Major progress in MHD turbulence: NCAR and beyond

or

Ciao, Annick!

An incomplete personal view of the long and productive relationship between NCAR and the French school of turbulence theory   -- by W Matthaeus

precursors

- Turbulence theory (1960-1970)
  - Kraichnan (DIA), Orszag (EDQNMA)…
- Turbulence computation (1971 –
  - Orzsag Patterson PRL 1971
  - Herring et al, 1973, 1974

NCAR !!

- Computers! (CDC 7600, Cyber 200, CRAY…
  - NCAR CRAY 1A (serial #3) first one purchased 1977

NCAR: site of the marriage of numerical simulations and turbulence theory

1971…1974…1977

Numerical Simulation of Three-Dimensional Homogeneous Isotropic Turbulence

Steven A. Orszag*
Department of Mathematics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

G. S. Patterson, Jr.†
Department of Engineering, Swarthmore College, Swarthmore, Pennsylvania 19081
(Received 6 December 1971)

J. Fluid Mech. (1974), *vol.* 66, *part* 3, *pp.* 417–444 417
Printed in Great Britain

Decay of two-dimensional homogeneous turbulence

By J. R. HERRING,
Advanced Study Program, National Center for Atmospheric Research, Boulder, Colorado 80303

S. A. ORSZAG,
Department of Mathematics, Massachusetts Institute of Technology, Cambridge

R. H. KRAICHNAN
Dublin, New Hampshire 03444

AND D. G. FOX
Meteorological Laboratory, National Environmental Research Center, Environmental Protection Agency, Research Triangle Park, North Carolina†

Emergence of the French turbulence group at CNRS-Obs. de Nice & relationship with NCAR begins

- 1975

J. Fluid Mech. (1975), *vol.* 68, *part* 4, *pp.* 769–778 769
Printed in Great Britain

Possibility of an inverse cascade of magnetic helicity in magnetohydrodynamic turbulence

By U. FRISCH, A. POUQUET,
Centre National de la Recherche Scientifique, Observatoire de Nice, France
J. LÉORAT AND A. MAZURE
Université Paris VII, Observatoire de Meudon, France

- 1976…

A. Pouquet, These d'Etat (PhD) 1976

J. Fluid Mech. (1976), *vol.* 77, *part* 2, *pp.* 321–354 321
Printed in Great Britain

Strong MHD helical turbulence and the nonlinear dynamo effect

By A. POUQUET, U. FRISCH
Centre National de la Recherche Scientifique, Observatoire de Nice, France
AND J. LÉORAT
Université Paris VII, Observatoire de Meudon, France

Big computations in MHD: Nice/NCAR

- Annick for MHD, like Steve Orszag for hydro, has led the development of computational methods to accomplish ***state-of-the-art* computations**

- E.g., 1981: helicity effects on dynamo action

Helical and Nonhelical Turbulent Dynamos

M. Meneguzzi

Centre National de la Recherche Scientifique and Section d'Astrophysique, Division de la Physique, Centre d'Etudes Nucléaires de Saclay, F-91191 Gif-Sur-Yvette, France

and

U. Frisch

Centre National de la Recherche Scientifique, Observatoire de Nice, F-06007 Nice, France

and

A. Pouquet[a]

Centre National de la Recherche Scientifique, Observatoire de Meudon, F-92190 Meudon, France

(Received 13 April 1981)

Around ‘81, Annick & WHM Meet at Nice, discuss virtues of (avoiding) automobile care

Dynamic alignment

- **Large amplitude "Alfven waves"**
  $v = \pm b$ (Alfven units) is a soln. of MHD with/without mean field B_0

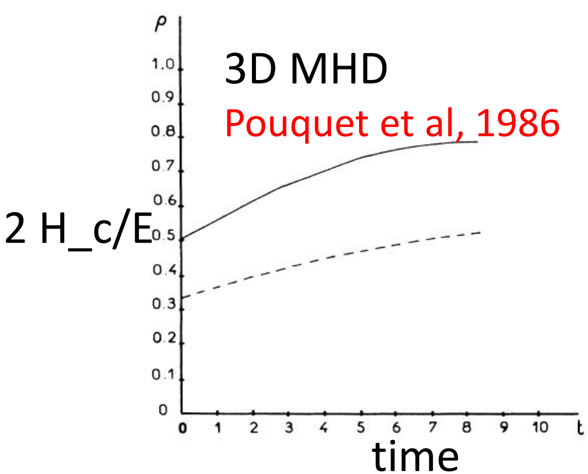
- Cascade times are such that cross helicity decays slower than energy

