Dissipation in the turbulent ISM

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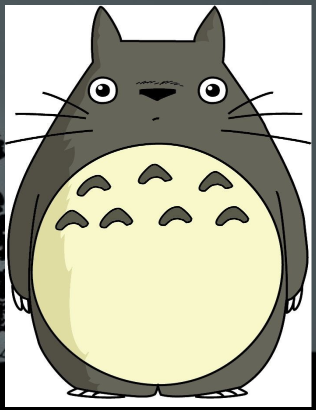
Totoro



Molecules, magnetic fields and Intermittency in coSmic Turbulence

Following the energy trail...

(a beach in the Maldives)

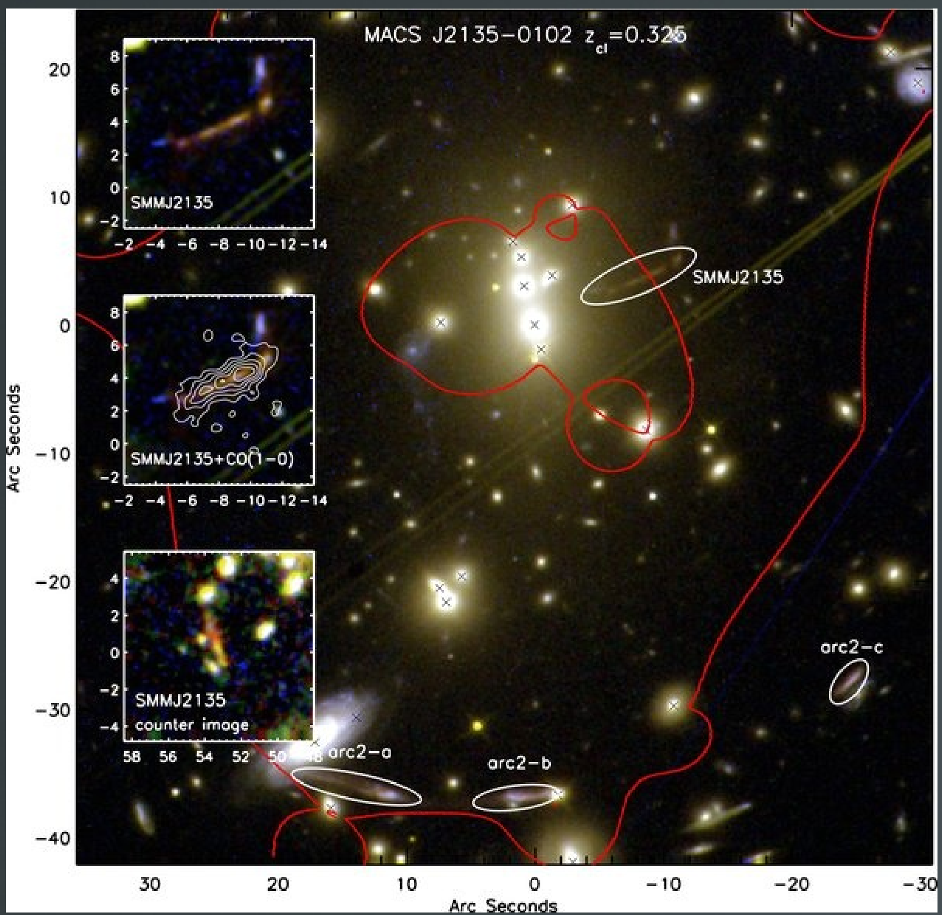
Bioluminescence in waves: plancton highlights
Strong shear change

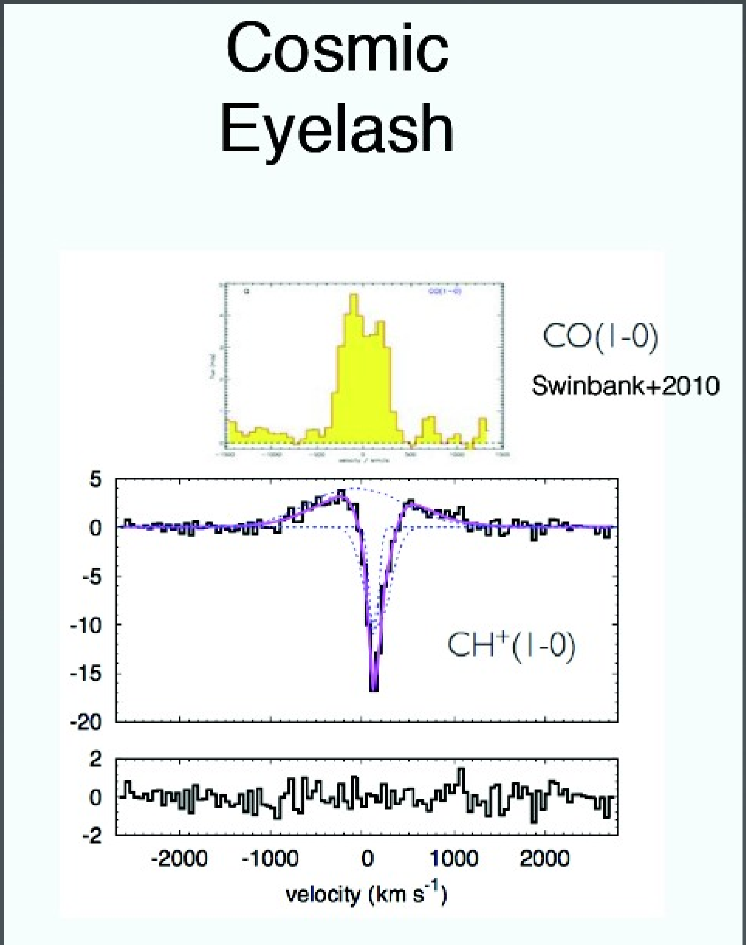
MISTy questions

- Origin of molecules in dilute and violent media ?
    - CO observed in diffuse irradiated media
    - Warm H2
    - extragalactic and galactic CH+
- Origin of the clumpy structure of the cold ISM ?
- Origin and Structure of the B field, its link with matter ?
- ↔ MHD turbulence dissipation (energy is dissipated in localised structures which affect the chemistry and magnetic fields)

The blink of the cosmic eyelash

A galaxy seen through a gravitational lense





Swinbank+2010
Redshift z=2.33

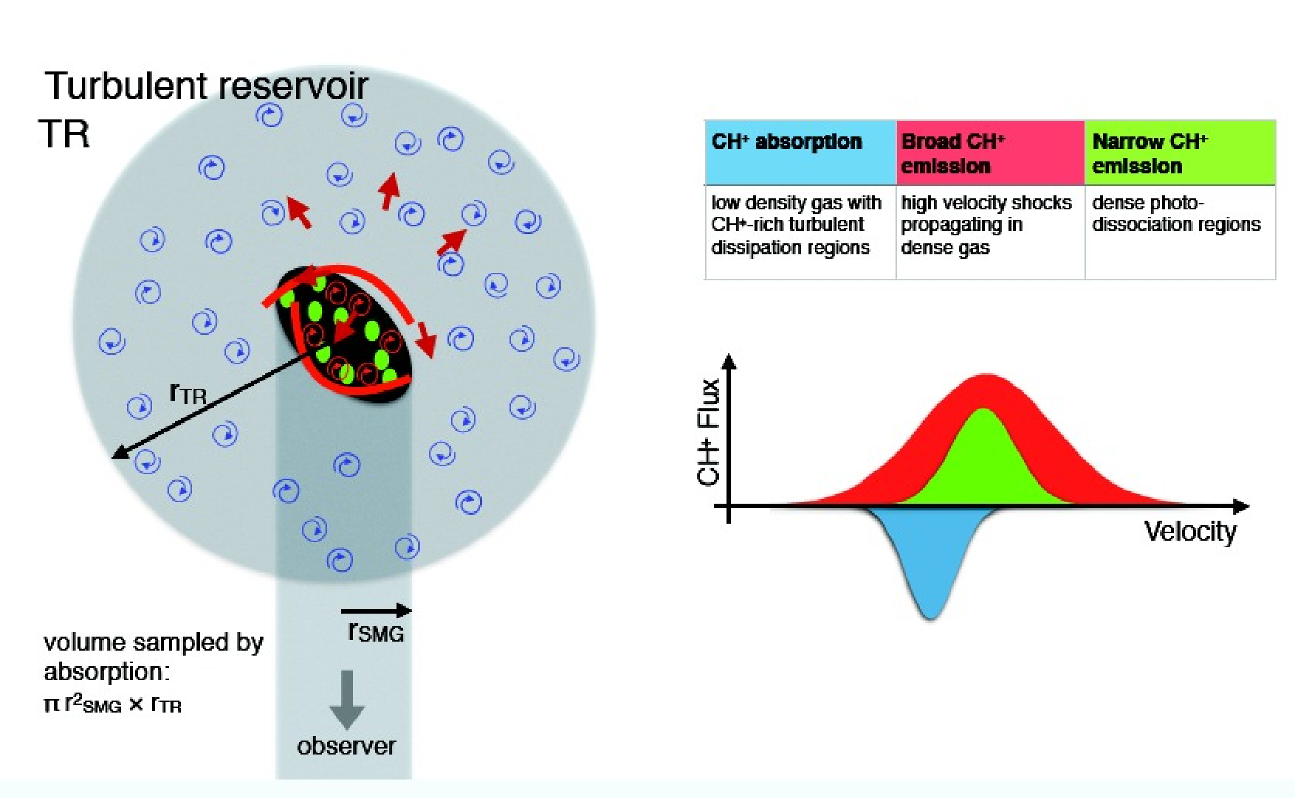
Falgarone+2017

Observational Context

- Broad lines of CH+ in emission and absorption in high-z galaxies (Falgarone+17 Nature, 548, 430)
- Molecular emission in colliding galaxies (Stefan's Quintet)
- Molecular emission hints at very dense and cool, probably clumpy media
- Broad lines: equipartition between large scale

  thermal energy (10^7 K) and kinetic energy of dense cool gas.

The blink of the cosmic eyelash

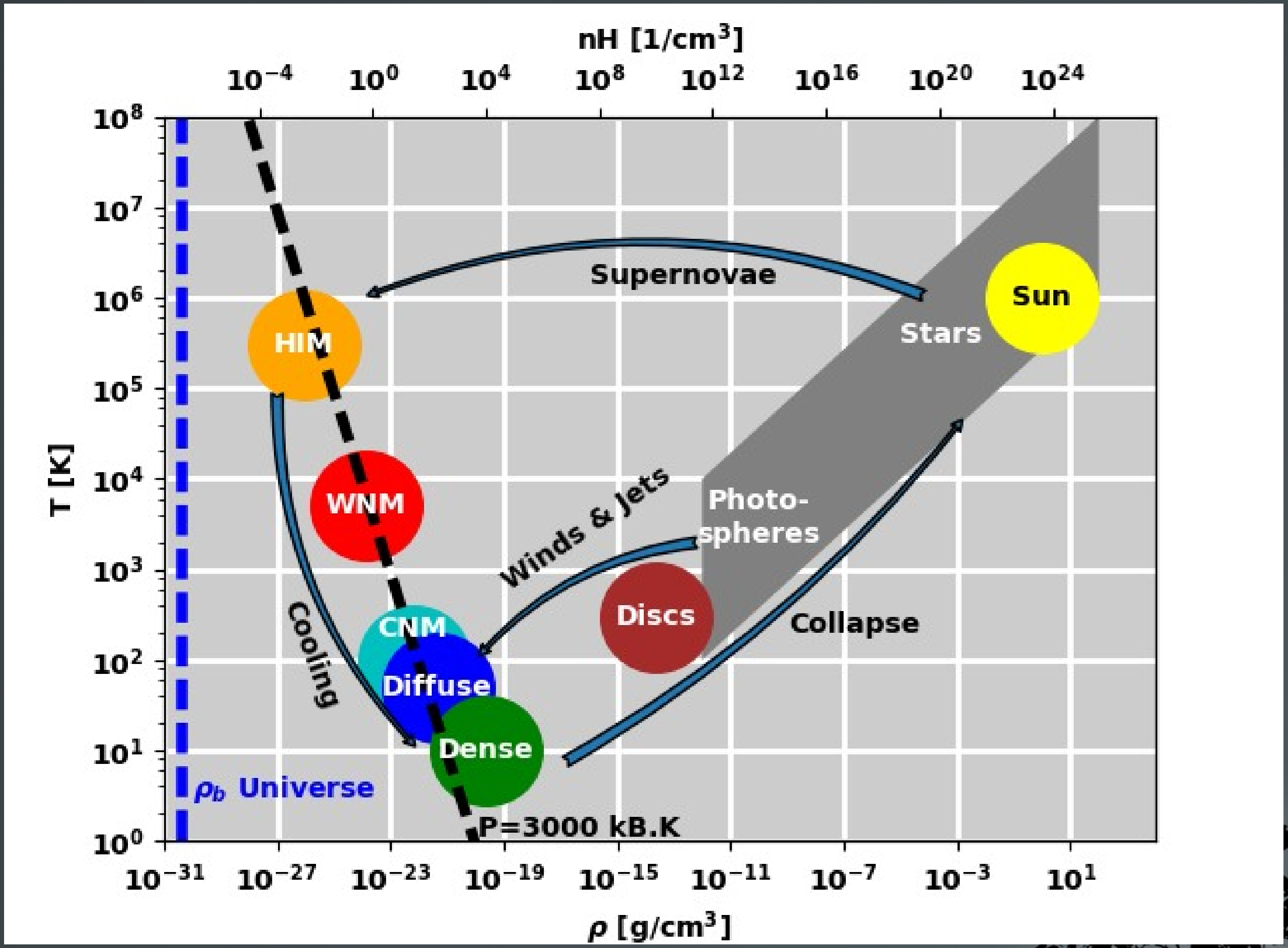


Falgarone+2017

Interpretation in MIST
The energy trail(s)

- Large scale energy is transferred to smaller scales by turbulent cascade (stretching and compression) and by cooling cascade (condensation)
- The cooling cascade proceeds with a phase separation. How is kinetic energy shared between phases ?
- Energy is radiated in bursty dissipative structures
- Molecules are produced and excited by these dissipative structures (e.g. vortex, shocks)

The phases of the ISM



Typical values

- Huge dynamical range of length scales,
- but not so big for velocity
- Reynolds number: UxL / dissipation coefficient

