Dissipation and Intermittency in the magnetised ISM

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Motivation / Outline

- The diffuse ISM contains a lot of complex molecules and they are excited (e.g. bright CO, warm H2, CH^+).
- Large scale turbulent motions dissipate at small scales, with intense bursts of heating.
- How much of the molecular content can be explained by this localised heating ?
- How can we characterize observationnaly these strongly dissipative structures ?

0) Introduction on intermittency

I) 3D simulations to probe their geometry and statistics

II) 2D simulations to start probing their chemistry

0) Intermittency

Intermittency

- The variance of dissipation is larger at small scales

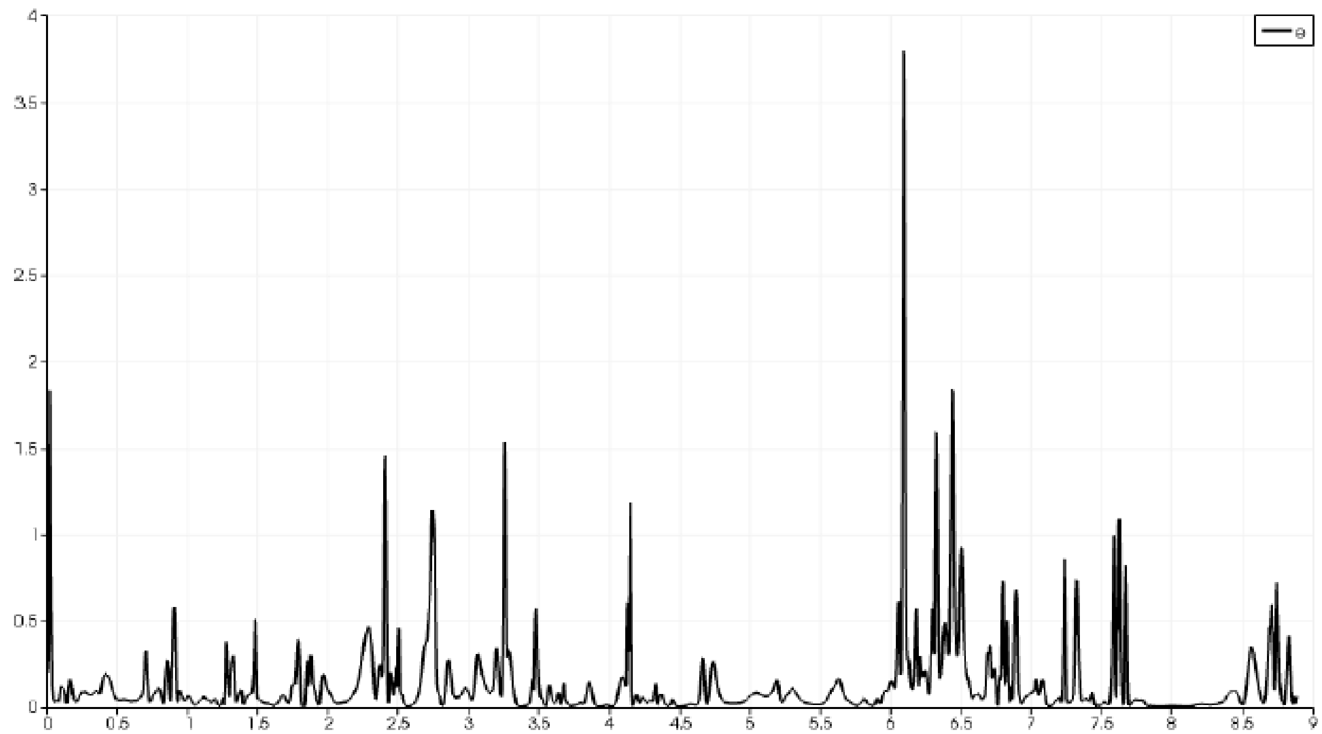

Figure 2.4: Viscous dissipation rate along a fixed line from a 1024^3 incompressible magnetohydrodynamics simulation with initial condition based on the ABC flow. The snapshot shown is at the temporal peak of total (ohmic + viscous) dissipation [G. Momferratos, unpublished].

Intermittency

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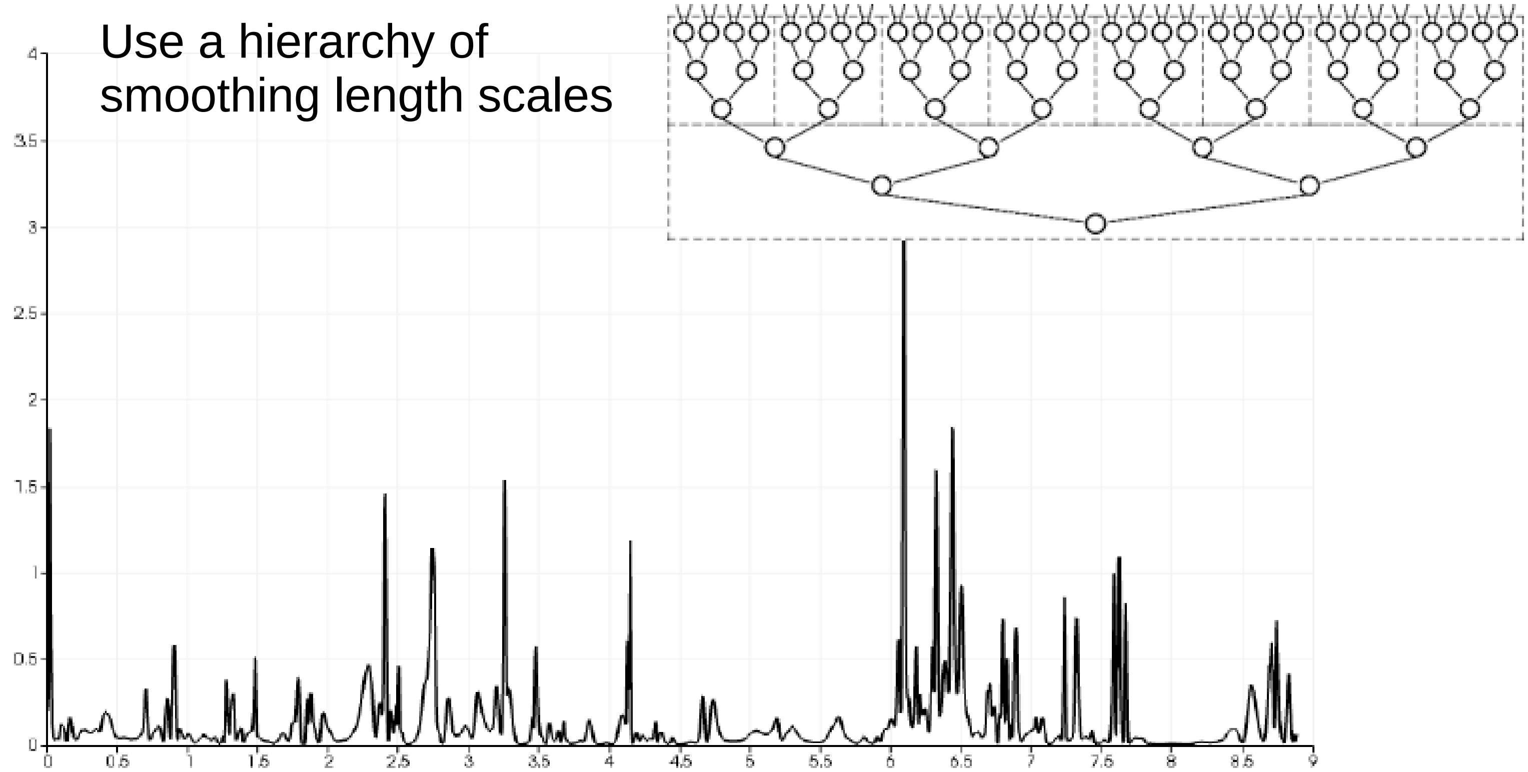

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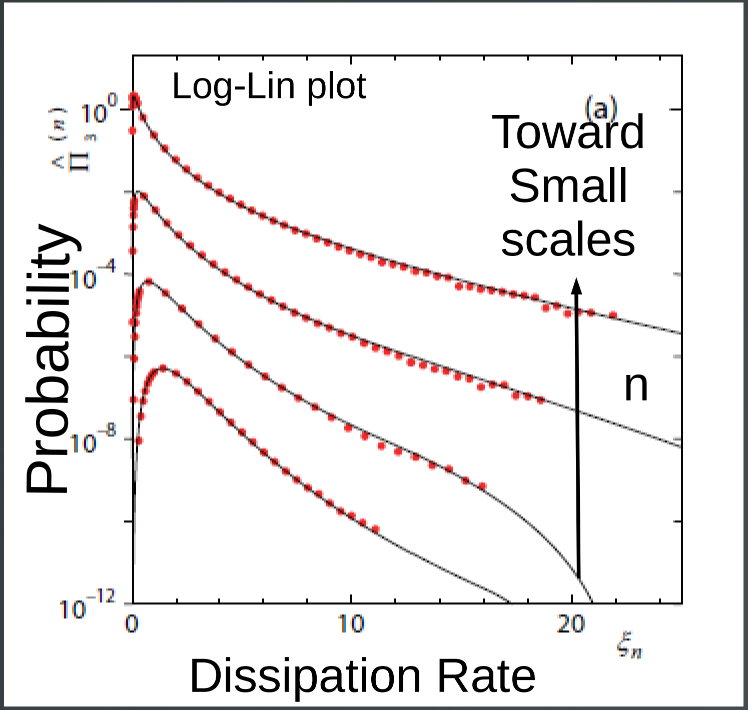
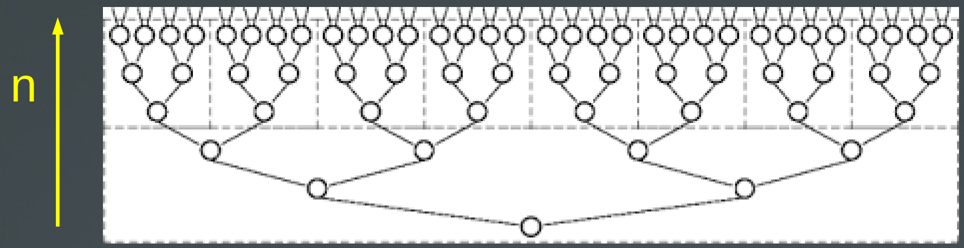
Intermittency: PDFs

- Large deviations are not so rare at small scales



$$\xi_n = \varepsilon_n / \langle\langle \varepsilon_n^2 \rangle\rangle_c^{1/2}$$

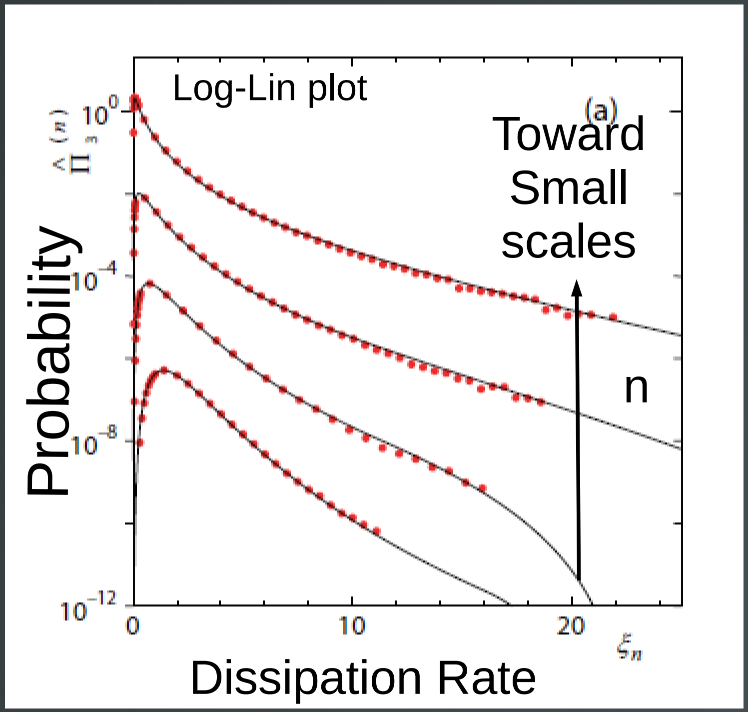


Statistics of the Dissipation field Smoothed at various scales

Circles: Wind tunnel data by Mouri et al. (2008),
Solid line: Model by Arimitsu^2, Mouri (2012)

Intermittency: PDFs

- Large deviations are not so rare at small scales



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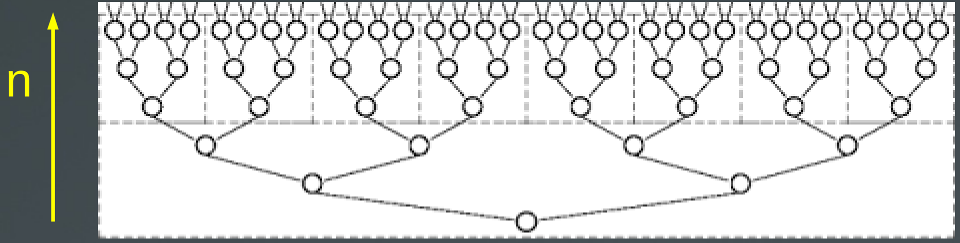

Statistics of the Dissipation field Smoothed at various scales

This graph does not show how $\langle\langle \varepsilon_n^2 \rangle\rangle$ varies with smoothing length

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Intermittency: PDFs

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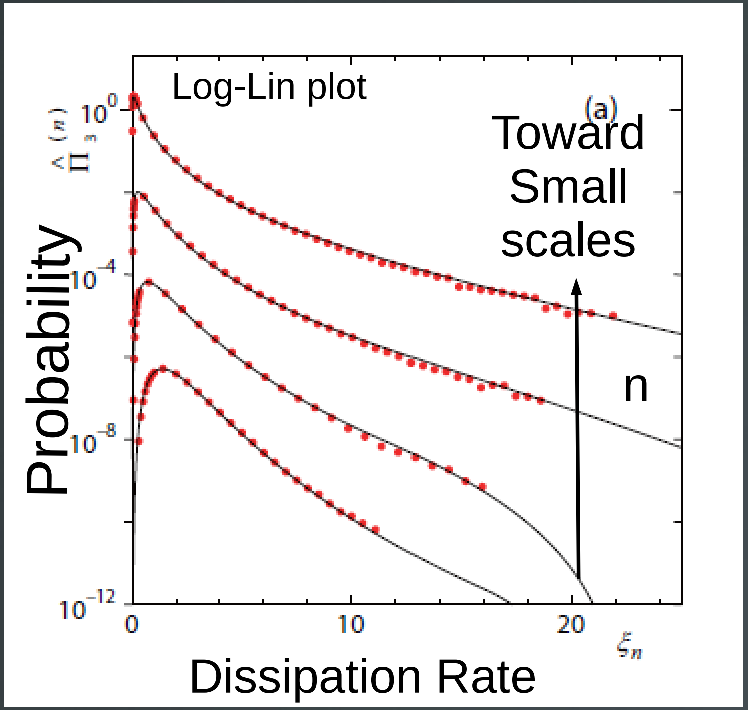

