Turbulent energy dissipation in the interstellar medium, near and far

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«The local truth: star formation and feedback in the SOFIA era »,
October 17-20, 2016, Asilomar, USA

Mid-IR *Spitzer* image of the bow shock in front of the run-away star ζ Oph

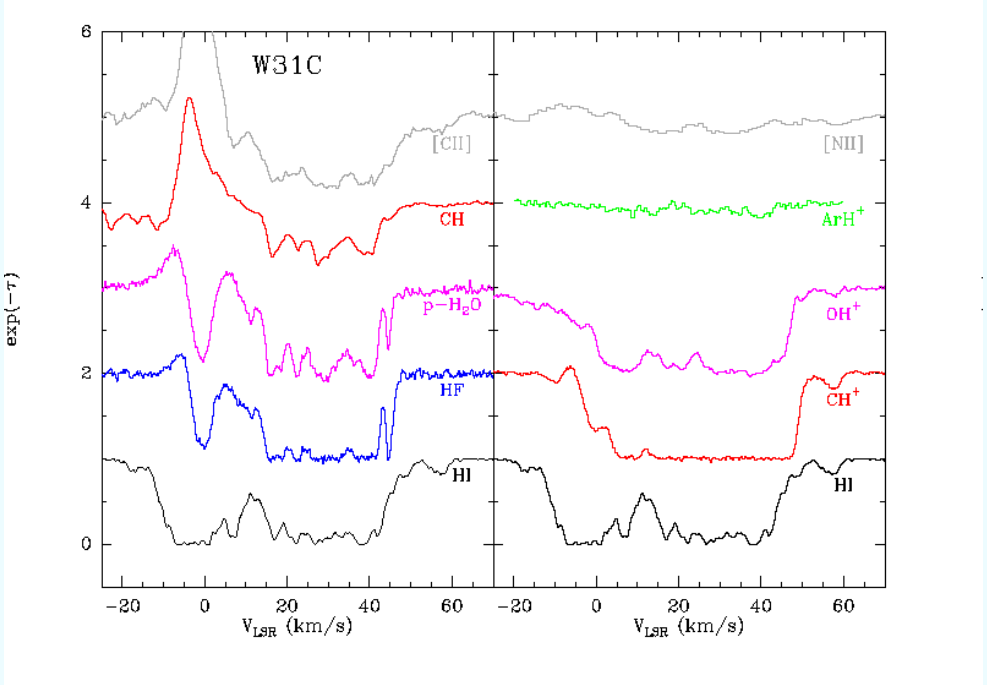
« A central issue in theories of galaxy formation is the relative importance of purely gravitational effects and gas dynamical effects involving dissipation and radiative cooling. » White & Rees 1998

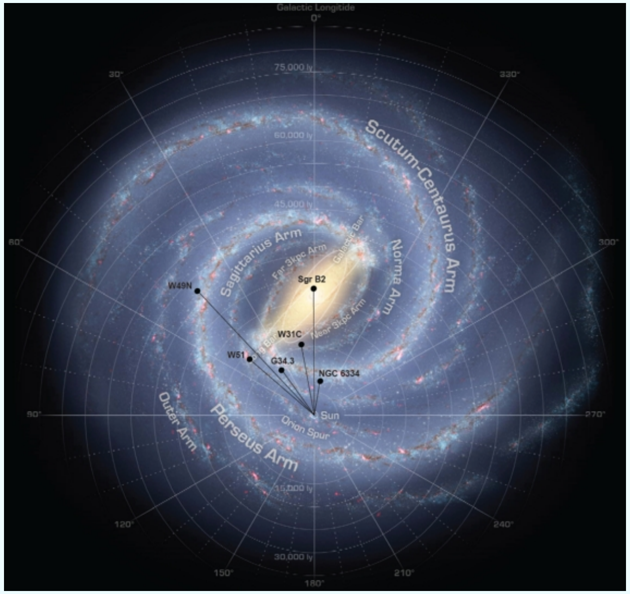
Outline

- The unexpected molecular richness of the diffuse ISM
- A missing energy source in the diffuse ISM: dissipation of MHD turbulence
- Dissipation of non-ideal MHD turbulence : dedicated numerical simulations
- Confrontation to observables
- Challenges for SOFIA

The unexpected molecular richness of the diffuse ISM

Herschel/HIFI absorption spectroscopy





HF : tracer of H_2 , exothermic F + H_2

CH : tracer of H_2 (density larger than 100 cm^{-3})

OH^+ : tracer of CR, destroyed by collisions with H and H_2

CH^+ : tracer of energy dissipation, destroyed by collisions H and H_2

ArH^+ : tracer of HI, $f_{H2}<10^{-3}$ and CR

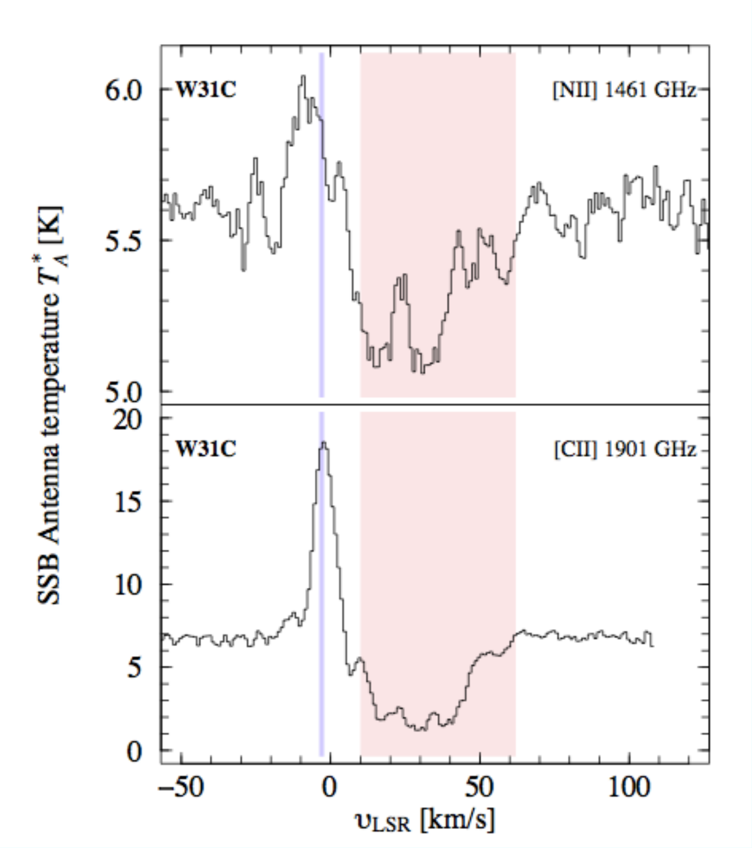
➭ **different families: PCA analysis**
Neufeld + 2015

HI : EVLA, Brunthaler + in prep
CII : Gerin + 2015
NII : Persson + 2014
CH : Gerin + 2010a
HF and H_2O : Neufeld + 2010
ArH^+ : Schilke + 2014
OH^+ : Gerin + 2010b
CH^+ : Falgarone + 2010, Godard + 2012

PRISMAS

PI: M. Gerin

[NII] and [CII] absorption in diffuse gas



[CII] and [NII] have similar critical densities

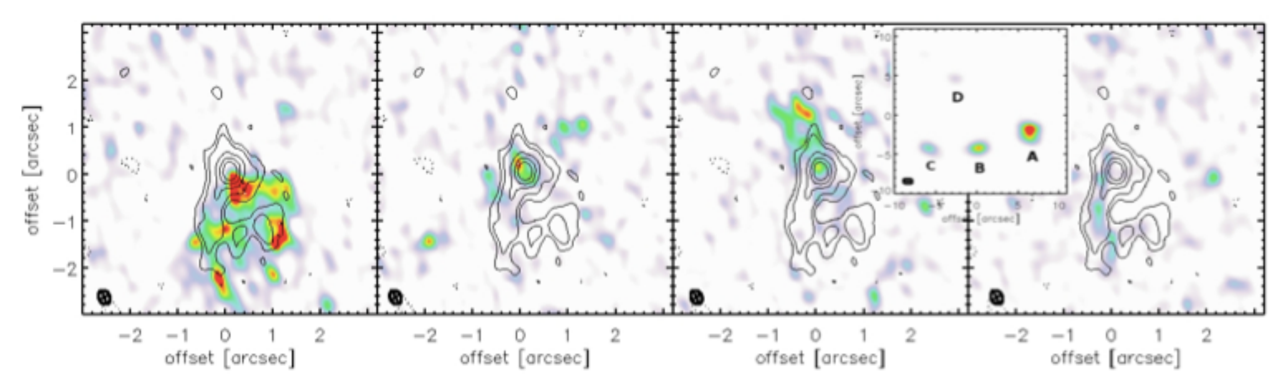
[NII] emission line : HII regions in star forming regions

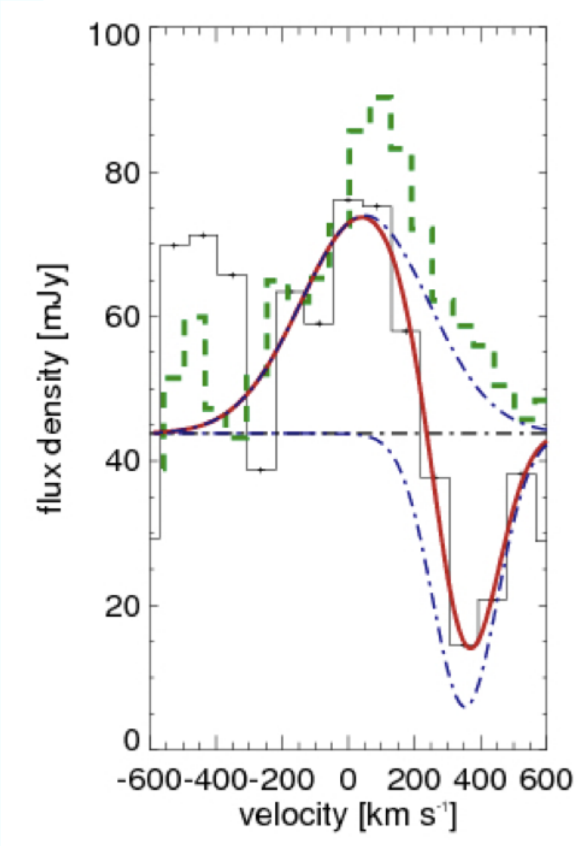
[NII] absorption line : WIM
Mean n_e ~ 0.1 cm^{-3}
for LOS filling factor 0.5 to 0.7
$N(N^+)$ ~ 1.5 x 10^{17} cm^{-2}

- ➪ 7 – 10 % of all C^+ in the WIM
- ➪ **Absorption by intervening CNM severely affects [CII] and [NII] emission**

Persson + 2014

First detection of [CII] absorption at high redshift



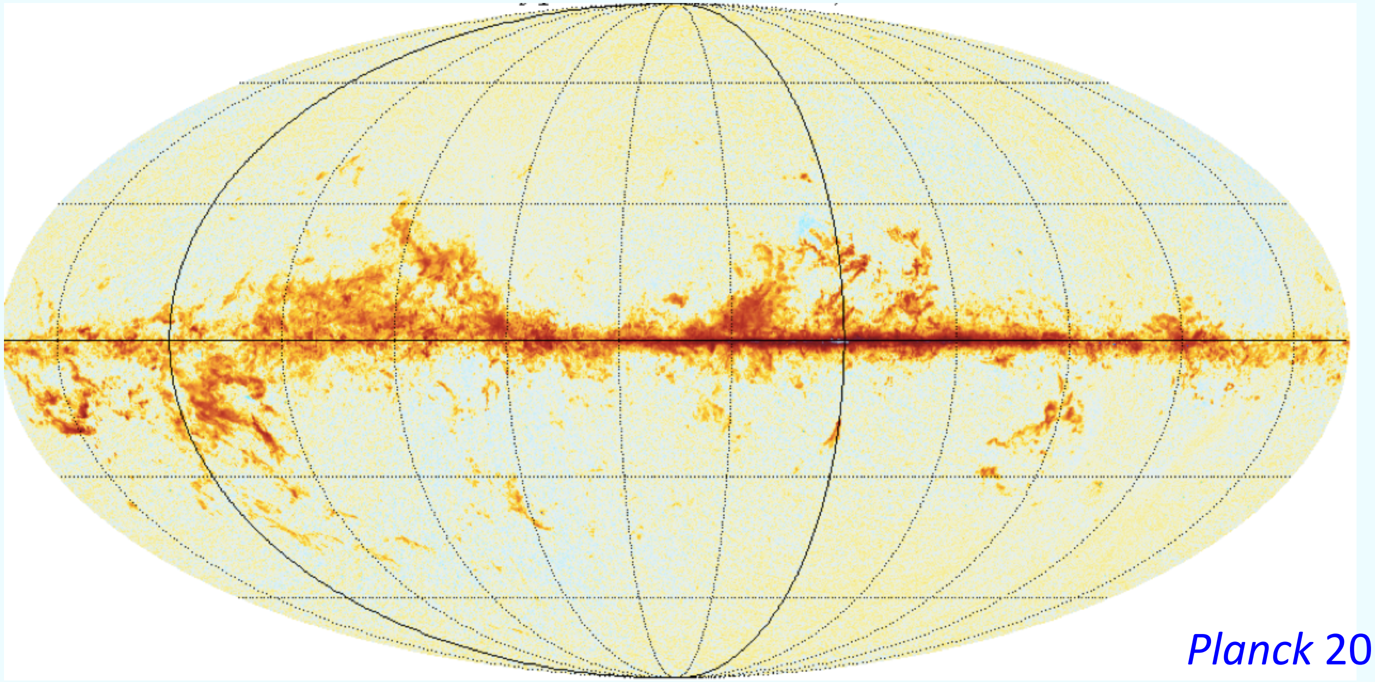


CI dashed green
[CII] black

Planck dusty GEMS
Canameras + 2015
Flux 400 mJy at 350 µm
z=3.4

ALMA [CII] observations
➪ [CII] absorption from inflowing diffuse gas
Nesvadba et al. 2016

