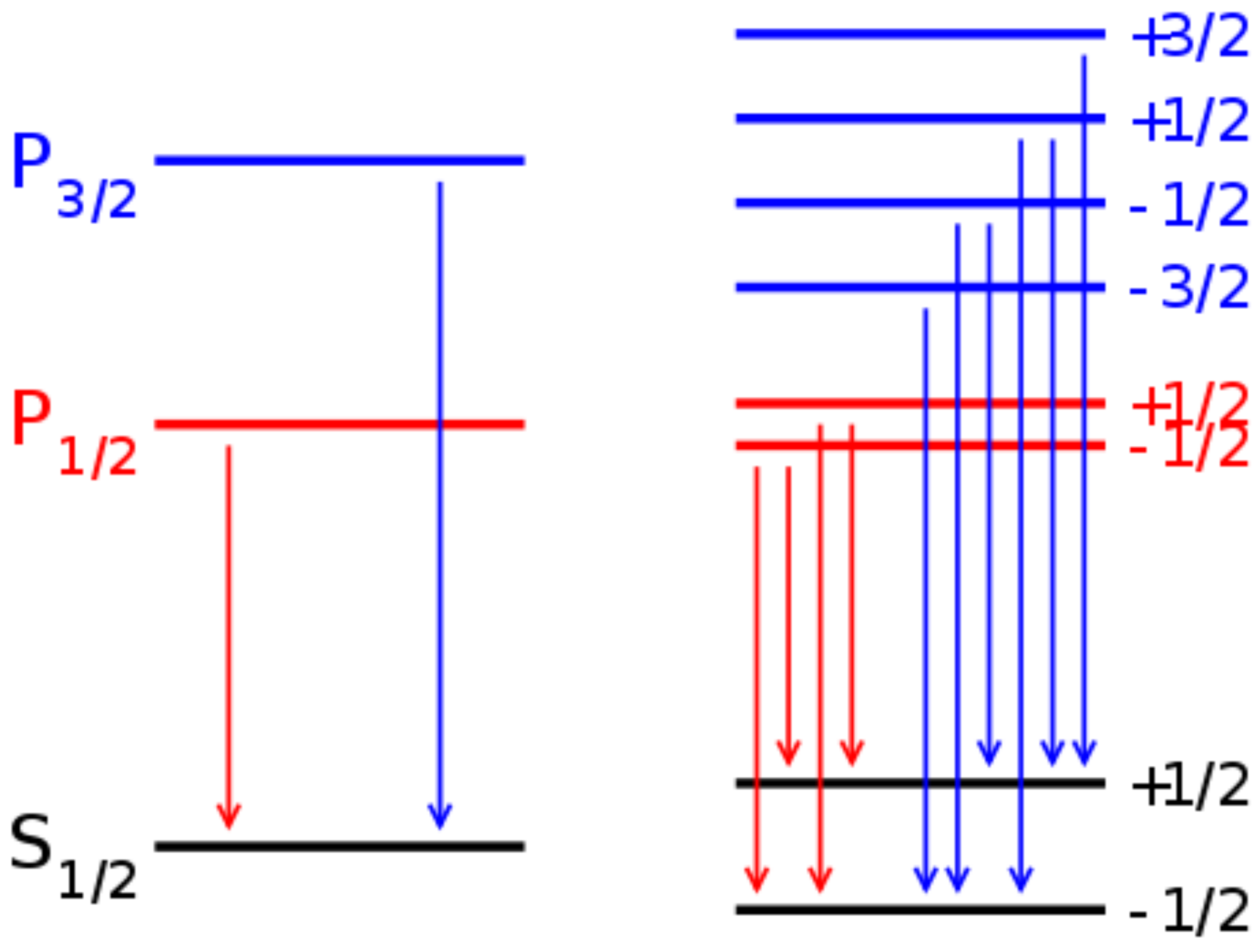
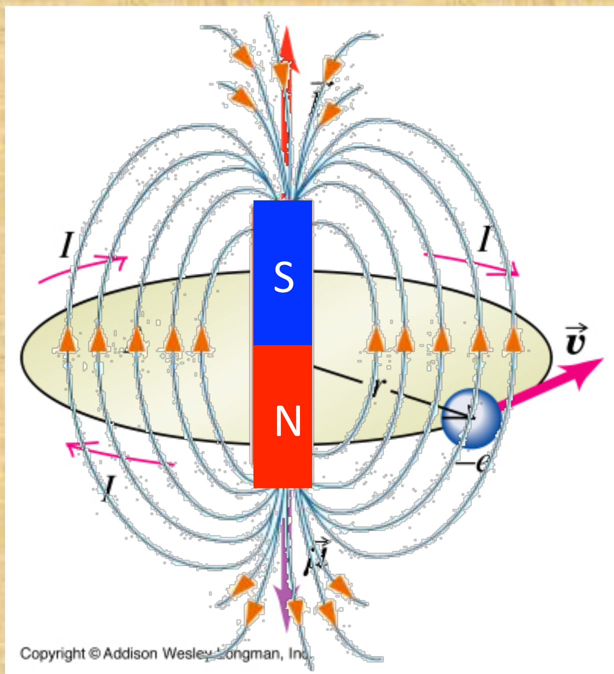
Testing Star Formation theories—Zeeman splitting applied

Zeeman splitting – An Introduction

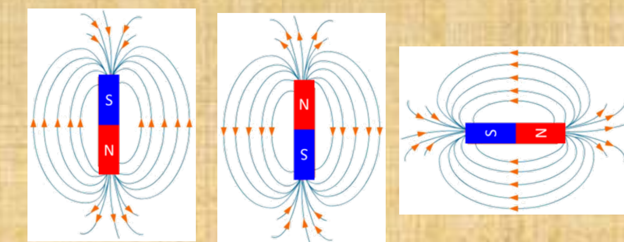


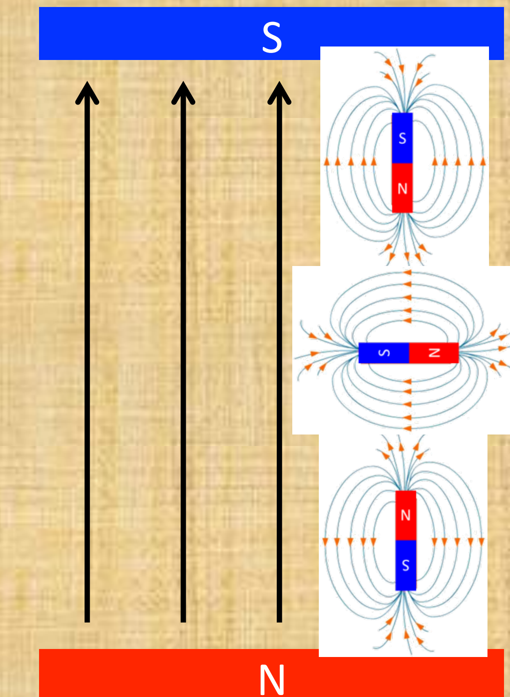
Zeeman What ?

A particle with angular momentum essentially is like a magnet.

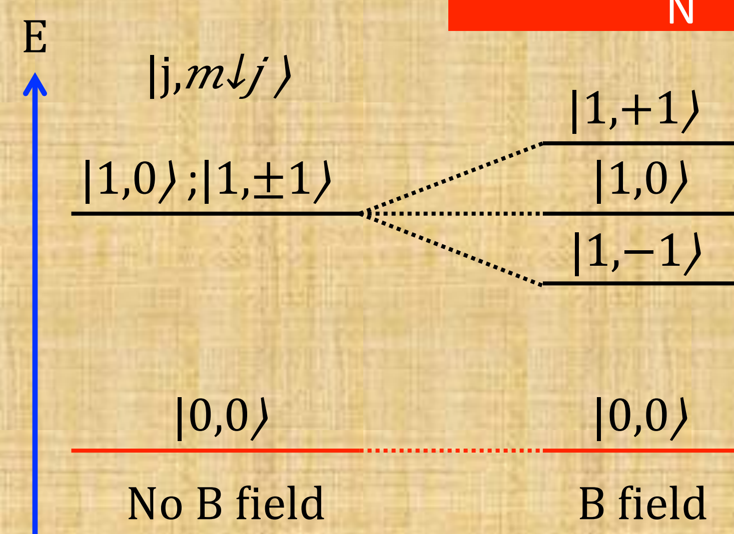


With no external field, any orientation would have same energy.



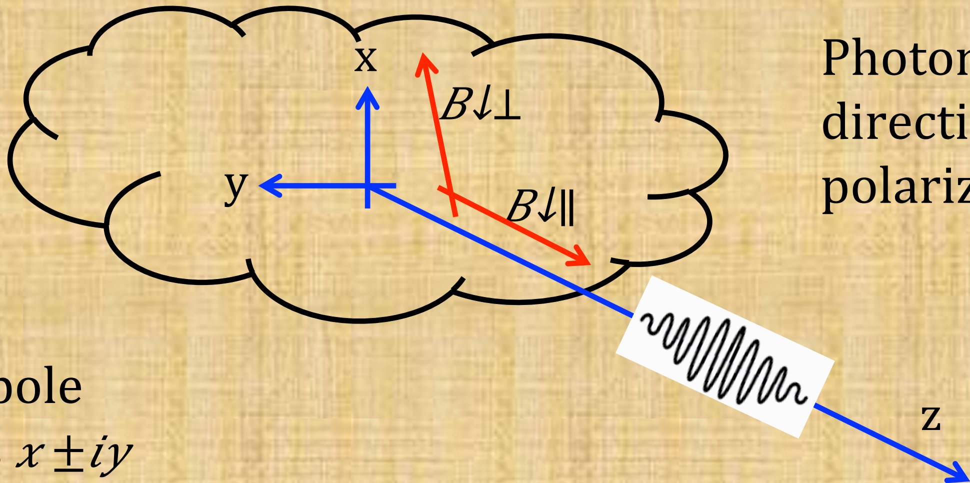


$$\Delta E = -\vec{\mu}\cdot\vec{B} = \frac{g\mu_B}{\hbar}\vec{J}\cdot\vec{B}$$
$$\approx 1.4\cdot g\cdot m_j\,[\mathrm{Hz}/\mu\mathrm{G}]$$



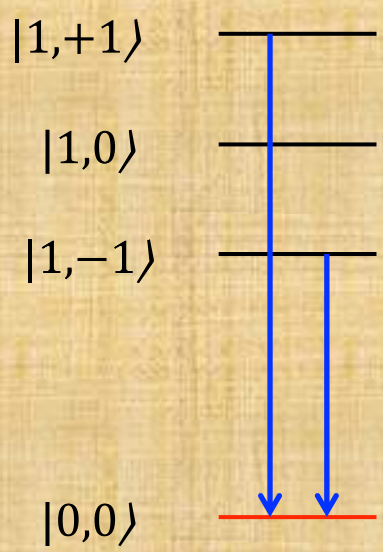
g: Landé g-factor

Zeeman Splitting—How it works???