	HIM	WNM	CNM	Diffuse	Dense	Discs	Sun
Density ρ [cm^{-3}]	0.004	0.6	30	200	10^4	10^{10}	1 $g.cm^{-3}$
Temperature T [K]	3.10^5	5000	100	50	10	300	10^6
Length scale L [pc]	100	50	10	3	0.1	200 AU	5.10^{-3} AU
Velocity U [$km.s^{-1}$]	10	10	10	3	0.1	0.1	1
$\mathcal{M}$	0.2	2	13	7	0.5	0.1	0.02
$\mathcal{M}_{\mathcal{G}}$	130	20	15	6	0.8	0.08	0.003
$\mathcal{R}$	10^2	10^5	10^7	10^7	10^6	10^9	10^{17}
$\mathcal{R}_m$	10^{21}	10^{20}	10^{18}	10^{17}	10^{15}	10^9	10^{10}
$\mathcal{R}_{AD}$	10^3	10^3	10^2	10^3	10^4	10^5	10^{20}
Ionisation fraction	1	10^{-2}	10^{-4}	10^{-4}	10^{-4}	10^{-7}	1
Mass per ion [amu]	1	1	12	12	12	24	1
1/10x $N_e B_z$ [$10^{19} cm^{-2} 3 \mu G$]	0.12	0.09	0.009	0.01	0.02	0.2	3×10^{15}
1/10x N_e[$10^{19} cm^{-2}$]	0.05	0.5	0.3	0.3	0.1	10^3	10^{27}

Dissipation in decaying turbulence

(incompressible runs)

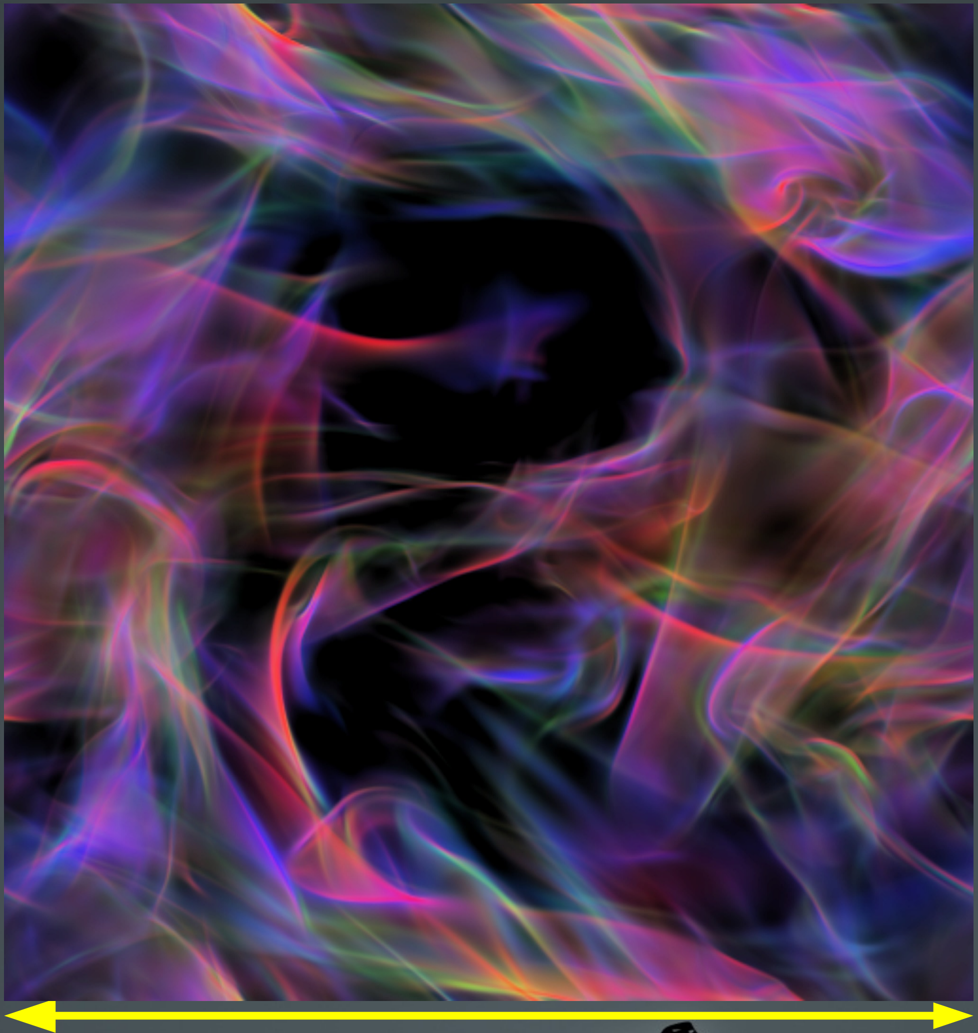
$n_H \sim 100/cm^3$

$<u^2> \sim <b^2/\rho>$

$Re = LU/\nu \sim$ ~~2.10^7~~ 10^3

$Re_m = LU/\eta \sim$ ~~2.10^{17}~~ 10^3

$Re_{AD} = L/U/t_{AD} \sim 10^2$



Line of sight integrated dissipation:

$$\epsilon_{\rm diss} = \nu\rho S_{ij}[u]\partial_i u_j + \eta|\nabla \times B|^2 + F_{in}|u-v|^2$$

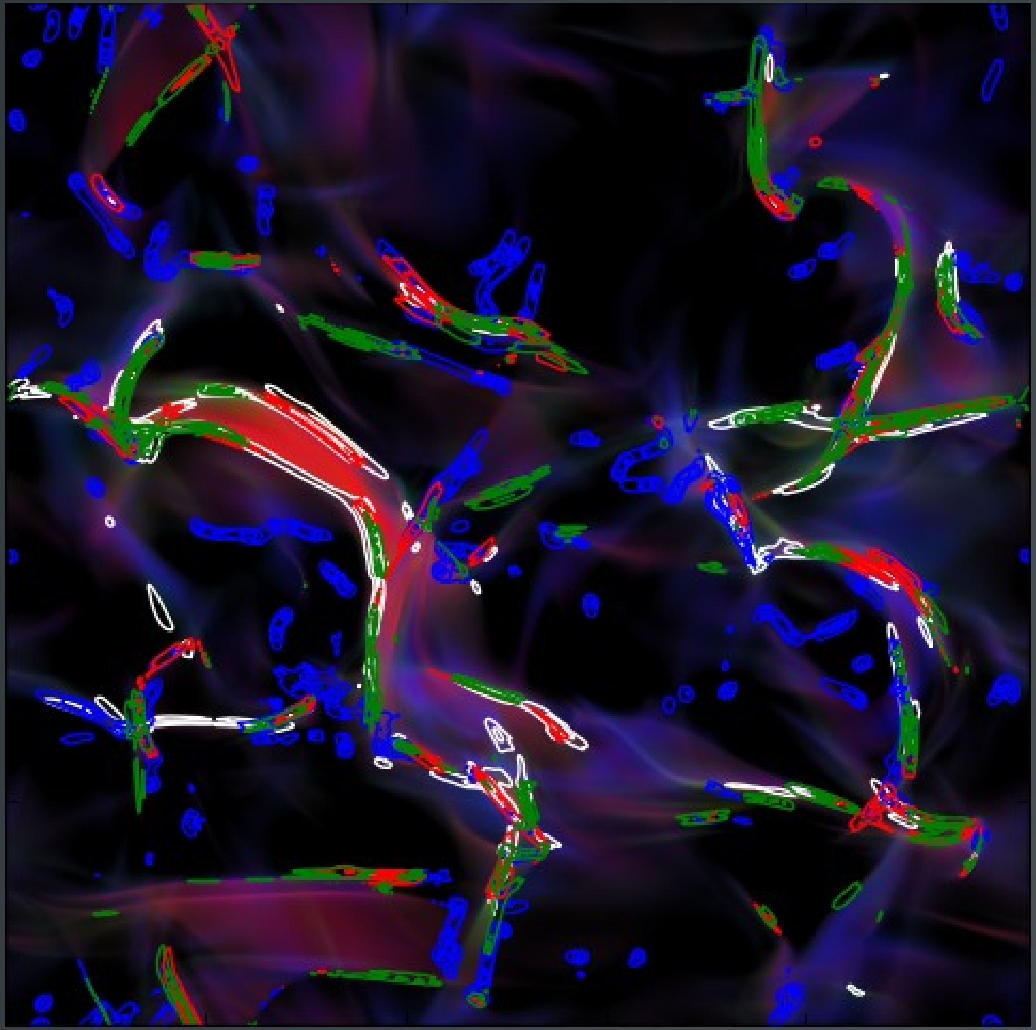
(Momferratos PhD thesis: 512^3 spec. elts
Incompressible simulations by ANK, pseudo-spectral code with AD)

Giorgos' PhD: Decaying Incompressible MHD + AD

- Dissipation localised on sheets, structure extraction
- Measured statistics of dissipative structures (PDFs and correlation between characteristic prop.$^{\text{ties}}$)
- Each sheet is 'pure' in its dissipation nature: viscous, ohmic or ambipolar heating
- Correlations between dissipation proj. and increments
- Initial conditions matter a lot
- B field orientation is not random w.r.t. to dissipation in slices
- A.D. Forces jxb=0 from small scales towards large

Observable increments vs. dissipation

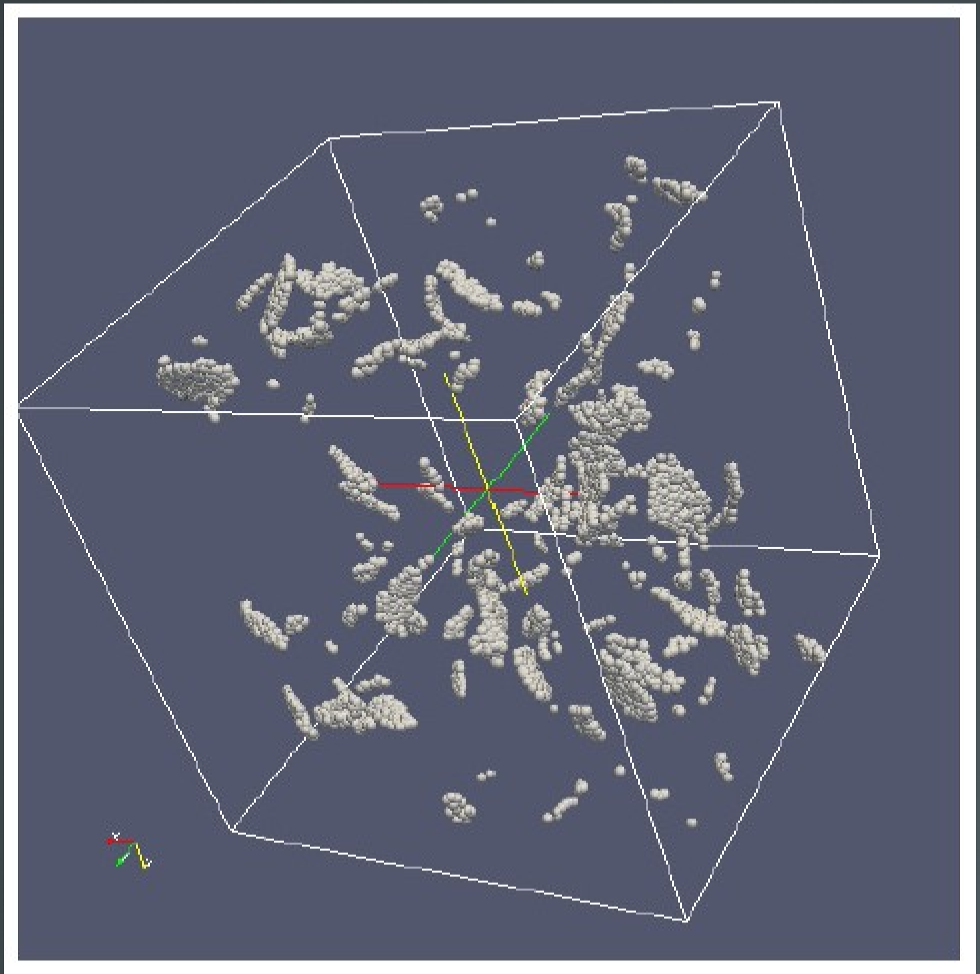
Lbox / 2



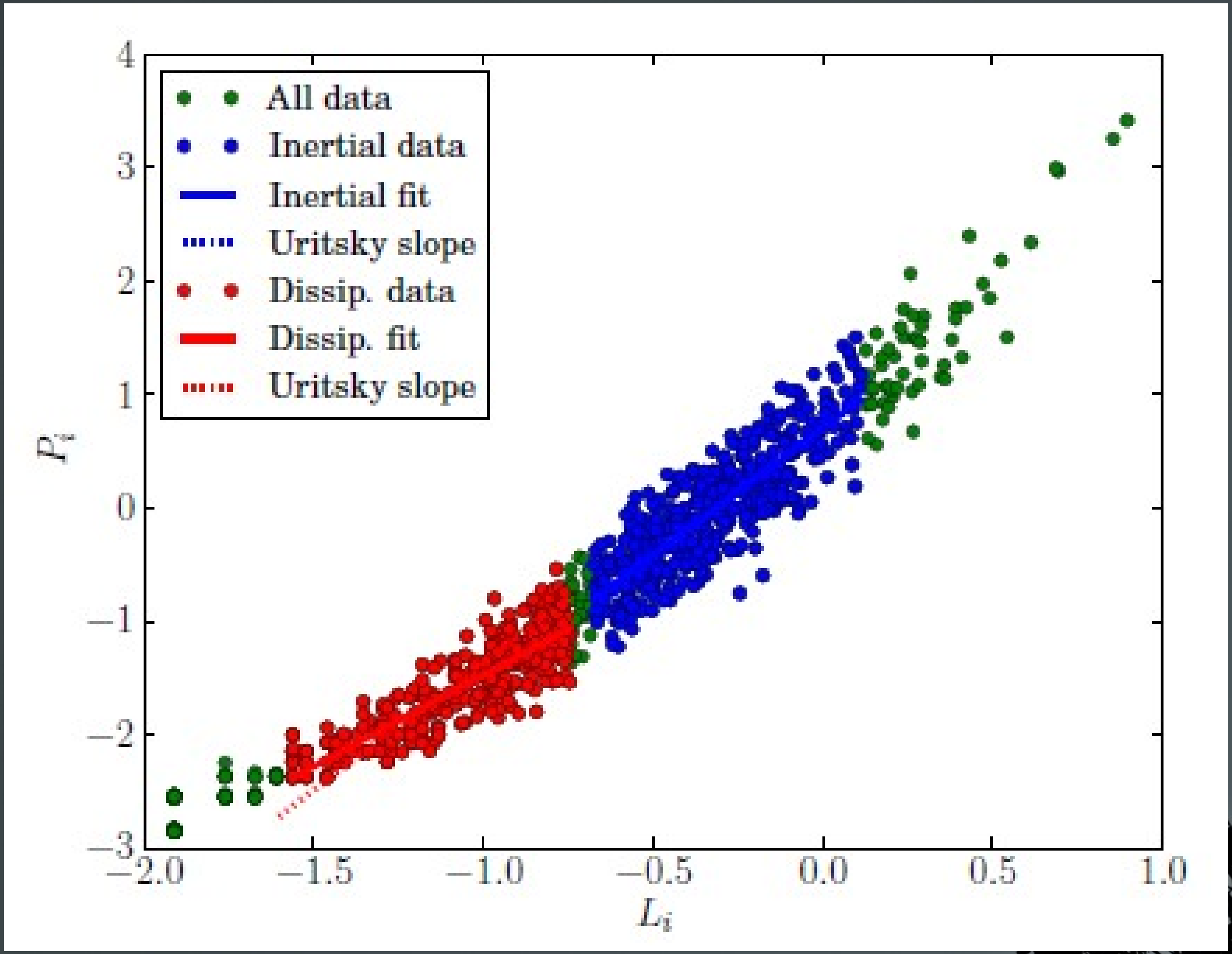
- <u>Background</u>:
  Dissipation rates
  Ohmic Viscous AD
- <u>Contours:</u>
  Increments of integrated observables:
  - **LOS velocity (white)**
  - **Stokes Q (green)**
  - **Stokes U (red)**
  - **POS polarisation angle (blue)**

<u>NOTE:</u> increment of polarisation angle (blue contours) are less correlated to dissipation. Better use Q,U.