Planck : all-sky CO



Planck 2013 Results XIII (2014)

Properties of the all-sky CO emission:

☐ at high latitude, power law distributions of size and flux of hundreds of « patches »

☐ CO is a reliable molecular gas mass tracer within a factor of a few over 3 orders of magnitude of gas column densities (see Bolatto + 2013)

☐ From 3-2/2-1 and 2-1/1-0 ratios, the bulk of the mass of molecular gas in the Inner Galaxy lies in gas at density < 600 cm^{-3} and temperature > 20K

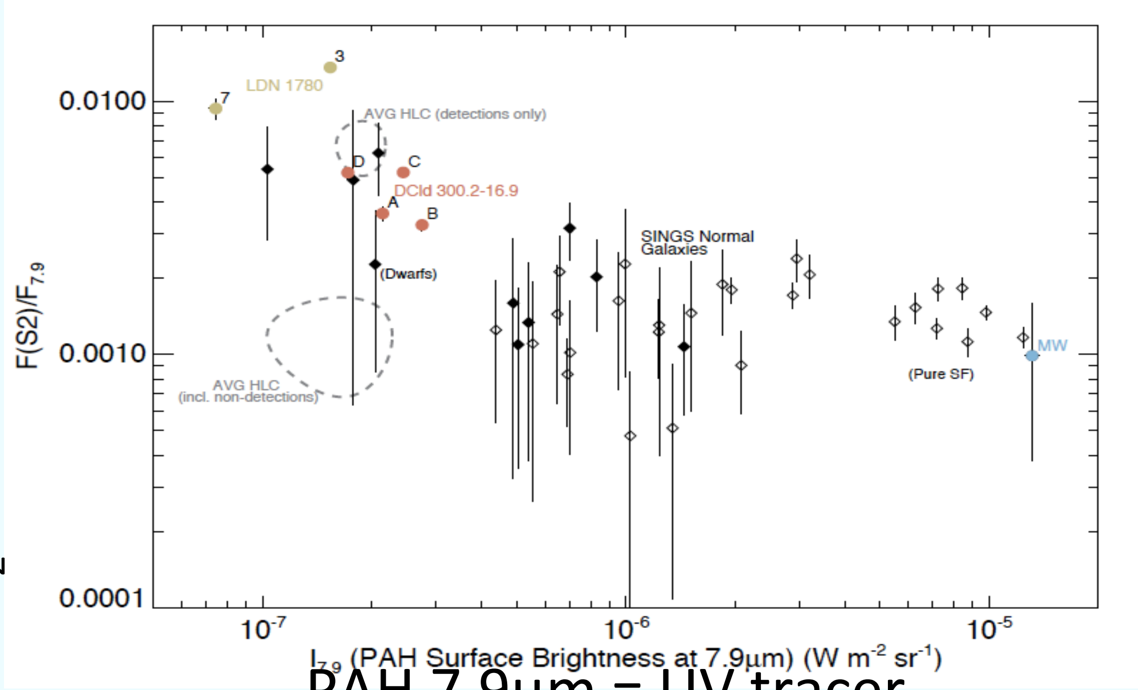
☐ CO emission of the CO-dark gas

Planck Collaboration (in prep.)

A missing energy source for the diffuse ISM

H_2 pure rotational emission in galactic cirrus

$H_2S(2)$ / PAH 7.9µm



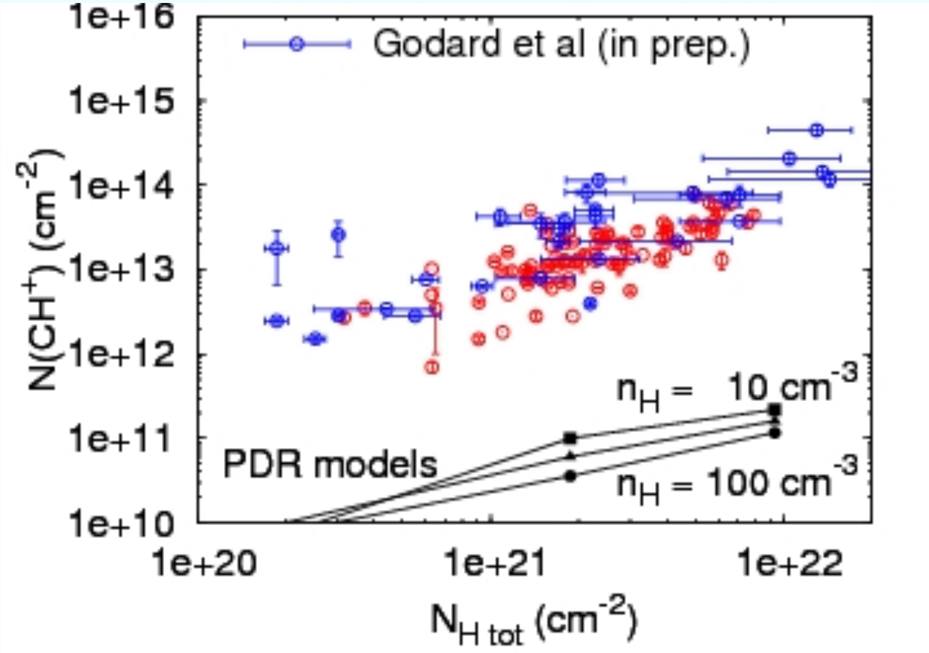
PAH 7.9µm = UV tracer

Spitzer/IRS
Ingalls et al. 2011

- ➪ UV pumping not sole source of excitation
- ➪ H_2 brightness per H ~ constant (*Spitzer*/IRS)

At the galactic scale, ISO-SWS spectra Falgarone et al. 2005

Large CH^+ abundances in diffuse gas



Red: visible absorption lines

Crane + 95, Gredel 97, Weselak + 08

Blue: Submm lines

Godard et al. 2014

Extremely short lifetime
(destroyed by collisions H – H_2)

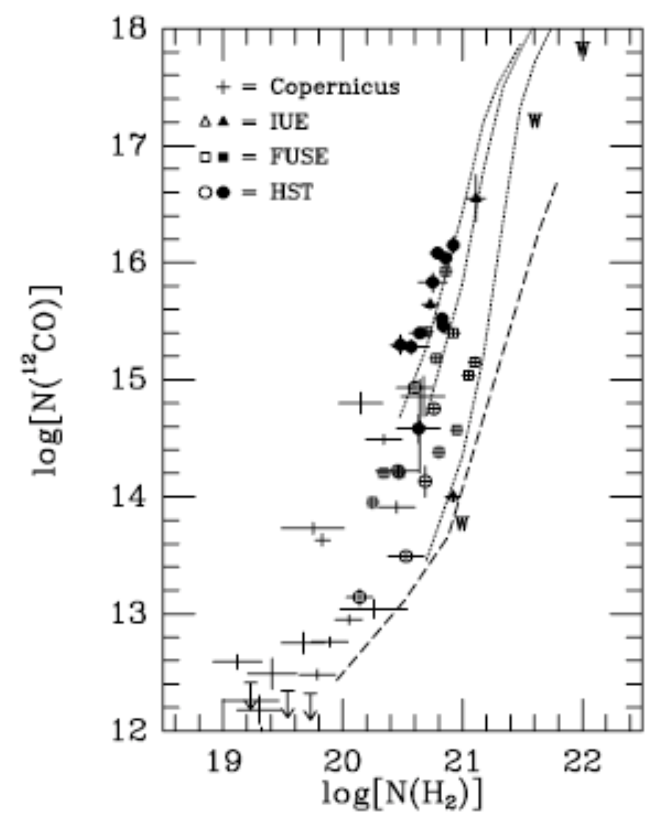
$$t = 1\mathrm{yr}/f_{\mathrm{H_2}}(n_{\mathrm{H}}/50\,\mathrm{cm}^{-3})^{-1}$$

