Radiation, Magnetic Fields and Turbulence

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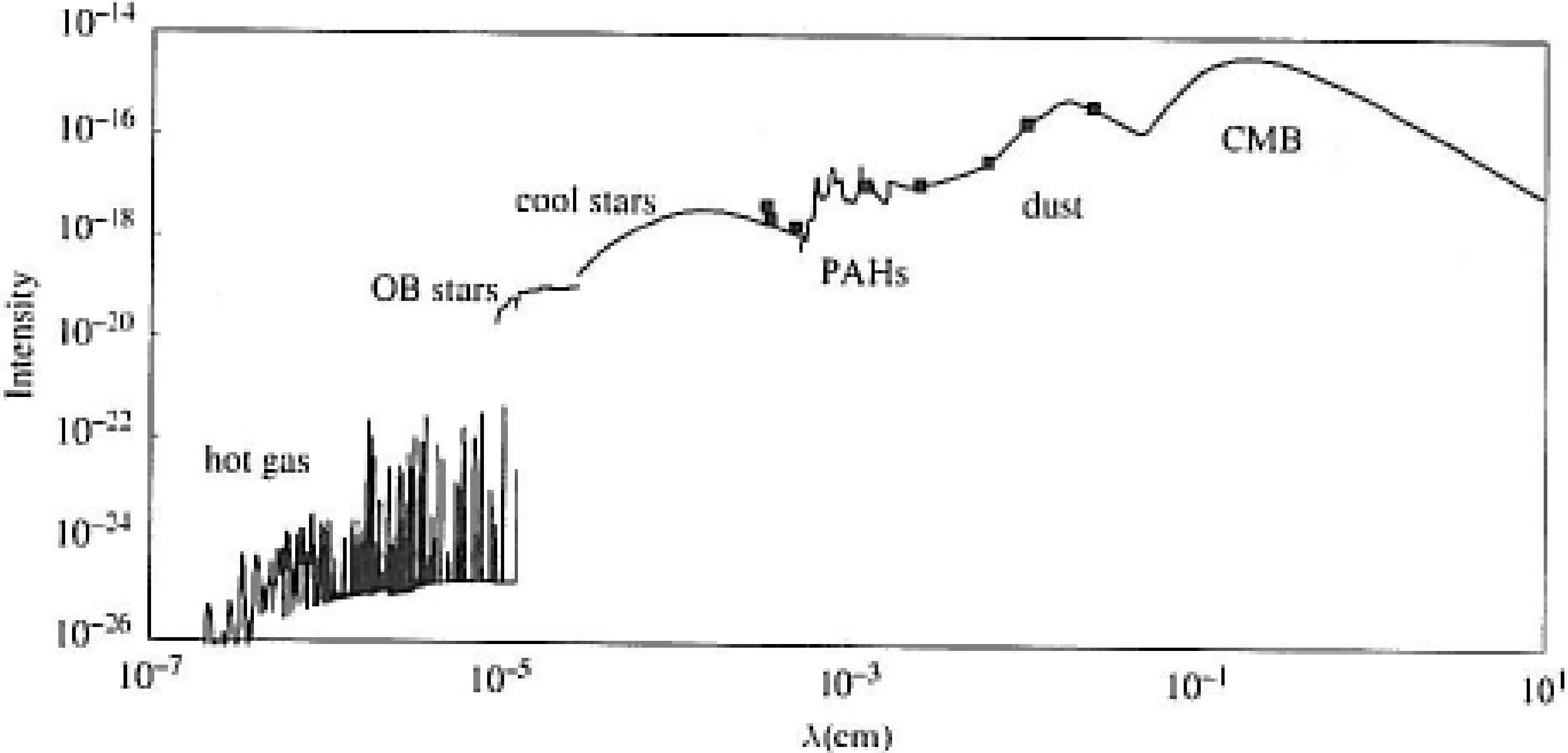
Gyration radius of particle (mass Am_p, energy per nucleon E_n) in a magnetic field B:

$$R = 3.3 \times 10^{12}\mathrm{cm}\frac{E_n(\mathrm{GeV})}{B(\mu\mathrm{G})}A$$

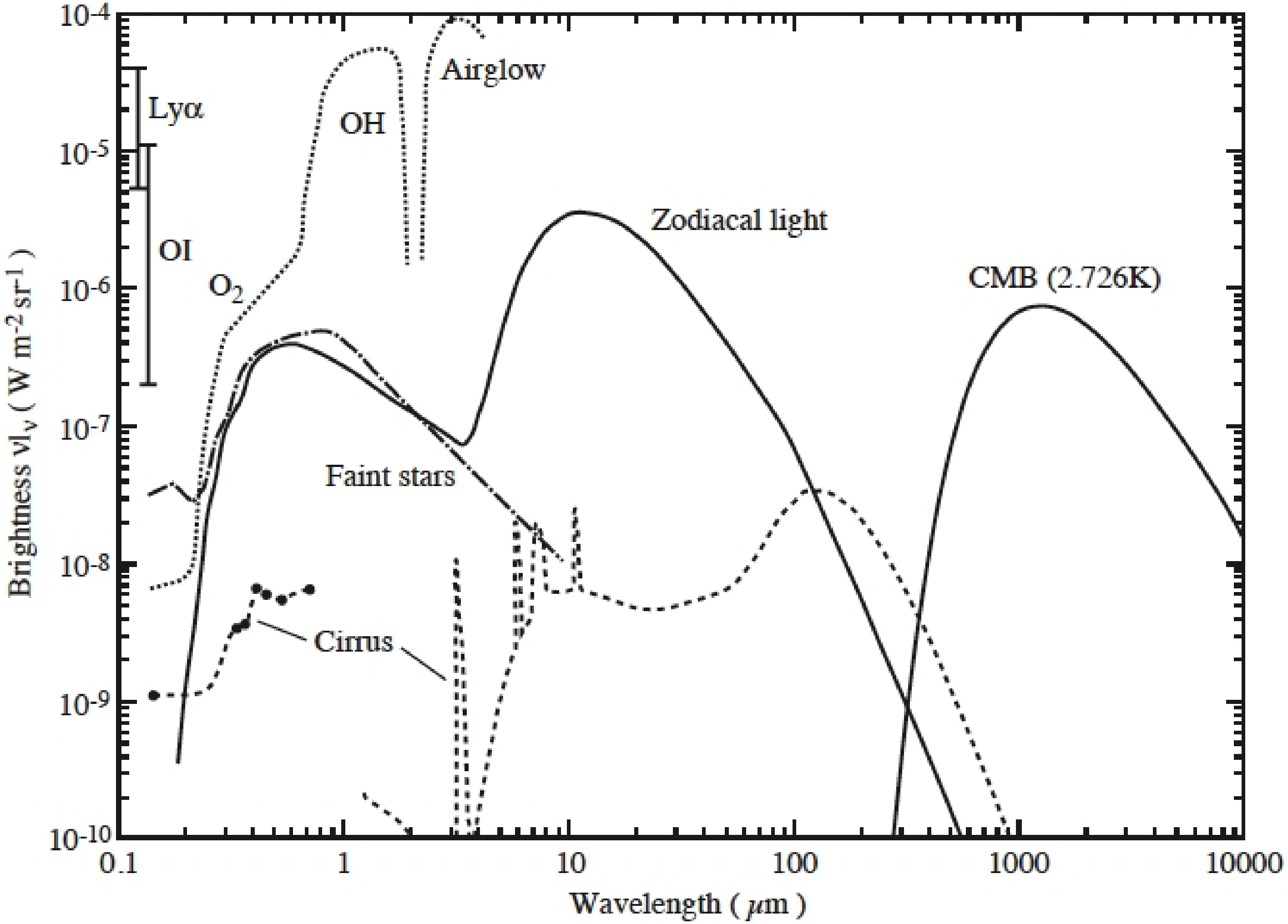
Protons in the ISM ($B = 6\mu$G):
$E_n = 3 \times 10^{11}$ GeV, $R = 50$ kpc, $\sim$ Galaxy size
$E_n = 600$ GeV, $R = 20$ AU, $\sim$ smallest structures in the ISM

1 - RADIATION: Mean Galactic Background Spectrum



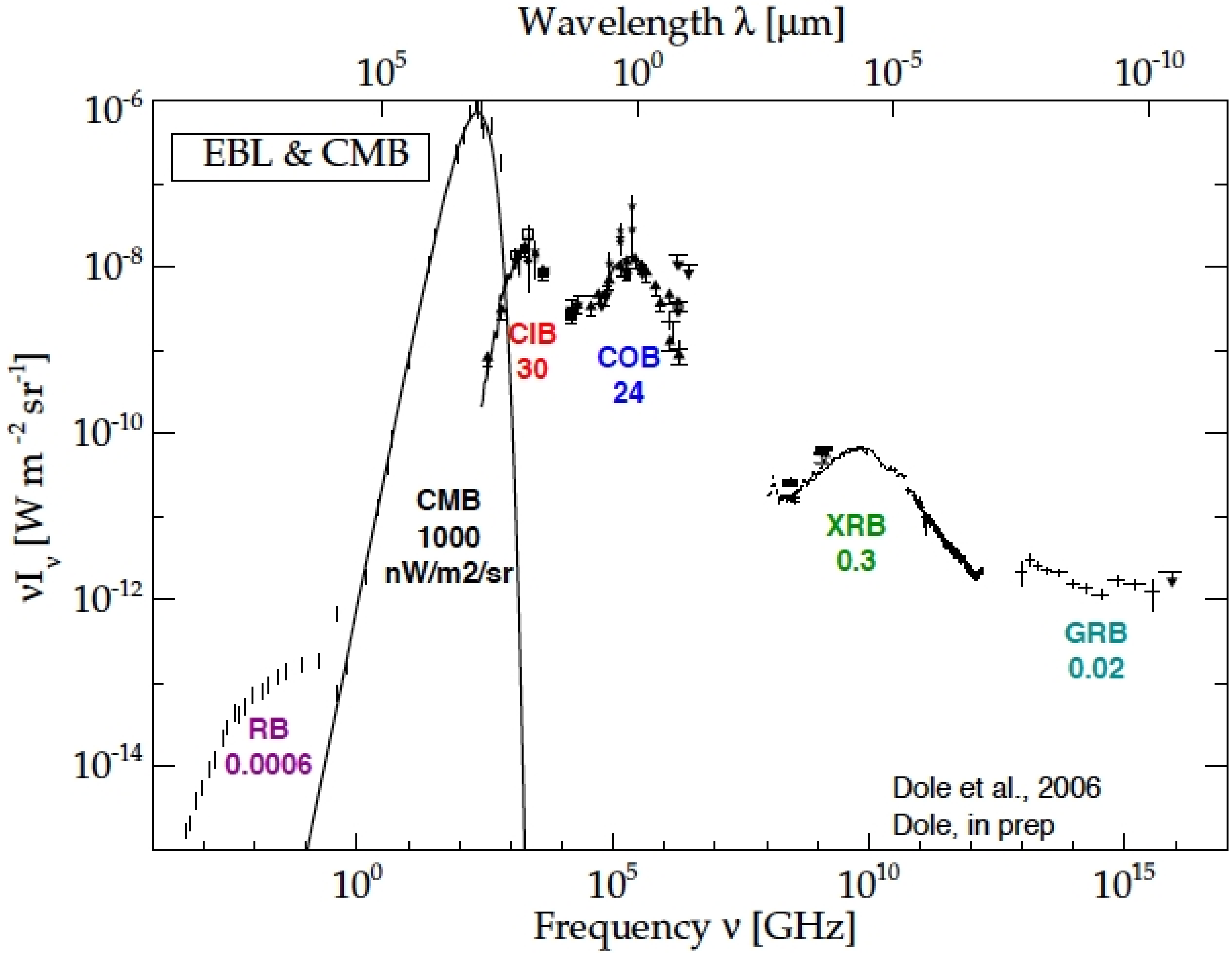
Units: erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}, $\nu I_\nu \sim$ cst above 0.1μm
compilation from Tielens 2006, using Slavin priv. comm., Black 1996, Boulanger 2000, Giard et al. 1994

High Latitude Night sky

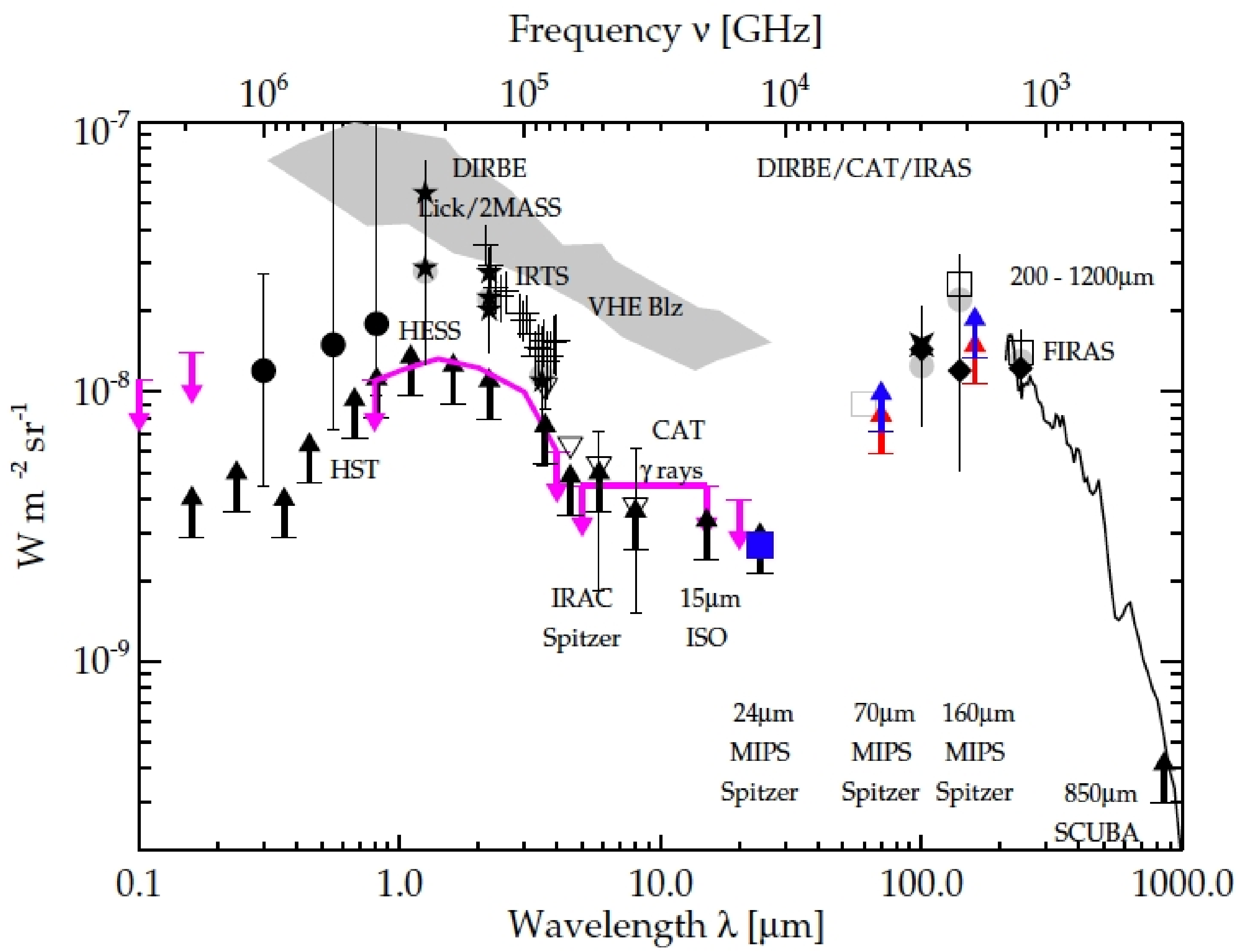


Leinert et al. 1998

Extragalactic Background Light: most recent view



Extragalactic Background



Dole et al. 2006

Visible: NGC1365 spiral galaxy

Barred Galaxy NGC 1365
(VLT UT1 + FORS1)

