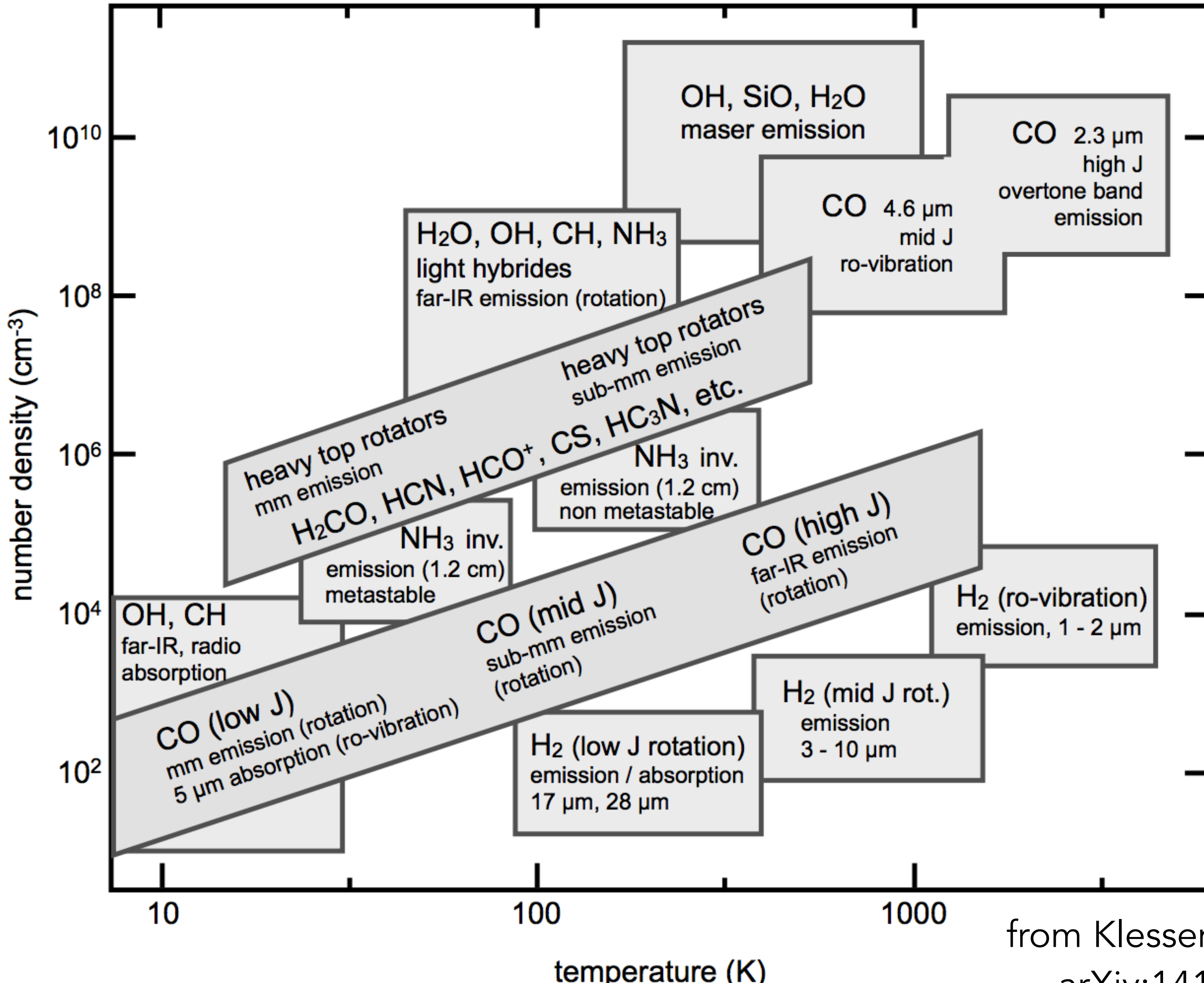
Physics 224
The Interstellar Medium

Lecture #17

Summary of Molecular Tracers of H_2



from Klessen & Glover
arXiv:1412.5182

Magnetic Fields in the ISM

Observational Tracers:

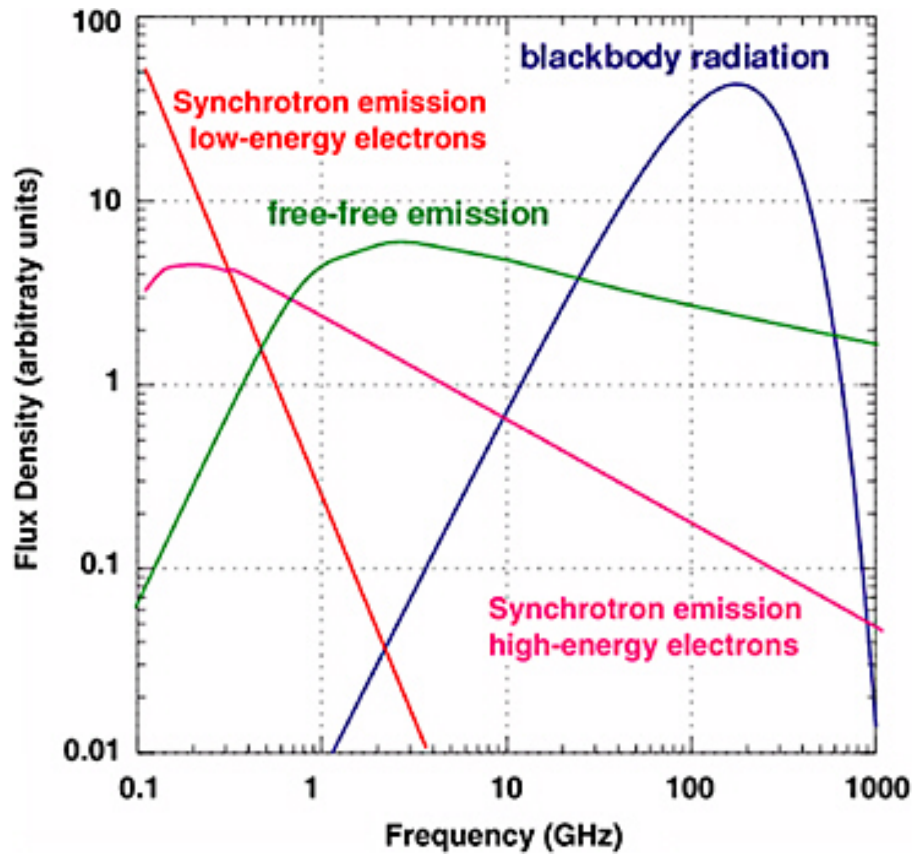
- Synchrotron emission
- Faraday Rotation
- Starlight & Dust Thermal Emission Polarization
- Zeeman splitting

Synchrotron Emission

Radiation produced by relativistic charged particles spiraling around magnetic field lines.

Luminosity depends on energy density of B-field (U_B) and of the relativistic electrons (U_e).

"Equipartition" assumption - given synchrotron luminosity results from the minimum $U_e + U_B$



from NAS "Handbook of Frequency Allocations..."

Can use luminosity and polarization to constrain B.