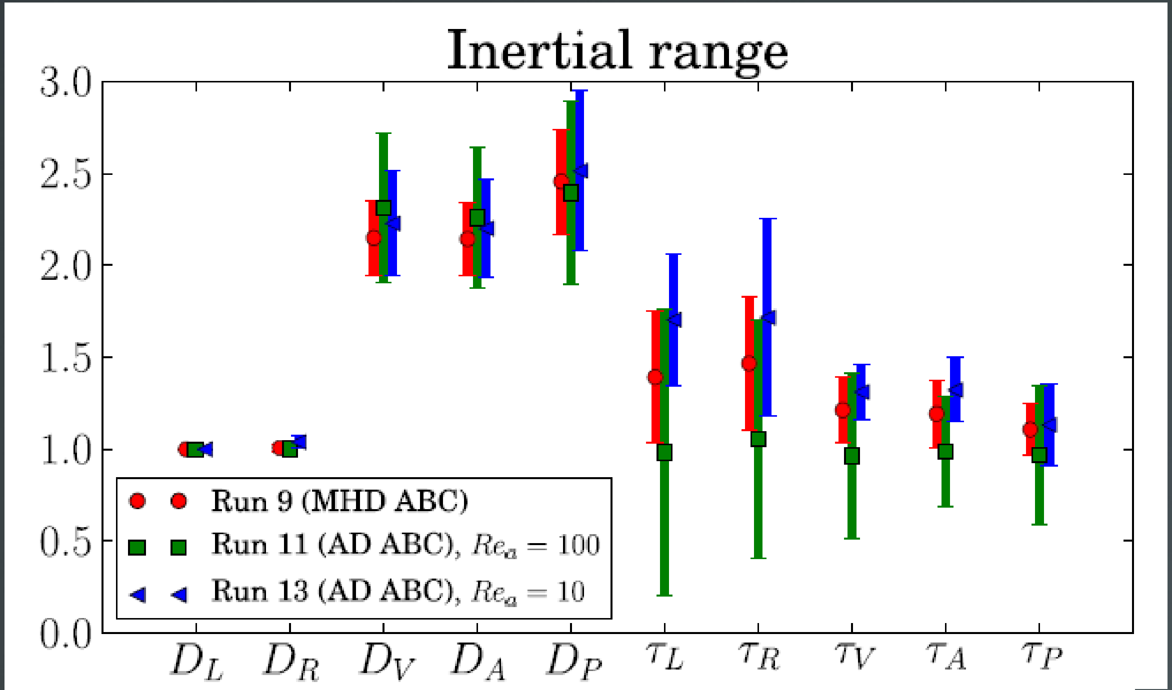
Dissipative structures
(locii of intense dissipation, > $\mu+2\sigma$)

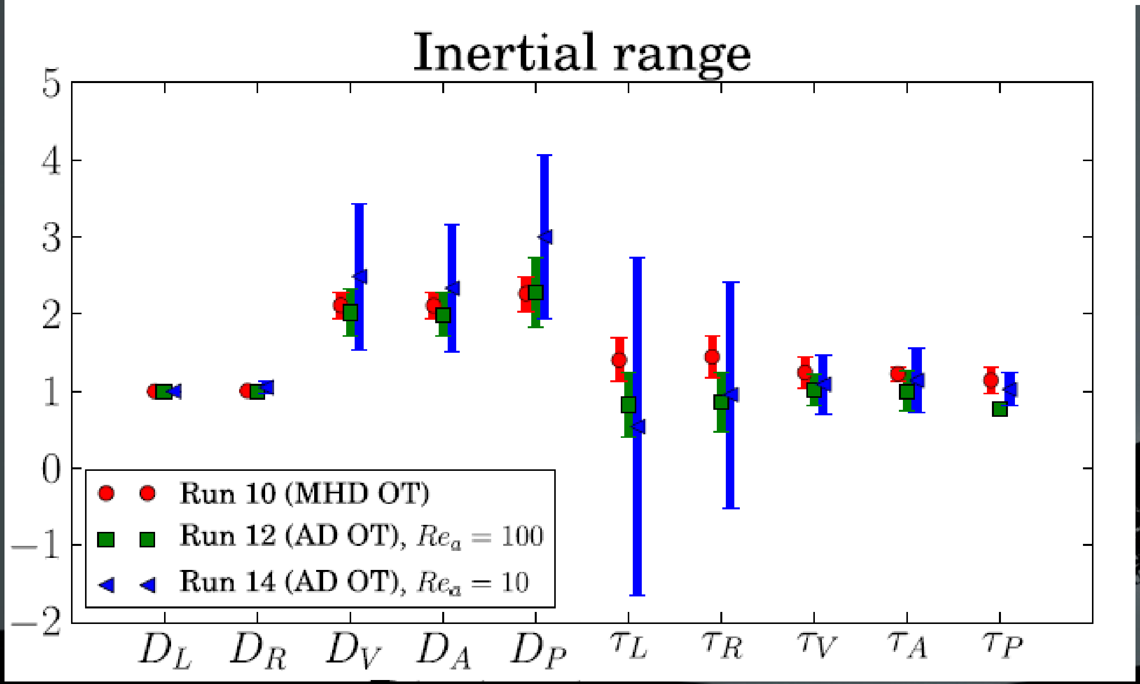


Structure statistics (one example)

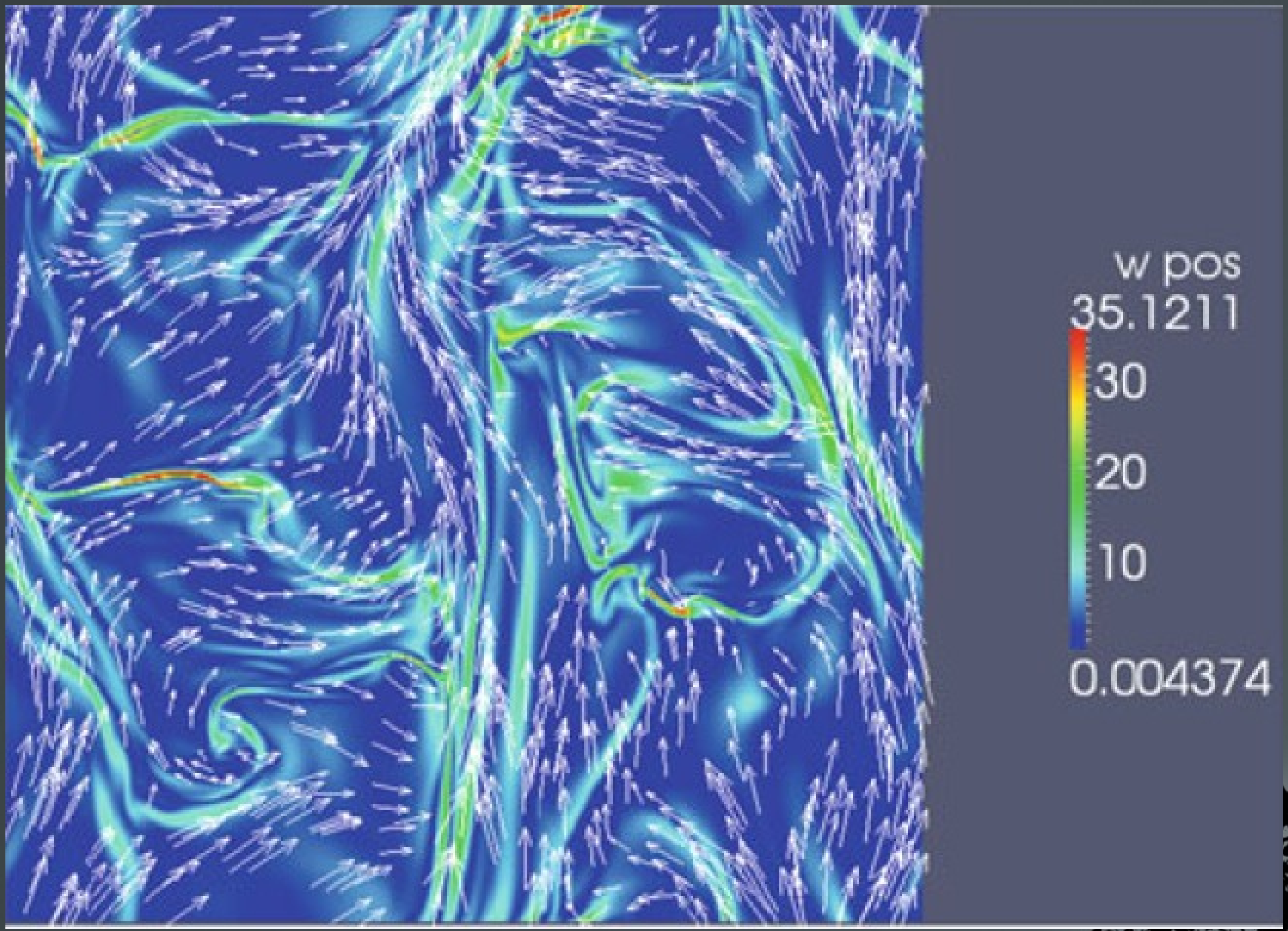


Initial conditions matter





Slice of B(p.o.s.) and |curl(u)| relative orientation not random



JxB ~ 0 with ambipolar diffusion

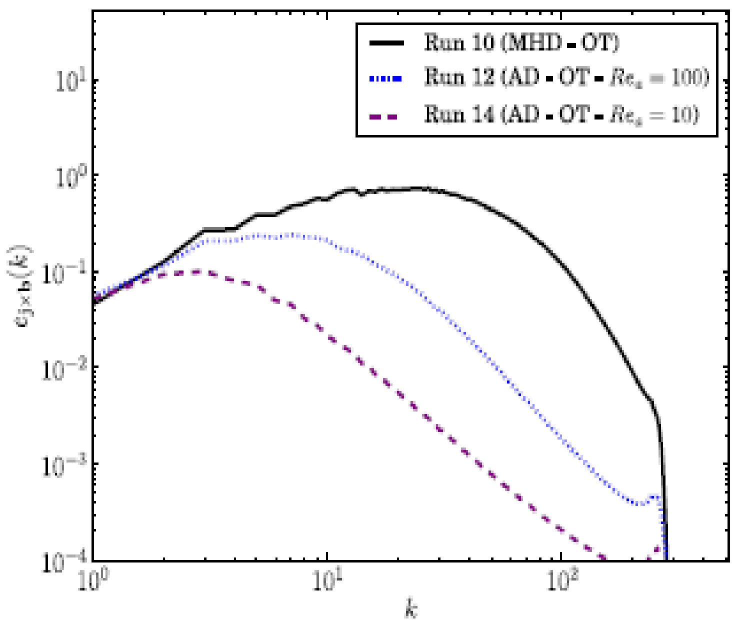


Figure 4.6: Power spectra of $\mathbf{j} \times \mathbf{b}$ for high resolution runs 10,12 and 14. The field becomes force-free at small scales when the strength of the AD is increased.

Ques: does this mean that at small scales, Hydrodynamic turbulence prevails ?
And Bfield is force-free (jxb=0), independent ?
Maybe not: induction equation must be compatible with force-free.

Simulations of decaying turbulence.

Compressible: Isothermal 3D MHD (Mach 4, ABC)

~1 pc

$n_H \sim 100/cm^3$

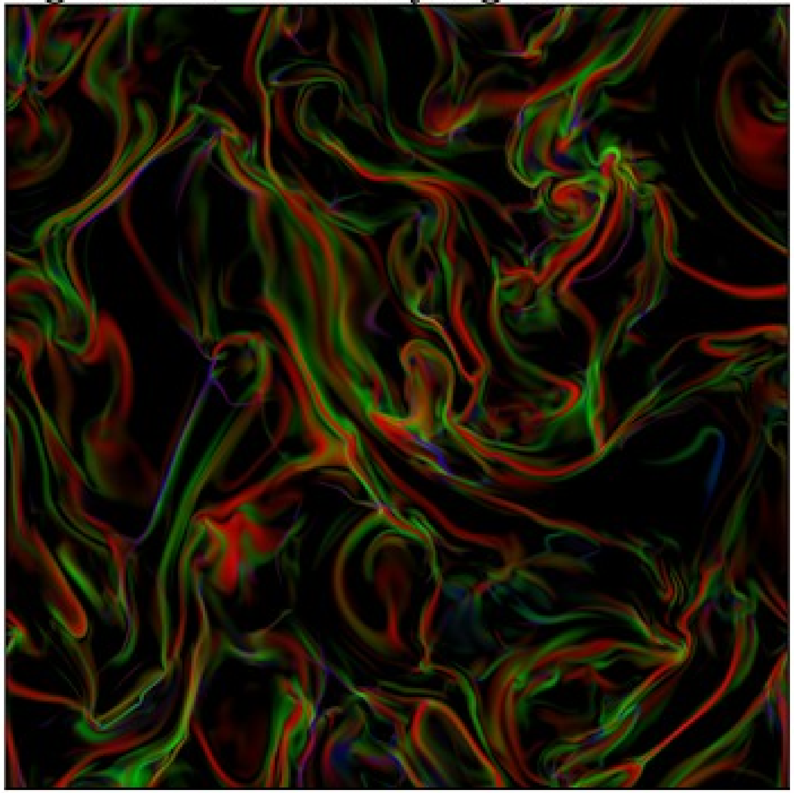
$\langle u^2 \rangle \sim \langle b^2/\rho \rangle$

$Re=LU/\nu \sim$ ~~2.10^7~~ 10^3

$Re_m=LU/\eta \sim$ ~~2.10^{17}~~ 10^3

(1020^3 pixels)