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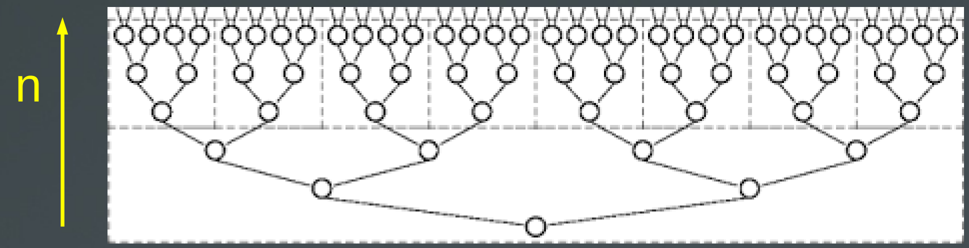
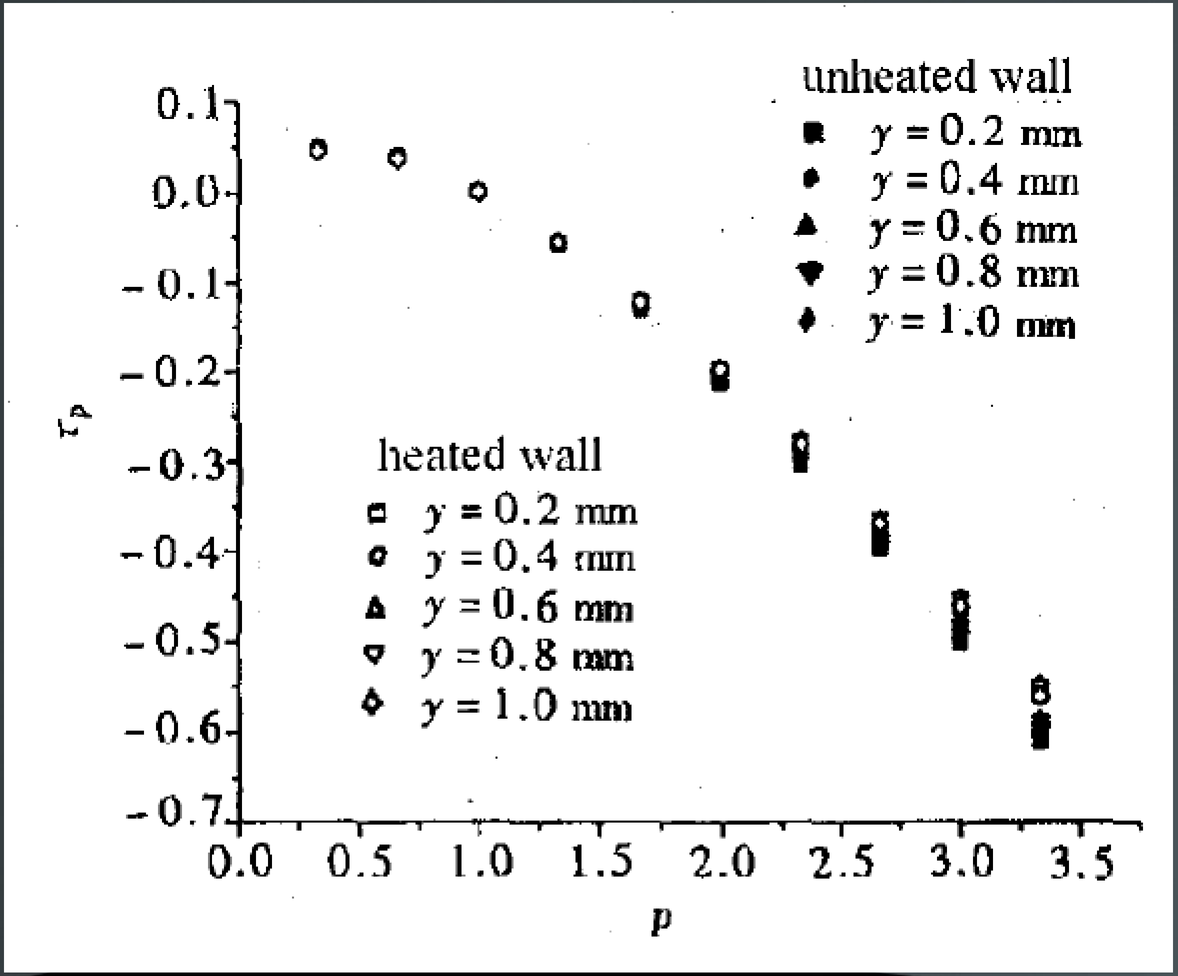


Messing up with the branches does not change the statistics at any level of smoothing => These statistics are sensitive to topology *only to a certain extent, and they miss space/time delays.*

Circles: Wind tunnel data by Mouri et al. (2008),
Solid line: Model by Arimitsu^2, Mouri (2012)

Intermittency: exponents of structure functions

- Increments have various scalings with distance when put to various powers.



Dissipation exponents:

$$\langle \varepsilon_r^p \rangle \propto \langle \varepsilon \rangle^p \left(\frac{r}{L_i} \right)^{\tau_p}$$

Jiang, Wang, Shu, Wang (2002)
Wind tunnel experiment

Intermittency: exponents of structure functions

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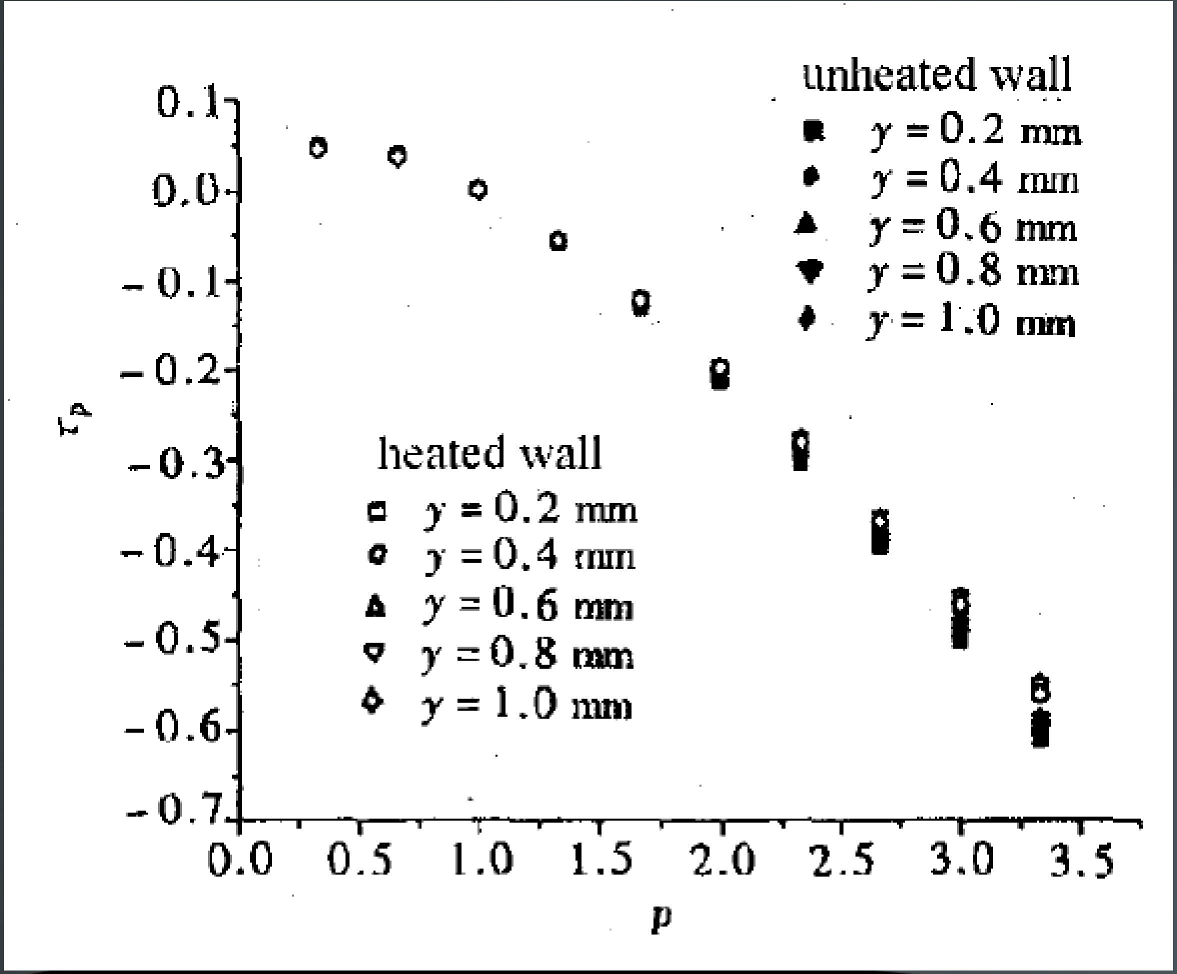

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Jiang, Wang, Shu, Wang (2002)
Wind tunnel experiment

***Note:* velocity structure exponents:**

$$\zeta(m)=m/3+\tau(m/3)$$

Intermittency: multifractal formalism

- Dissipation scales as $\varepsilon_n/\varepsilon = (\ell_n/\ell_0)^{\alpha-1}$ on fractal sets of dimension f(α)

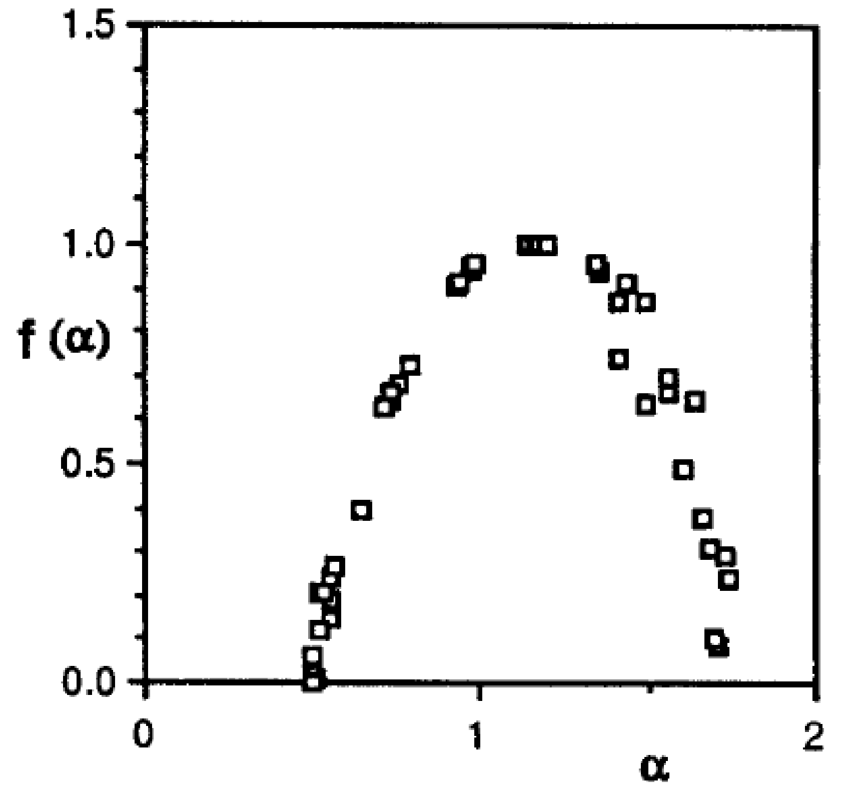


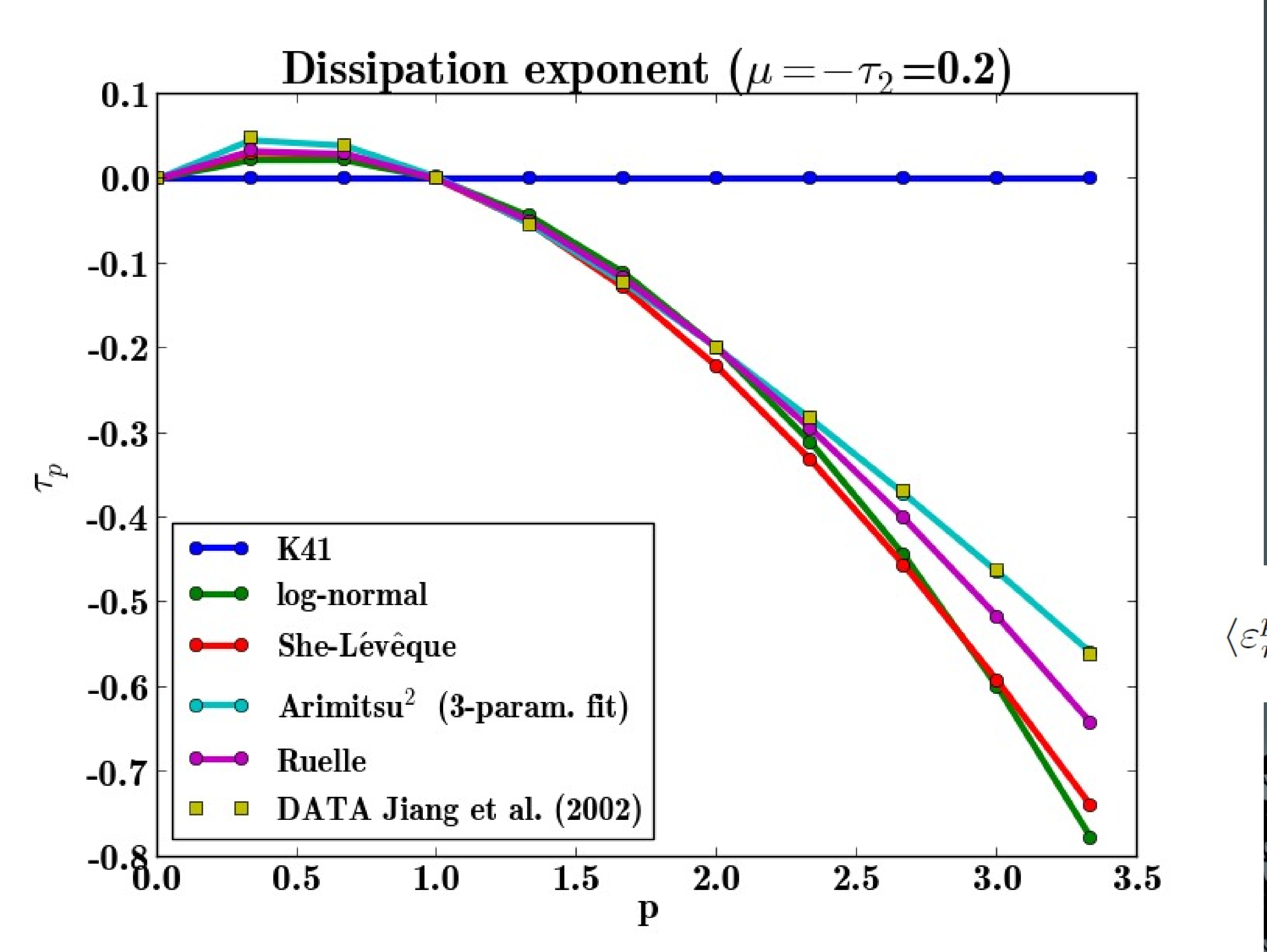
Figure12. Multifractal spectrum

Meneveau and Srivinasan (1987) Wake of a cylinder

Intermittency: Various Models

- Log-Normal: Kolmogorov (1962), Obukhov (1962)
- She-Lévêque (generalised Log-Poisson)
- Arimitsu & Arimitsu (2000, etc...)
- Multiplicative cascade and Beta-model (Frish, 1995)
- Hierarchical statistical mechanics (Ruelle 2012)
- Stochastic equations for vorticity (Zybin et al. 2007)

Intermittency: Various Models



$$\langle \varepsilon_r^p \rangle \propto \langle \varepsilon \rangle^p \left(\frac{r}{L_i} \right)^{\tau_p}$$

Intermittency: Various aspects are equivalent

- PDFs ↔ Exponents ↔ Multifractals

  (Large deviation theory, steepest descent argument, moments generating function, …)

- But equivalence requires full knowledge of the scaling coefficients: each vision focuses on one aspect of intermittency.

- Notes:

  - None of these visions strongly constrains the shape of the dissipation structures.
  - They are blind to time & space lags.

I) 3D Simulations with controled dissipation

Characteristics of the ISM

- Diffuse $n_H \sim 30/cm^3$, Molecular $n_H \sim 200/cm^3$
- $\langle u^2\rangle \sim \langle b^2/\rho\rangle$ (Alfvénic Mach number ~ 1)
- Sonic Mach number ~ 4

Decaying MHD turbulence simulations:

- *Incompressible* with $\langle u^2\rangle \sim \langle b^2/\rho\rangle$ [code ANK]
- Compressible *isothermal* with Mach ~ 4 [DUMSES]

(Resolution: 512^3 and 1020^3
Mean B = 0)

Dissipation in the ISM

- Viscous friction: $Re = LU/\nu \sim 2.10^{7}$
- Resistivity: $Re_m = LU/\eta \sim 2.10^{17}$
- Ambipolar diffusion: $Re_a = L/Ut_a \sim 10^{2}\text{-}10^{3}$
- $L \sim 3 - 10$ pc $>> l_a >> l_\nu >> l_\eta$

Dissipation in our simulations

- Viscous friction: $Re = LU/\nu \sim 2.10^{7}$ 10^{3}
- Resistivity: $Re_m = LU/\eta \sim 2.10^{17}$ 10^{3}
- Ambipolar diffusion: $Re_a = L/Ut_a \sim 10^{2}\text{-}10^{3}$
- Plus: some dissipation due to the numerical scheme with $l_{num} \sim L/512$ or $L/1020$
- $L \gg l_a \gg l_\nu \sim l_\eta > l_{num}$ (Warning: $Prm = \nu/\eta = 1$ ...)

Note: no Ambipolar Diffusion (A.D.) in our compressible runs yet.

