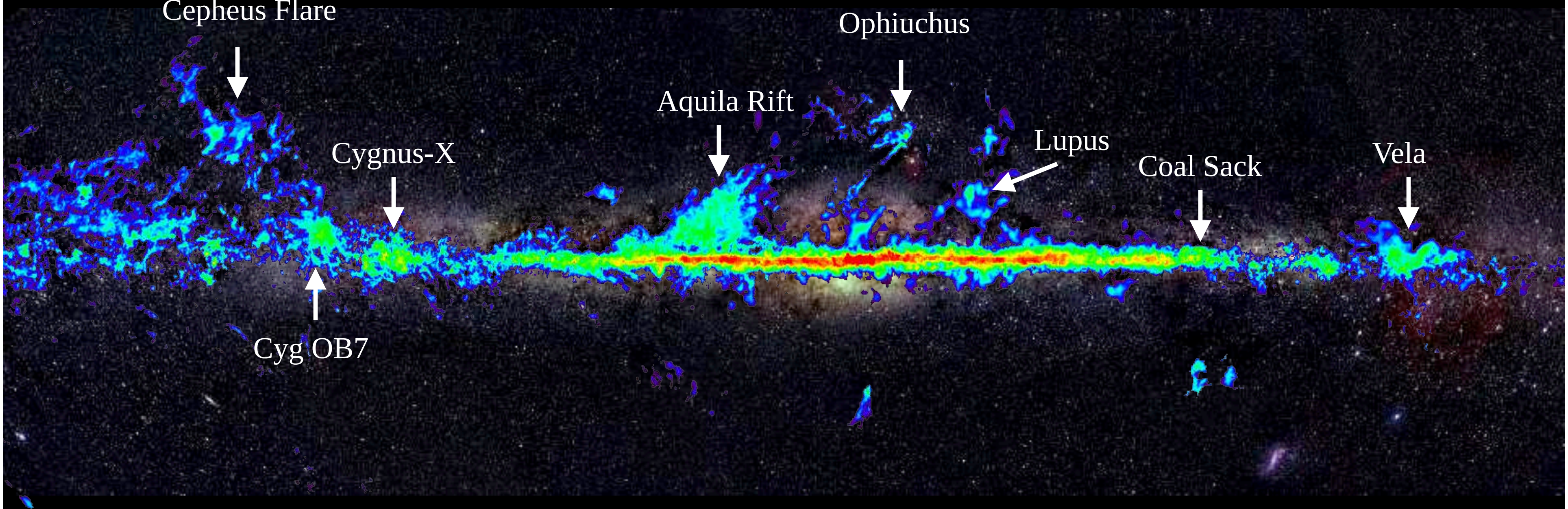
Magnetic Fields in the Periphery of Giant Molecular Clouds – Zeeman Effect Observations



λ 2.6 mm ^{12}CO, J=1-0, Dame et al. (2001)

Recent collaborators

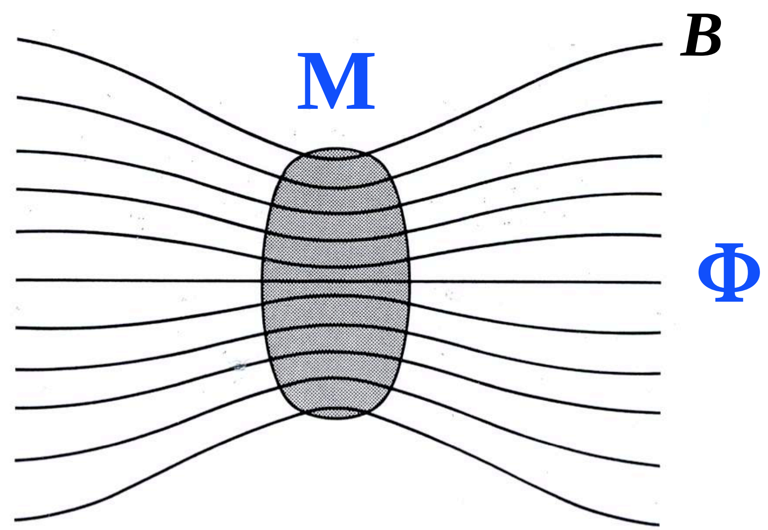
- Richard Crutcher (University of Illinois)
- Edith Falgarone (ENS, Paris)
- Carl Heiles (Berkeley)
- Kristin Thompson (Ph.D., University of Kentucky)

With partial support from the US National Science Foundation

1. Background – E_{grav}/E_{mag}

- λ is the normalized M/Φ ratio, where

$$\lambda \approx (E_{grav}/E_{mag})^{1/2}$$



Note **-** λ **is the same thing as McKee's** μ_ϕ

1. Background – E_{grav}/E_{mag}

- **If $\lambda > 1$**
  - *Gravity dominant ($E_{grav} > E_{mag}$)*
  - Cloud is magnetically "*supercritical*"
  - *B* alone *cannot* prevent collapse of cloud

- **If $\lambda < 1$**
  - *Magnetic field dominant ($E_{mag} > E_{grav}$)*
  - Cloud is magnetically "*subcritical*"
  - *B* alone *will* prevent collapse of cloud (as long as flux freezing is maintained)

1. Background – E_{grav}/E_{mag}

- The mass-to-flux ratio is an *observable* since

$$\frac{M}{\Phi} = \frac{\left(\frac{M}{area}\right)}{\left(\frac{\Phi}{area}\right)} \propto \frac{N(H)}{B}$$

- Converted to observing units

$$\lambda \approx 5 \times 10^{-21} \frac{N(H)}{B_{\mu G}}$$

2. Measuring *B* via Zeeman Effect

- **Only known method to measure *strength* of *B* in localized regions of ISM.**
- **Involves measurement of *very weak circular polarization* in radio frequency spectral lines.**
- **Reveals *line-of-sight* component B_{los} *only* (with rare exceptions).**
- **Only practical for spectral lines from species with *electronic angular momentum* (e.g. HI, OH, CN).**

2. Measuring *B* via Zeeman Effect

- **The three Zeeman species sample *different densities***

Species	Wavelength	n(H) sampled
HI	21 cm	$10^1 - 10^2$ cm^{-3} (diffuse gas)
OH	18 cm	$10^3 - 10^4$ cm^{-3}
CN	2.6 mm (N=1-0) 1.3 mm (N=2-1)	$10^5 - 10^7$ cm^{-3}

