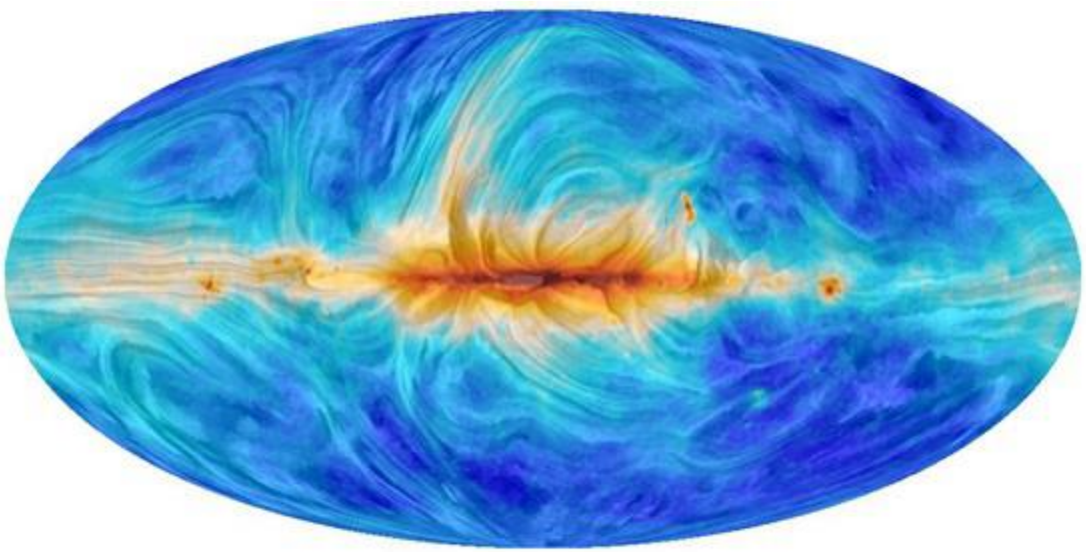
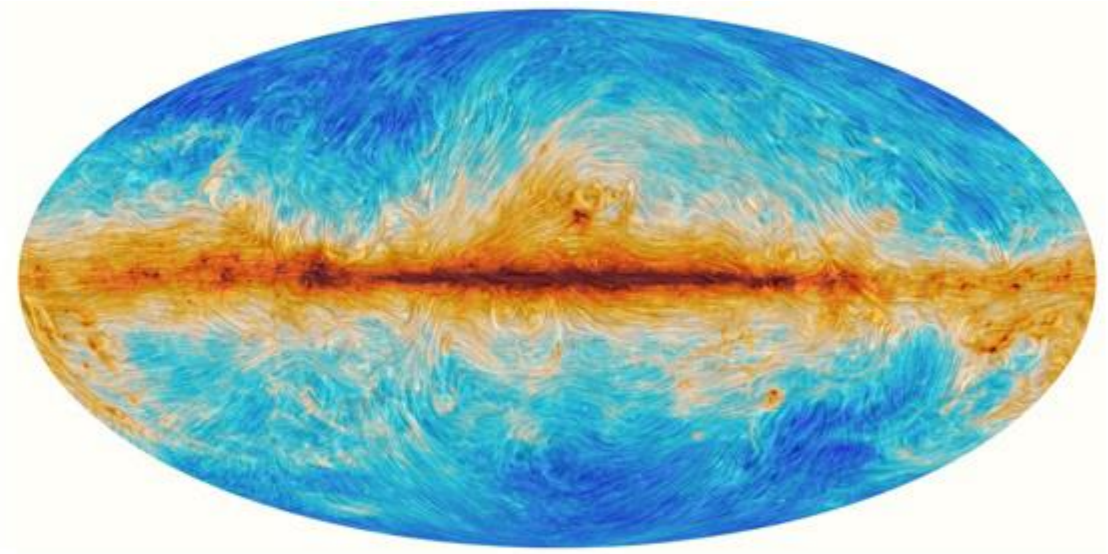
Synchrotron-dominated



Dust-dominated



Creating full-sky emission maps: A turbulence point of view

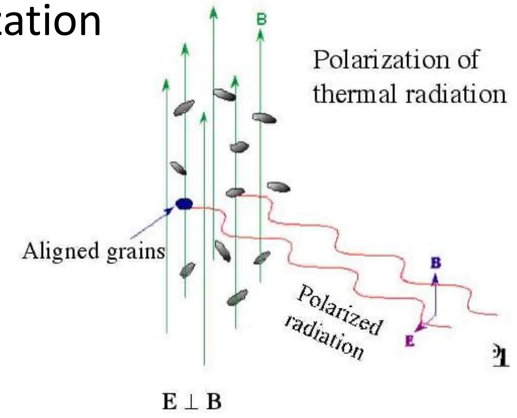
Ka Ho Yuen (Astronomy Department, UW)

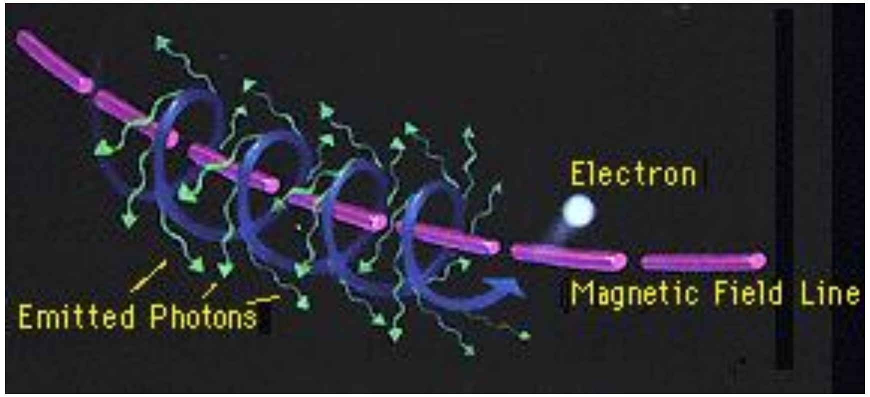
Adviser: Alex Lazarian

Studying magnetic fields are difficult!