Heating nature in decaying MHD turbulence



Red: Ohmic heating

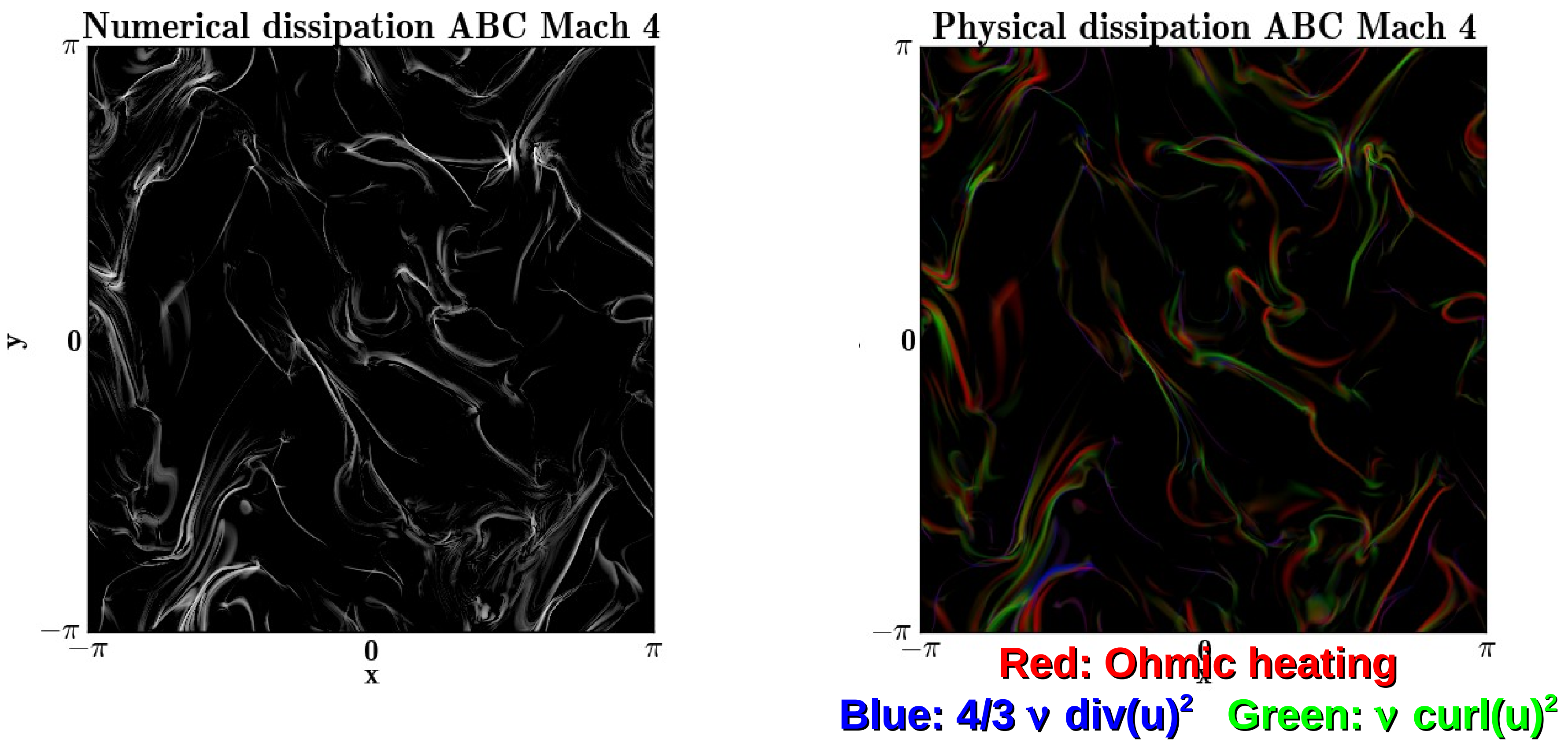
Blue: 4/3 ν div(u)^2 Green: ν curl(u)^2

(Momferratos PhD thesis:
DUMSES simulations with careful treatment of viscous and resistive dissipation)

Thibaud's Internship (& PhD)
Decay Compressible MHD (no AD)

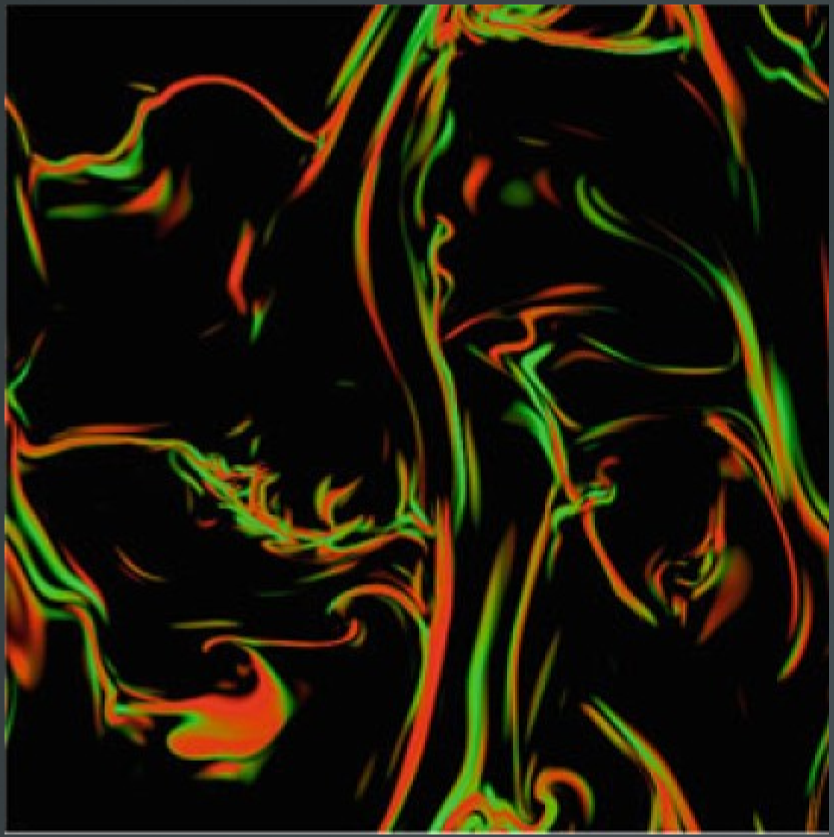
- Nature of dissipation is mixed
- [grid => need to recover dissipation from grid]
- B field // dissipative structures in 3D
  (but not in projection)
- Dissipation is dominated by low convergence

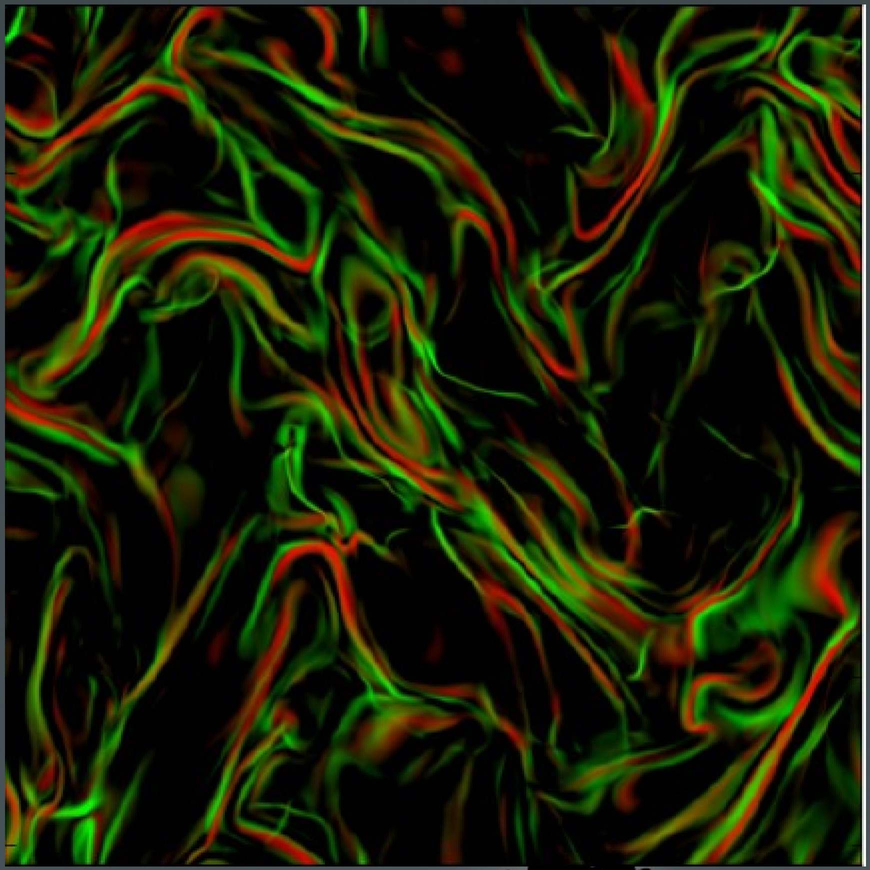
Grid Dissipation



Need to estimate *numerical* dissipation
to recover the properties of the *total* dissipation