Formation energy:
$C^+ + H_2 \rightarrow CH^+$

$$E_{form} = 0.4eV$$

⇨ **Need for a supra-thermal energy source**

Unexplained CO at low N_{H2}



CO abundances in diffuse gas cannot be reproduced with UV-driven chemistry

Sonnentrucker + 07

- **PDR models : C^+**

  $C^+ + OH$ and $H_2O \rightarrow CO$

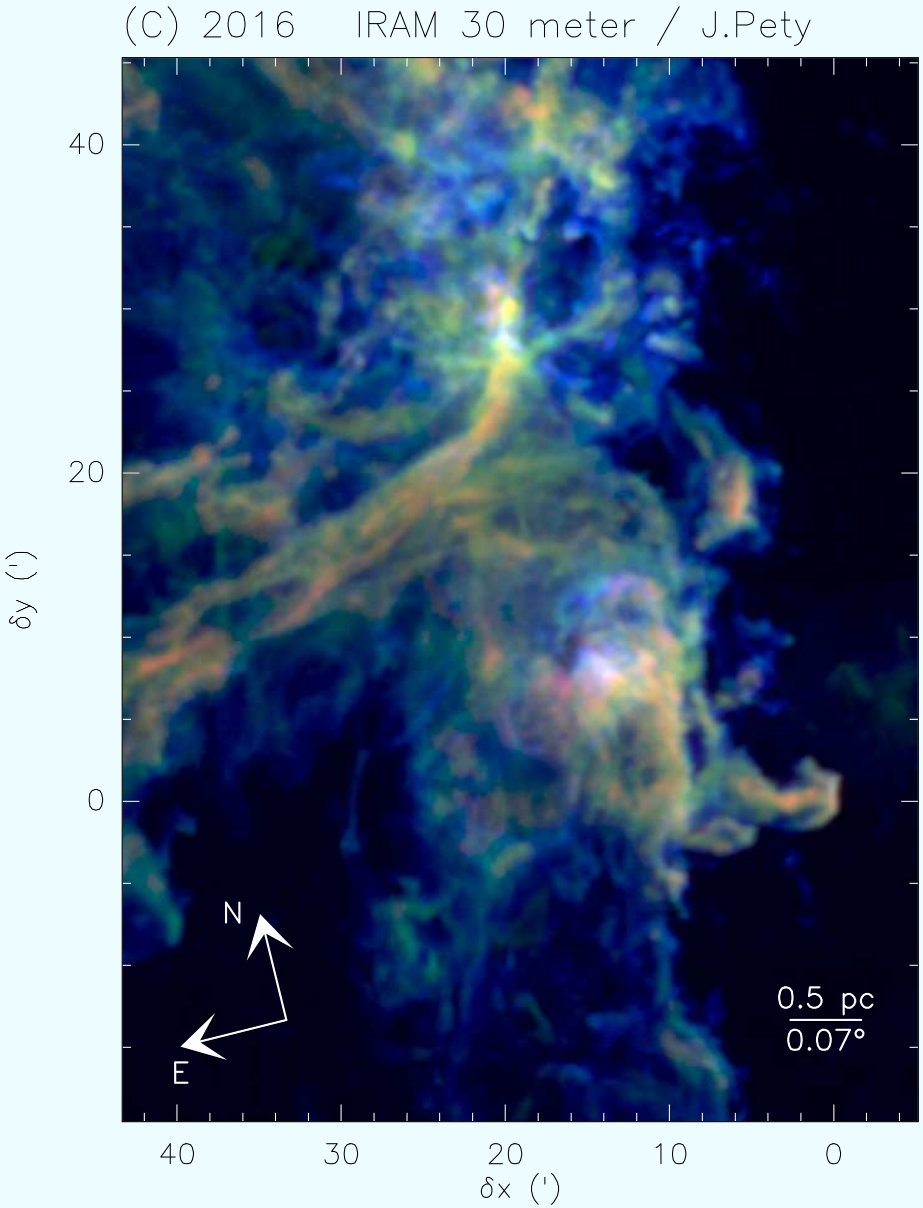
- **Alternative: CH_3^+**

  if highly endothermic route $C^+ + H_2 \rightarrow CH^+$ opened

  $CH^+ + H_2 \rightarrow CH_2^+ \rightarrow CH_3^+$

  ⇨ **only H_2 and C^+ needed**

^{13}CO(1-0) unbiased spectral survey of the Orion B Complex



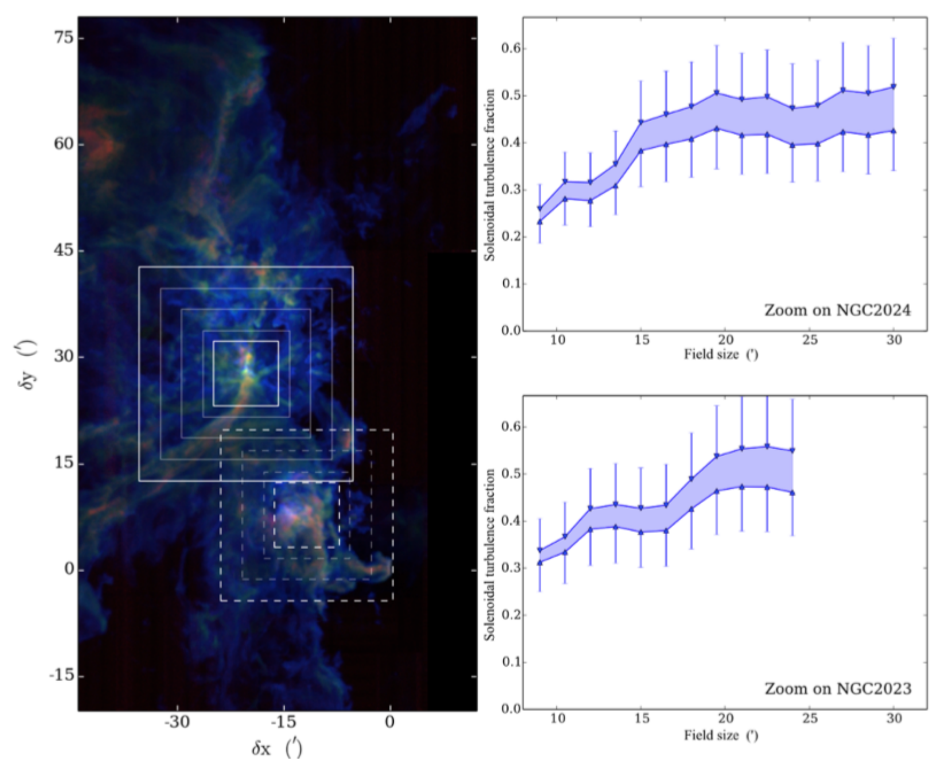
IRAM-30m
Cube: 370 × 650 pixel
Resolution: 9″ × 9″ × 0.5 km s^{-1}
1.5 degree^{2}

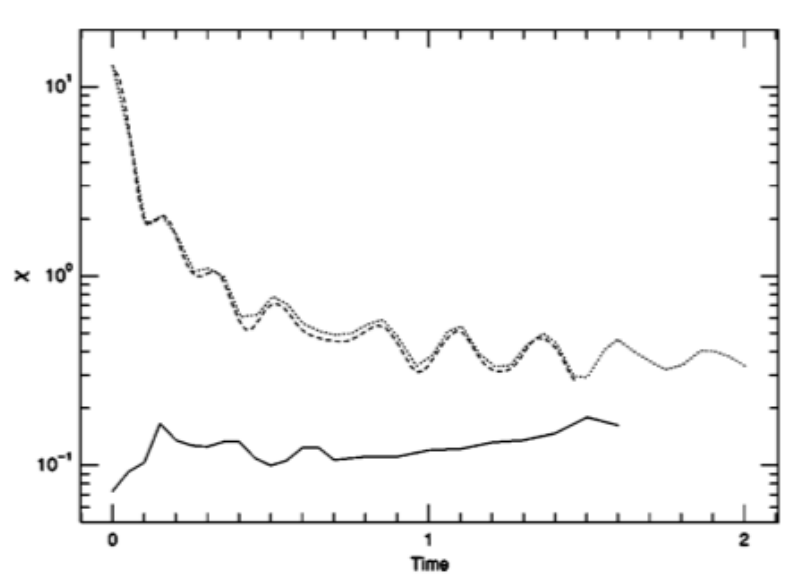
NGC 2024: HII region (O stars)
NGC 2023: reflection nebula (B stars)
IC 434: PDR (σOri), Hα emission, Horsehead

➪ Which turbulence modes prevail in different regions of the molecular cloud?
Solenoidal flow : dominated by rotation motions (vortices and eddies)
Compressive flow : creation of over-densities ⇒ self-gravity ⇒ star formation ⇒ expansion of HII regions

Pety et al. In prep.

Solenoidal fraction vs. compressive fraction





Method: Brunt & Federrath 2014

Solenoidal fraction for the full field:

$0.72 < R_{13CO} < 1$

➪ less than 28% of compressive motions ?

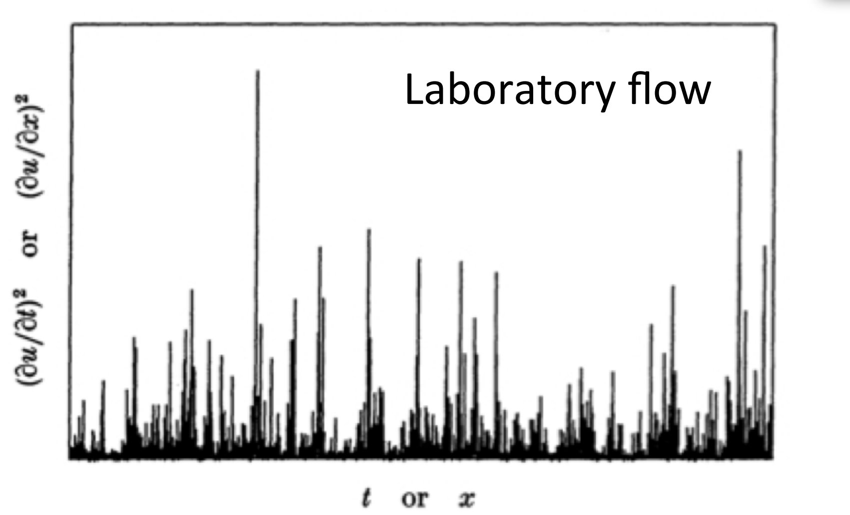
R'= fraction of compressive/solenoidal energy versus time in NS of compressible turbulence

Different initial conditions

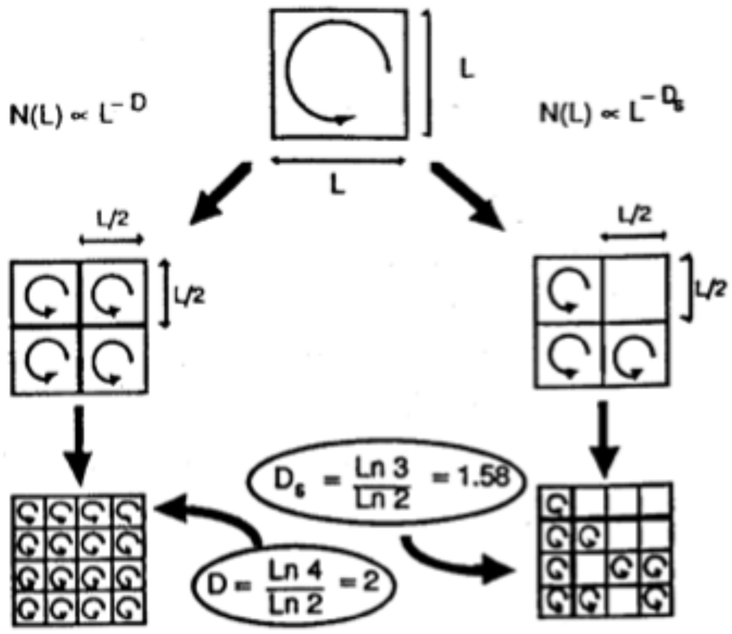
➪ convergence at R'=1/3

Porter Pouquet Woodward 2002

Energy transfer from scale to scale in turbulence is strongly intermittent in space and time

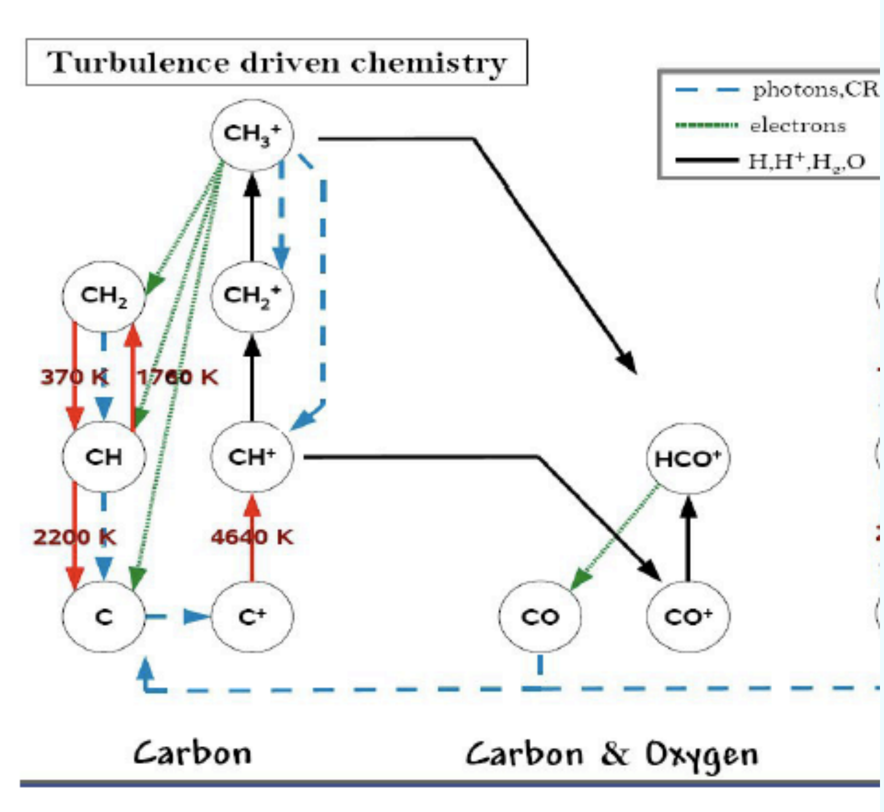


Méneveau & Sreenivasan (1991)