ESO PR Photo 08a/99 (27 February 1999)

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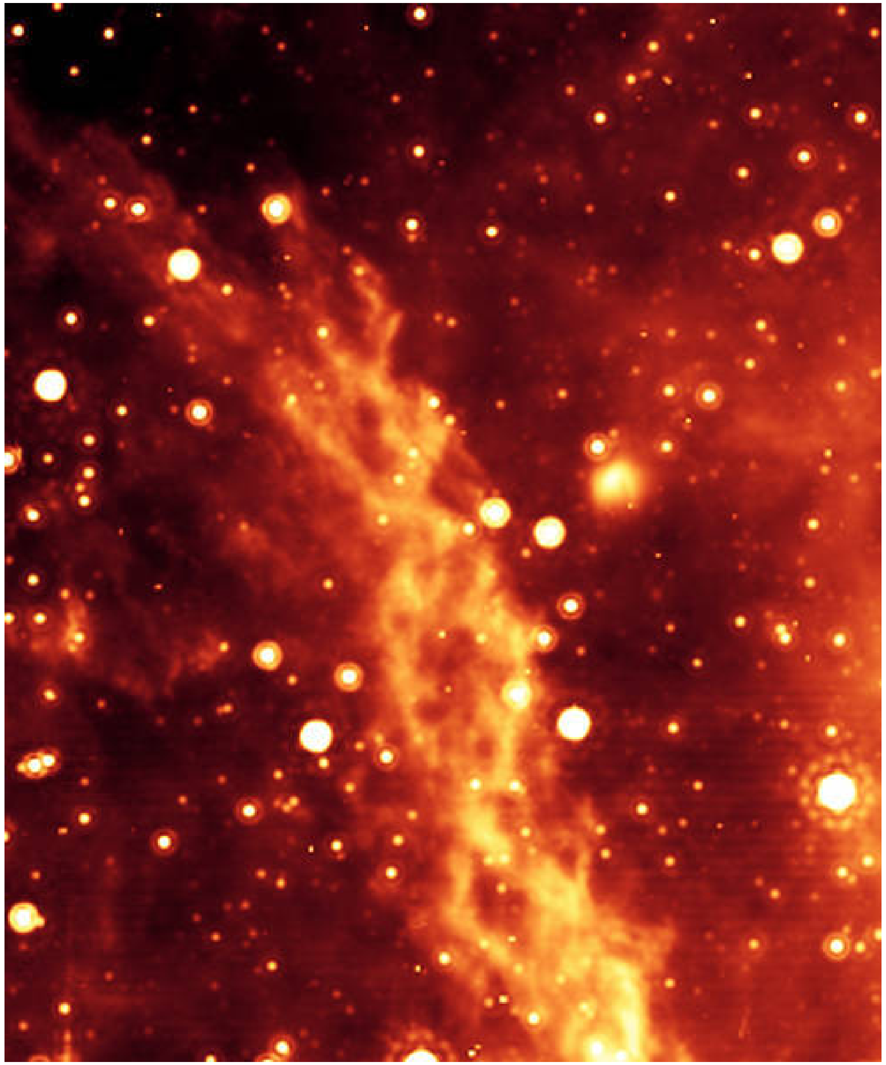
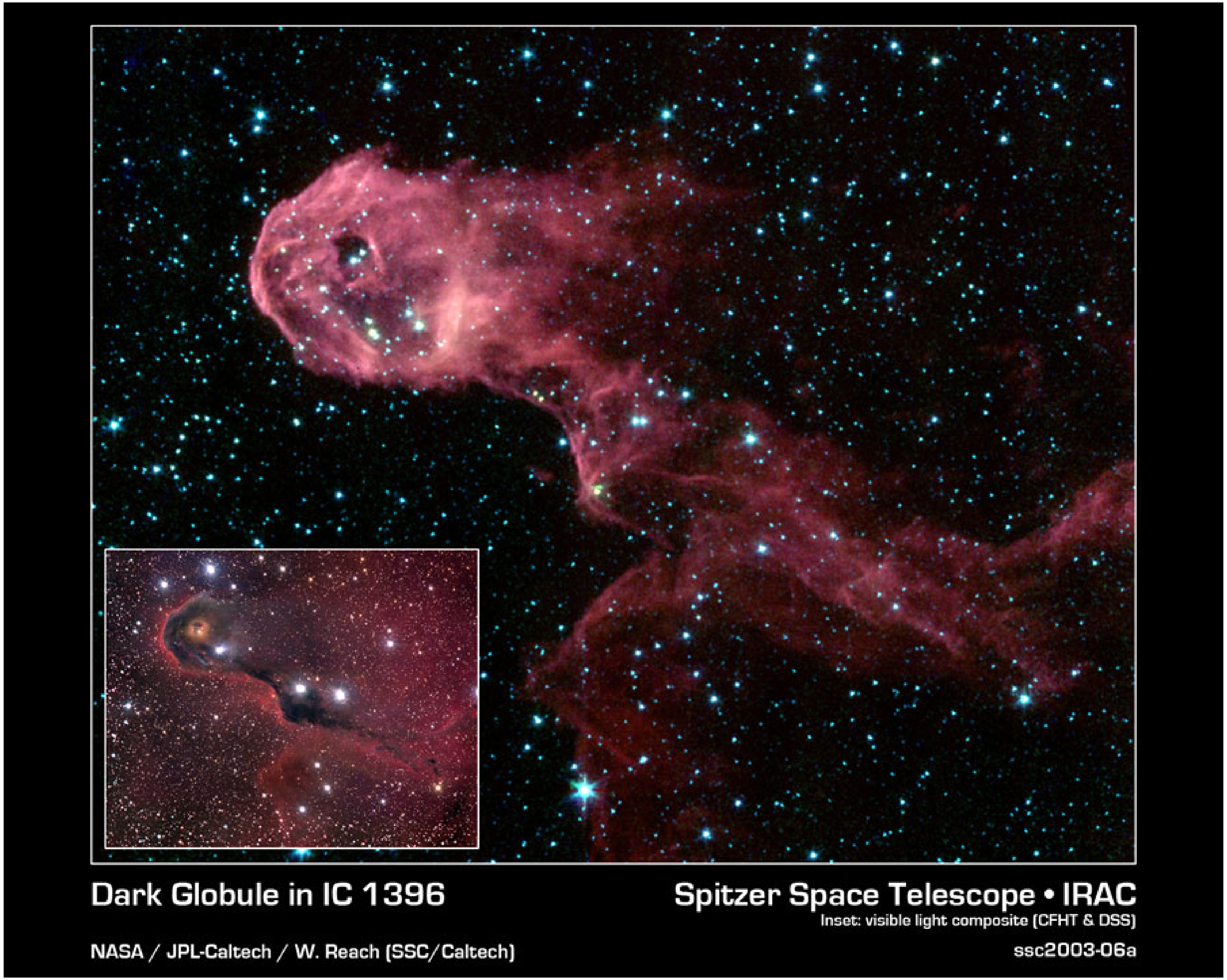
Far-IR: 30 pc-long double helix close to the Galactic Center



SST/MIPS: length 30 pc, $B \sim 10^3$ G, 100 pc from massive BH

Wolpert & Stuart, Nature 2006

Near-IR: Massive Star Forming Region



SST/IRAC: IC 1396 in Cepheus. Resolution 2mpc at $d = 500$ pc

2 - MAGNETIC FIELDS: Methods of B measurements

$B_\perp$ = **B** plane-of-the-sky component
$B_\parallel$ = **B** line-of-sight component
Polarization of dust thermal emission or absorption
Sensitive to $B_\perp$ **orientation**
Polarization of thermal emission $\perp B_\perp$,
Polarization of absorption $\parallel B_\perp$
Faraday Rotation
RM = variation of the polarization angle of a linearly polarized wave due to free electrons
$RM \propto \lambda^2 \int B_\parallel n_e dl$
n_e estimated with DM = plasma dispersion measure
$DM \propto \int n_e dl$
inferred from $\Delta t \propto (\nu_1^{-2} - \nu_2^{-2})\, DM$ (pulsars)
$\rightarrow \langle B_\parallel \rangle = RM/DM$
Polarization of synchrotron emission
Radiation intensity $I(\nu) \propto L B_\perp^{n+1} \nu^{-n}$
Spectrum of relativistic electrons $N(E)dE \propto E^{-p} dE$ with $n = (p-1)/2$
Linearly polarized emission $\perp B_t$

Measurements of B intensity

Zeeman effect: H, OH, CN, C_2H lines

Break of degeneracy of a level of total angular momentum **J=L+S** by **B** in an atom or molecule of non-zero magnetic momentum due to either:

- the total orbital momentum of electrons
- the spin of an unpaired electron,

$\mu_B \propto \hbar e/2m_e c = 1.4$ Hz/μG, Bohr magneton

- the nucleus spin, $\mu_p \propto \mu_B/1840$

$\nu_{\sigma\pm} = \nu_0 \pm \nu_Z$ circularly polarized

$\nu_\pi = \nu_0$, linearly polarized

$\nu_Z = B_{\parallel} Z$, Z in Hz/μG depends on atom/radical/molecule and transition

Fluctuation of **B** orientation in the POS

Statistical method proposed by Chandrasekhar & Fermi (1953):

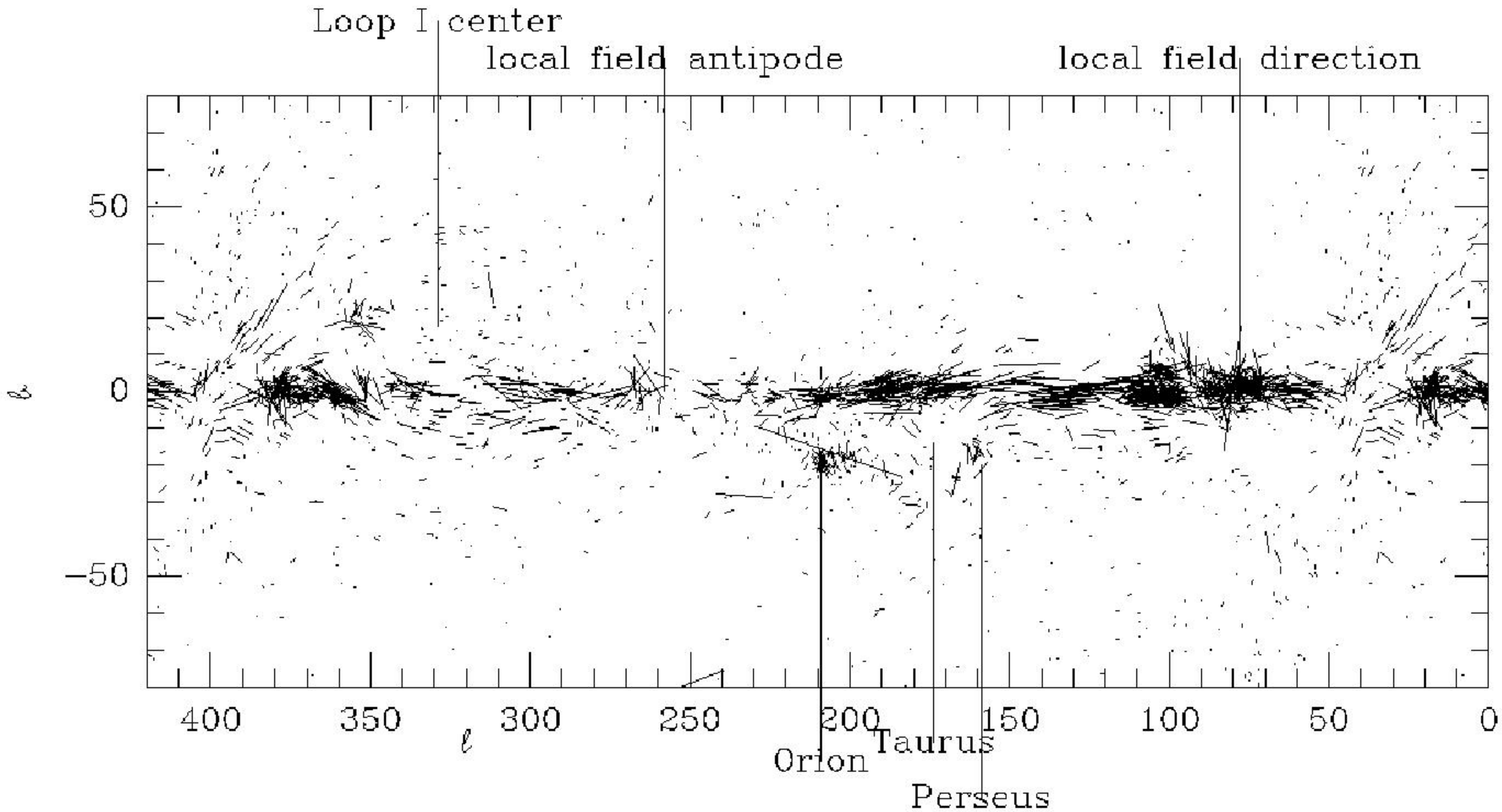
$B_\perp = Q\sqrt{4\pi\rho}\delta v/\delta\phi$