Recover the Numerical Dissipation

- Method 0 (bench): use shock solution and fit it
- We designed several general methods:

Method 1

Consider the evolution equation of kinetic and magnetic energy:

$$\partial_t(\tfrac{1}{2}\rho u^2 + \tfrac{1}{2}B^2) + \nabla.\mathcal{F}_1 = -u.\nabla(p) - q$$

where q is the total irreversible heating and where the flux $\mathcal{F}_1$ reads:

$$\mathcal{F}_1 = \mathbf{u}(\tfrac{1}{2}\rho u^2) + (B \times u) \times B + \nu\sigma.u + \eta J \times B.$$

Positive, more or less accurate (60% overestimate in worst case)

Method 2

$$\partial_t(\tfrac{1}{2}\rho u^2 + \tfrac{1}{2}B^2 + p\log\rho) + \nabla.\mathcal{F}_2 = -q$$

where

$$\mathcal{F}_2 = \mathcal{F}_1 + \mathbf{u}p(\log\rho + 1).$$

Asymetric, negative

Method 3

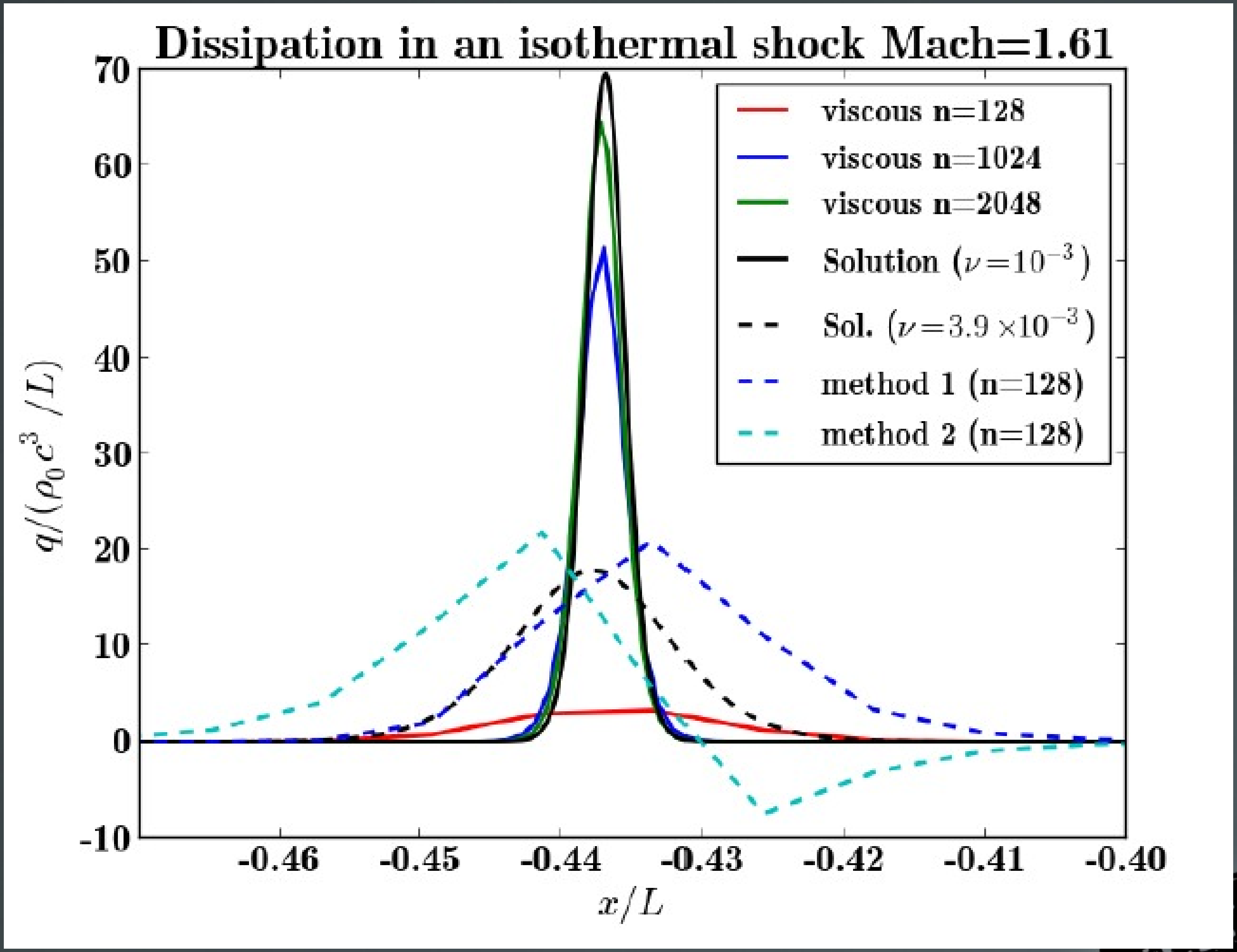
$$\partial_t(\tfrac{1}{2}\rho u^2 + \tfrac{1}{2}B^2) + \nabla.\mathcal{F}_3 = p\nabla.u - q$$

where

$$\mathcal{F}_3 = \mathcal{F}_1 + \mathbf{u}p.$$

Inaccurate

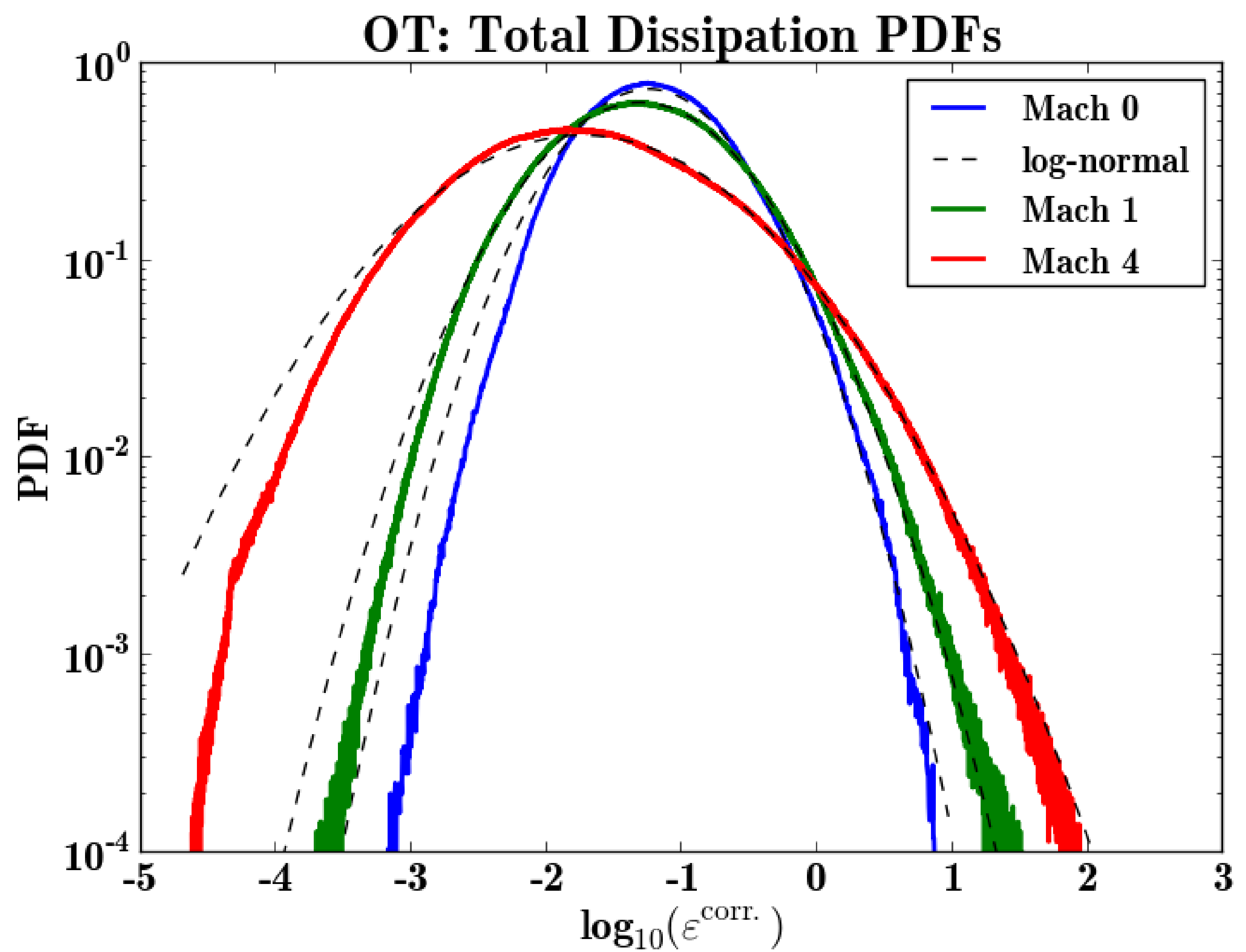
Recover the Numerical Dissipation



=> We get the total dissipation more or less correct, but we are aware that the shock width is overestimated

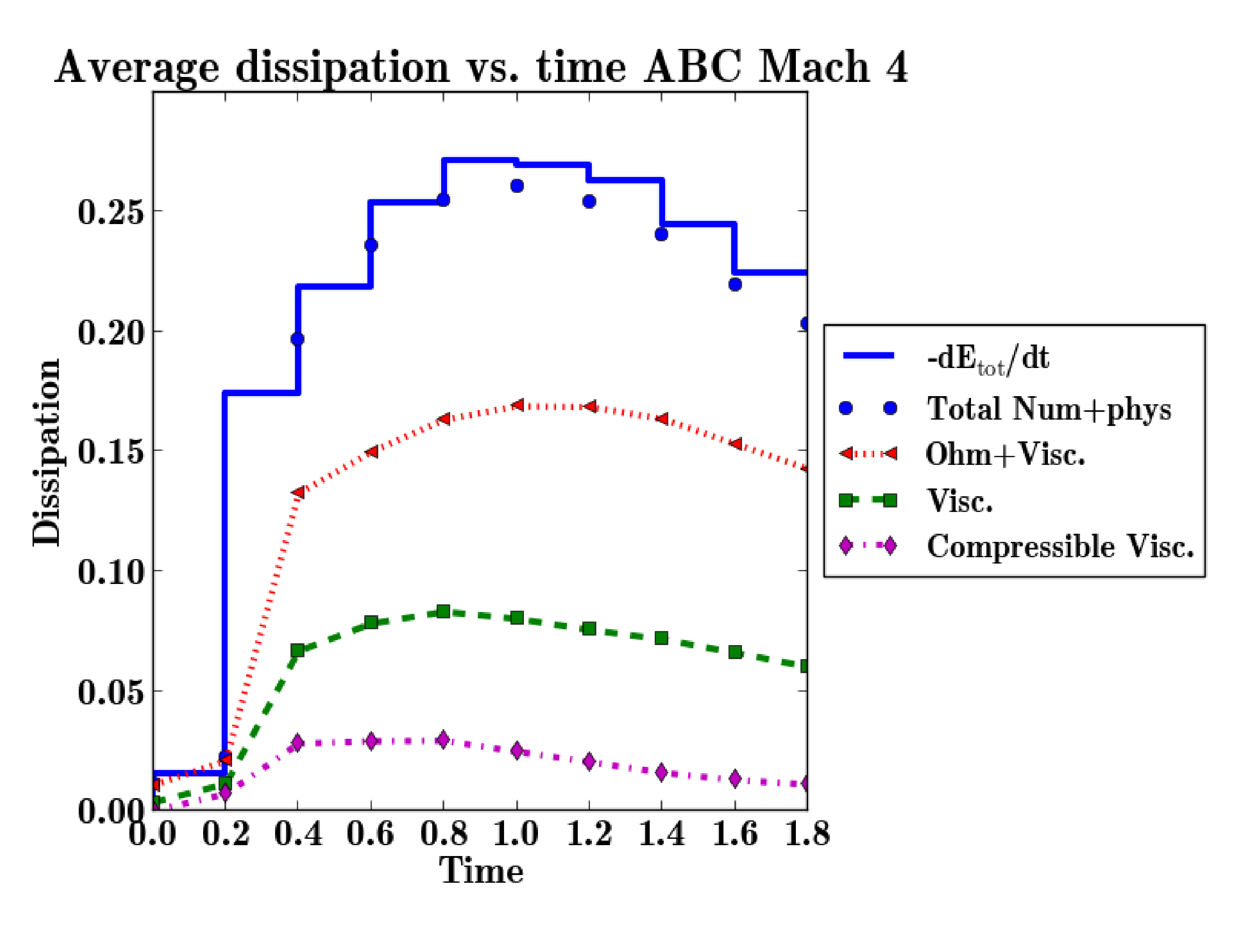
Log-Normal dissipation PDF

(not Tsallis...)



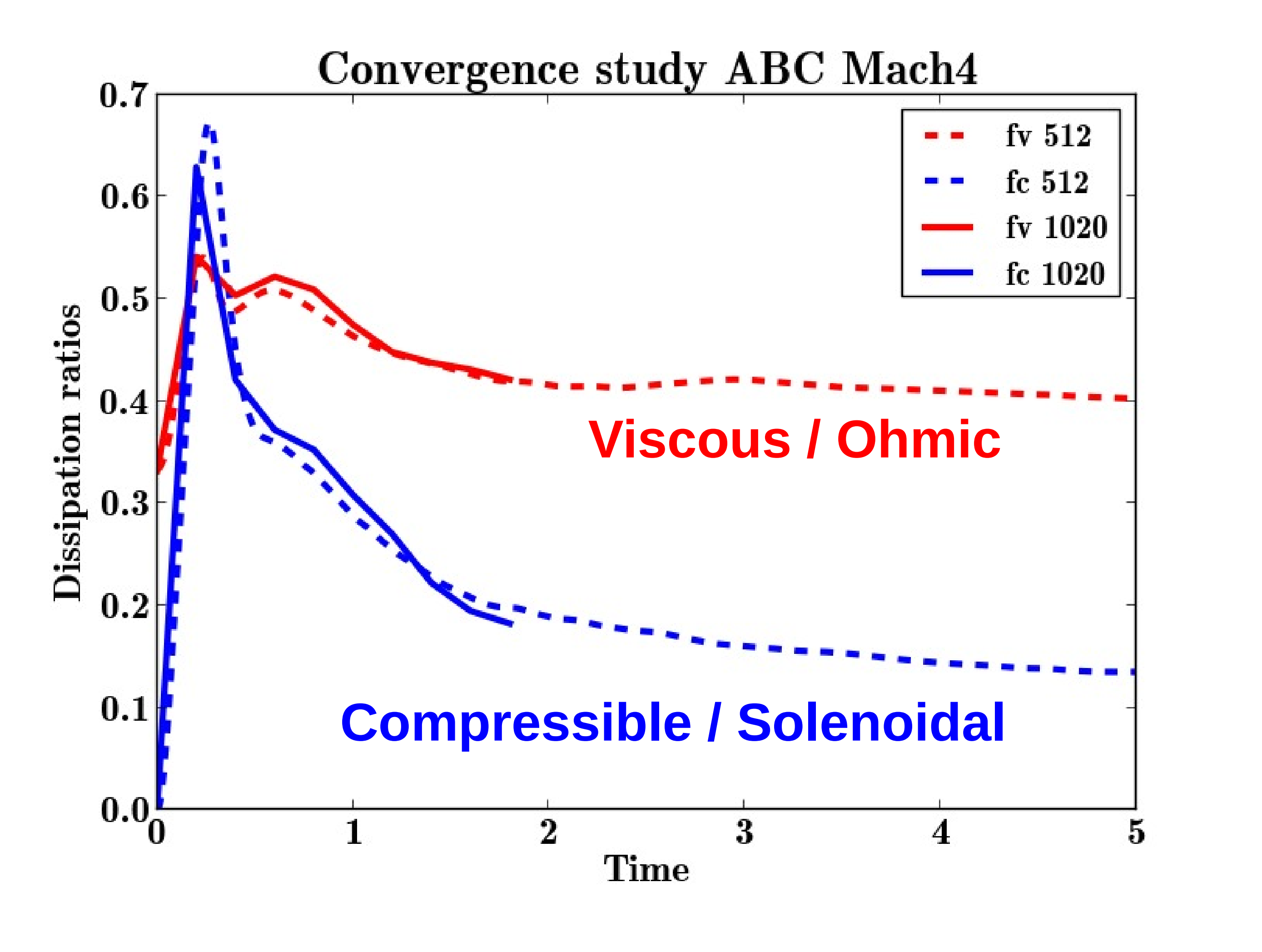
Extreme events are more frequent as Mach number increases

Dissipation vs. time



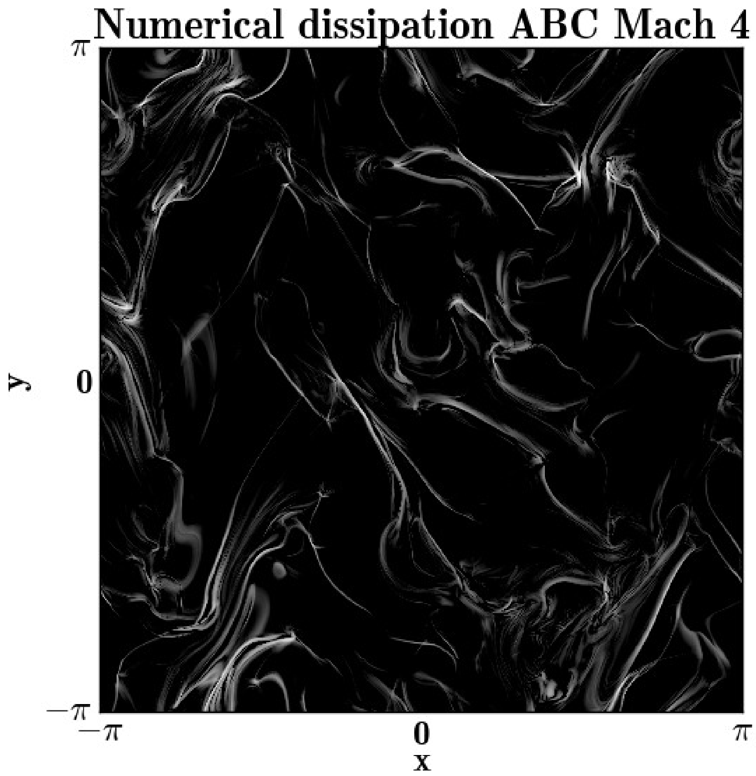
$$E_{\rm tot} = \frac{1}{2}\langle \rho \mathbf{u}^2 \rangle + \frac{1}{8\pi}\langle \mathbf{B}^2 \rangle + \langle p \log \rho \rangle$$