2. Measuring *B* via Zeeman Effect

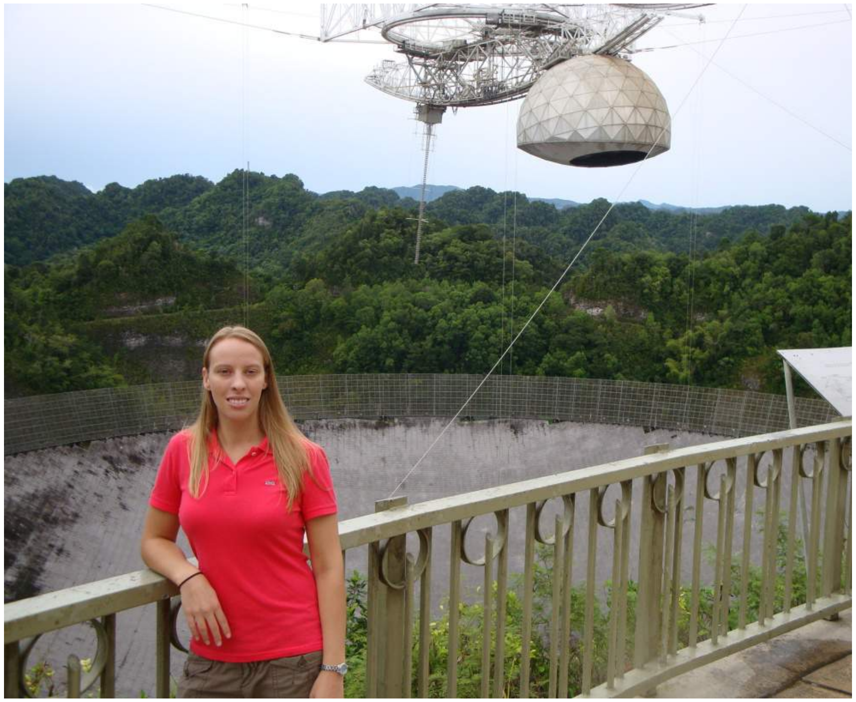
- Published Zeeman data comprise 161 measurements of B_{los}

Data set	Reference	No. of B_{los}
Compilation (HI, OH, CN as of 1999)	Crutcher 1999	27
OH absorption	Bourke, Myers, Robinson & Hyland 2001	22
Arecibo HI absorption Millennium Survey	Heiles & Troland 2004, 2005	67
Arecibo OH emission (dark clouds)	Troland & Crutcher 2008	34
IRAM 30m CN, 1-0 emission	Falgarone, Troland, Crutcher & Paubert 2008	11

3. Zeeman Effect in Molecular Cloud Peripheries

- **Thompson, Troland & Heiles* used Arecibo to study Zeeman effect in galactic *OH absorption lines* (1665 & 1667 MHz) toward extra-galactic continuum sources.**

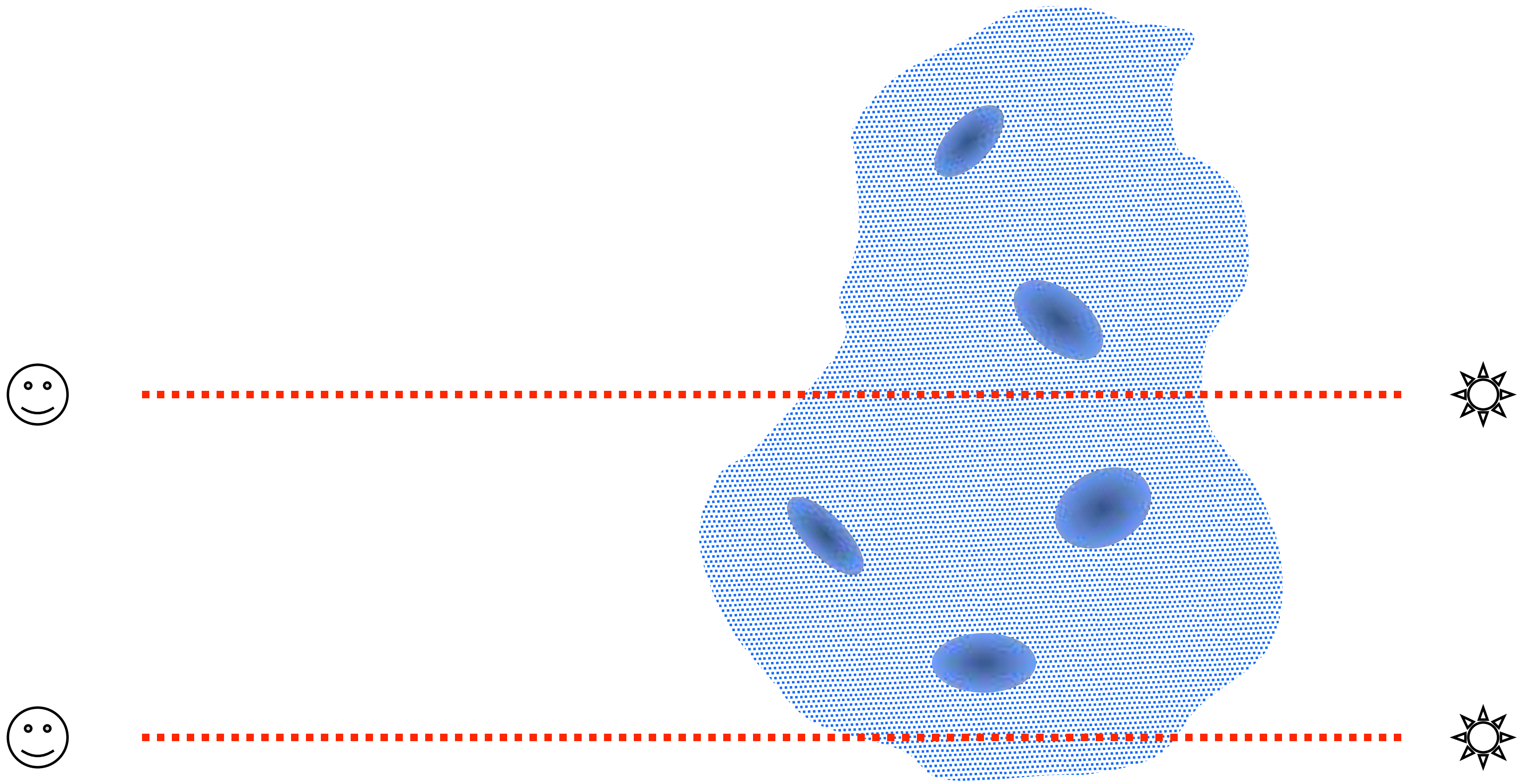
- **Sources chosen to lie *behind galactic molecular clouds*.**



