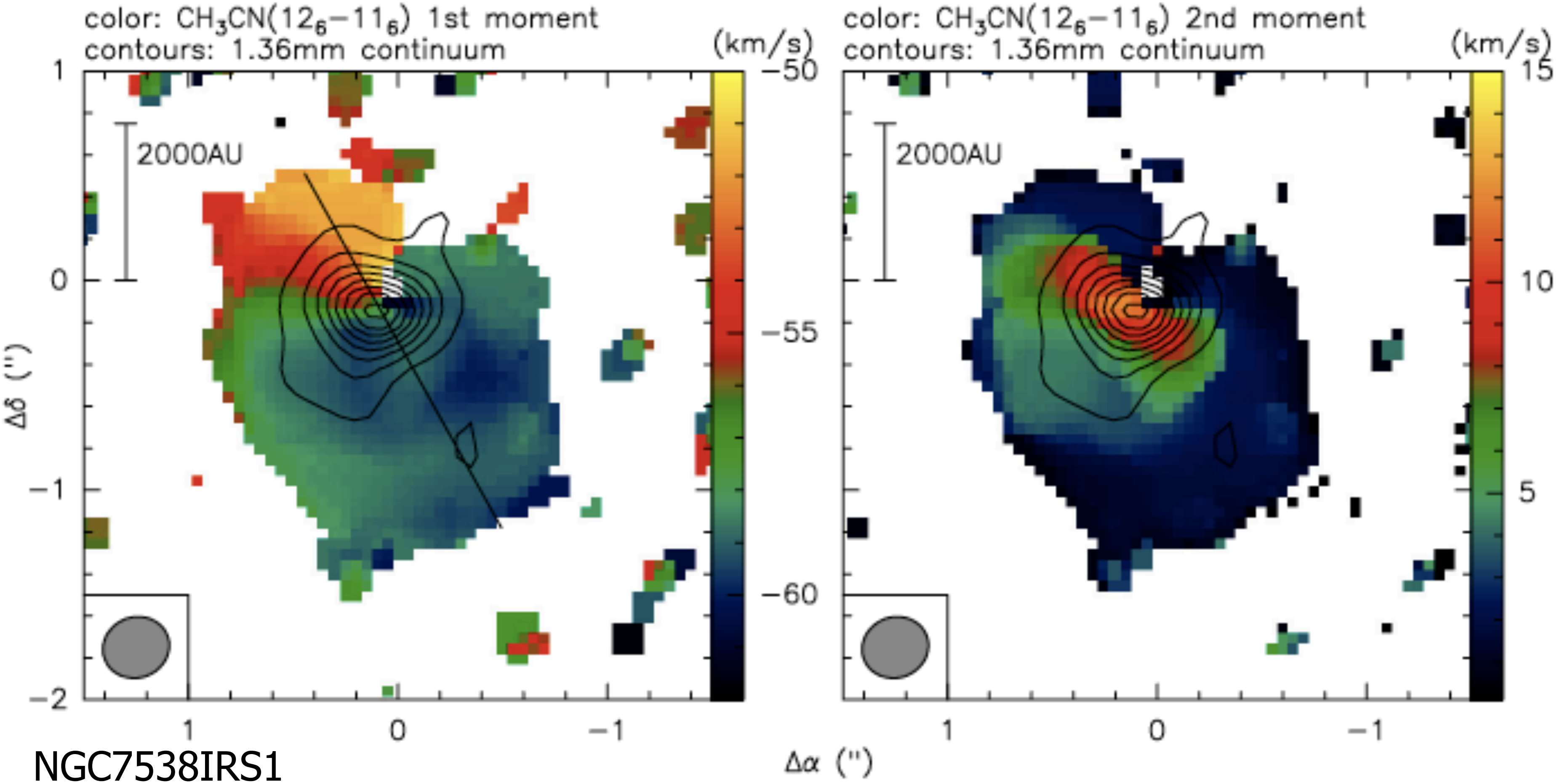




Velocity structure of molecular clouds