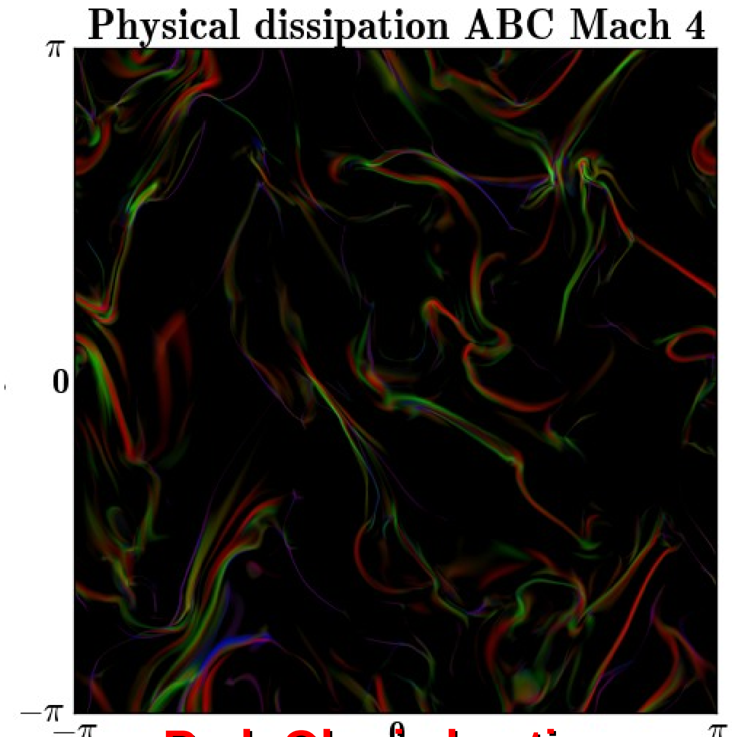
Convergence



(Prm=1)

Dissipation maps



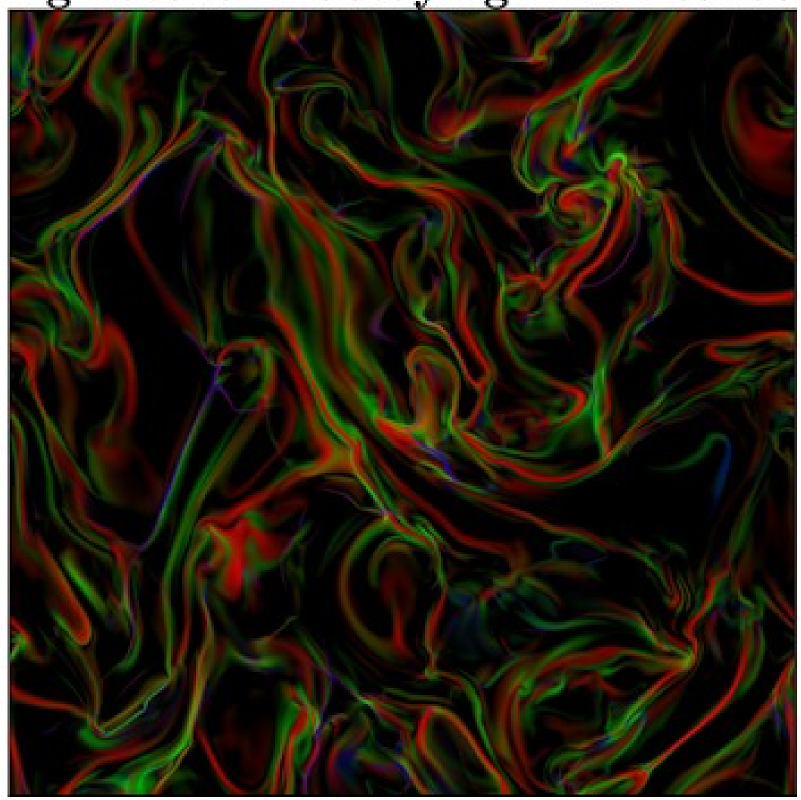


Red: Ohmic heating

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

Dissipation nature
Compressible MHD (Mach 4, ABC)

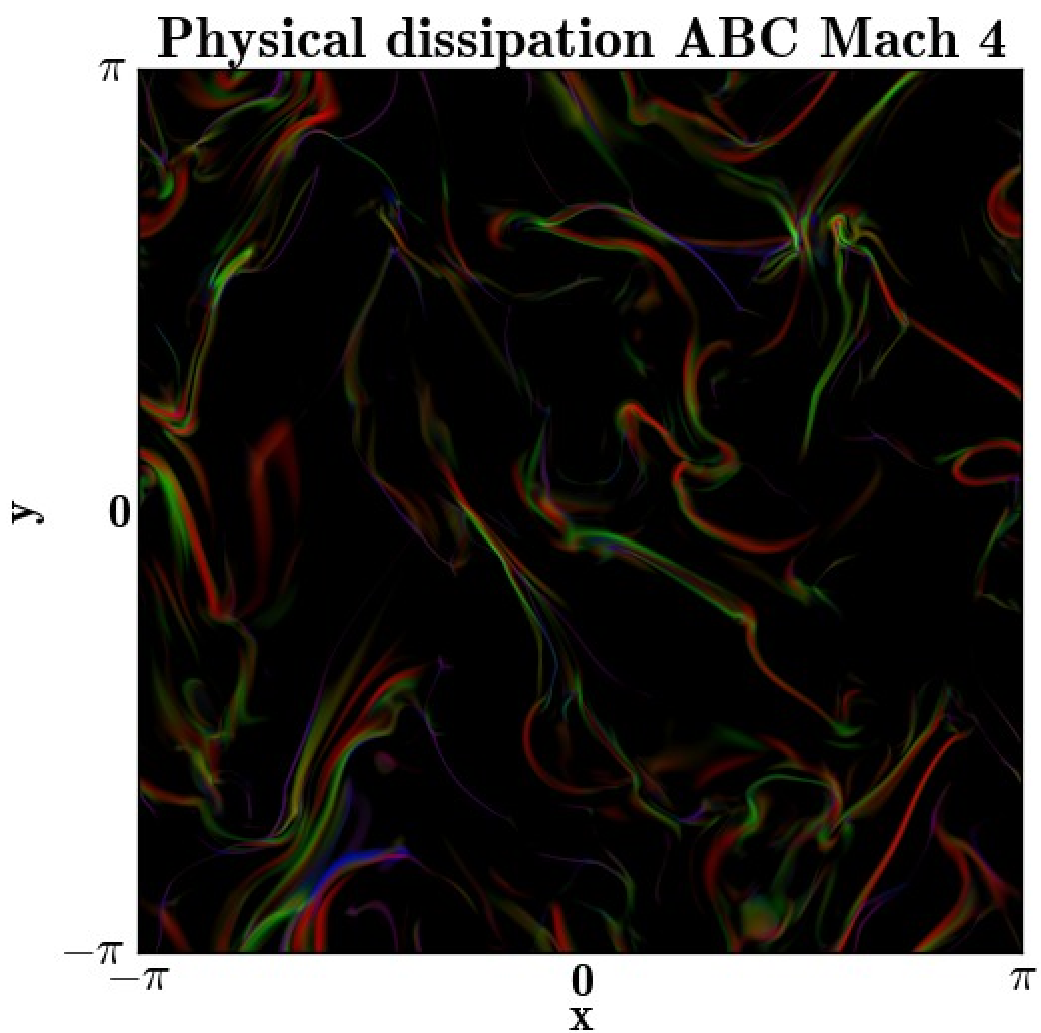
Heating nature in decaying MHD turbulence



Red: Ohmic, Green: Viscous shear, Blue: Viscous compression

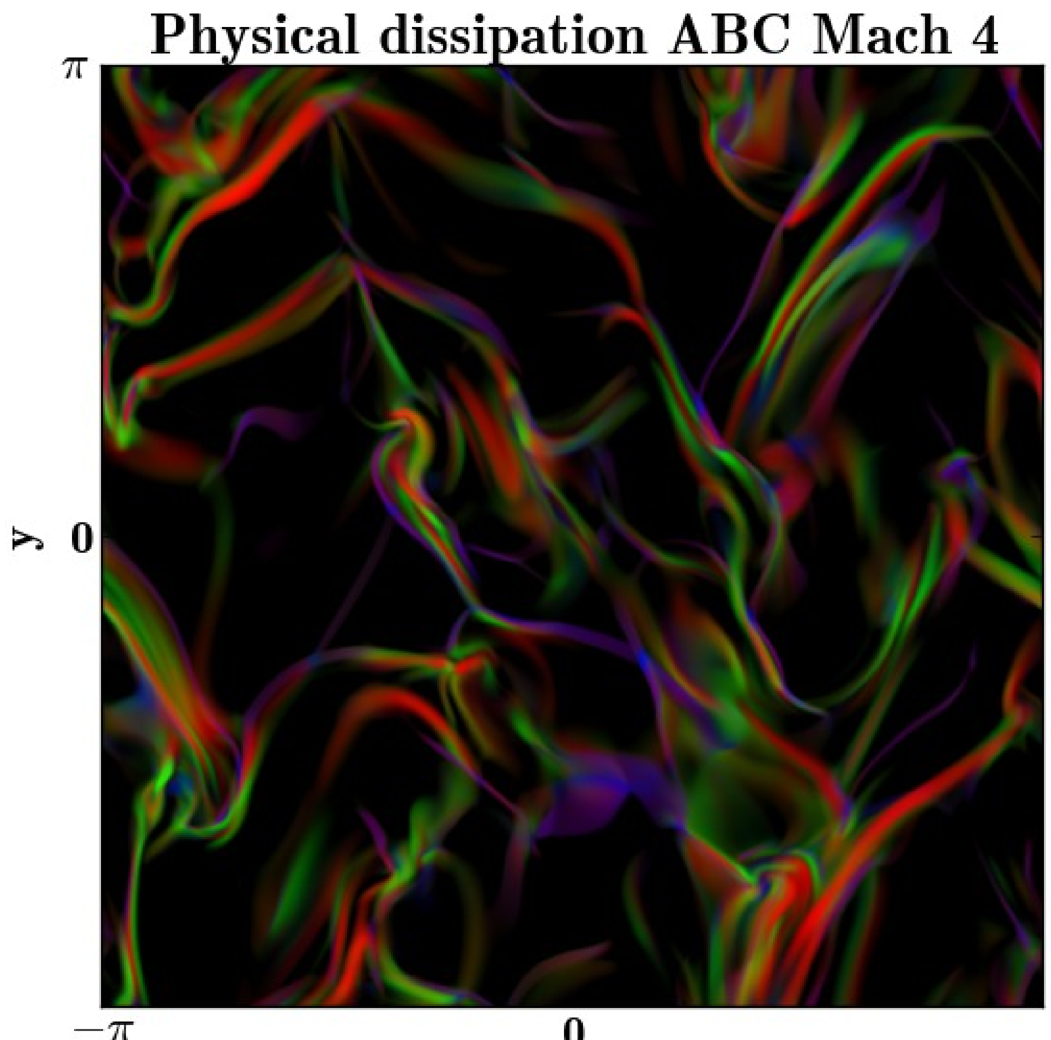
Red: Ohmic heating Blue: $4/3\ \nu\ \mathrm{div}(u)^2$ Green: $\nu\ \mathrm{curl}(u)^2$

Dissipation in a one pixel Slice



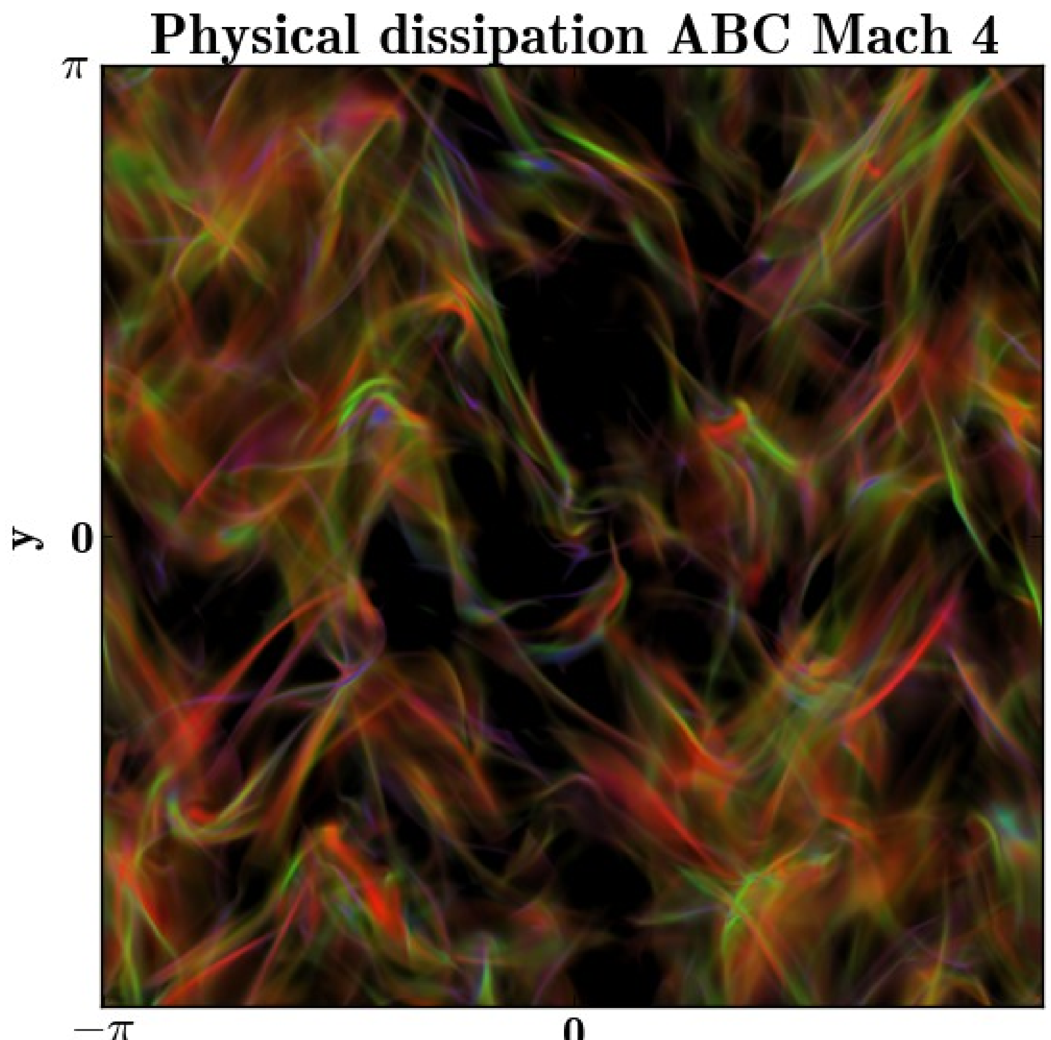
Red: Ohmic heating Blue: 4/3 ν div(u)^2 Green: ν curl(u)^2