Faraday Rotation

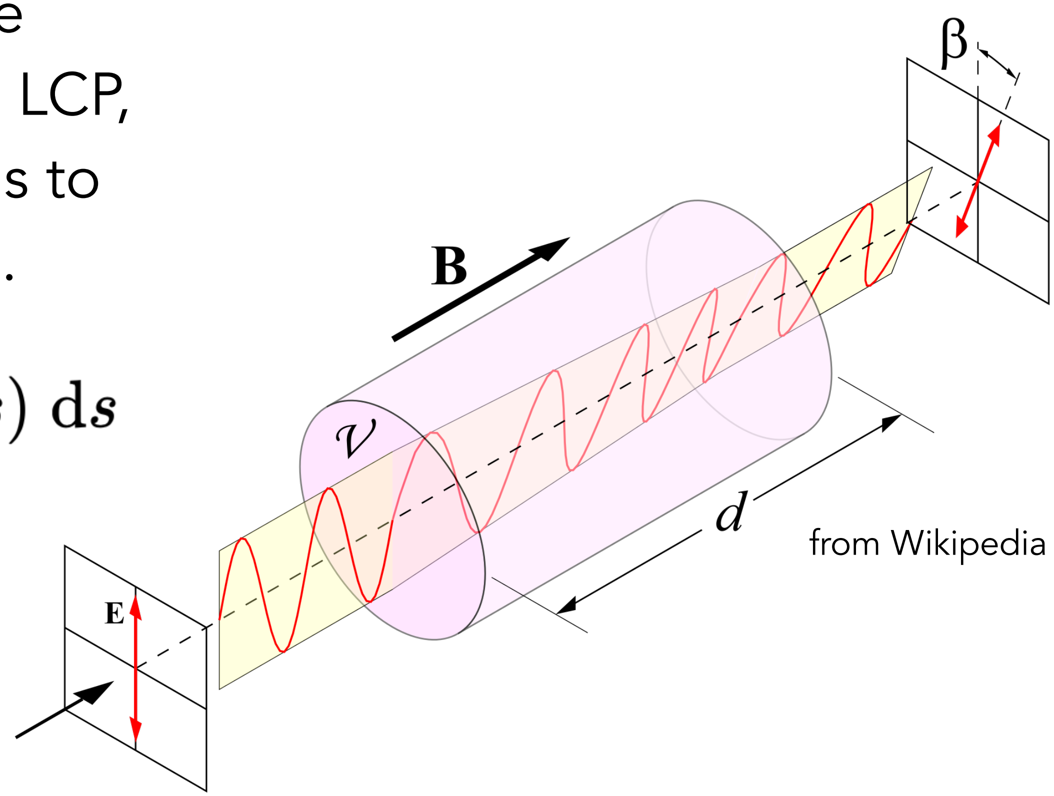
Right & left circularly polarized light has different phase velocities in a magnetized plasma. Difference depends on strength of B-field parallel to line of sight and n_e.

Linearly polarized light can be represented as a sum of RCP and LCP, difference in phase velocity leads to rotation of polarziation angle.

$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

shift depends on wavelength

$$\beta = \mathrm{RM}\lambda^2$$

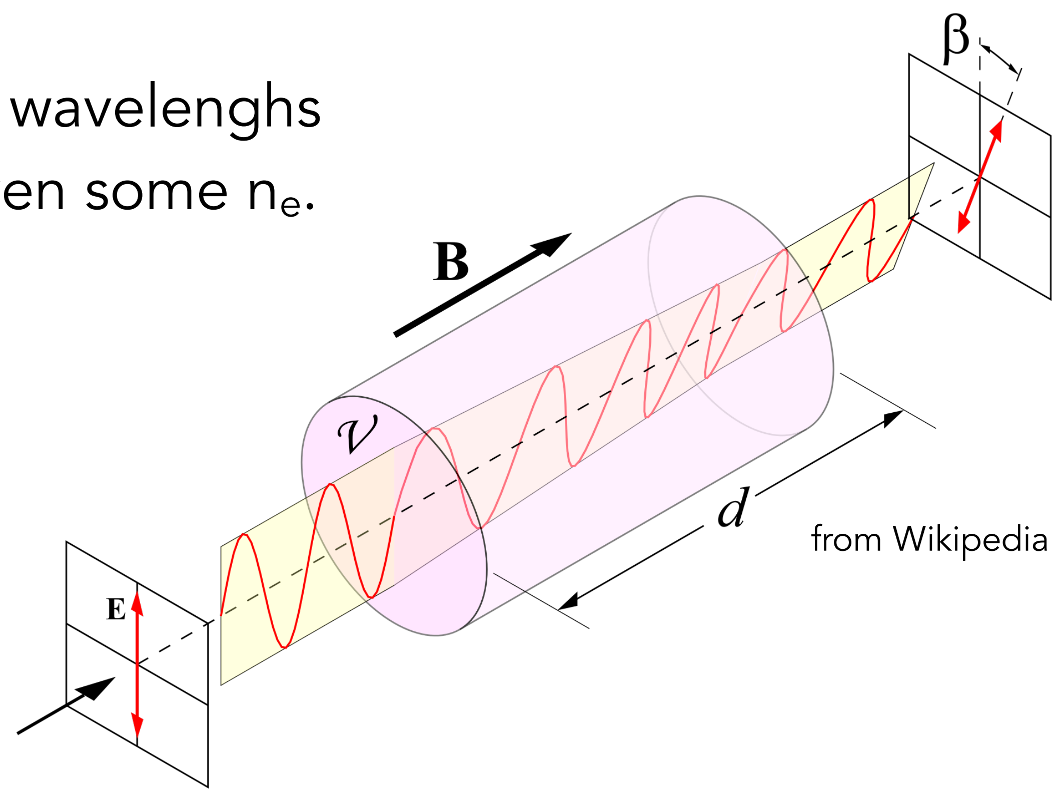


from Wikipedia

Faraday Rotation

Right & left circularly polarized light has different phase velocities in a magnetized plasma. Difference depends on strength of B-field parallel to line of sight and n_e.

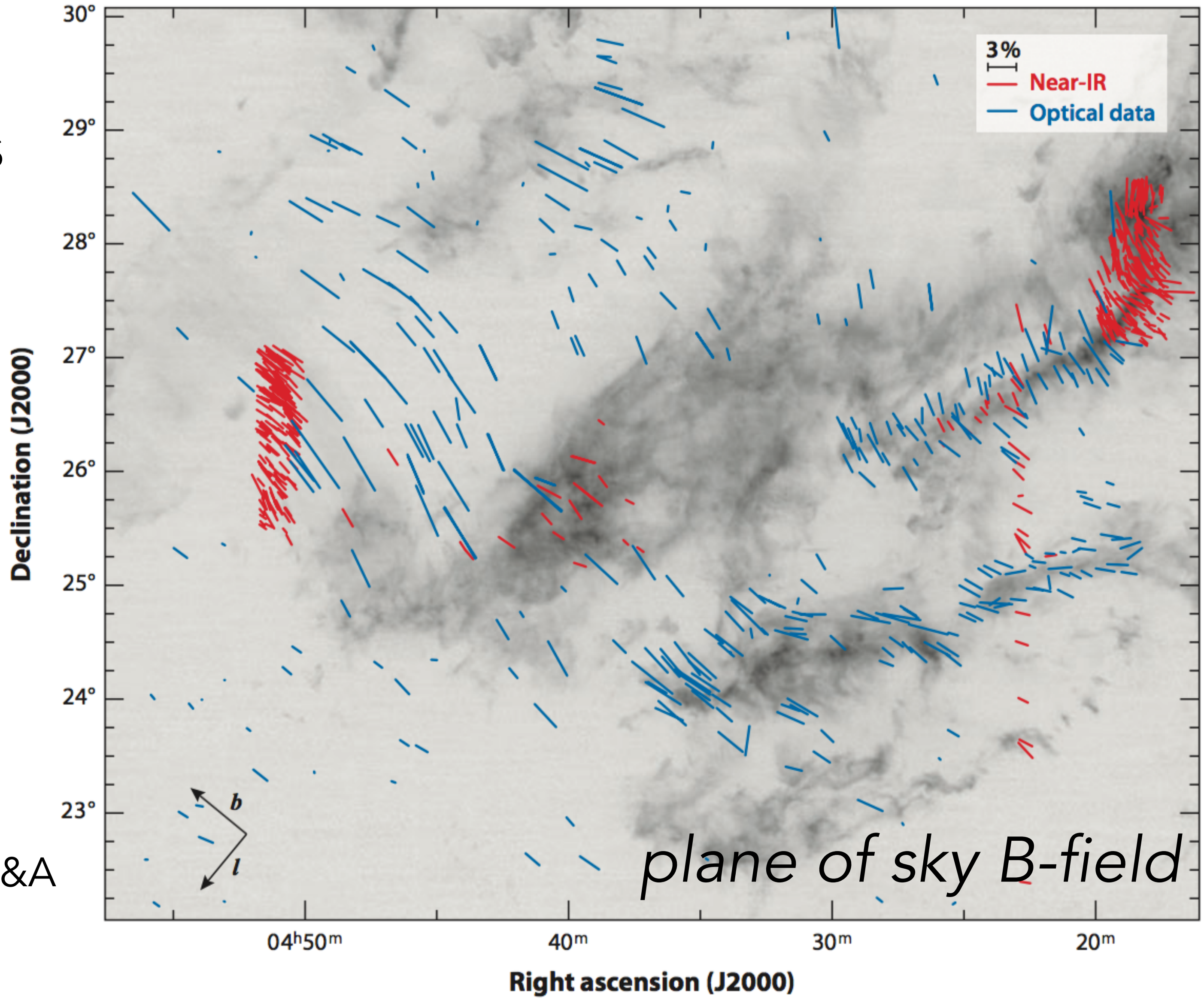
Can measure angle at different wavelenghs and use that to calculate $B_{||}$ given some n_e.



from Wikipedia

Polarization of Starlight

Crutcher 2012



Polarization of starlight in Taurus due to alignment of dust grains with the B-field.