  [Dobrowolny, Mangeney & Veltri PRL (1980)]

- cross helicity/energy grows and flow become Alfvenic in time

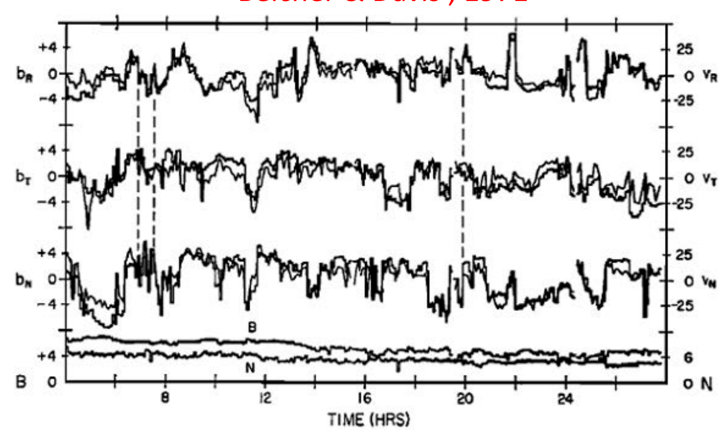
$$\frac{2\,\langle v \cdot b \rangle}{\langle v^2 + b^2 \rangle} = 2\,H\_c/E \;\rightarrow \pm 1$$

- *Evidence in simulations, and in solar wind*

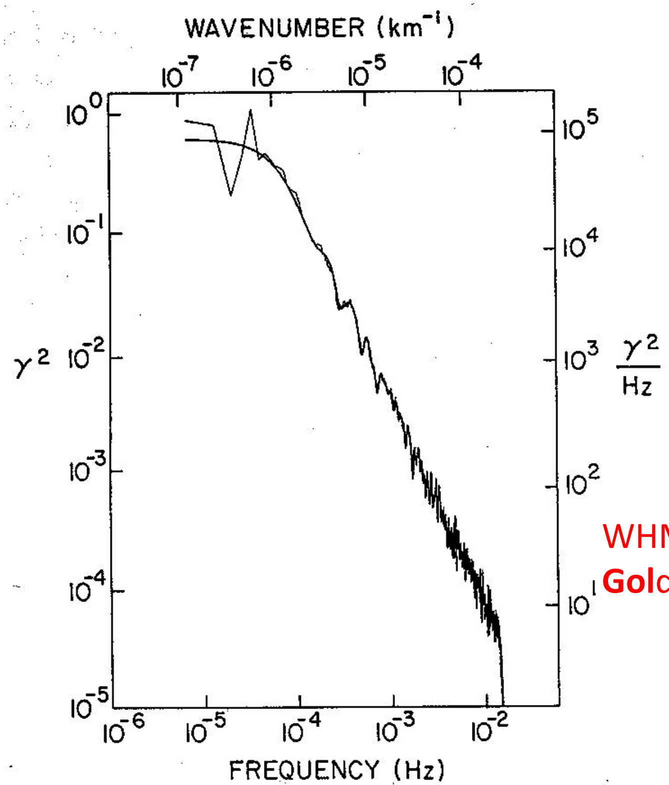


Very Alfvenic solar wind turbuelnce

Belcher & Davis , 1971



- For nearly 50 years there have been arguments about whether solar wind turbulence is “active” or a “fossil” of solar dynamics

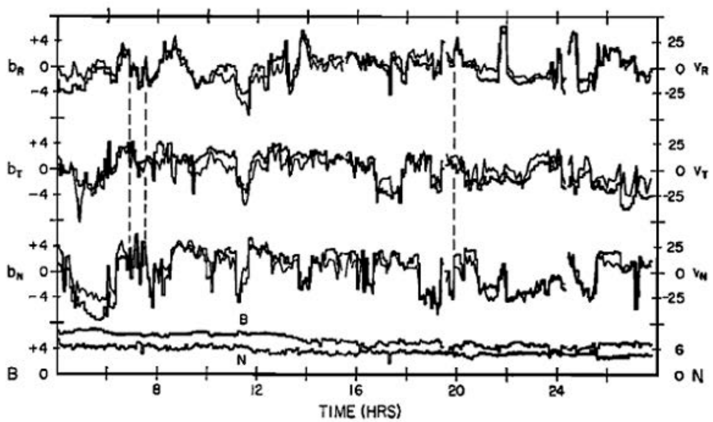


WHM & **Gol**dstein, 1982

Turbulence or waves???