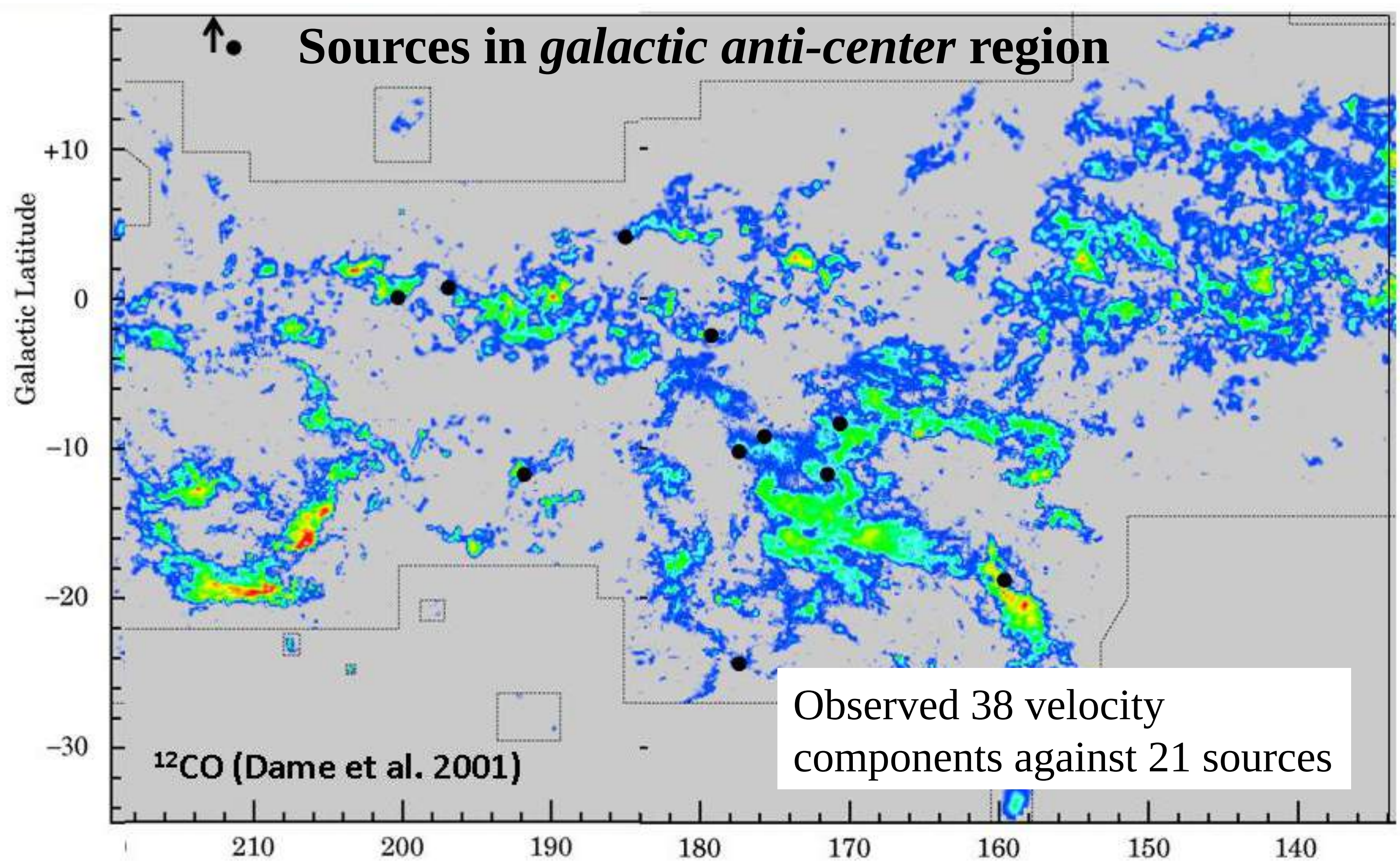
***to be submitted fall, 2015**

3. Zeeman Effect in Molecular Cloud Peripheries

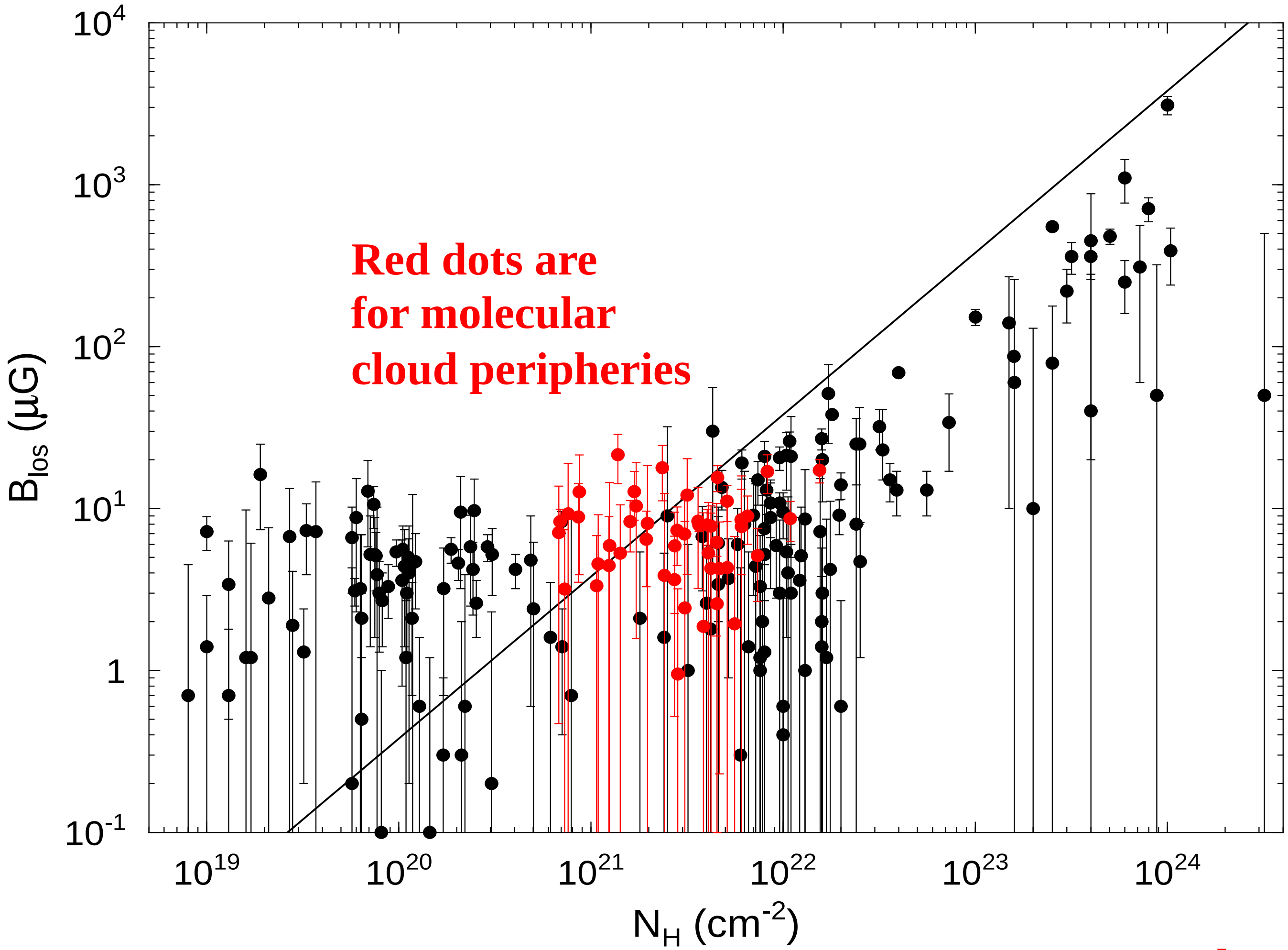
- **Lines-of-sight from background continuum sources do *not* sample molecular cores preferentially.**