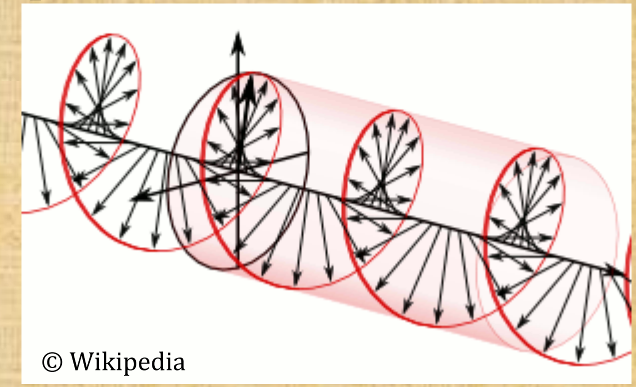


Photon propagating in the z direction can only have polarization in the x-y plane.

Electric dipole transitions $x \pm iy$



Photons will be circularly polarized for this case.

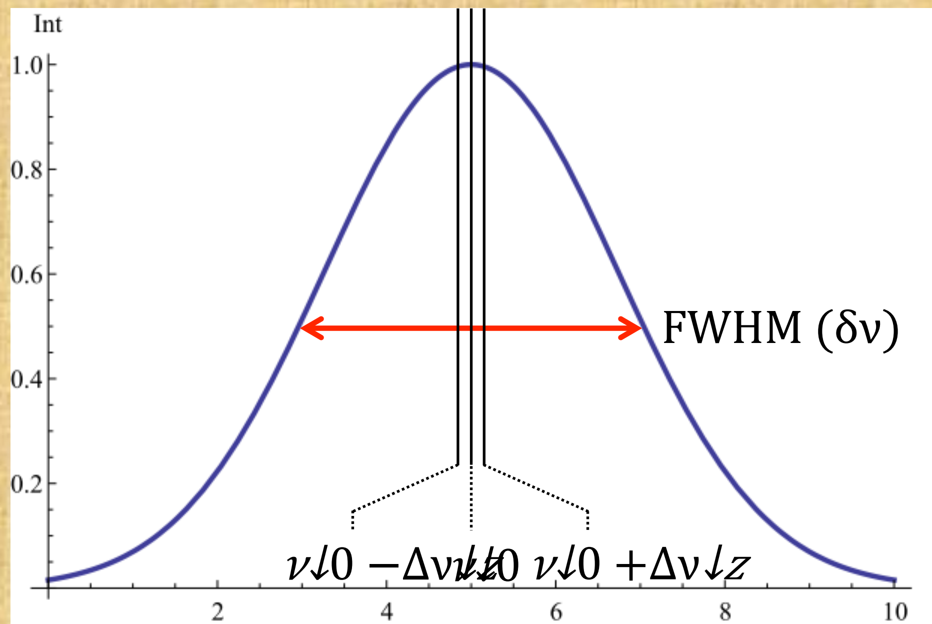


→ We can measure the Stokes' V spectrum

http://www.tcd.ie/Physics/people/Peter.Gallagher/lectures/js_atomic/JS_atomic_lecture12.pdf

Zeeman Splitting—Measurement

1. In the ISM, Zeeman splitting $\Delta\nu_Z$ is typically much smaller than line broadening $\delta\nu$

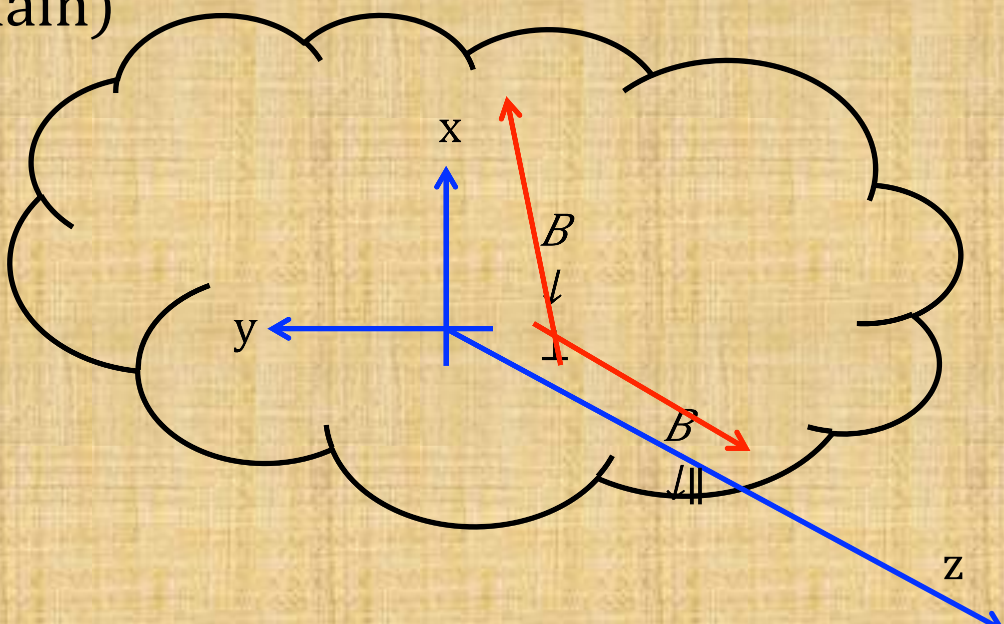


For better detectability, we need to choose molecules with larger splitting $\Delta\nu_Z$ at lower central frequency ν_0 (since $\delta\nu$ is proportional to ν_0).

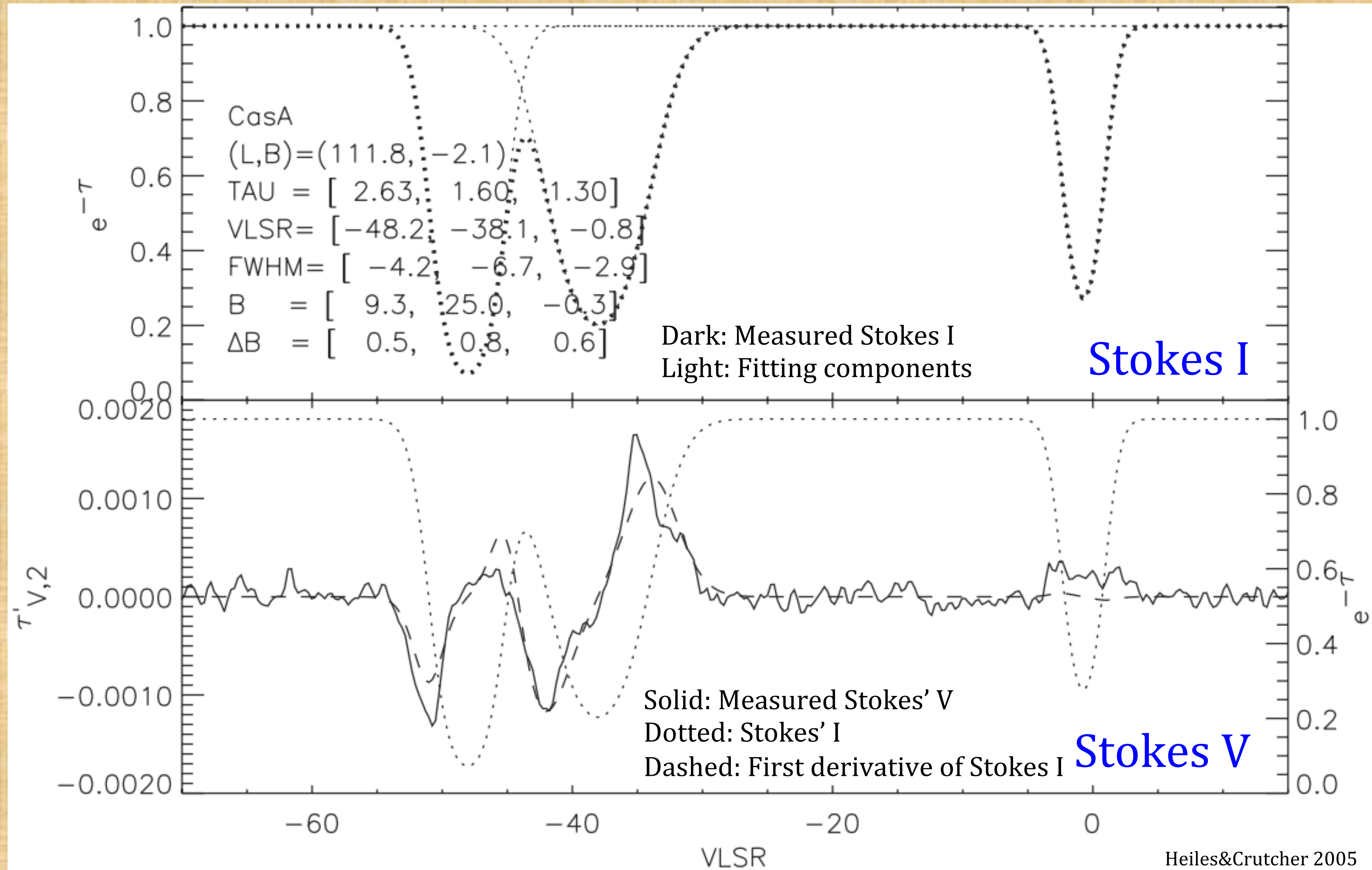
Examples : $\nu_0 < 11.2 GHz$ – OH, CH, C_4H, C_2S