Polarimetry

Dust Polarization

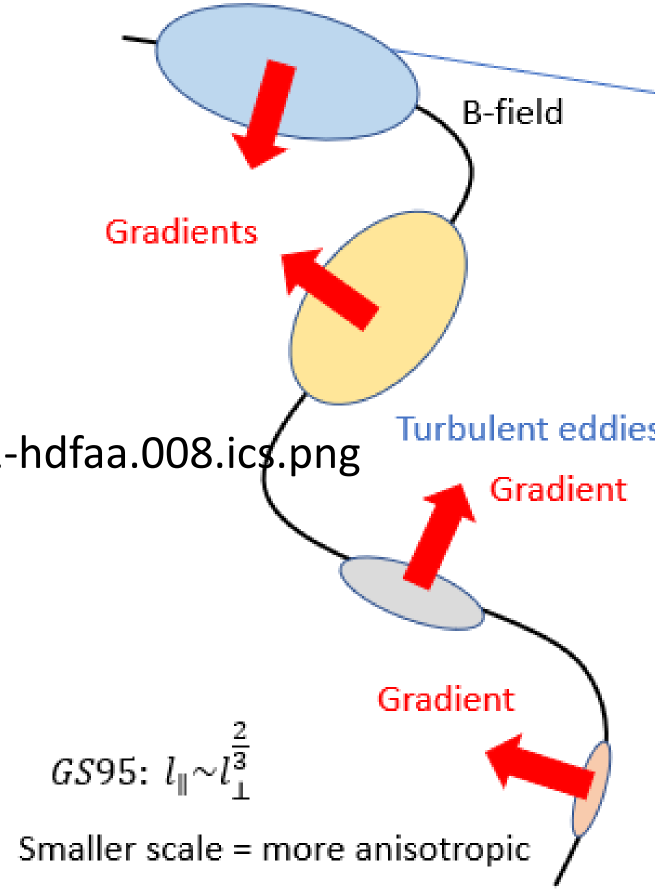




Synchrotron Polarization

Velocity Gradient Technique

Velocity Gradients

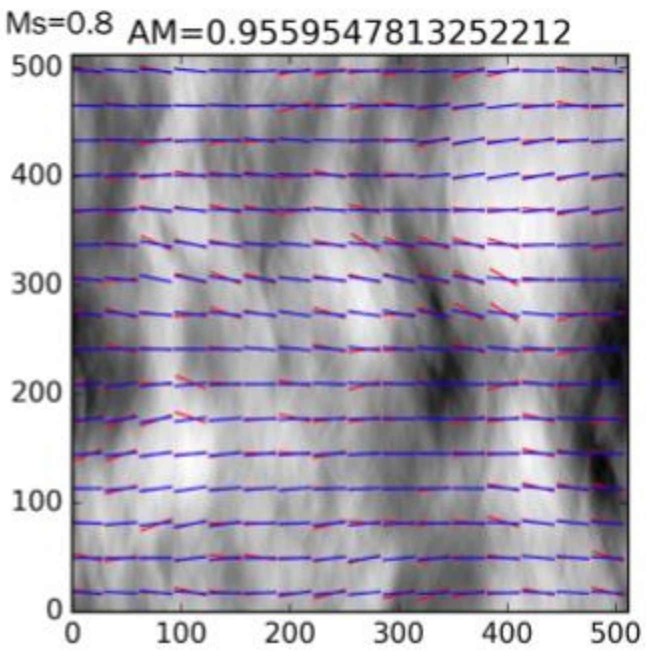


b52-hdfaa.008.ics.png

$GS95\colon\ l_{\parallel} \sim l_{\perp}^{\frac{2}{3}}$

Smaller scale = more anisotropic

Synchrotron Intensity Gradients

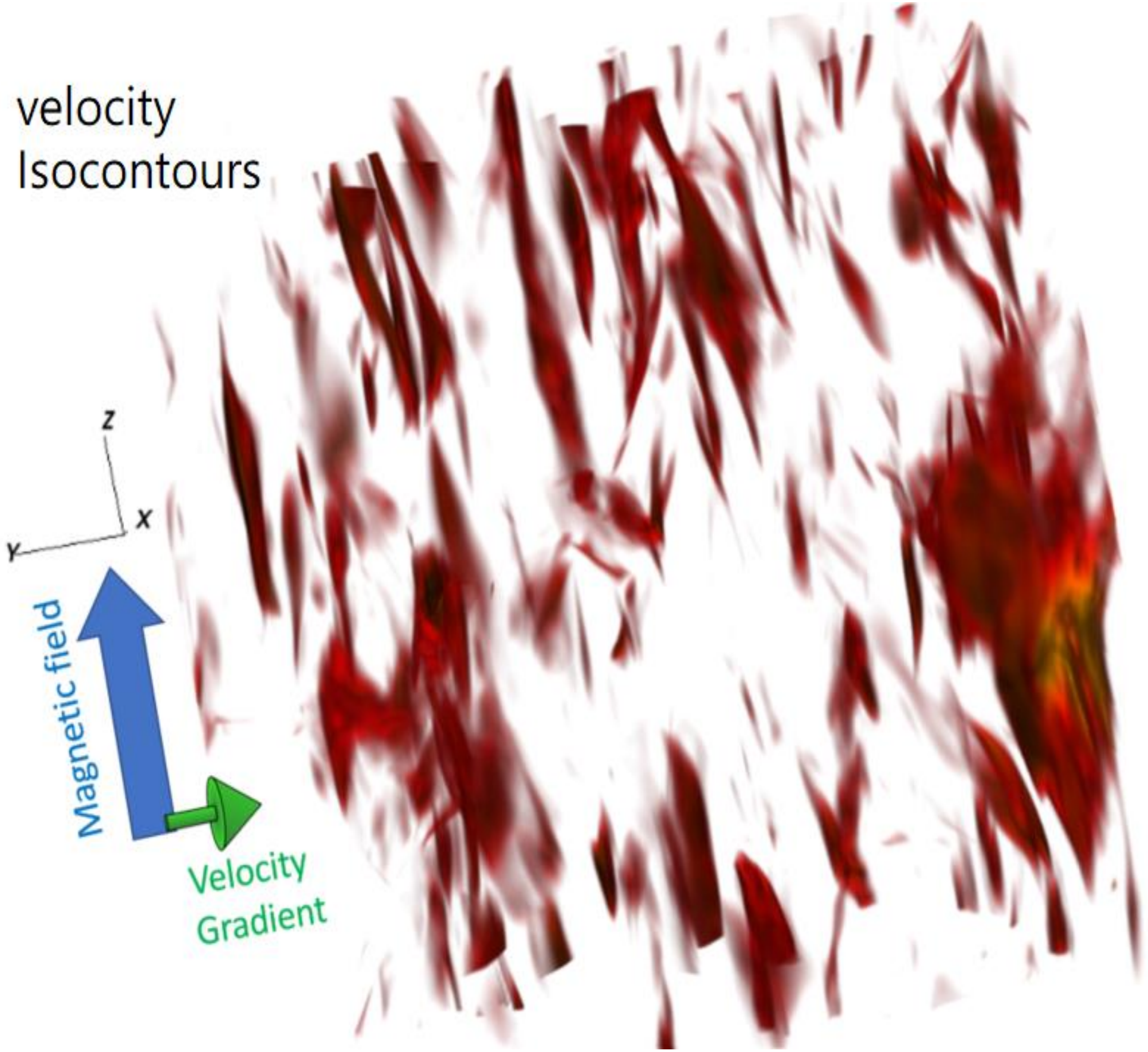


Studying magnetic field morphology using the velocity gradient technique

1. Gonz´alez-Casanova & Lazarian 2017 : Foundation of VGT
2. Yuen & Lazarian 2017a: Blocks introduced
3. Lazarian, Yuen, Lee & Cho 2017: 1^{st} paper on Synchrotron Intensity Gradients
4. Yuen & Lazarian 2017b: Shocks & Self-grav
5. Lazarian, Yuen & Sun: Mode analysis, advanced techniques on gradients, channel gradients
6. Gonz´alez-Casanova, Lazarian & Burkhart 2017: Self-absorbing media

At least 7 more to come!

Explanation of Velocity Gradient approach is given in Alex's talk



Goldreich & Sridhar (1995)

Local direction follows from the turbulent reconnection theory in Lazarian & Vishniac (1999)

Ways to make gradients really *tracing* magnetic field

Sub-block averaging

- Making use of statistical nature of turbulence scaling
- Self-consistent way of determining gradient value + error estimation