Dissipation integrated over Lbox/64



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

Dissipation integrated over full Lbox



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

Integrated Observables

Centroid velocity: first moment of the l.o.s. velocity

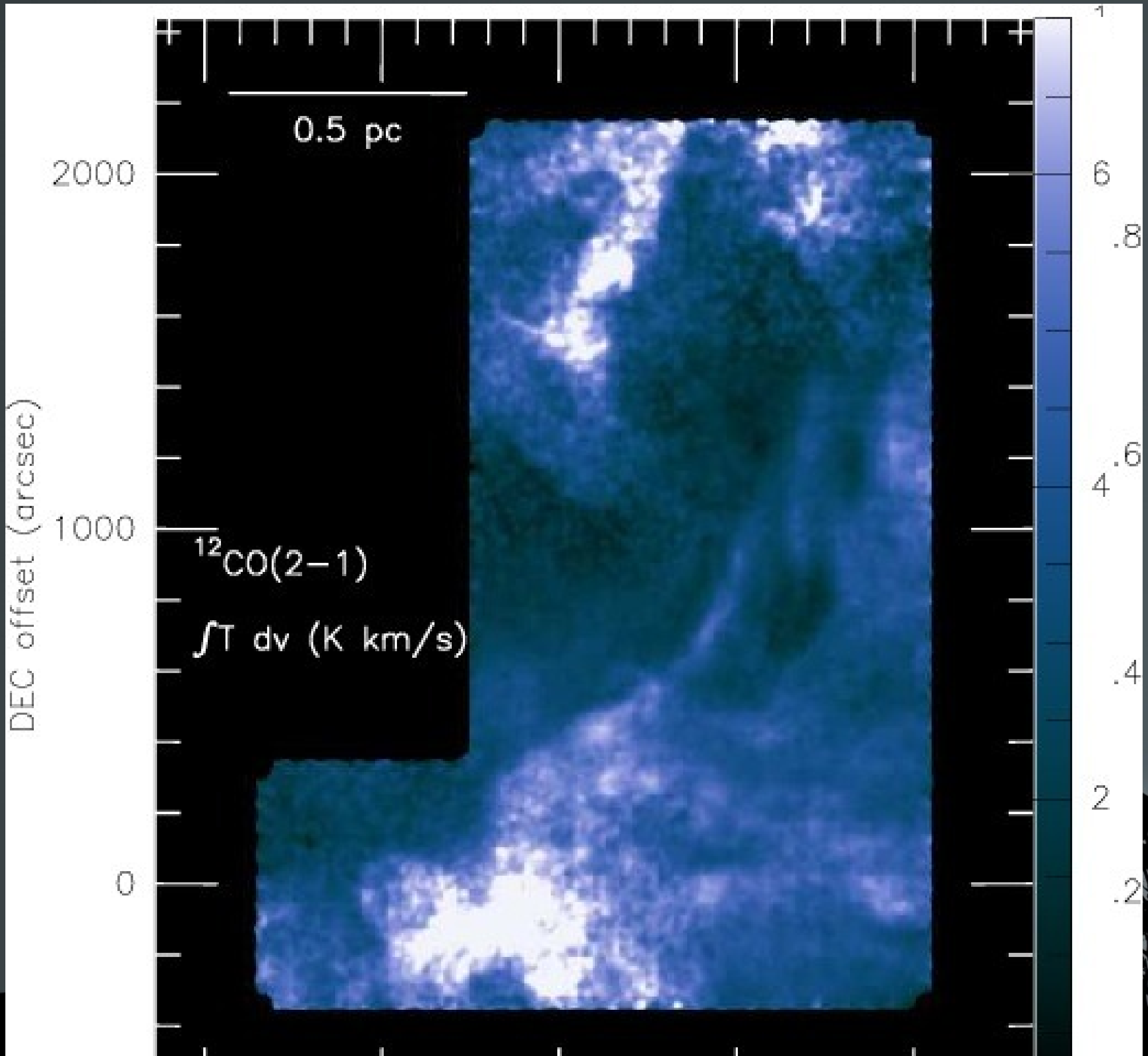
$$\mathrm{CV}(x,y) = \int_0^L u_z(x,y,z)\; dz$$

Assuming that total dissipation powers the line
(or that a chemical tracer appears right where there is heating):

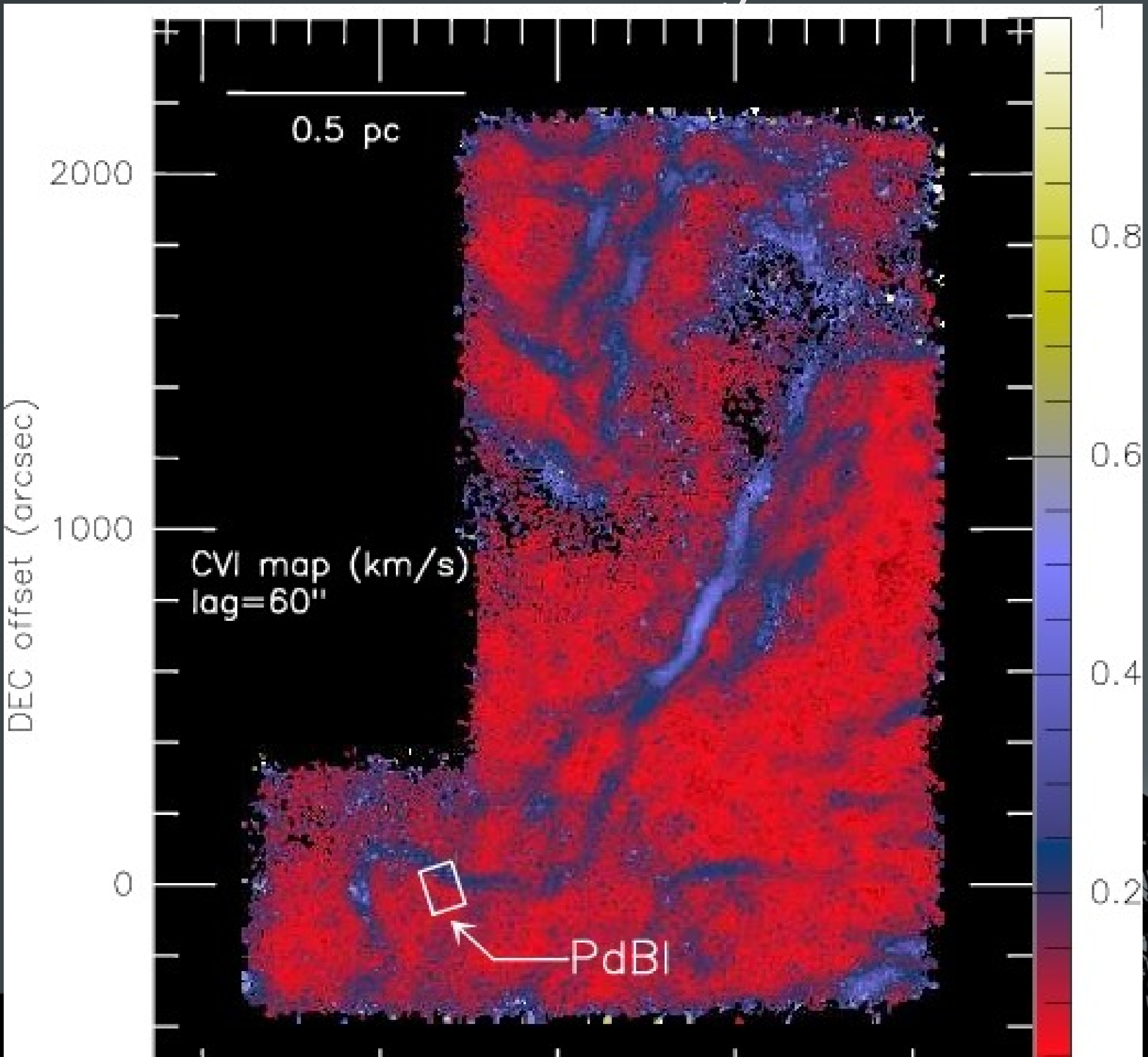
$$\mathrm{CV}_w(x,y) = \frac{1}{\langle \varepsilon \rangle} \int_0^L \varepsilon(x,y,z)\; u_z(x,y,z)\; dz$$

Other variables:
Stokes parameters of the polarization (Q, U, I, P)...
(assuming grains are perfectly aligned to local B)

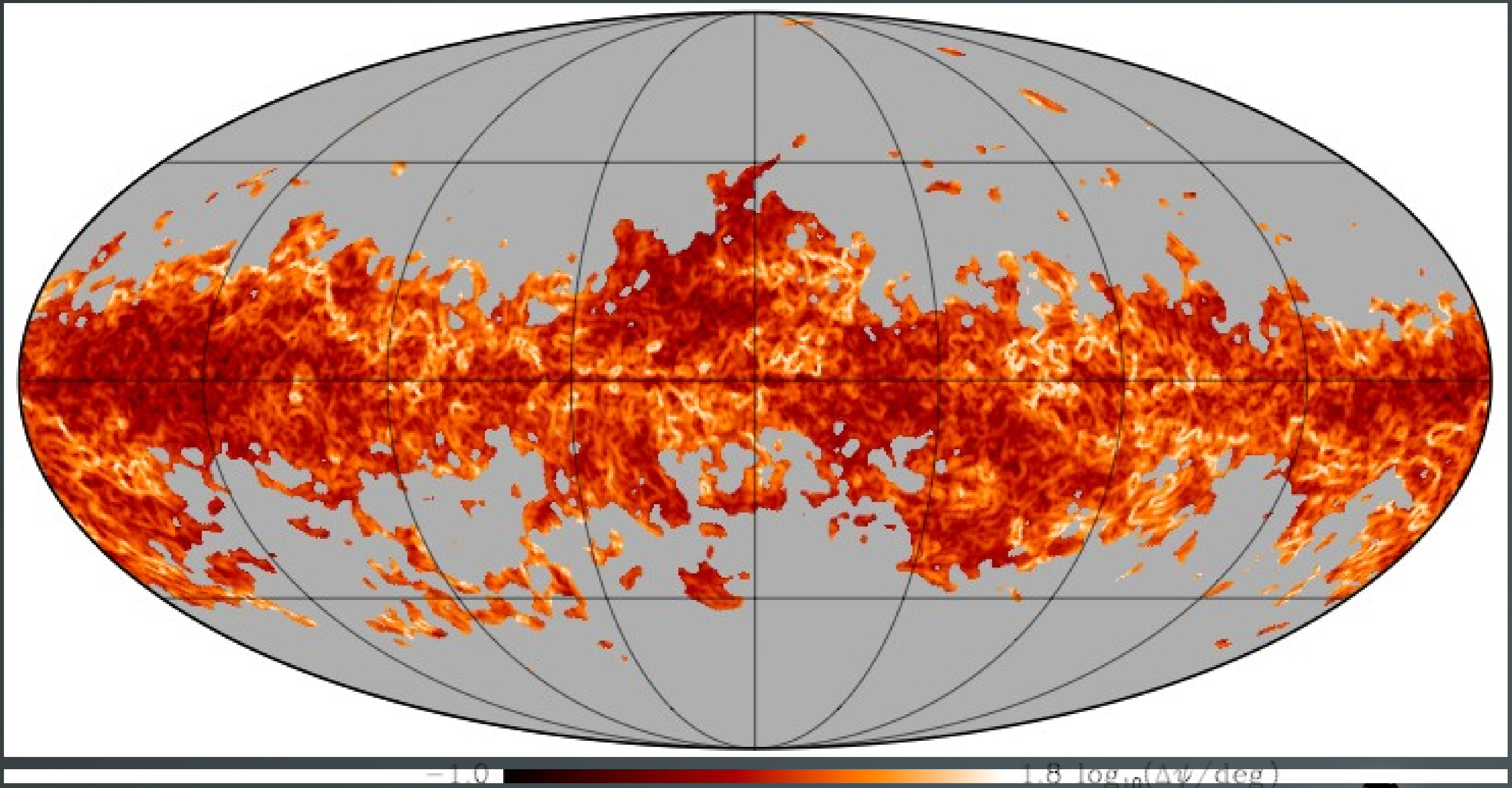
Integrated Observables
Line intensities in Polaris flare



Integrated Observables
Centroid Velocity *Increments*



Increments of Polarisation angles

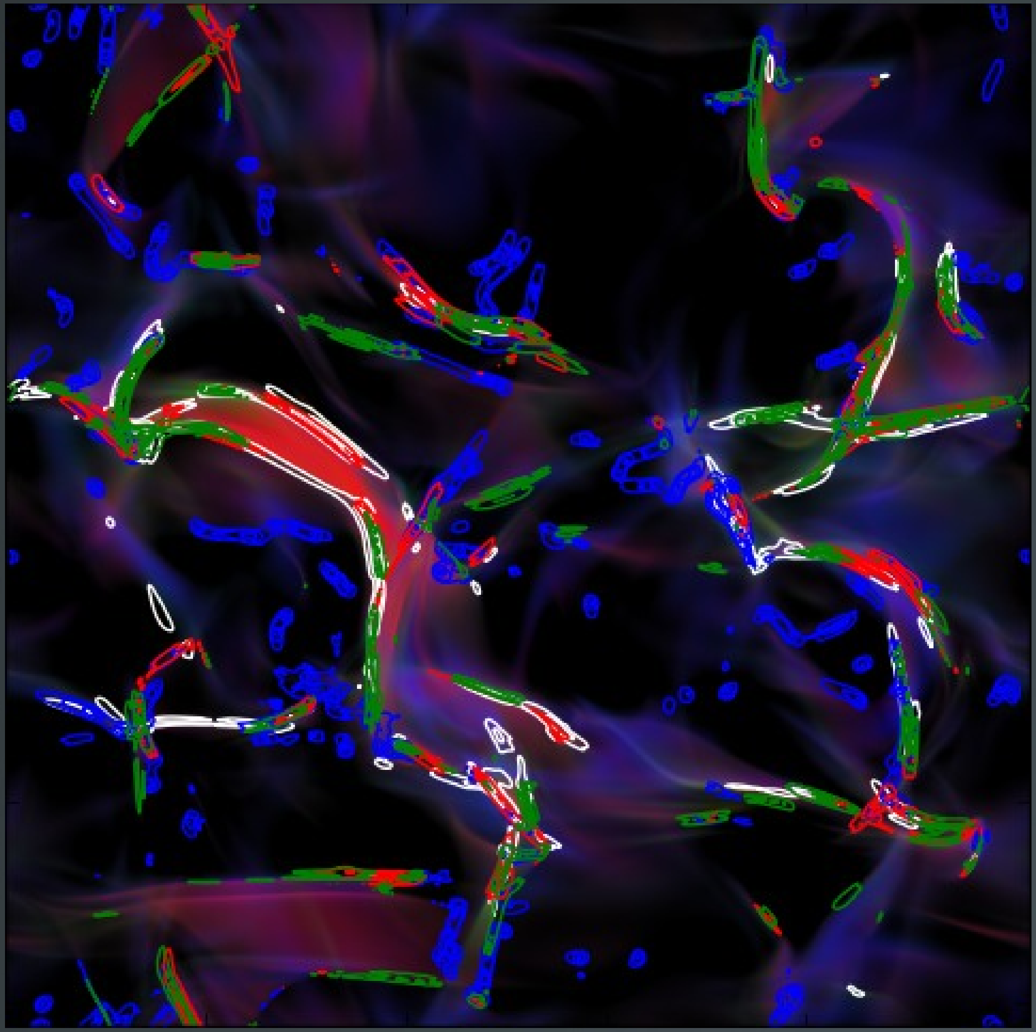


1° resolution
30’ lag

$$\Delta\psi^2(l) = \frac{1}{N}\sum_{i=1}^{N}\left[\psi\left(\mathbf{r}\right) - \psi\left(\mathbf{r} + \mathbf{l}_i\right)\right]^2$$

Observable increments vs. dissipation

Lbox / 2



- <u>Background</u>:

Dissipation rates

Ohmic Viscous AD

- <u>Contours:</u>

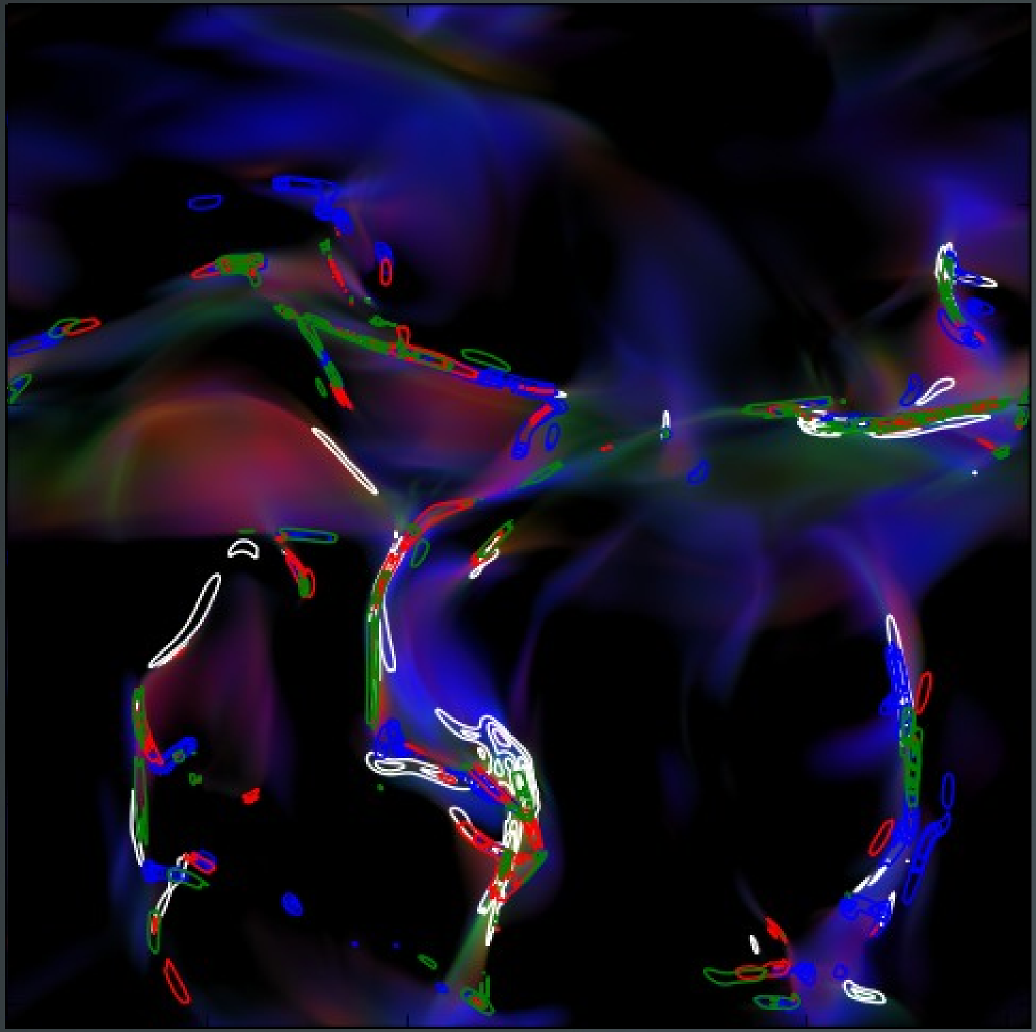
Increments of integrated observables:

- **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.