Zeeman Splitting—Measurement

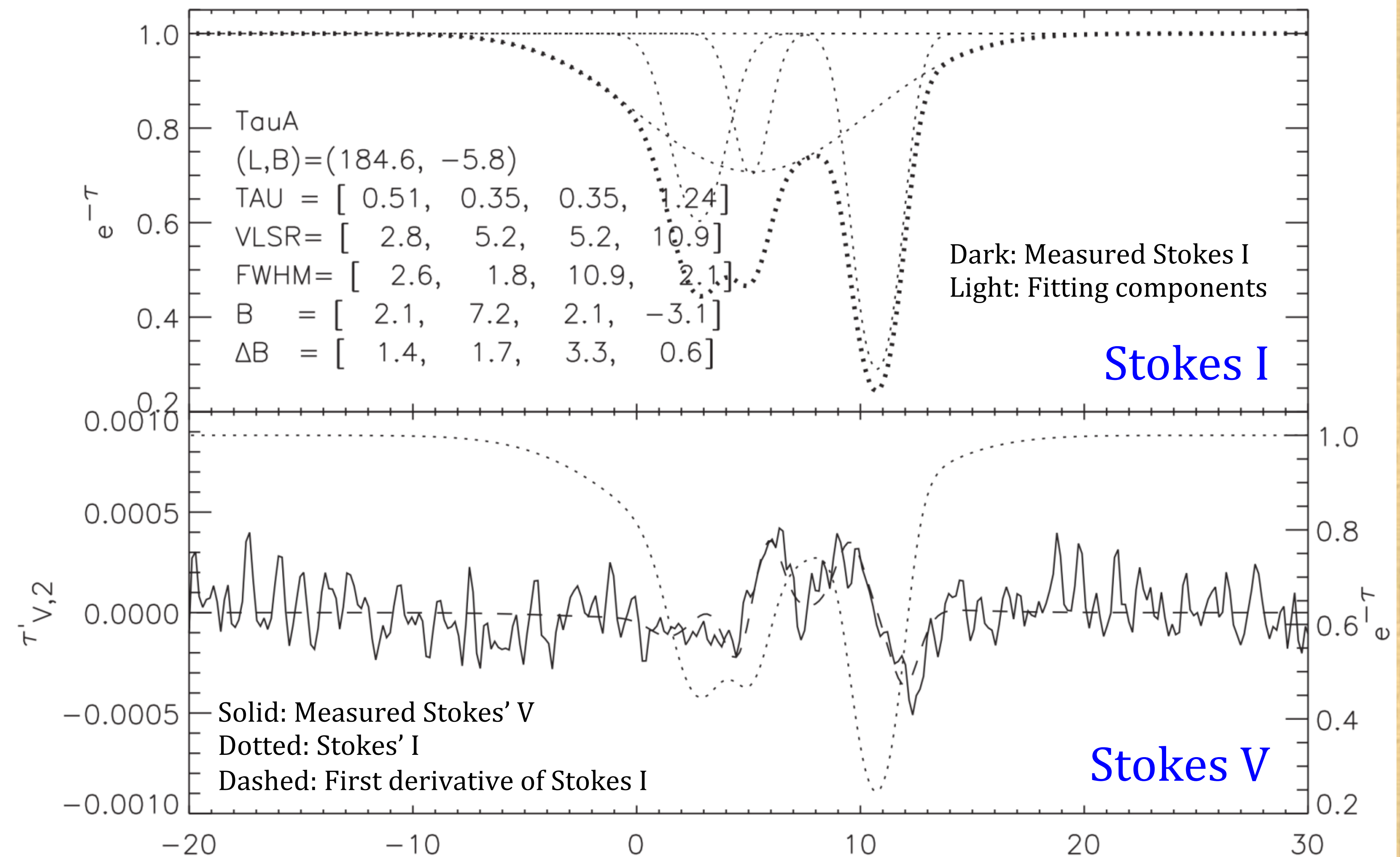
2. Typically we can measure $B\downarrow\parallel$ by using Stokes' V parameter which is related to the first derivative of Stokes' I. (Technical details omitted as it will probably take half an hour to explain)



Zeeman Splitting – CasA



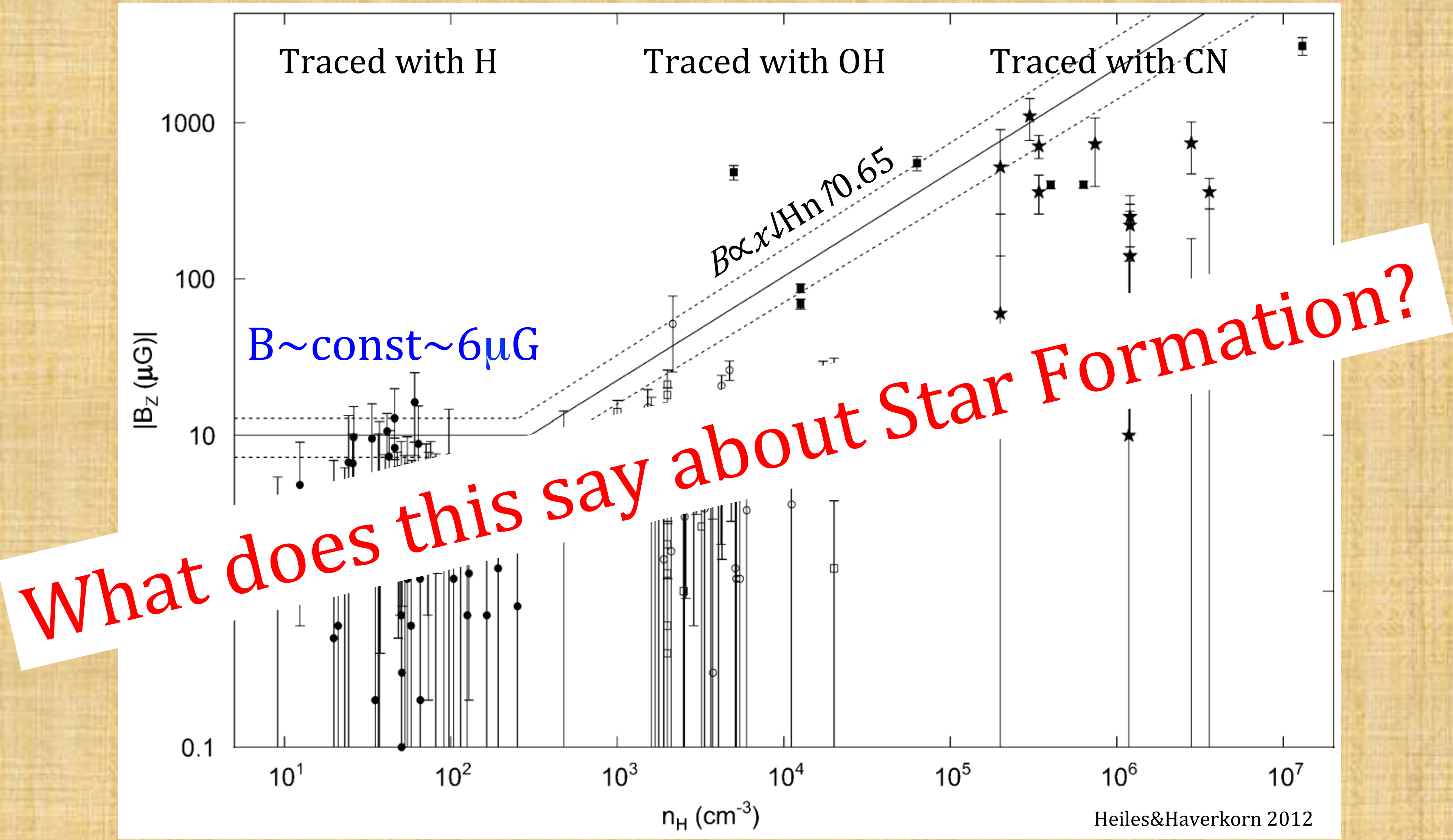
Zeeman Splitting – TauA



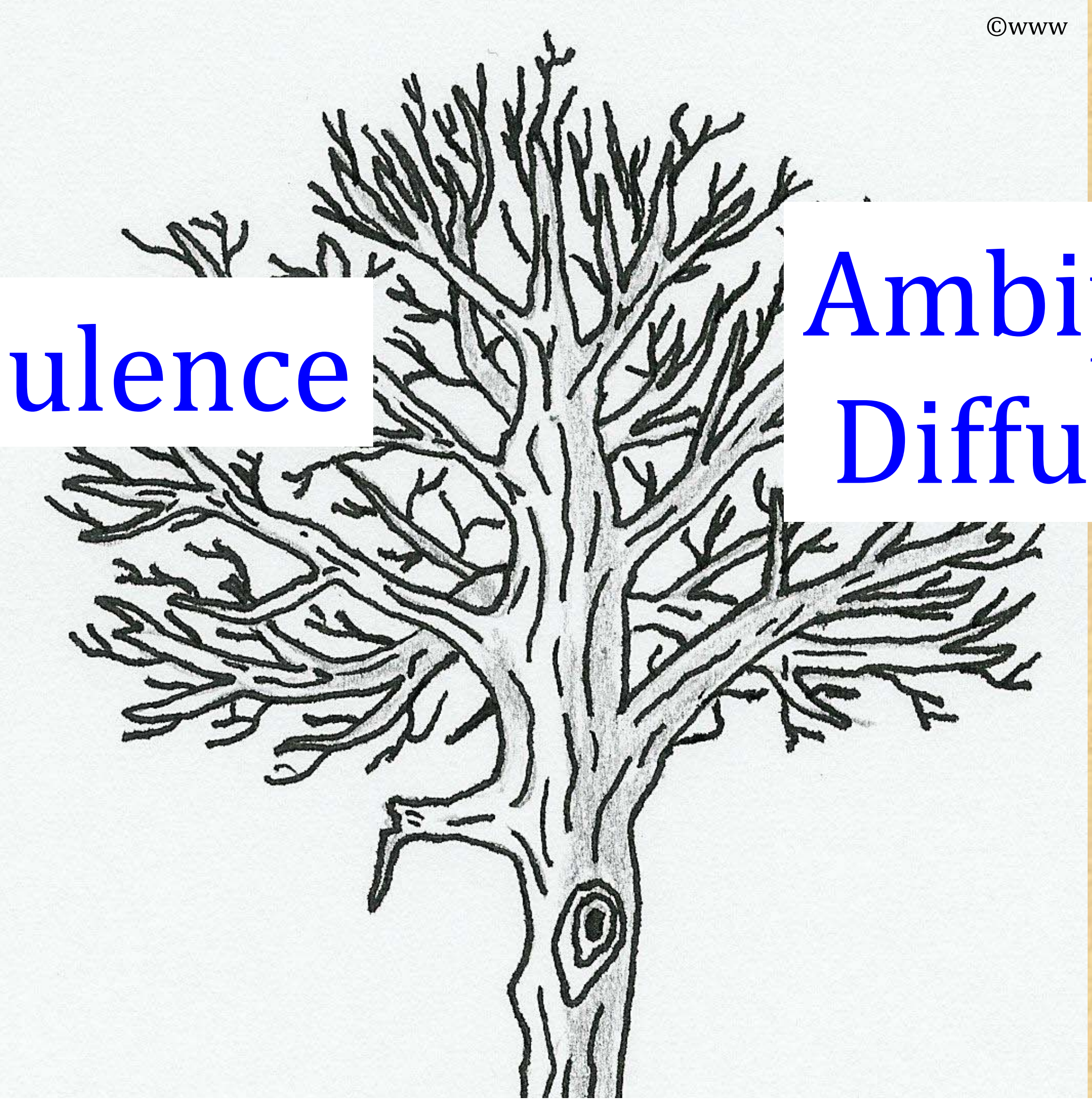
Heiles&Crutcher 2005

Stack it up!