Moving Window

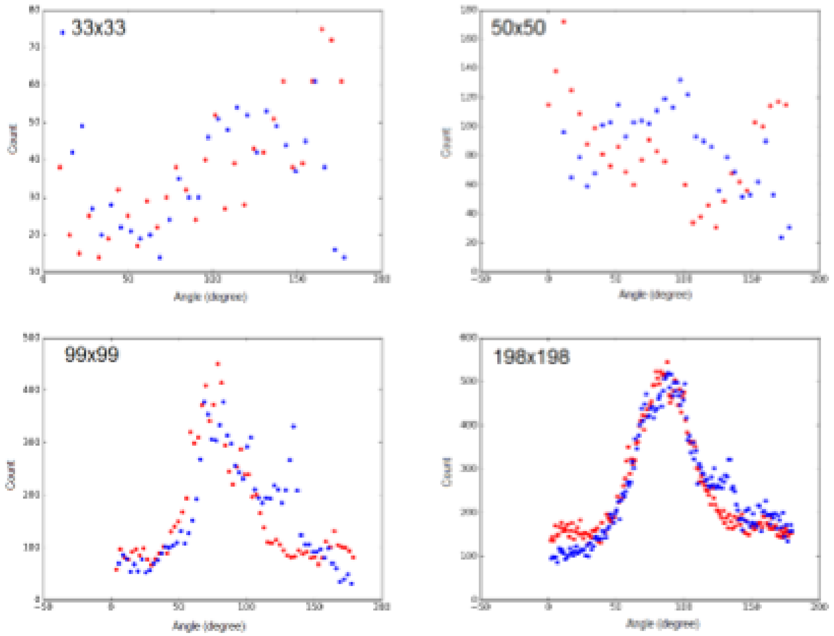
- Making use of field continuity + per-point sub-block averaging

Angle-Constraining

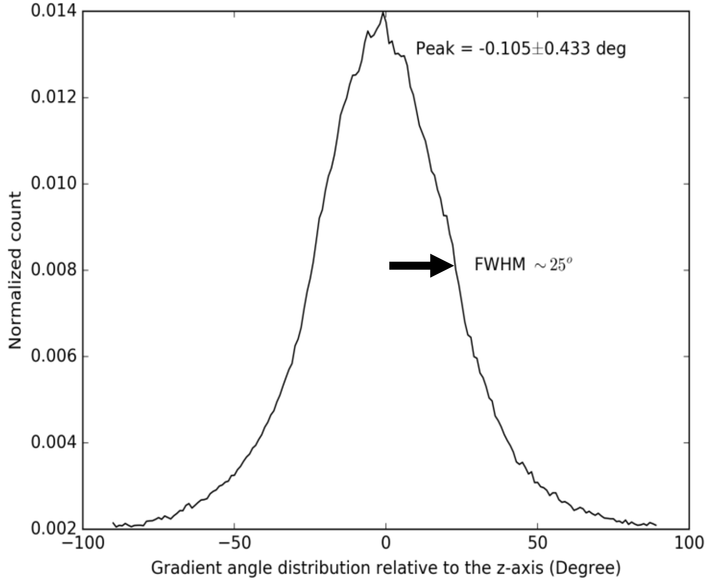
- Making use of the *exact* GS95 scaling relation to constrain the angle variation

Sub-block Averaging

Self-consistent way to probe magnetic field direction



Yuen & Lazarian 2017a



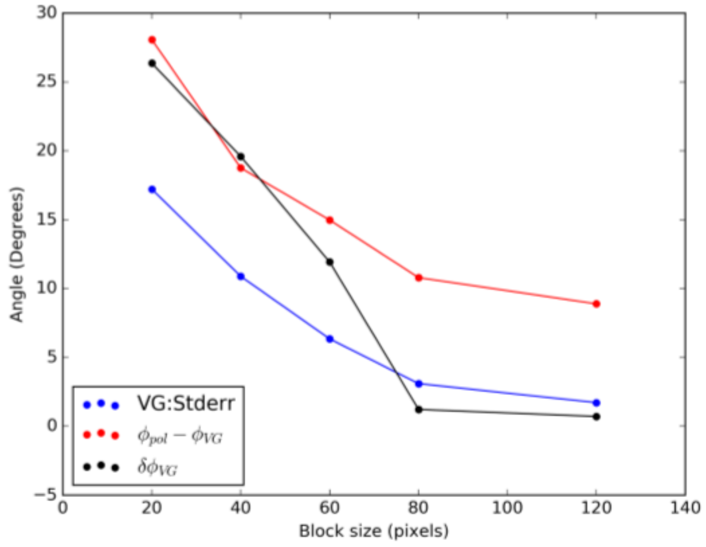


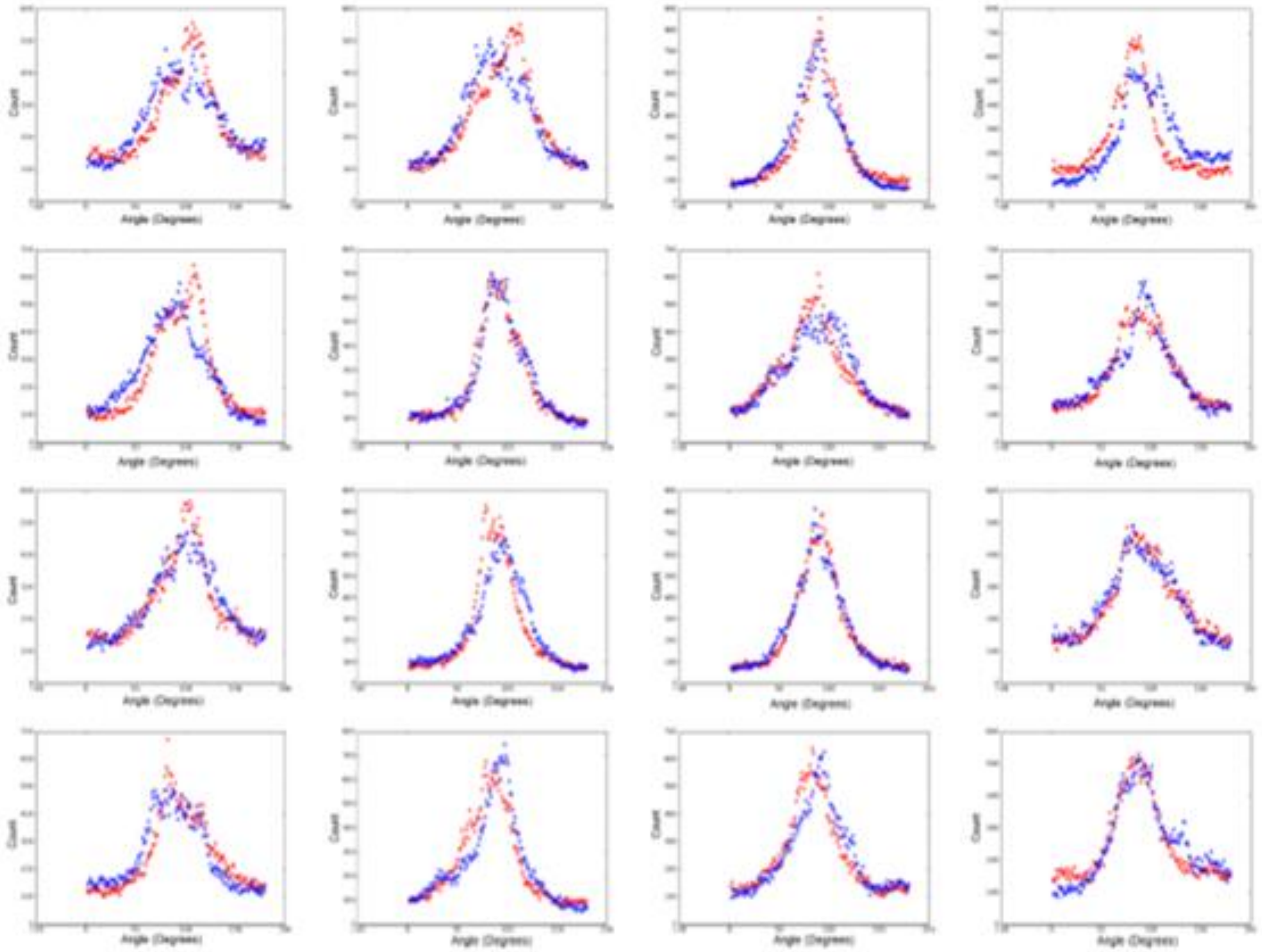
Figure 1. The average error estimate from the Gaussian fitting function (Stderr), the angle differences between magnetic field directions from polarization and VCG orientation ($\phi_{pol} - \phi_{VG}$) and the dispersion of VCGs ($\delta\phi_{VG}$) for the velocity centroid map of cube 23 plotted against the change of block size.