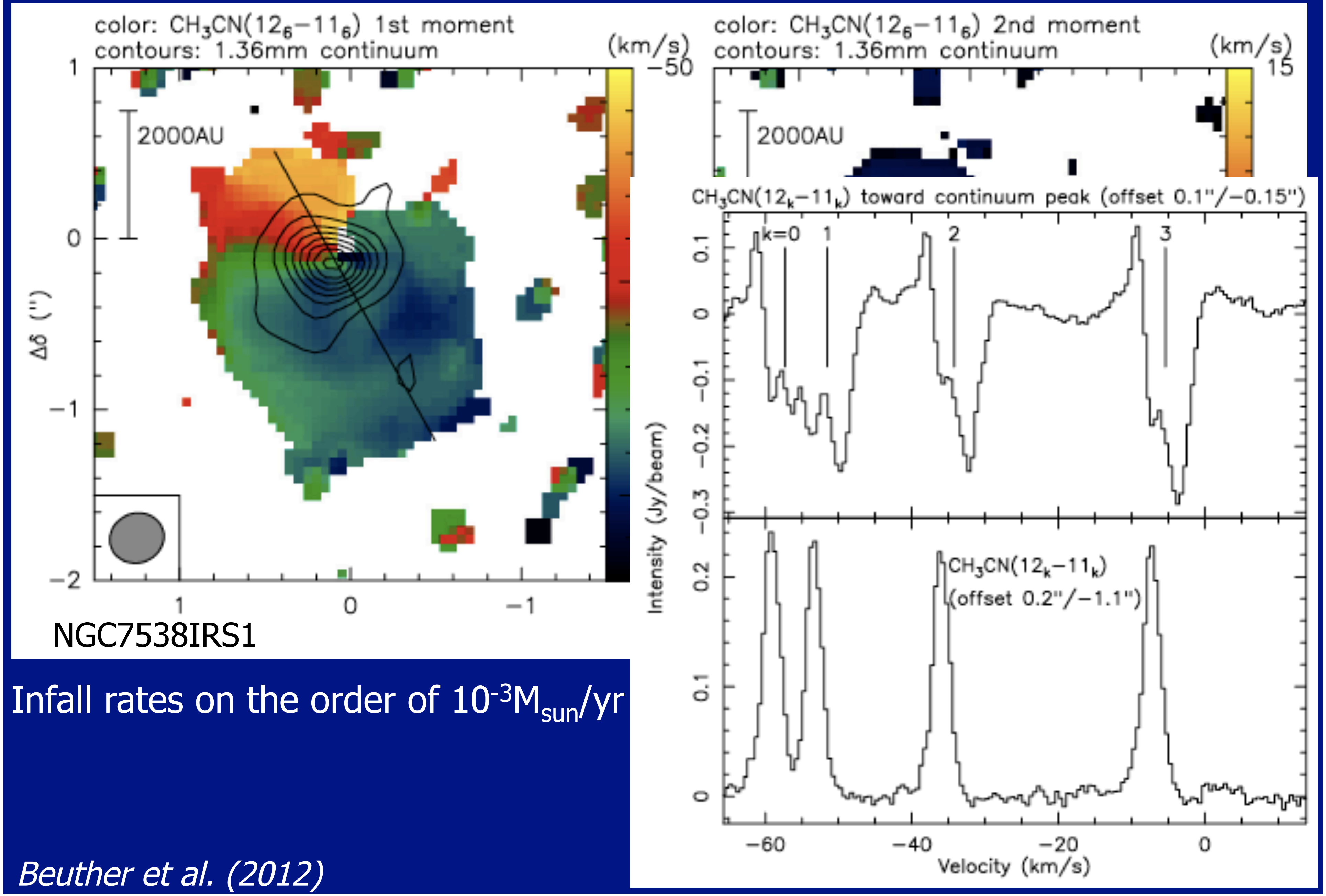
Infall and rotation



NGC7538IRS1

Beuther et al. (2012)