Applying the method to different clouds, a pattern emerges…



Heiles&Haverkorn 2012

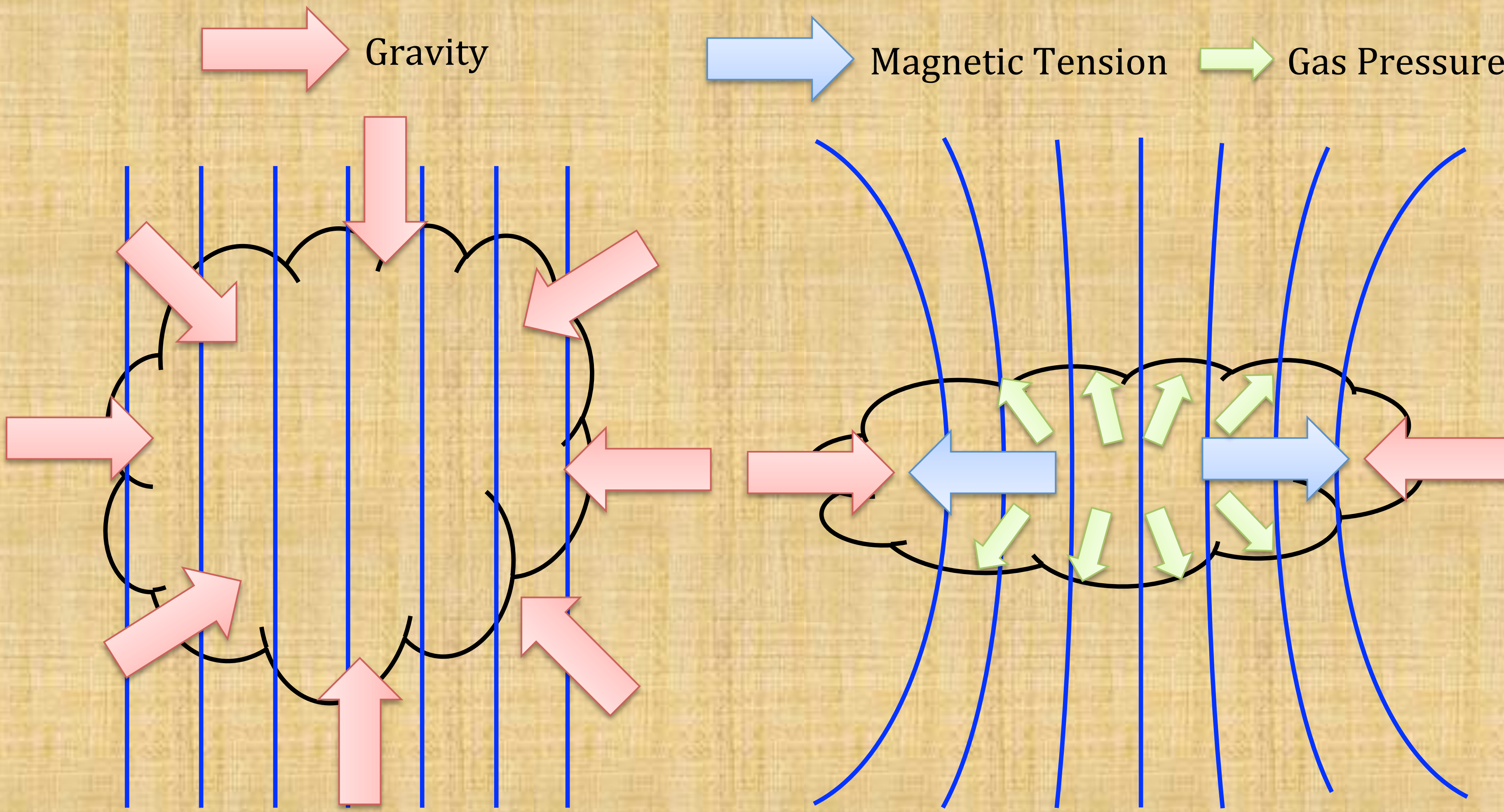


Turbulence

Ambipolar Diffusion

Star Formation Theories

Star Formation—Ambipolar Diffusion

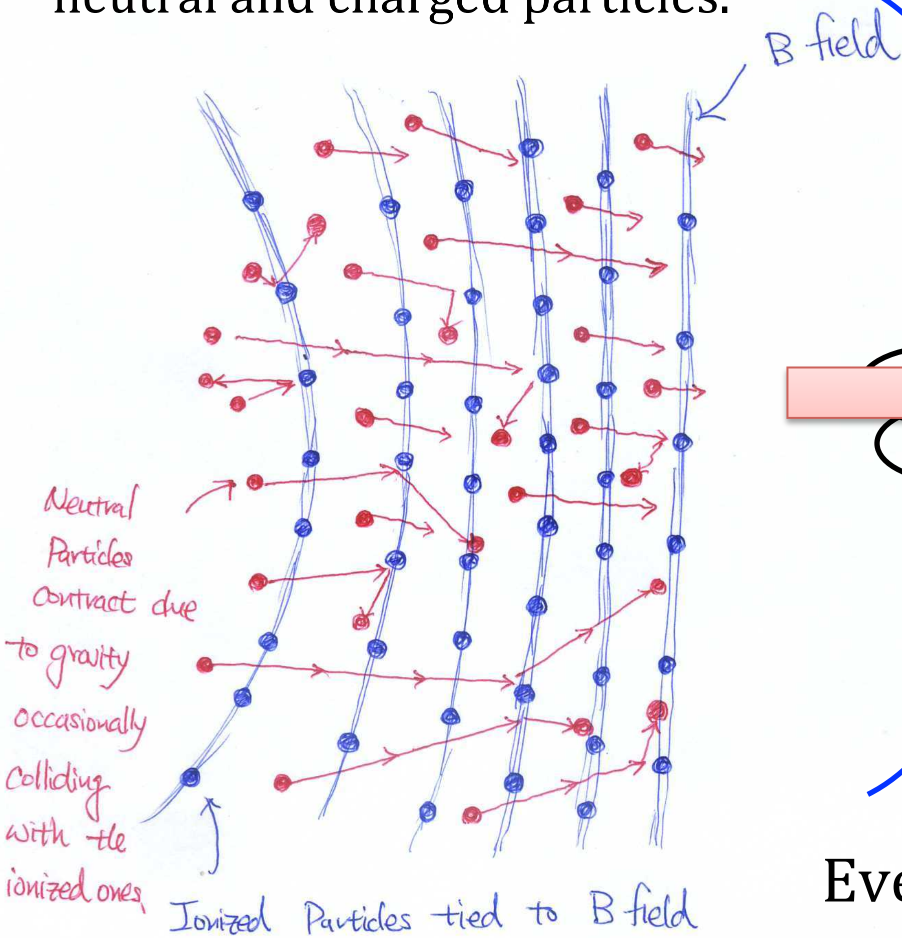


A spherical cloud compressed by gravity

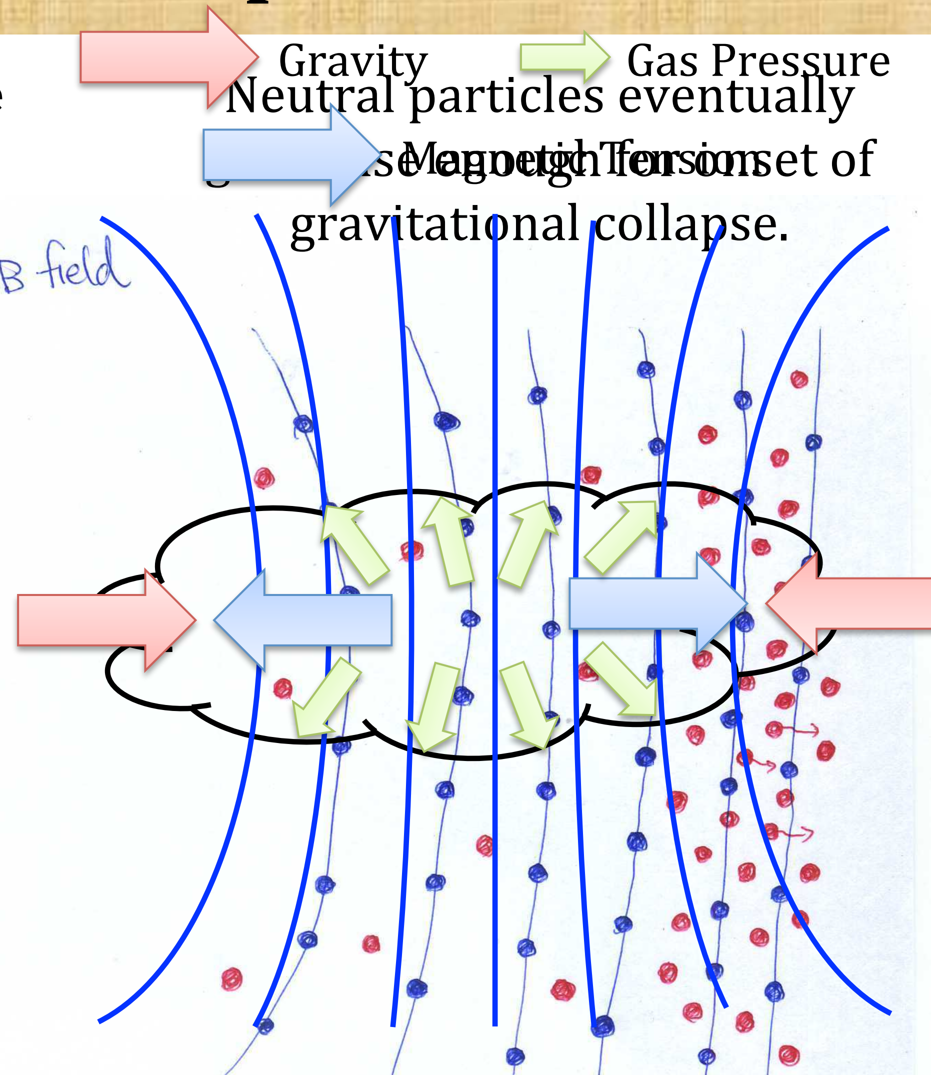
Eventually forms a magnetically supported hourglass shape

Star Formation—Ambipolar Diffusion

Within the hourglass shape, there is relative motion between the neutral and charged particles.