Magnetic fields review: Crutcher 2012 ARA&A

Grain alignment review: Andersson et al. 2015 ARA&A

Dust Grain Alignment

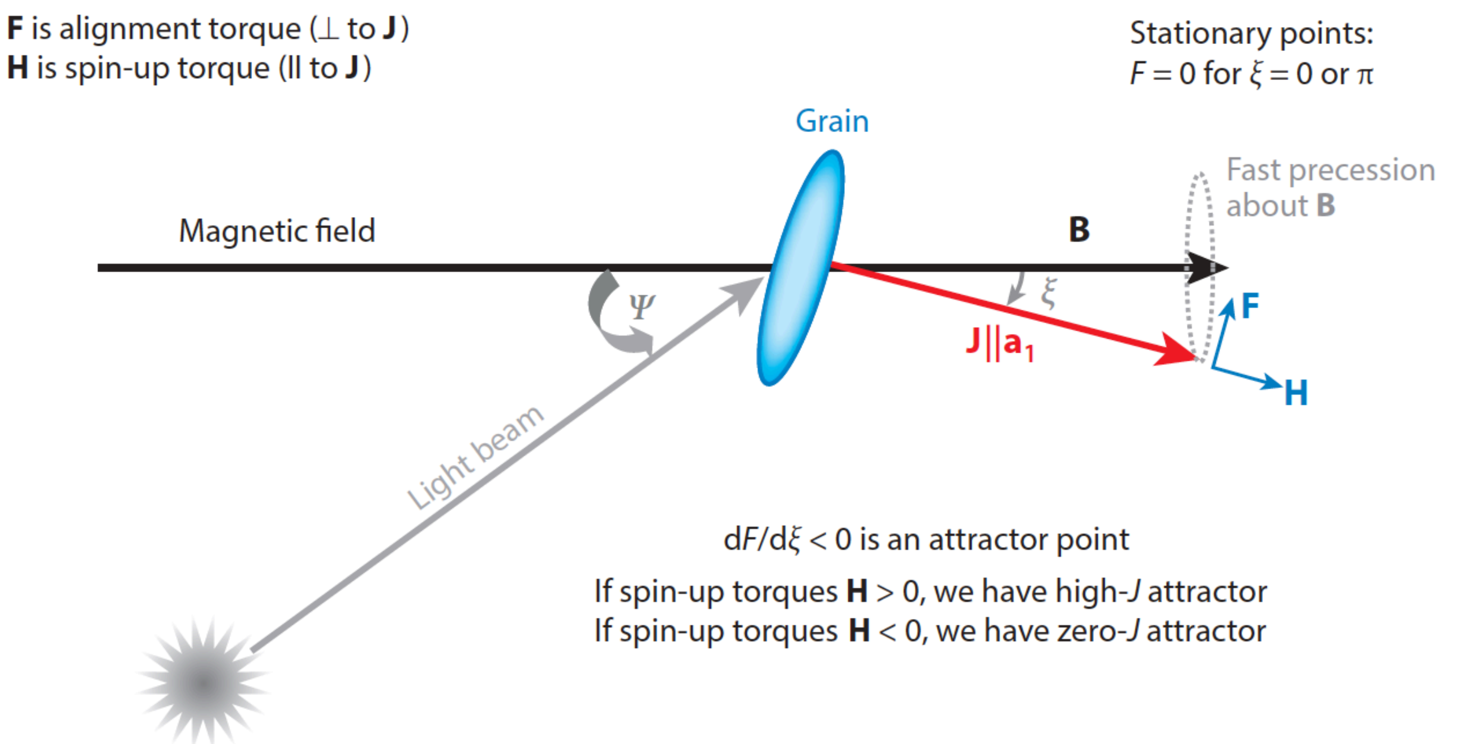
Andersson et al. 2015 ARA&A

Table 1 Summary of grain alignment results to date[a]

Observation	Larger grains are better aligned	General alignment only active for $a > 0.045$ µm	H_2 formation enhances alignment	H_2 formation not required for alignment	Alignment seen when $T_{gas} = T_{dust}$	Alignment is not correlated with ferromagnetic inclusions	Alignment is lost at $A_V \sim 20$ mag	Alignment depends on angle between radiation and magnetic fields	Carbon grains are unaligned
Theory									
Davis-Greenstein	–				–				
Super-paramagnetic	+				–	–			
Suprathermal			+	–					
Mechanical			–				–		–
Radiative alignment torque	+	+	+				+	+	+

[a]Green plus sign (+), observational support of a specific theoretical prediction; red minus sign (–), a contradiction between theory and observations. Gray boxes indicate no prediction or ambiguous results.