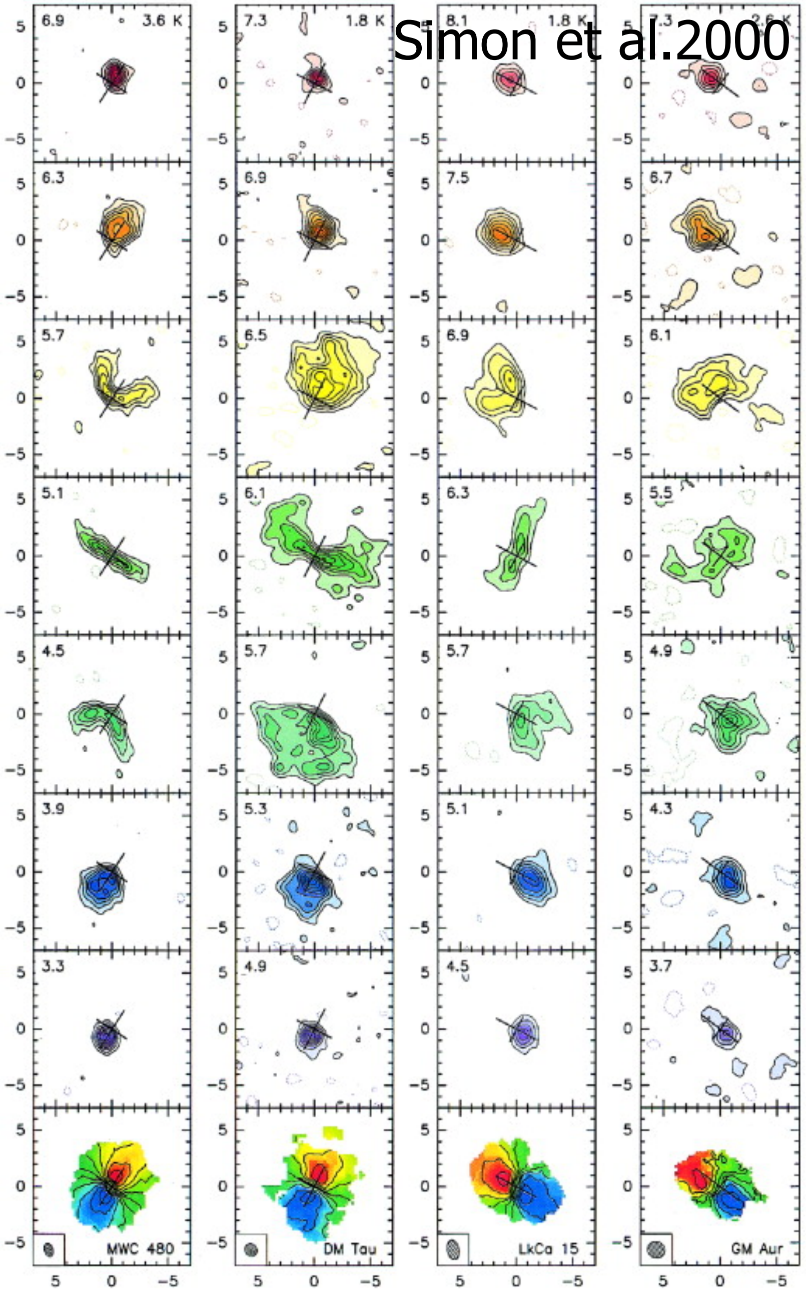
Infall and rotation

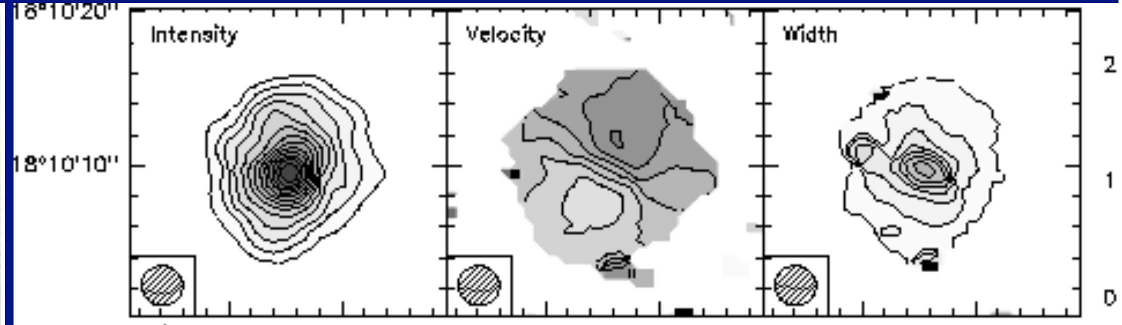


Infall rates on the order of $10^{-3} M_{sun}/yr$

Beuther et al. (2012)

