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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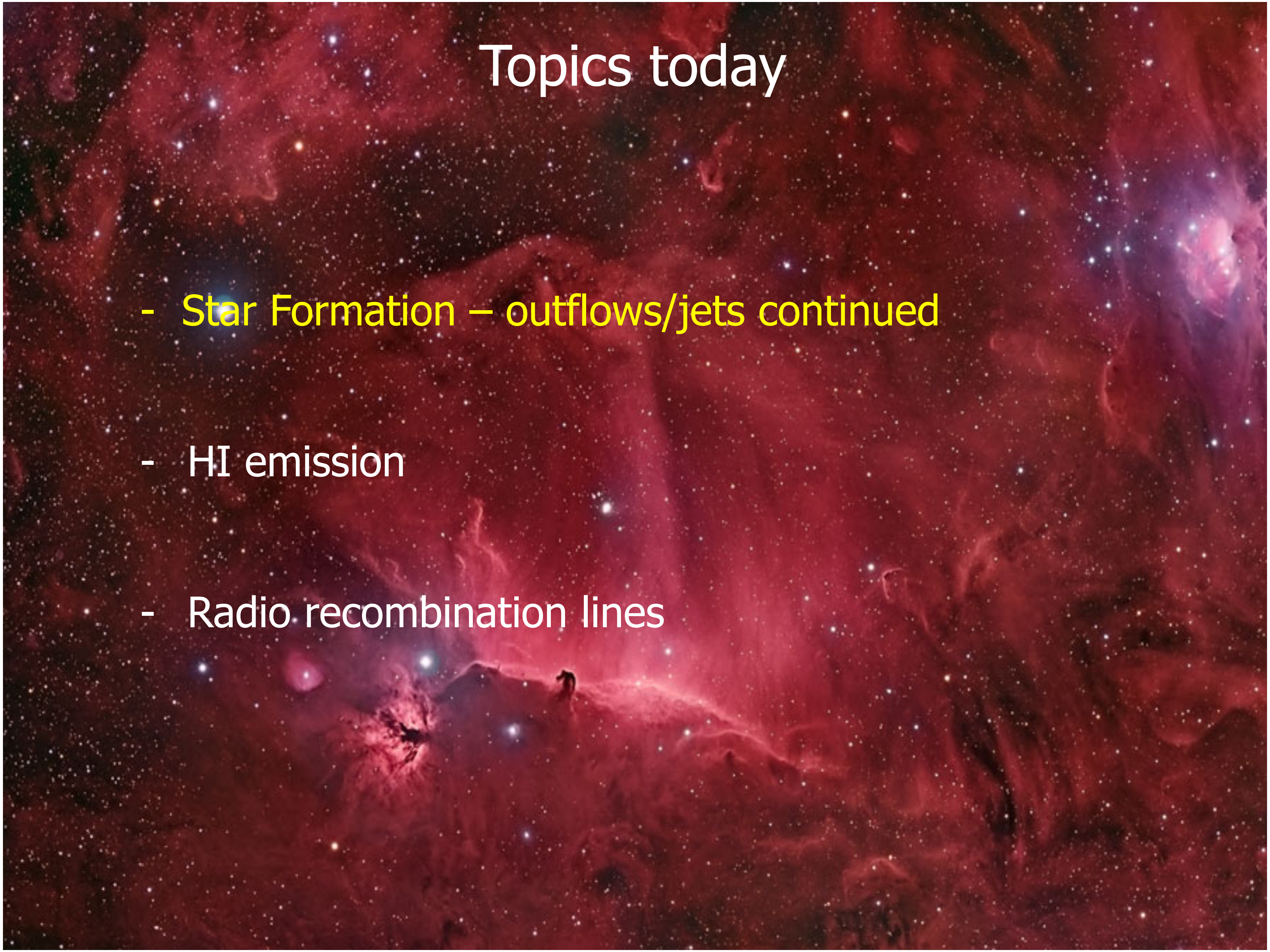
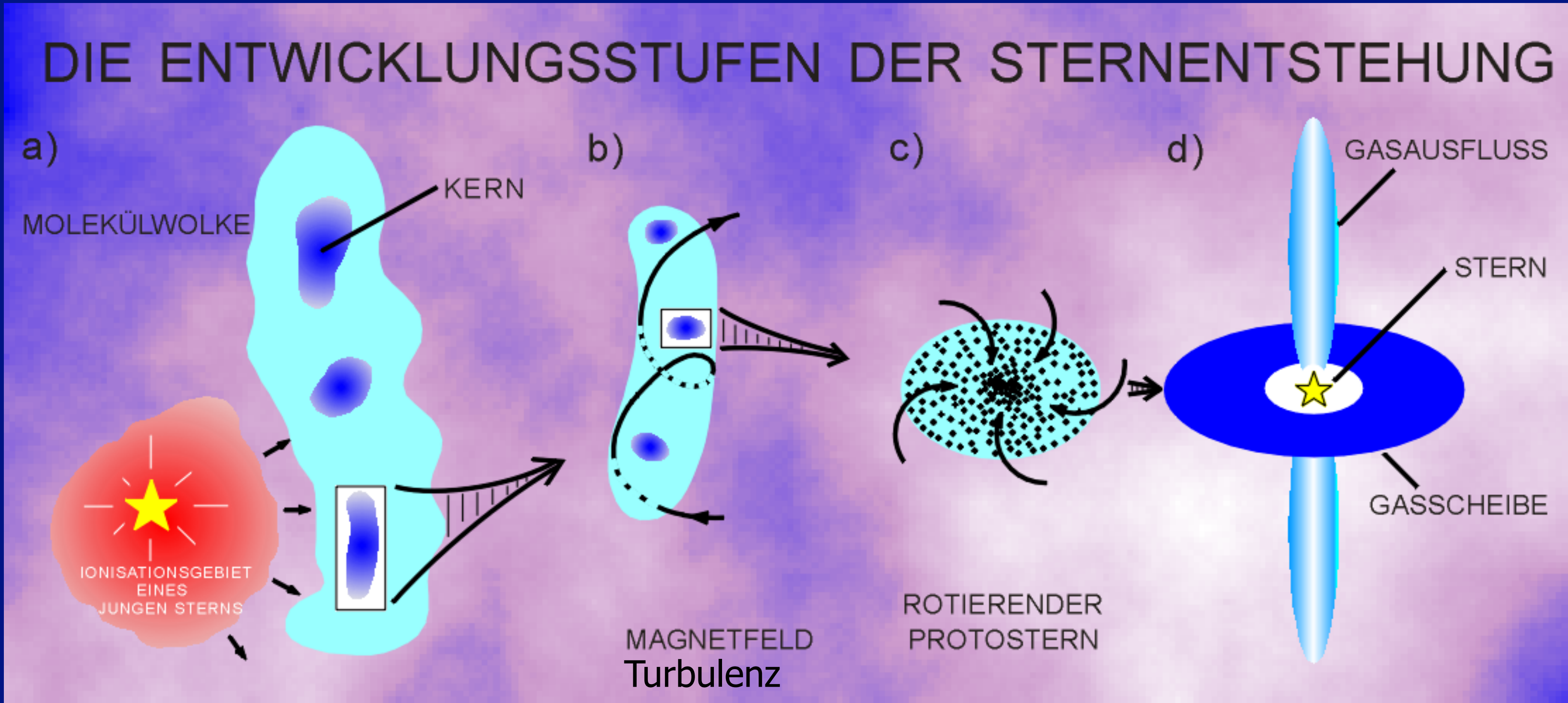


Topics today

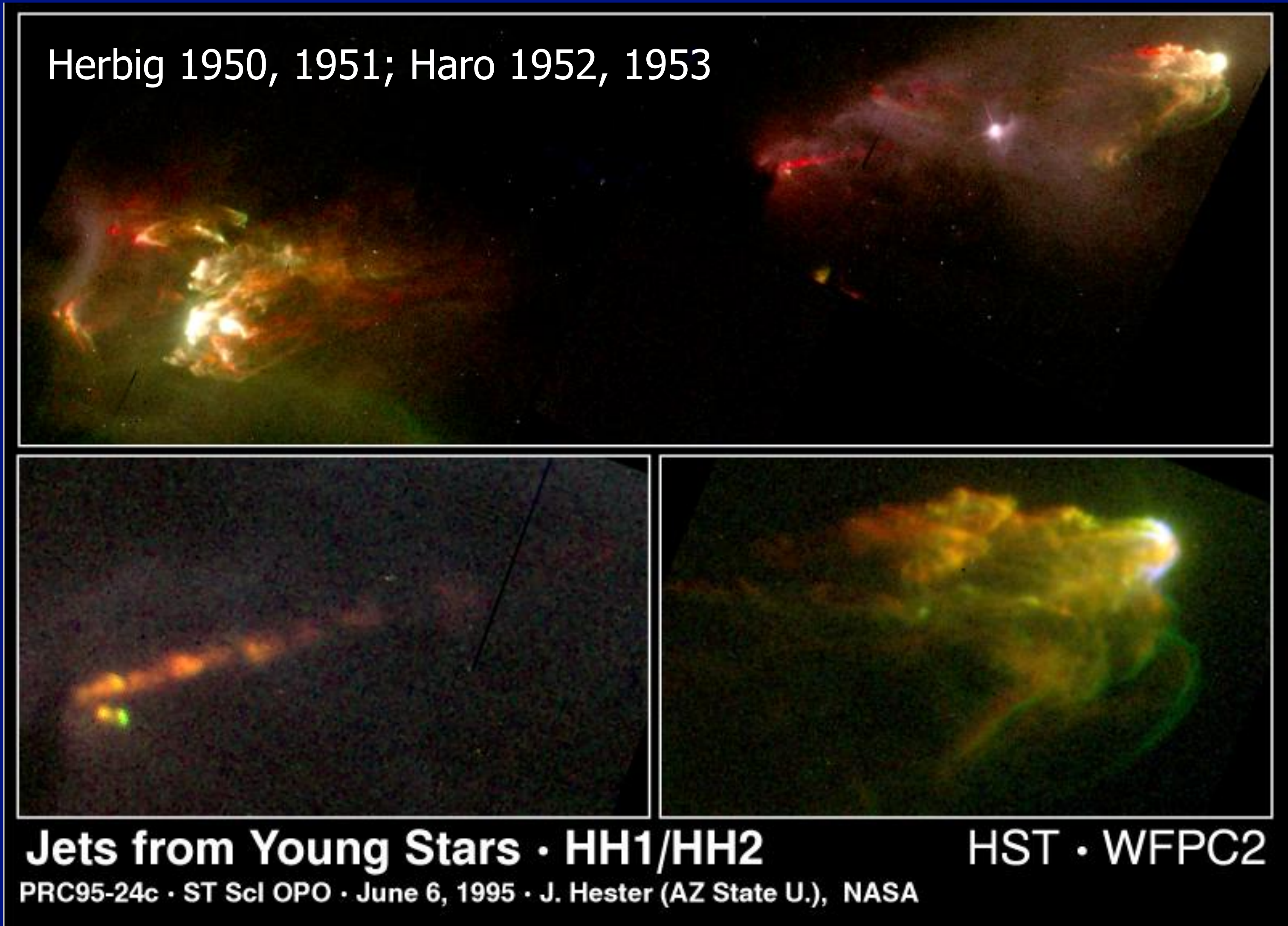
- Star Formation – outflows/jets continued
- HI emission
- Radio recombination lines