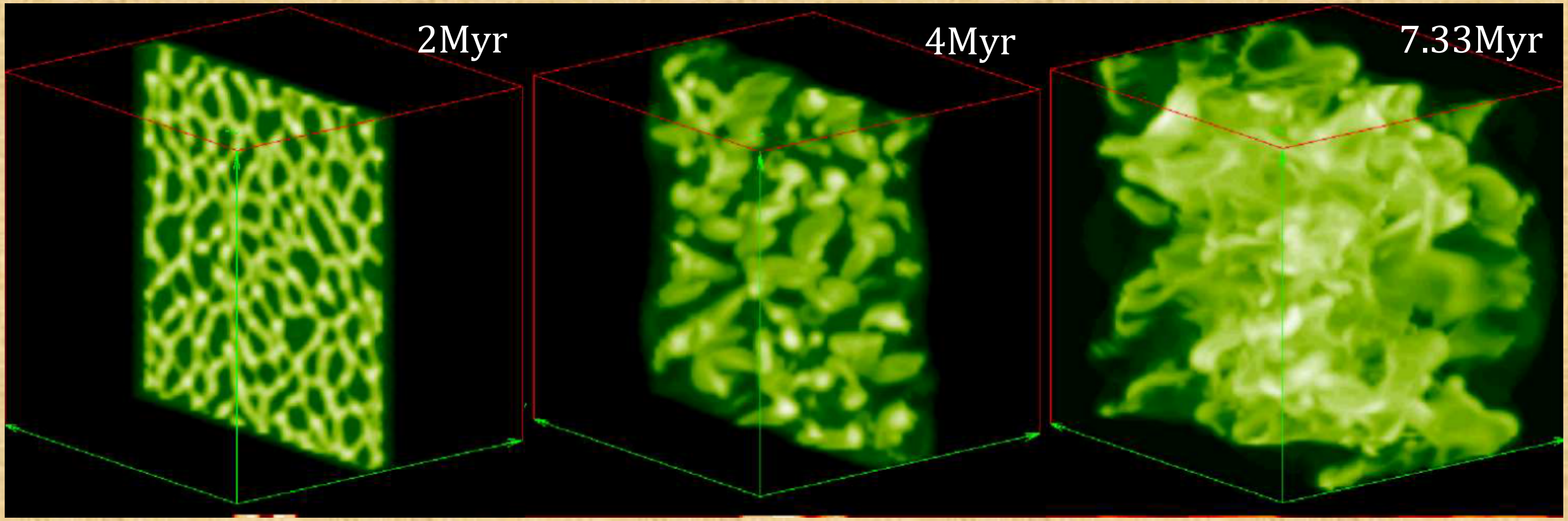
Neutral particles eventually [illegible]se enough for onset of gravitational collapse.



Eventually forms a magnetically supported hourglass shape

Star Formation—Turbulence

Scattered turbulent compression events (e.g. SN driven) might at some point have different streams converge and form dense Molecular Clouds that collapse.

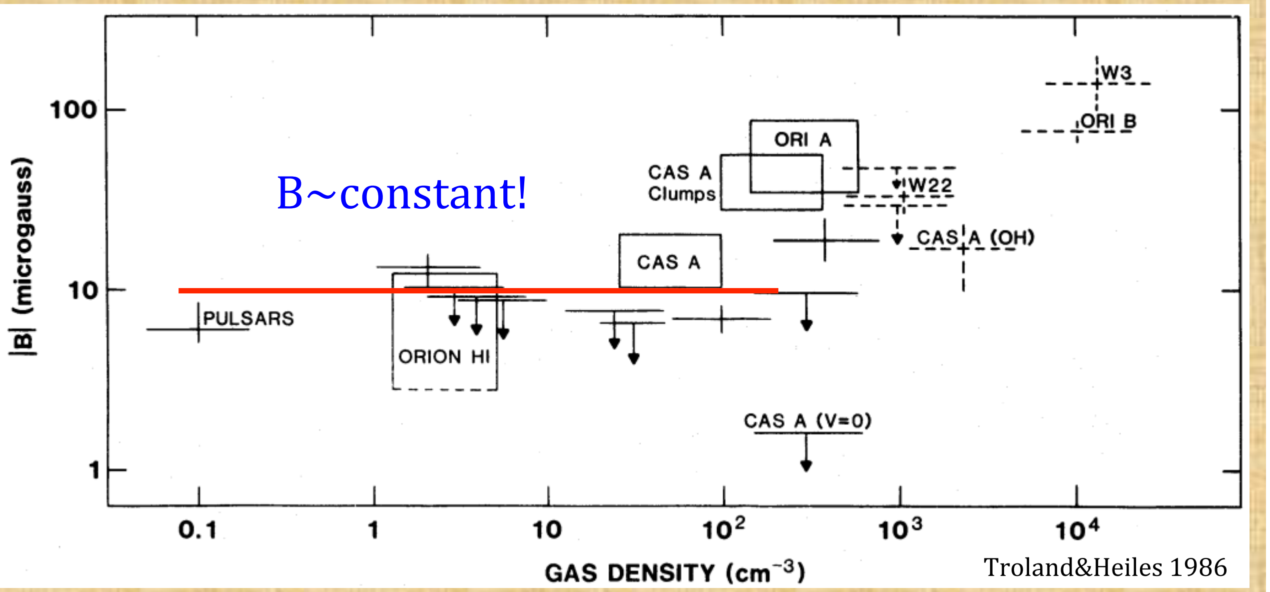


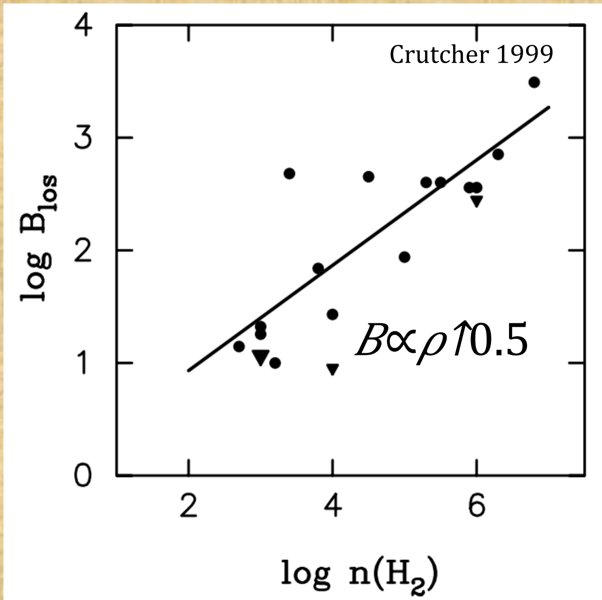
Projections of the density field in a simulation of MC formation by the collision of convergent streams, each at a Mach number M = 2.4.

The panels illustrate how the collision first forms a thin sheet that then fragments, becomes turbulent, and thickens, until it becomes a fully three-dimensional cloud.

B-ρ Scaling relation

Model	Condition	Scaling
Ambipolar Diffusion	Subcritical phase (envelope)	$B\sim const$
Ambipolar Diffusion	Supercritical phase (core)	$B\propto\rho\uparrow 0.5$
Turbulent	Collapsing core with no significant magnetic/kinetic support	$B\propto\rho\uparrow 2/3$

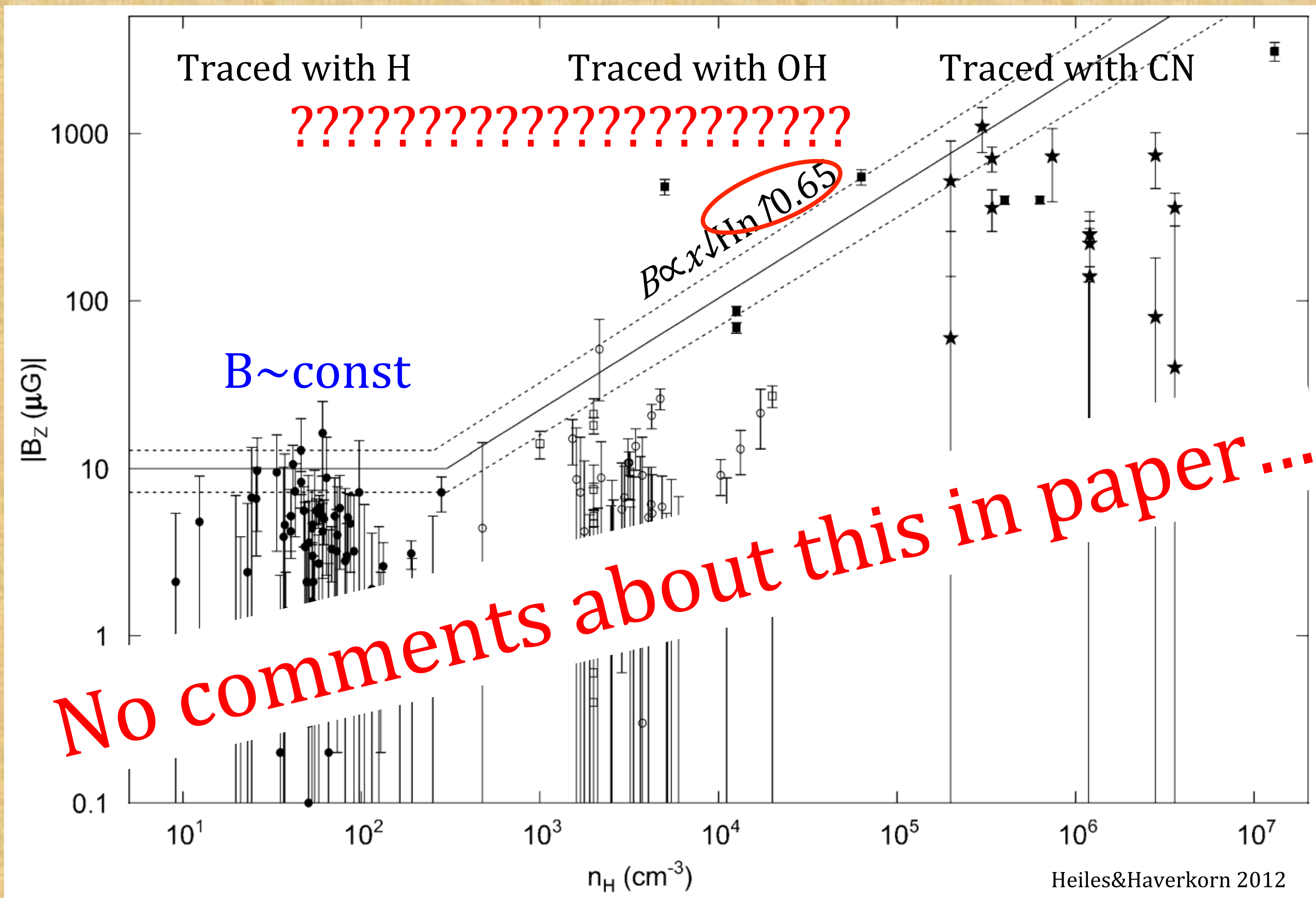




Ambipolar Diffusion Wins???