Disk dynamics: Keplerian motion


Simon et al.2000

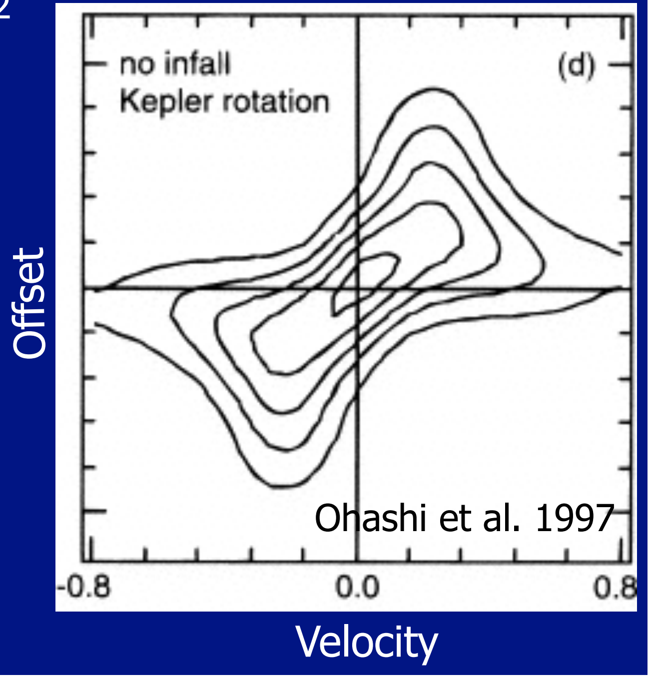


DM Tau Guilloteau et al. 1998

For a Keplerian supported disk, centrifugal force should equal grav. force.

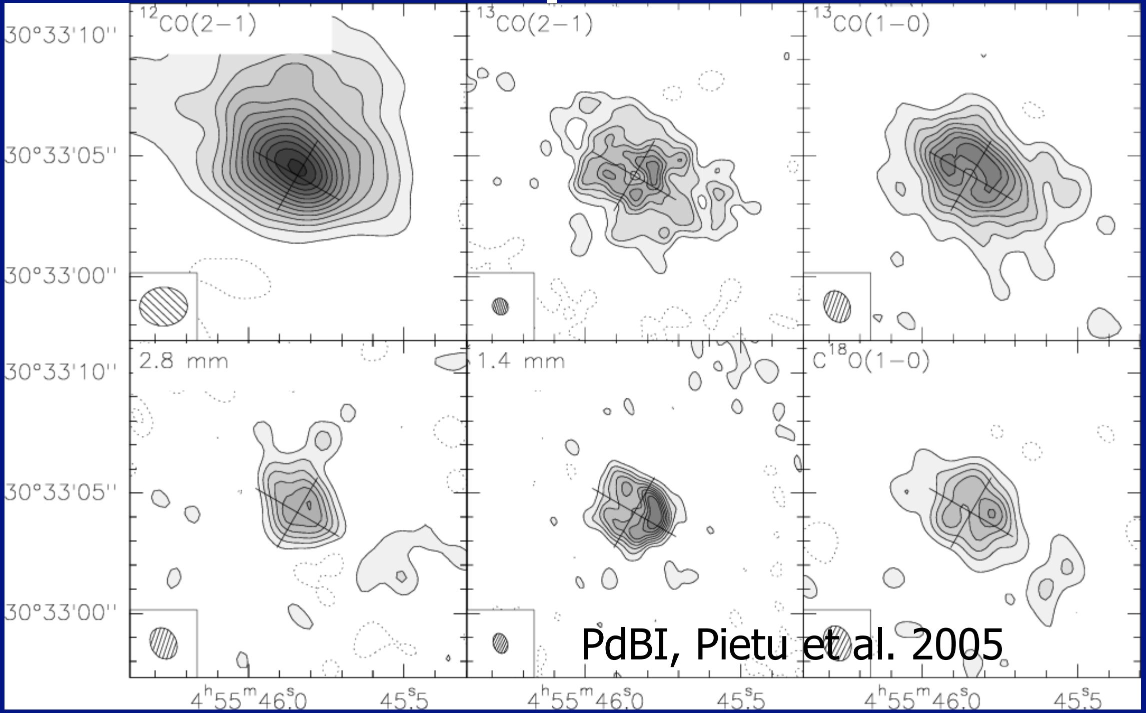
$$F_{cen} = mv^2/r = F_{grav} = Gm_*m/r^2$$