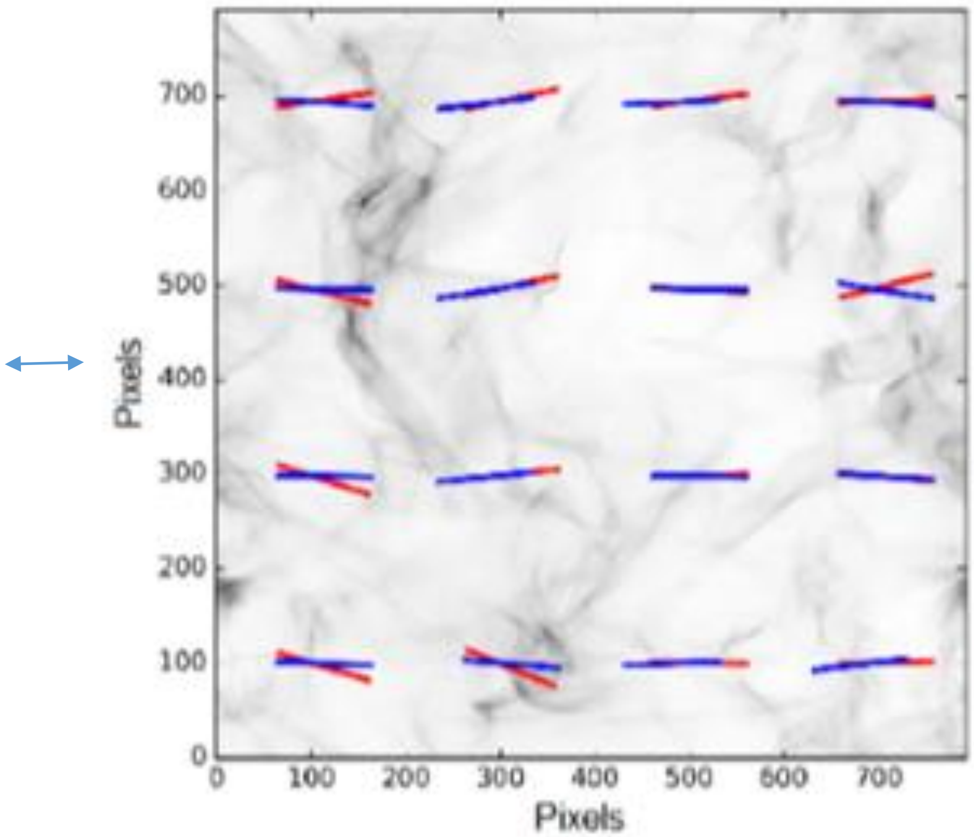
Yuen & Lazarian 2017b

Select a block size → Fit by a Gaussian → Determine error by Gaussian Fitting

Sub-block Averaging

Local gradient angle distributions have similar behavior



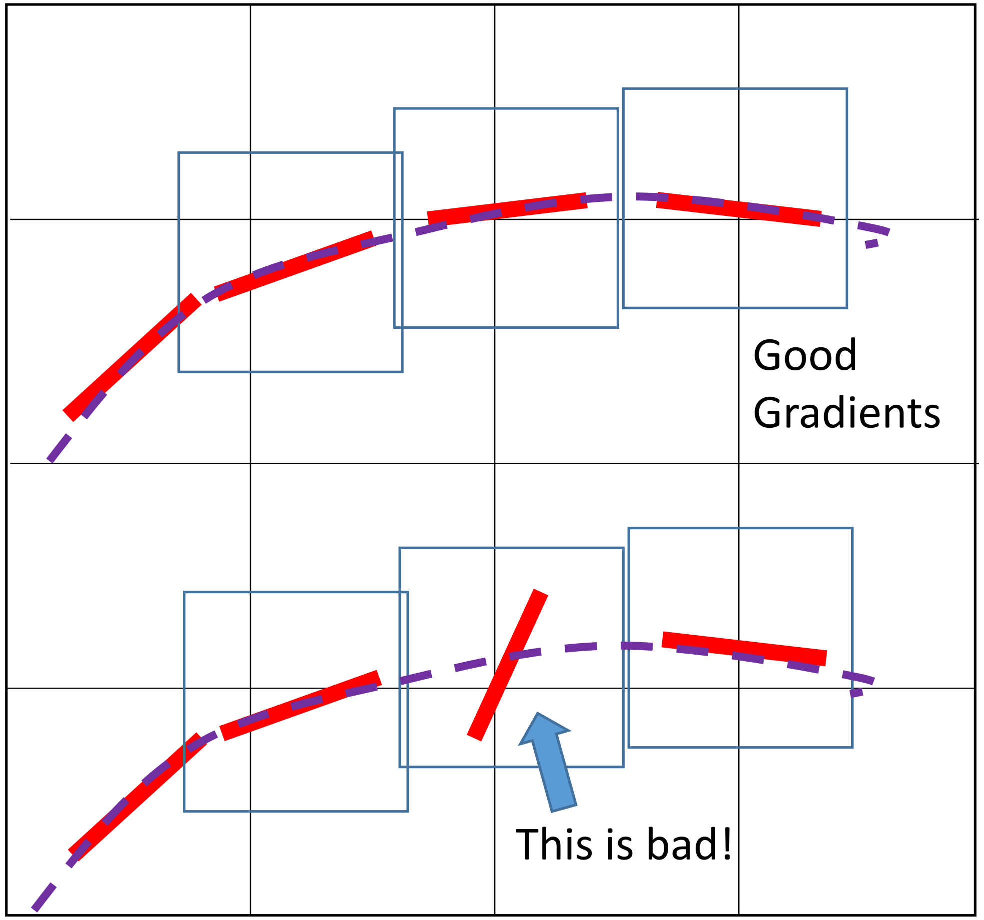


Yuen & Lazarian 2017a

Moving window

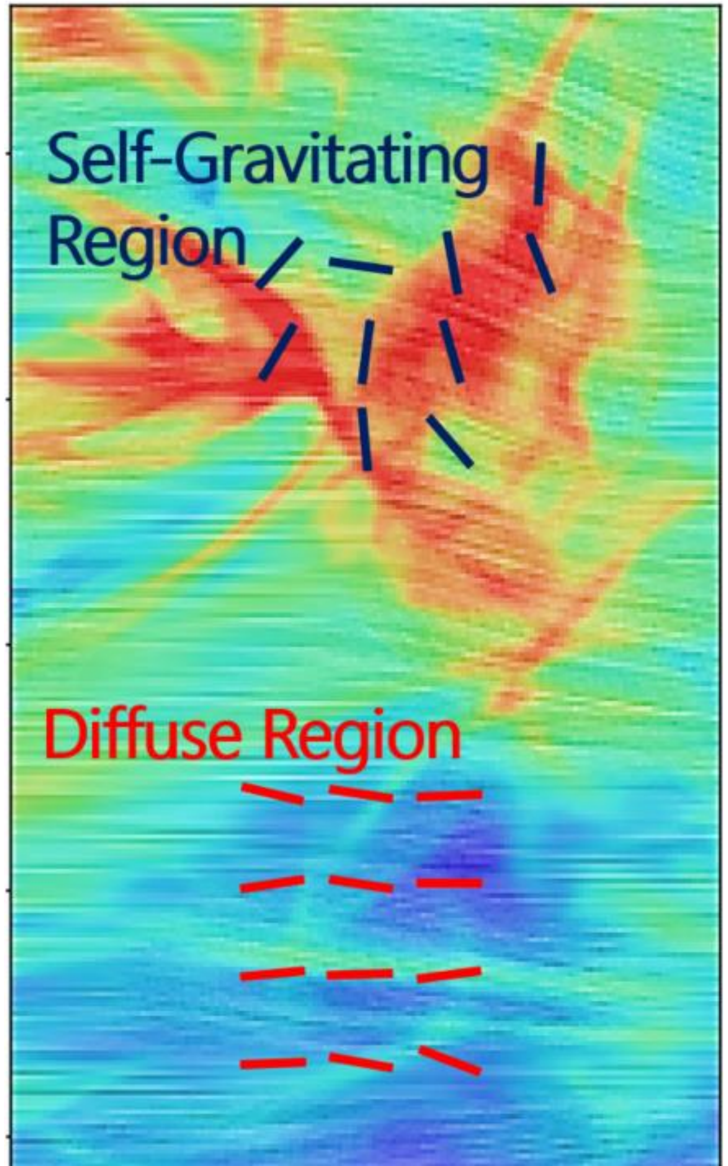
Following field line direction to create local blocks