Dust Grain Alignment



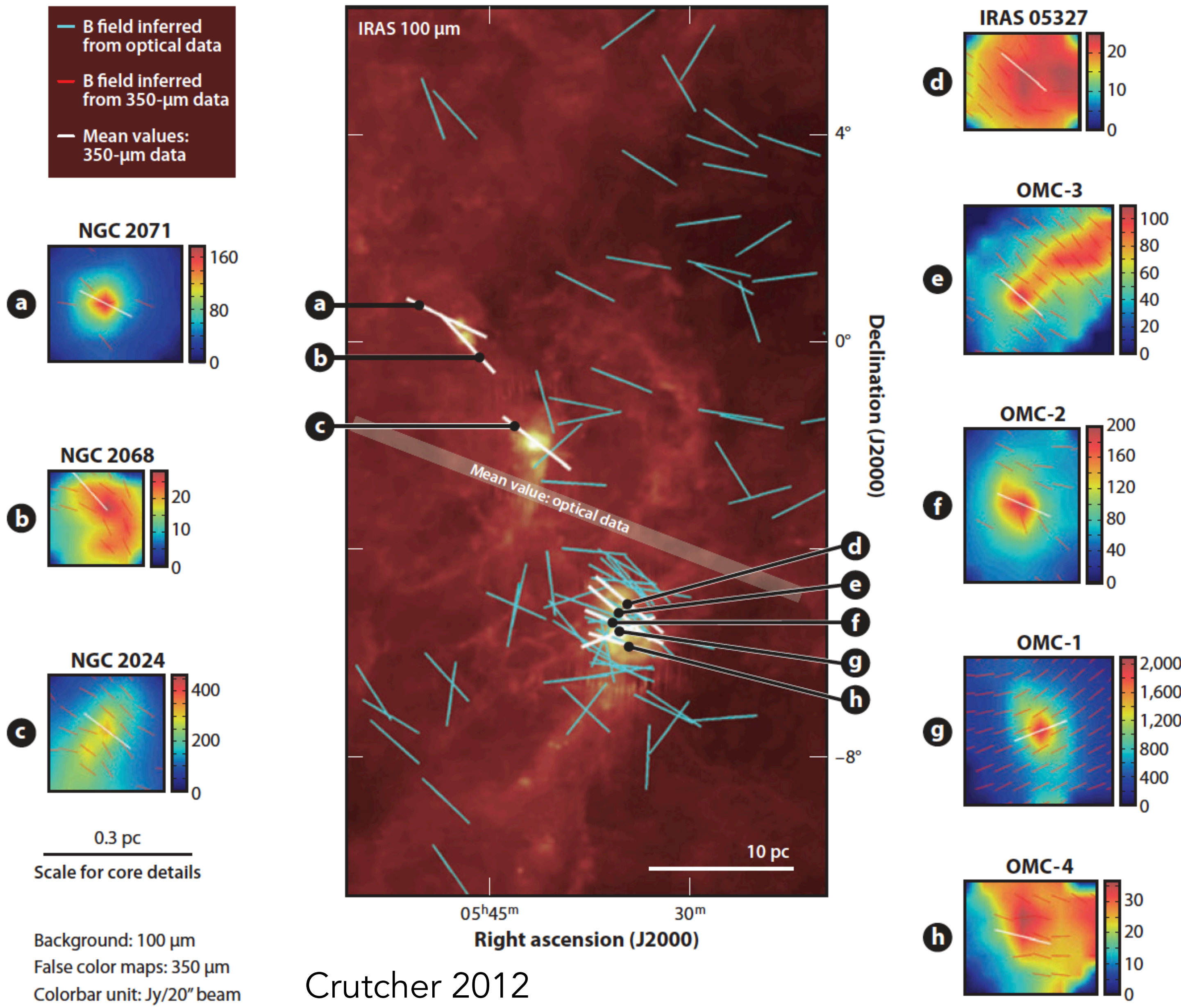
Andersson et al. 2015 ARA&A

Figure 5

A simplified explanation of the grain alignment by radiative torques. The grain, depicted here as an ellipsoid, should, in fact, be irregular in order to generate nonzero radiative torques. The grain has aligned (via internal alignment) with its spin axis **J** parallel to its maximal moment of inertia, $\mathbf{a}_1$, and precesses about the magnetic field **B** with angle ξ. Due to the incident radiation field, at angle Ψ with respect to **B**, the grain experiences a net torque with components **H** ∥ **J** and **F** ⊥ **H**. As shown by Lazarian & Hoang (2007a), the positions **J** parallel (or antiparallel) to **B** correspond to stationary points in which the alignment torque **F**, which changes the angle ξ, vanishes and the grain becomes aligned with the long axis perpendicular to **B**. Reprinted from Lazarian & Hoang (2011) with permission of the Astronomical Society of the Pacific.

Polarization of Thermal Dust Emission

Polarization of thermal dust emission in Orion



Crutcher 2012

Magnetic fields review: Crutcher 2012 ARA&A

Grain alignment review: Andersson et al. 2015 ARA&A

Polarization of Thermal Dust Emission

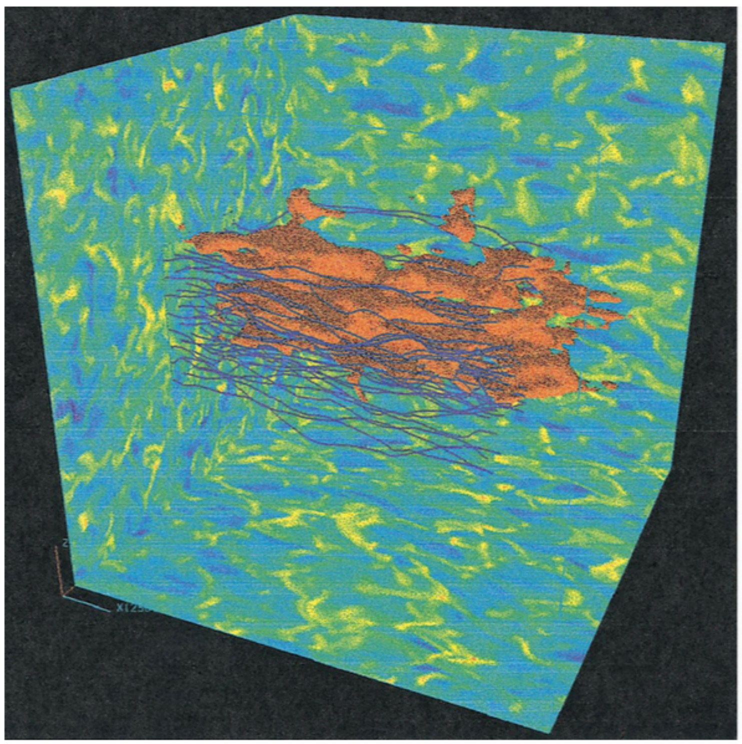
Dust polarization gives direction of B-field on sky and percent polarization as a function of wavelength (related to grain properties and alignment)

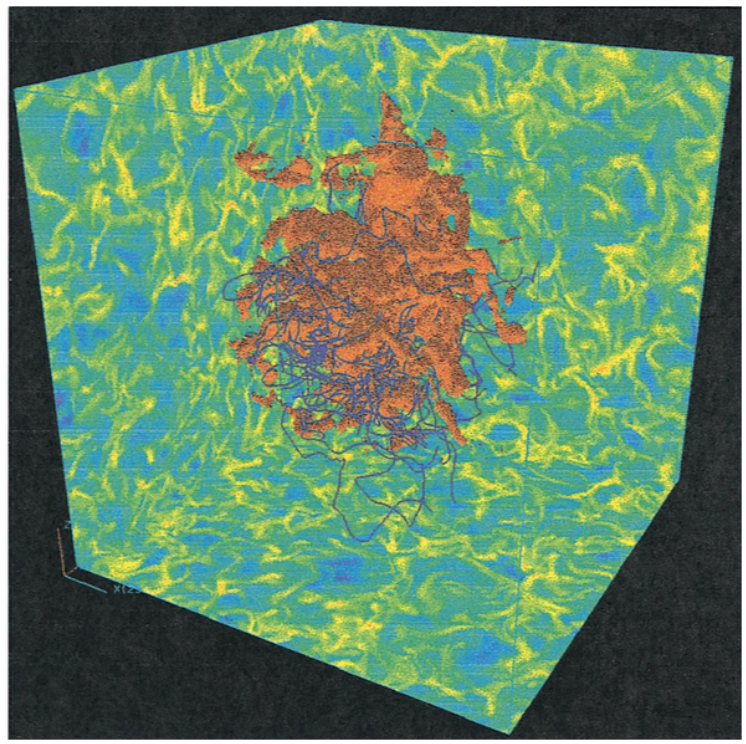
These are not directly related to the B-field strength.

Polarization of Thermal Dust Emission

Chandrasekhar & Fermi (1953) Method:
relate disorder in polarization angle to strength of B-field relative to the turbulent velocity dispersion