Observable increments vs. dissipation

Lbox / 8



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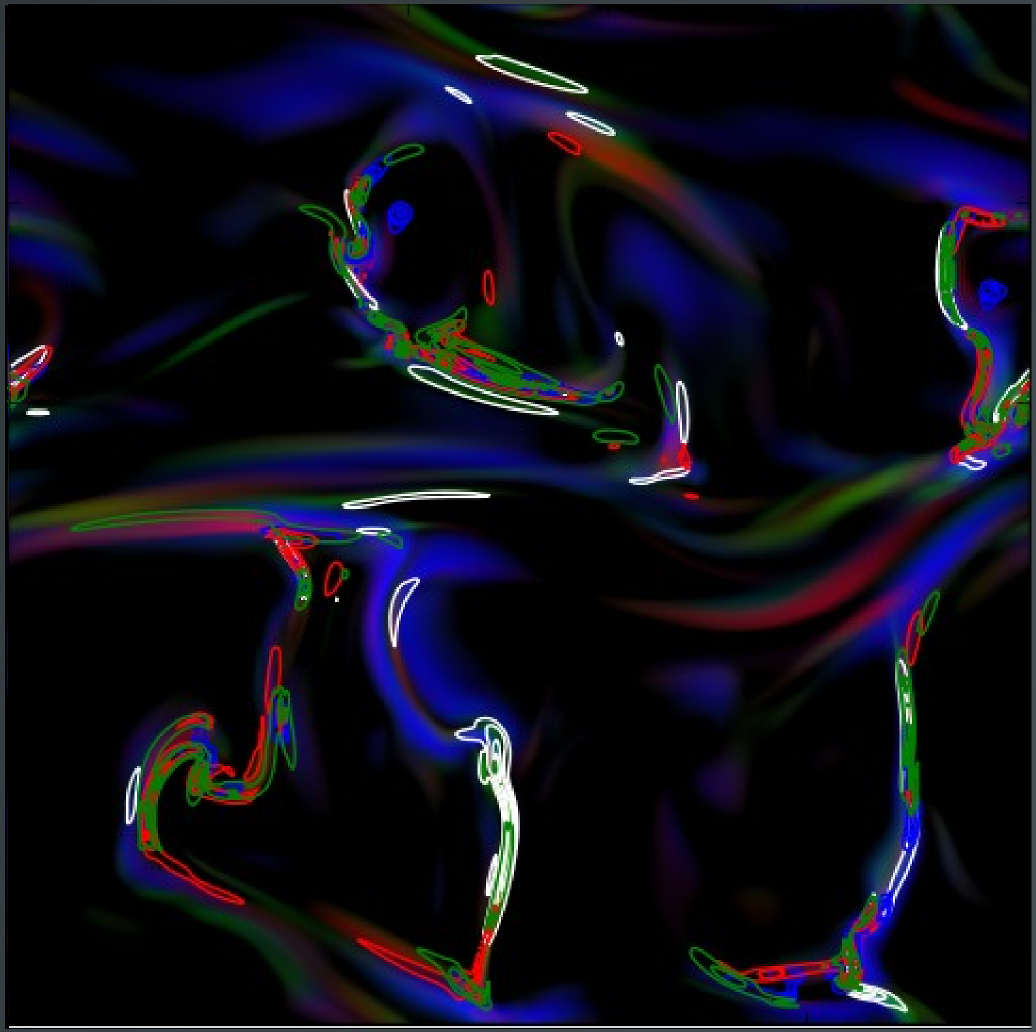
Observable increments vs. dissipation

Lbox / 64



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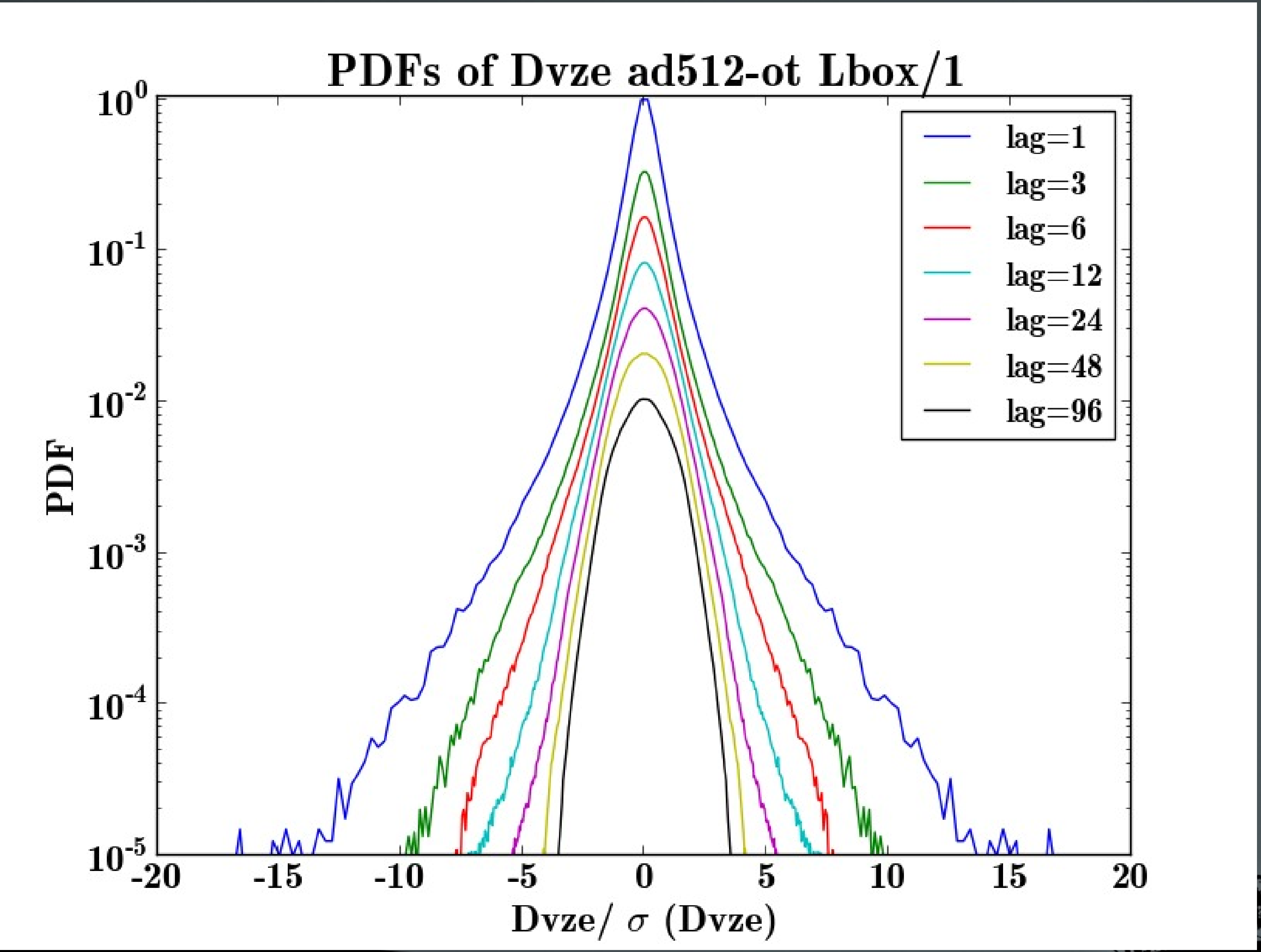
- **Stokes U (red)**
- **POS polarisation angle (blue)**

<u>NOTE:</u> ***different observables trace different parts of the dissipative structures***

PDFs of Velocity increments

From Gaussian to exponential wings → signature of intermittency



PDFs of Velocity increments

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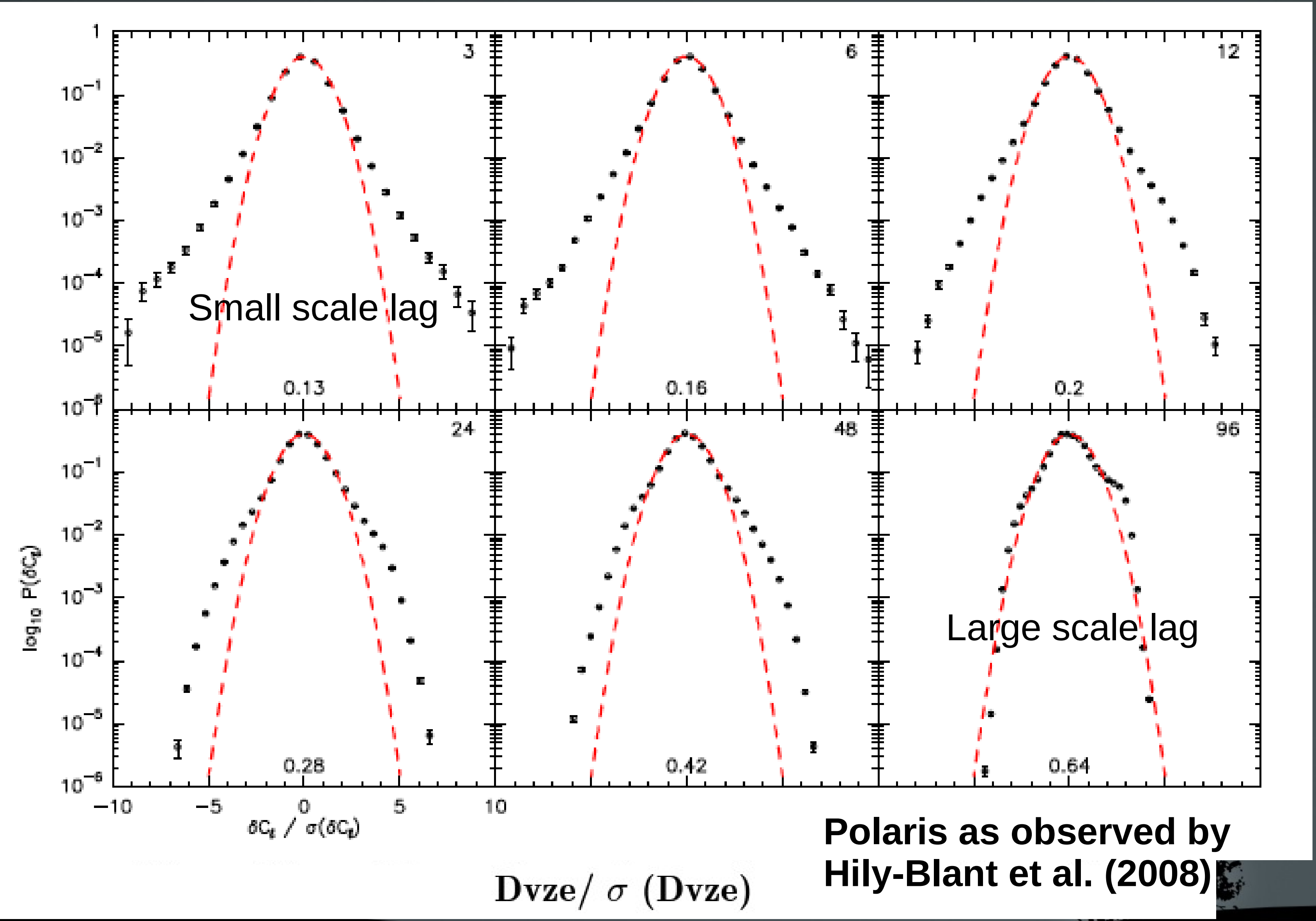
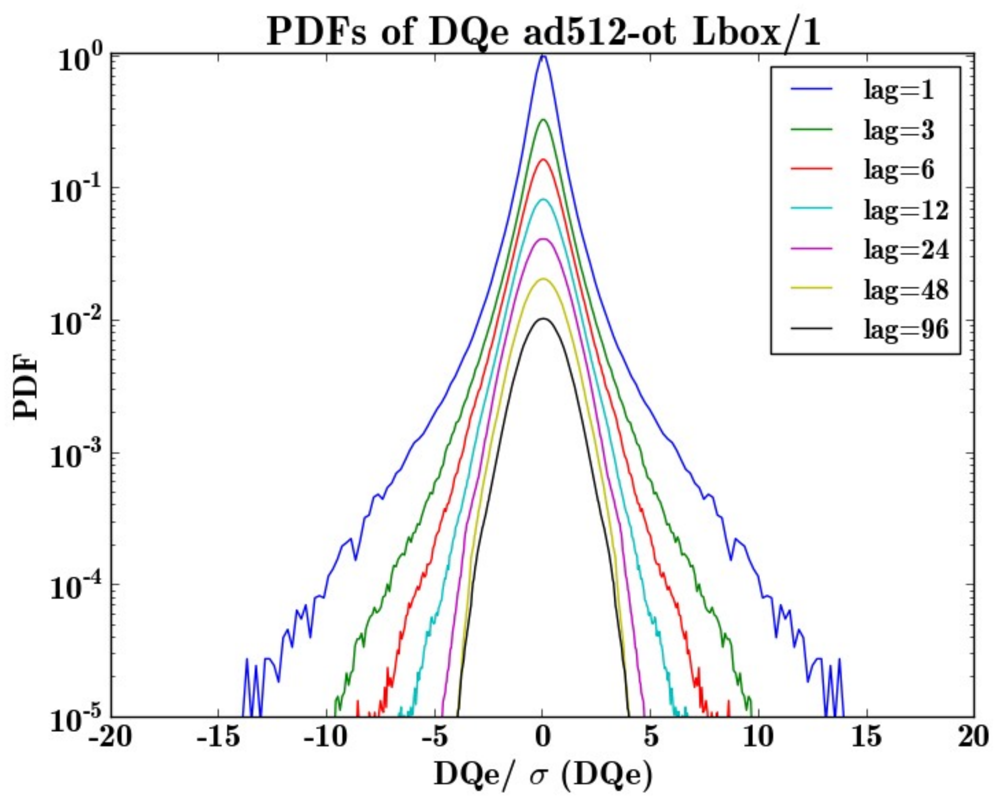
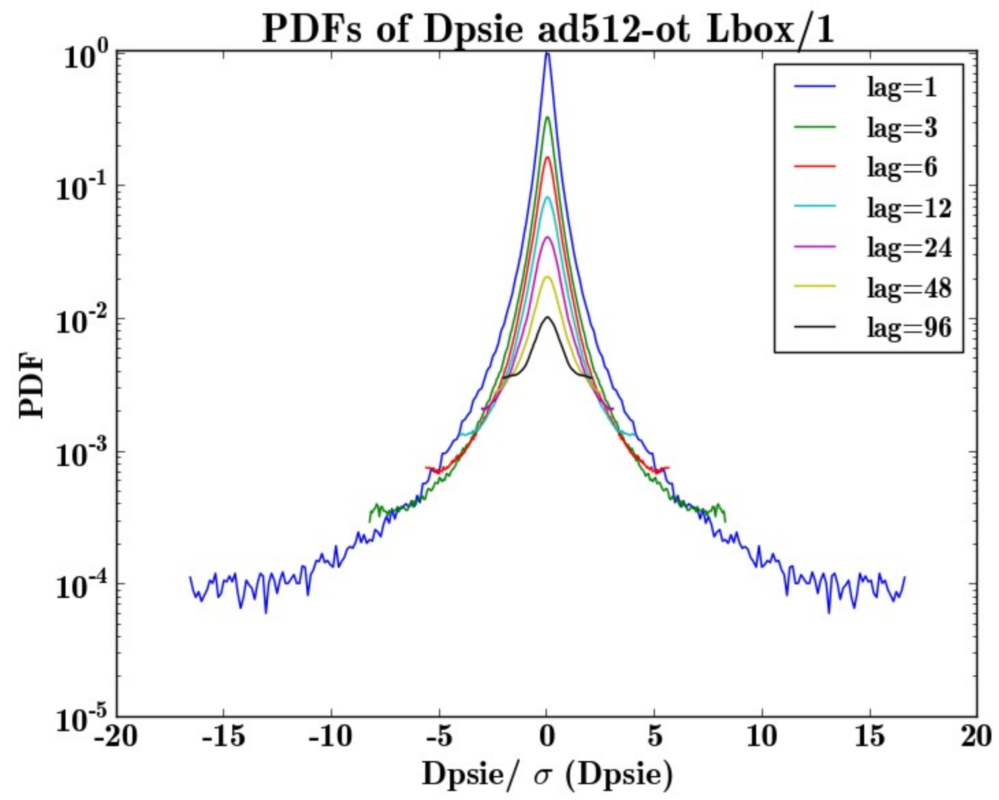