$\delta\phi = \delta B_\perp / B_\perp$

$Q \approx 0.5$ from MHD numerical simulations (Ostriker et al. 2001)

two complementary methods

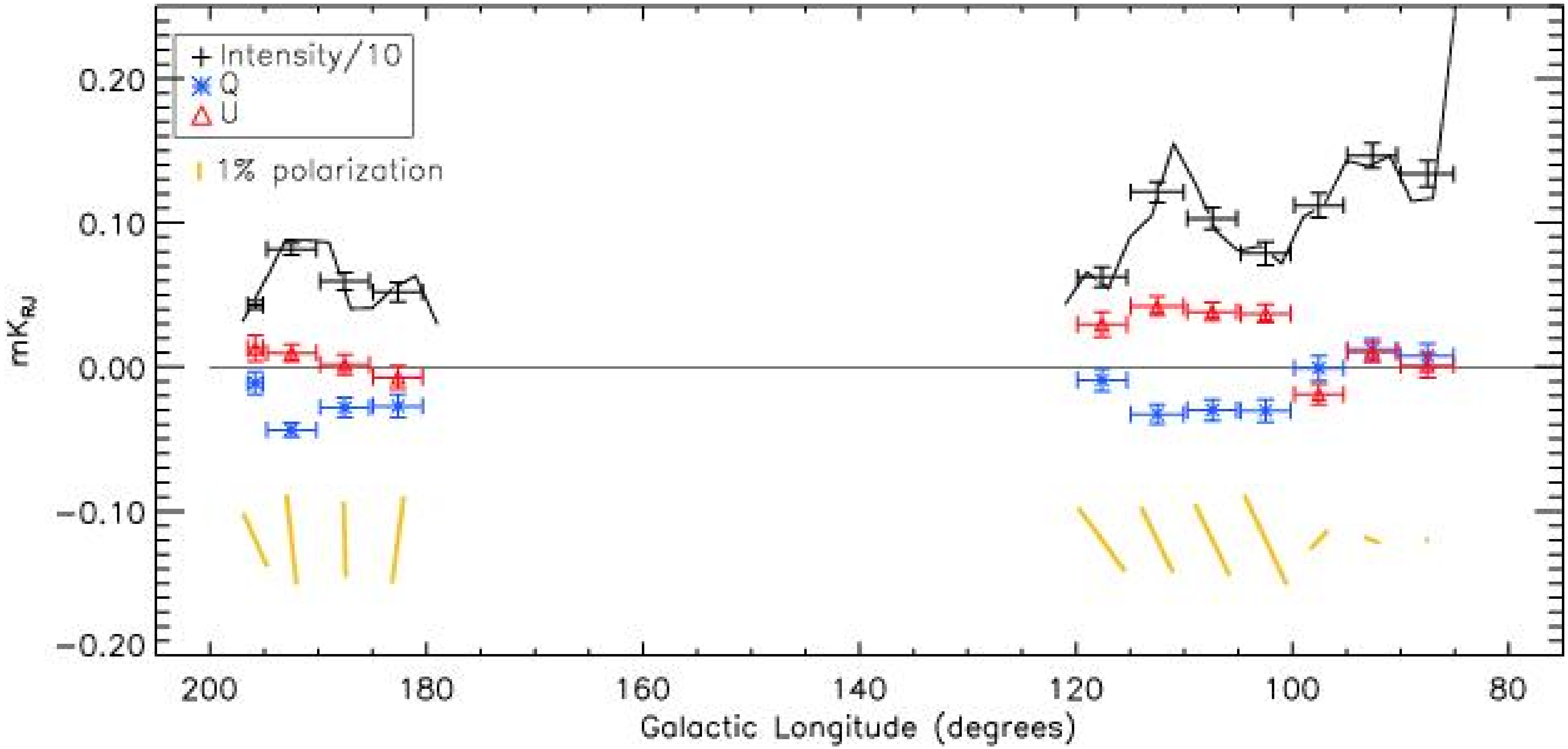
Optical starlight polarization due to dust absorption



10^4 stars, polarization $\parallel B_\perp$, max 3%, $B_u/B_r \sim 0.8$

(Crutcher, Heiles, Troland 2001)

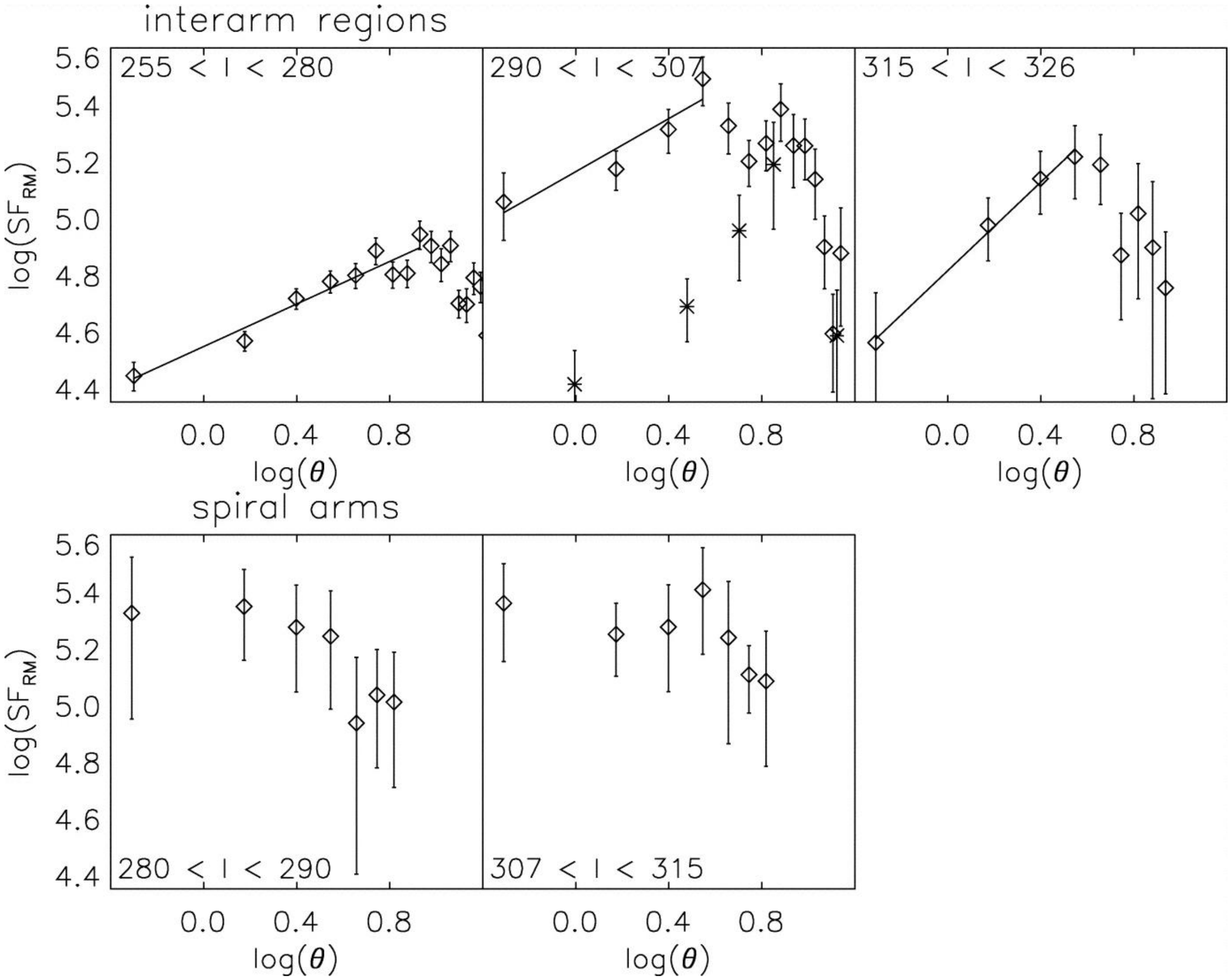
Polarization of diffuse dust emission: Archeops balloon 850 μm



Polarisation $\perp B_\perp$

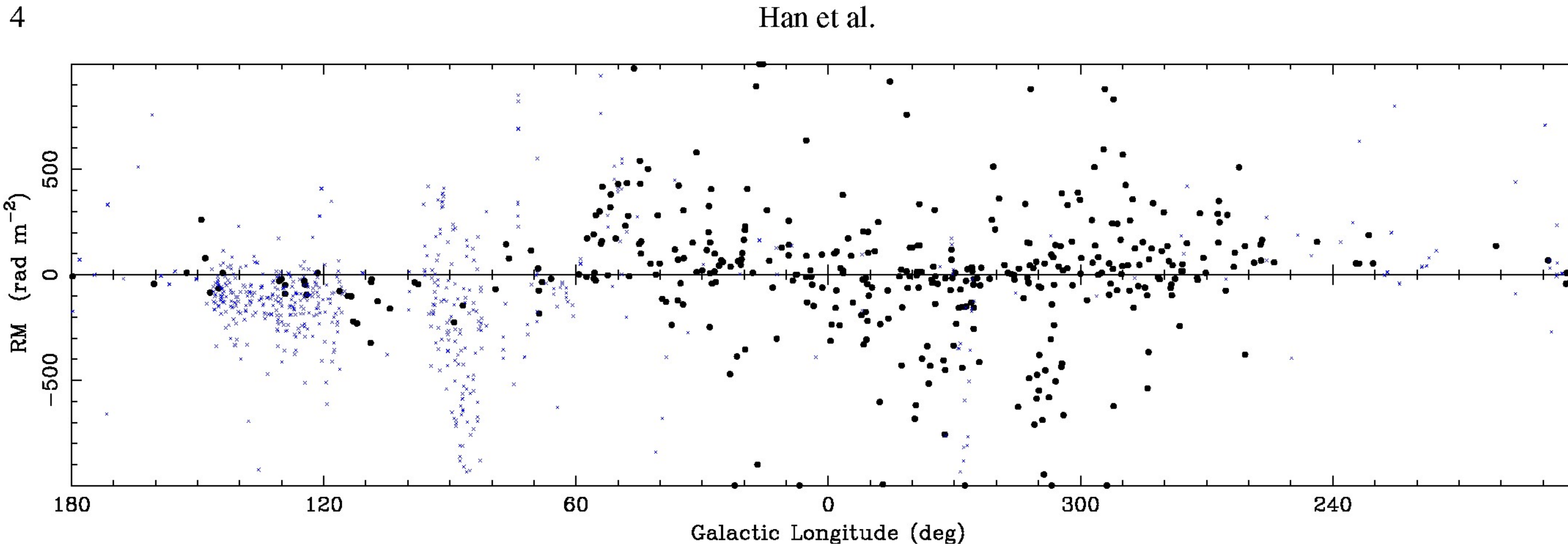
Average $|b| < 2^\circ$ (Benoît et al. 2004)

Enhanced small scale Faraday rotation in spiral arms



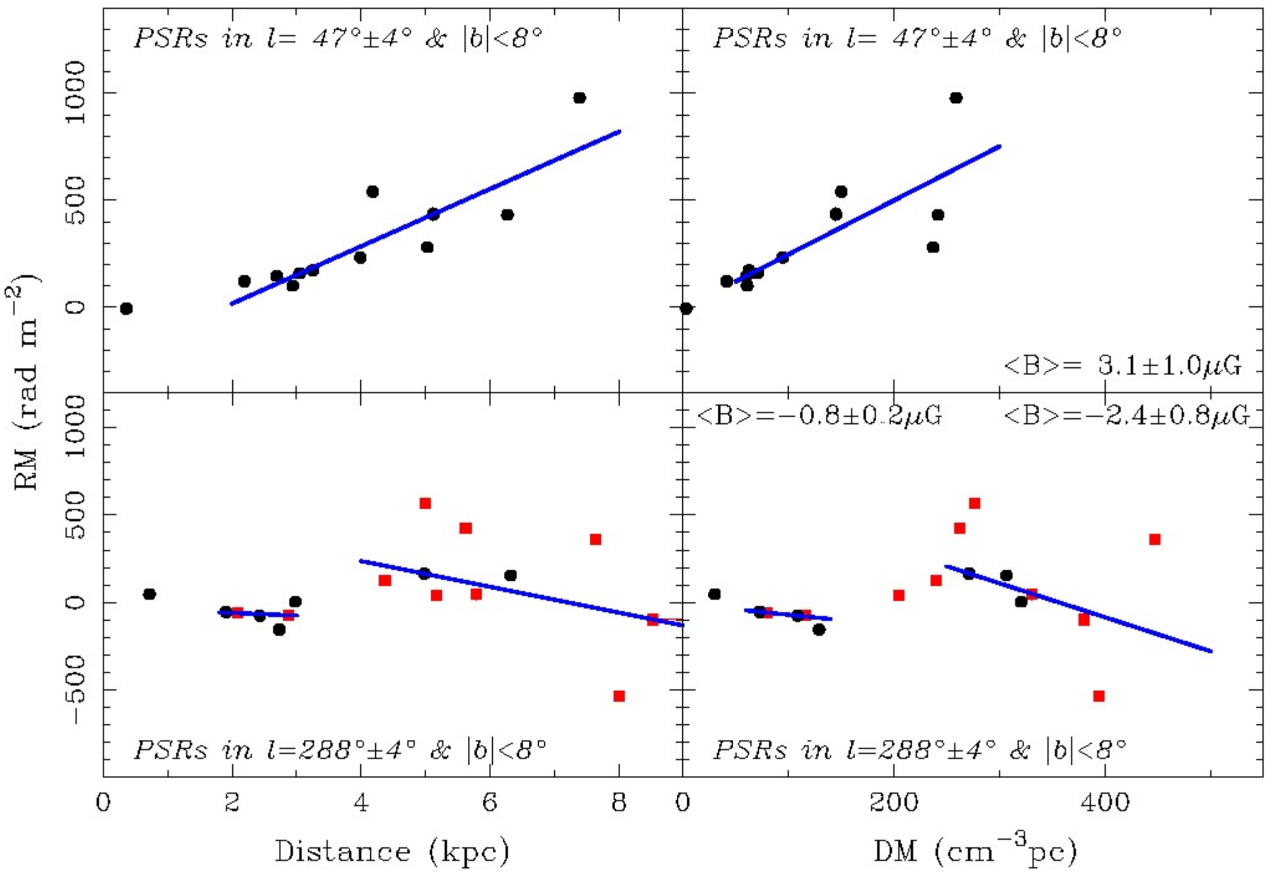
RM structure functions: more field coherence between arms (Haverkorn M. et al. 2006)