Sternentstehungsparadigma



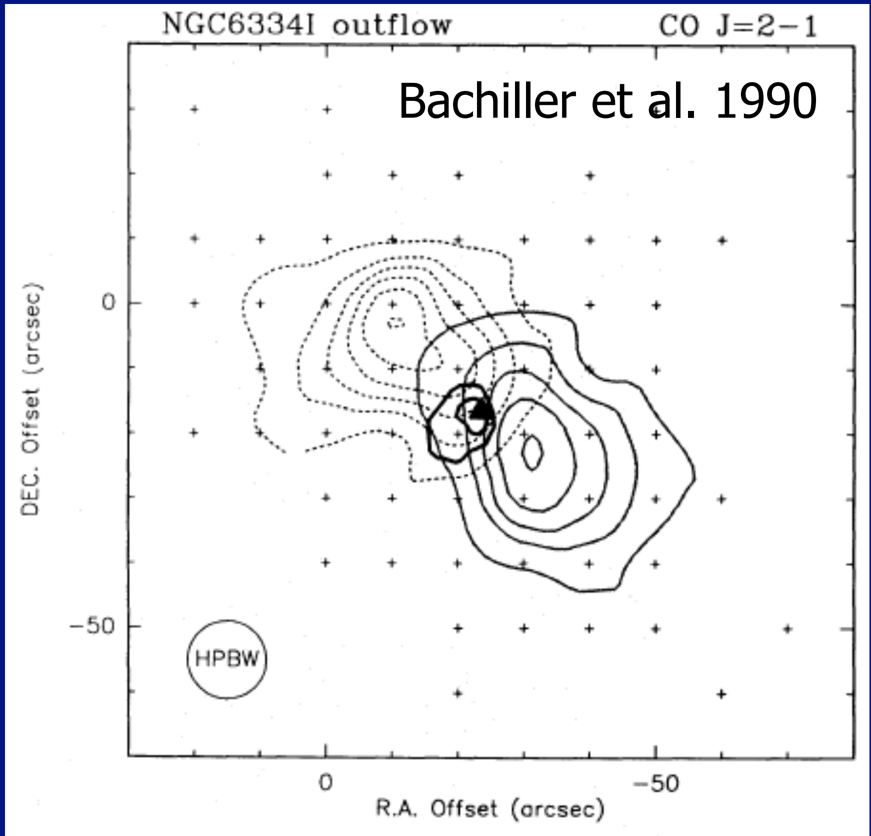
Time scales: Main accretion phase ~500 000 years
Pre-main-sequence evolution ~2e6 years

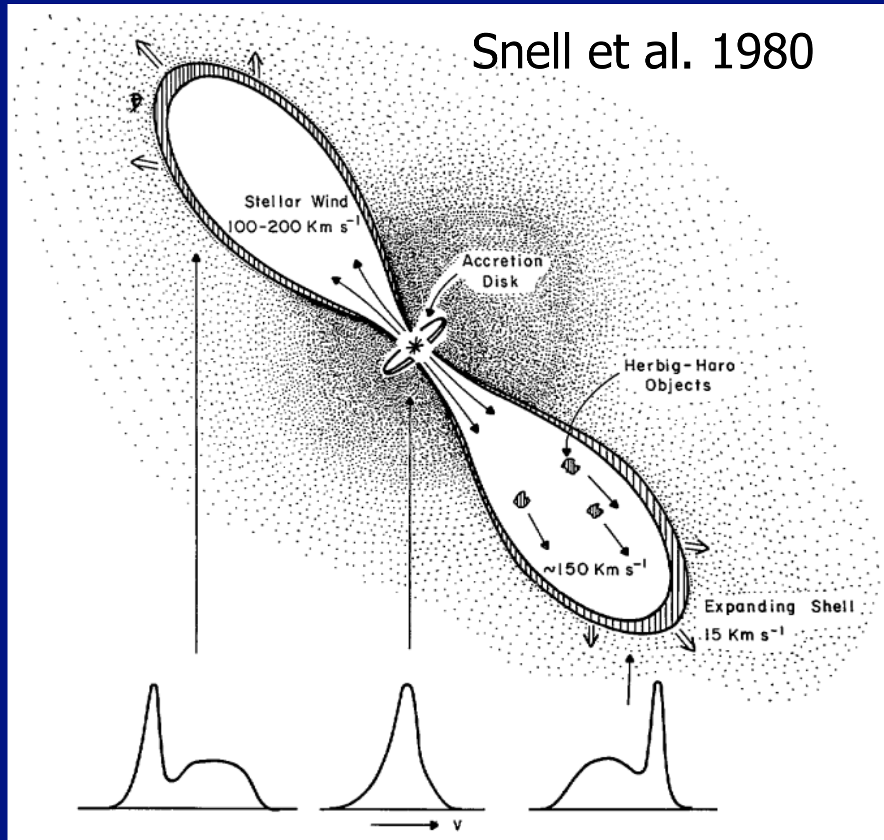
Discovery of outflows I



Initially thought to be embedded protostars but soon spectra were recognized as caused by shock waves → jets and outflows indicated

Discovery of outflows II

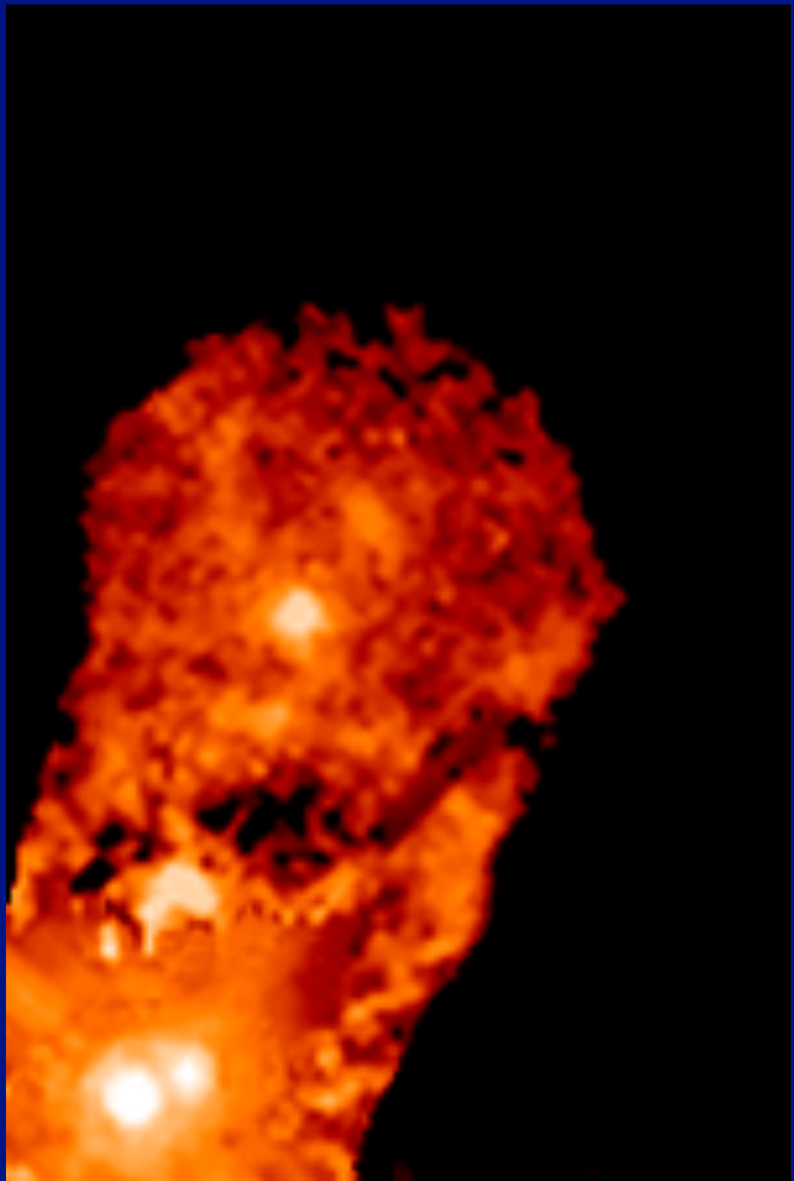




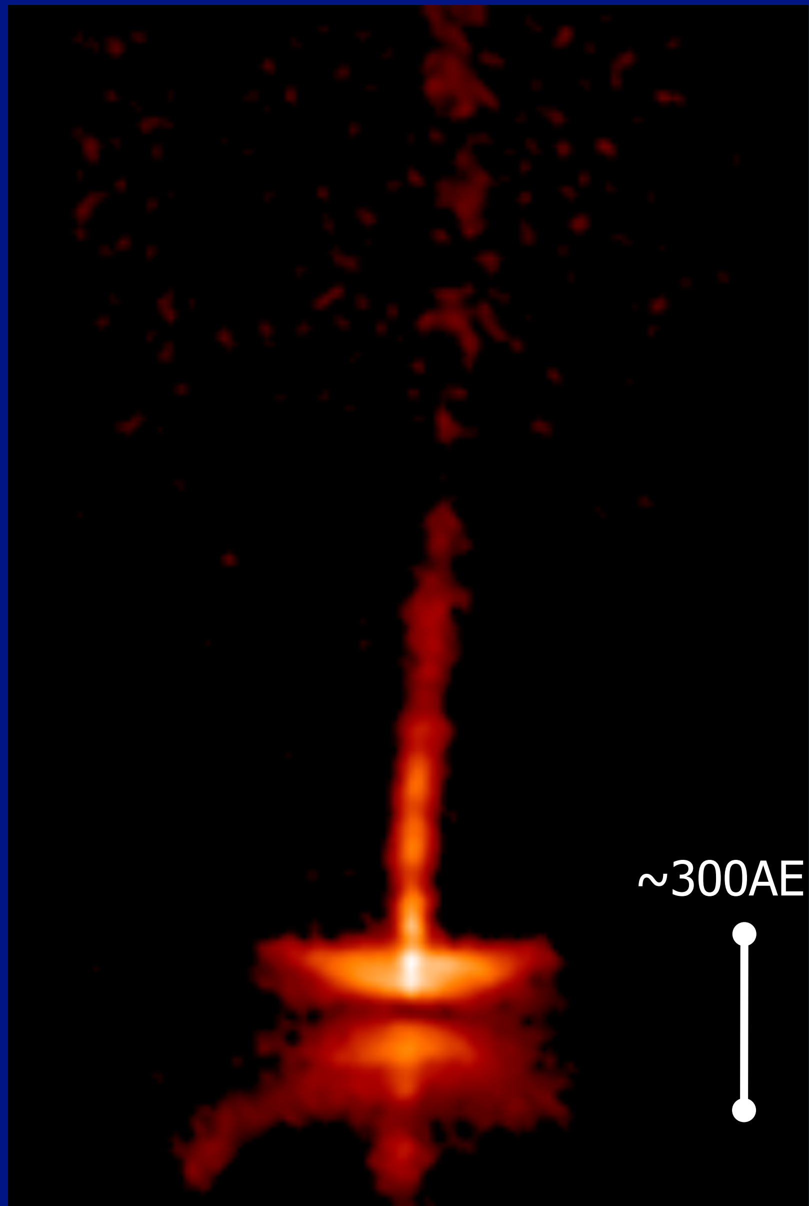
- In the mid to late 70th, first CO non-Gaussian line wing emission detected (Kwan & Scovile 1976).
- Bipolar structures, extremely energetic, often associated with HH objects