B-ρ Scaling relation

What happened here!?



Which is dominant in the CNM?

Thermal Energy

Magnetic Energy

Turbulent Energy

	Quantities	Energy density
Thermal	T=50K	nkT
Turbulent	$\Delta v_{turb} = 1.2 km/s$	$\rho \Delta v_{turb}^2$
Magnetic	$B_{tot} = 6\,\mu G$	$B^2/8\pi$

Thermal

≈ 0.29

Magnetic Energy

Turbulent

≈ 1.3

Magnetic Energy

Close to Equipartition!

Equipartition… is it expected?

Ambipolar Diffusion：

Ambipolar diffusion is a model with slow steady evolution (until collapse) therefore the forces are in near static equilibrium.

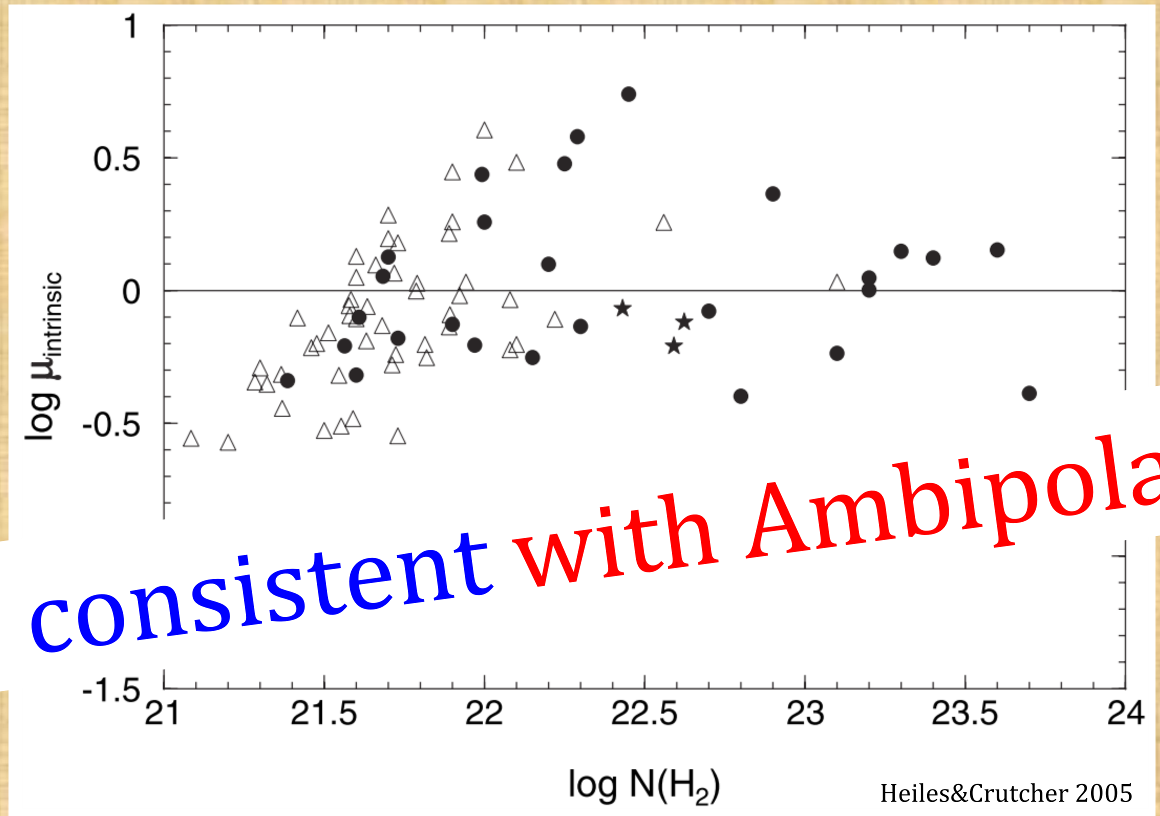
Turbulent：

Since CNM are regions of converging turbulent flows, with magnetic fields being the main halting mechanism, it is natural that magnetic and turbulent energy densities are in Equipartition…

Both theories can explain the result!

Mass to Flux (M/Φ) ratio

Senario	Predictions
Ambipolar Diffusion	M/Φ should gradually increase from <1 to ≳1
Turbulence	*Seems to be very model dependent?? (I have no idea…)*



Seems consistent with Ambipolar Idea

Turning tides ?

In 2009... it was found that for 4 regions, the M/Φ seems to be higher for the envelope!

Relative Mass/Flux — Crutcher 2009

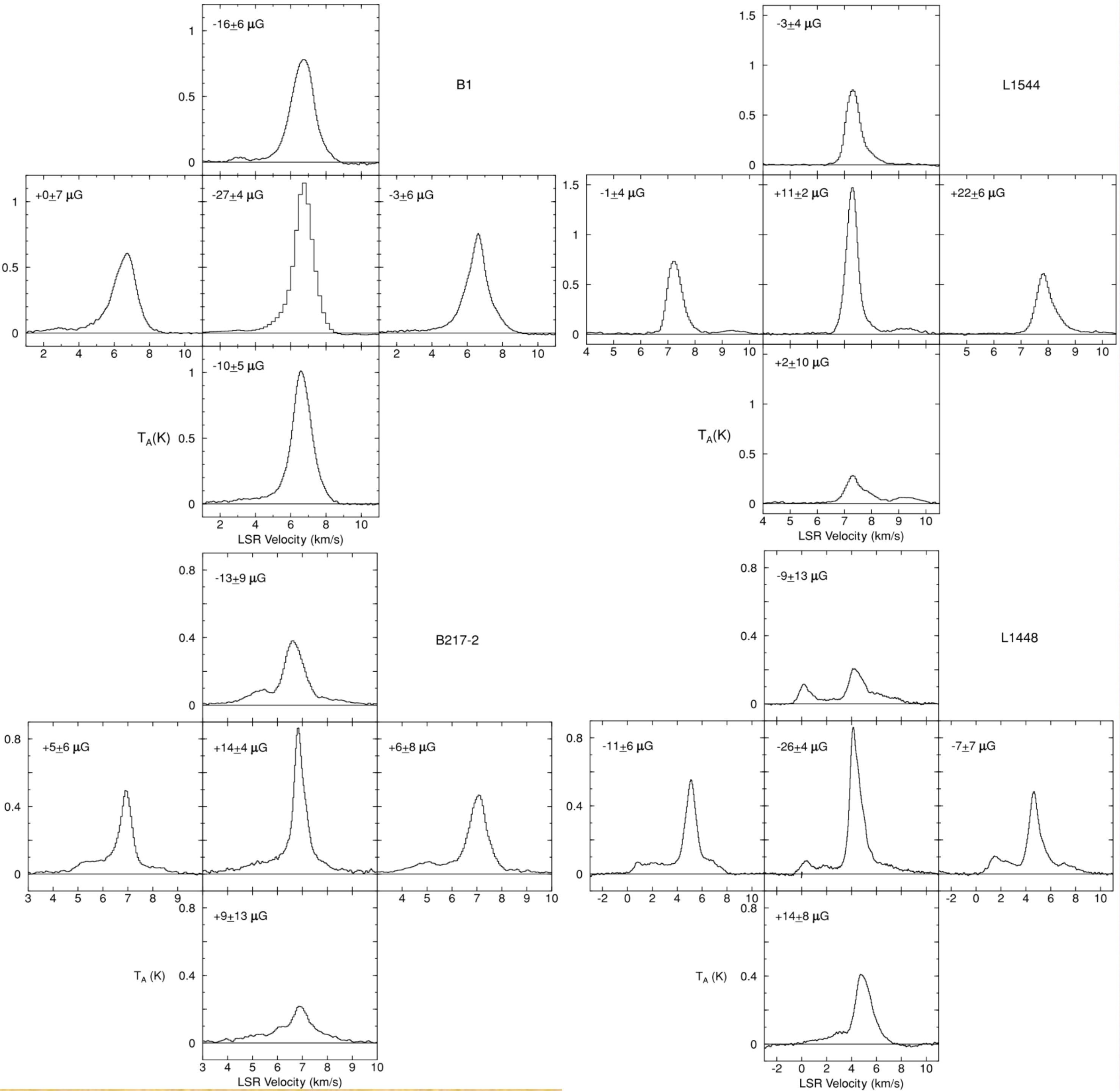
Cloud	$\mathcal{R}$	$\mathcal{R}'$	Probability $\mathcal{R}$ or $\mathcal{R}' > 1$
L1448CO	0.02 ± 0.36	0.07 ± 0.34	0.005
B217-2	0.15 ± 0.43	0.19 ± 0.41	0.05
L1544	0.42 ± 0.46	0.46 ± 0.43	0.11
B1	0.41 ± 0.20	0.44 ± 0.19	0.010

$$\mathcal{R} \equiv \frac{M_{\rm core}/\Phi_{\rm core}}{M_{\rm envelope}/\Phi_{\rm envelope}}$$

$$\mathcal{R}' \equiv \frac{M_{\rm core}/\Phi_{\rm core}}{M_{\rm core+envelope}/\Phi_{\rm core+envelope}}$$

Model	Core	Reference	Prediction
Ambipolar	L1544	Ciolek&Basu 2000	R'~1.25
Ambipolar	B1	Crutcher+ 1994	R'~2.4
Turbulent	general	Lunttila+ 20	