Large scale structure of galactic magnetic field



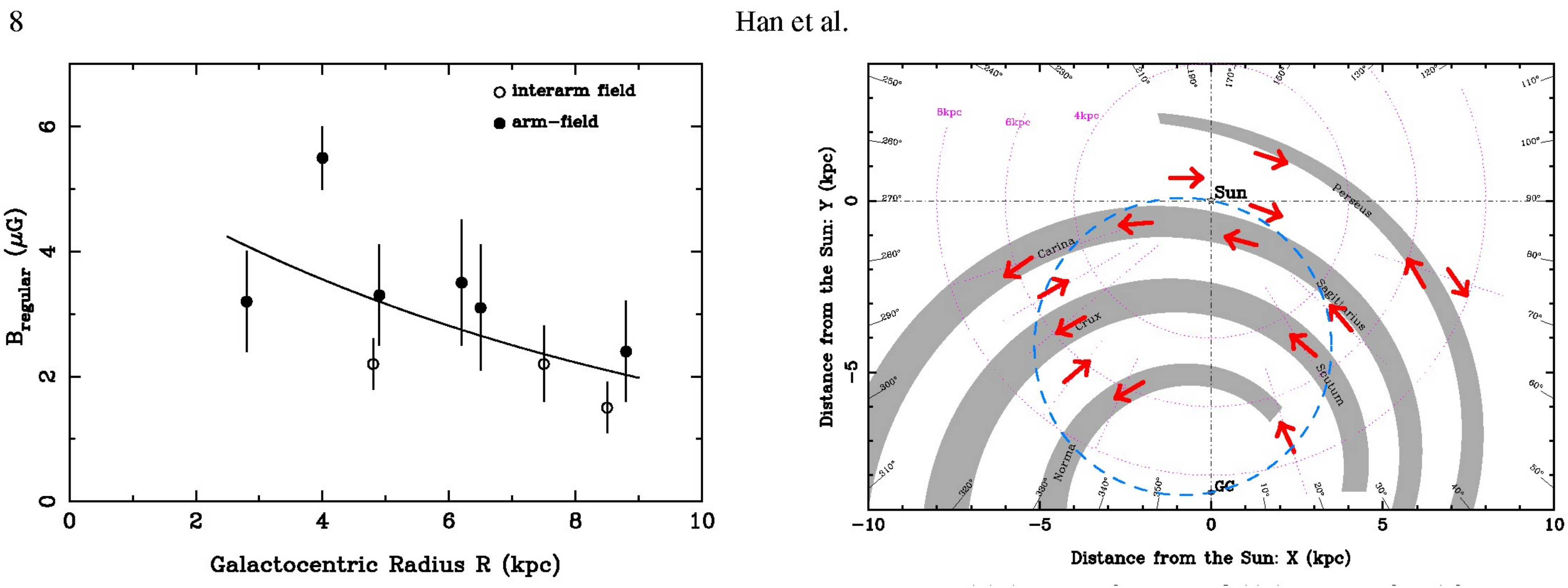
RMs from pulsars (dots), EG radio sources (crosses) (Han et al. 2006)

Examples of B determinations from RM/DM



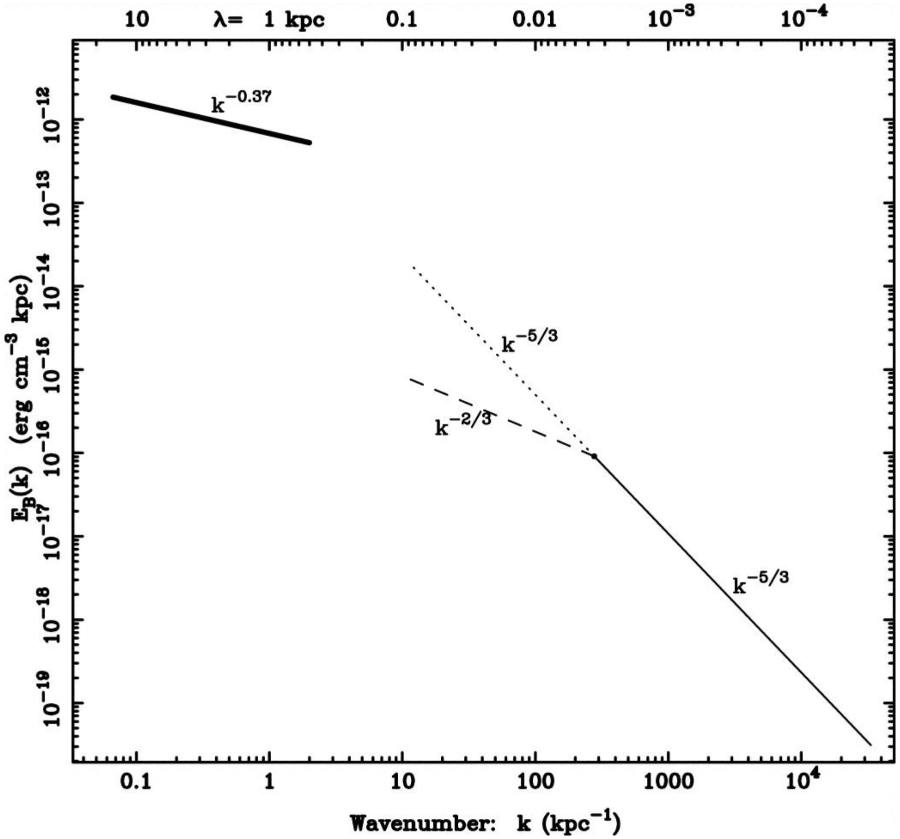
223 RM measurements, (Han et al. 2006)

Arm/Interarm field: intensity and reversals



Han et al. 2006

Composite magnetic energy spectrum



Han, Ferrière & Manchester 2004

Combined RM/DM of 490 pulsars known distances, up to 10 kpc

$E_B(k) = Ck^{-\alpha}$, $\alpha = -0.37 \pm 0.10$, $B_{rms} \sim 6\mu$G

Small scale spectrum from high latitude field, Hα data (Minter & Spangler 1996)

3 pc $< l <$100pc, uncertain 2-D turbulence

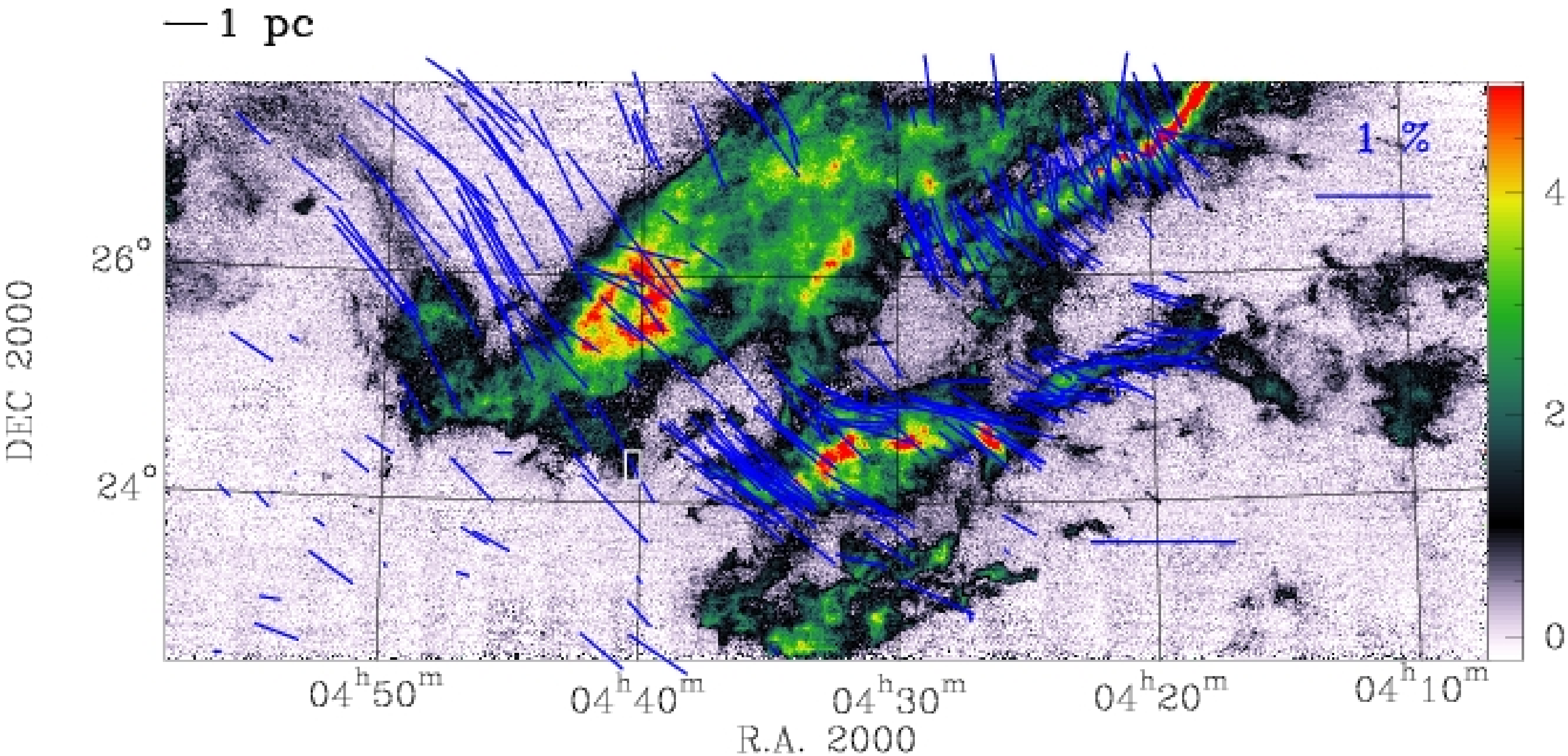
Possibly significant discontinuity at $\sim$ 80 pc:

- energy injection scale: inverse cascade of magnetic helicity, direct cascade of magnetic energy
- spectra of different regions

Random B_r versus uniform B_u magnetic field?

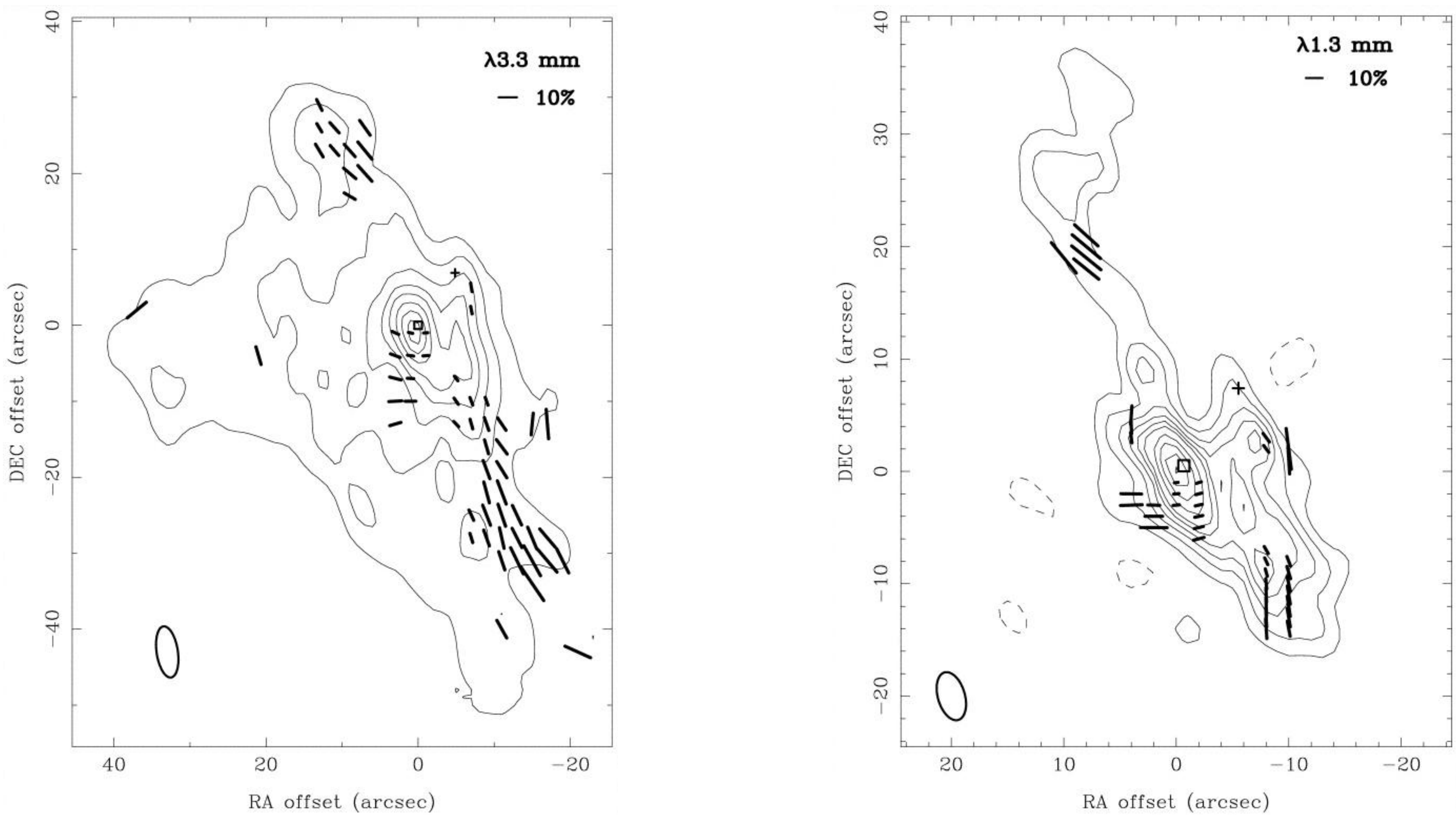
- At large scales (starlight polarization and synchrotron radiation):
$B_r \sim B_u$
- Field fluctuations are parallel to **B** (field reversals)
- RM pulsars $B_r \sim 5\mu$G, $B_u \sim 1.5\mu$G
- More field coherence in interarm regions, less coherence in spiral arms and giant SFR (at 100 pc scale)
- B_r/B_u decreases as density increases, at small scales in star forming regions (dense cores)