Eigenbewegungen von Jets

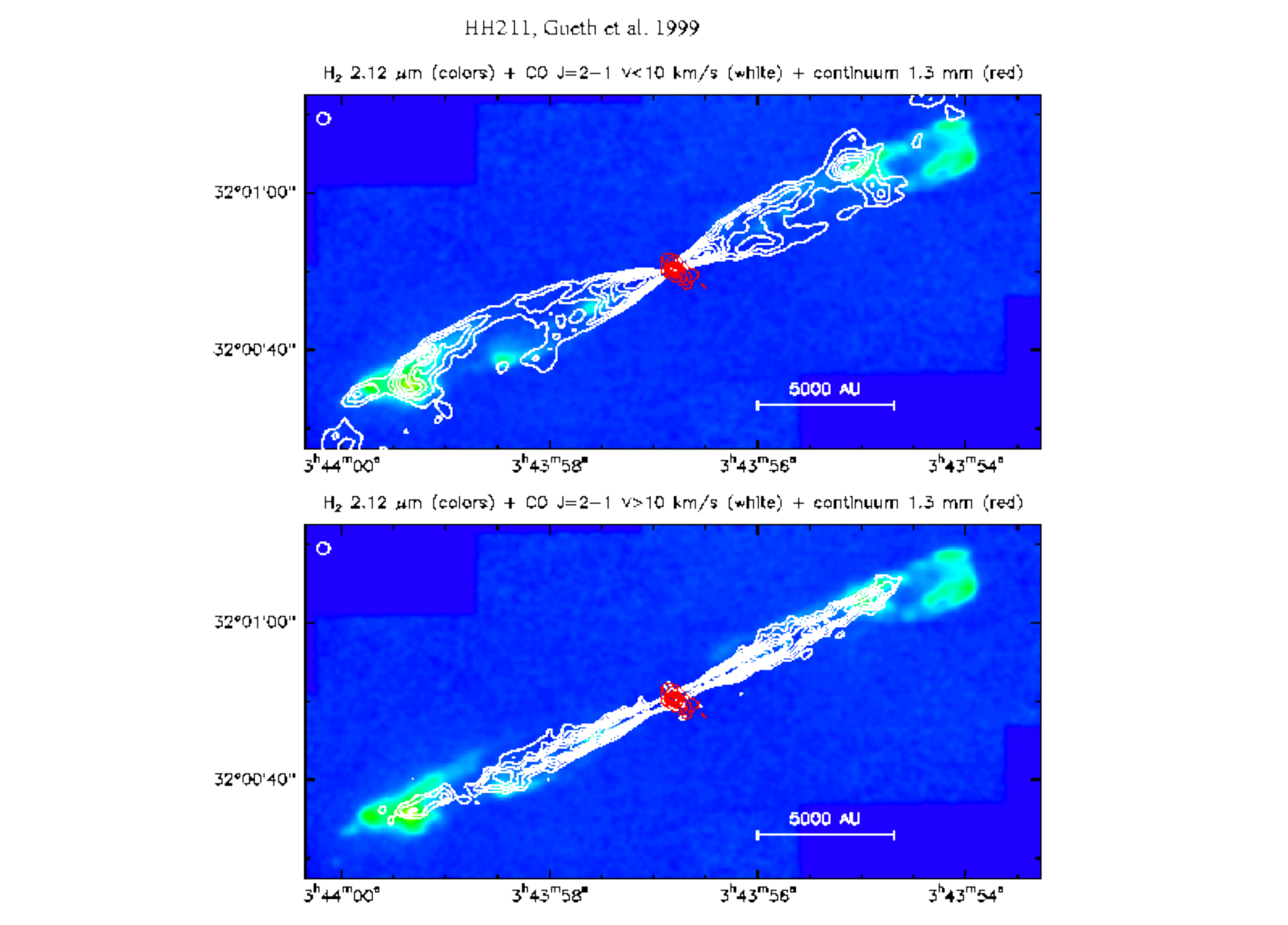
XZ Tauri



HH30



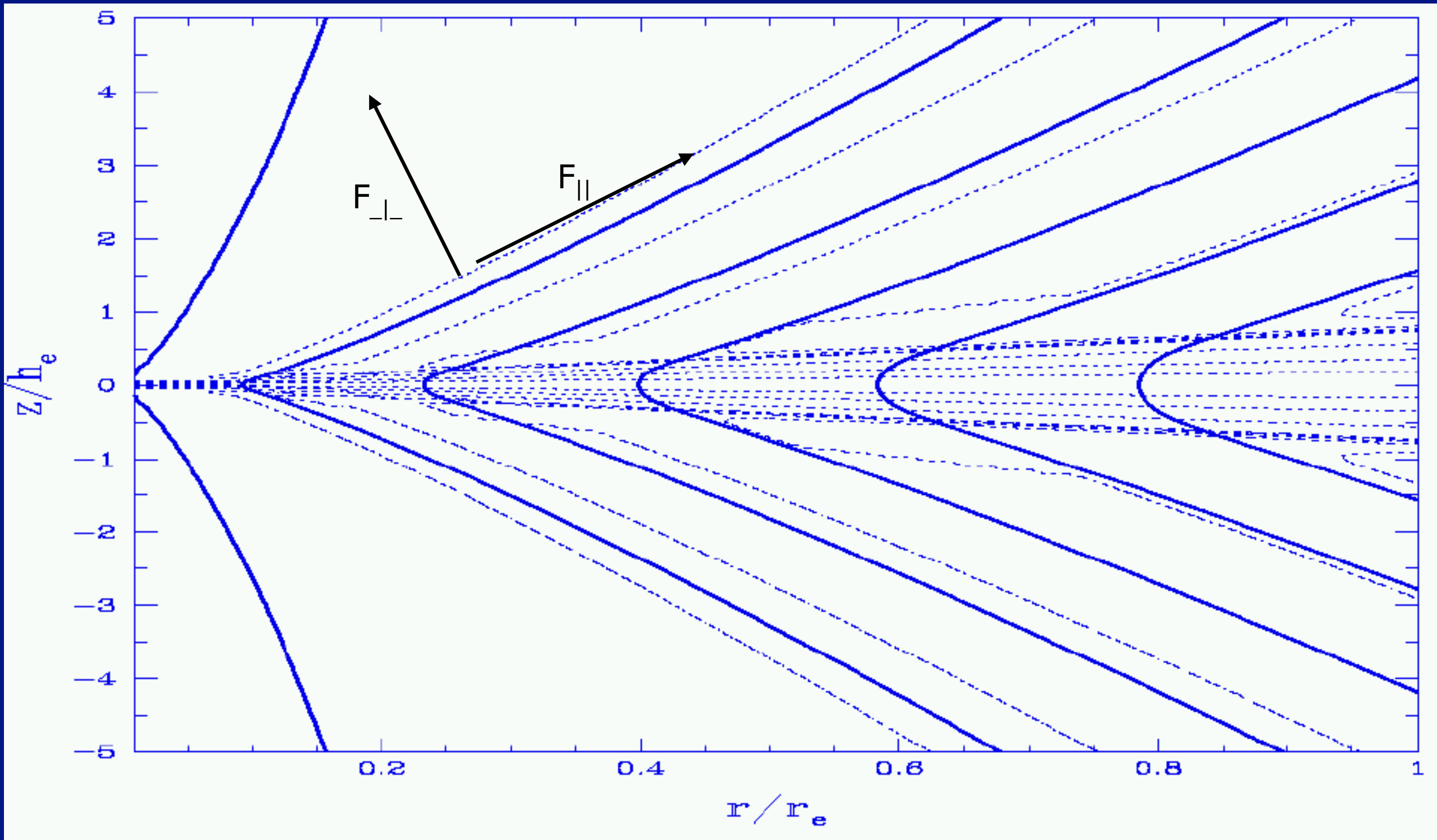
The prototypical molecular outflow HH211



Jet launching from accretion disks

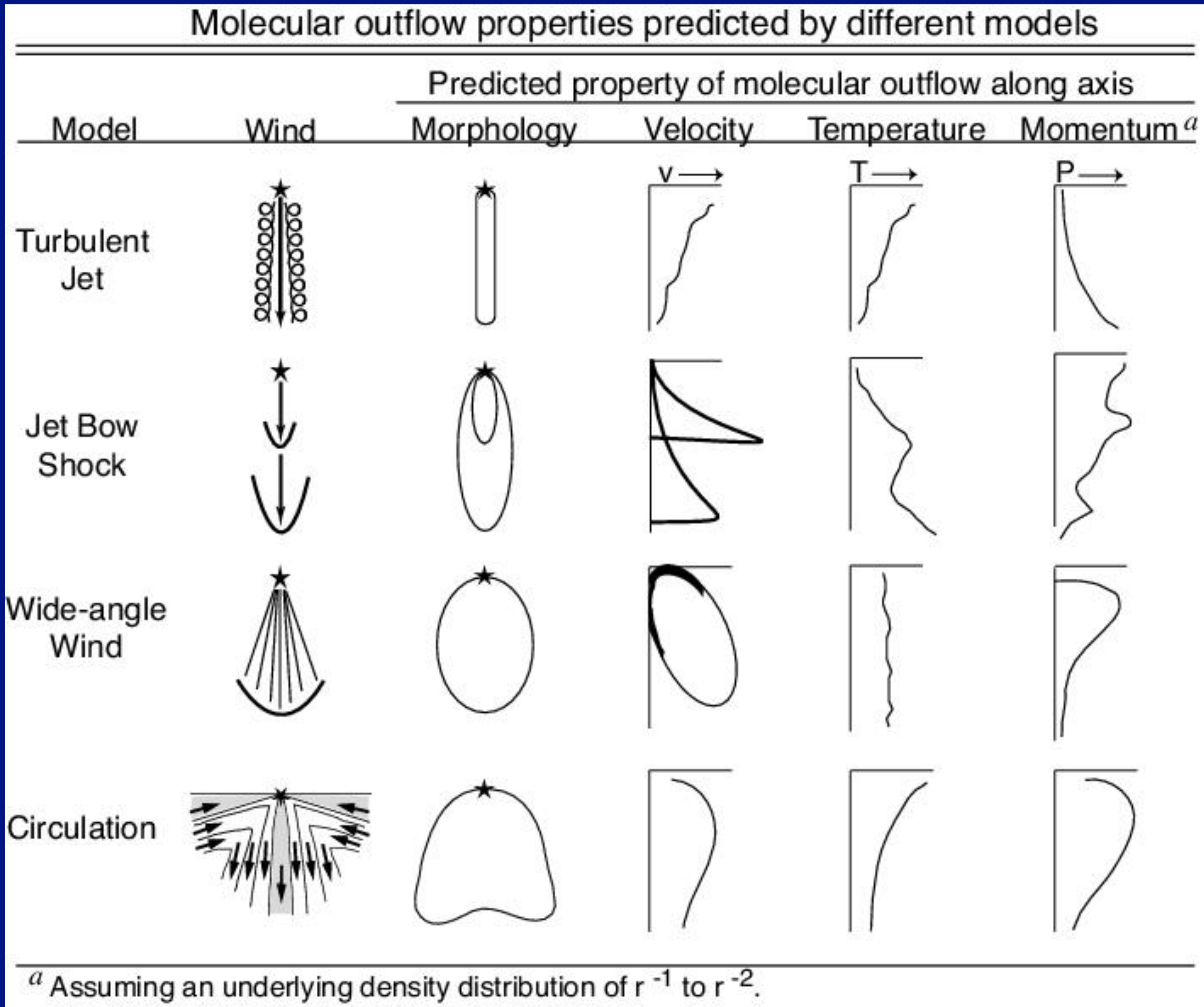
"magnetic accretion-ejection structures" (Ferreira et al 1995-1997):