Now ohmic and viscous dissipation are mixed

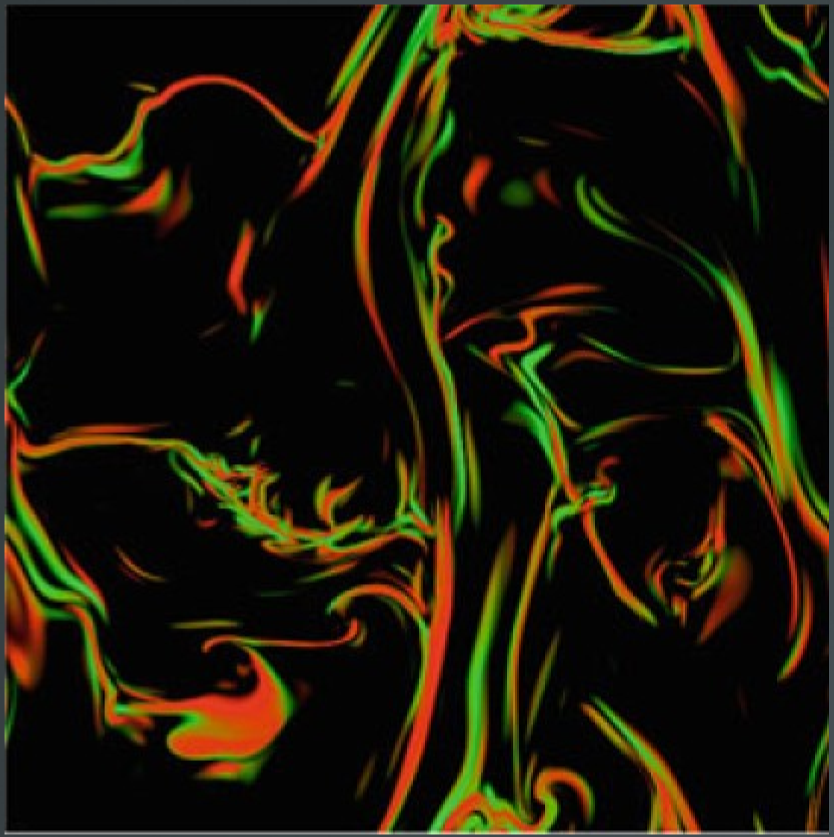


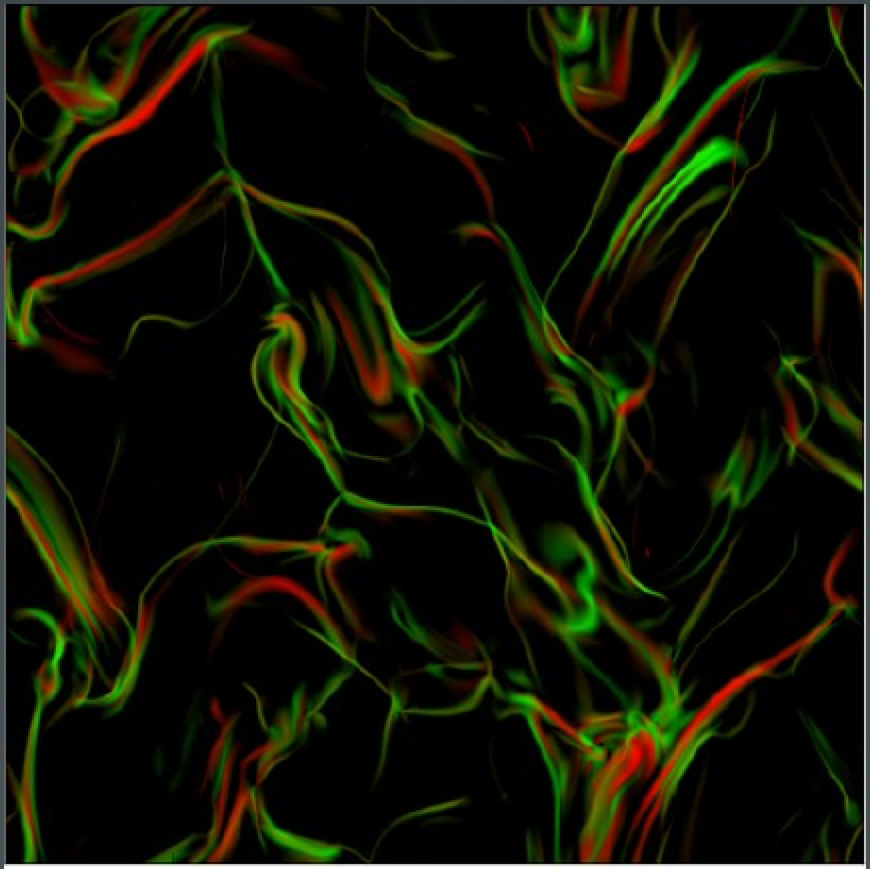


Mach 0

Mach 1

Now ohmic and viscous dissipation are mixed

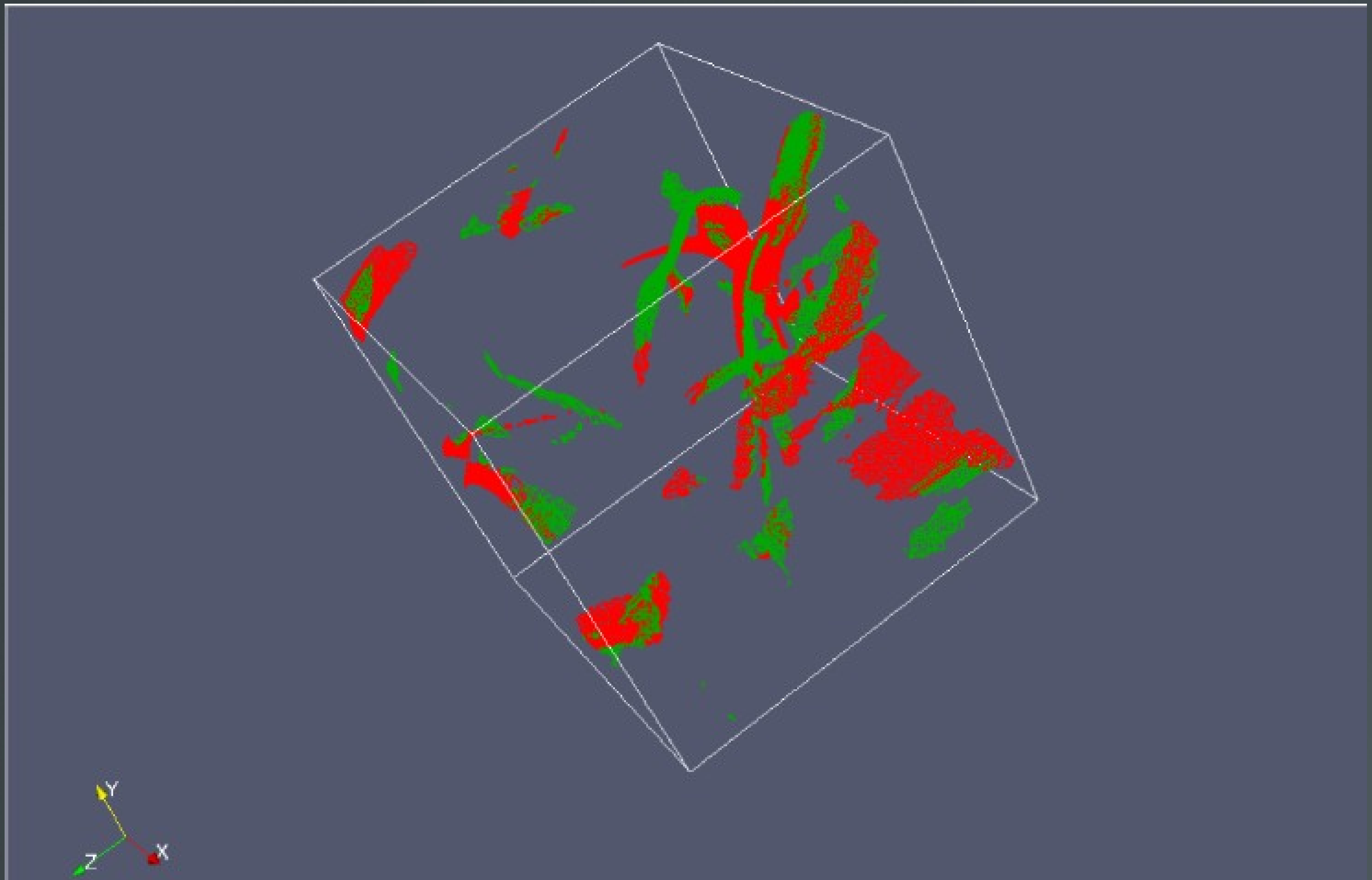




Mach 0

Mach 4

Viscous and Ohmic dissipation



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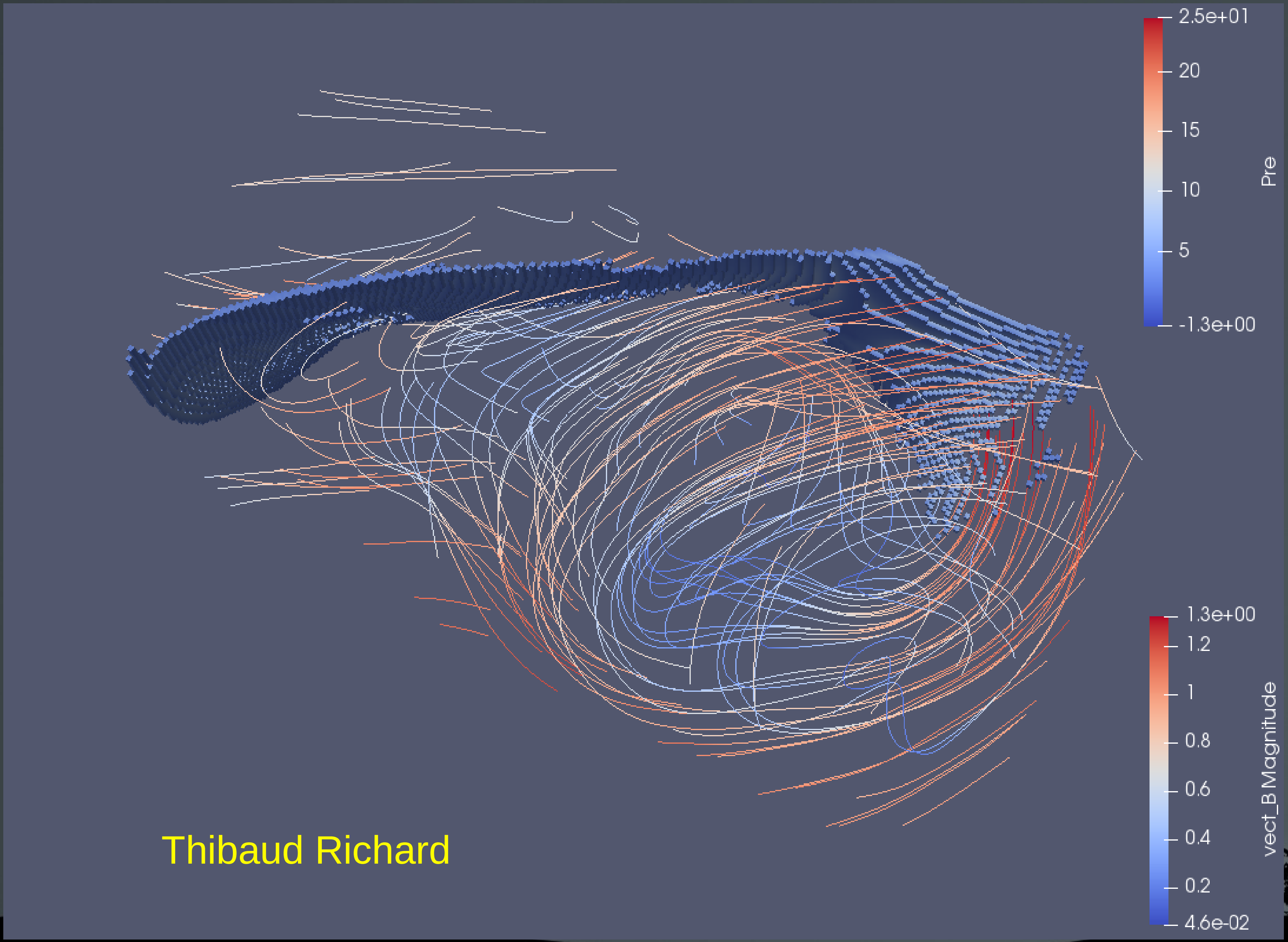
Dissipative structures extraction

Find connected sets where dissipation > mean + 2.std



B field is mostly parallel to structures

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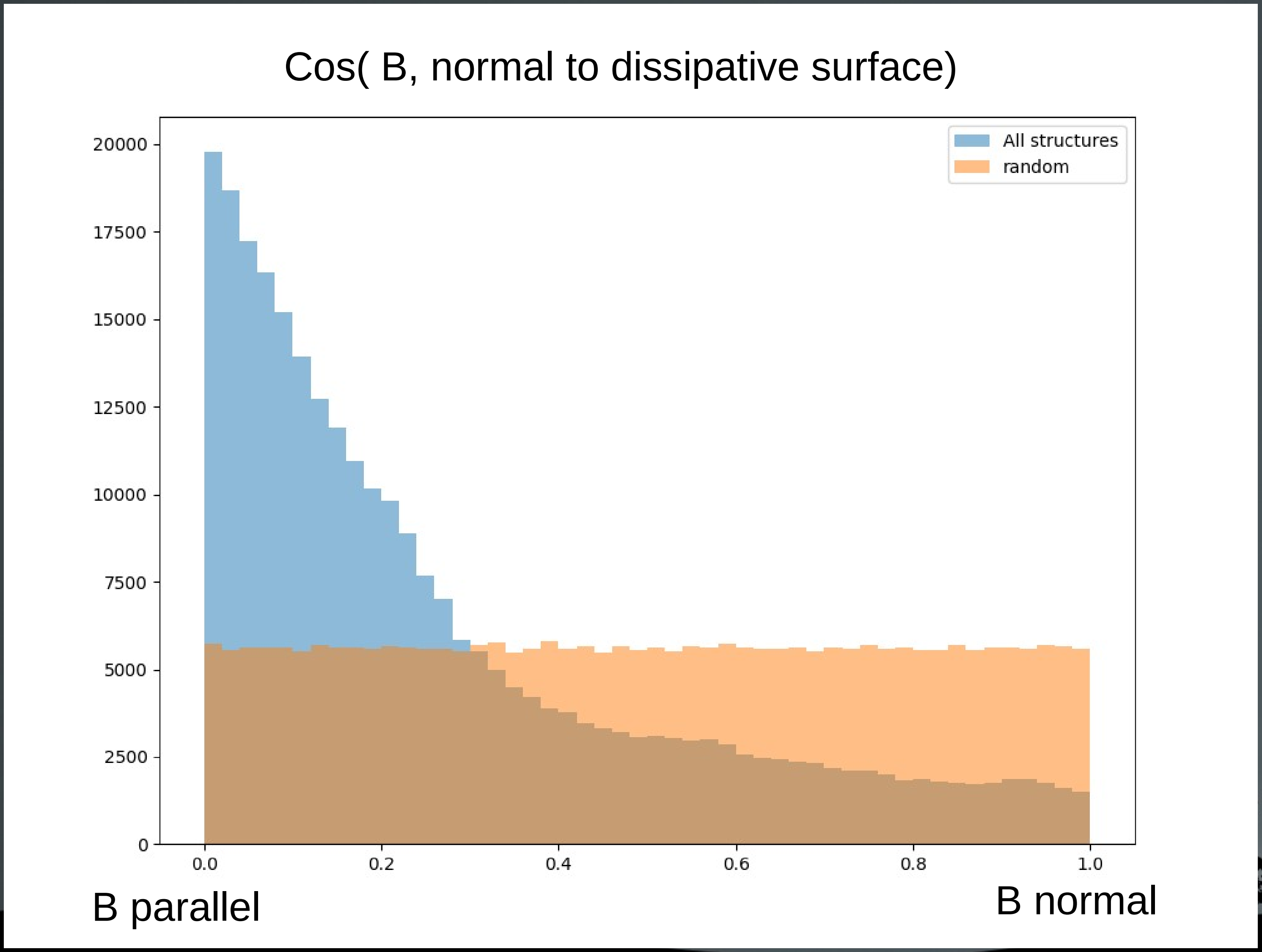
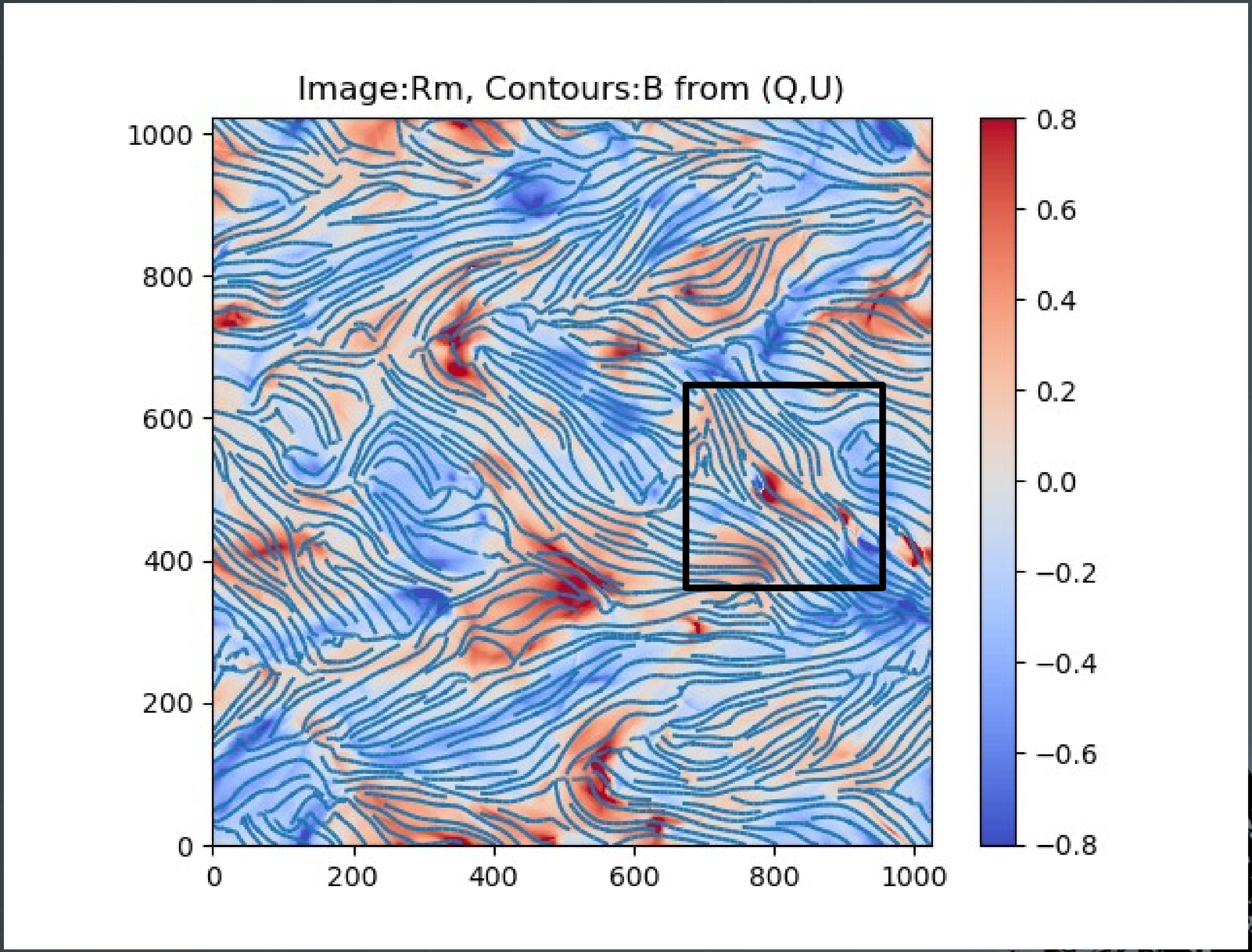