Anselmet et al. 2001

Turbulent dissipation : the promises of warm chemistry



- **PDR models : C^+**

  $C^+ + OH$ and $H_2O \rightarrow CO$

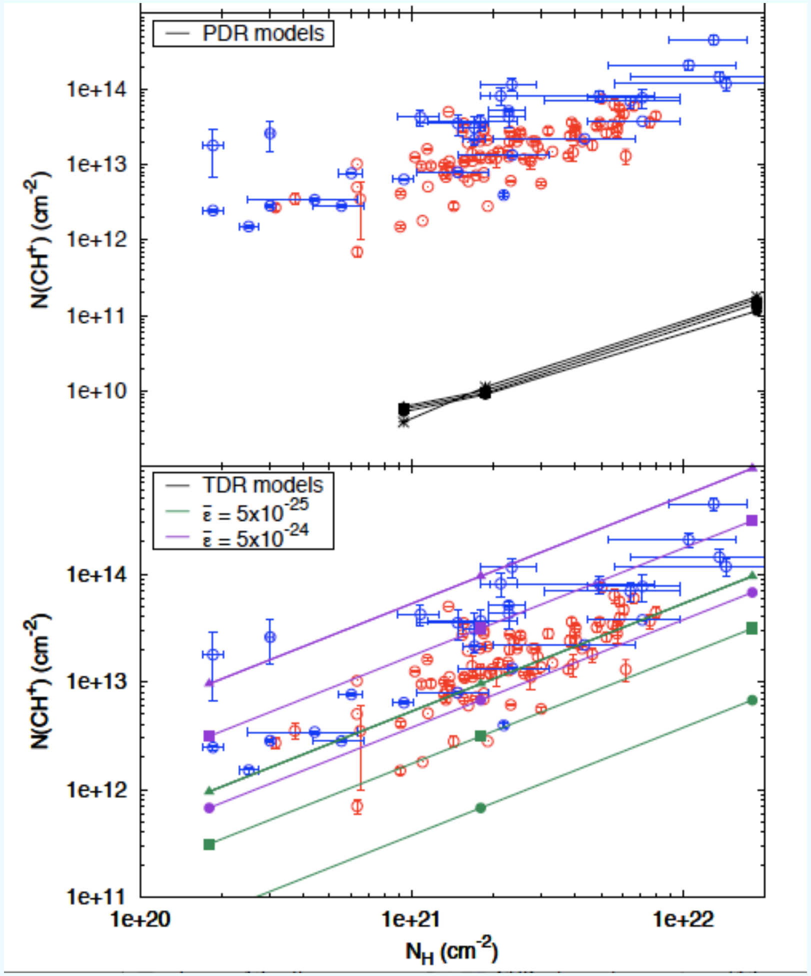
- **Alternative: CH_3^+**

  if highly endothermic route $C^+ + H_2 \rightarrow CH^+$ opened

  $CH^+ + H_2 \rightarrow CH_2^+ \rightarrow CH_3^+$

  ⇨ **warm chemistry fed by intermittent turbulent dissipation**

Models of Turbulent Dissipation Regions in diffuse gas



TDR models for n_H= 30, 50, 100 cm^{-3}

- $N(\mathrm{CH}^+)$ increases with UV-field
  - $N(\mathrm{CH}^+)$ proportional to **turbulent injection rate**

- **Direct measure of the energy flux:**

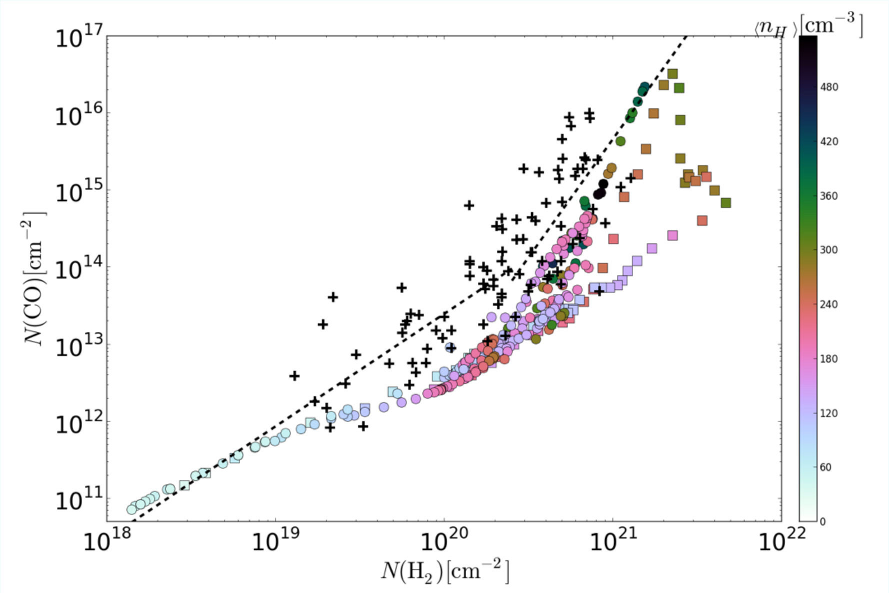
$$\dot{E} = N(\mathrm{CH}^+) E_{form}/t$$

Warm chemistry driven by ion-neutral friction

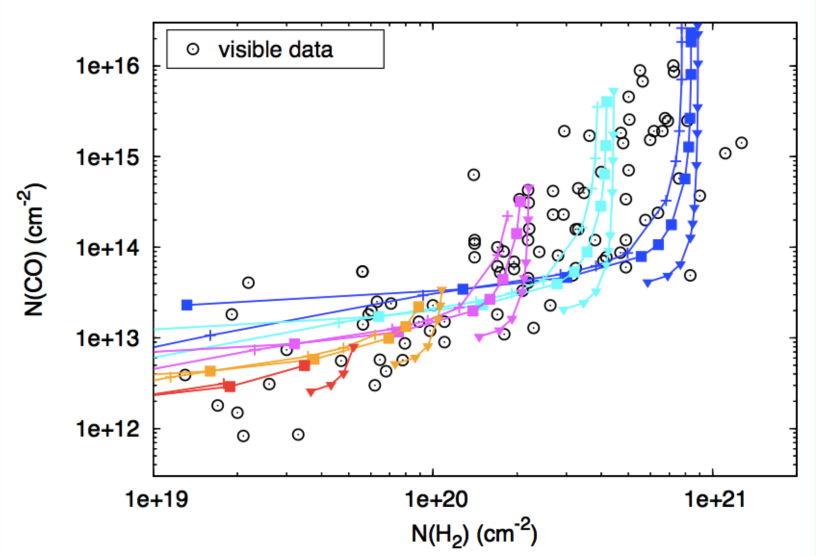
Godard et al. 2014

Turbulent dissipation in difuse gas: CO formation

CO : visible data (absorption lines against nearby stars)
Sheffer + 08, Pan + 05, Rachford + 09, Snow + 08



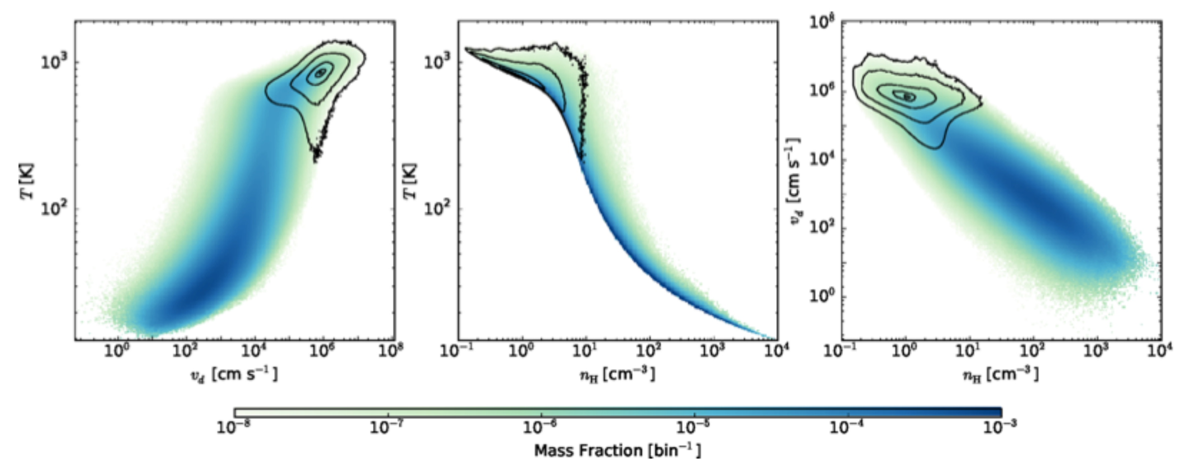
Post-treatment:
PDR models in MHD colliding
flow simulations
Levrier + 2012



Turbulent dissipation regions:
model predictions for low densities
Godard + 2014

Alternative approaches

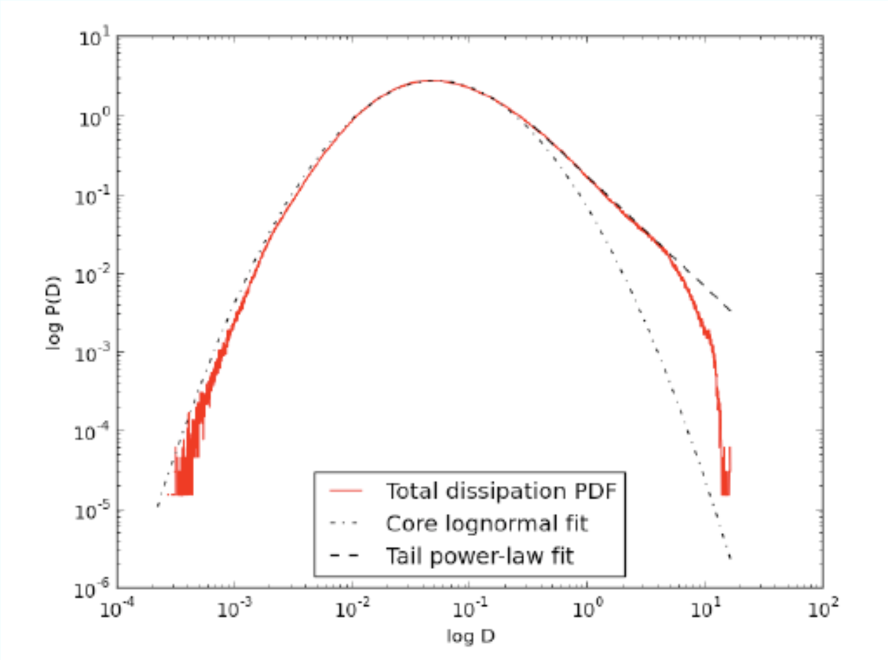
- Low velocity C-shocks Draine & Katz 1986
- Irradiated low-velocity C-shocks Lesaffre + 2013
- Alfvén waves Federman + 1996
- Turbulent mixing CNM /WNM, non-steady state H_2 abundances Valdivia + 2016, in prep.
- MHD turbulence in diffuse gas Myers + 2015