Taurus molecular complex: ^{13}CO and B direction



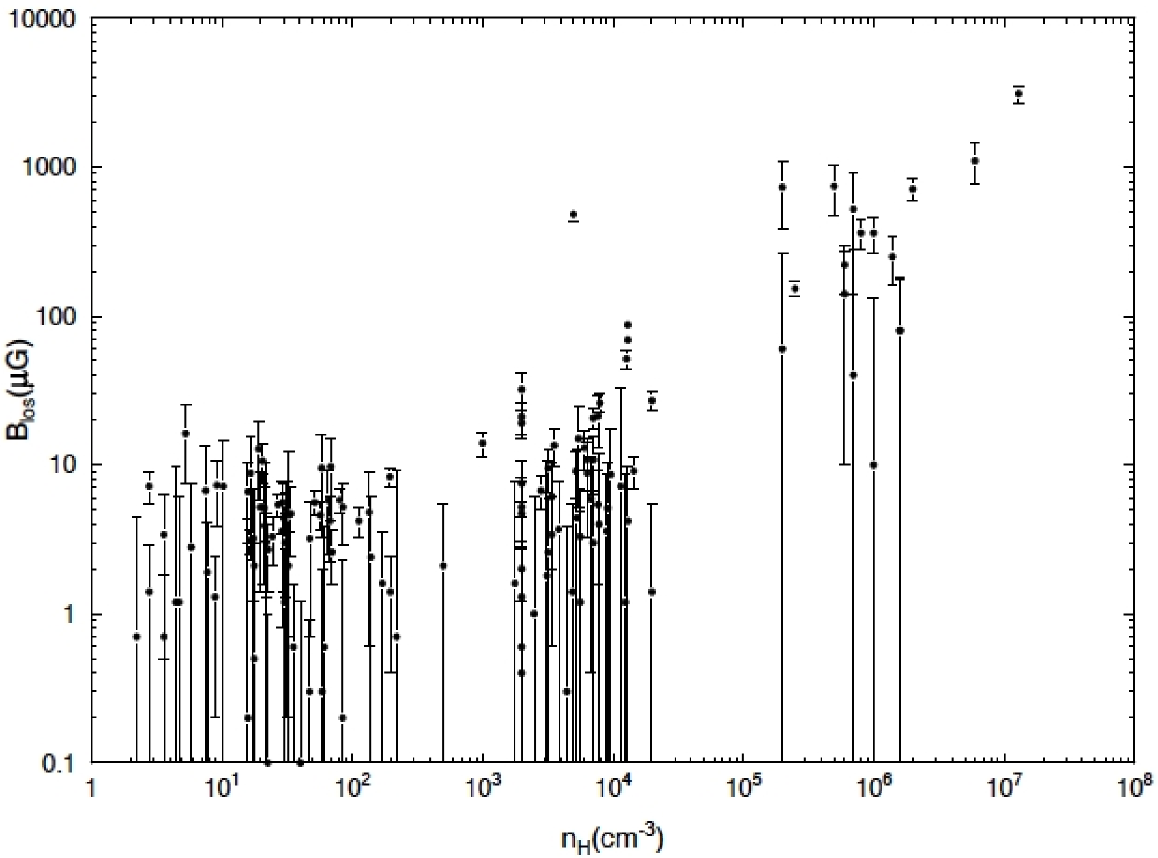
P. Hily-Blant (PhD, 2004), Golsdmith et al. (2008)

Polarization of the dust millimeter emission in a star forming region



Orion-KL Rao et al. 1998

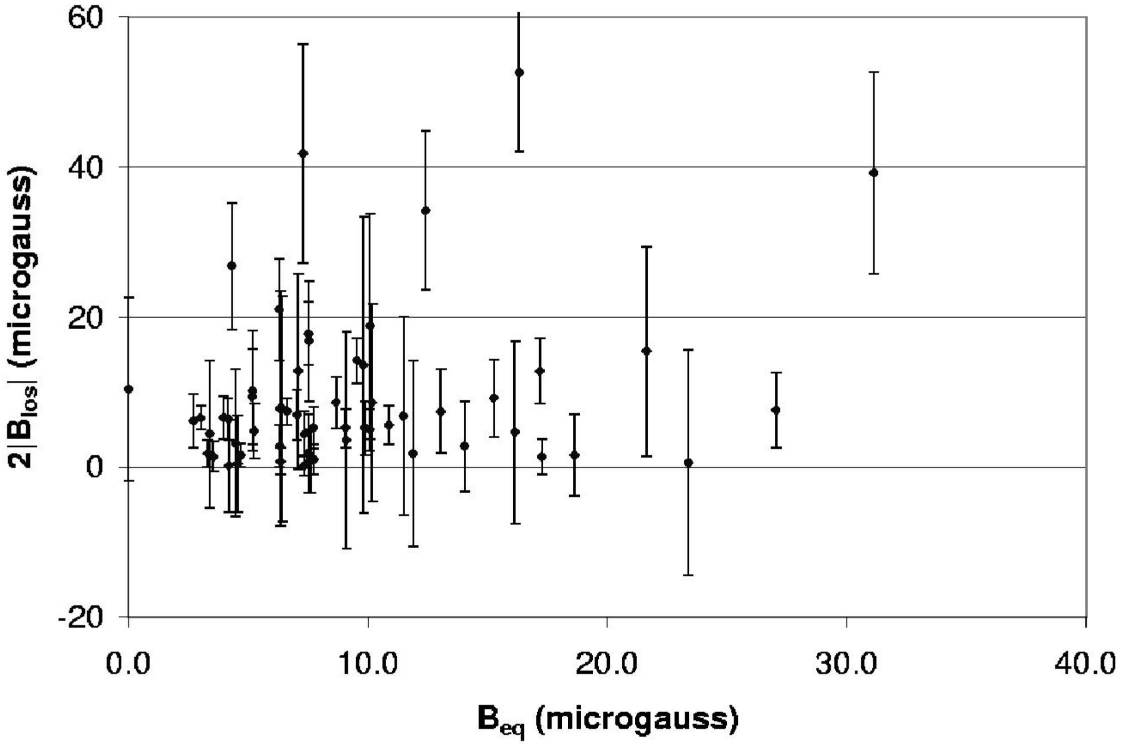
B_{tot} vs. density from Bayesian analysis of Zeeman effect results



Median free parameters $B_0 = 10\ \mu$G, $n_0 = 300\ \text{cm}^{-3}$, $\alpha = 0.67$, $f = 0.03$

Crutcher et al. in prep.

CNM: non-thermal kinetic energy and magnétic energy

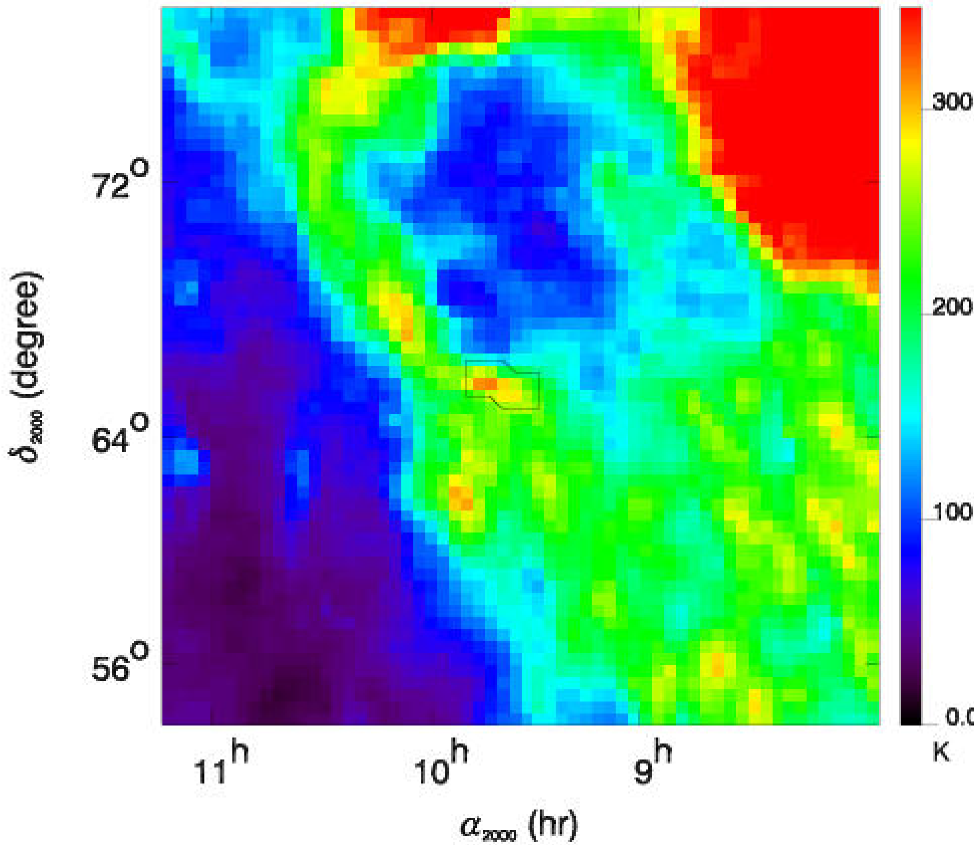


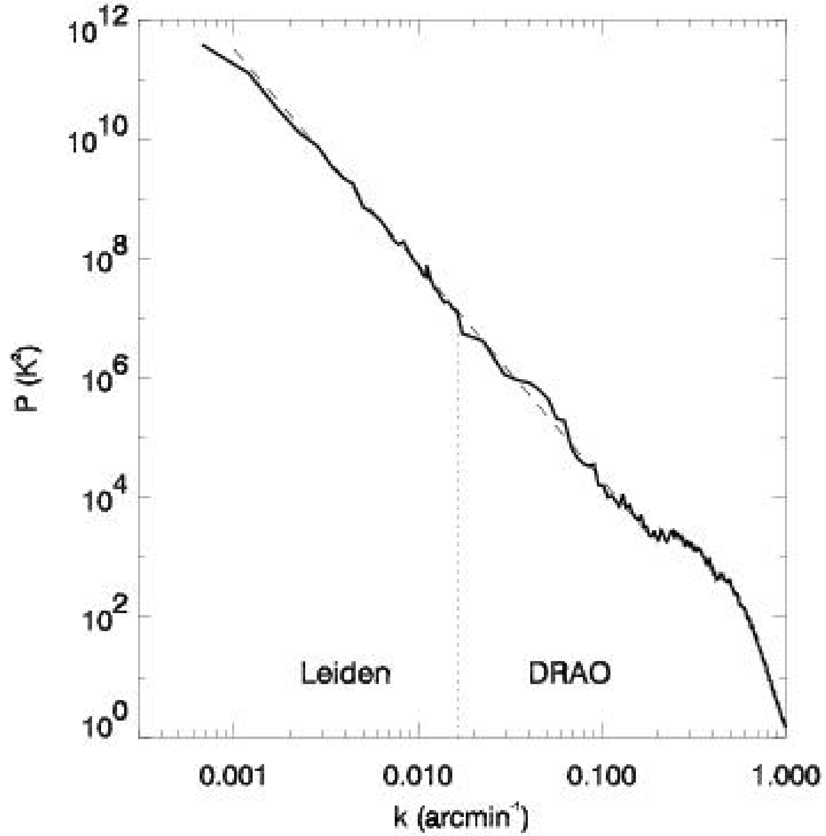
(Crutcher et al. 2001) $B_{eq} = 0.4\sqrt{n_{\mathrm{H}}}\Delta v_{NT}$

$\mid B_{los} \mid$ from HI Zeeman, B_{eq} for $n_{\mathrm{H}} = 100$ cm^{-3}

$\rightarrow$ **CNM close to magnetic/kinetic equipartition**

3 - TURBULENCE - HI emission in the Ursa Major high latitude cloud

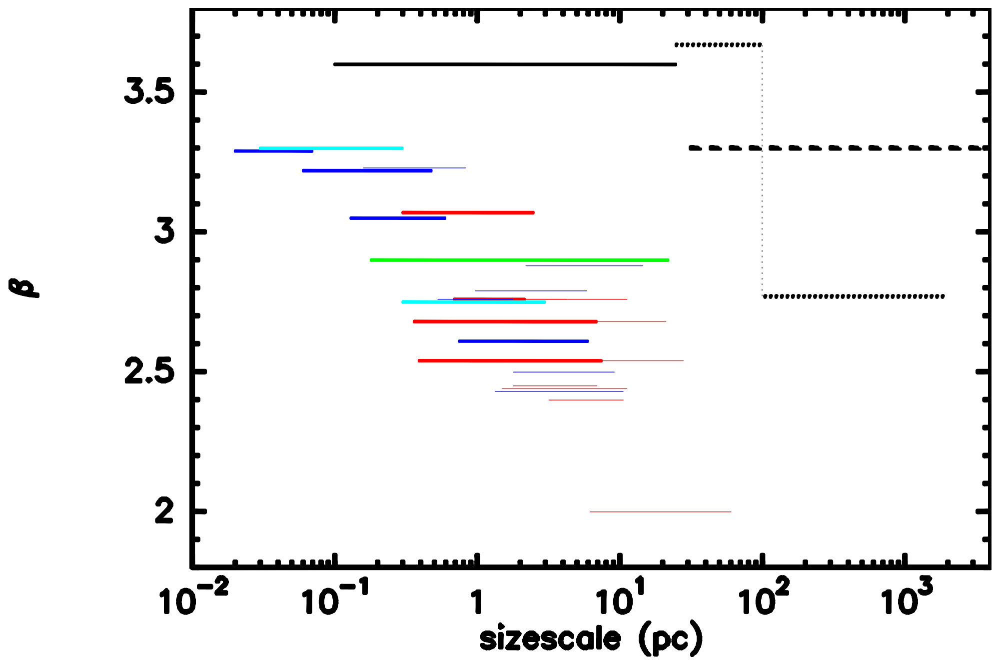




HI data from Leiden-Dwingeloo survey (Hartmann & Burton) +DRAO interferometer, slope power spectrum -3.6±0.1, Kolmogorov

Miville-Deschênes et al. 2003

Power spectra of HI and CO(1-0) integrated emission



Falgarone, Levrier, Hily-Blant 2003

For fBm fields in 3-dim space,

Stutzki et al. (1998)

β=γ(3-α)