3. Zeeman Effect in Molecular Cloud Peripheries

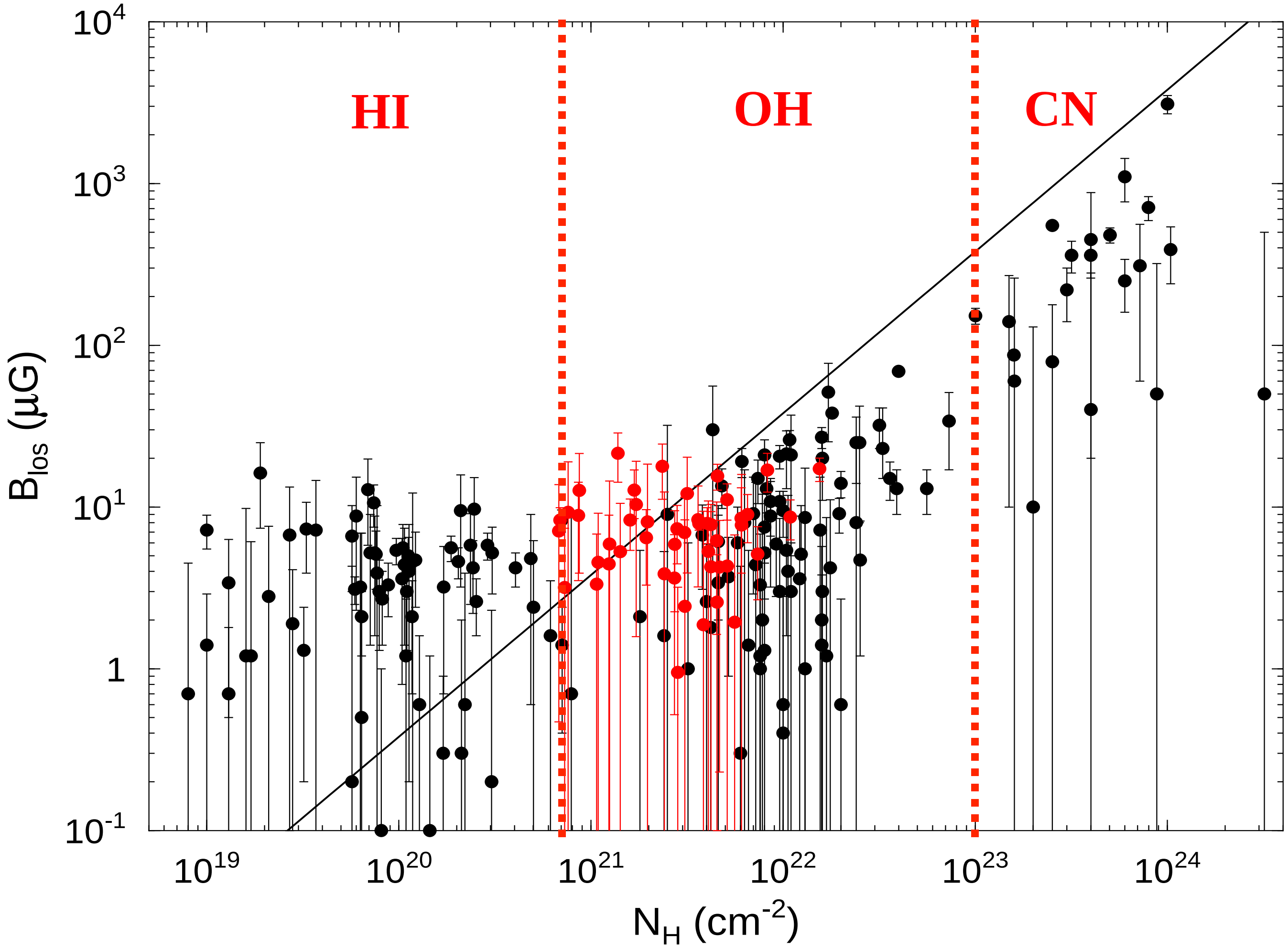


4. Zeeman Effect – All Data

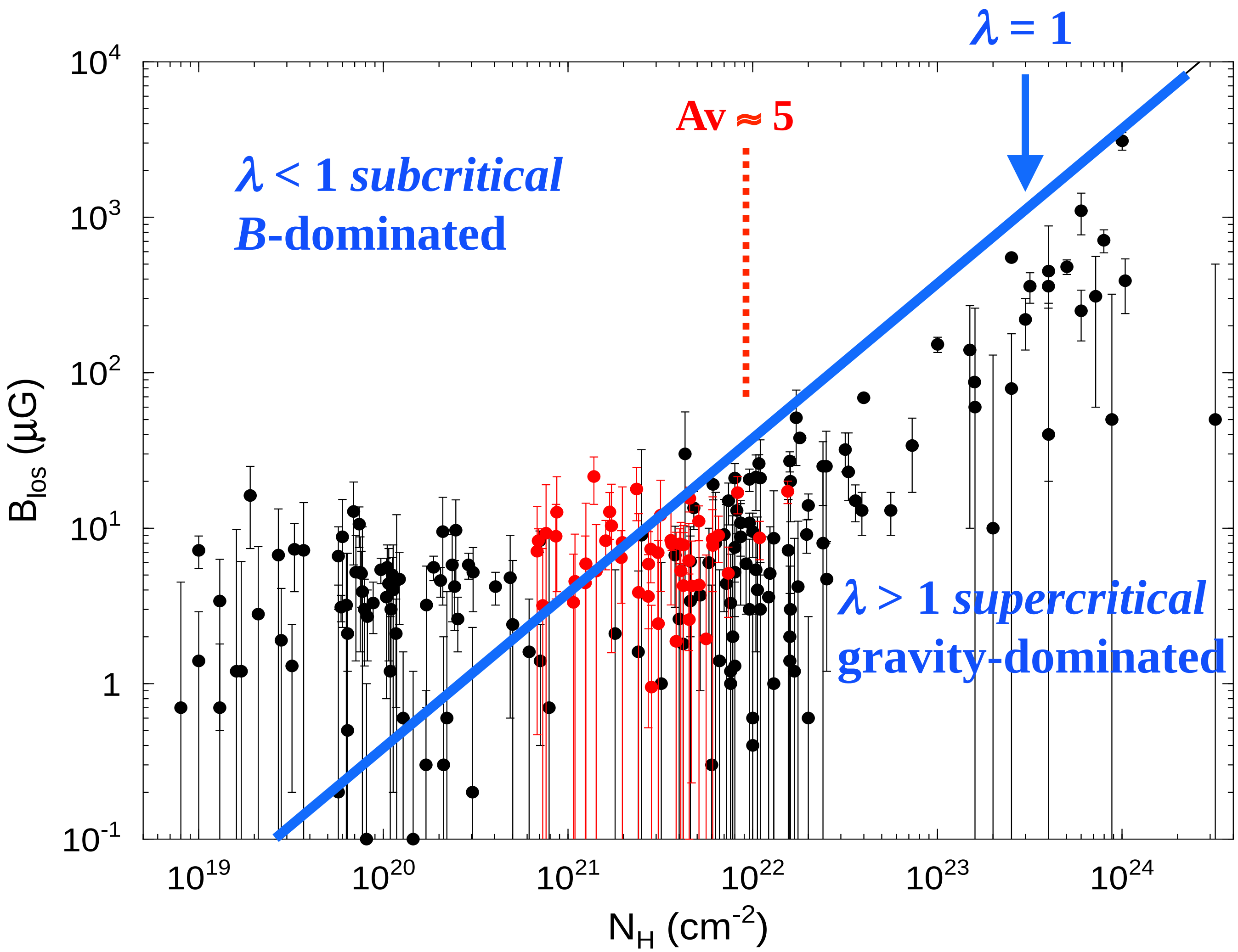


See Crutcher, ARAA, 2012

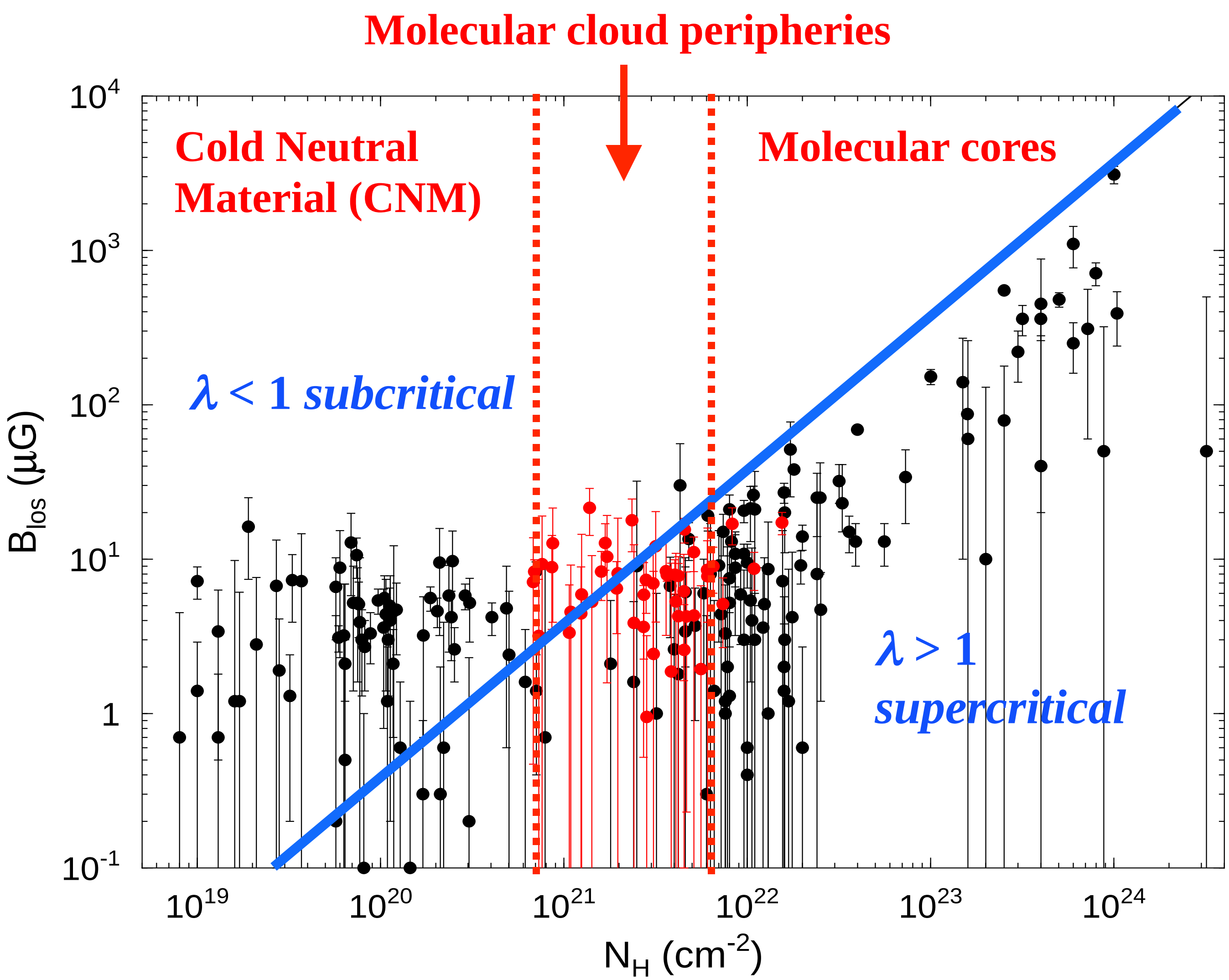
4. Zeeman Effect – All Data



4. Zeeman Effect – All Data