$$B_{POS} = \sqrt{4\pi\rho}\,\delta V / \delta\phi$$

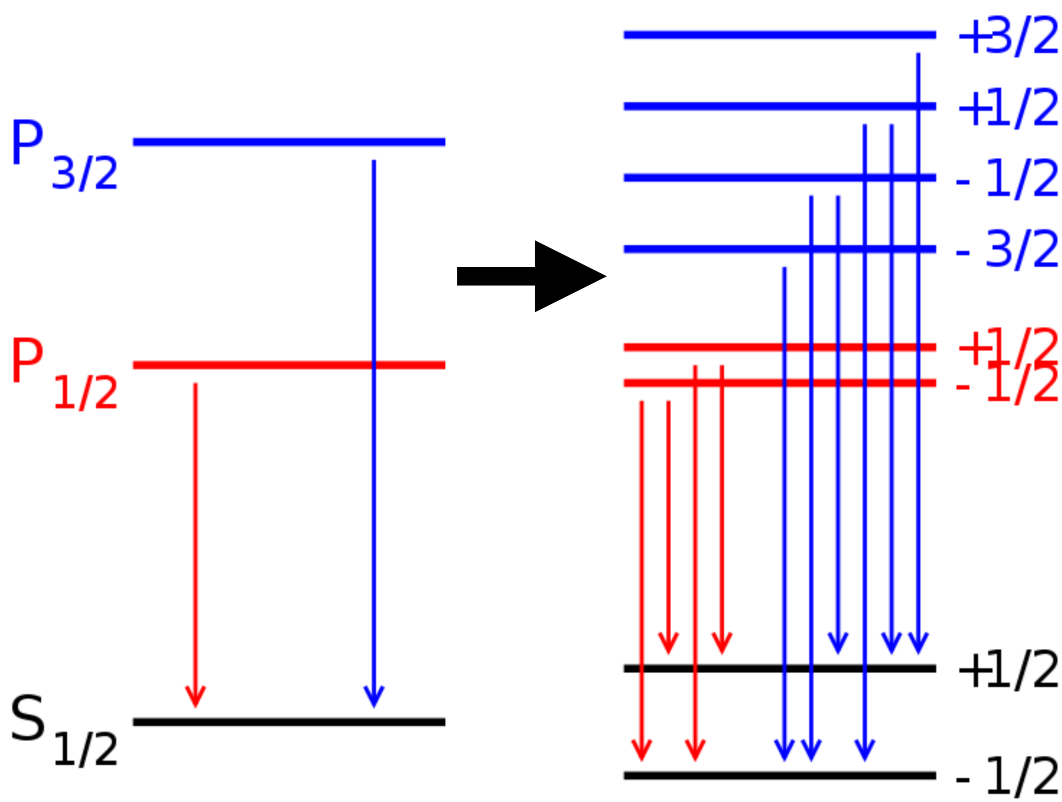




from Krumholz "Notes on Star Formation"

Zeeman Effect

In presence of a B-field,
energy levels in atoms/molecules with different orientations of net angular momentum have different energies, causing a shift.



$\Delta\nu = BZ$

where B is B-field
and Z is a constant
for each molecule/atom

for OH
$Z = 0.98$ Hz/μGauss
tiny!!

Zeeman Effect

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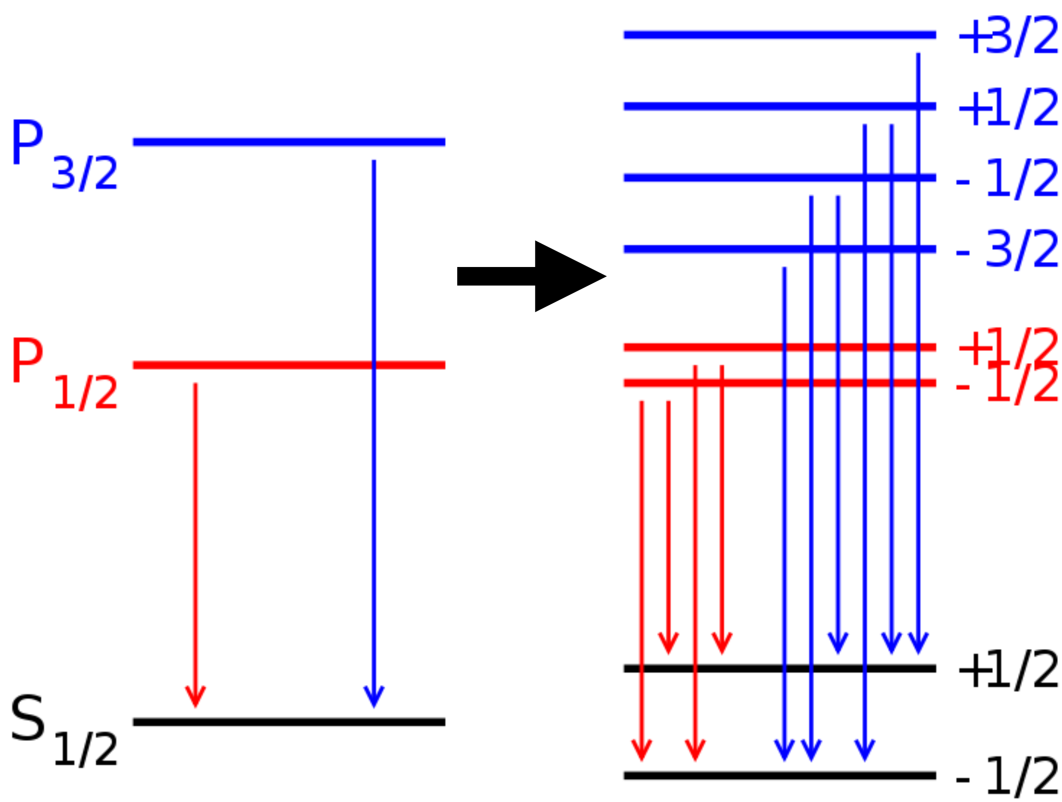


Zeeman splitting is largest when there is an unpaired electron in outer shell:
e.g. HI, OH, CN, CH, CCS, SO, and O_2

Even then, energy shift is small, but different levels have different circular polarizations.

Zeeman Effect

Quick review of polarization:

$$E_x(z,t) = E_{0x} e^{i(kz - 2\pi\nu t + \delta_x)} \,,$$
$$E_y(z,t) = E_{0y} e^{i(kz - 2\pi\nu t + \delta_y)} \,.$$

Electric field of plane wave traveling in +z direction with +x north and +y east.

$$I \equiv \langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle \,,$$
$$Q \equiv \langle E_x E_x^* \rangle - \langle E_y E_y^* \rangle \,,$$
$$U \equiv \langle E_x E_y^* \rangle + \langle E_x^* E_y \rangle \,,$$
$$V \equiv i \left(\langle E_x E_y^* \rangle - \langle E_x^* E_y \rangle \right) \,,$$

Stokes vectors: completely quantify the propagation of polarized radiation.

Brackets = time averages

* = complex conjugate

Zeeman Effect

Normalized Jones and Stokes Vectors for Simple Polarization States

Polarization State (1)	α (2)	δ (3)	$\mathbf{E}_o$ (4)	$\mathbf{E}_o$(CP) (5)	S (6)
Linear Horizontal	0°	...	$\begin{bmatrix}1\\0\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\begin{bmatrix}1\\1\\0\\0\end{bmatrix}$
Linear Vertical..................	90°	...	$\begin{bmatrix}0\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}i\\-i\end{bmatrix}$	$\begin{bmatrix}1\\-1\\0\\0\end{bmatrix}$
Linear at $\alpha = +45°$	+45°	0°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1+i\\1-i\end{bmatrix}$	$\begin{bmatrix}1\\0\\1\\0\end{bmatrix}$
Right-Handed Circular (RCP)...	...	+90°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\i\end{bmatrix}$	$\begin{bmatrix}1\\0\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\1\end{bmatrix}$
Left-Handed Circular (LCP)	...	−90°	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-i\end{bmatrix}$	$\begin{bmatrix}0\\1\end{bmatrix}$	$\begin{bmatrix}1\\0\\0\\-1\end{bmatrix}$

My favorite reference on polarization & Zeeman splitting:

T. Robishaw Ph.D. Thesis, 2008, Berkeley

Zeeman Effect

Quick review of polarization:

The parameter I simply represents the total intensity of the radiation; it does not store any polarization information. The parameter Q can be thought of as the tendency for linear polarization to be aligned horizontally rather than vertically. If $Q > 0$ there is an excess of polarized radiation along the horizontal, while for $Q < 0$, there is an excess of vertically polarized light. Likewise, the U parameter is the tendency for the linear polarization to be aligned at $+45°$ to the horizontal, with $U < 0$ meaning an excess in linear polarization at an angle $-45°$ to the horizontal. Finally, the Stokes V parameter is a direct measure of the circular polarization, and is the difference between the right-handed circular polarization and the left-handed circular polarization. For positive Stokes V, there is an excess of RCP over LCP when using the IEEE conventions. Since V is proportional to the sine of the relative phase δ, RCP ($0 < \delta < \pi$) corresponds to positive V, and it is reiterated that, should we reverse our definitions of the relative phase to $\delta \equiv \delta_x - \delta_y$ or of the absolute phase to $(\omega t - kz)$, the sense of Stokes V will change. We will revisit the details of circular polarization conventions in § 2.4.2 The Stokes vector is listed for simple polarization states in Table 2.1.