Very Alfvenic solar wind turbuelnce

Belcher & Davis , 1971



Theory to the rescue!!

- 1998 Politano-Pouquet exact relations (Kolmogorov-Yalgom law for third order moments)

PHYSICAL REVIEW E VOLUME 57, NUMBER 1 JANUARY 1998

von Kármán–Howarth equation for magnetohydrodynamics and its consequences on third-order longitudinal structure and correlation functions

H. Politano and A. Pouquet
Centre National de la Recherche Scientifique, UMR 6529, Observatoire de la Côte d'Azur, Boîte Postale 4229, 06304 Nice Cedex 4, France

$$\langle \delta z_L^{+\,2}(\mathbf{r})\, \delta z_L^{-}(\mathbf{r}) \rangle = -C_d \epsilon^{+} r,$$

$$\langle \delta z_L^{-\,2}(\mathbf{r})\, \delta z_L^{+}(\mathbf{r}) \rangle = -C_d \epsilon^{-} r.$$

Solar wind puzzle solved!

There has been a mini-industry in solar wind third order observations

The Astrophysical Journal, 679:1644–1660, 2008 June 1

THE TURBULENT CASCADE AT 1 AU: ENERGY TRANSFER AND THE THIRD-ORDER SCALING FOR MHD

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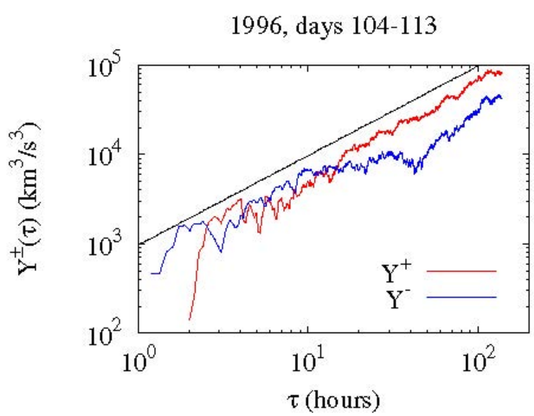
Physics Department, Space Science Center, University of New Hampshire, Durham, NH; BTMB@unh.edu, Charles.Smith@unh.edu
and
Miriam A. Forman
Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, NY; Miriam.Forman@sunysb.edu
Received 2007 August 9; accepted 2008 January 4

L 99, 115001 (2007) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2007

Observation of Inertial Energy Cascade in Interplanetary Space Plasma

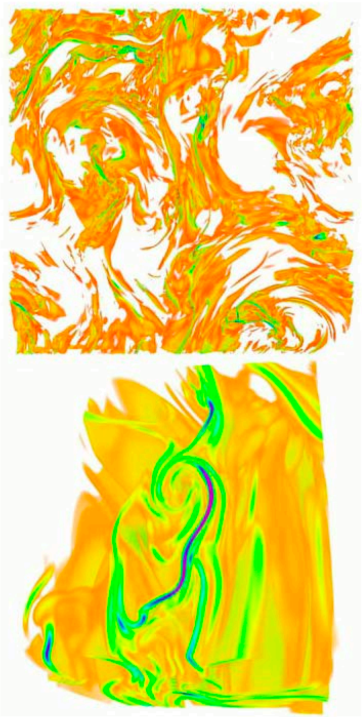
L. Sorriso-Valvo,[1] R. Marino,[2] V. Carbone,[2] A. Noullez,[3] F. Lepreti,[2] P. Veltri,[2] R. Bruno,[4] B. Bavassano,[4] and E. Pietropaolo[5]
[1]*Licryl Regional Laboratory - INFM/CNR, Ponte P. Bucci, Cubo 33C, 87036 Rende (CS), Italy*
[2]*Dipartimento di Fisica, Università della Calabria, Ponte P. Bucci Cubo 31C, 87036 Rende (CS), Italy*
[3]*Observatoire de la Côte d'Azur, Nice, France*
[4]*IFSI/CNR, Via Fosso del Cavaliere, Roma, Italy*
[5]*Dipartimento di Fisica, Università dell'Aquila, L'Aquila, Italy*
(Received 27 February 2007; published 12 September 2007)