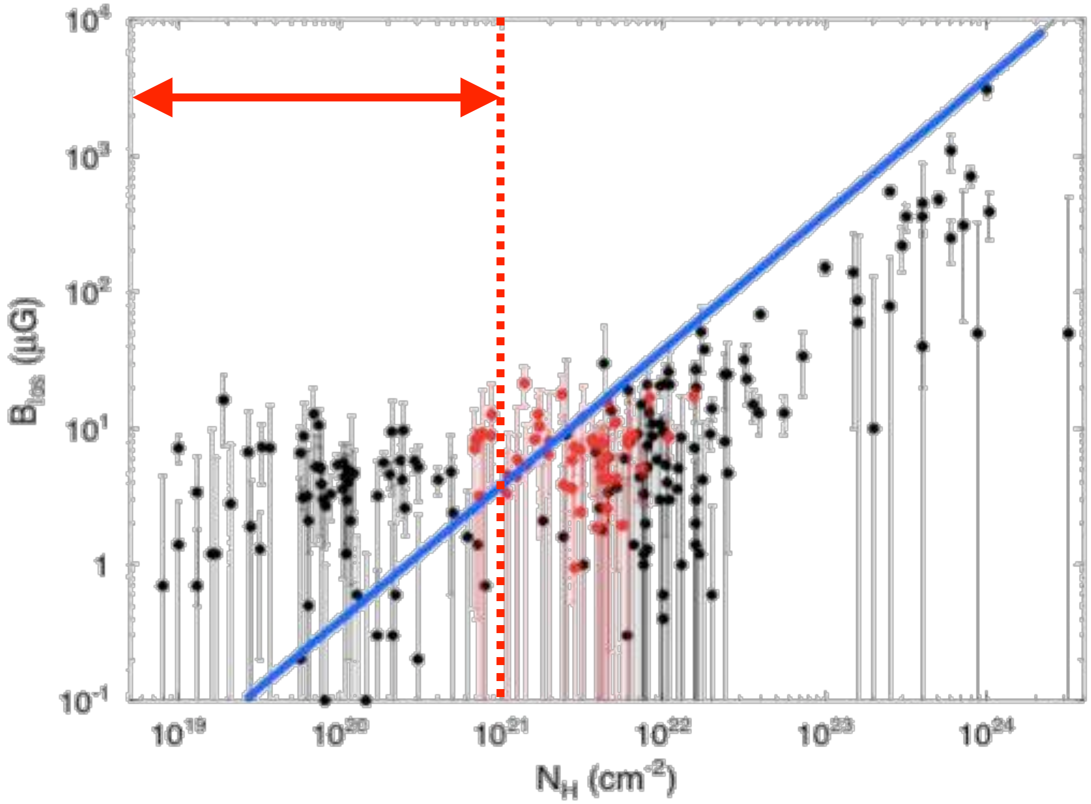
4. Zeeman Effect – All Data



5. Zeeman Effect Results

A. For $N(H) < 10^{21}$ cm^{-2}

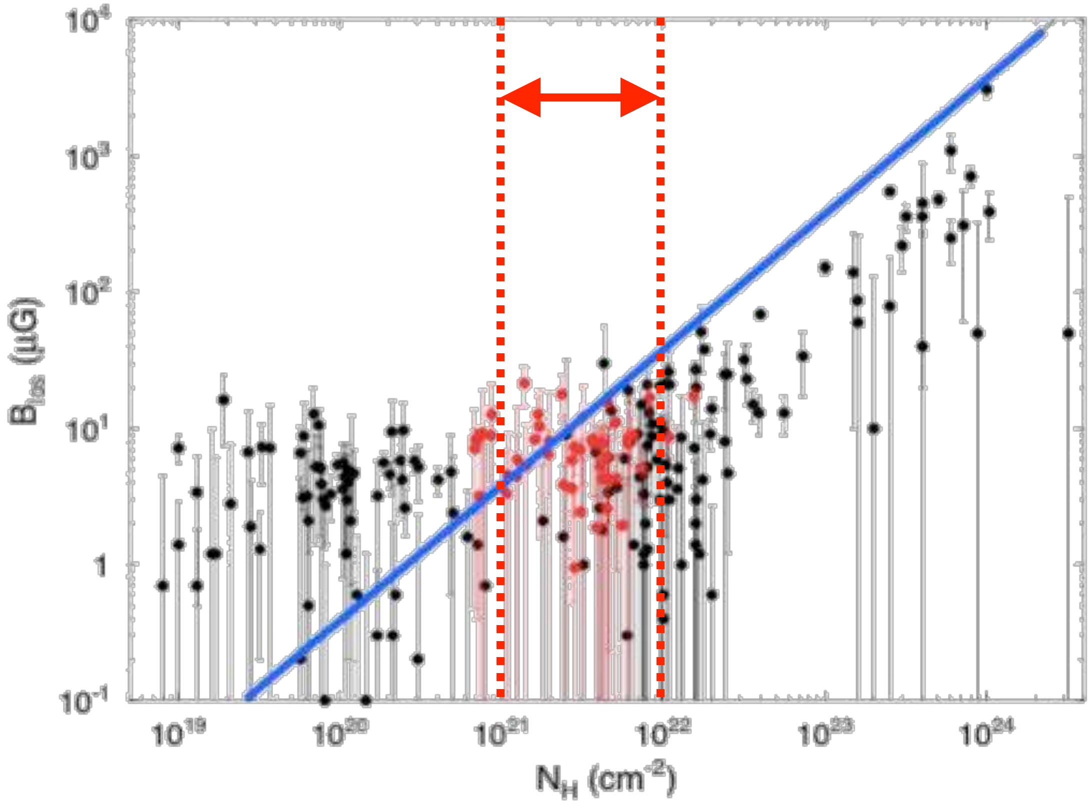
– $\lambda < 1$ (i.e. diffuse H^0 gas is magnetically *subcritical*)



5. Zeeman Effect Results

B. For N(H) ≈ 10^{21} to 10^{22} cm^{-2}