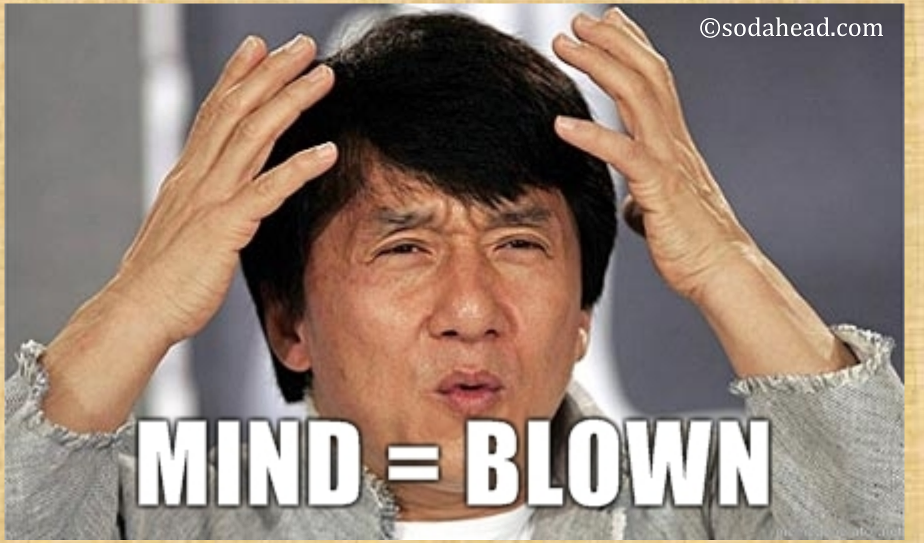
Seems inconsistent with Ambipolar Idea


B1
-16±6 μG
+0±7 μG
-27±4 μG
-3±6 μG
-10±5 μG
T_A(K)
LSR Velocity (km/s)
L1544
-3±4 μG
-1±4 μG
+11±2 μG
+22±6 μG
+2±10 μG
T_A(K)
LSR Velocity (km/s)
B217-2
-13±9 μG
+5±6 μG
+14±4 μG
+6±8 μG
+9±13 μG
T_A (K)
LSR Velocity (km/s)
L1448
-9±13 μG
-11±6 μG
-26±4 μG
-7±7 μG
+14±8 μG
T_A (K)
LSR Velocity (km/s)

que será, será

"The observational interpretation and conclusions of Crutcher+ 2010b are sharply criticized by Mouschovias and Tassis (2009), and a rather severe controversy has erupted; the situation is not yet resolved Crutcher+ 2010a."

"Perhaps some clouds form and evolve via turbulence and some via the quasi-equilibrium models, as implied by the discussion of Crutcher et al. (2010b)."



"As they say, "que será, será". "

So much for SF theories…

And they fxxin' formed… And no one knows why…

Astrophysical Masers

Masers often occur in PDRs around massive stars and can be used as tracers for regions of density ~ $10^{6}-10$ ☒ cm^{-3}

Along with Zeeman splitting, they can reveal the magnetic field in regions of high density.

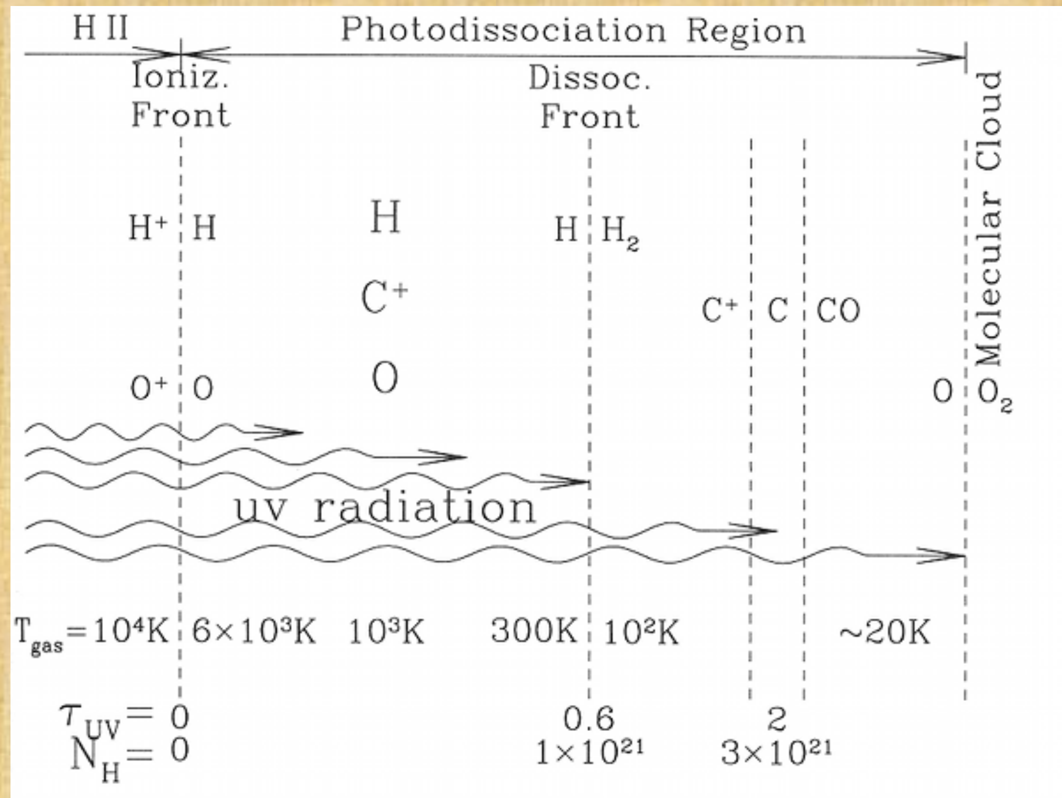


Figure 31.2 Structure of a PDR at the interface between an H II region and a dense molecular cloud. Physics of the interstellar and intergalactic medium, Draine 2011

species	Ref	$n(cm^{-3})$	B (mG)
OH	Fish+ 2003	10^{7}	0.1~10
H/2			

Why?

*Line width shows temperature way below the brightness temperature.

*Polarization is exceedingly high.