α=slope of mass spectrum

$\sim$ 1.8 from $M = 10^{-3}$ to 10^{6} $M_\odot$

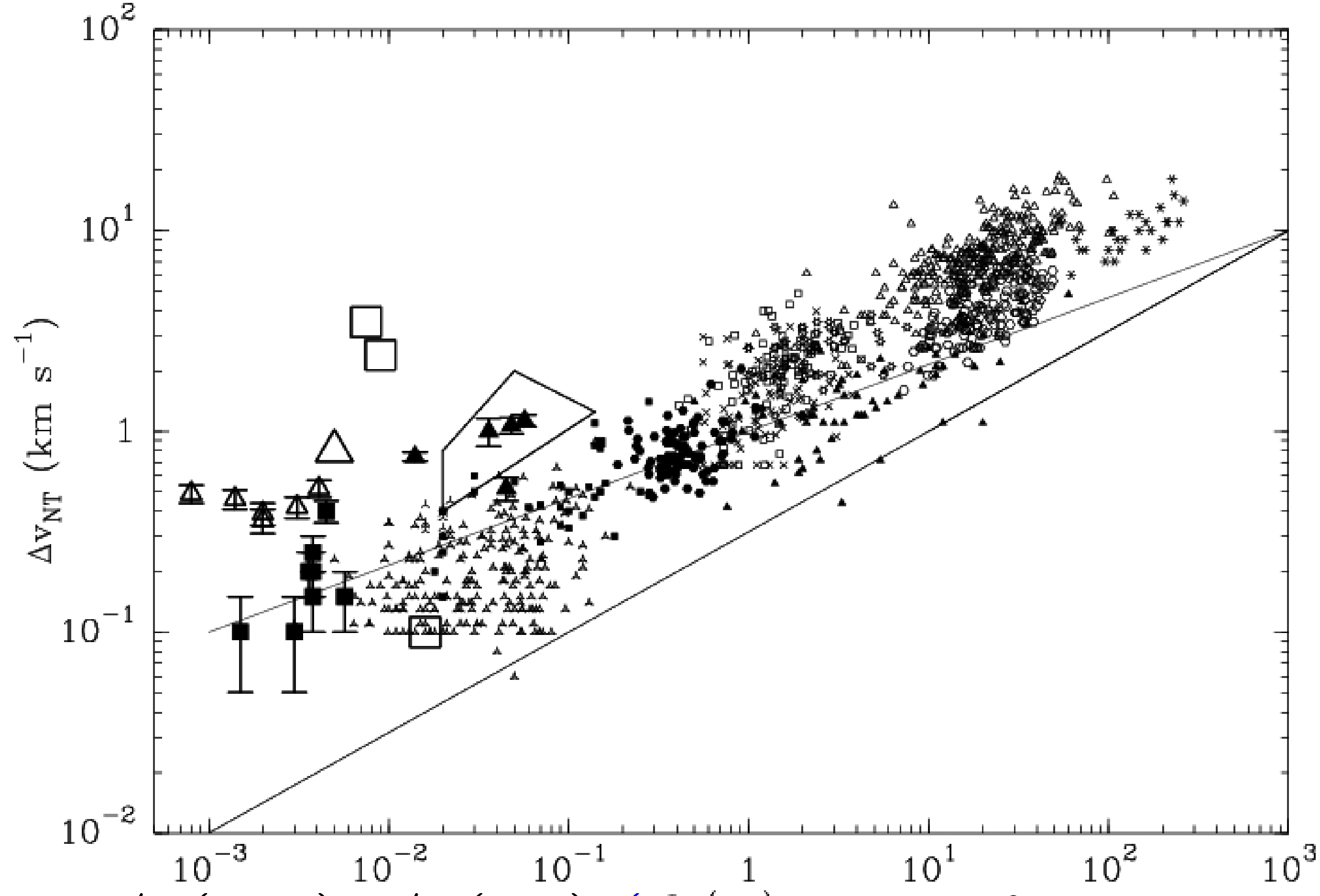
β= slope of power spectrum

γ=fractal dimension [γ=3 for β=3.6]

Data from Bensch et al. (2001), Gautier et al. (1992), Elmegreen et al. (2001), Stanimirovic & Lazarian (2001), Miville-Deschênes et al. (2003)

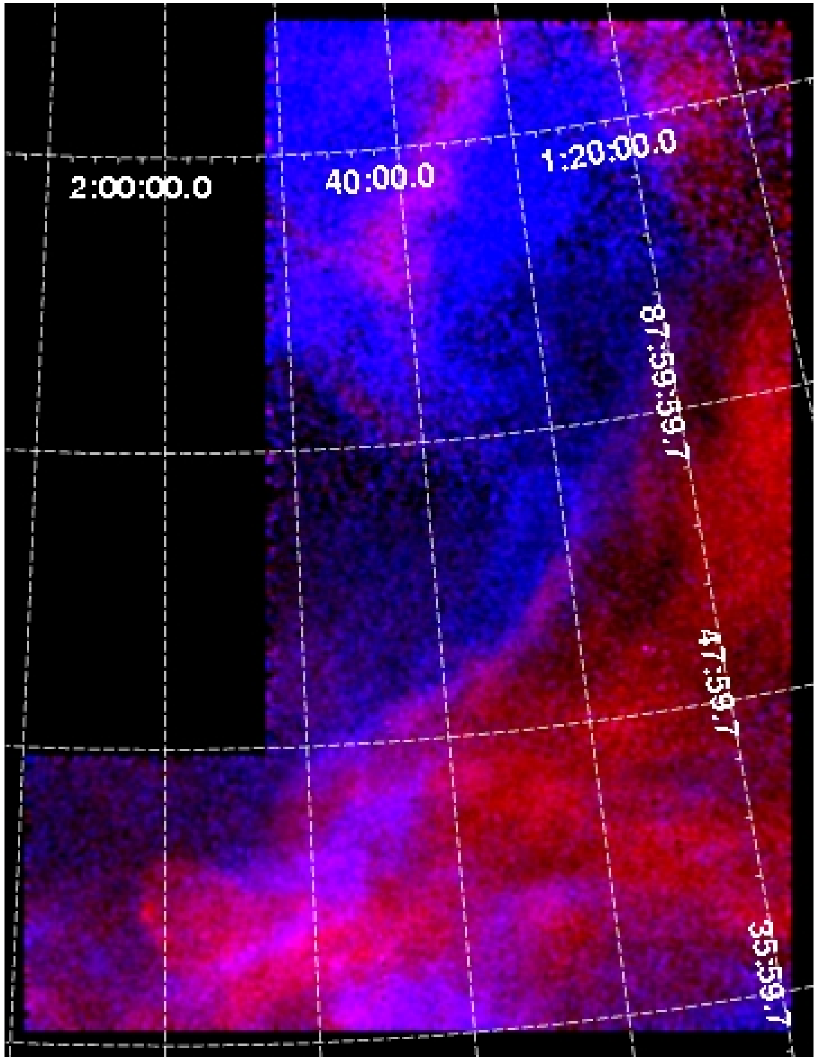
Common statistical properties below 10^{-2}pc?

Size-linewidth scaling law from the $^{12}CO(1-0)$ line



Slopes: 1/2 (thick), 1/3 (thin), (Falgarone, Pety & Hily-Blant 2009)

Parsec-scale field in a turbulent high latitude cloud



IRAM-30m, HERA mosaic,
On-The-Fly + FS mapping,

Polaris Flare
$A_v = 0.6$ to 0.8 mag
$^{12}CO(2\text{-}1)$ line

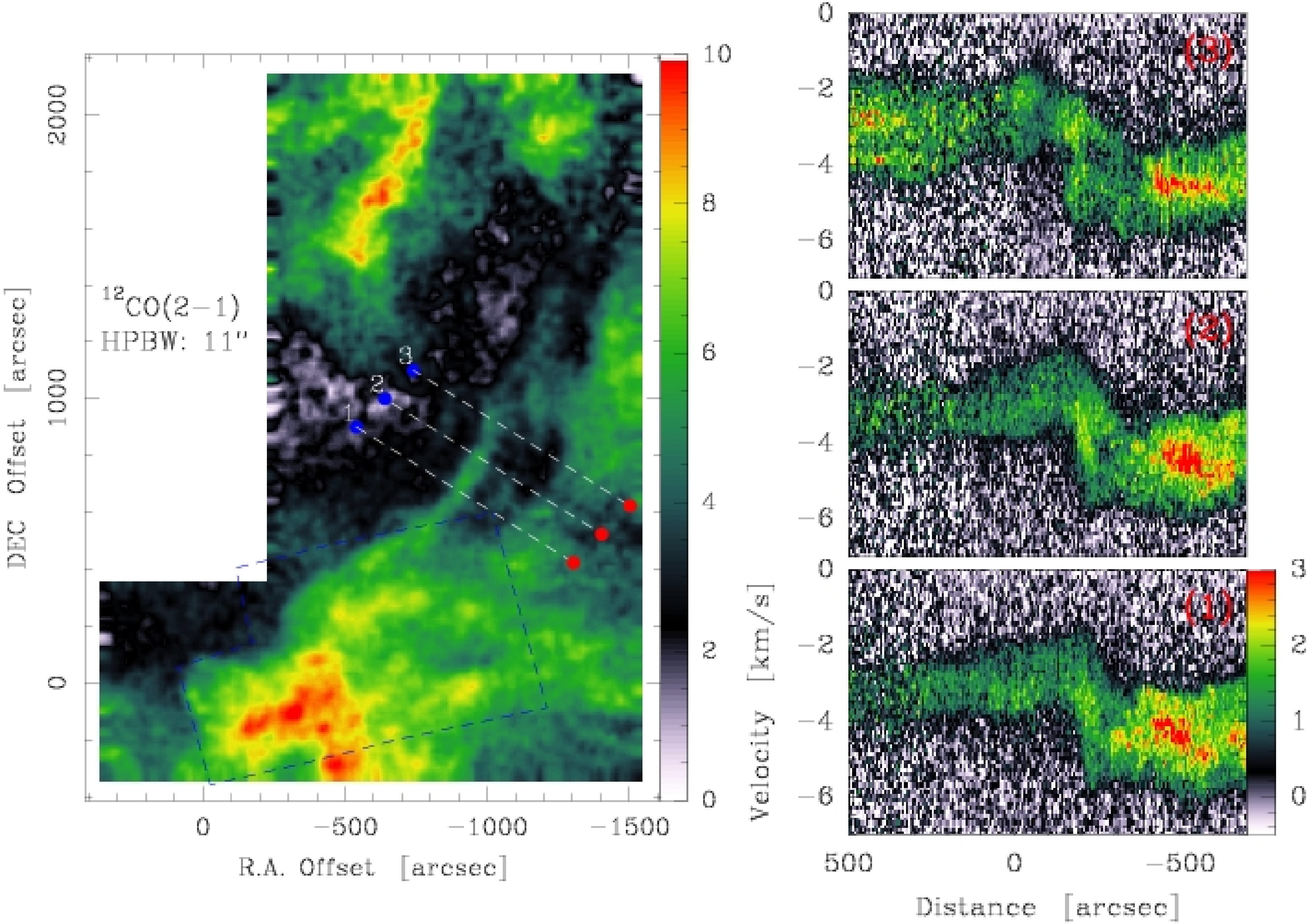
1.5 million spectra,
$\sim 10^5$ independent spectra,

Field size: 43'$\times$ 33', ~ 2 pc
Pixel size: 7.5 mpc

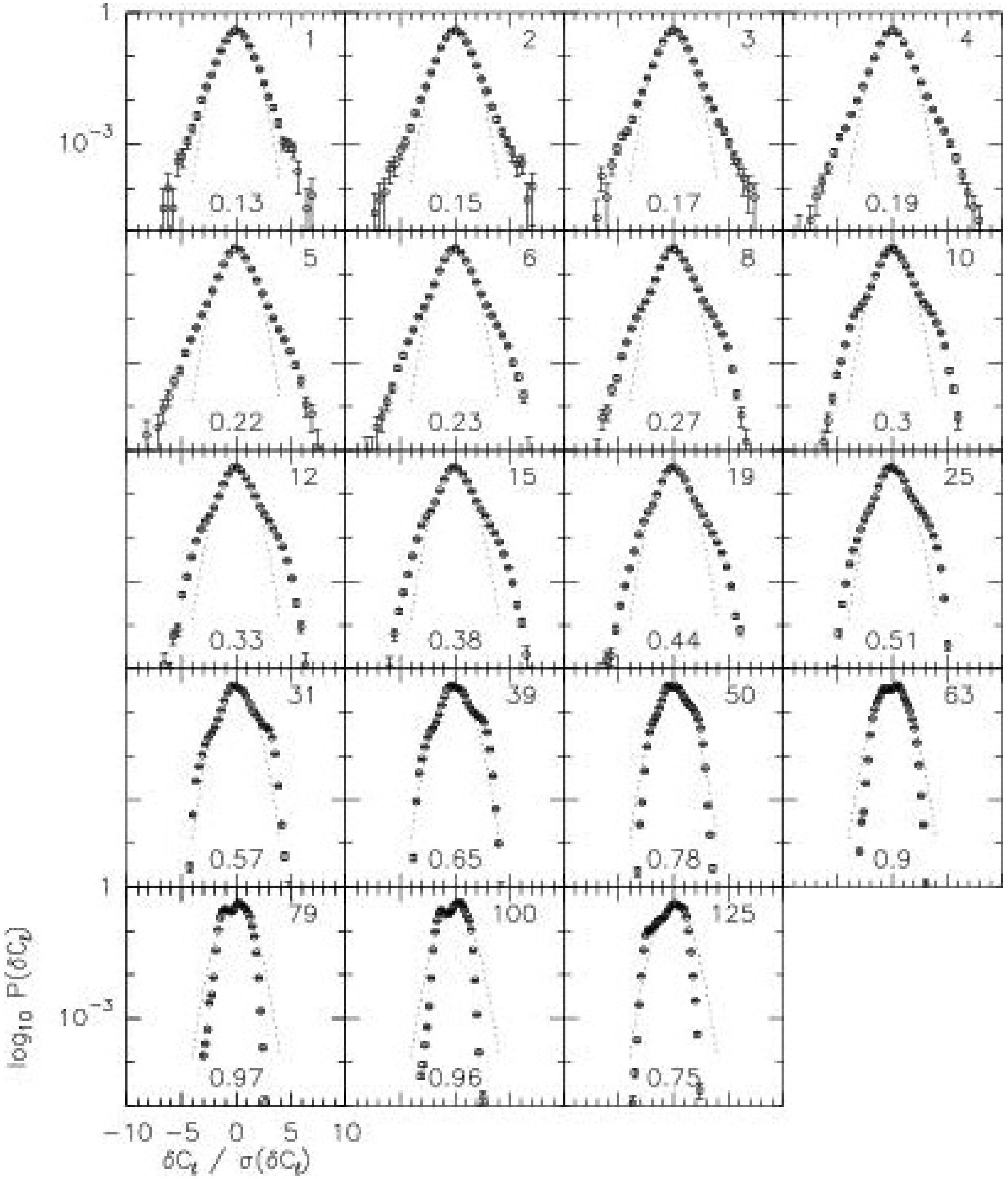
Small spatial overlap of the two velocity components