Projection over simulations

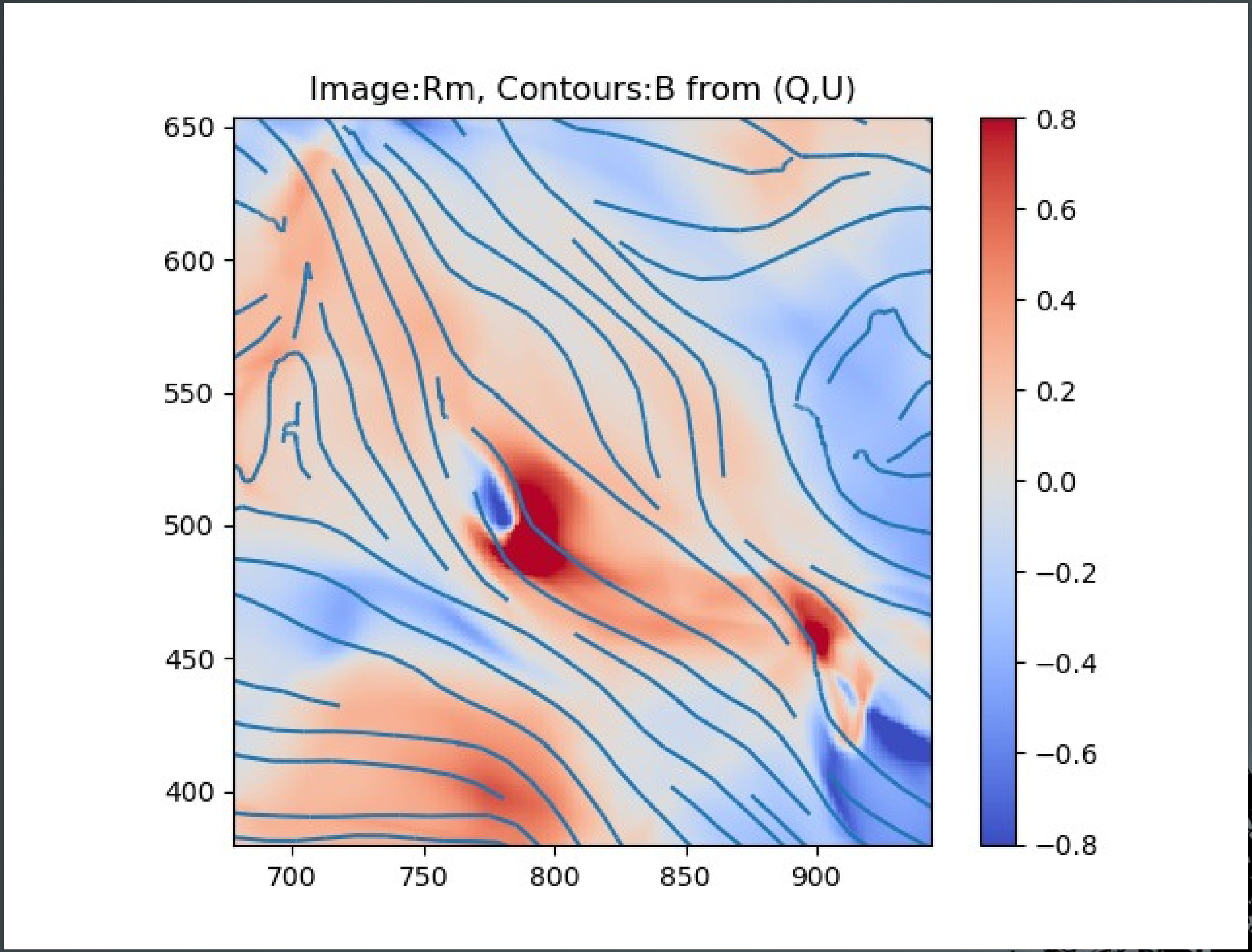
Rotation measure overlayed with p.o.s. B field direction



Mach 4, ABC

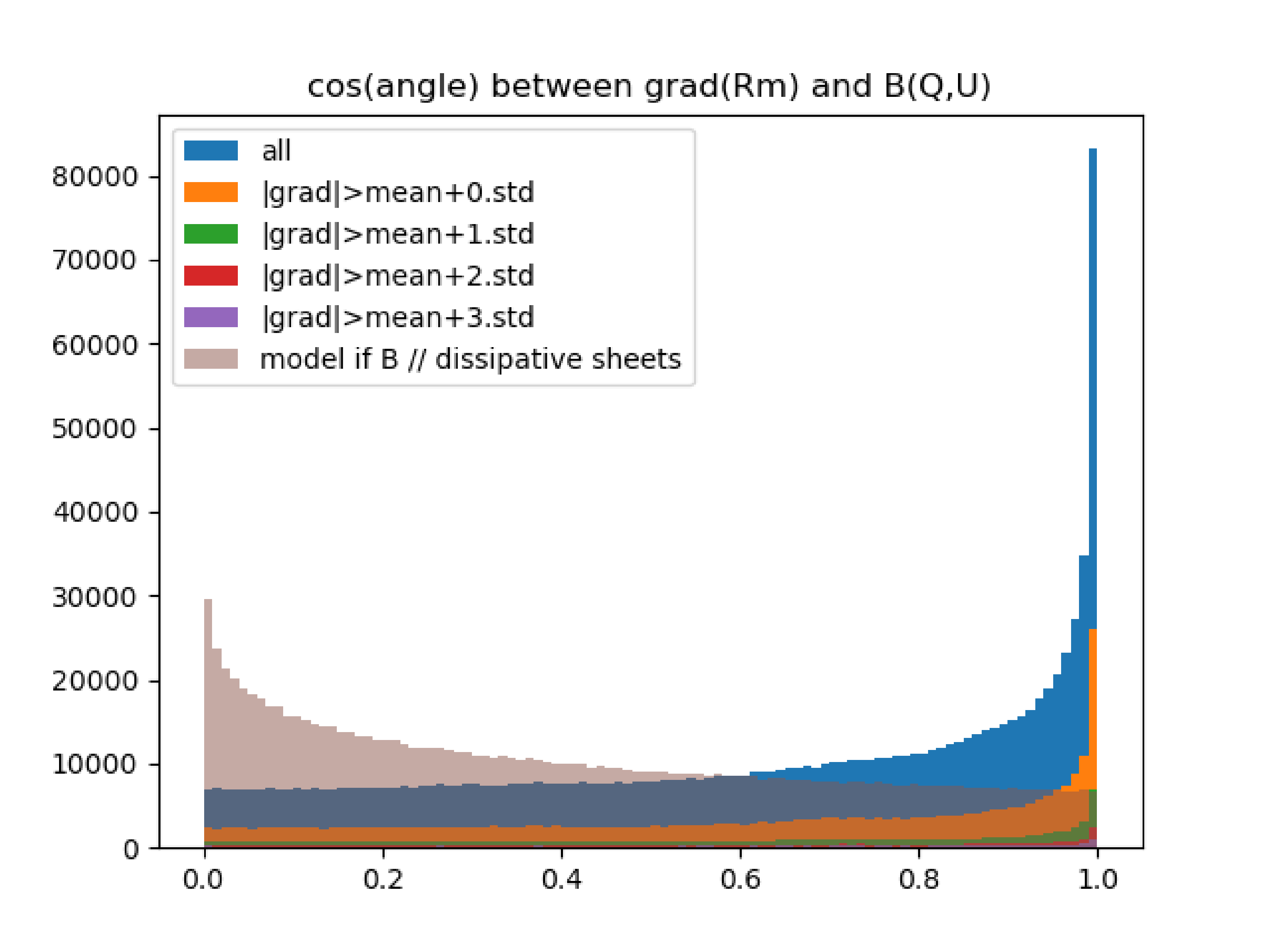
Projection over simulations

Rotation measure overlayed with p.o.s. B field direction



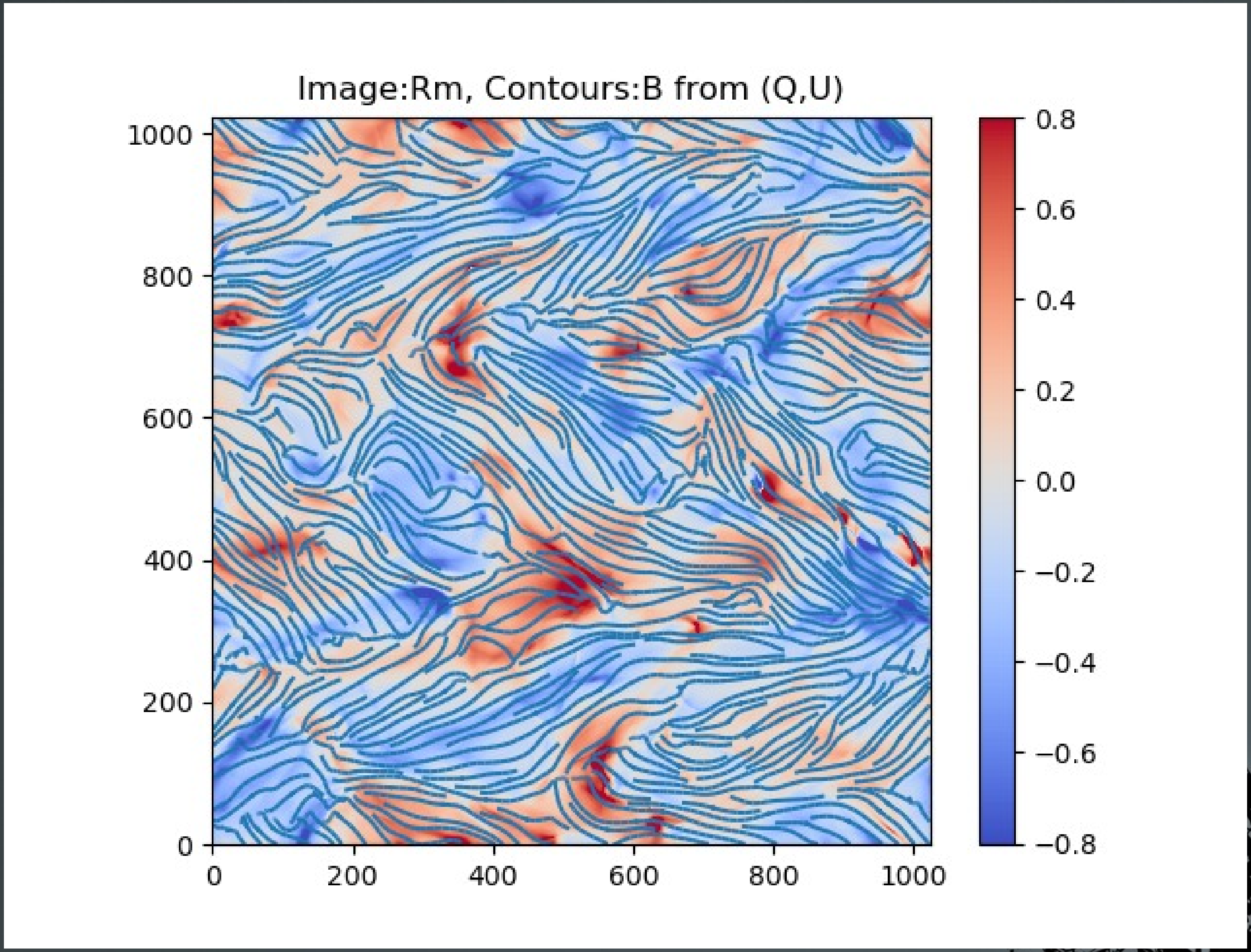
Mach 4, ABC

Orientation statistics



Projection over simulations

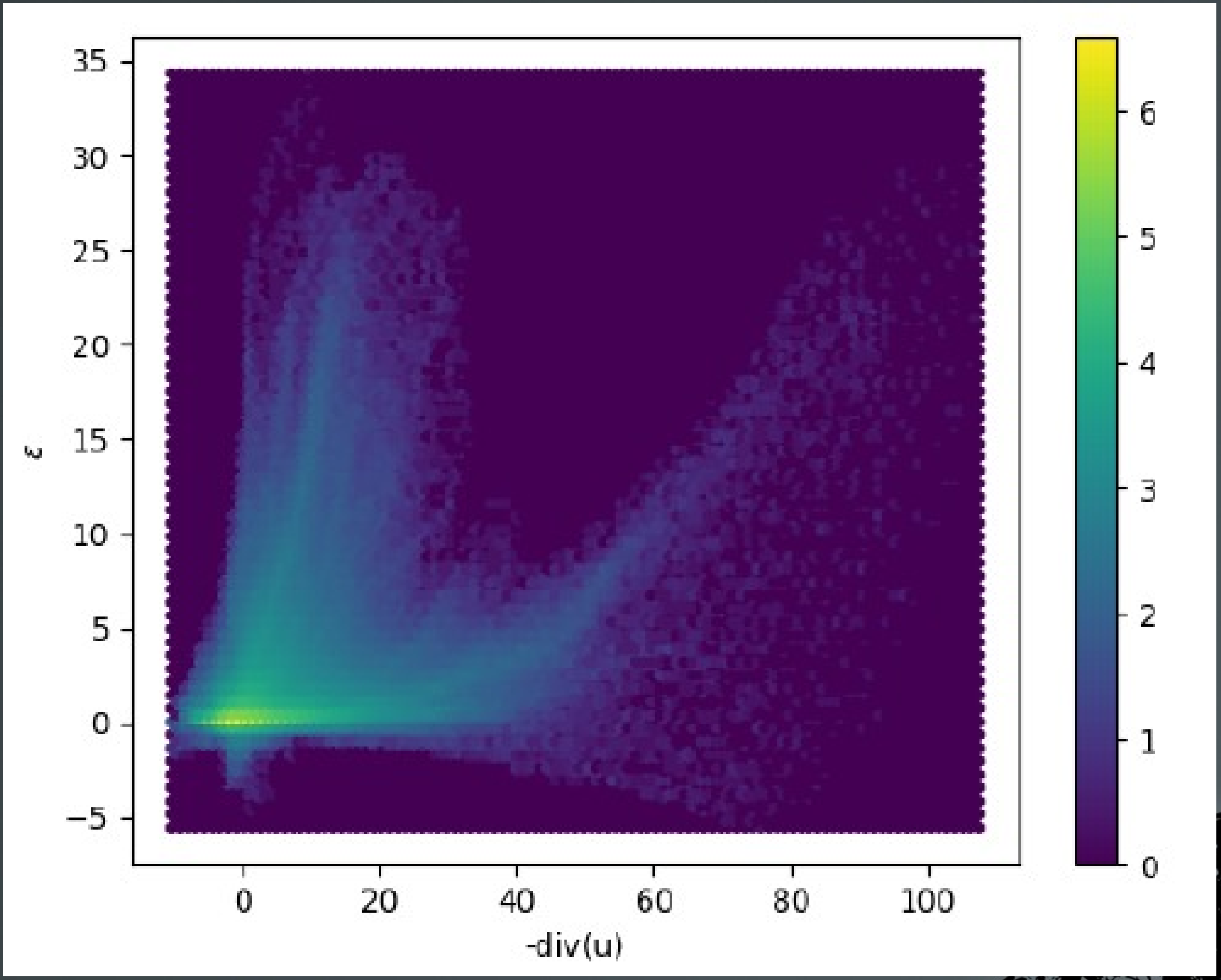
Rotation measure overlayed with p.o.s. B field direction