1) disk material diffuses across magnetic field lines, 2) is lifted upwards by MHD forces, then
3) couples to the field and 4) becomes accelerated magnetocentrifugally and 5) collimated



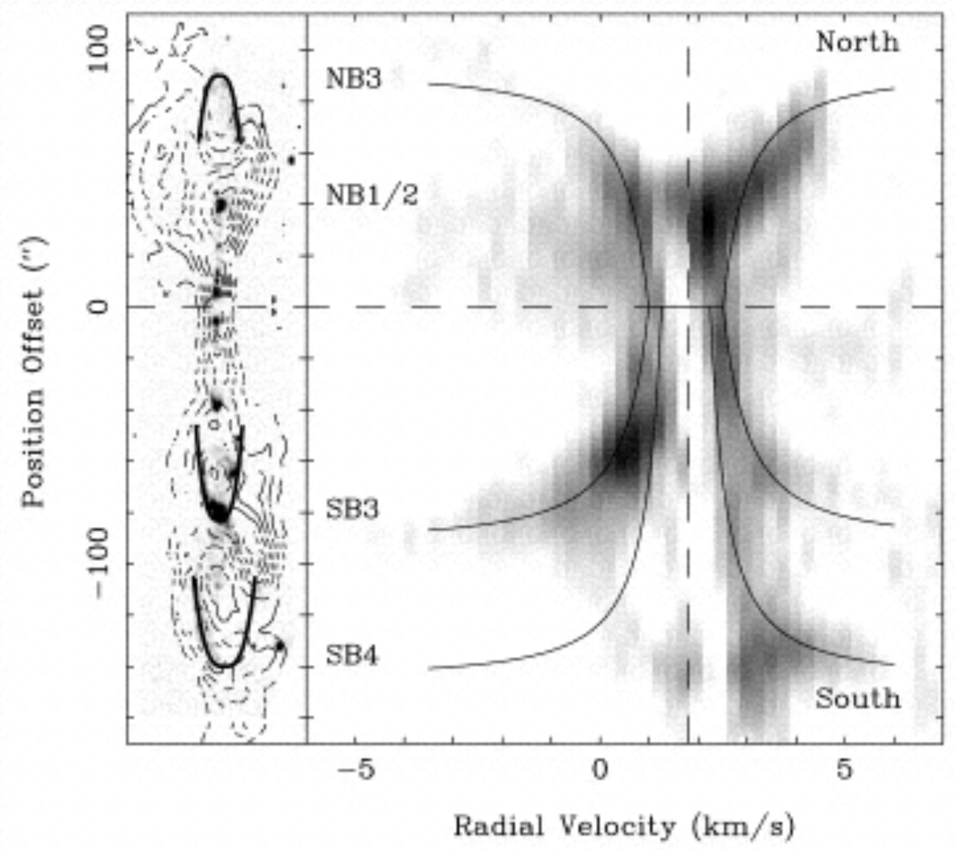
Magnetic field lines (thick) and streamlines (dashed)

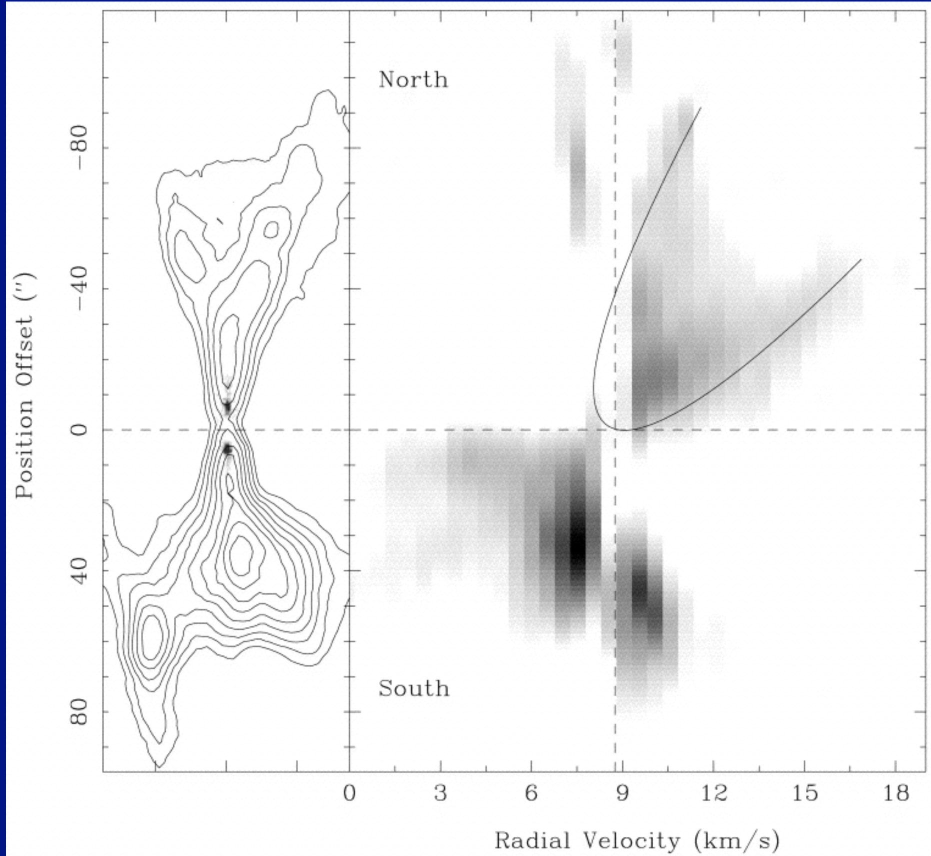
Outflow entrainment models



Arce et al. 2002

Collimation and pv-structure





HH212: consistent with jet-driving

VLA0548: consistent with wind-driving

- pv-structure of jet- and wind-driven models very different
- Often Hubble-law observed --> increasing velocity with increasing distance from the protostar

Lee et al. 2001

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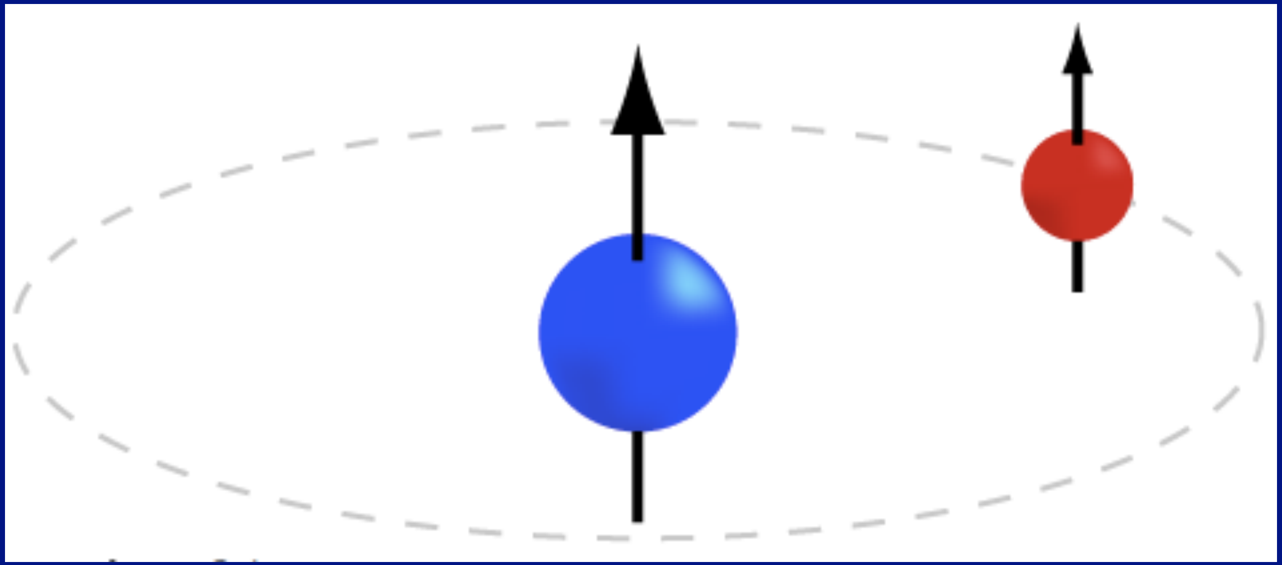
- HI emission