Hily-Blant & Falgarone 2009

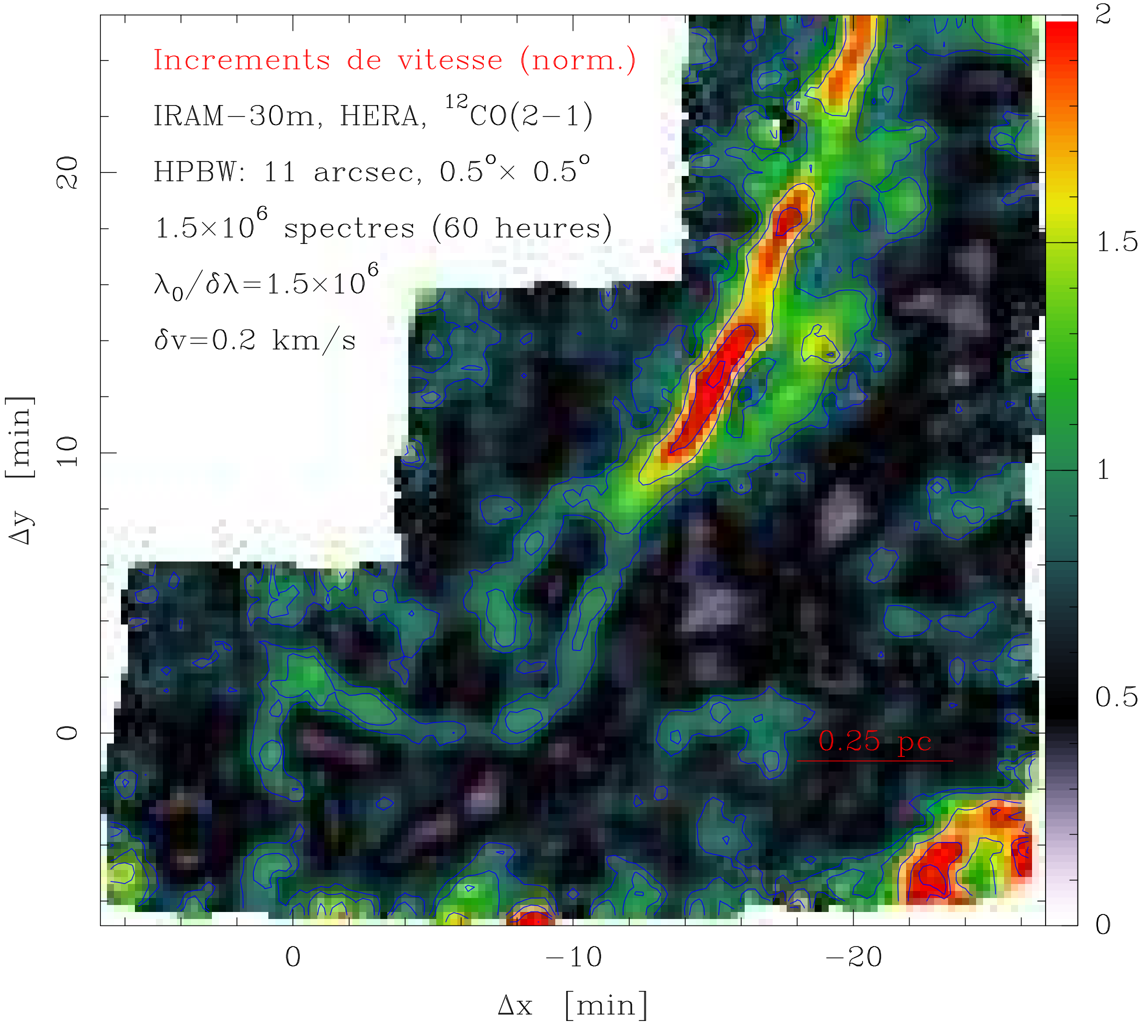
Space-velocity cuts: max shear ~ 40 km s^{-1}/pc



PDFs of Centroid Velocity Increments with variable lags

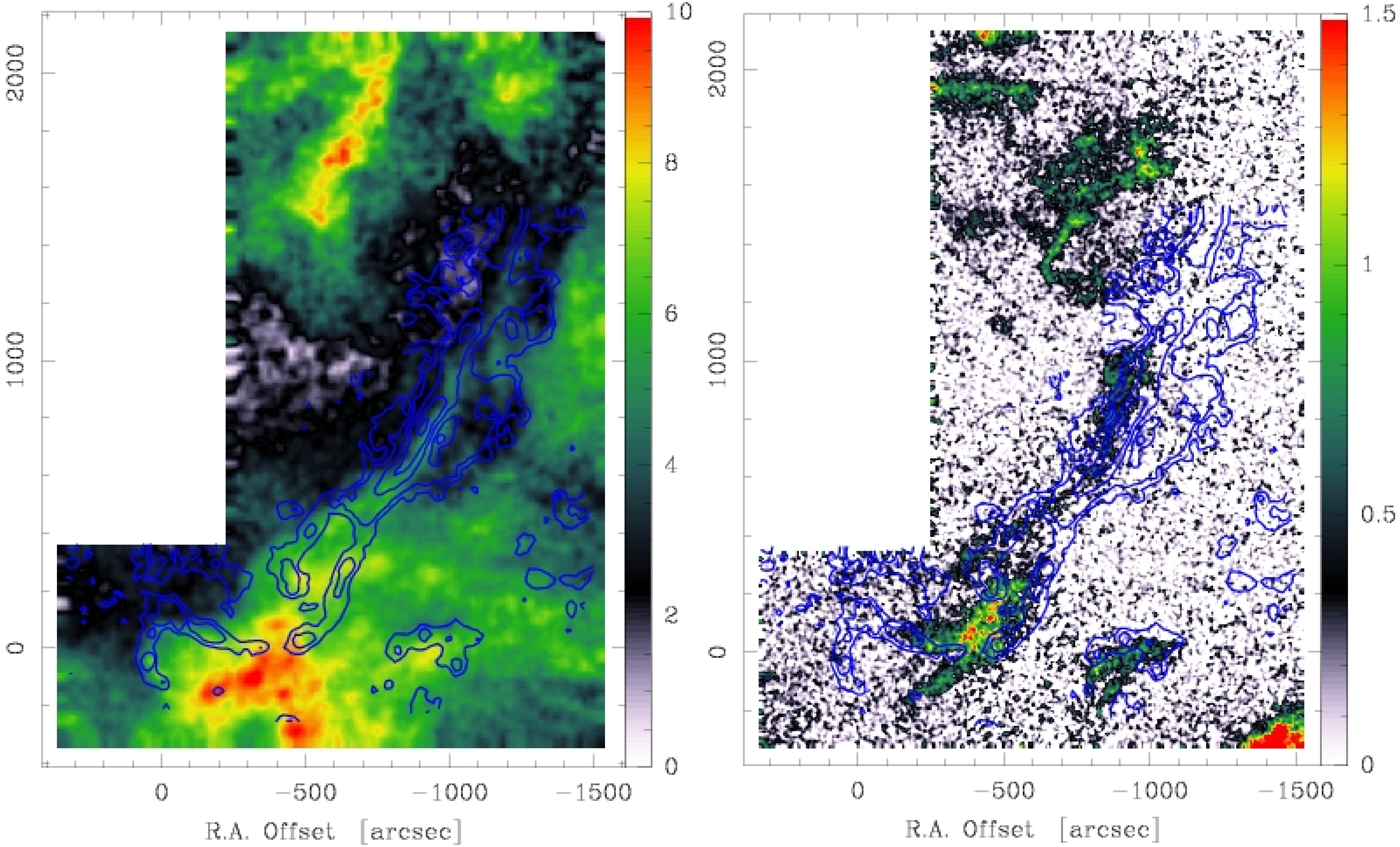


Spatial distribution of largest CVIs (E-CVI)

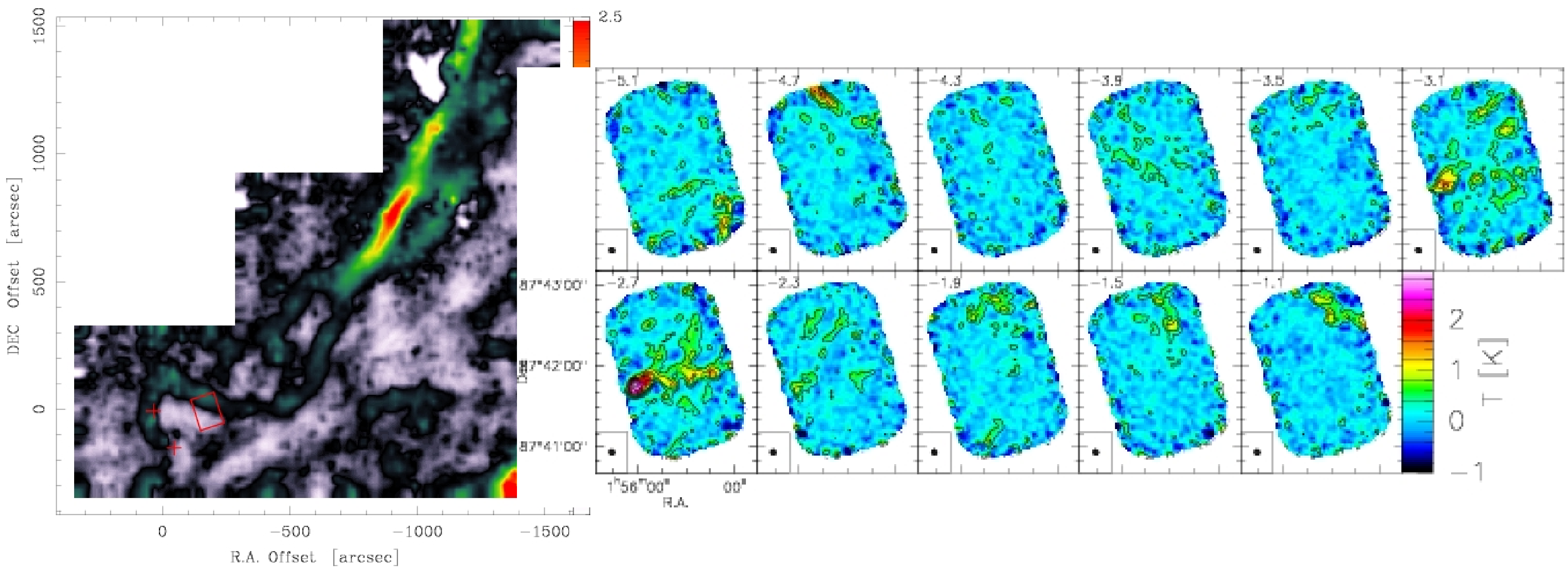


- **coherent structure** over more than a pc, thinner than 7.5mpc
- pure velocity structure
- splits into **several branches**
- CVI_{max} in Polaris $\sim$ 2.5 CVI_{max} in Taurus edge

E-CVIs: W(CO) (left) and Blue linewing (right)



Milliparsec scale structure of an E-CVI: PdBI only

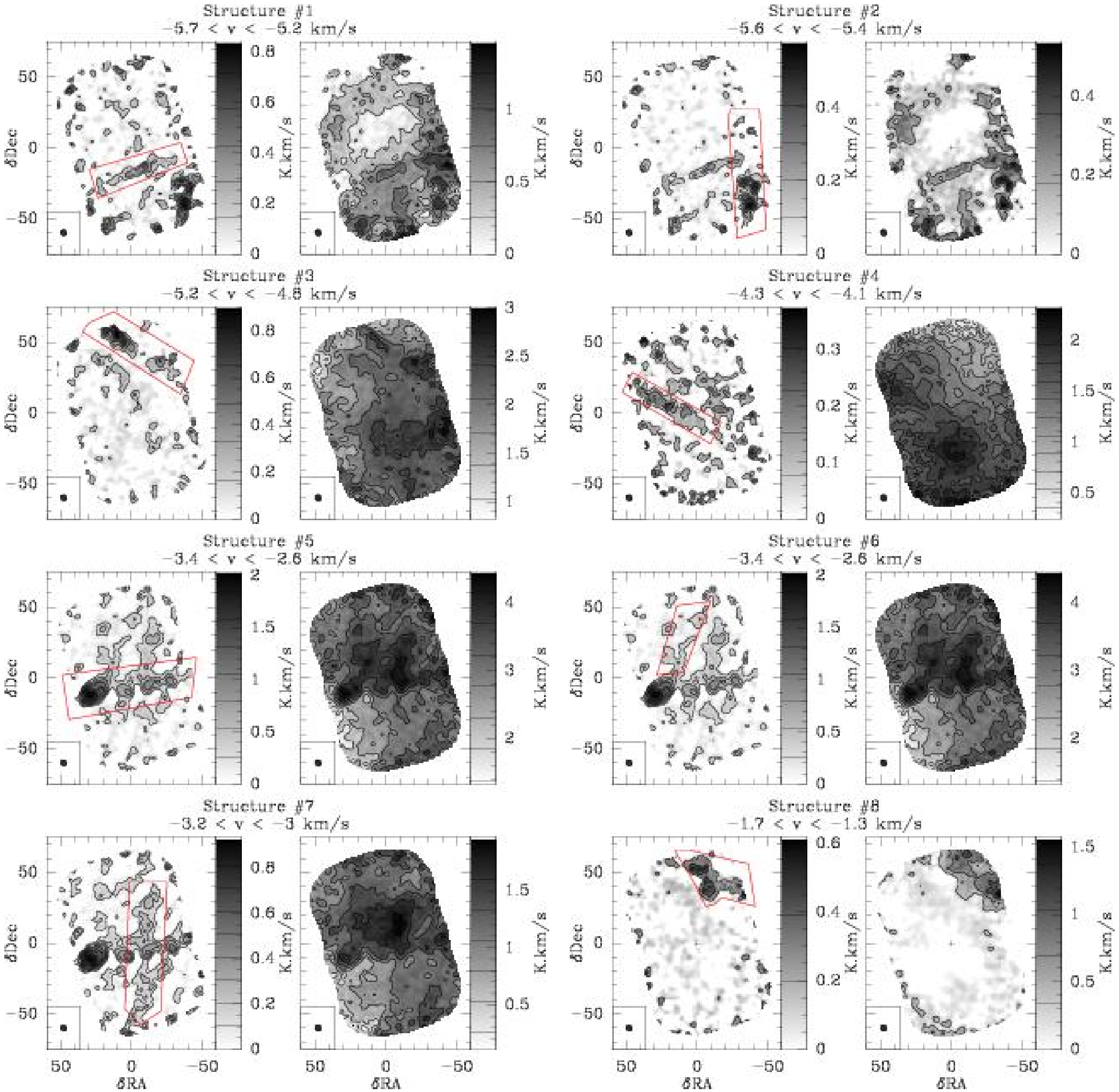


IRAM Plateau de Bure Interferometer, **180 hours integration**

Mosaic of 13 fields, ^{12}CO(1-0) line, Pixel size 3mpc, Field size 0.09 by 0.045 pc