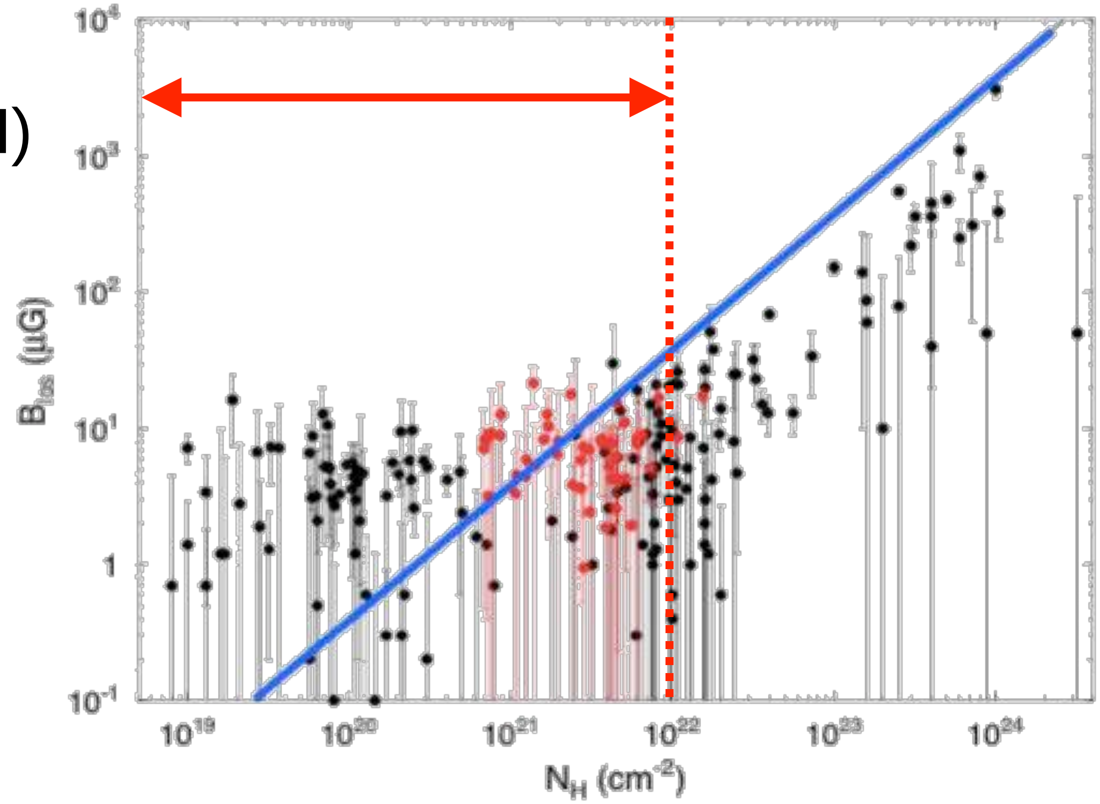
– $\lambda \approx 1$ in molecular cloud peripheries (red dots)



5. Zeeman Effect Results

C. For N(H) < 10^{22} cm^{-2}

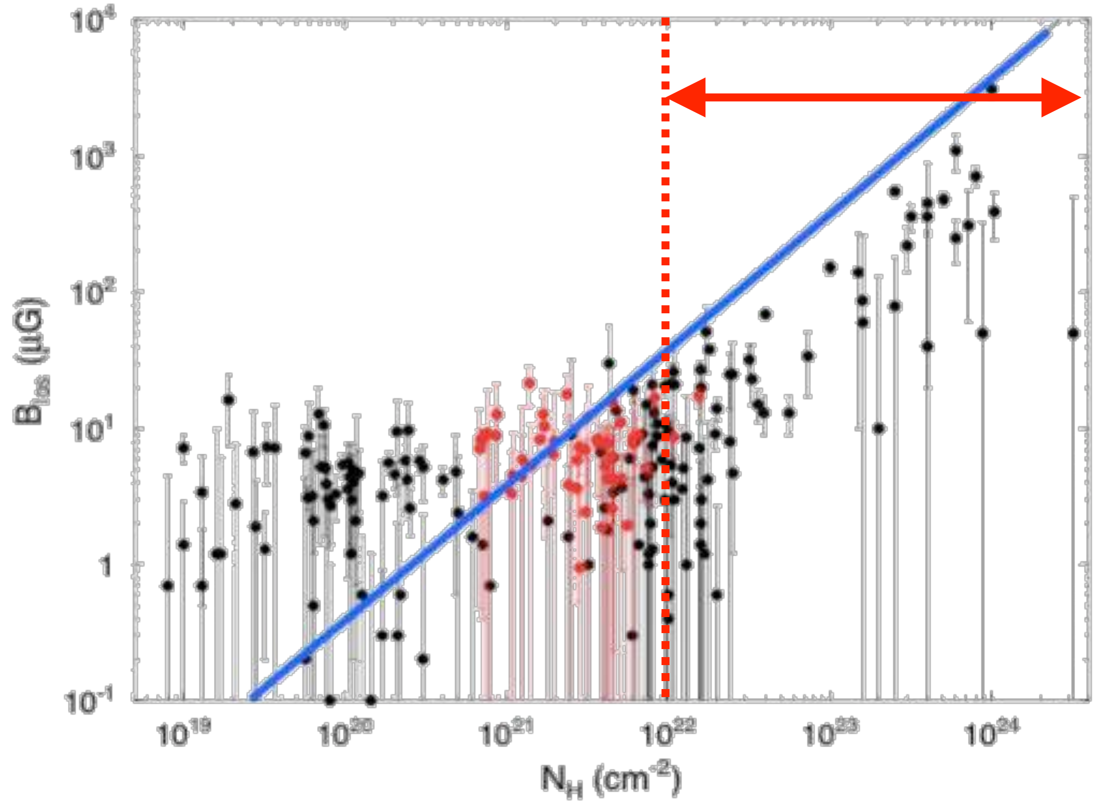
- B constant with increasing N(H) - from diffuse H^0 gas through molecular cloud peripheries
- λ increases with N(H)