Geometry	Latitude	Outward $\epsilon \pm \sigma_\epsilon$ (10^2 J kg^{-1} s^{-1})	Inward	Total
Full 3D	Ecliptic	57 ± 5	51 ± 5	54 ± 7
Isotropic	Ecliptic	105 ± 2	25 ± 1	65 ± 1
2D + 1D	Ecliptic	140 ± 3	18 ± 3	79 ± 2
Isotropic	Poles	1.8 ± 0.7	1.6 ± 0.5	1.7 ± 0.9



Using Politano-Pouquet relations, the SW cascade rates are directly measured as 300-1000 J/Kg-s at 1AU

MHD turbulence produces complex flux tube and electric current structures: manifestations of intermittency



Slice & blowup

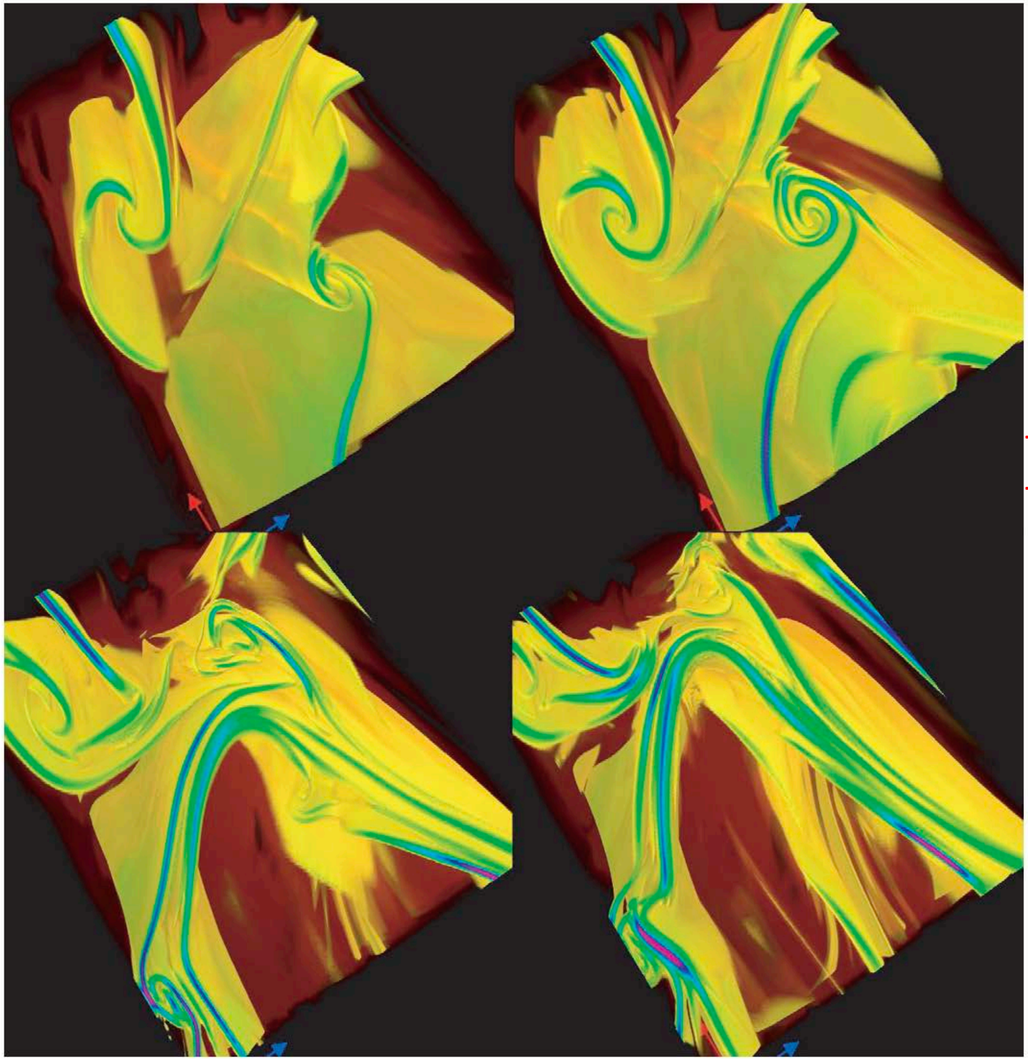


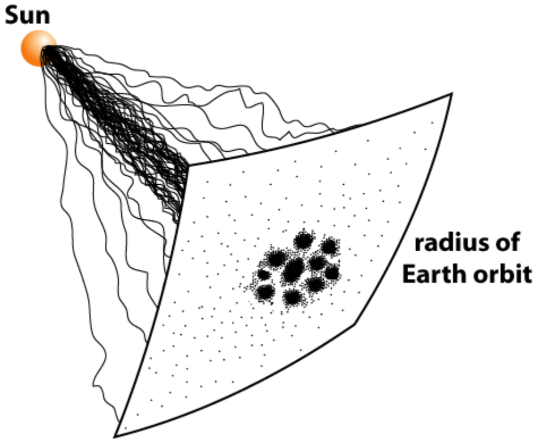