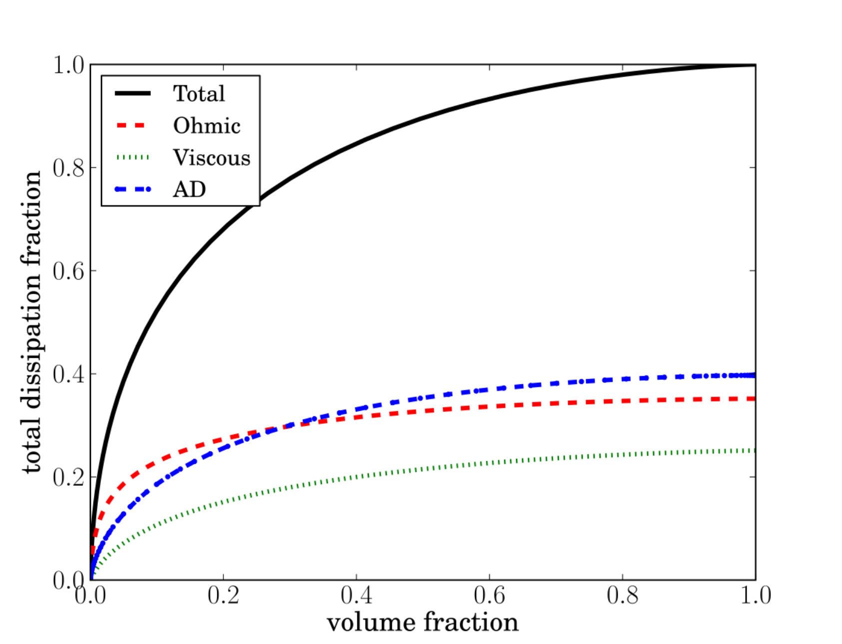


MHD simulations, post-treatment of chemistry, steady-state H_2 abundances

Dissipation of non-ideal MHD turbulence : dedicated numerical simulations

Non-ideal incompressible MHD turbulence





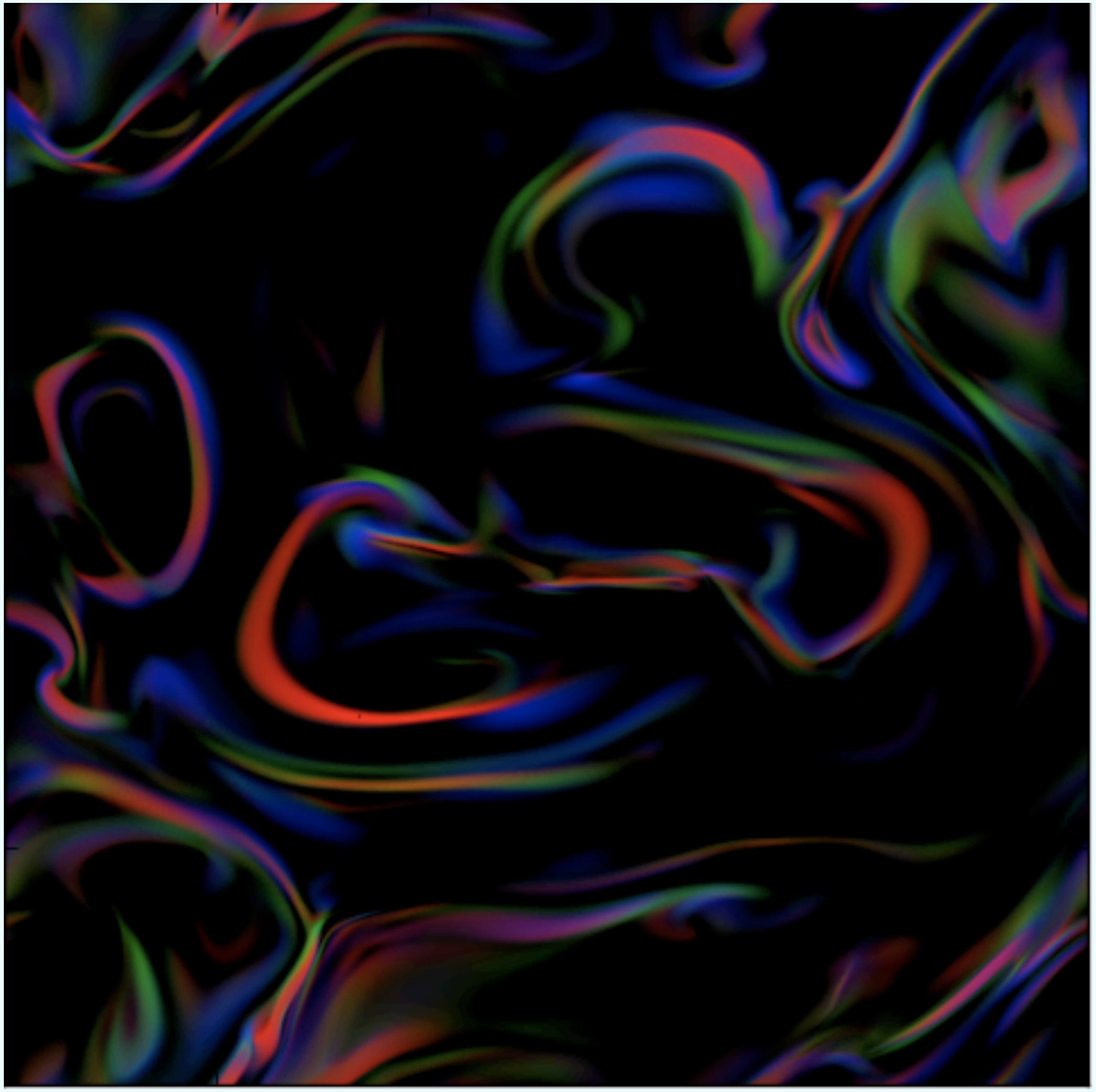
Ohmic dissipation: $D_{ohm} = \eta j^2$, j=curl B
Viscous dissipation: $D_{visc} = \nu\omega^2$
Dissipation by ion-neutral friction:
$D_{AD} = \alpha(j \times B)^2$

➪ Half of the total dissipation is concentrated in 10% of the volume

➪ Ohmic, AD and viscous have comparable contributions to total dissipation

512^3 Spectral NS, decaying, different initial conditions Momferratos et al. 2014

Extrema of dissipation



Slice

Ohmic dissipation:

$D_{ohm} = \eta j^2$

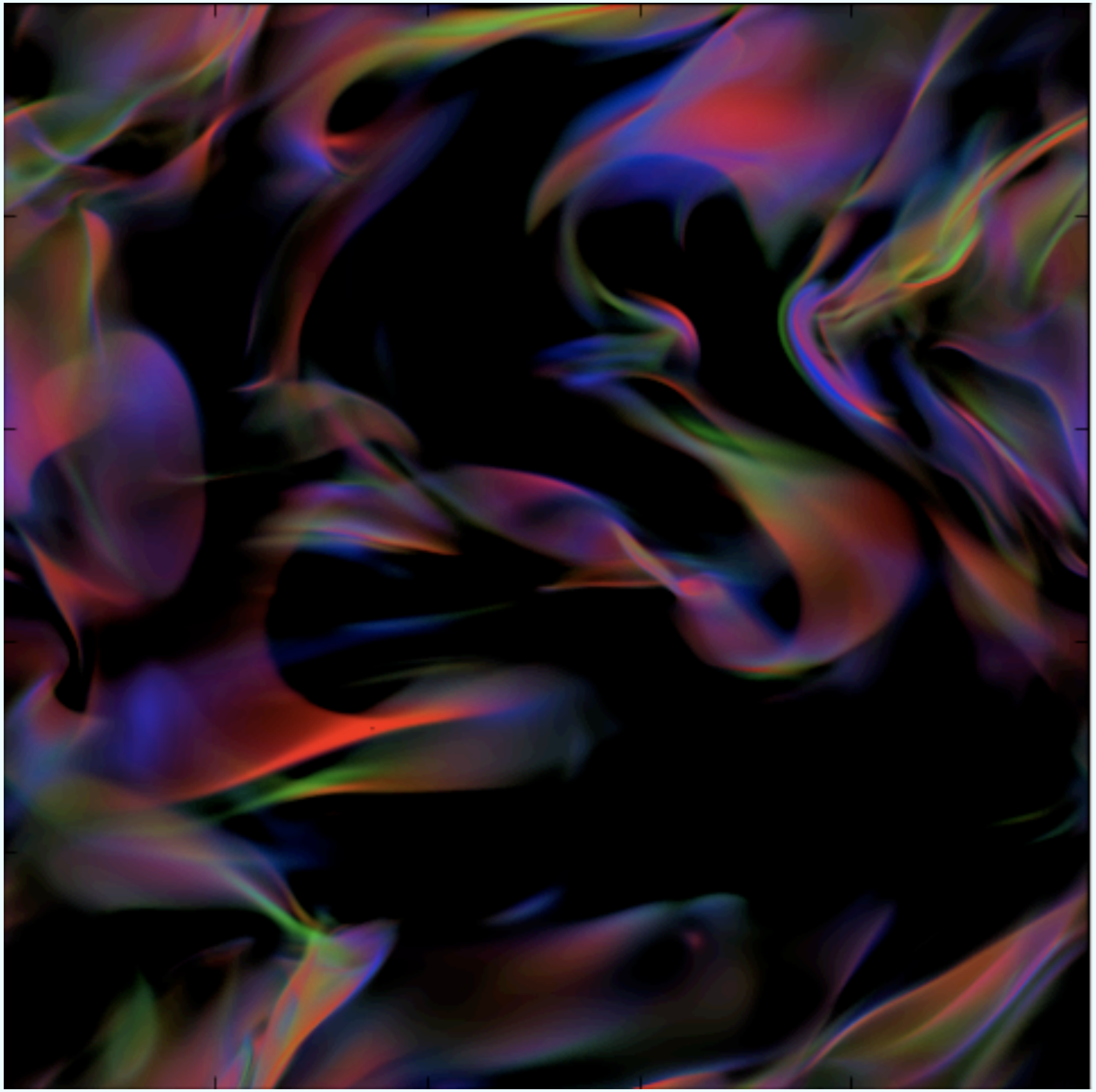
Viscous dissipation:

$D_{visc} = \nu\omega^2$

Dissipation by ion-neutral friction:

$D_{AD} = \alpha(j \times B)^2$

- ➪ AD produces force-free field at small scales
- ➪ AD dissipation regions larger



Extrema of dissipation

Ohmic dissipation:

$D_{ohm} = \eta\, j^2$

Viscous dissipation:

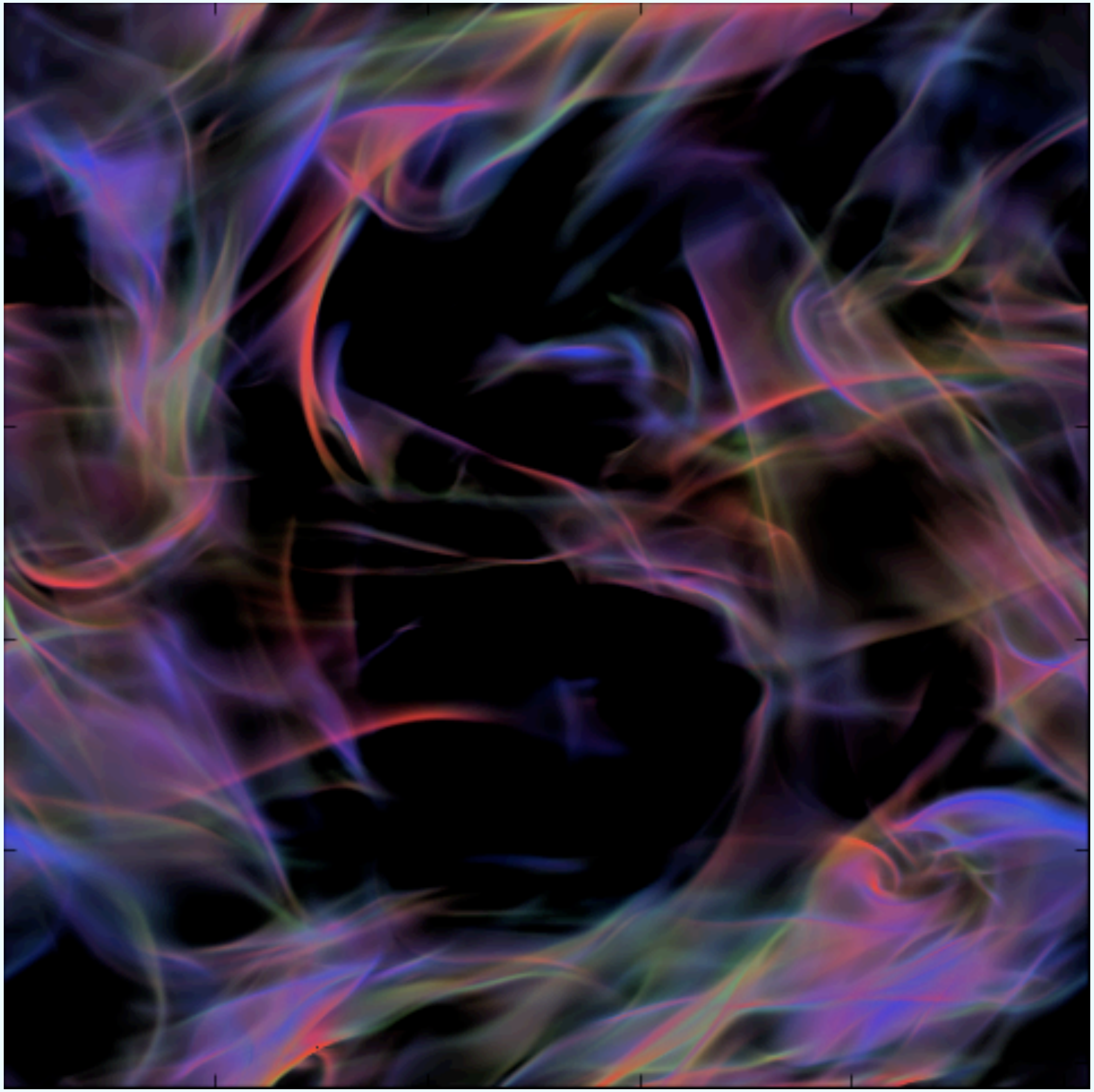
$D_{visc} = \nu\omega^2$

Dissipation by
 ion-neutral friction:

$D_{AD} = \alpha(j\times B)^2$

$L_{box}/8$

Extrema of dissipation



Full box

Ohmic dissipation:

$D_{ohm} = \eta\, j^2$

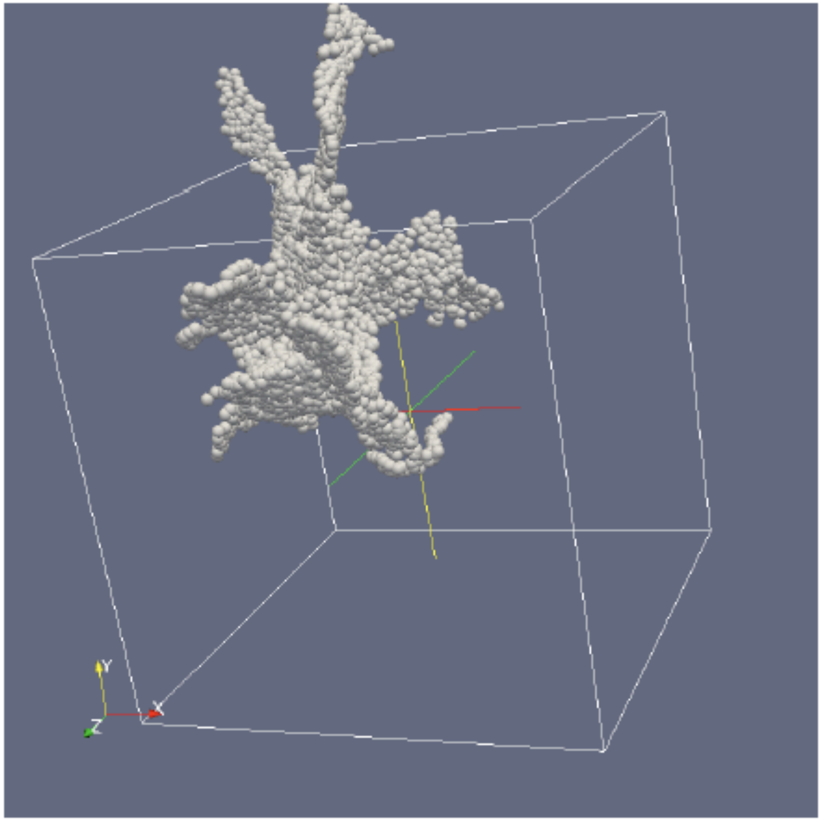
Viscous dissipation:

$D_{visc} = \nu\omega^2$

Dissipation by ion-neutral friction:

$D_{AD} = \alpha(j\times B)^2$

Extraction of structures of dissipation rate extremum



Momferratos et al. 2014

Connected sets of points with total dissipation rate 3σ above mean value

Fractal dimension $X_i \propto L_i^{D_X}$

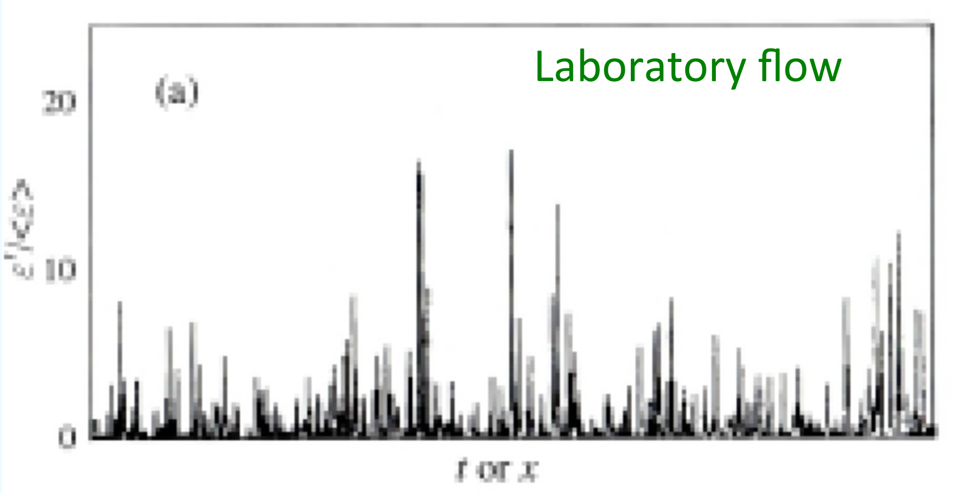
Scaling of the probability distribution functions

$$\mathcal{P}(X_i) \propto X_i^{-\tau_X}$$

⇨ sheet like geometry

Confrontation to observables

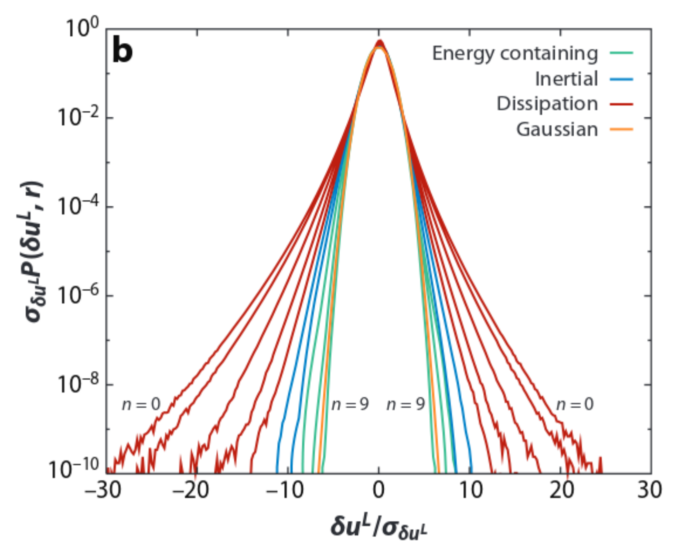
Signatures of turbulent intermittency



Laboratory flow

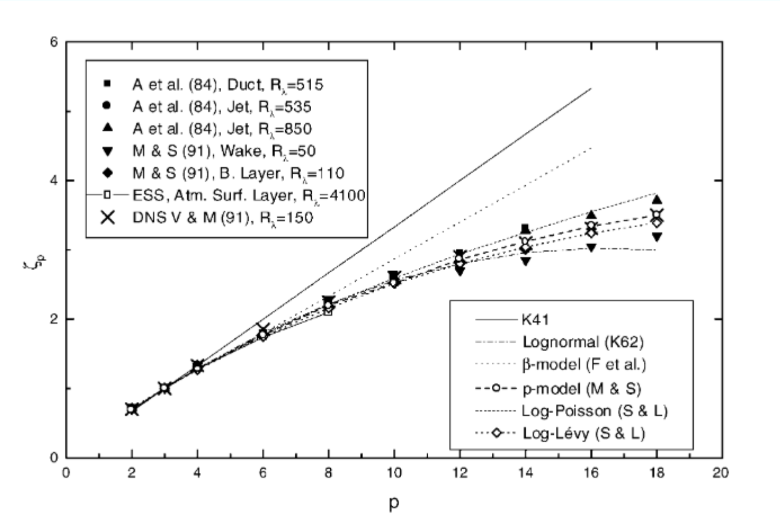
Méneveau & Sreenivasan (1991)

- Dissipation bursts



- Non-Gaussian PDF of velocity increments

She 1991, Ishihara + 09



- Anomalous scaling of high order structure functions

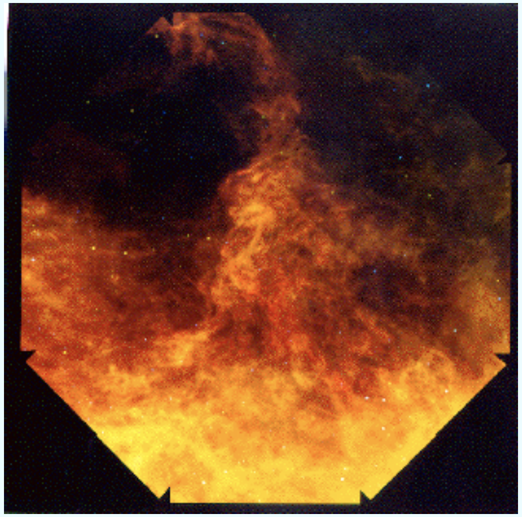
Polaris Flare

➪ highly turbulent,

➪ only two (prestellar?) dense cores

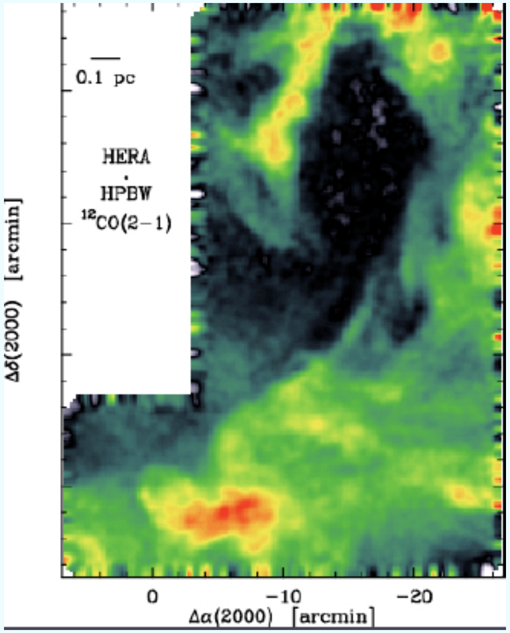
Heithausen et al. 2002

Ideal template to study early phases of star formation



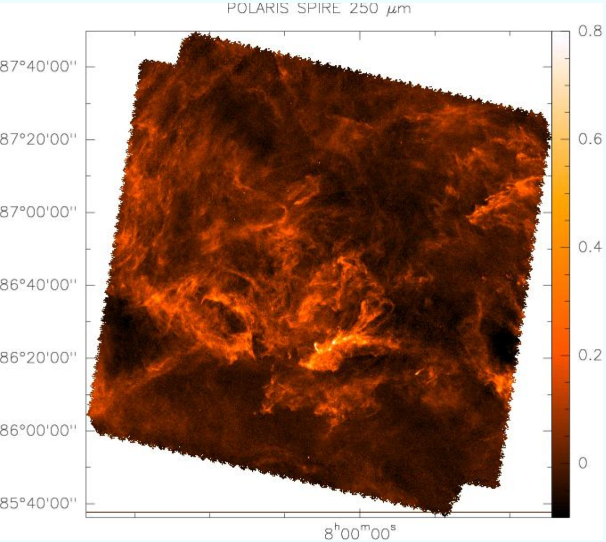
100 pc to 0.2 pc

IRAS 100µm



2 pc to 7 mpc,

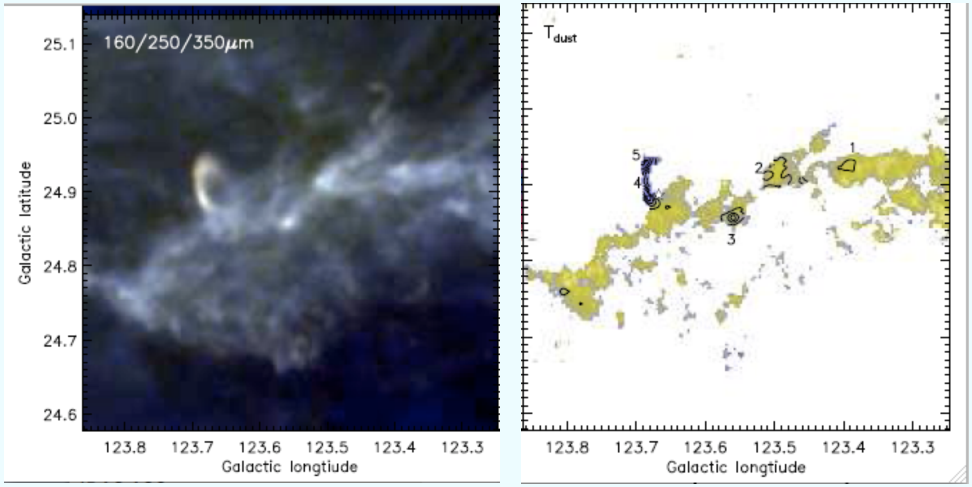
IRAM ^{12}CO(2-1) Hily-Blant et al. 2008