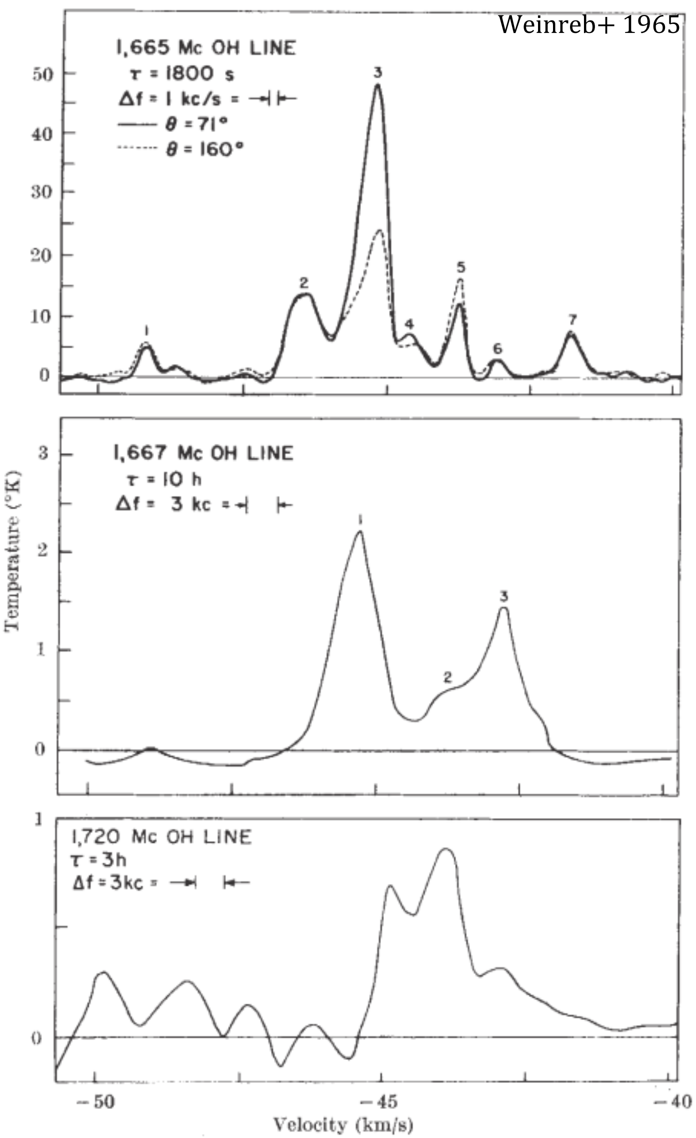


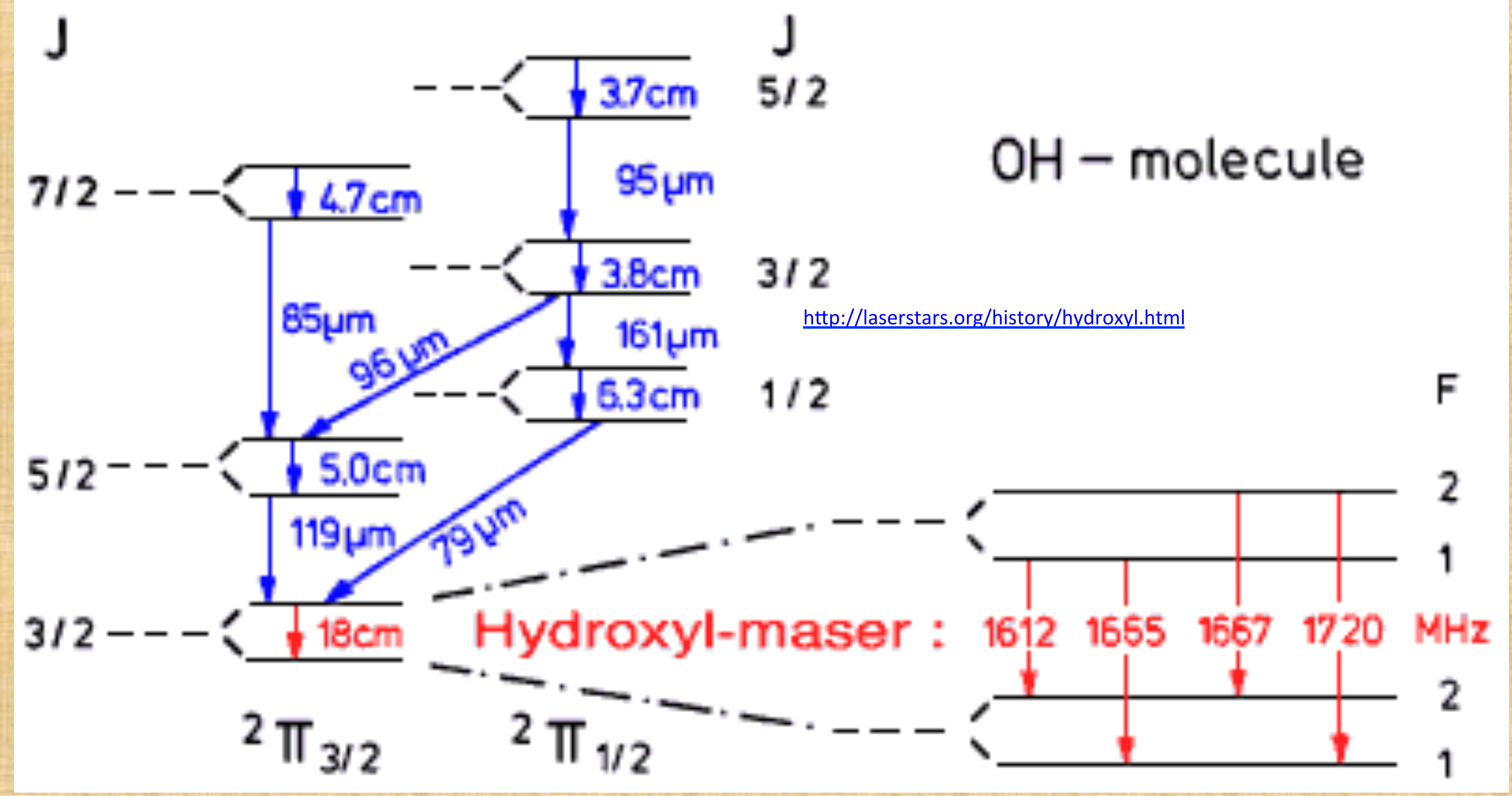
Fig. 1. Examples of OH-line spectra at 1,665, 1,667 and 1,720 Mc/s. The antenna temperatures are shown as a function of velocity relative to the local standard of rest. The data presented in Table 1 are, in some cases, of longer integration time and higher resolution than the examples presented in this figure

Table 1. SUMMARY OF PRINCIPAL OH SPECTRAL FEATURES

Feature No.	Velocity (OH) (km/s)	Feature width (kc/s)*	Average antenna temp. (°K)	Polarization (per cent)	Position angle	Comments
1,665 Mc/s, 1 kc/s resolution:						
1	−49·1	1·3 ± 0·3	6·1 ± 0·6	30 ± 12	145° ± 10°	
2	−46·5	3·0 ± 0·4	14·3 ± 1·5	2 ± 6		Appears as two or more blended lines
3	−45·2	3·0 ± 0·2	35·4 ± 3·0	37 ± 6	65° ± 4°	Line profile changes with feed position angle
4	−44·5	1·7 ± 0·3	7·0 ± 0·7	22 ± 16	107° ± 22°	Line blended with adjacent lines
5	−43·7	1·6 ± 0·2	14·8 ± 1·5	22 ± 10	140° ± 16°	
6	−43·1	1·2 ± 0·4	3·1 ± 0·3	10 ± 10		
7	−41·7	1·6 ± 0·3	7·2 ± 0·7	16 ± 16		
1,667 Mc/s, 1 kc/s resolution:						
1	−45·5	3·0 ± 0·5	2·2 ± 0·3	10 ± 10		
2	−43·8	1·2 ± 0·5	1·3 ± 0·3			
3	−43·0	1·6 ± 0·5	1·7 ± 0·3			
1,720 Mc/s, 3 kc/s resolution:						
	~ −44		0·85 ± 0·3			Spectrum not resolved due to poor signal-to-noise ratio

How?

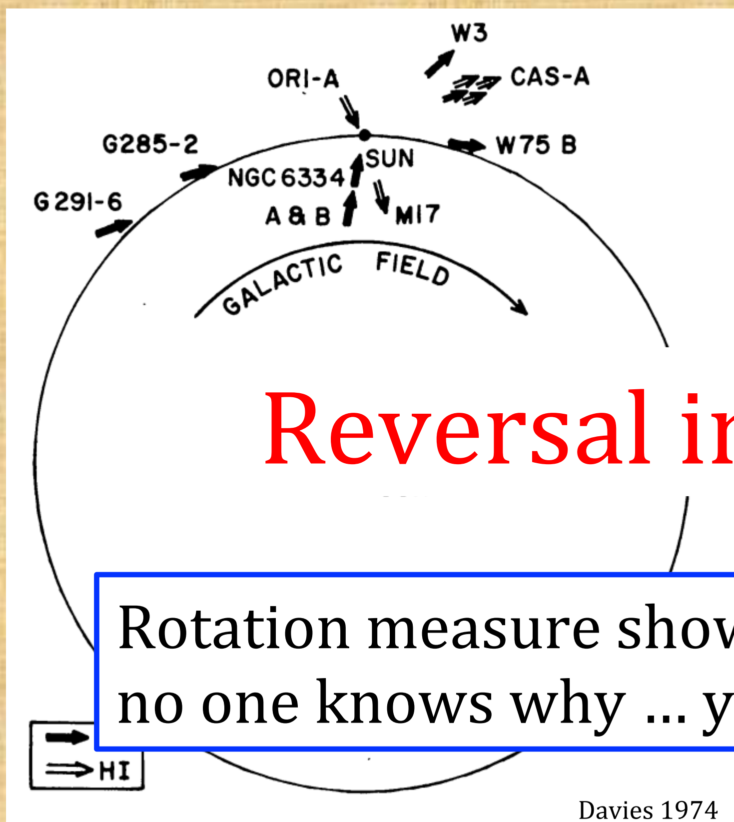
Pump, cascade, and population inversion.



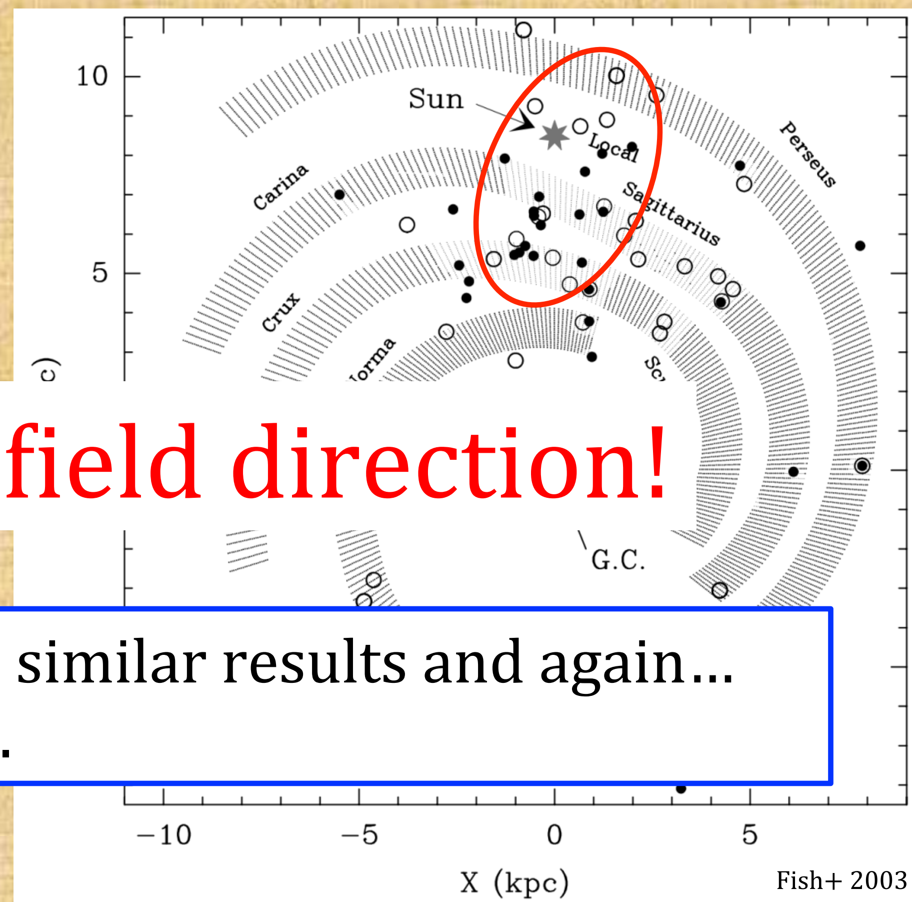
http://laserstars.org/history/hydroxyl.html

OH Masers – Probing the galactic field

Assuming that SFRs somehow preserve their initial field directions, then we can use these star forming regions to probe the galactic magnetic field structure



Davies 1974



Fish+ 2003

Reversal in field direction!

Rotation measure shows similar results and again… no one knows why … yet.

For more details about B fields in galaxies http://arxiv.org/ftp/arxiv/papers/1302/1302.5663.pdf

References

Carl Heiles&Marijke Haverkorn, SSRv, 166, 293 (2012)
(Assigned paper, contains very little details about Zeeman splitting)

Heiles&Crutcher, LNP, 664, 137 (2005)
(A detailed review on different Zeeman detection methods, history and tests on SF theories)

Heiles, C., Goodman, A. A., McKee, C. F., & Zweibel, E. G., Protostars and planets III, p. 279-326
(lots of fundamentals about the Zeeman detection part and choice of molecules)

Crutcher, R. M., Troland, T. H., Goodman, A. A., Heiles, C., Kazes, I., & Myers, P. C., ApJ, 407, 175 (1993) (details about relation between Stokes' I, Q, U, V)

Mordecai-Mark Mac Low & Ralf S. Klessen, Rev. Mod. Phys., 76, 125 (2004)
(detailed review about turbulence formation theory)

Lecture notes on Star Formation in General Astronomy course given by Mouschovias, T. C.

Troland, T. H., Heiles, C, ApJ, 301, 339 (1986) (B-n figure)
Crutcher, R. M., ApJ, 520, 706 (1999) (B-n figure)

Davies, R. D., IAUS, 60, 275 (1974) (A very nice detailed paper about OH maser line and Zeeman)
Fish et al., ApJ, 596, 328 (2003) (more recent analysis of galactic magnetic field using OH masers)

And…. Lots of Wikipedia…