- Moving the block according to the direction of neighboring sub-block averaged gradient orientation
- Equivalent to “per-pixel” sub-blocks
- Correcting wrong gradients by neighboring trends



Lazarian & Yuen 2017

Velocity gradients are perpendicular to local direction of B-field in diffuse regions and parallel to B-field in regions of gravitational collapse



Our procedure of block averaging allows us to identify the regions where the direction of gradients flips 90 degrees

Yuen & AL 2017

Velocity gradient technique *in one page*

Tracing magnetic field morphology using spectroscopic data

Requirement

- High resolution spectroscopic data ->
  Velocity Centroid + Intensity gradients
- Velocity channel information preferred ->
  Thin channels + thick channels

Toolbox

- Sub-block average:
  Tells accuracy + resolution requirement
- Moving window:
  Constraining smoothed magnetic field
- Angle constraining:
  Correction of gradients through turbulent anisotropy

Physics that can be obtained

- Magnetic field morphology
- Magnetic field strength (through CF method)
- Determination of self-gravitating regions (stage of collapse)
- Shock boundary

Applied observation data

- Galactic HI data: GALFA (dr1+dr2), HI4PY
- Dark cloud
- Filamentary structures
- Self-gravitating regions

Existing techniques of VGT

Block-averaging algorithm (YL17a)

Acquiring the most probable directions and errors of gradients in a certain region

Moving Window method (LY17)

Continuity of B-field→ Enforcing gradients after block-averaging to be continuous

Angle-constraining (LY17)

$l_{\parallel} \sim l_{\perp}^{2/3}$ from GS95 → Max gradient angle $|\tan\theta_{\nabla}| \sim l_{\perp}/l_{\parallel} \sim l_{\perp}^{1/3}$

Physics Identified by VGT

B-field direction & strength (GL17, YL17ab)

$B \sim \sqrt{4\pi\rho}\frac{\delta v}{\sqrt{\delta\phi_{\nabla}}}$

Shock (YL17b)

Density Gradients turns with respect to Velocity Gradient

Self-gravity (YL17b)

Gradual rotation of gradients from $\nabla v \perp B \rightarrow \nabla v \parallel B$, depending on the importance of gravity

Density information also trace turbulence anisotropy

Velocity is superior than density in turbulent environment

- Density information is an indirect tracer of turbulence anisotropy (Kowal, Lazarian & Beresnyak 2006)

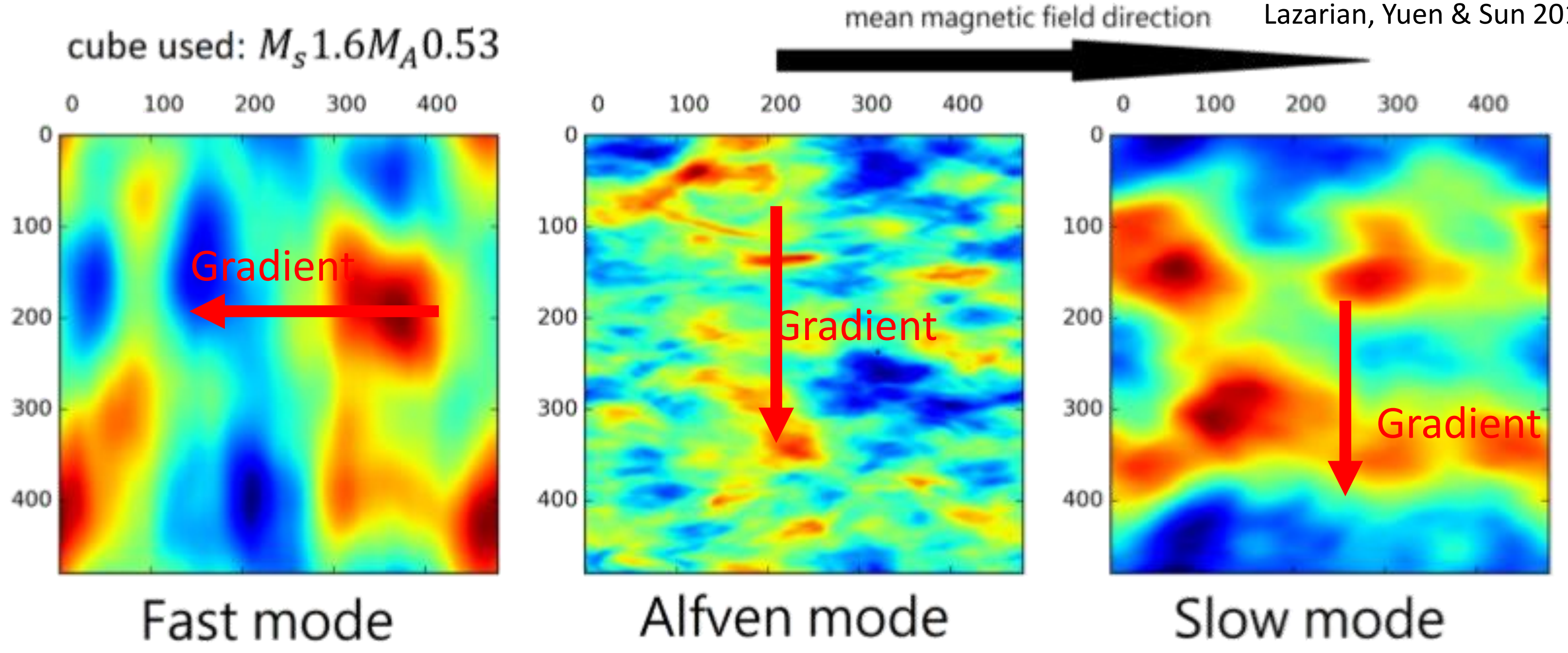
Alfven modes dominate (Cho & Lazarian 2002)

$\nabla\rho$ depends on fast and slow modes only → $\nabla\rho \cdot B$ depends on the relative ratio of slow/fast