Zeeman Effect

Stokes Parameters for Classical Derivation of the Zeeman Effect

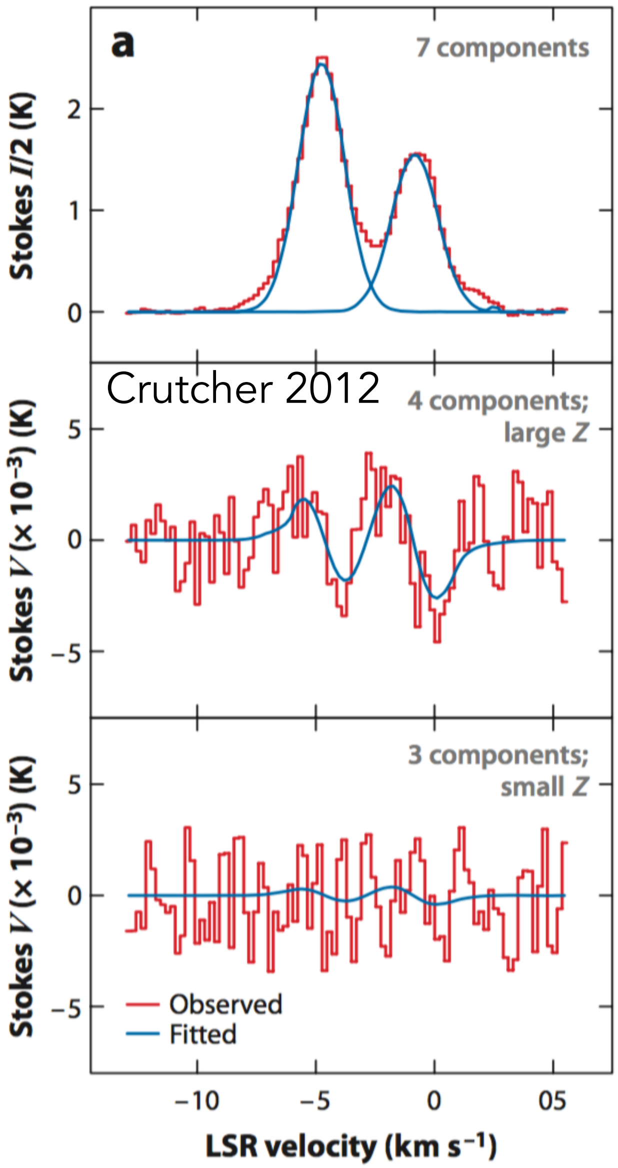
$$S = \frac{1}{4}\left(I(\nu - \nu_-)\begin{bmatrix} 1+\cos^2\theta \\ -\sin^2\theta \\ 0 \\ -2\cos\theta \end{bmatrix} + I(\nu - \nu_0)\begin{bmatrix} 2\sin^2\theta \\ 2\sin^2\theta \\ 0 \\ 0 \end{bmatrix} + I(\nu - \nu_+)\begin{bmatrix} 1+\cos^2\theta \\ -\sin^2\theta \\ 0 \\ 2\cos\theta \end{bmatrix} \right)$$

where θ is angle between B-field and observer
θ=0 is pointing towards observer, θ=180 points away

for unpolarized spectral line: $S = I(\nu - \nu_0)\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$

Zeeman Effect

Total intensity
7 hyperfine components for mm rotational lines of CN
two velocity components along line of sight.



Impossible to see the shift in total intensity (Stokes I) due to Doppler width of lines.

Circularly polarized emission:
4 components with large Zeeman splitting

Signatures of Zeeman effect in the Stokes V component

Circularly polarized emission:
3 components with small Zeeman splitting

For a given transition, amplitude of Zeeman pattern tells you line of sight B-field.

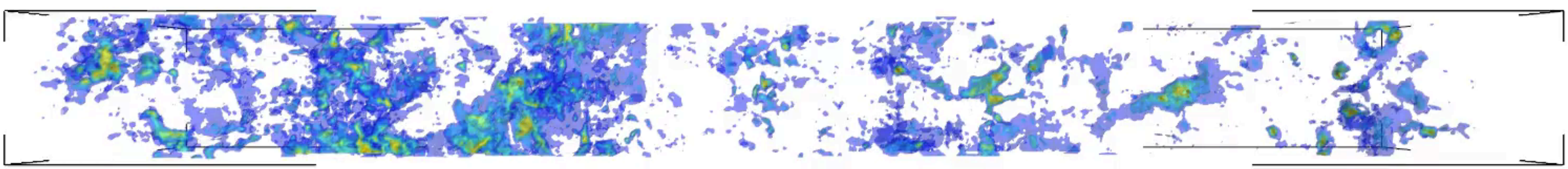
Magnetic Fields in the ISM

Observational Tracers:

- Synchrotron emission - indirect B-field strength from equipartition and CF method
- Faraday Rotation - integral of B-field and n_e along line of sight
- Starlight & Dust Thermal Emission Polarization - get B-field direction, CF method for strength
- Zeeman splitting - direct measure of strength, but challenging to detect

Molecular Clouds

- Observational definition: Discrete regions of CO emission in position-position-velocity space.



MOPRA Galactic Plane Survey ^{12}CO ppv - Braiding et al. 2015

Molecular Clouds

Observed Characteristics

- Self-Gravity
- Turbulence
- Substructure
- Magnetic Fields
- Mass Spectrum
- Lifetimes
- Star Formation

Molecular Clouds

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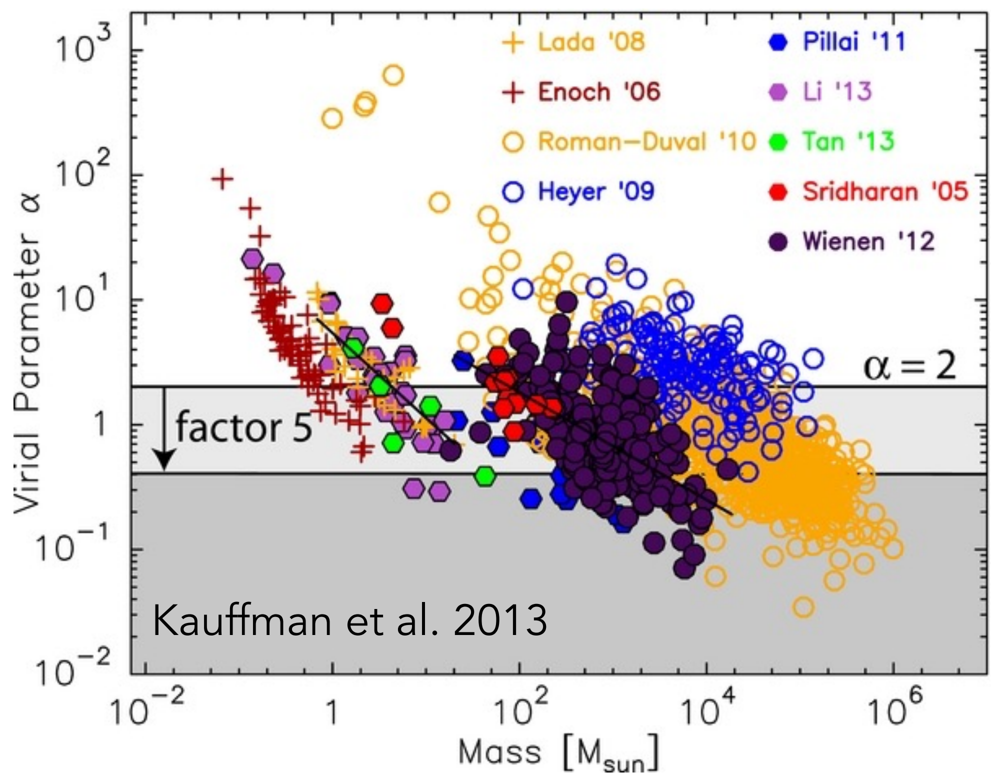
Continuing controversy over whether GMCs are gravitationally bound.

Regardless, $\alpha_{vir} = 5\sigma_v R/GM$ ~ order unity



Molecular Clouds

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Also note that GMCs are "over-pressurized" wrt diffuse ISM:

WNM/CNM: P ~ 3800 cm^{-3} K

GMC (T=10, n=10^4): P ~ 10^5 cm^{-3} K

Without self-gravity, GMCs would be transient.