5. Zeeman Effect Results

D. For N(H) > 10^{22} cm^{-2}

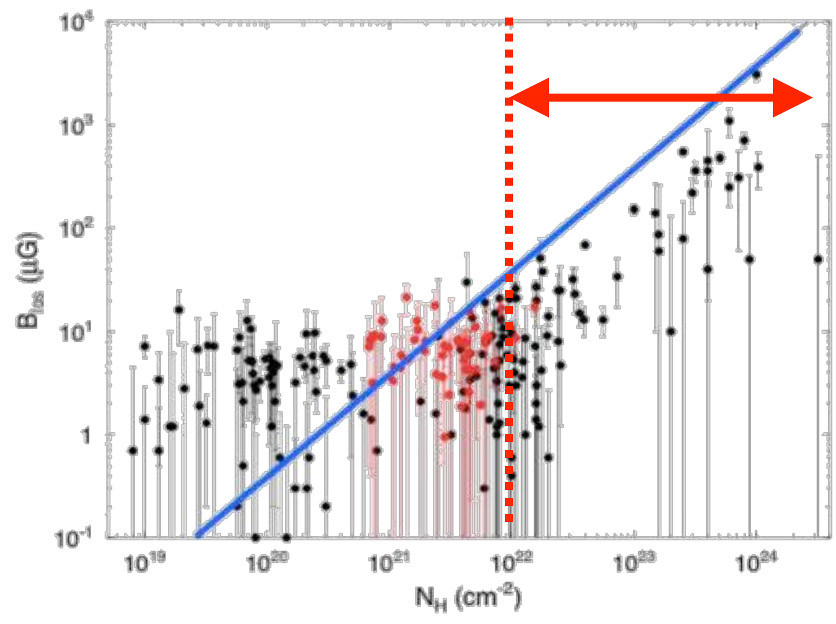
– B increases with N(H) - λ becomes constant ≈ 2-4 (i.e. molecular cores are mildly *supercritical*)

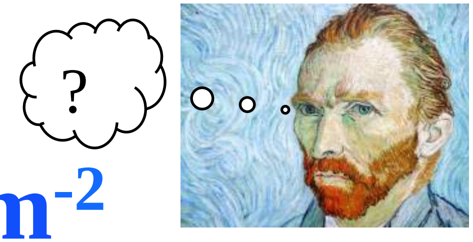


6. Toward a critical N(H) ≈ 10^{22} cm^{-2}

- ***N*(H) ≈ 10^{22} cm^{-2} appears to be a critical value, above which the role of the magnetic field changes.**

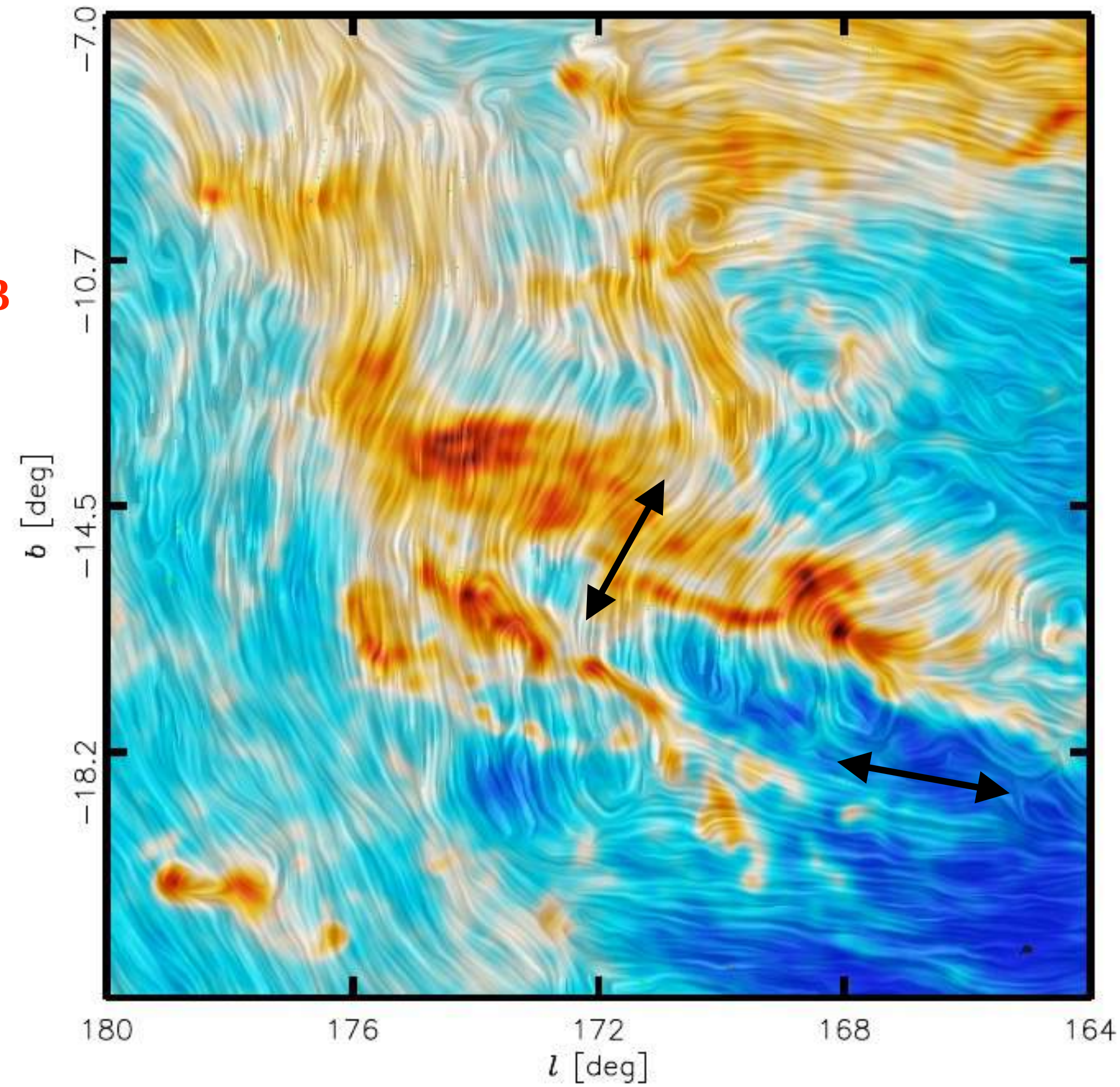
  – As previously noted, *B* rises with *N*(H) for *N*(H) > 10^{22} cm^{-2}