5pc to 0.01 pc

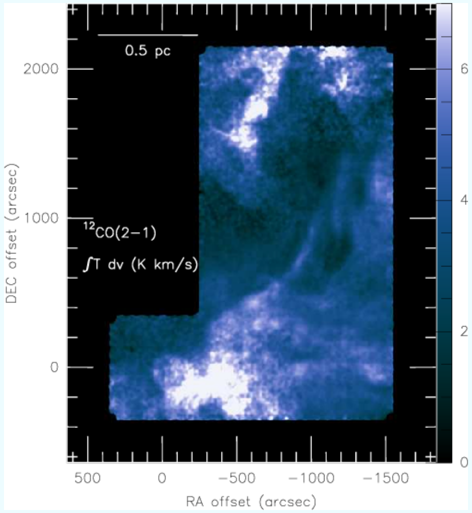
Herschel/SPIRE 250 µm

Men'shchikov et al 2010



Ward-Thomson et al. 2010

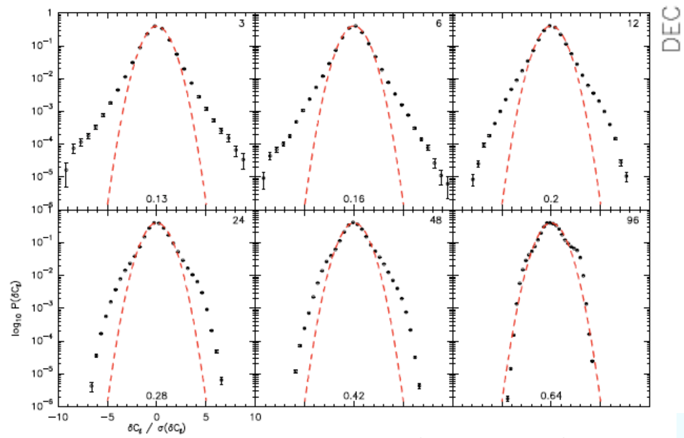
Non-Gaussian statistics of velocity increments



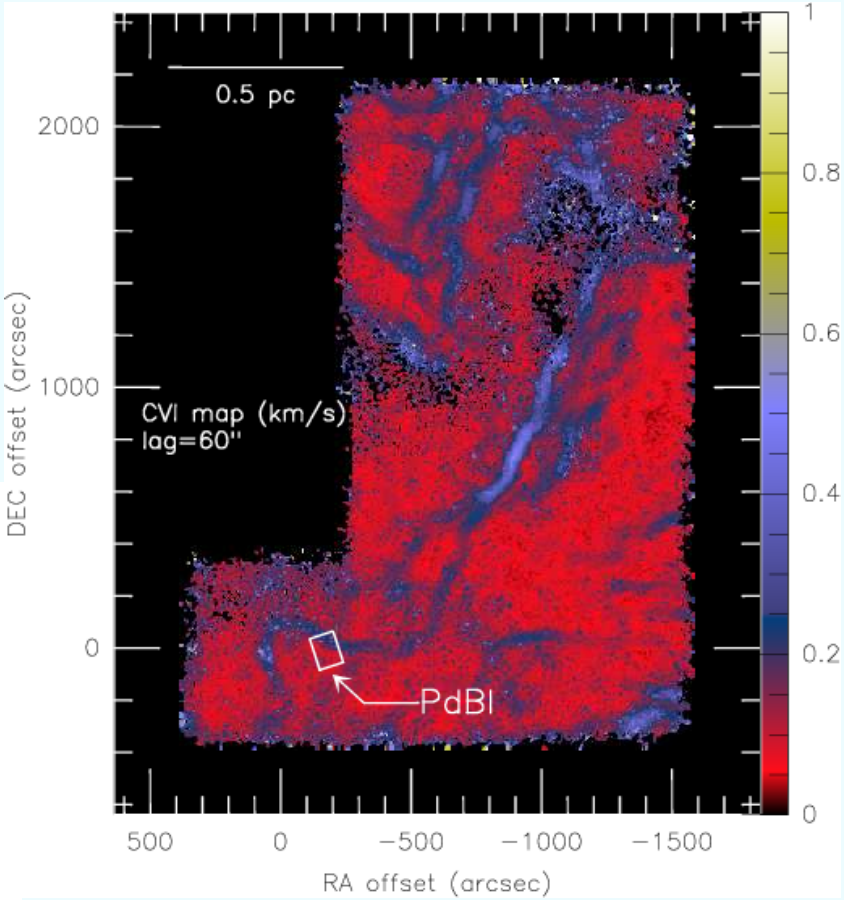
IRAM-30m ^{12}CO(2-1)

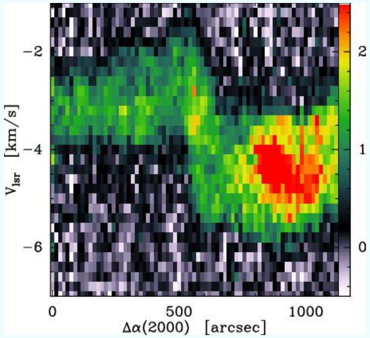
A few 10^5 independent spectra

smallest lags …



… largest lags



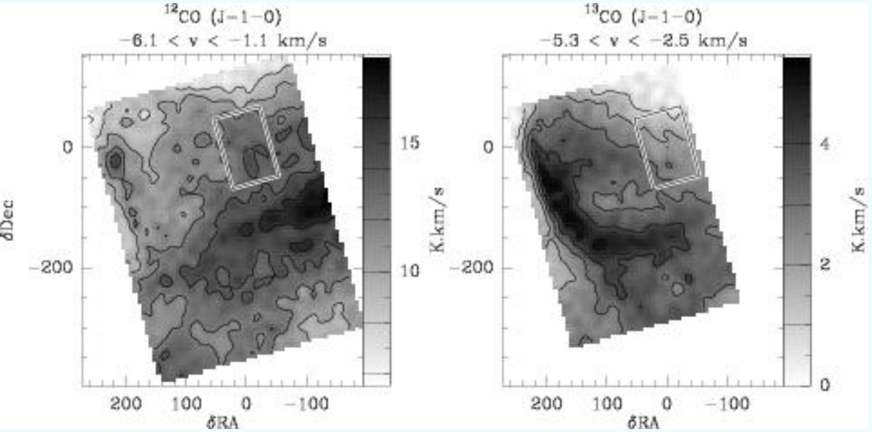


Velocity-shear

40 km s^{-1} pc^{-1}

⇨ pc-scale coherent structures of velocity-shear

^{12}CO emission structures ~ 10 mpc thin

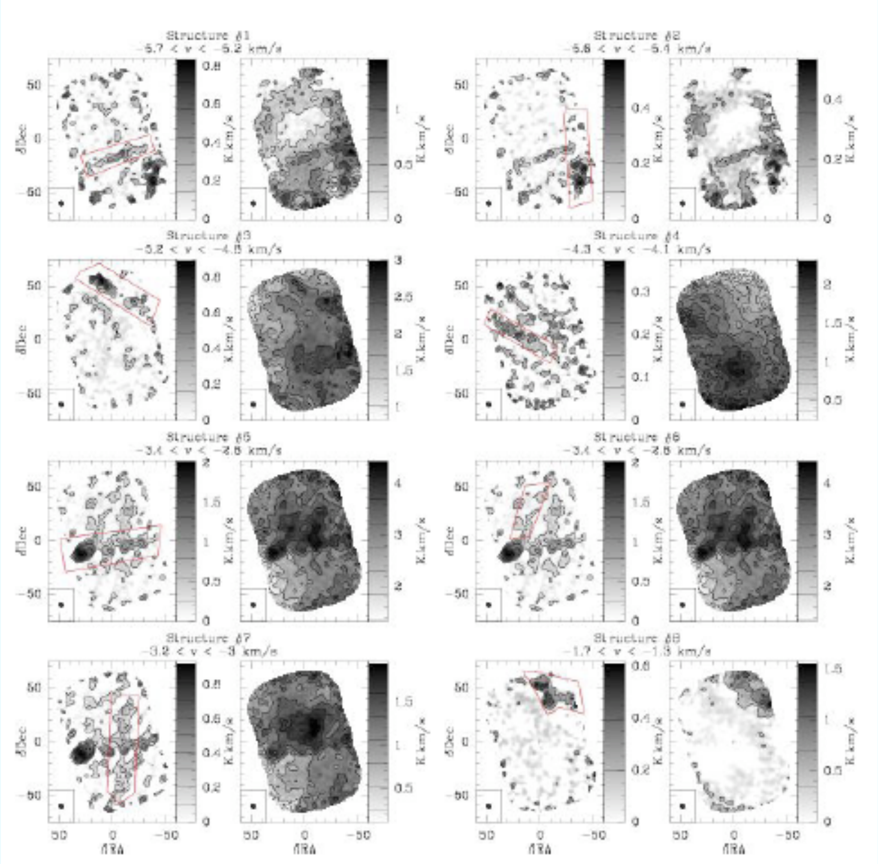


Polaris Flare

IRAM-Pdbi mosaic print

(13 fields)