Mach 4, ABC

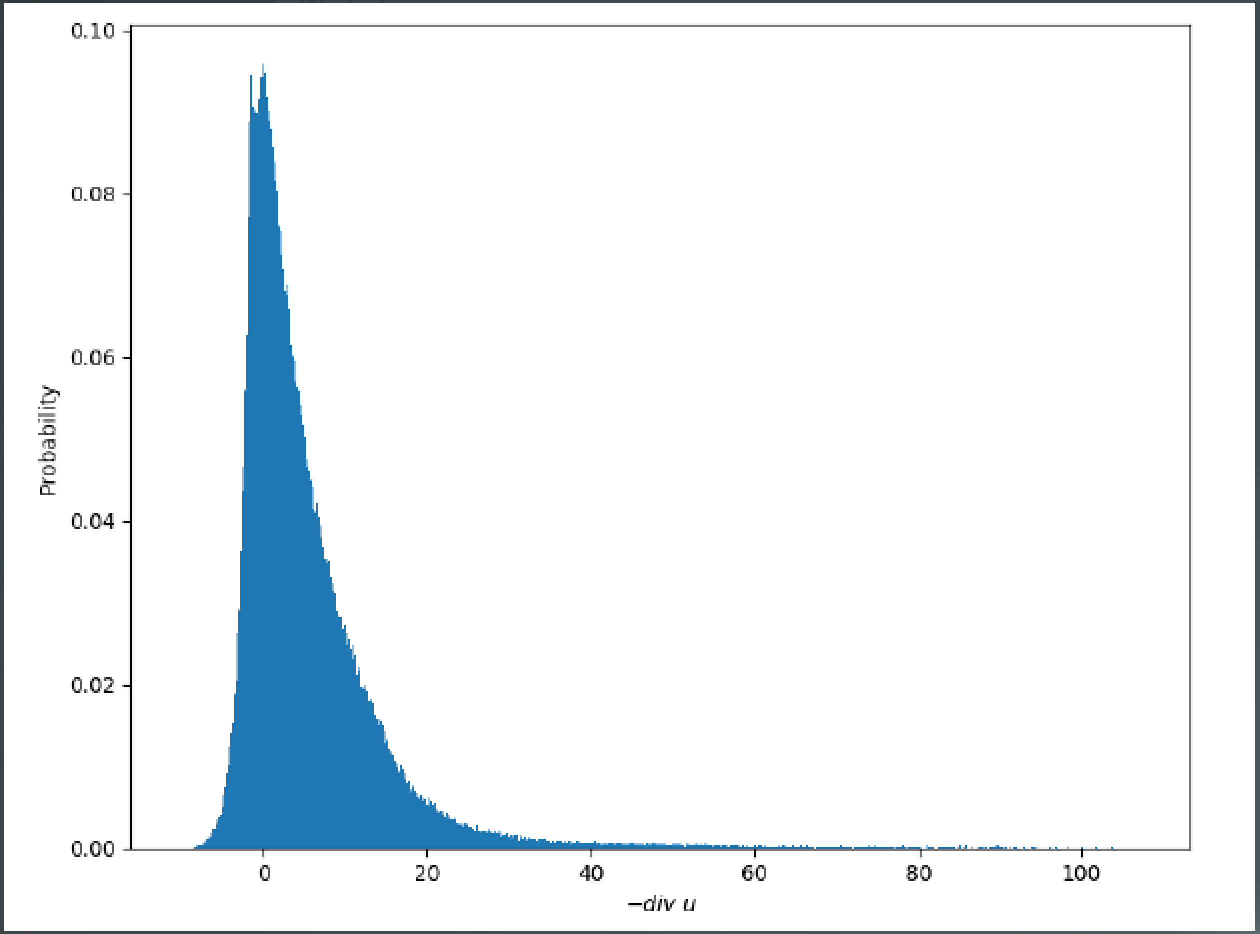
Dissipation is mostly incompressible

Volume fraction occupied by bins of (dissipation.convergence)



Dissipation is mostly incompressible

Fraction
Of the total
Dissipation



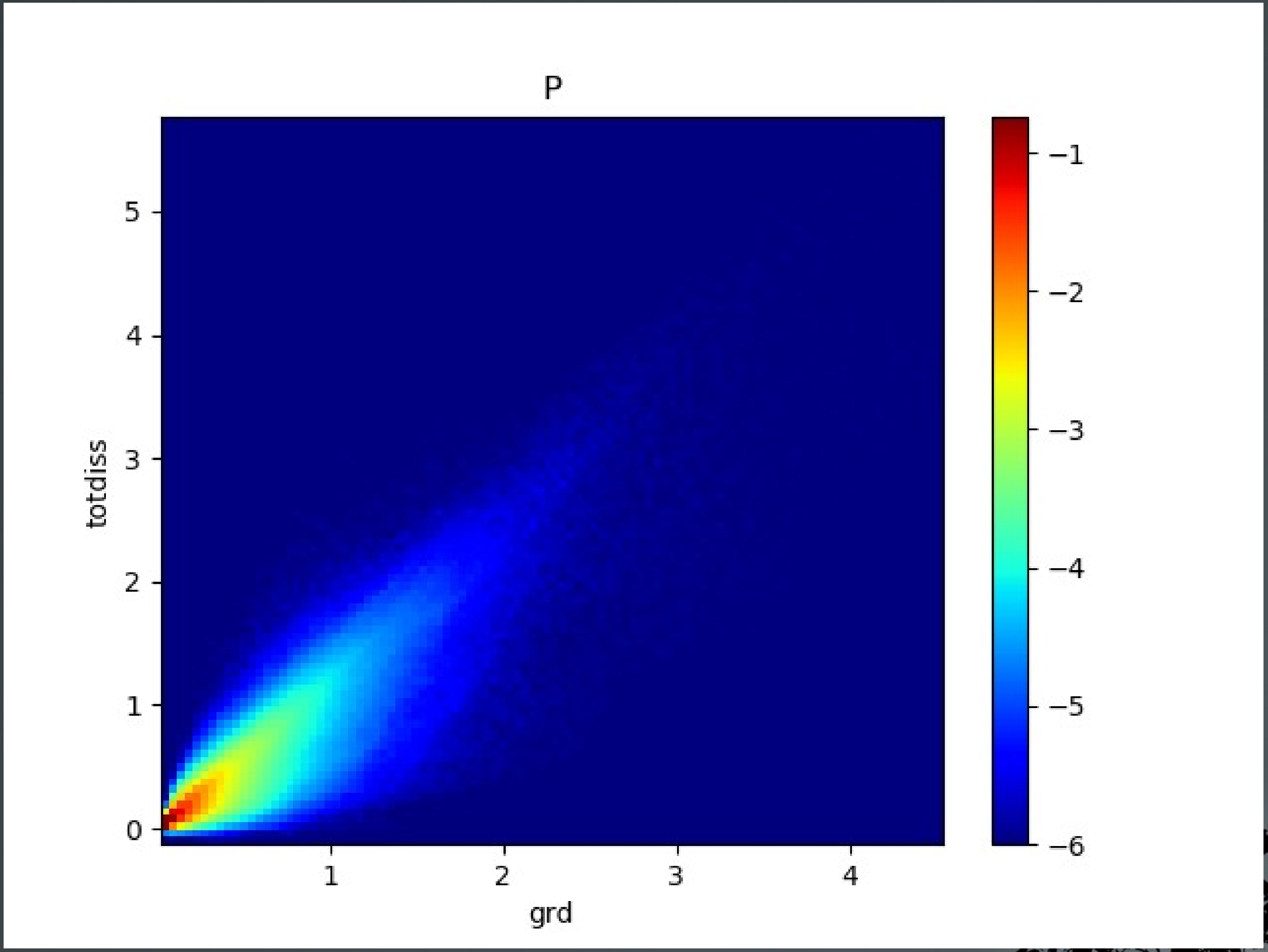
Convergence (unitless)

Pierre (+Thibaud, Andrew, Ben)

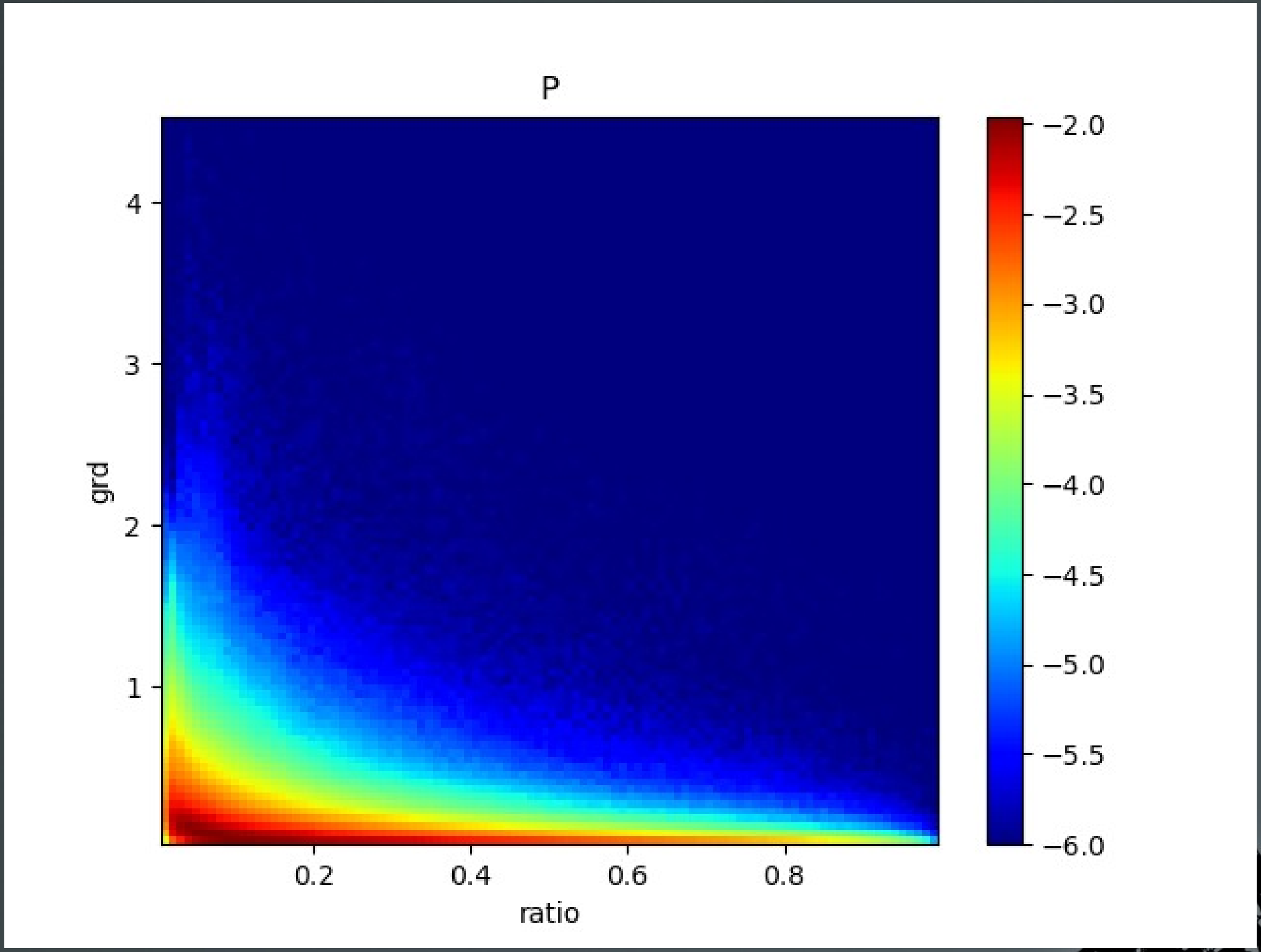
- Look at MHD variables: **w**=(rho, u, b) and search for direction of max gradient of **w**.
- Large gradients have a well determined orientation (meaning: plane-parallel is OK)
- Decompose gradients in fast/intermerdiate/slow waves
- Result: OK for single planar shocks, messy in compressible turbulence...

TODO: get shocks and parameters, measure stats, shock collisions ?

Total Dissipation vs Gradient



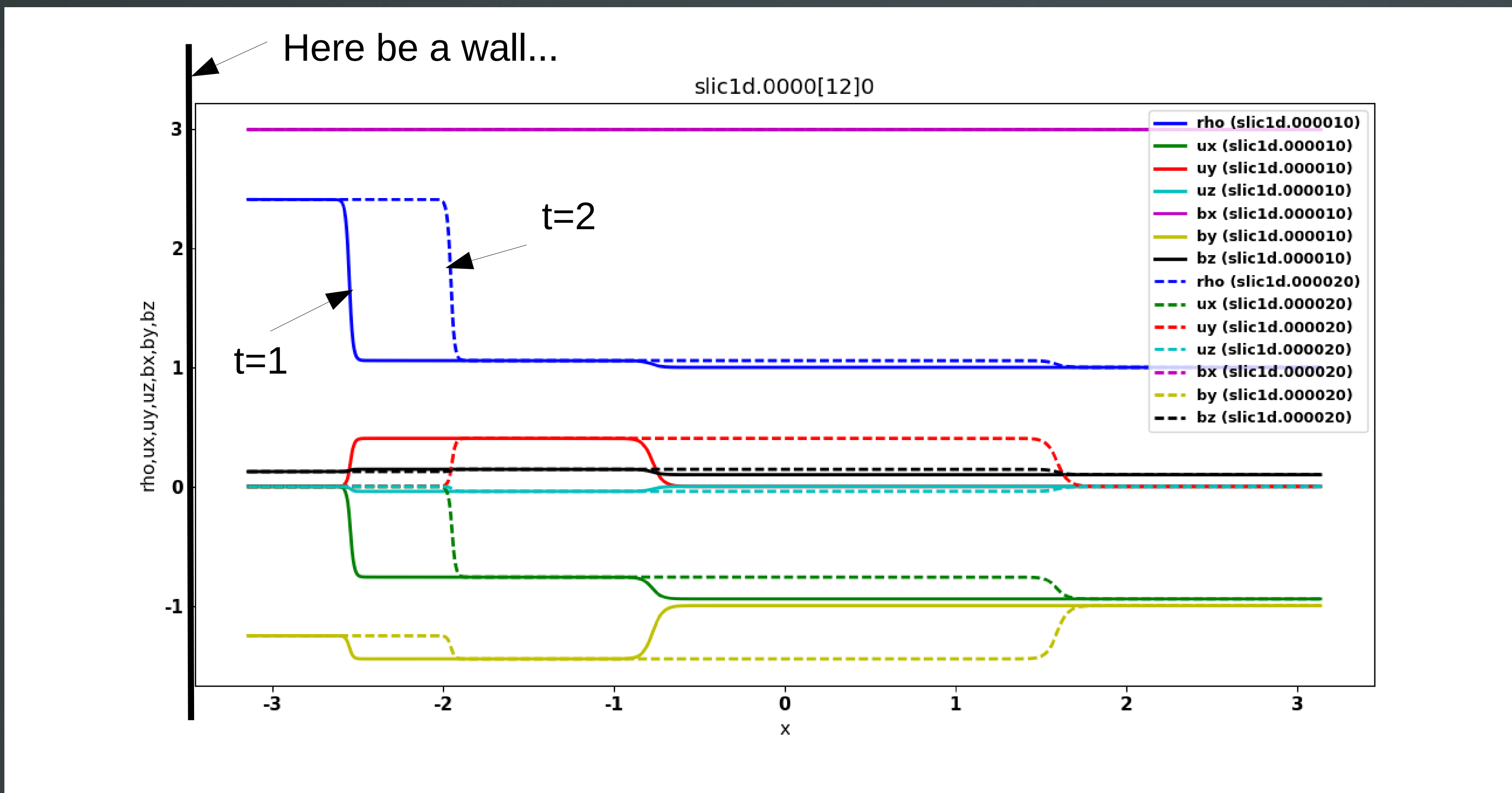
Isotropy (a2/a3) vs Gradient



Test Slow & Fast shock

Gas flows from right onto a wall on the left. 2 snapshots shown.