Figure 10. Same as in figure 9, but showing only the current intensity. The associated movie (available from stacks.iop.org/NJP/10/125007/mmedia) shows the temporal evolution.

1536^3 3D MHD

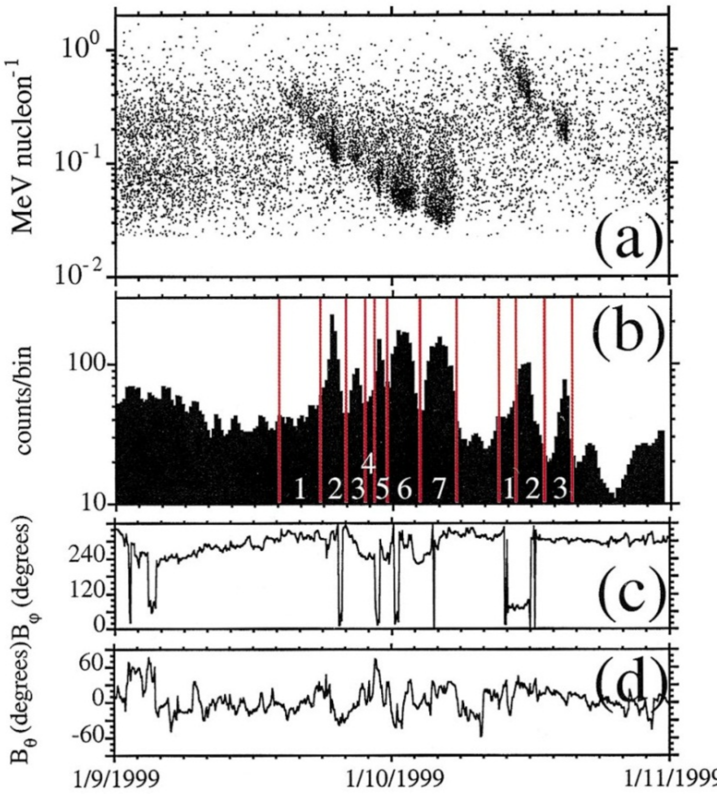
- Mininni et al NJP
- 2008

Very large scales (10^13 cm): Spatially structured turbulence produces transport or "trapping" boundaries

Boundaries are observed: "dropouts" of Solar energetic particles



Ruffolo et al.2003



H-FE ions vs arrival time
For 9 Jan 1999 SEP event
From Mazur et al, ApJ (2000)