Molecular Clouds

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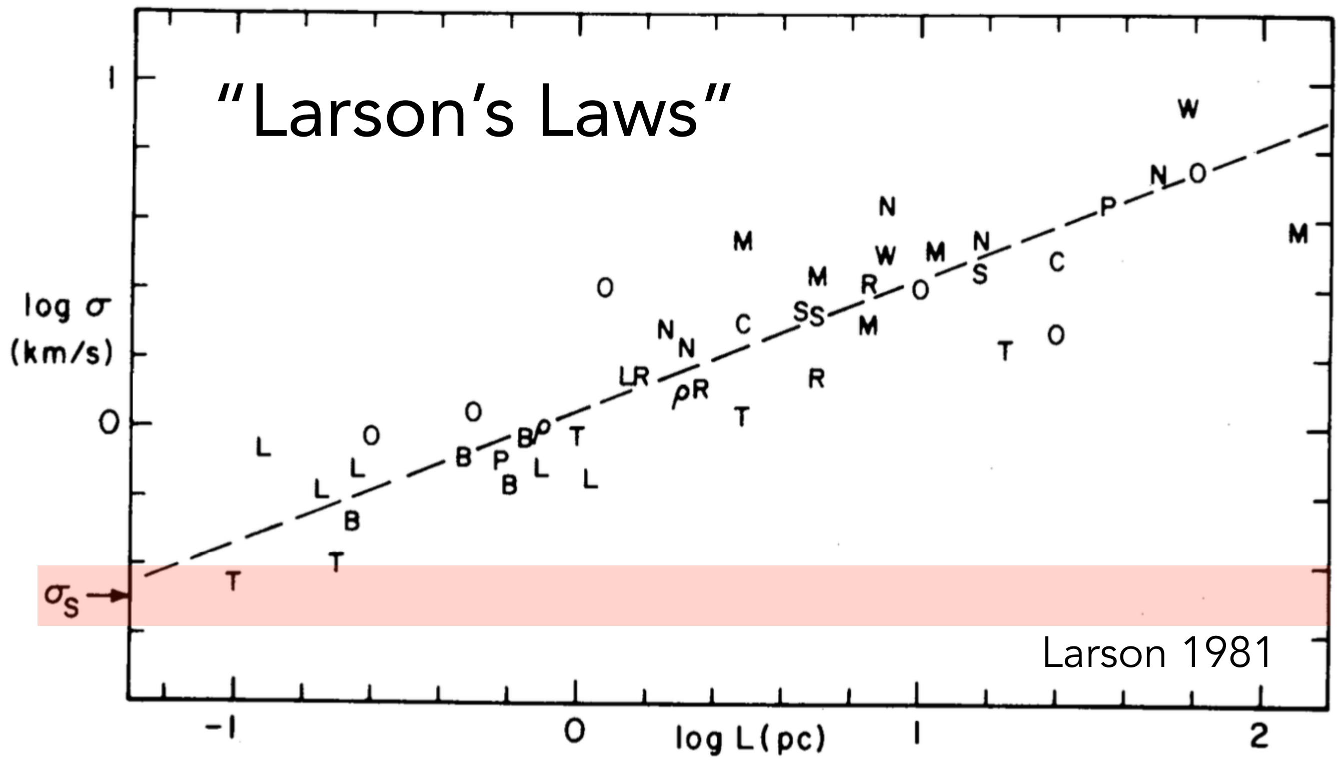

Velocity dispersion is >> sound speed, supersonic turbulence provides support against gravity.

Molecular Clouds

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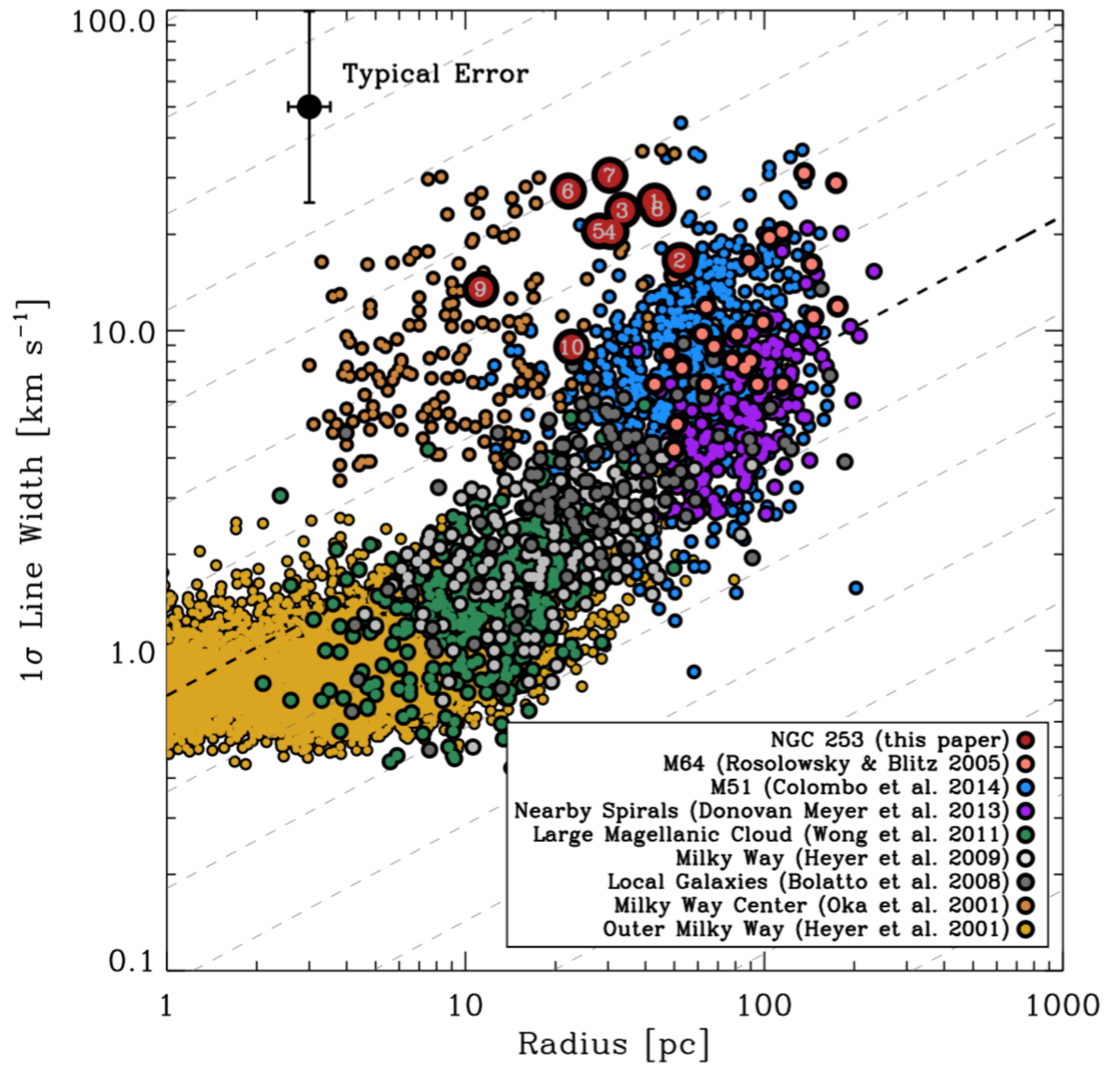
Leroy et al. 2015