Direction of the inflow



Isothermal MHD equations

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla}.(\rho \boldsymbol{u}) = 0$$

$$\partial_t \rho u_i + \partial_j(\rho u_i u_j + p\delta_{ij}) - \boldsymbol{j} \times \boldsymbol{b}_i + \partial_j(\rho \nu S_{ij}[u]) = 0$$

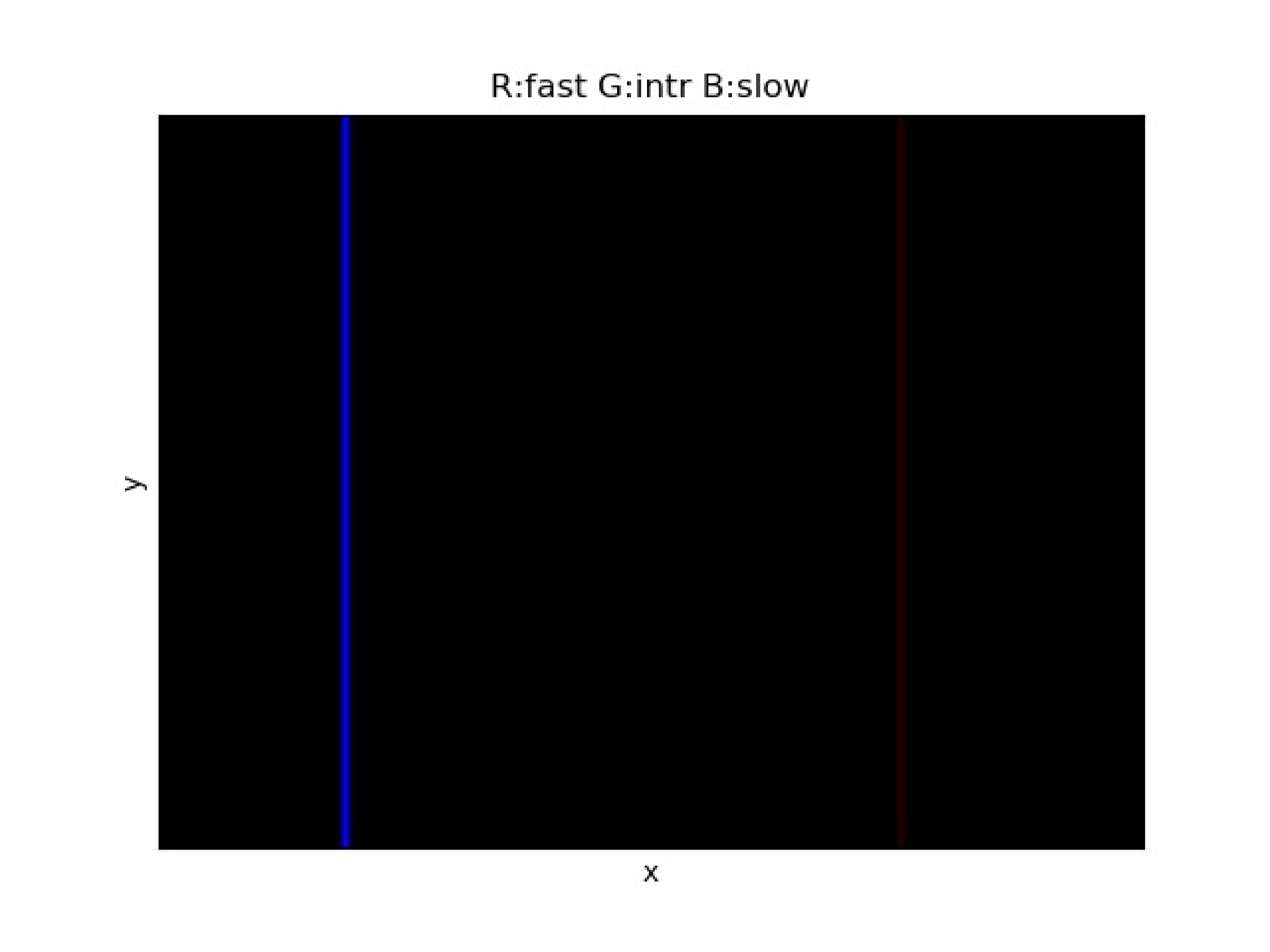
$$\partial_t \boldsymbol{b} - \boldsymbol{\nabla} \times (\boldsymbol{u} \times \boldsymbol{b}) + \boldsymbol{\nabla} \times (\eta \boldsymbol{j}) = \boldsymbol{0}$$

$$\boldsymbol{j} = \boldsymbol{\nabla} \times \boldsymbol{b}$$

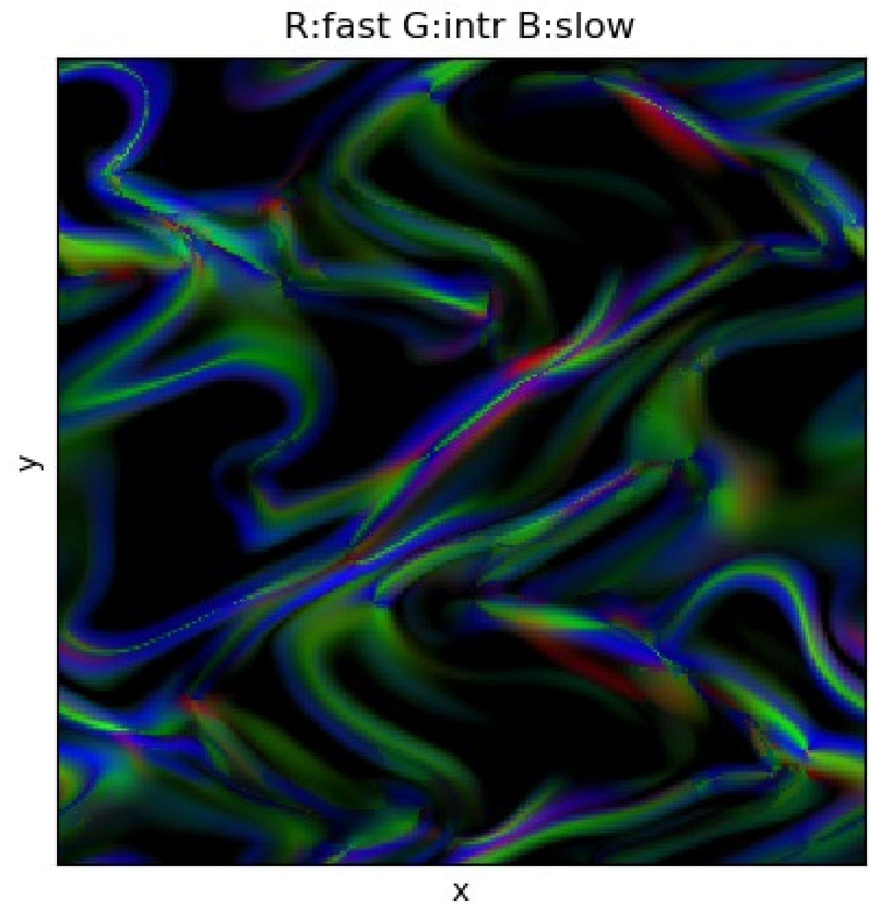
$$p = \rho c^2$$

$$S_{ij}[u] = \frac{1}{2}(\partial_i u_j + \partial_j u_i) - \frac{1}{3}\partial_k u_k \delta_{ij}$$

Gradient Decomposition



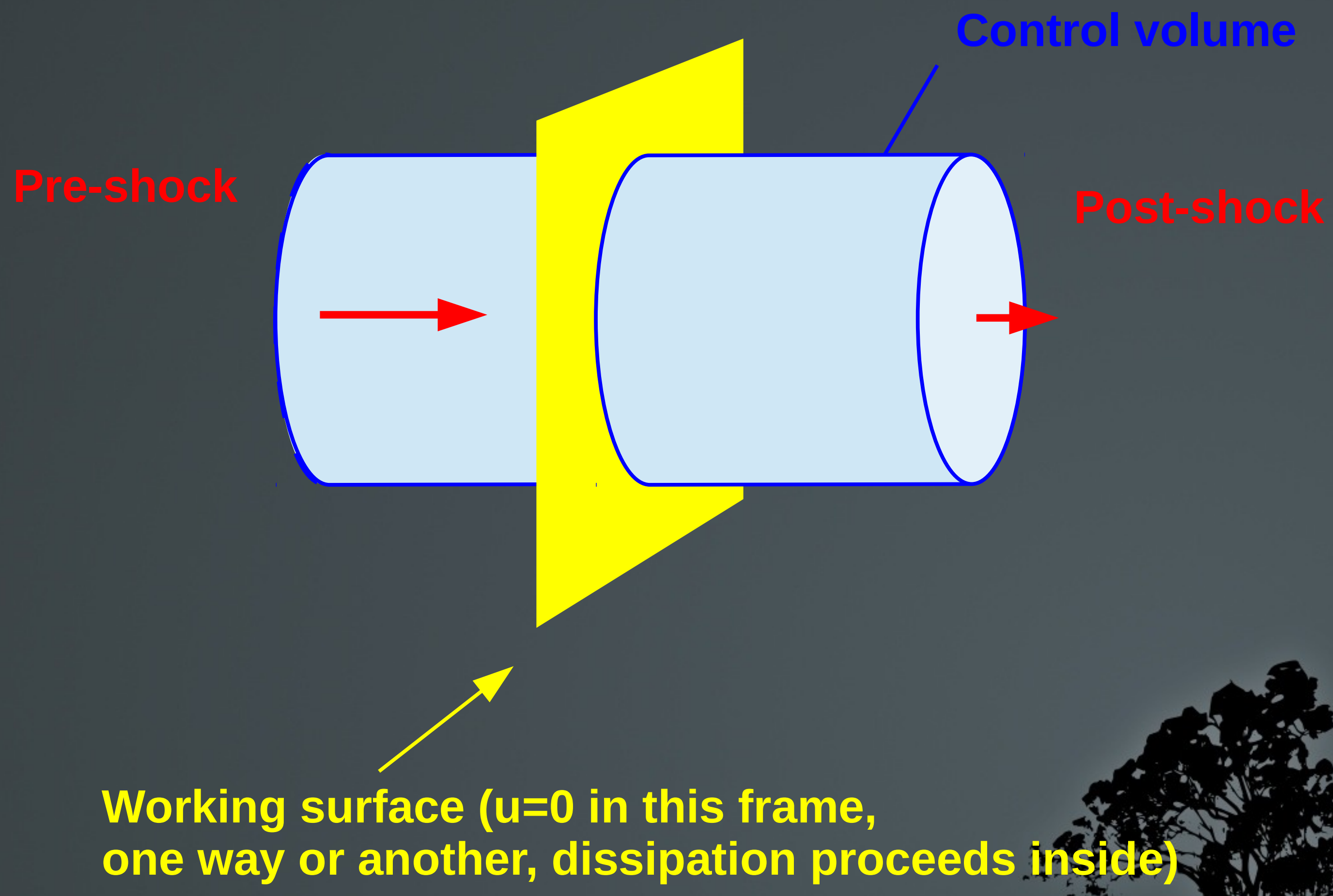
Gradient Decomposition in MHD compressible turbulence



Fast, Intermediate, Slow

Rankine Hugoniot

- Flux conservation through a *steady* planar shock



Rankine Hugoniot

- Conservation of mass, momentum and magnetic flux *in the steady shock frame* induces relationships between pre-shock and post-shock physical conditions.

$$\left[B_x\right]_{pre}^{post} = 0$$
$$\left[\rho\ u_x\right]_{pre}^{post} = 0$$
$$\left[(B \times u)_y\right]_{pre}^{post} = 0$$
$$\left[(B \times u)_z\right]_{pre}^{post} = 0$$
$$\left[\rho u_x u_y - B_x B_y\right]_{pre}^{post} = 0$$
$$\left[\rho u_x u_z - B_x B_z\right]_{pre}^{post} = 0$$
$$\left[\rho u_x^2 + P\right]_{pre}^{post} = 0$$

- Examples:

* Compression = Mach^2 in an isothermal shock
* Max temperature ~ u^2 expressses conversion of kinetic to thermal energy in a viscous front

For the molecular weight of the ISM: $T_{\rm max} = 53\,{\rm K}\,(u/1\,{\rm km\ s^{-1}})^2$

Questions, ToDo

- What can we do to link to observations ?
- Single planar shock ? Single curved shock (Tram)?
- Link to Faraday rotation ?
- Collection of shocks ↔ Chemistry ?
- Focus of one structure in 3D MHD: how to reconstruct emissivity ?
- Test SHOCK_FIND. Improve on it ?
- Statistic theory of shocks ?
- Contact Discontinuity detection ↔ condensation fronts in thermal instability simulations

TODO

- Color 2d histo with div (u) / curl(u).
- Back to obs values for div(u), eps.
- Oblique shocks in Paris-Durham
- Statistics of slow / fast , convolve with Paris-Durham code => JWST predictions.
- Erwan: beware of scales of gradient: choose relevant ones for energy ?