- Radio recombination lines

Atomic hydrogen HI



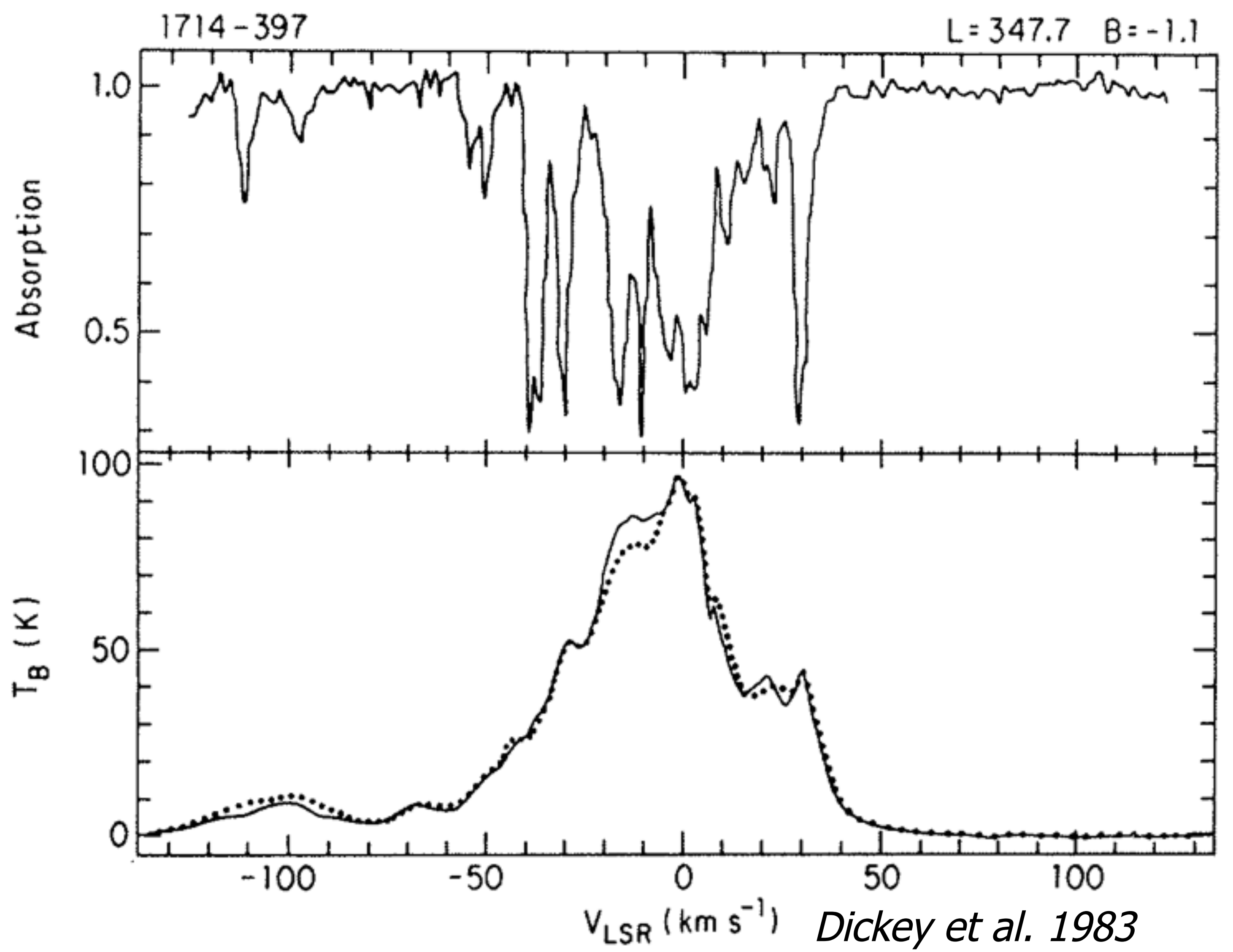
Two energy levels from the magnetic interaction between proton and e^- spin.
→ Spin flip causes line emission at 1.4GHz or 21cm

Einstein A coefficient $A_{10} \approx 2.85 \times 10^{-15}\ \mathrm{s}^{-1}$ very low!

That results in a half-time: $\tau_{1/2} = A_{10}^{-1} \approx 3.5 \times 10^{14}\ \mathrm{s} \approx 11\ \text{million years}$

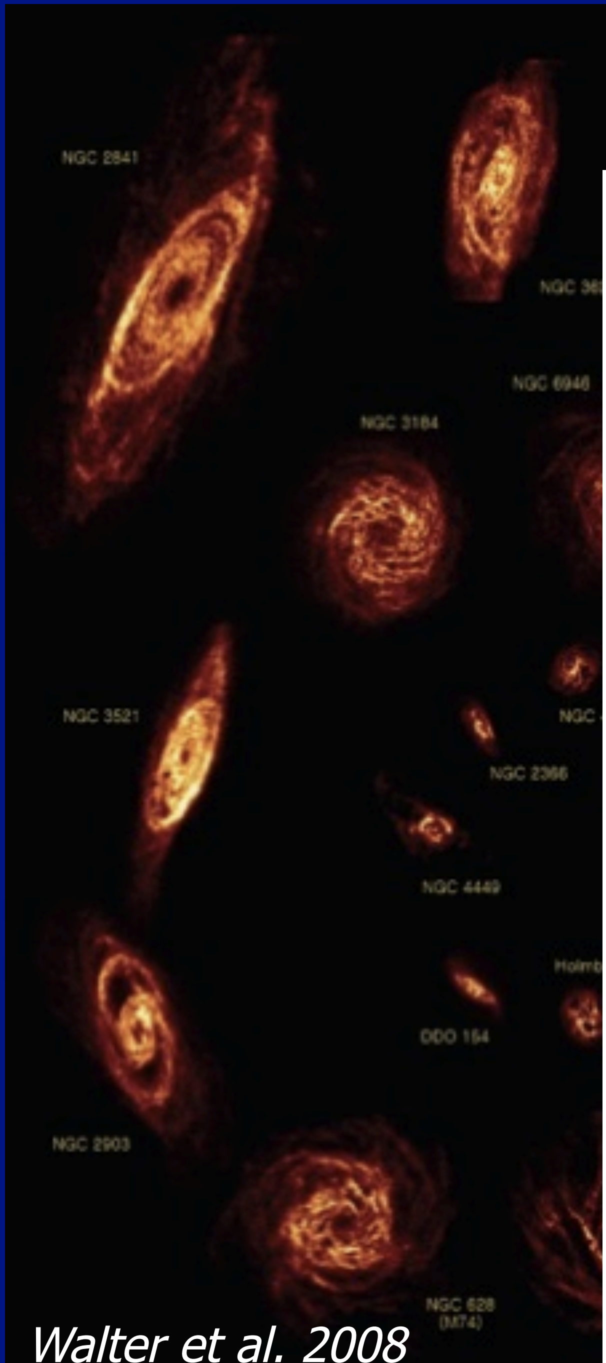
This implies critical densities <<1cm^{-3} and collisional equilibrium can easily be maintained.
→ Early detections were only possible at low densities of ISM!

HI in emission and absorption

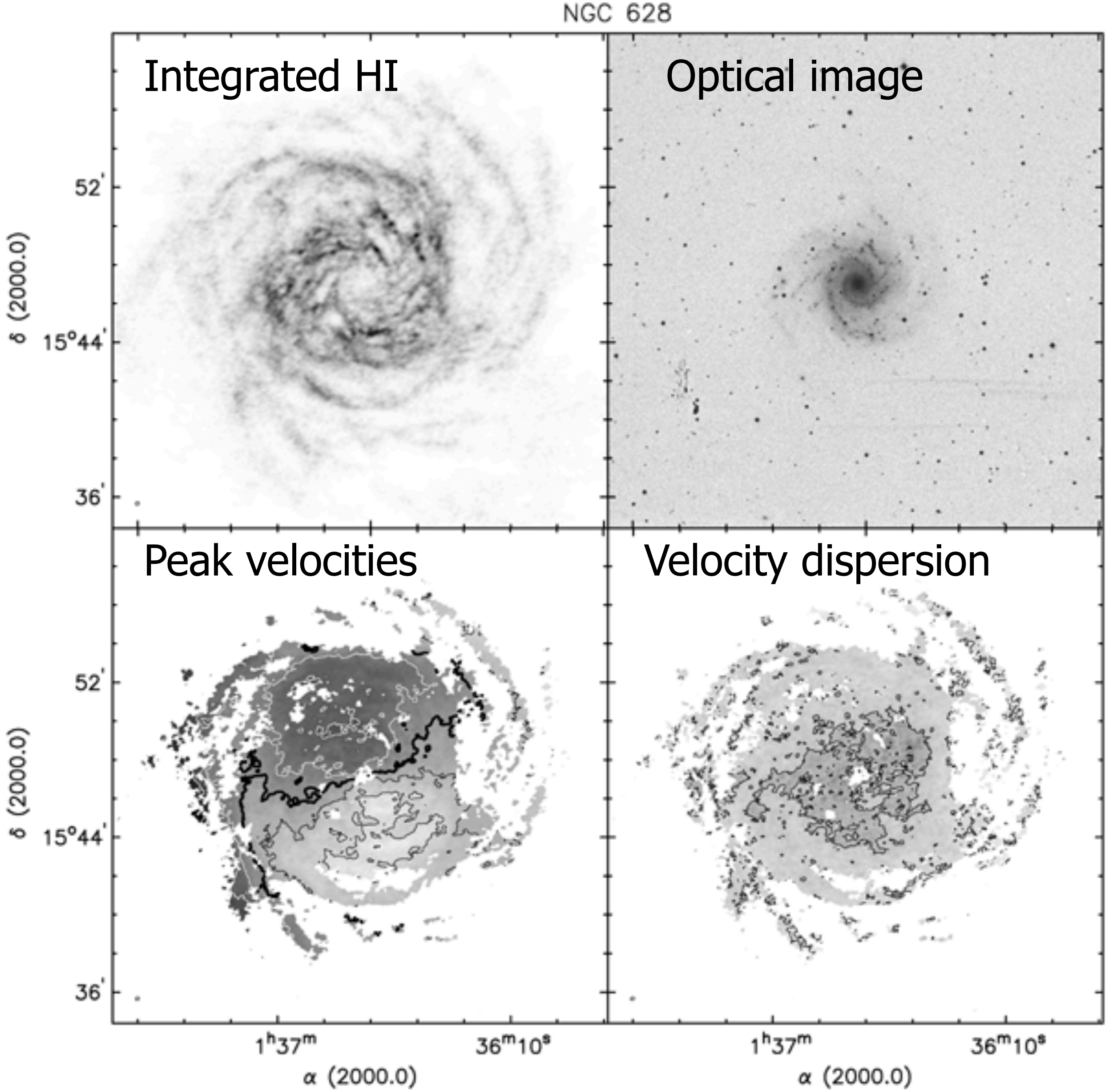


Dickey et al. 1983

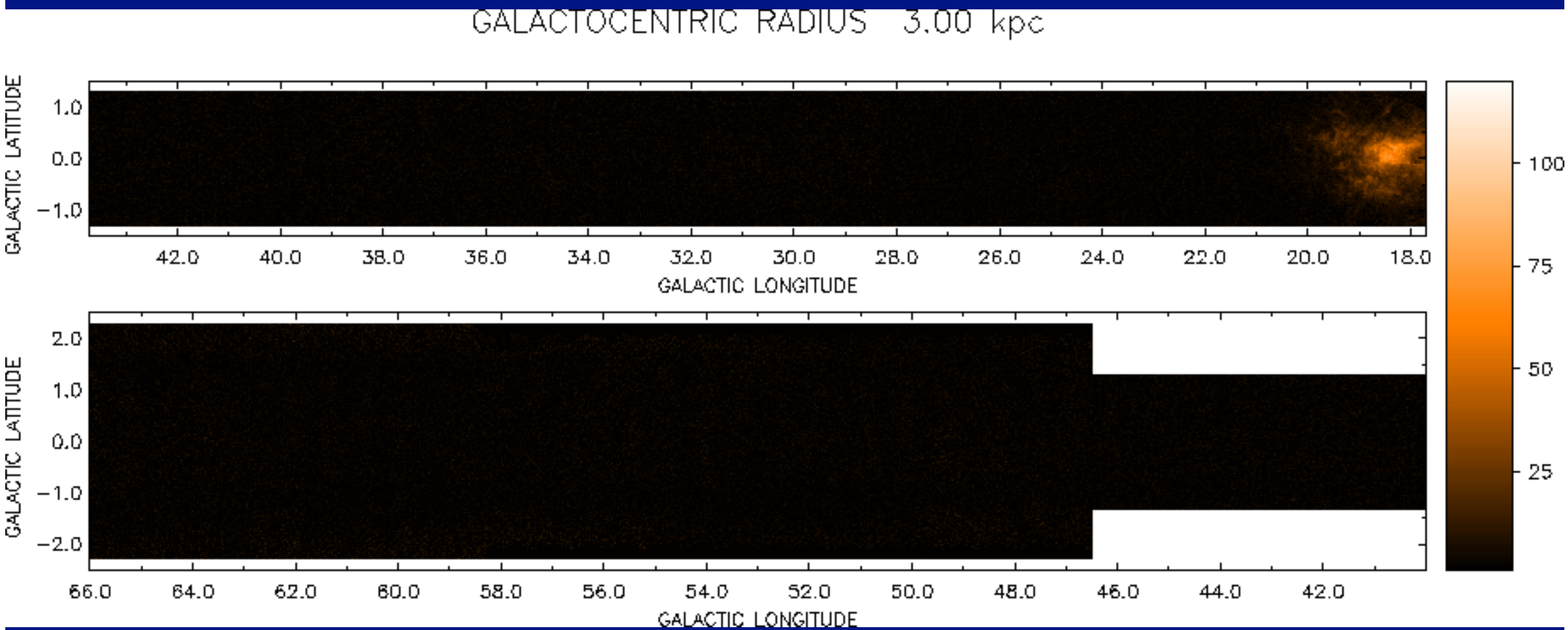
THINGS



Walter et al. 2008



HI in the Milky Way



Stil et al.