--> $v = (Gm_*/r)^{1/2}$

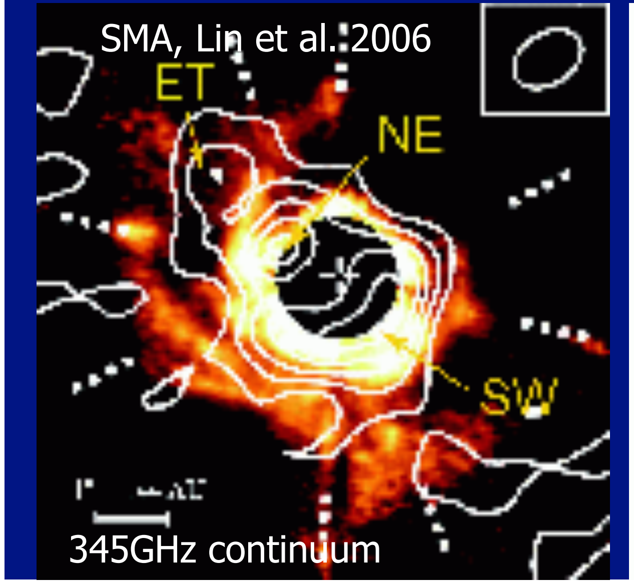


Ohashi et al. 1997

Non-Keplerian motion: AB Aur

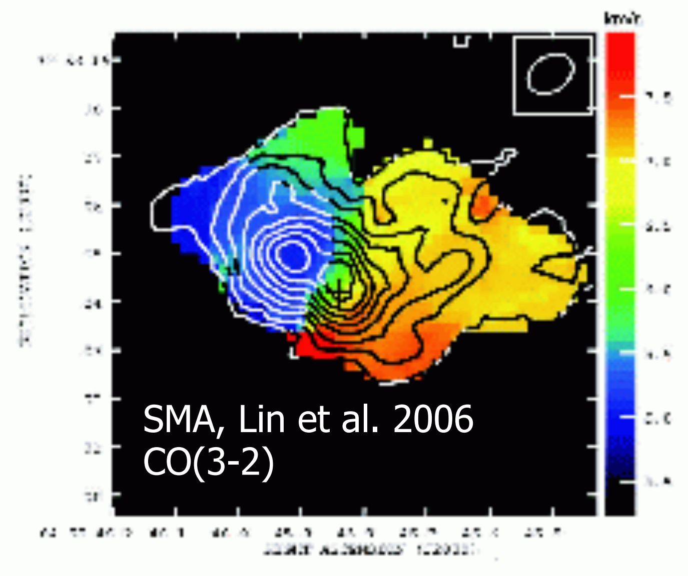


PdBI, Pietu et al. 2005



SMA, Lin et al. 2006

345GHz continuum

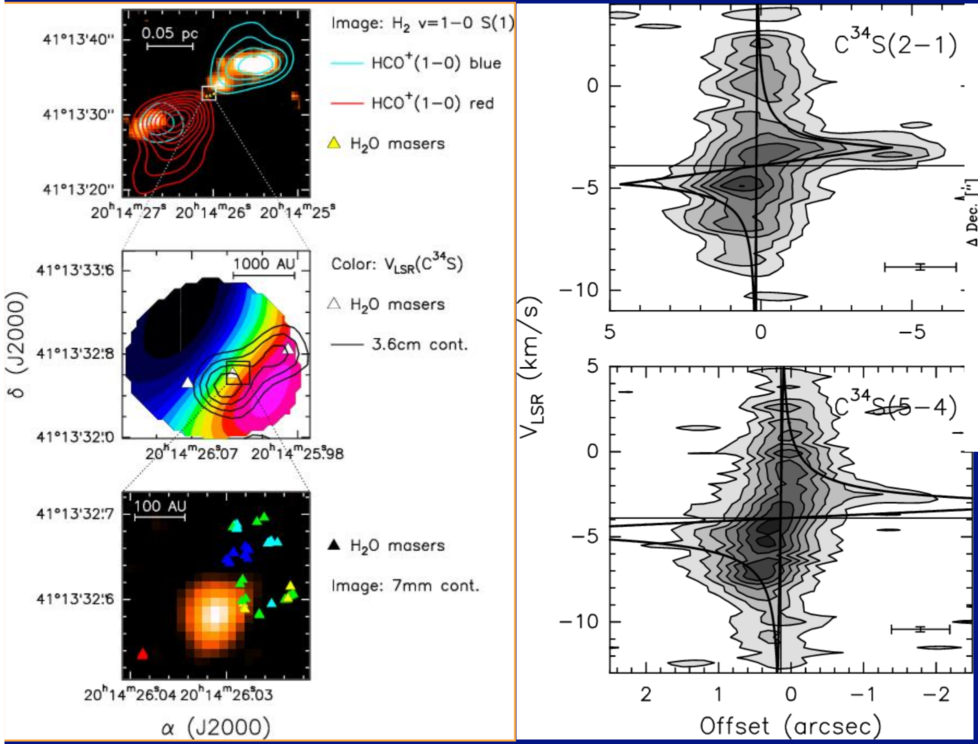


SMA, Lin et al. 2006
CO(3-2)

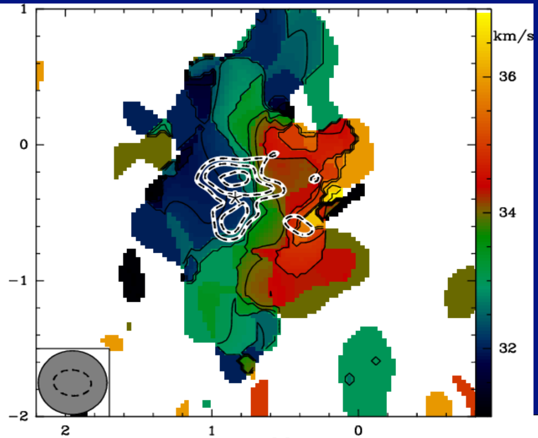
- Central depression in cold dust and gas emission.
- Non-Keplerian velocity profile $v \propto r^{-0.4+-0.01}$

- Possible explanations
  - Formation of low-mass companion or planet in inner disk.
  - Early evolutionary phase where Keplerian motion is not established yet (large envelope).

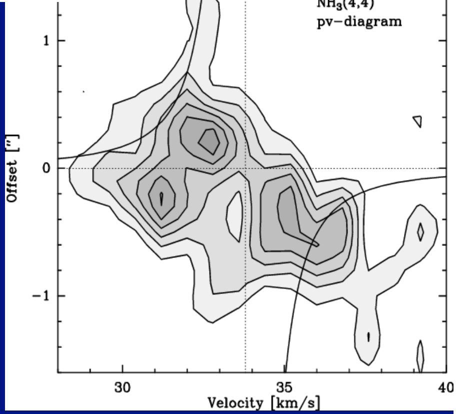
Disks in massive star formation



IRAS20126+4104, *Cesaroni et al. 1997, 1997, 2005*
Keplerians disk around central protostar of ~7M_{sun}



IRAS18089-1732
(*Beuther & Walsh 2008*)
Hot rotating structure
not in Keplerian motion.



- Still deeply embedded, large distances, clustered environment --> confusion
- Keplerian motion possible but not necessarily observed on large scales.
- (Sub)mm interferometry important to disentangle the spatial confusion.
- The right spectral line tracer still difficult to identify which can distinguish the disk emission from the surrounding envelope emission.

Outflows/jets to be continued in the coming lectures

Radio and mm astronomy

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