Molecular Clouds

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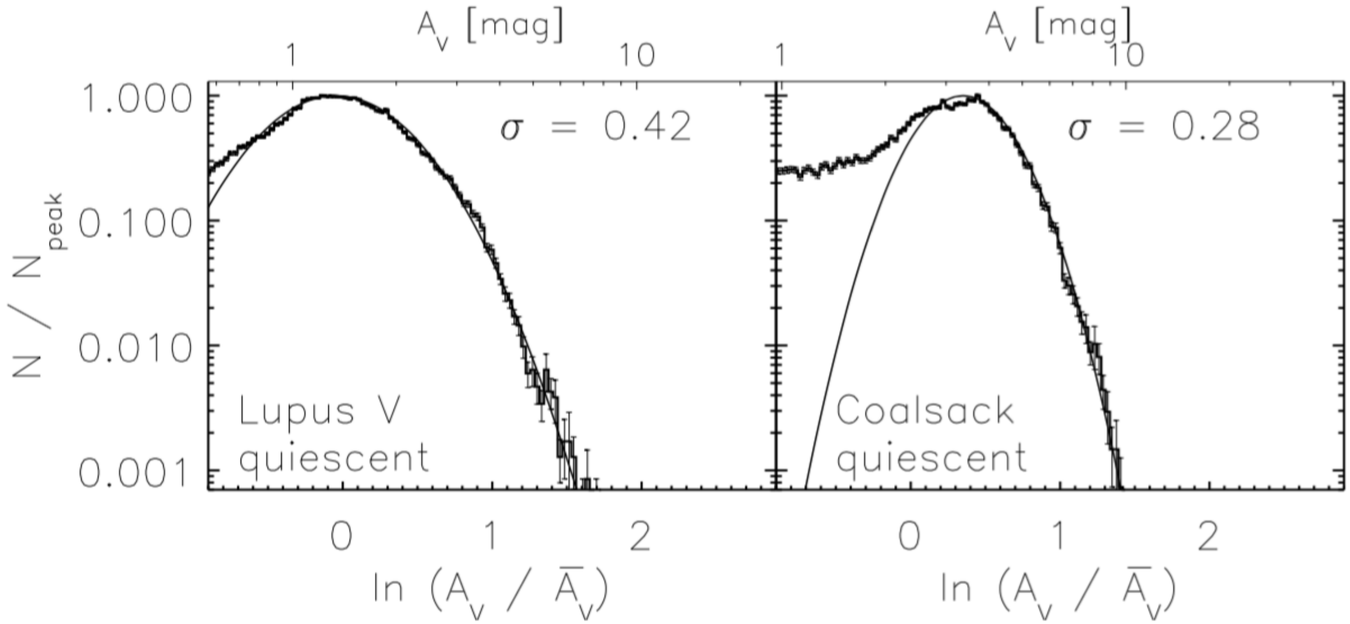

Kainulainen et al. 2009

Log-Normal PDF of column density observed in molecular clouds.

Molecular Clouds

Observed Characteristics

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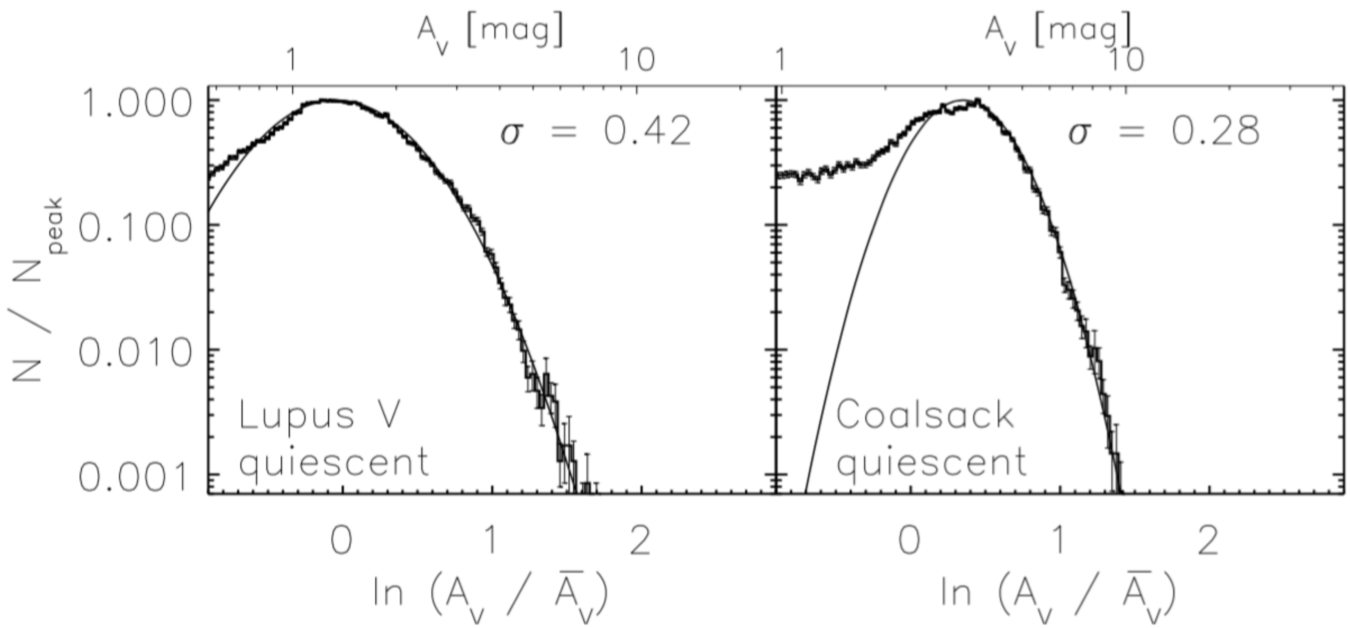

Simulations of supersonic turbulence predict a lognormal density PDF.

$$p(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s-s_0)^2}{2\sigma_s^2}\right]$$

where:

$s = \ln(\rho/\overline{\rho})$

Molecular Clouds

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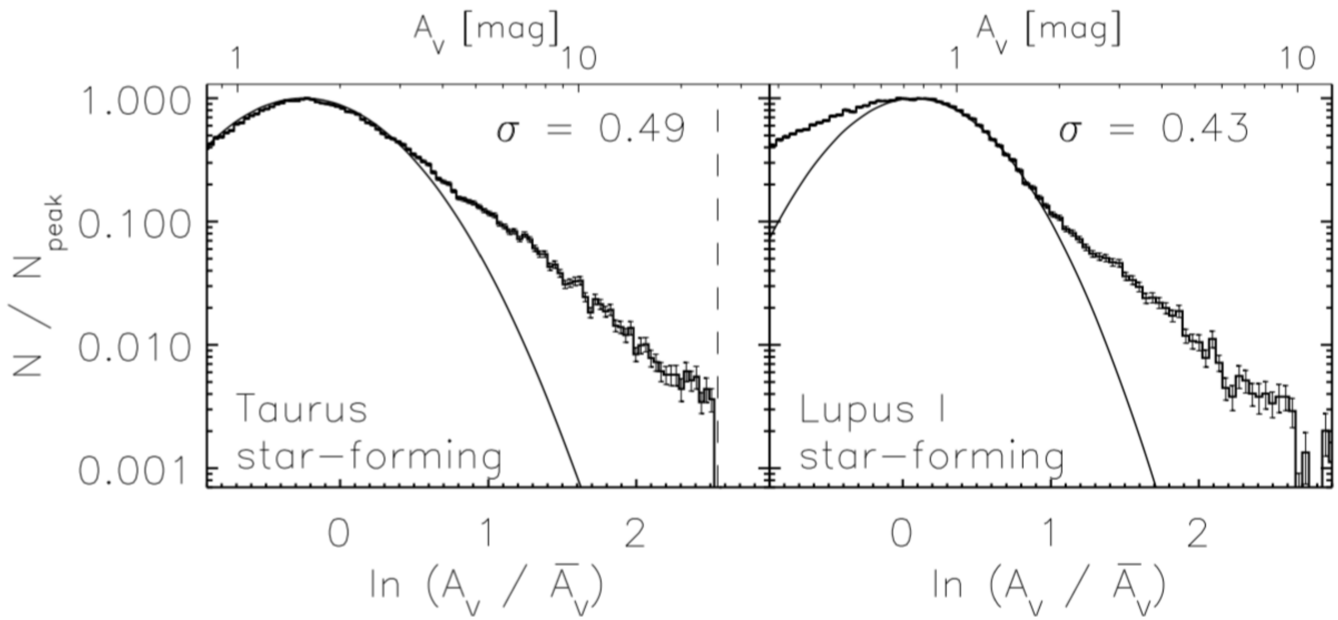

Kainulainen et al. 2009

Actively star-forming clouds show power-law tail at high column. Signature of gravitational collapse?