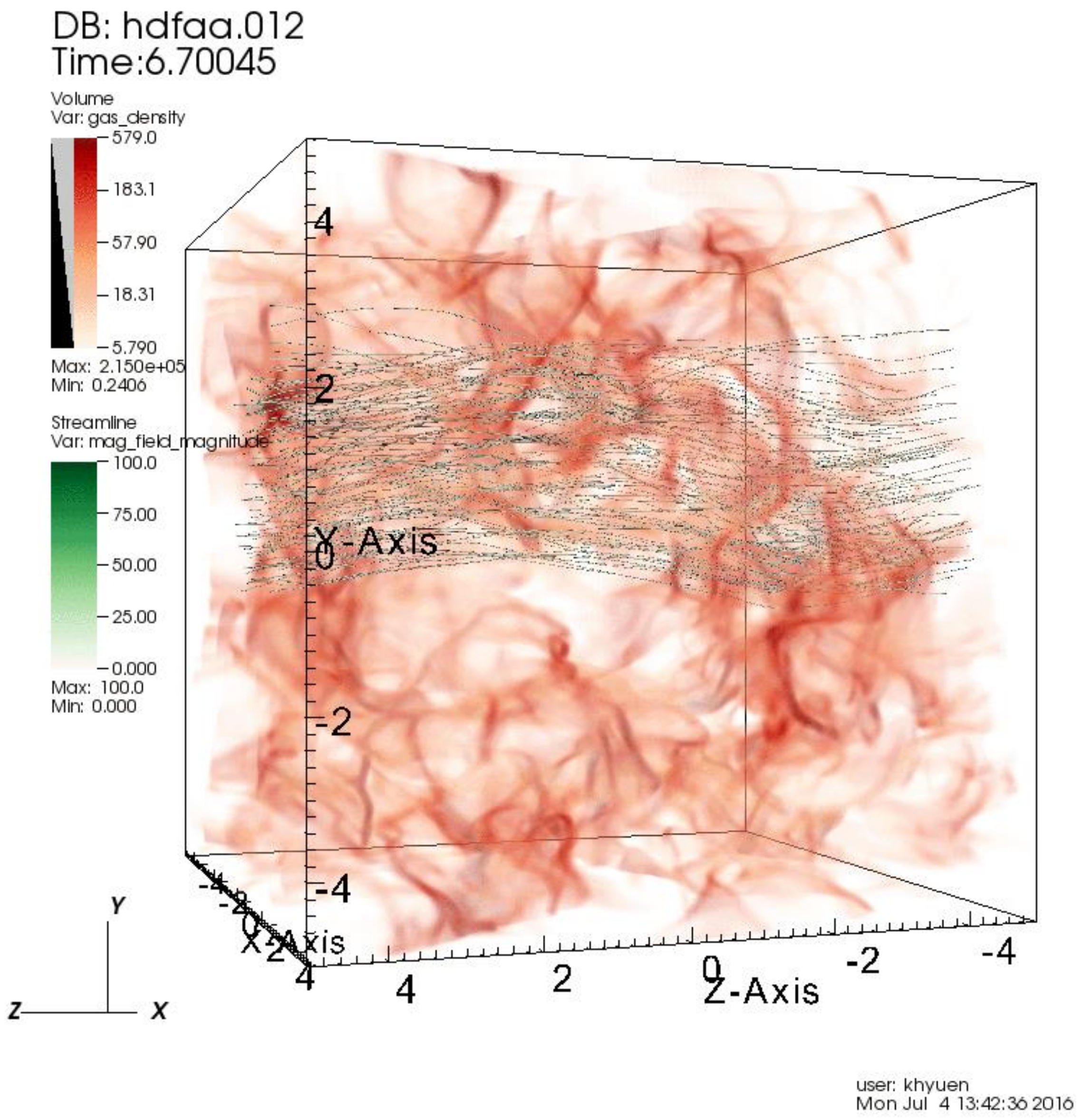
∇v depends on all modes → $\nabla v \cdot B$ depends mostly on Alfven modes!

Lazarian, Yuen & Sun 2017

Velocity Gradients:



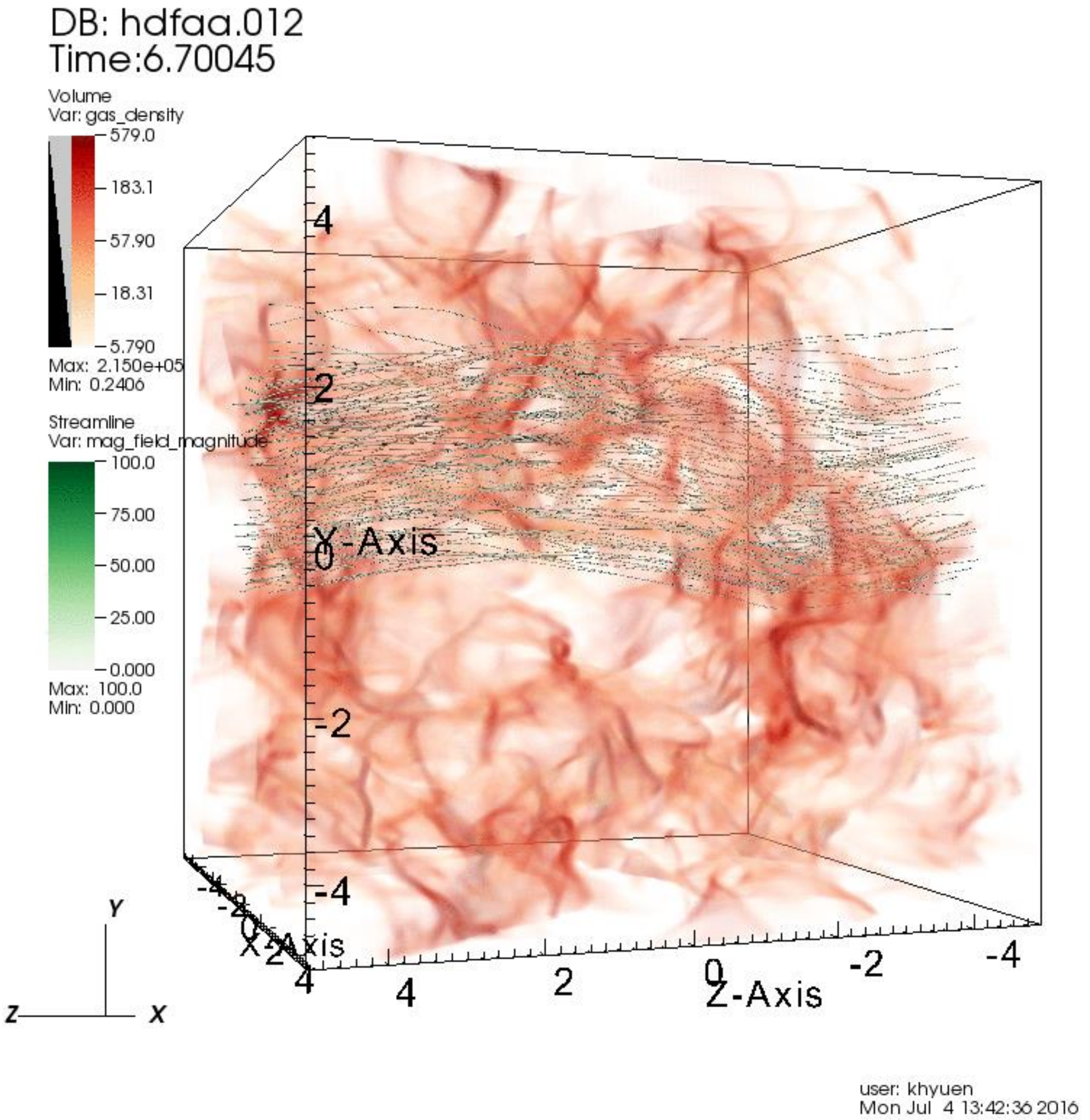
Actual high contrast density filament are mostly perpendicular to magnetic fields: filament in the channel maps arise from velocities mostly