Topics today

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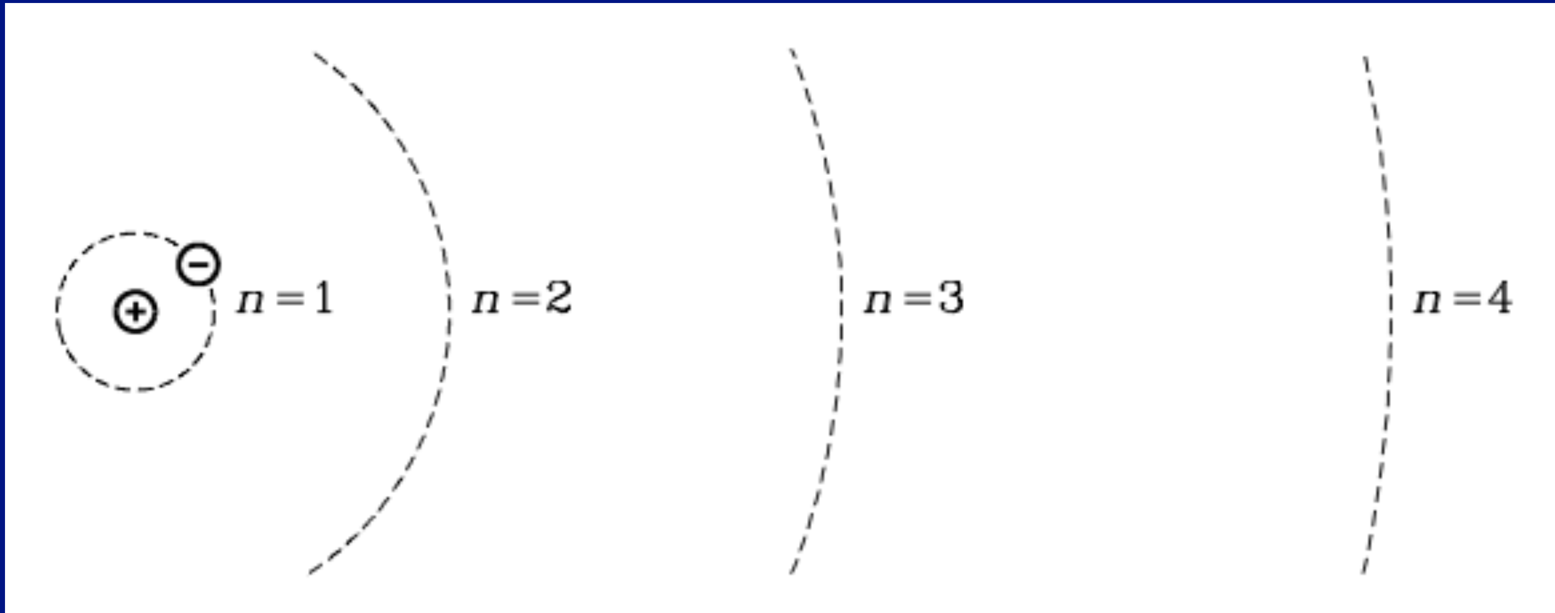
- Radio recombination lines

Recombination lines I

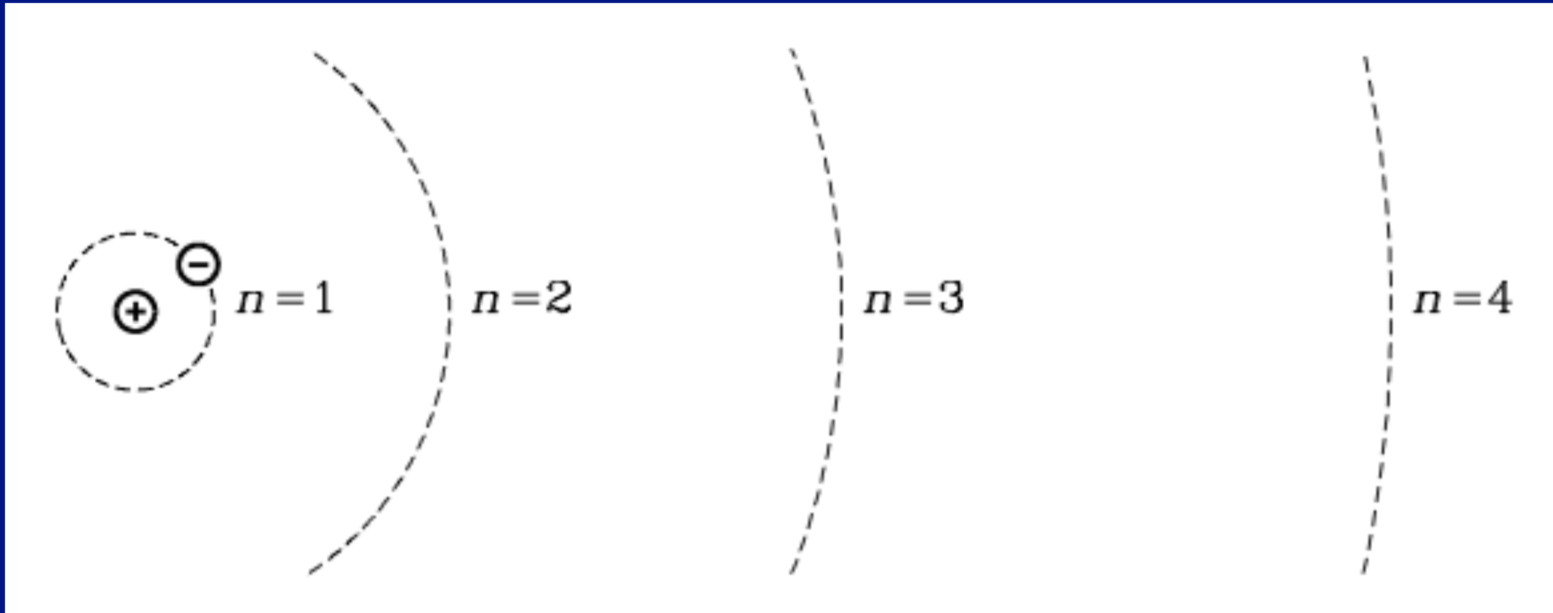


- After recombination, the electron can cascade down the “shells”
  → these transitions are called recombination lines
- De-Broglie wavelength $\lambda = \frac{h}{p} = \frac{h}{m_e v}$ with m_e = mass electron
- Only orbits with circumferences of an integer number of n correspond to standing waves and are permitted:

$$2\pi a_n = n\lambda = \frac{nh}{m_e v}$$

with a_n = Bohr radius

Recombination lines II

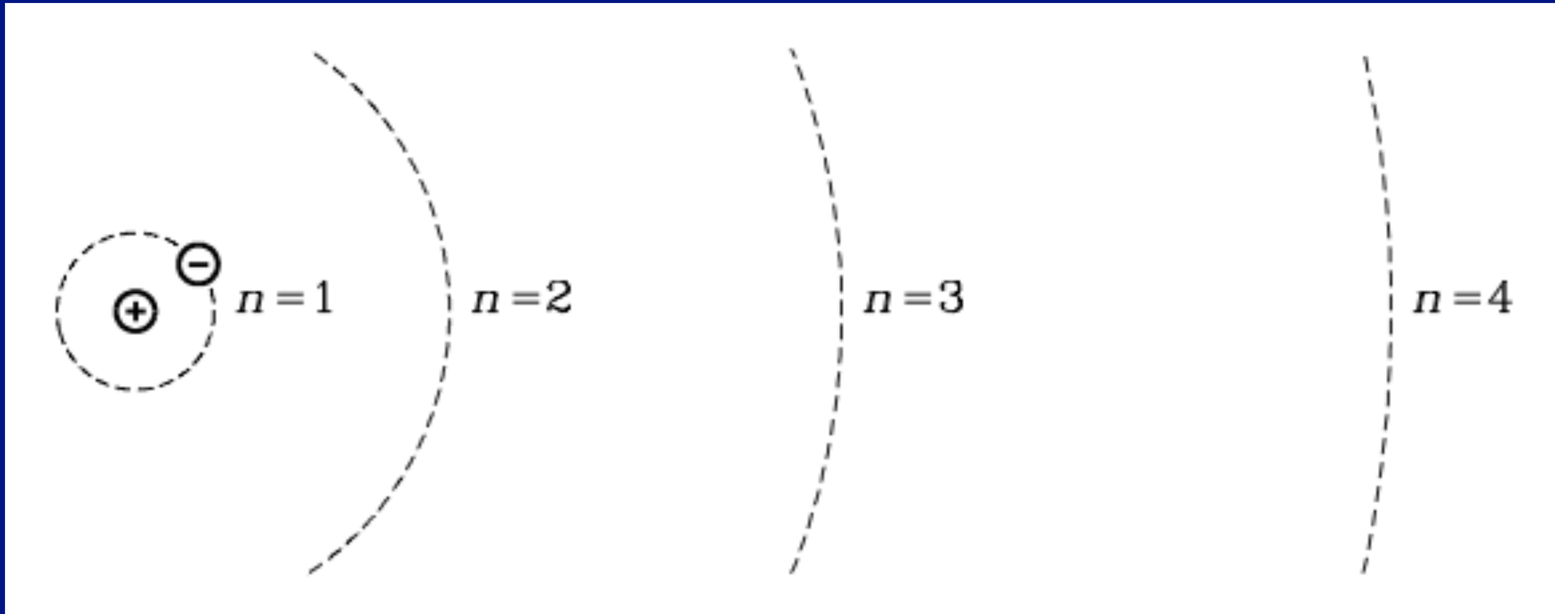


→ $$a_\mathrm{n} = \frac{nh}{2\pi m_\mathrm{e} v} = \frac{n\hbar}{m_\mathrm{e} v}$$