6. Toward a critical $N(\mathrm{H}) \approx 10^{22}$ cm^{-2}

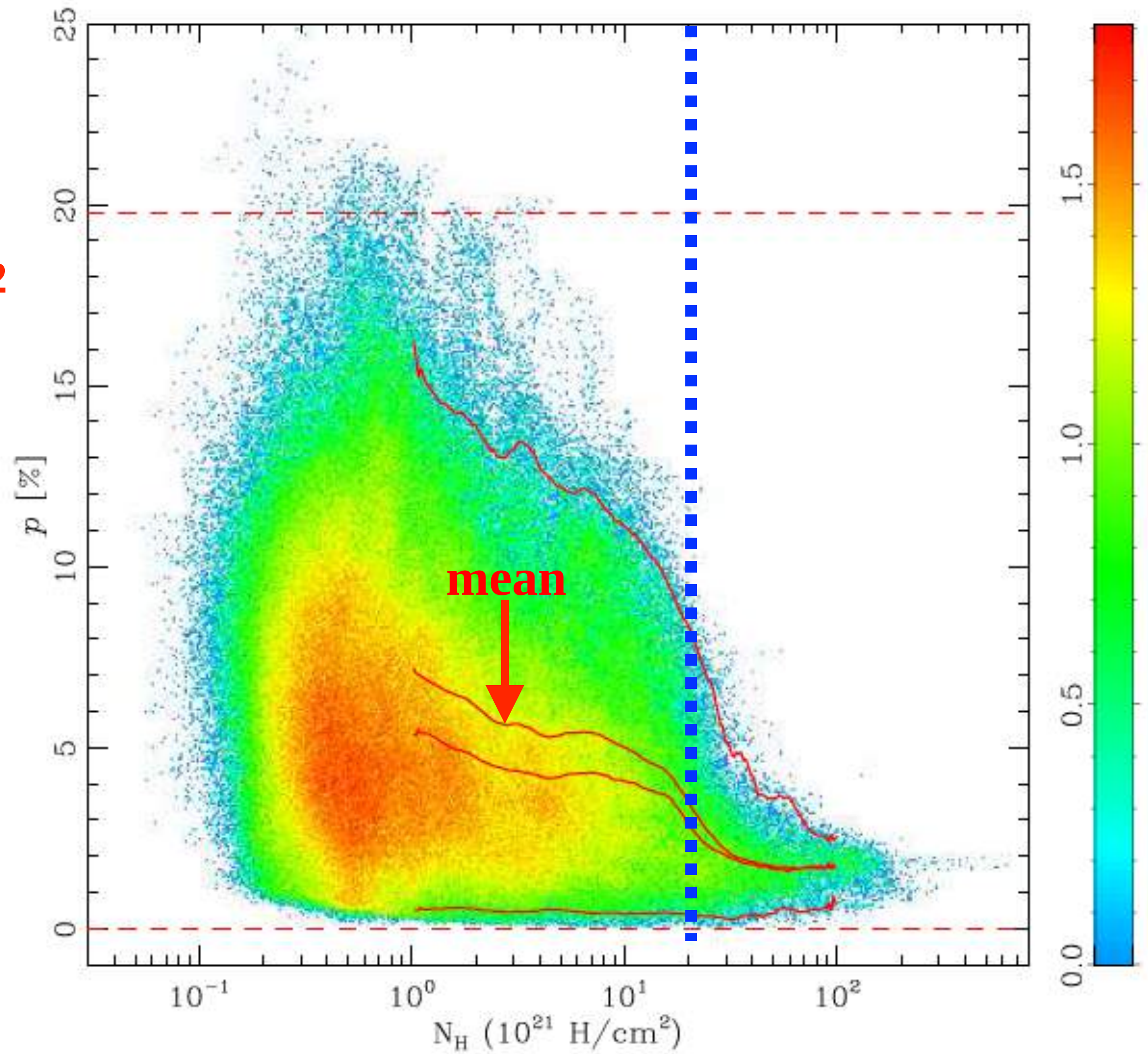
- **Cloud alignment changes from *parallel* to *perpendicular* to *B* for $N(\mathrm{H}) > 5\times10^{21}$ cm^{-3}**



***Taurus Molecular Cloud* - Planck Collaboration XXXV (J. Soler)**

6. Toward a critical N(H) ≈ 10^{22} cm^{-2}

- **Fractional polarization p% declines sharply for N(H) > 2 × 10^{22} cm^{-2}**



Planck Collaboration XIX (J-P Bernard)

6. Toward a critical N(H) ≈ 10^{22} cm^{-2}

Parameter	**Trend**	**If N(H) > (cm^{-2})**	**Reference**
B	Increases	few $\times 10^{22}$	Zeeman results
p %	Decreases sharply	2×10^{22}	Planck XIX (J-P Bernard)
Cloud alignment	Changes from *parallel* to *perpendicular* to B	0.5×10^{22}	Planck XXXV (J. Soler)

6. Toward a Critical N(H) ≈ 10^{22} cm^{-2}

- **Crutcher et al. (2010) analyzed Zeeman data as a function of *volume* density n(H).**

- **They find B rises with n(H) for $n(\mathrm{H})_{crit}$ > 300 cm^{-3}.**

- **If $N(\mathrm{H})_{crit} \approx 10^{22}$ cm^{-2}, then a *critical magnetic scale length* ≈ $N(\mathrm{H})_{crit}/n(\mathrm{H})_{crit} \approx$ 10 pc (sub-GMC size)**

- **10 pc is close to Jeans length for a gas with $n(\mathrm{H}) \approx 300$ cm^{-3} and T = 50 K.**

6. Toward a Critical N(H) $\approx 10^{22}$ cm^{-2}

- **Onset of gravitational instability occurs when *total galactic mid-plane pressure* P_o equals the *gravitational pressure* P_G (the mean weight of material in a cloud)[1].**

- **$P_o \approx 4\times10^{-12}$ dyn cm^{-2} (Boulares & Cox, 1990),
$P_G \approx (3\pi/20)\times G\,\Sigma^2$ (Williams, Blitz & McKee, 1999).**

- **So N(H) $\approx 5\times10^{21}$ cm^{-2}**

[1]C. McKee, lunchtime communication (something I learned at this conference!)

7. Conclusions

- **The role of the magnetic field in cloud evolution changes once self gravitation becomes important.**
  - Size scale ≈ 5 -10 pc (sub-GMC scale)
  - n(H) ≈ few times 100 cm^{-3}
  - So N(H) ≈ 10^{22} cm^{-2}

- **As this point is reached**
  - *B* rises with *N*(H) and *n*(H), λ reaches 2-4 (supercritical)
  - *B* orientation changes from parallel to perpendicular to filament axes
  - *Per cent* linear polarization *p%* declines dramatically