Temporarily trapped
Particles-- Tooprakai et al, 2007

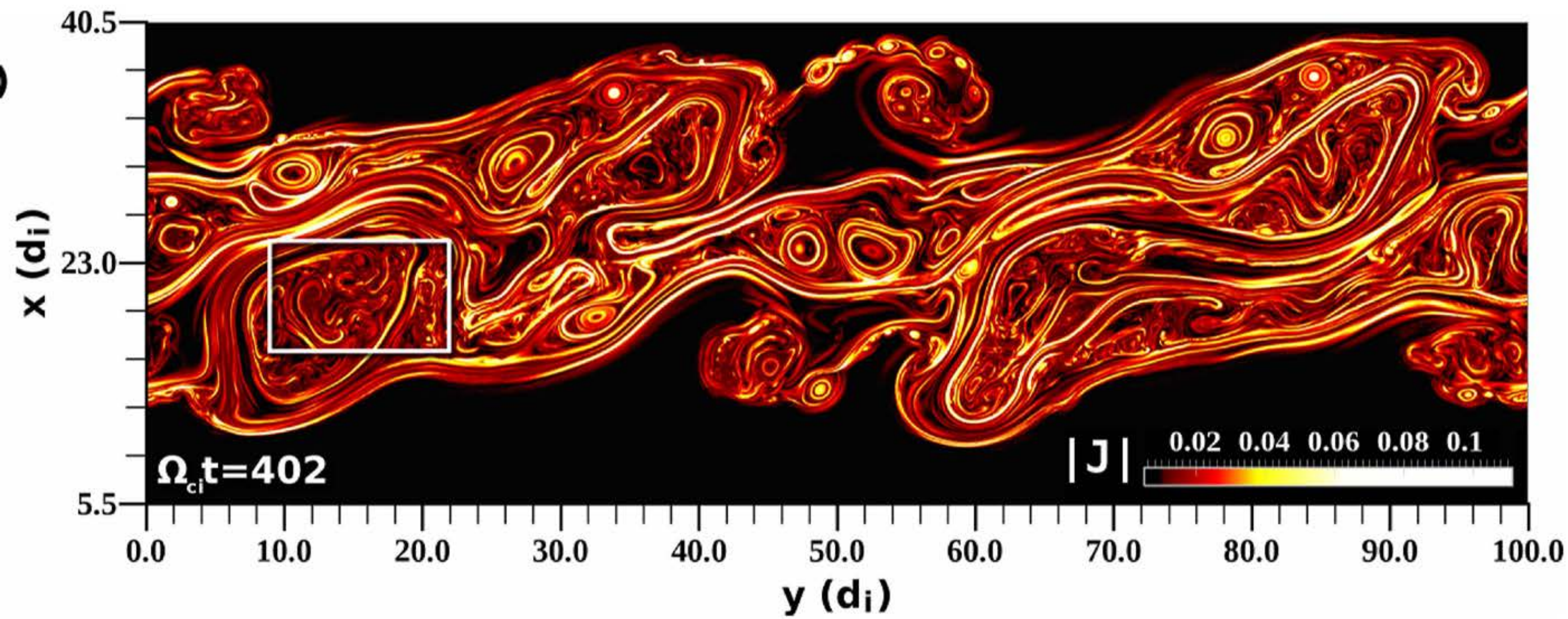
conclusion

- Annick: Keep up the good work!

- NCAR:
  - ***???***

Very small scale plasma kinetic structures:
High res. PIC simulations (H. Karimabadi, W. Daughton & V. Roytershteyn) show intermittent kinetic scale dissipation with structure to electron skin depth.

8192x16384 PIC driven by large scale shear, map of |J|



Detailed analyses:
Karimabadi et al, PoP 2013; Wan et al, PRL 2012; Wu et al, ApJ 2013

There has been enormous benefit and progress due to a long & committed relationship between turbulence theory and MHD/fluid computations

Theoretical work in turbulence in A.P.'s group in GTP in the past ~15 years

- Current sheets & vorticity
- Intermittency in 2D and 3D
- Lagrangian-averaged (Alpha) model
- Dynamo problem at non-unit Prandtl number
- Rotating fluids
- Local alignments
- Inverse cascade computations
- Long time states of MHD
- Non-universality in MHD (!!!)
- LES
- AMR and Spectral element computations
- Scale to scale transfer in MHD
- …etc

Applications of these ideas in:

- Planetary dynamo
- Stellar dynamo
- Coronal heating
- Solar wind cascade
- Transport and scattering of solar energetic particles
- Space Weather
- Crossover to fusion
- Geophysical fluid dynamics
    - Astrophysical flows (ISM, star formation, SNRs)
- Computational physics
- Parallel computing