Polaris as observed by Hily-Blant et al. (2008)

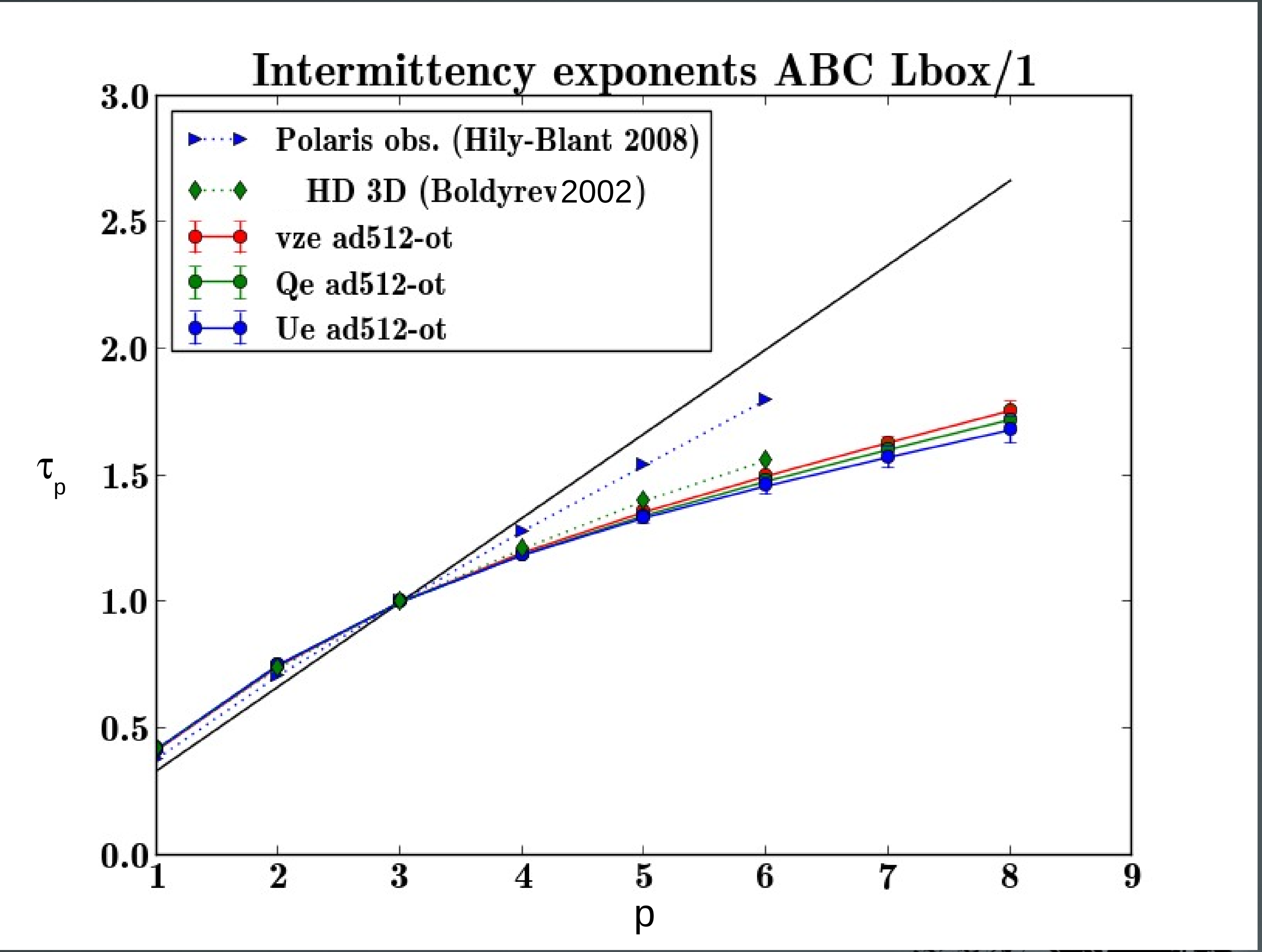
PDFs of Q or psi increments

Stokes Q or U characterise better intermittency than psi





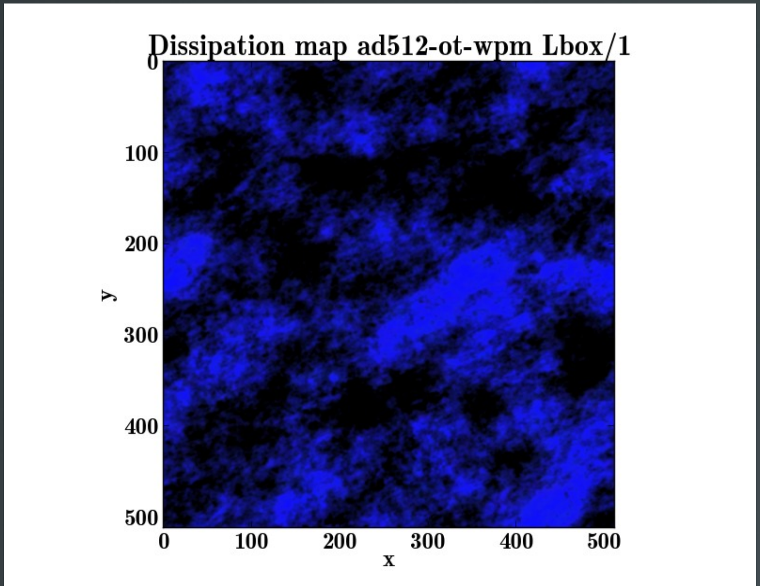
Intermittency exponents

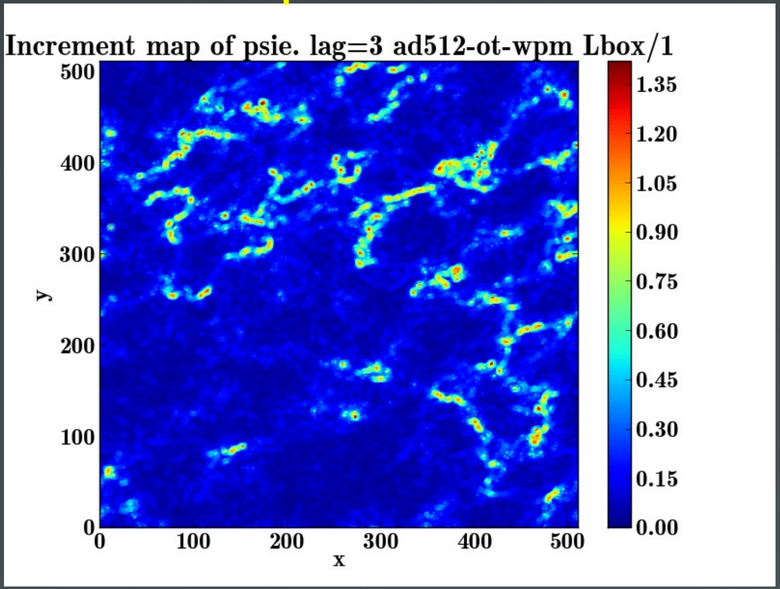


Mix the phases and everything disappears...

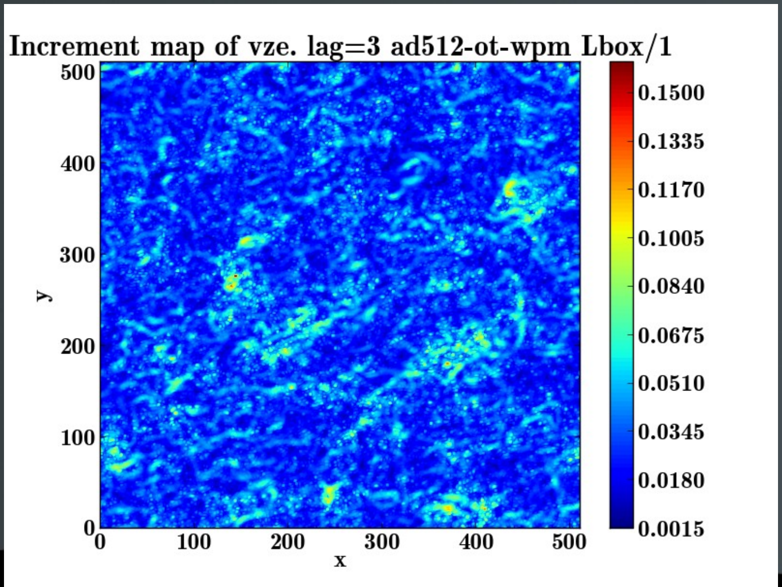
Dissipation

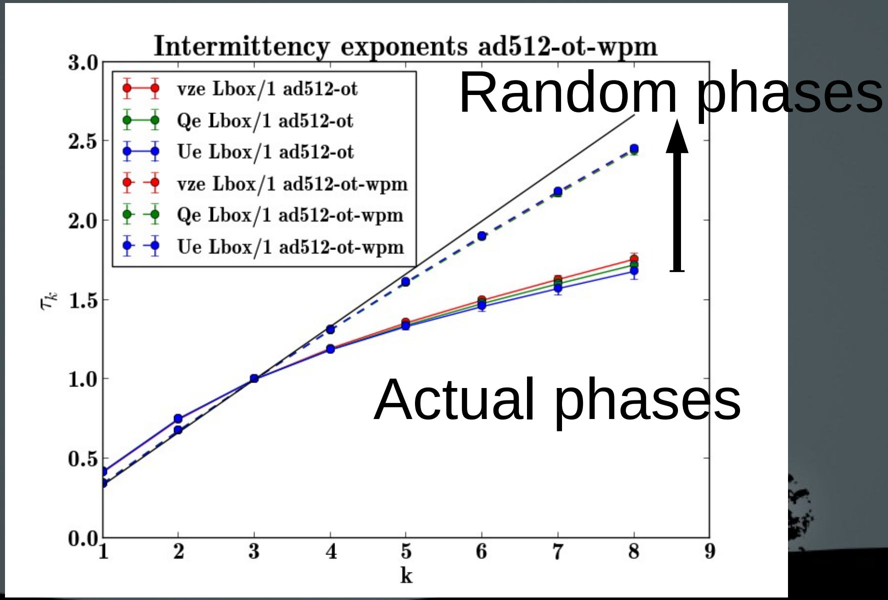
Dpsie





Dvze





Conclusions I

We ran 3D MHD simulations with dissipation in the conditions of the ISM except ν and η are hugely enhanced (and $\nu=\eta$ ...).

- We can recover the scheme's dissipation.
- Dissipative structures are single flavoured sheets, *coherent*, with remarkable scalings (cf. next talk)
- Increment maps and dissipative structures are strongly linked => observable signatures.

II) 2D Simulations with chemistry

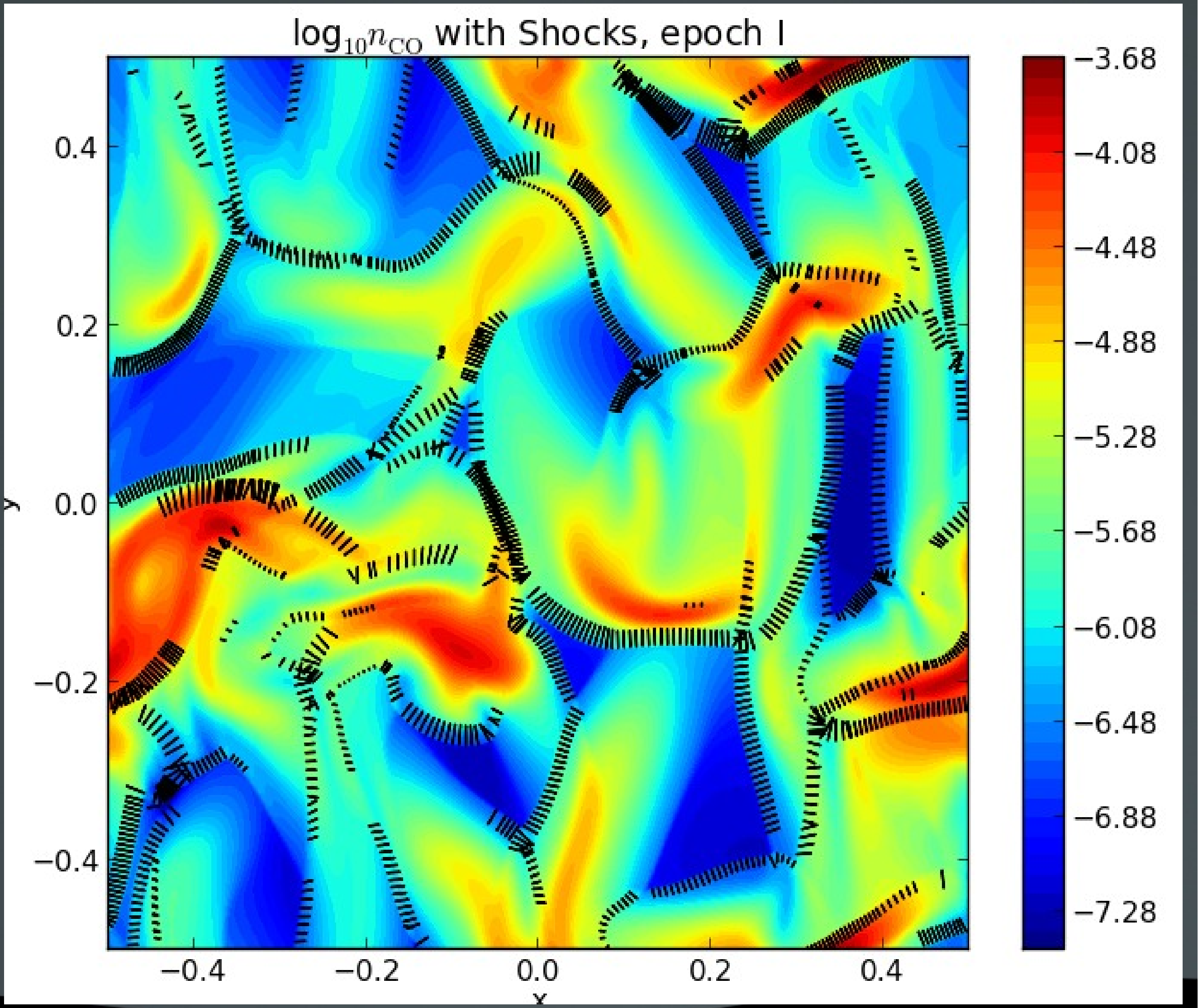
Chemical Signatures
CHEMSES = DUMSES + Paris-Durham

VERY SMALL domain
ACTUAL viscous diffusion

32 species,
7 H_2 levels
1024^2 pixels,
decaying 2D turbulence
U_{rms} ~2 km/s
(way above average,
But think intermittency)

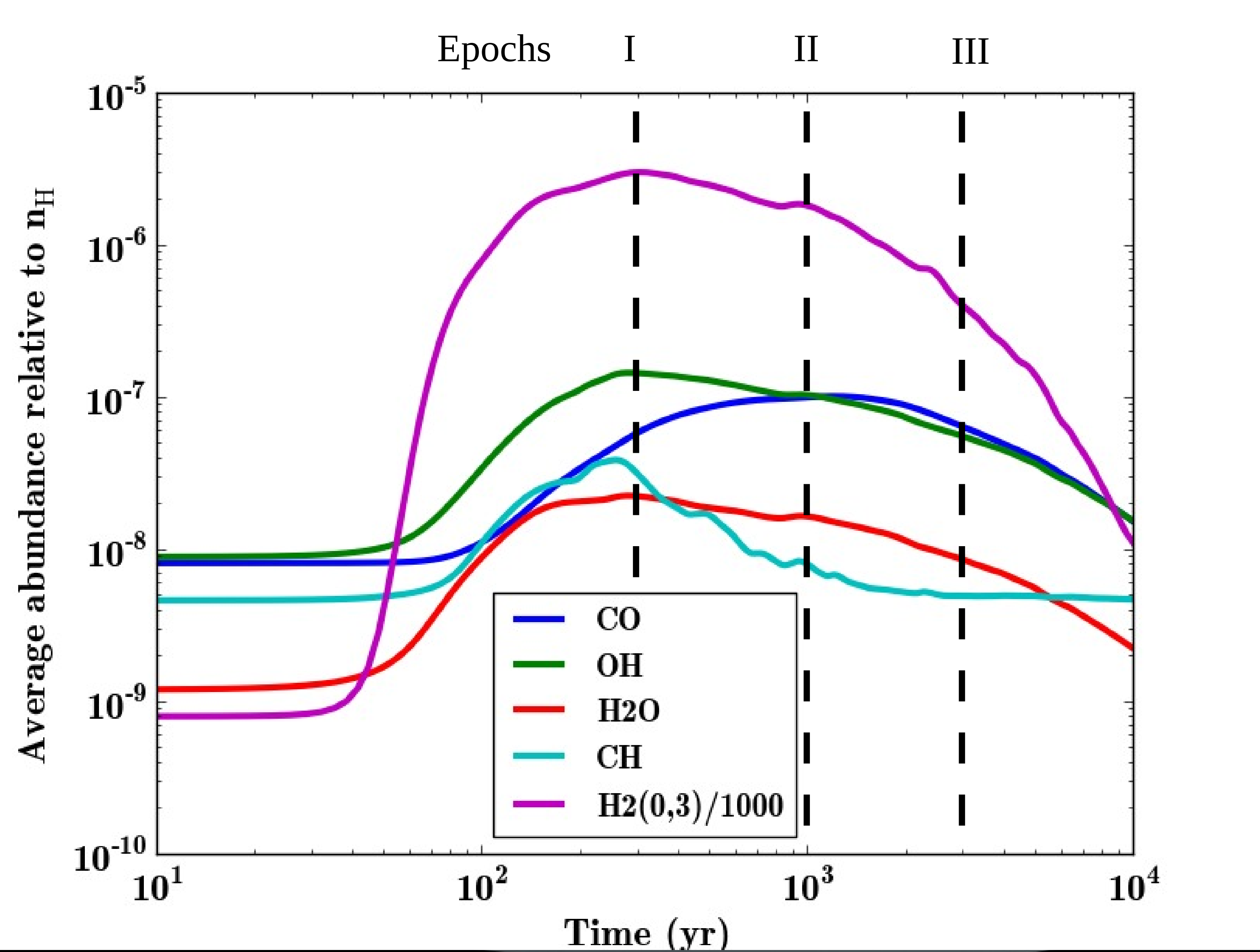
Homogeneous
Irradiation:
G0=1, Av=0.1
=> CO should not survive