- Relation between a and ν can be derived from equilibrium between coulomb force and centrifugal force: $$\frac{e^2}{a_\mathrm{n}^2} = \frac{m_\mathrm{e} v^2}{a_\mathrm{n}}$$

→ $$v^2 = \frac{e^2}{m_\mathrm{e} a_\mathrm{n}}$$ or $$a_\mathrm{n} = \frac{n^2\hbar^2}{m_\mathrm{e} e^2}$$

Recombination lines III



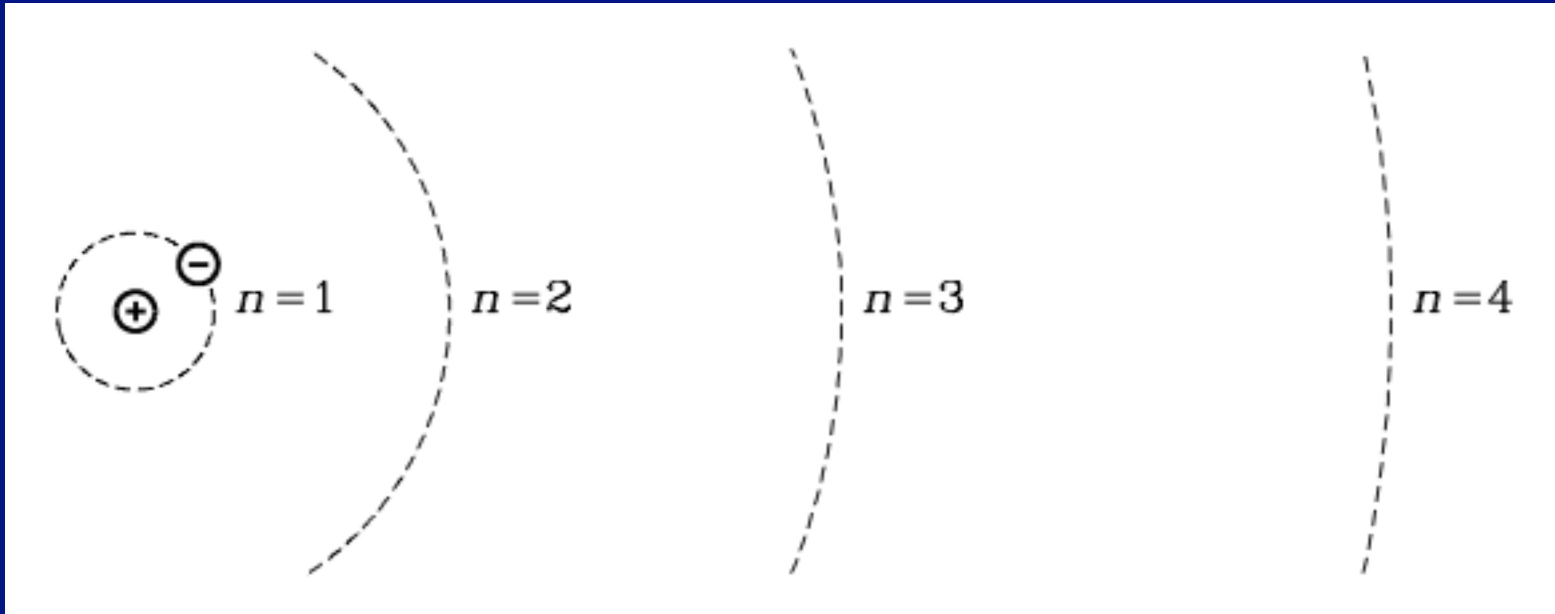
- Bohr radius of hydrogen atom: $$a_n = \frac{\hbar^2}{m_e e^2} n^2 \approx 0.53 \times 10^{-8}\ \mathrm{cm} \times n^2$$

  → radius depends on n^2 !

- For n=1 → $a_1 \sim 0.53 \times 10^{-8}$cm

- For n=100 → $a_{100} \sim 10^{-4}$cm = 1µm
  → nearly macroscopic sizes, larger than for example many viruses

Recombination lines IV



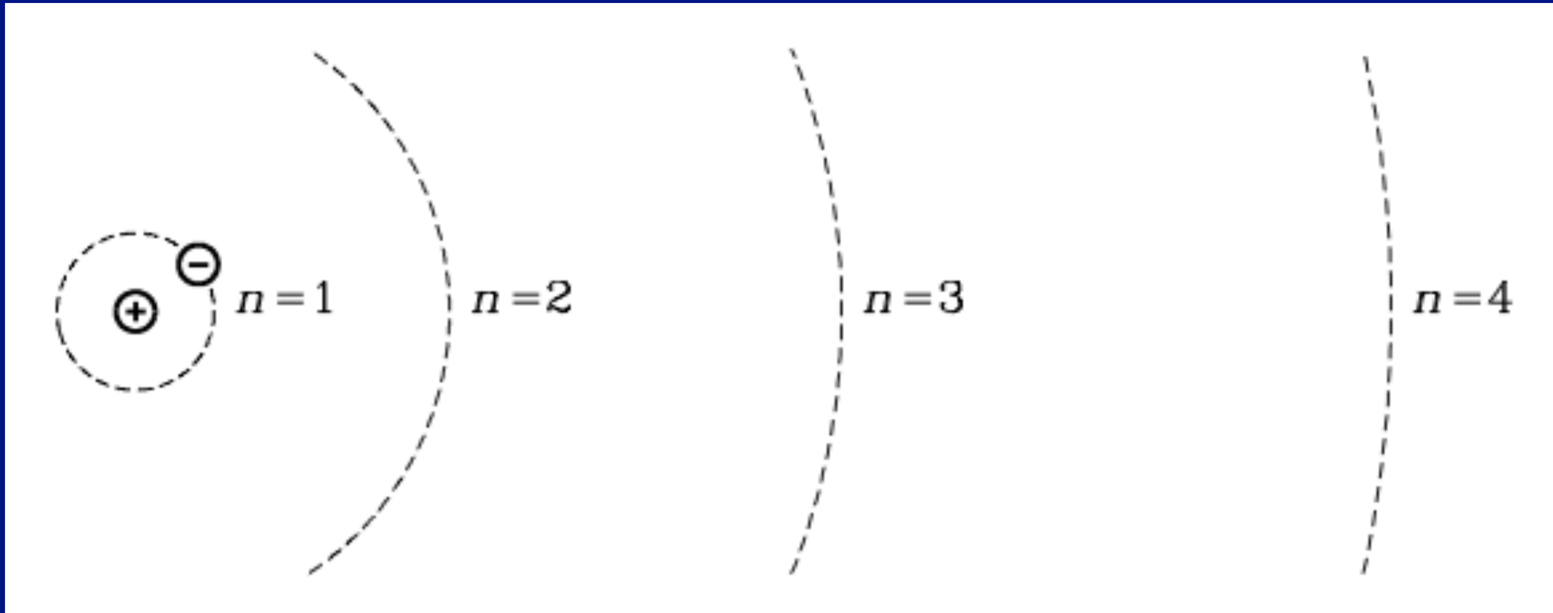
- Energy in n[th] level sum of kinetic and potential/coulomb energy

$$E_n = T + V = -T = V/2 = -\frac{e^2}{2a_n} = -\frac{e^2 m_e e^2}{2n^2\hbar^2} = -\frac{m_e e^4}{2\hbar^2 n^2}$$

→ energy change ΔE between levels n and n+Δn

$$\Delta E = \frac{m_e e^4}{2\hbar^2}\left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right] = h\nu$$

Recombination lines V



→ frequency: $\nu = \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) c \left[\frac{1}{n^2} - \frac{1}{(n+\Delta n)^2}\right]$

with Rydberg constant: $R_\infty \equiv \left(\frac{2\pi^2 m_e e^4}{h^3 c}\right) = 1.09737312\ldots \times 10^5\ \mathrm{cm}^{-1}$

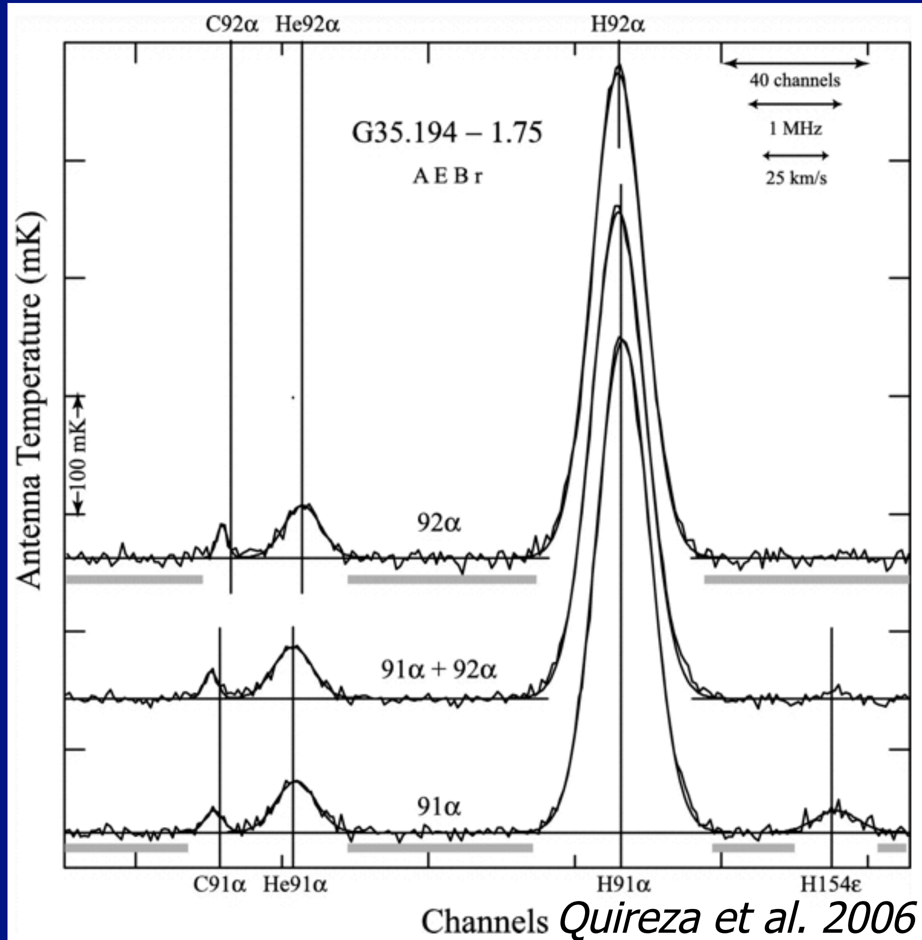
(infinite sign because mass of nucleus is considered large compared to electron mass in this analysis)

- Labeling for lines use lower level n and Δn

α for $\Delta n = 1$, β for $\Delta n = 2$, γ for $\Delta n = 3$

Recombination lines VI

- Low-n lines in the UV, optical and infrared, Lyman-alpha at 121.6nm
- Other famous series: n=2 Balmer, n=3 Paschen, n=4 Brackett
  n=5 Pfund, n=6 Humphreys (near- to mid-infrared)
- In the radio: H109α, 1965 by P. Mezger