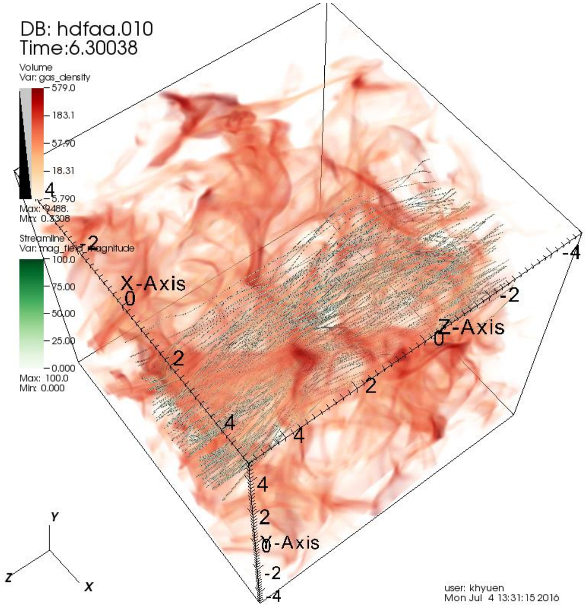
We have developed software to generate synthetic dust and synchrotron emission/polarization maps

- ZEUS-MP/3D
- With different sonic and magnetic conditions
- Stir with saturated turbulence

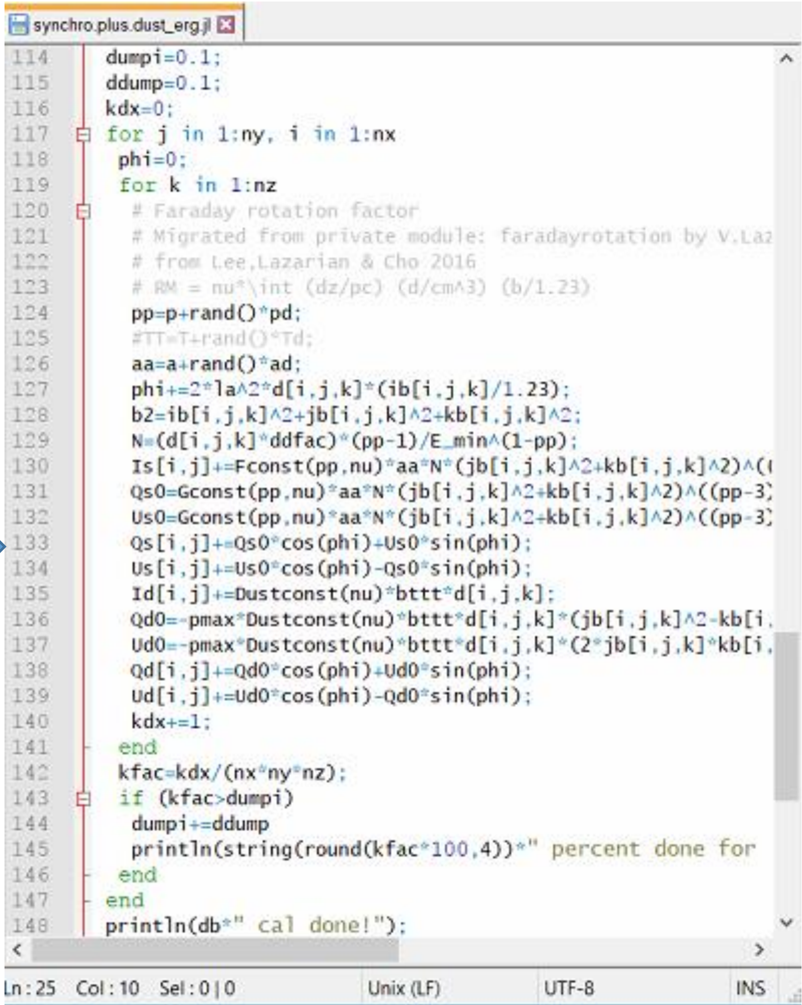
Model	M_s	M_A	$\beta = 2(\frac{M_A}{M_s})^2$
Ms0.2Ma0.02	0.2	0.02	0.02
Ms0.4Ma0.04	0.4	0.04	0.02
Ms0.8Ma0.08	0.8	0.08	0.02
Ms1.6Ma0.16	1.6	0.16	0.02
Ms3.2Ma0.32	3.2	0.32	0.02
Ms6.4Ma0.64	6.4	0.64	0.02
Ms0.2Ma0.07	0.2	0.07	0.22
Ms0.4Ma0.13	0.4	0.13	0.22
Ms0.8Ma0.26	0.8	0.26	0.22
Ms1.6Ma0.53	1.6	0.53	0.22
Ms0.2Ma0.2	0.2	0.2	2
Ms0.4Ma0.4	0.4	0.4	2
Ms0.8Ma0.8	0.8	0.8	2
Ms0.13Ma0.4	0.13	0.4	18
Ms0.20Ma0.66	0.20	0.66	18
Ms0.26Ma0.8	0.26	0.8	18
Ms0.04Ma0.4	0.04	0.4	200
Ms0.08Ma0.8	0.08	0.8	200
Ms0.2Ma2.0	0.2	2.0	200



Dust and synchrotron transfer module



- Highly simplified model in *Julia*
- Easily usable for other numerical simulation




```
dumpi=0.1;
ddump=0.1;
kdx=0;
for j in 1:ny, i in 1:nx
 phi=0;
 for k in 1:nz
  # Faraday rotation factor
  # Migrated from private module: faradayrotation by V.Laz
  # from Lee,Lazarian & Cho 2016
  # RM = nu*\int (dz/pc) (d/cm^3) (b/1.23)
  pp=p+rand()*pd;
  #TT=T+rand()*Td;
  aa=a+rand()*ad;
  phi+=2*la^2*d[i,j,k]*(ib[i,j,k]/1.23);
  b2=ib[i,j,k]^2+jb[i,j,k]^2+kb[i,j,k]^2;
  N=(d[i,j,k]*ddfac)*(pp-1)/E_min^(1-pp);
  Is[i,j]+=Fconst(pp,nu)*aa*N*(jb[i,j,k]^2+kb[i,j,k]^2)^((
  Qs0=Gconst(pp,nu)*aa*N*(jb[i,j,k]^2+kb[i,j,k]^2)^((pp-3)
  Us0=Gconst(pp,nu)*aa*N*(jb[i,j,k]^2+kb[i,j,k]^2)^((pp-3)
  Qs[i,j]+=Qs0*cos(phi)+Us0*sin(phi);
  Us[i,j]+=Us0*cos(phi)-Qs0*sin(phi);
  Id[i,j]+=Dustconst(nu)*bttt*d[i,j,k];
  Qd0=-pmax*Dustconst(nu)*bttt*d[i,j,k]*(jb[i,j,k]^2-kb[i,
  Ud0=-pmax*Dustconst(nu)*bttt*d[i,j,k]*(2*jb[i,j,k]*kb[i,
  Qd[i,j]+=Qd0*cos(phi)+Ud0*sin(phi);
  Ud[i,j]+=Ud0*cos(phi)-Qd0*sin(phi);
  kdx+=1;
 end
 kfac=kdx/(nx*ny*nz);
 if (kfac>dumpi)
  dumpi+=ddump
  println(string(round(kfac*100,4))*" percent done for
 end
end
println(db*" cal done!");
```


$$I_\nu^d = m_p \delta_{\rm DG} \int {\rm d}z\ n_{\rm H} \kappa_{545} \left(\frac{\nu}{545\,{\rm GHz}}\right)^\beta B_\nu(T_d)$$

$$Q_\nu^d = 0.2 m_p \delta_{\rm DG} \int {\rm d}z\ n_{\rm H} \kappa_{545} \left(\frac{\nu}{545\,{\rm GHz}}\right)^\beta B_\nu(T_d) \frac{B_x^2+B_y^2}{B^2} \frac{B_x^2-B_y^2}{B^2}$$

$$U_\nu^d = 0.2 m_p \delta_{\rm DG} \int {\rm d}z\ n_{\rm H} \kappa_{545} \left(\frac{\nu}{545\,{\rm GHz}}\right)^\beta B_\nu(T_d) \frac{B_x^2+B_y^2}{B^2} \frac{2B_xB_y}{B^2}$$