10^{16} cm



Molecules enhanced by dissipation of 2D turbulence

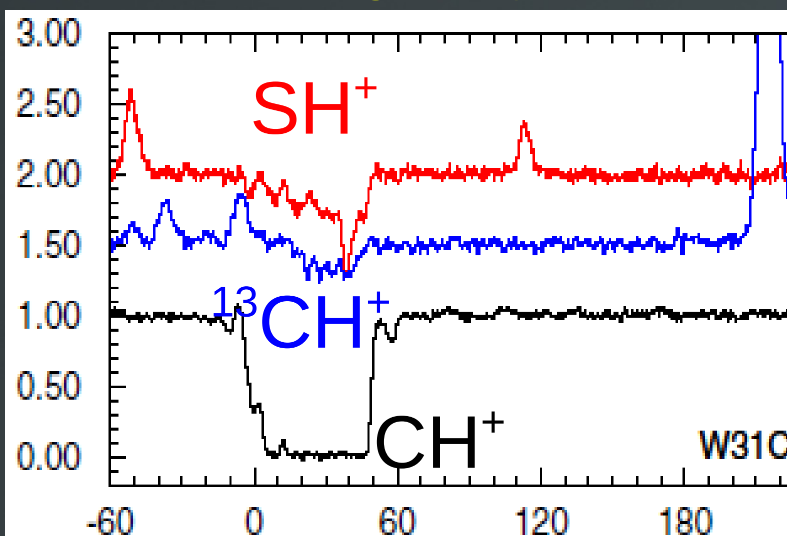
$G_0=1$
$Av=0.1$



<u>BUT</u> CH^+ and SH^+ molecules *require* neutral-ion drift due to B field.

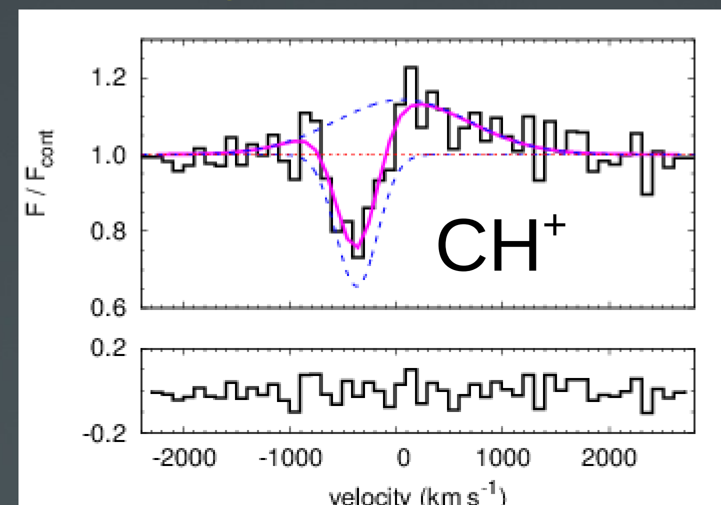
(see Godard et al. 2009)

In our galaxy:



***Herschel* obs. Godard et al (2012)**

In a galaxy at z=2.2:



(*Easy* ??)

$C^+ + H_2 \rightarrow CH^+ + H$ (4640K)

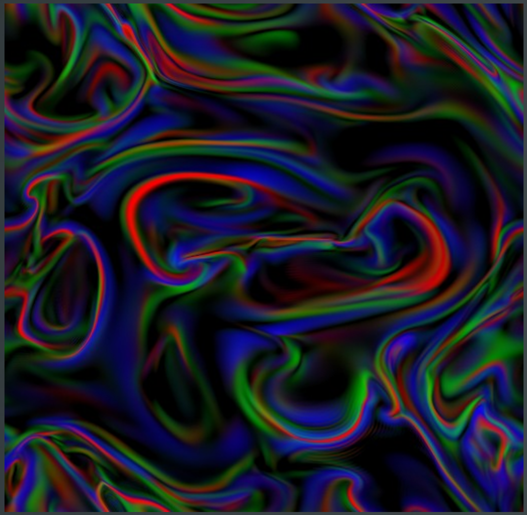
$S^+ + H_2 \rightarrow SH^+ + H$ (9860K)

Conclusions II

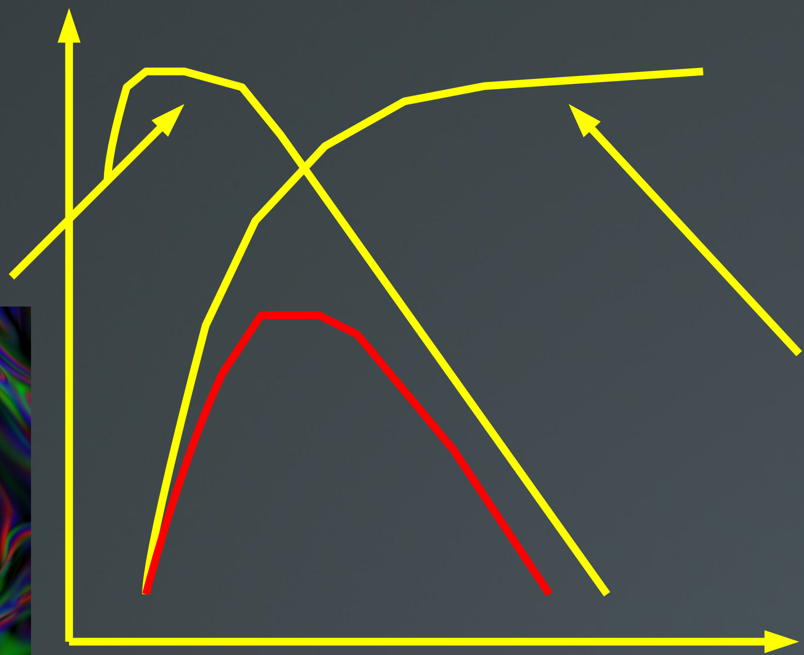
- Many molecules are sensitive to dissipation (amongst others, CO and H2)
- This chemistry needs extreme spatial resolution, and is absent from current large scale simulations.
- For some molecules (CH+, SH+), B field and ambipolar diffusion heating is needed (numerical challenge).

The cunning plan...

Intermittent statistics of the dissipation

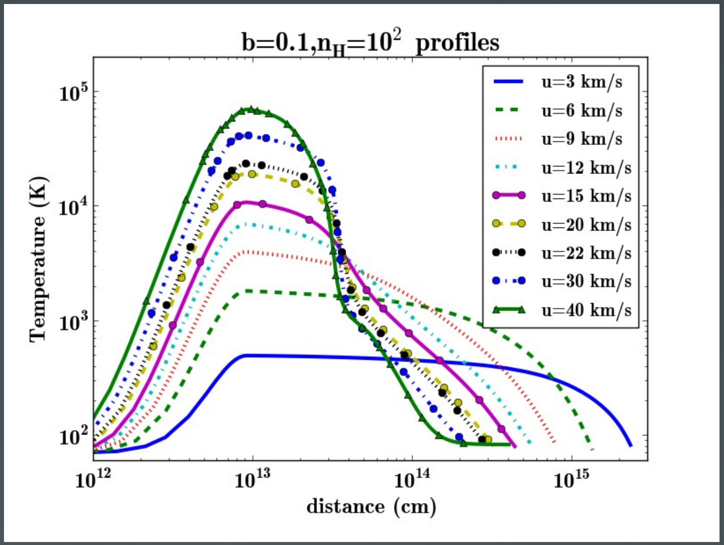


G. Momferratos

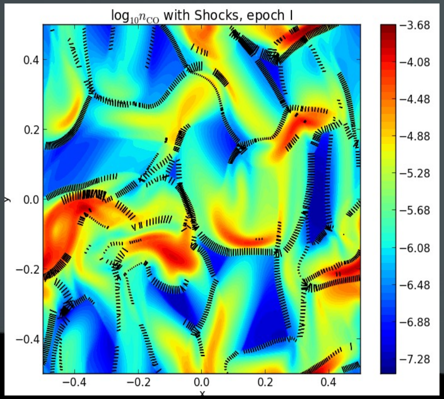


Dissipation strength

Molecular yields from Shocks (for example)

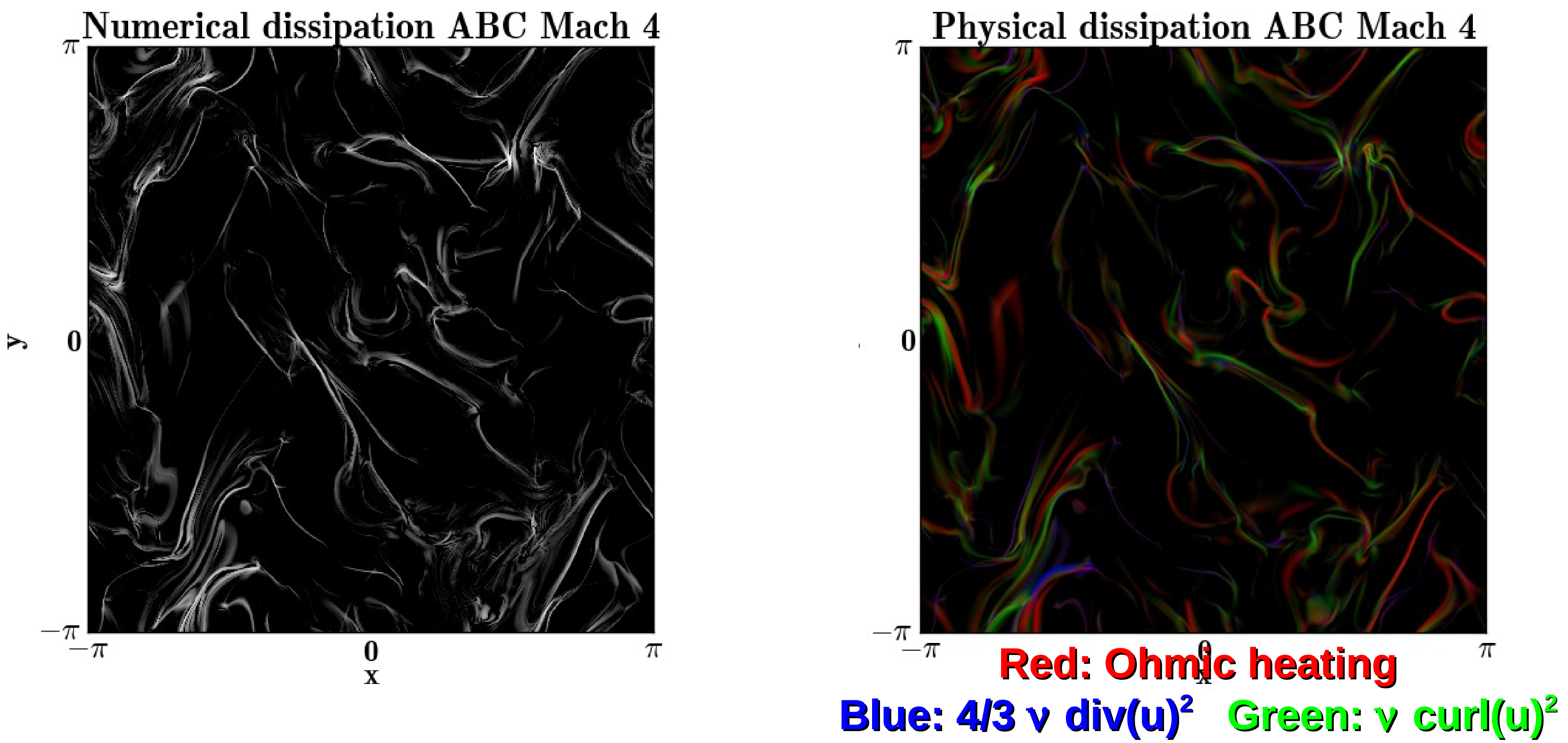


=> Molecules
Formation + excitation

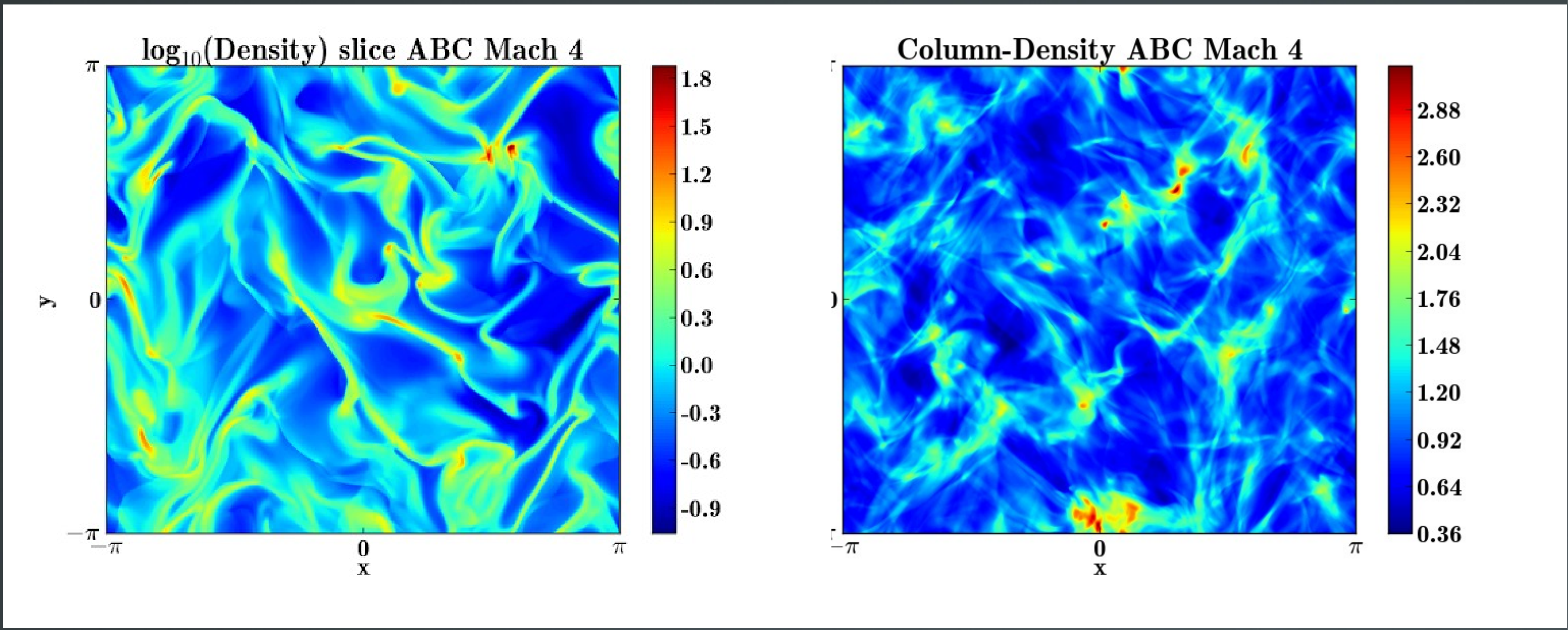


Thanks !

Dissipation maps



Density



log10(Density) slice ABC Mach 4
π
0
−π
y
−π
0
π
x
1.8
1.5
1.2
0.9
0.6
0.3
0.0
-0.3
-0.6
-0.9
Column-Density ABC Mach 4
−π
0
π
x
2.88
2.60
2.32
2.04
1.76
1.48
1.20
0.92
0.64
0.36