- Analysis with finite nuclear mass:
  Rydberg constant:

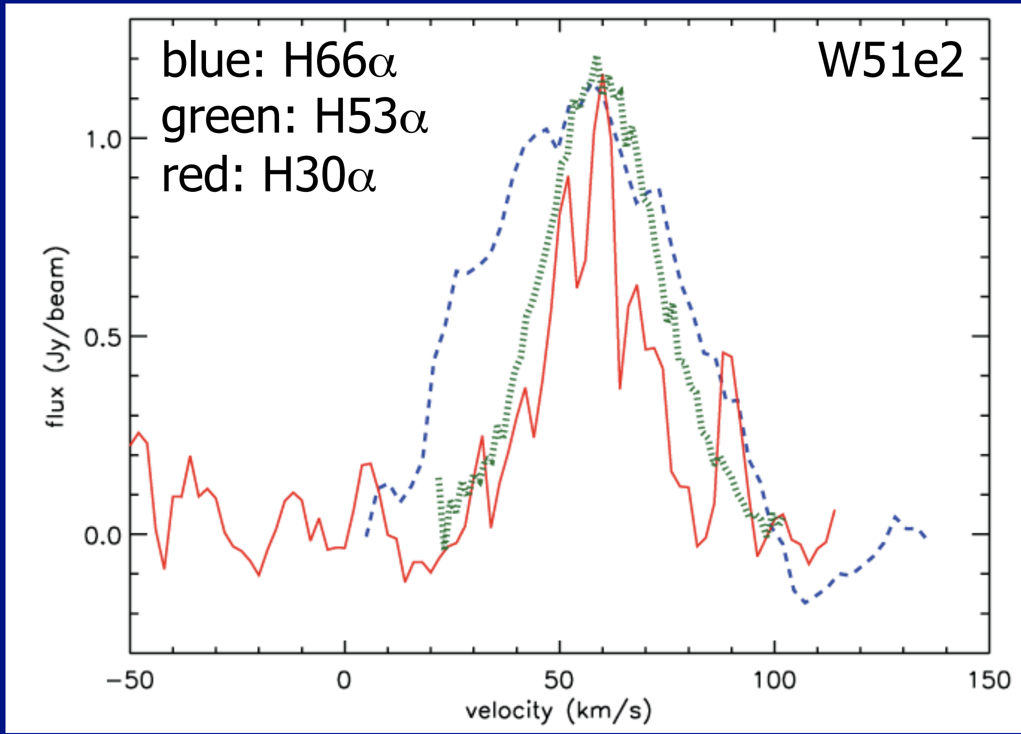
$$R_M \equiv R_\infty \left(1 + \frac{m_e}{M}\right)^{-1}$$

→ This implies that the frequencies of the heavier atoms' recombination lines are very close to hydrogen.

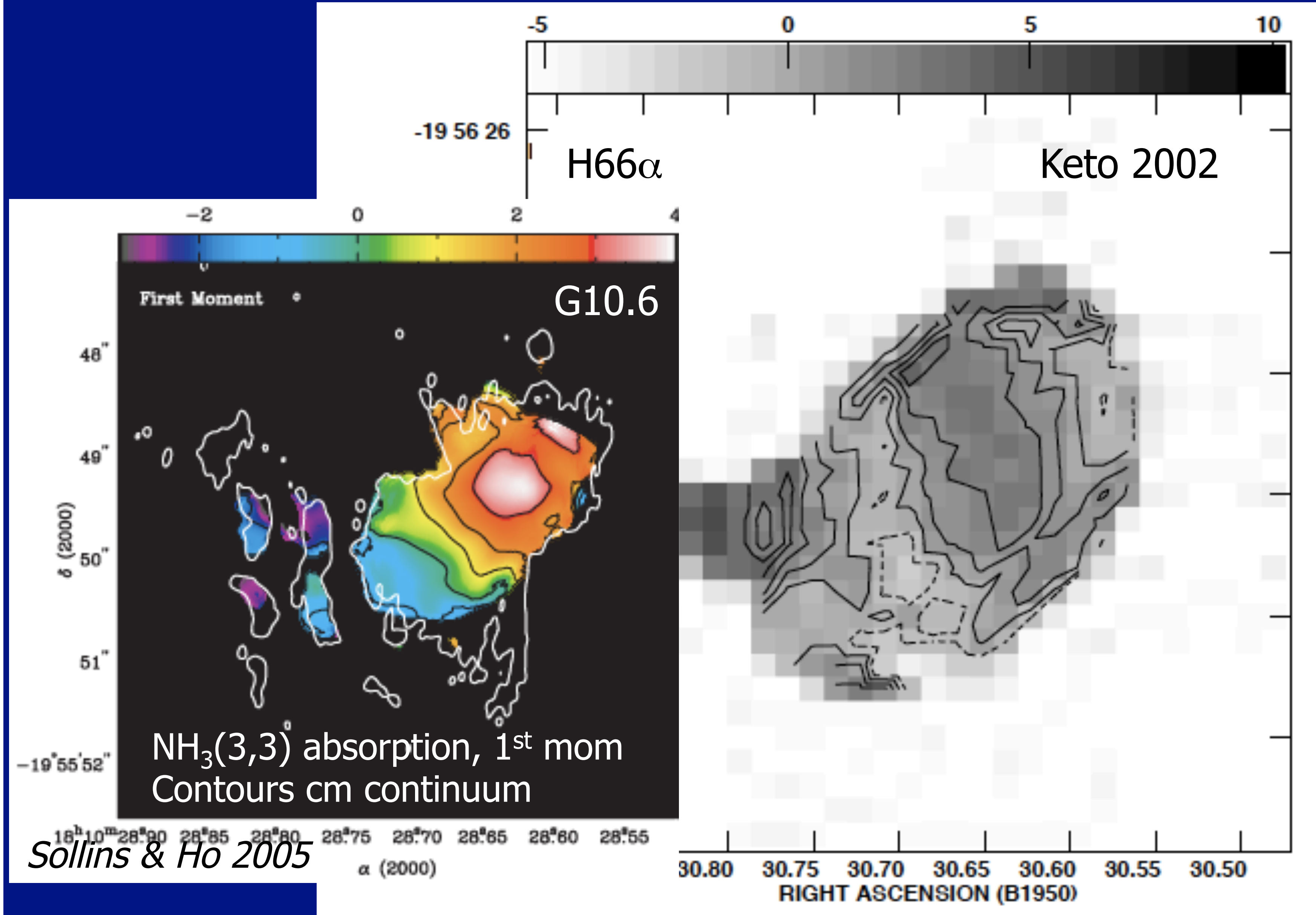
Recombination lines VII

- Line strength, Einstein A: $$A_{n+1,n} \approx \frac{64\pi^6 m_e e^{10}}{3\,c^3 h^6 n^5} \approx 5.3 \times 10^9 \left(\frac{1}{n^5}\right)\,\mathrm{s}^{-1}$$

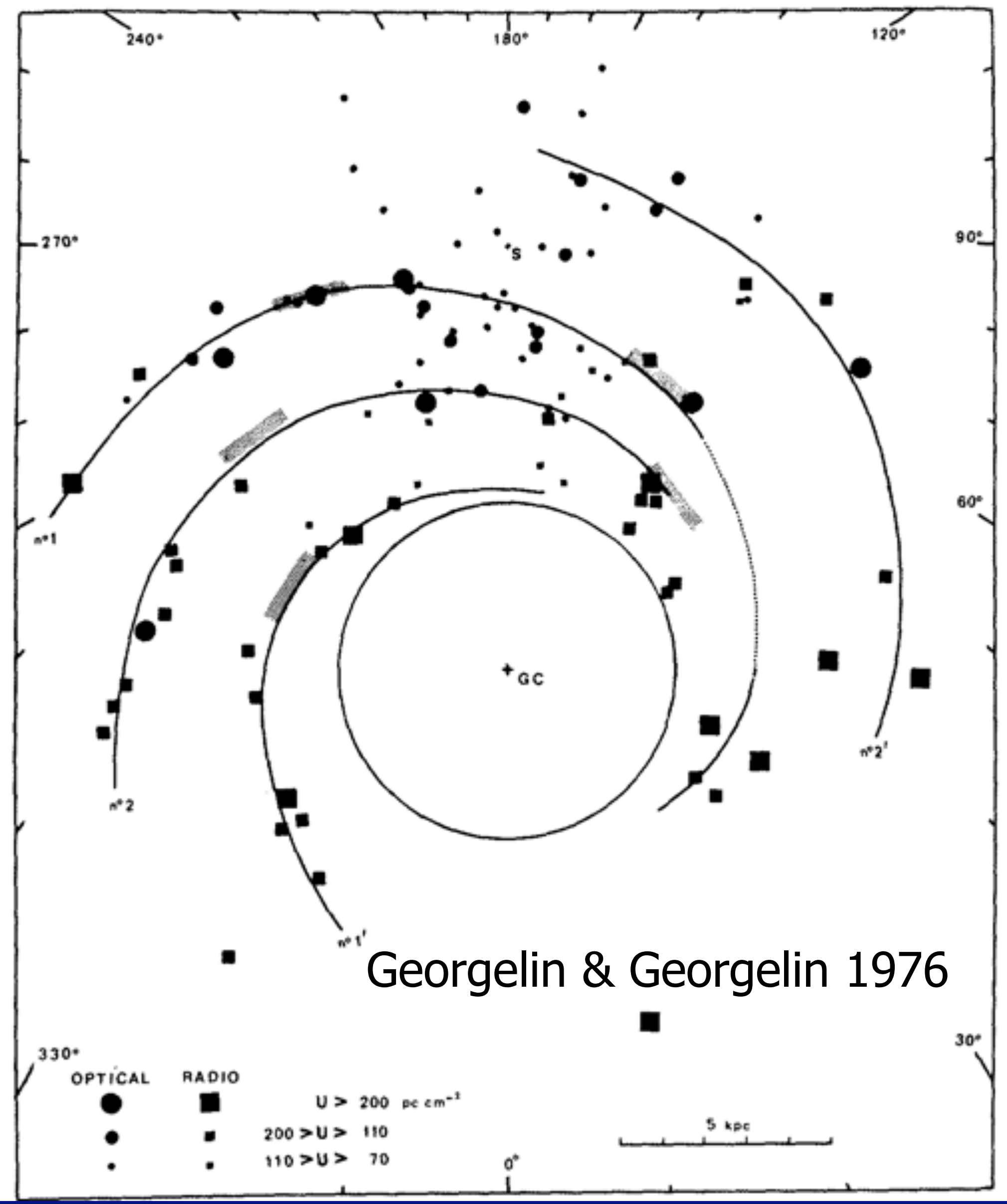
- Line width:
  - Natural: negligable
  - Thermal: Can be estimated from Maxwell distribution at given temperature: For HII region with T~10000K → Δv_{therm}~20km/s
  - Turbulent linewidth can be of similar magnitude
  - Collisional/pressure Stark broadening: Important for large n where interaction between atoms becomes significant.



Velocity pattern in HII regions



Velocity structure of the Milky Way



Georgelin & Georgelin 1976

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