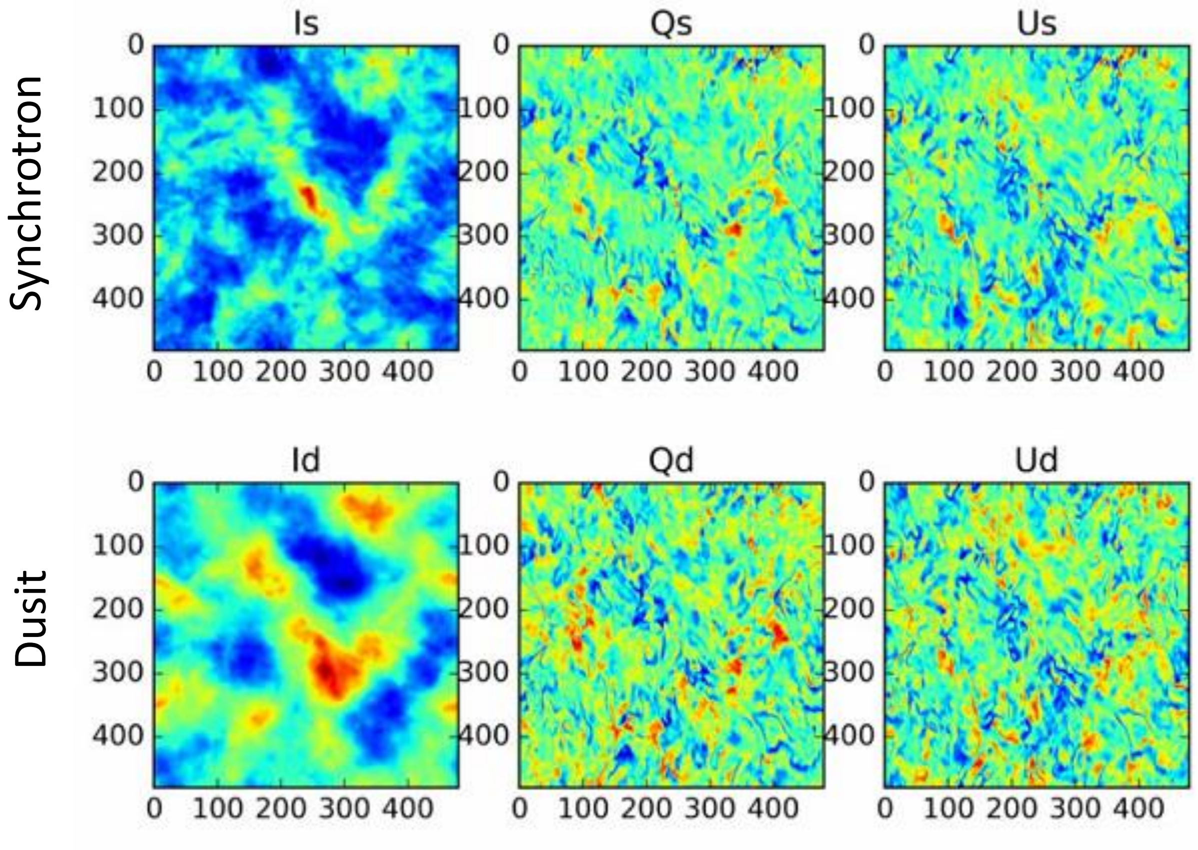
$$I_\nu^s = 2\int {\rm d}z\ \omega^{\frac{1-p}{2}} F(p) \left(B_x^2+B_y^2\right)^{\frac{p-3}{4}} \left(B_x^2+B_y^2\right)$$

$$Q_\nu^s = -2\int {\rm d}z\ \omega^{\frac{1-p}{2}} G(p) \left(B_x^2+B_y^2\right)^{\frac{p-3}{4}} \left(B_x^2-B_y^2\right)$$

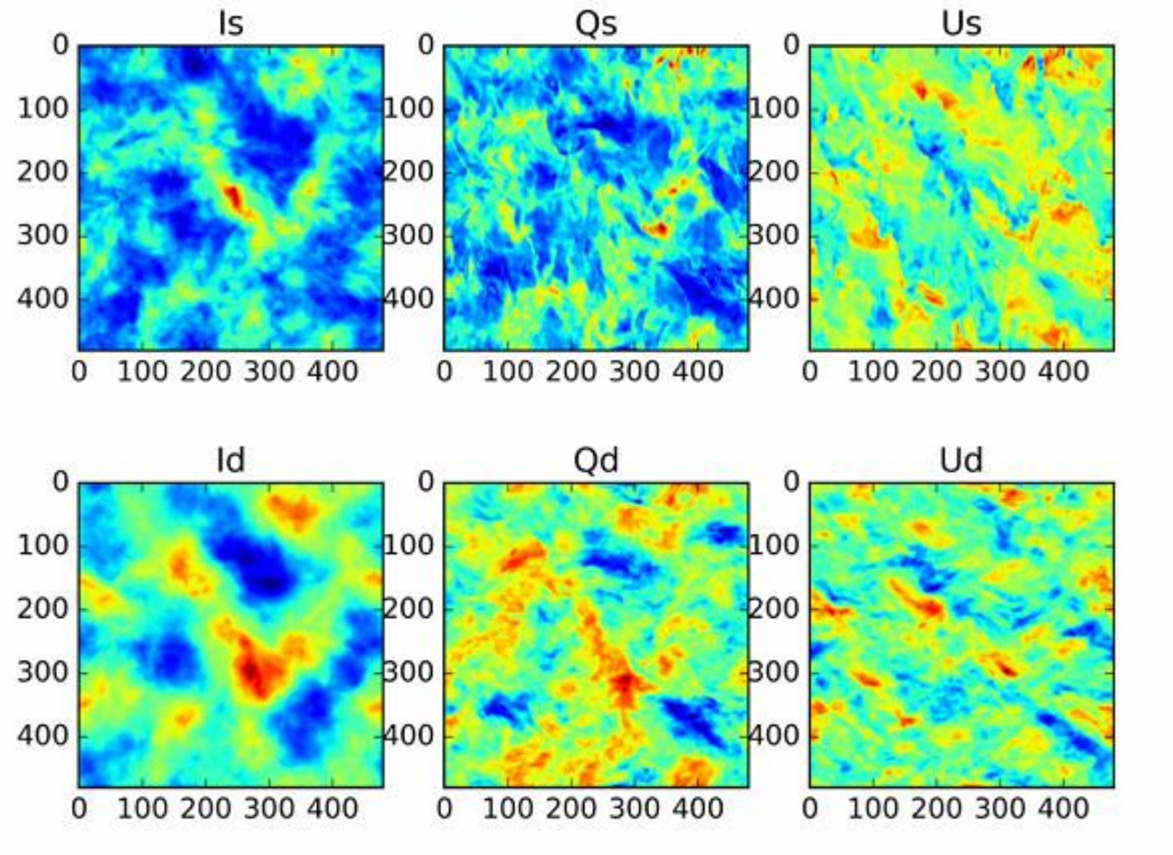
$$U_\nu^s = -2\int {\rm d}z\ \omega^{\frac{1-p}{2}} G(p) \left(B_x^2+B_y^2\right)^{\frac{p-3}{4}} 2\left(B_xB_y\right)$$

Synthesizing dust and synchrotron emission maps: Generation of data

$M_s = 0.26\ M_A = 0.8$ 20 Ghz



$M_s = 0.26\ M_A = 0.8$ 270 Ghz



Summary

1. It is wrong to use the model of foreground polarization consisting of regular and isotropic turbulent B-field.

2. Numerical simulations suggest a different model of turbulence for which we have a tested analytical representation.

3. Our group has expertize & tools and happy to collaborate with you in modeling polarized turbulent foregrounds