Falgarone, Pety, Hily-Blant 2009

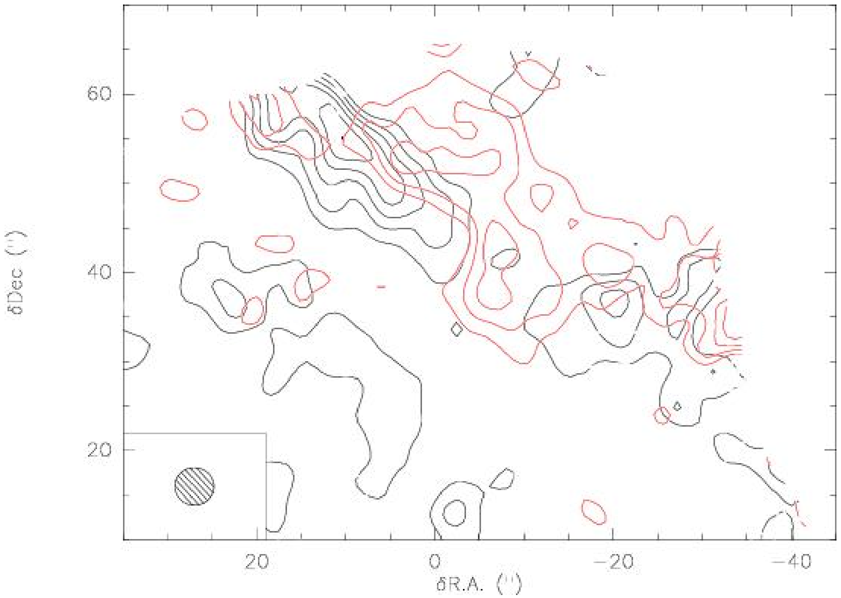
... and with short spacings from IRAM-30m

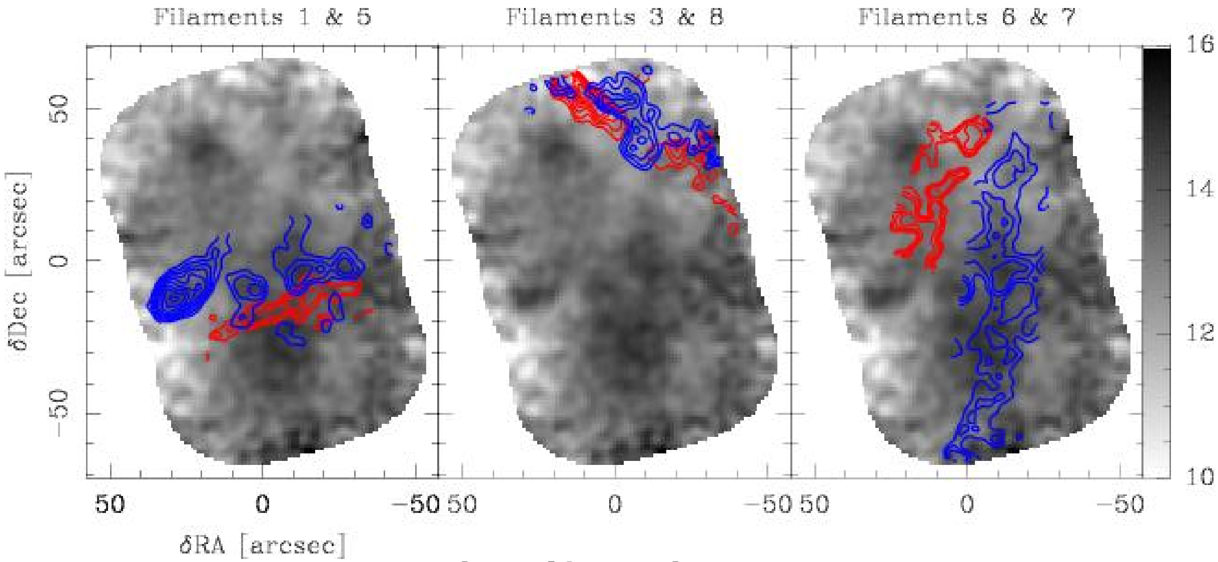


PdBI structures are **not filaments** but **sharp edges** of extended structures

Edges in space **and in velocity**
→ velocity shears

6 out of 8 are pairs (PdBI only)





$v = -5$ (black), $v = -1.5$ km s^{-1} (red)

Velocity shears:

264, 465 and 6 km s^{-1} pc^{-1}

Average velocity shear of molecular gas at the pc-scale: 1 km s^{-1} pc^{-1}

Non-Gaussian behavior of velocity-shear (vorticity) at mpc-scale

Current and vorticity sheets: MHD simulations

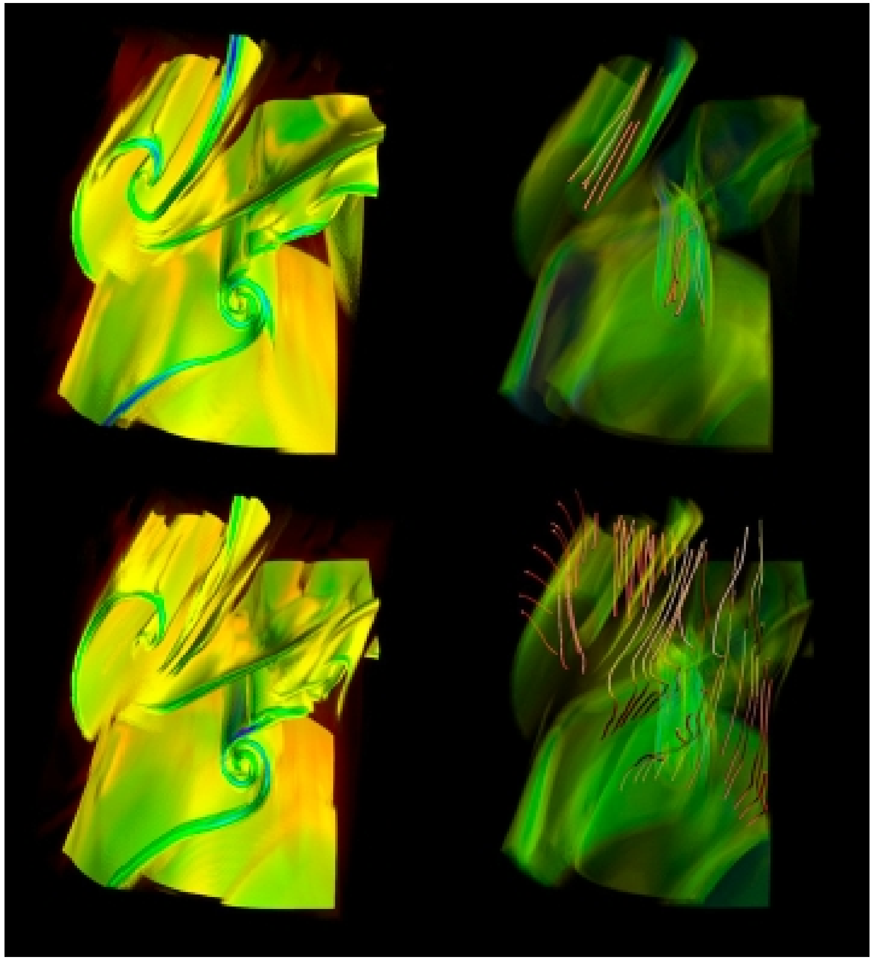


Figure 13. Above: visualization of current density intensity at $t \approx 1.6$ (left) and magnetic field lines superposed to the current density intensity (right). Below: vorticity intensity at the same time (left) and velocity field lines superposed to the vorticity intensity (right).

High Re decaying MHD turbulence, 1536^3, Mininni et al. 2006
Clyne, Mininni, Norton & Rast 2009

Current and vorticity sheets: MHD simulations

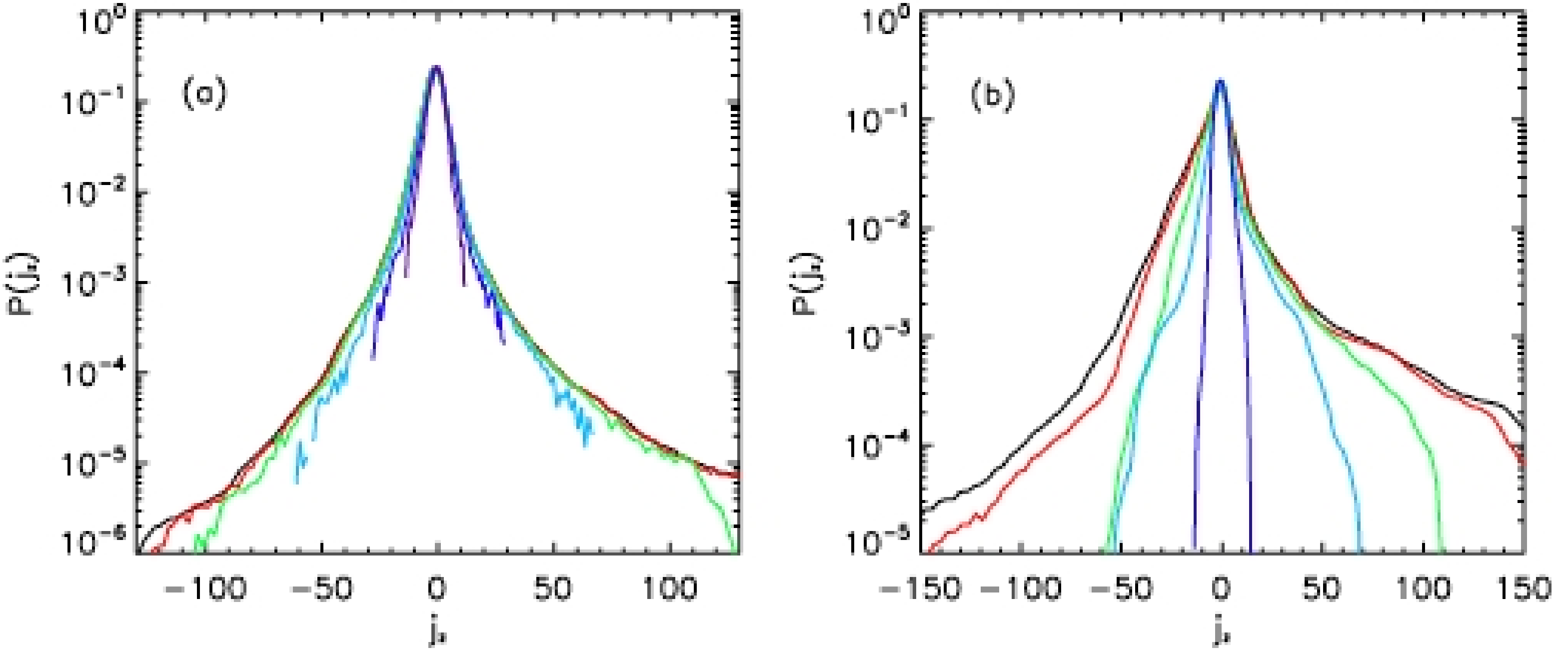


Figure 11. (a) Pdfs of the z component of the current density (j_z) in the slice with $1536 \times 1536 \times 150$ grid points shown in figure 10 at full resolution (black line), 1/2 resolution (red line), 1/4 (green line), 1/8 (cyan line), 1/16 (blue line) and 1/32 resolution (purple line). As the data is coarsened, strong gradients are removed leaving only the smooth large-scale components of the fields. (b) Pdfs of j_z in the subregion indicated in figure 10 at full resolution at different times: $t \approx 0.6$ (blue line), 1.1 (cyan line), 1.3 (green line), 1.5 (red line) and 1.6 (black line).

Summary

Radiation energy density:

- Universe: All galaxies/AGN (CIB+COB) contribute to only about 5% of CMB
- Milky Way: similar contributions, **on average**, of OB stars, cool stars, PAHs, dust thermal emission and CMB

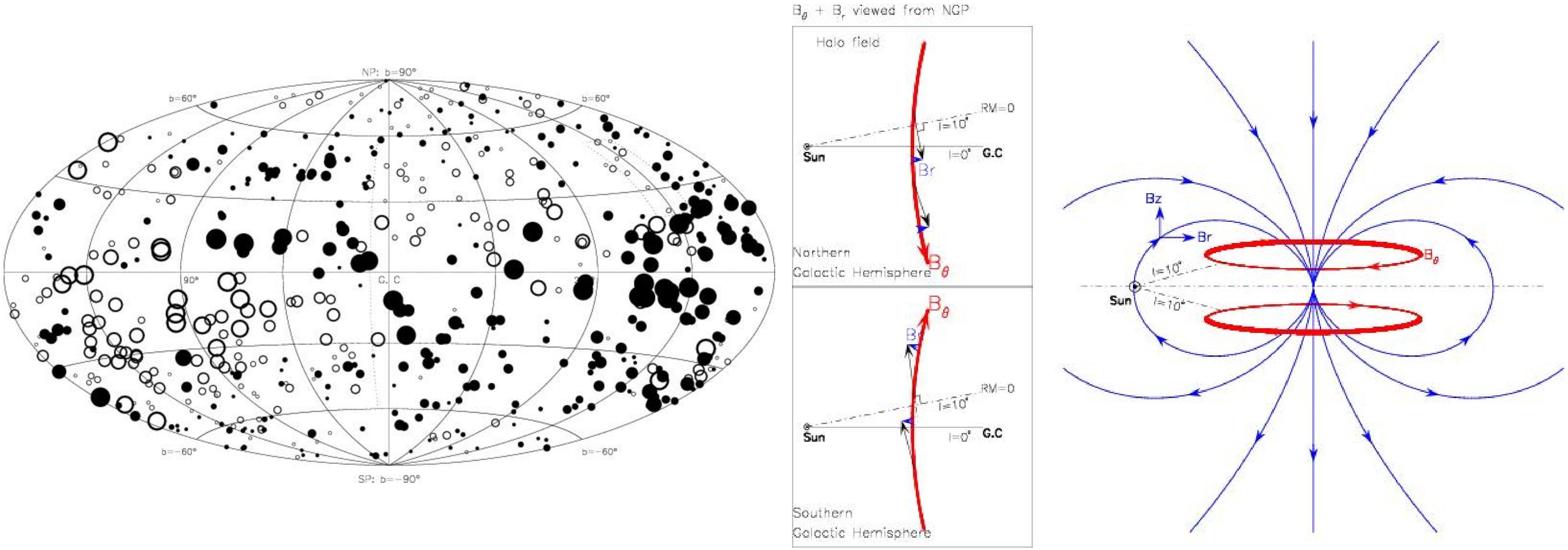
Magnetic fields:

- Large scale **field reversals** at the edge of spiral arms
- Interarm field direction **more coherent** than in spiral arms (RM and dust polarization)
- Field slightly more intense in spiral arms
- Large range of scales involved, **statistical methods in their infancy**
- $B \leq 10\mu$G and uniform below $n_0 = 300$ cm^{-3}, $B \propto n^{2/3}$ above
- Some large scale coherence of field direction in molecular clouds, poor in giant SFRs
- In Solar Neighborhood, at large scale $B_r \sim B_u$
- Field close to **equipartition** with supersonic turbulence in the cold medium

Turbulence:

- Kolmogorov spectrum in CNM and unbound molecular gas
- Different slope in gravitationally bound entities (GMCs at 50 pc scale and above)
- Strong intermittency of velocity shears (vorticity) at mpc scale in diffuse molecular gas. Anticipated similar intermittency of current (MHD simulations)

Antisymmetric RM distribution: evidence for an A0 dynamo



JinLin Han et al. 1997