See field location in previous slide



Left: PdBI-only, *Right:* PdBI + IRAM-30m short spacings

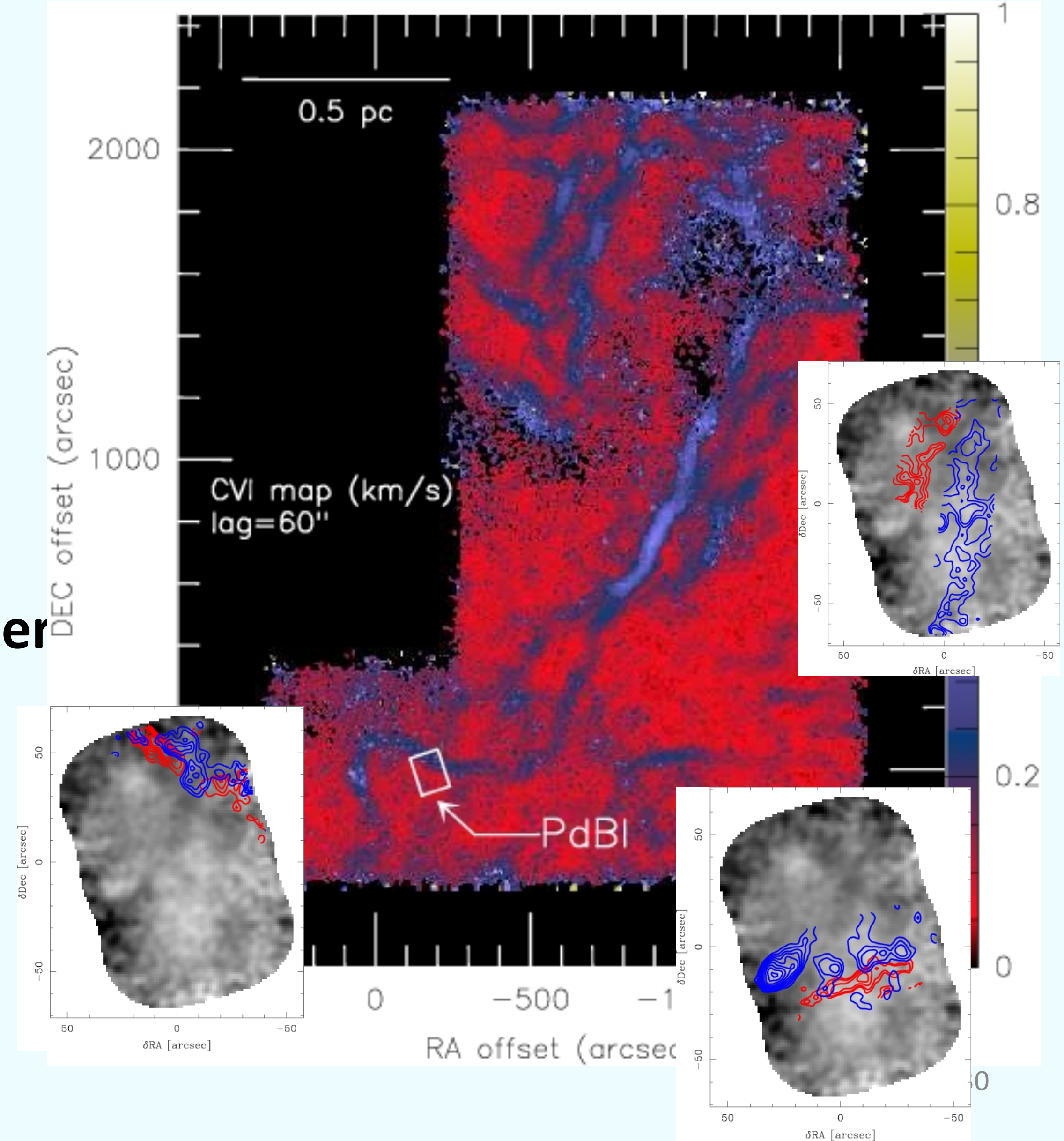
Falgarone + 2009

⇨ no cut-off in dust power spectrum down to 0.01 pc

See also Miville-Deschênes + 2016

Velocity-shears at pc- and mpc-scale

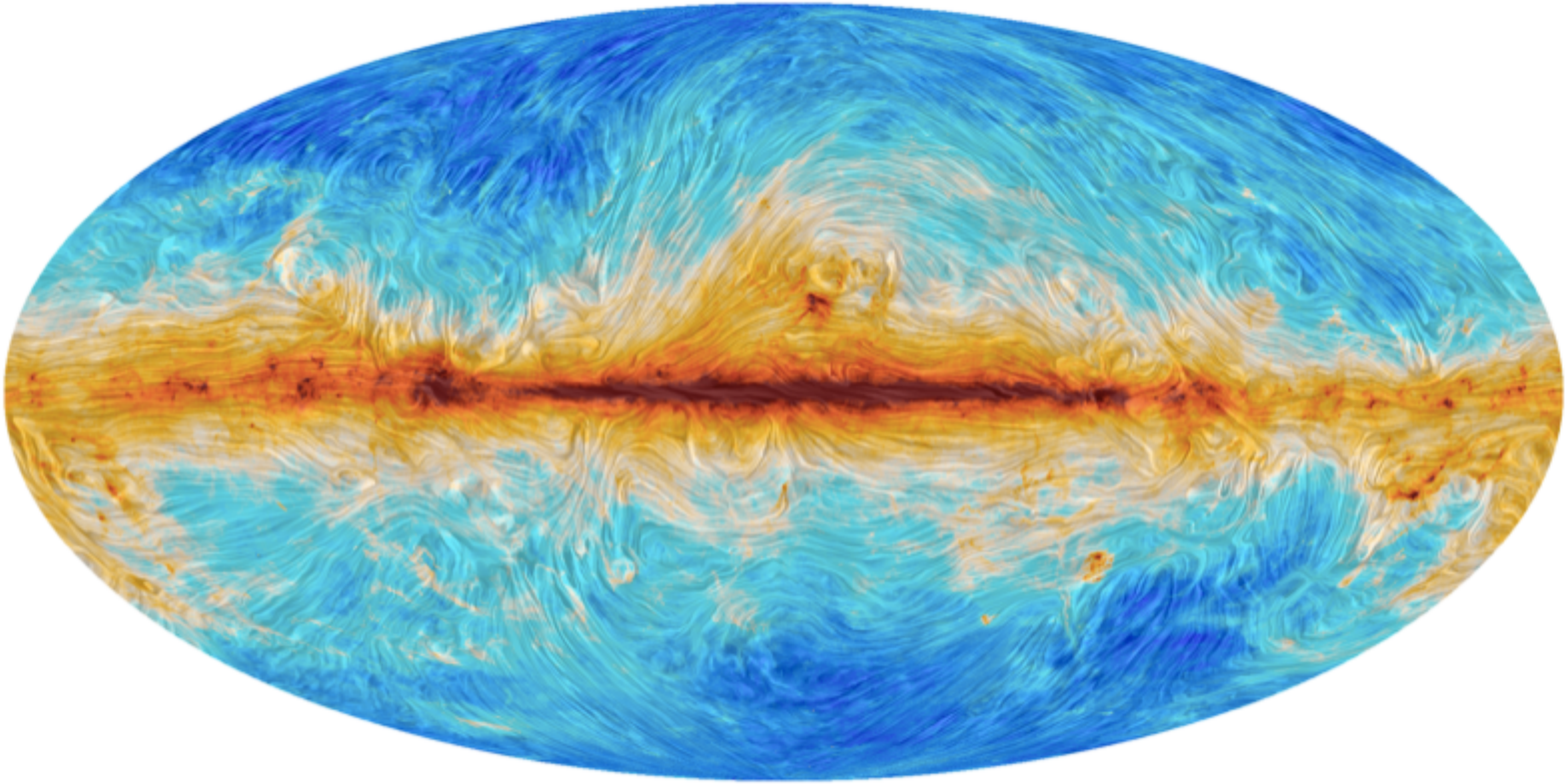
- 8 **straight** CO structures 3 to 10 mpc thick
- **sharp edges of layers**
- 6 are parallel pairs at different velocities = **velocity-shears** up to 700 km s^{-1} pc^{-1}
- **large (and similar) scatter of orientations found for mpc- and pc-scale shears**



Complex topology

IRAM-PdBI, Falgarone et al. 2009

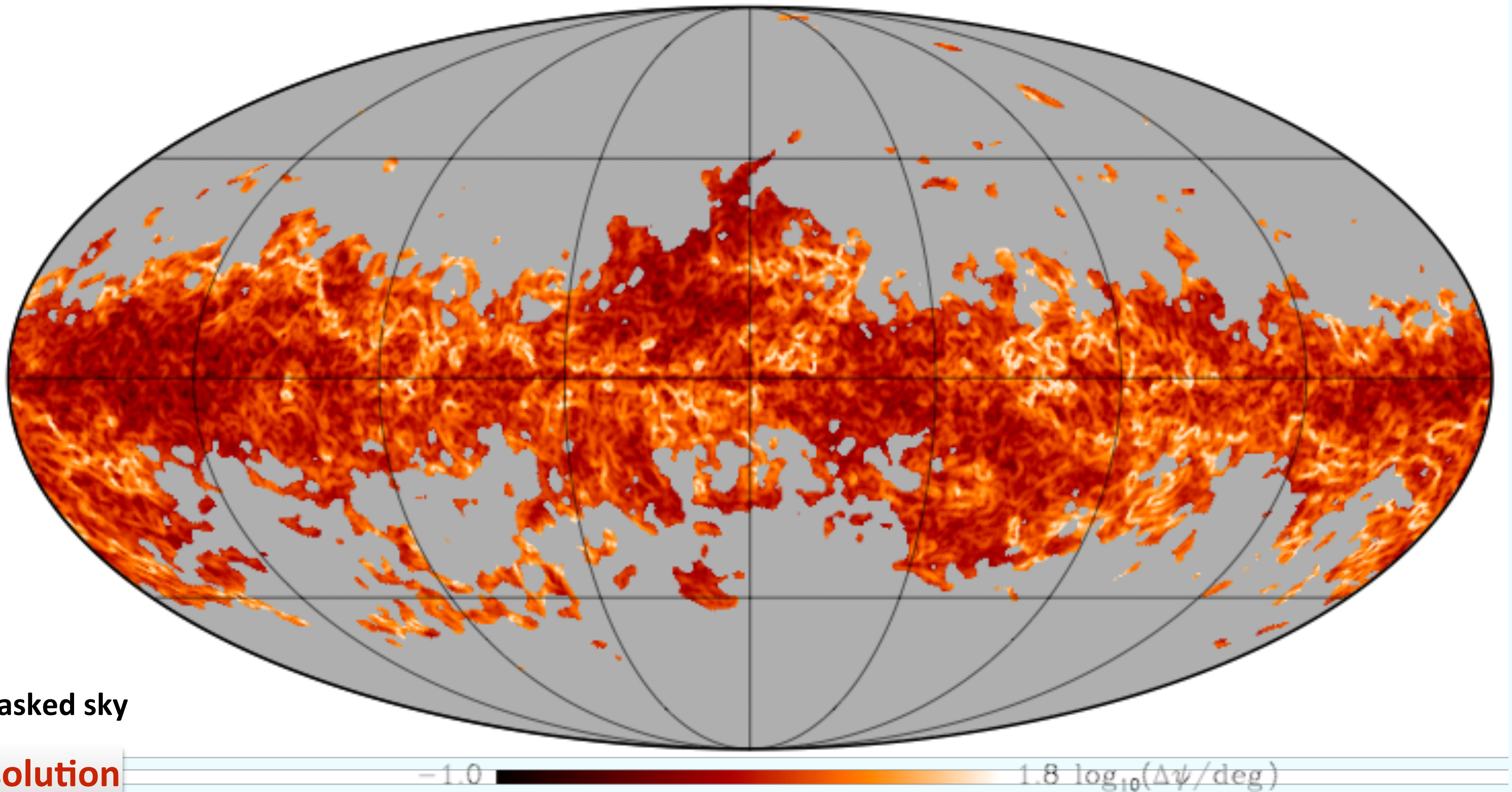
Planck all sky 353 GHz



Color scale : 353 GHz intensity
Drapery : B-field POS projection

Planck intermediate results XIX, 2014

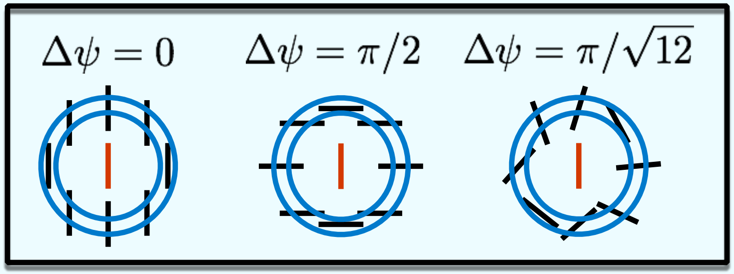
Polarization angle dispersion



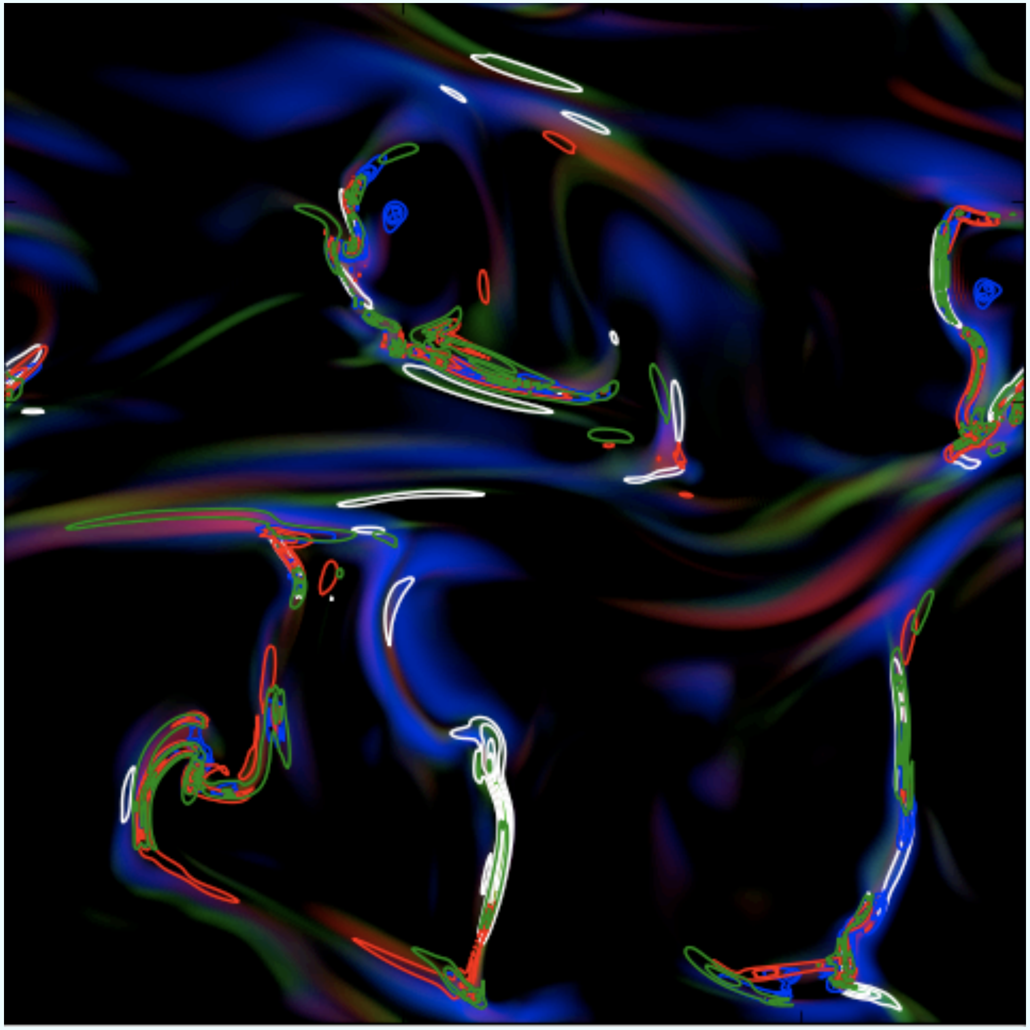
Whole masked sky

1° resolution
30’ lag

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



Planck intermediate results. XIX. 2014



$L_{box}/64$

Comparison to observables

- Dissipation rates

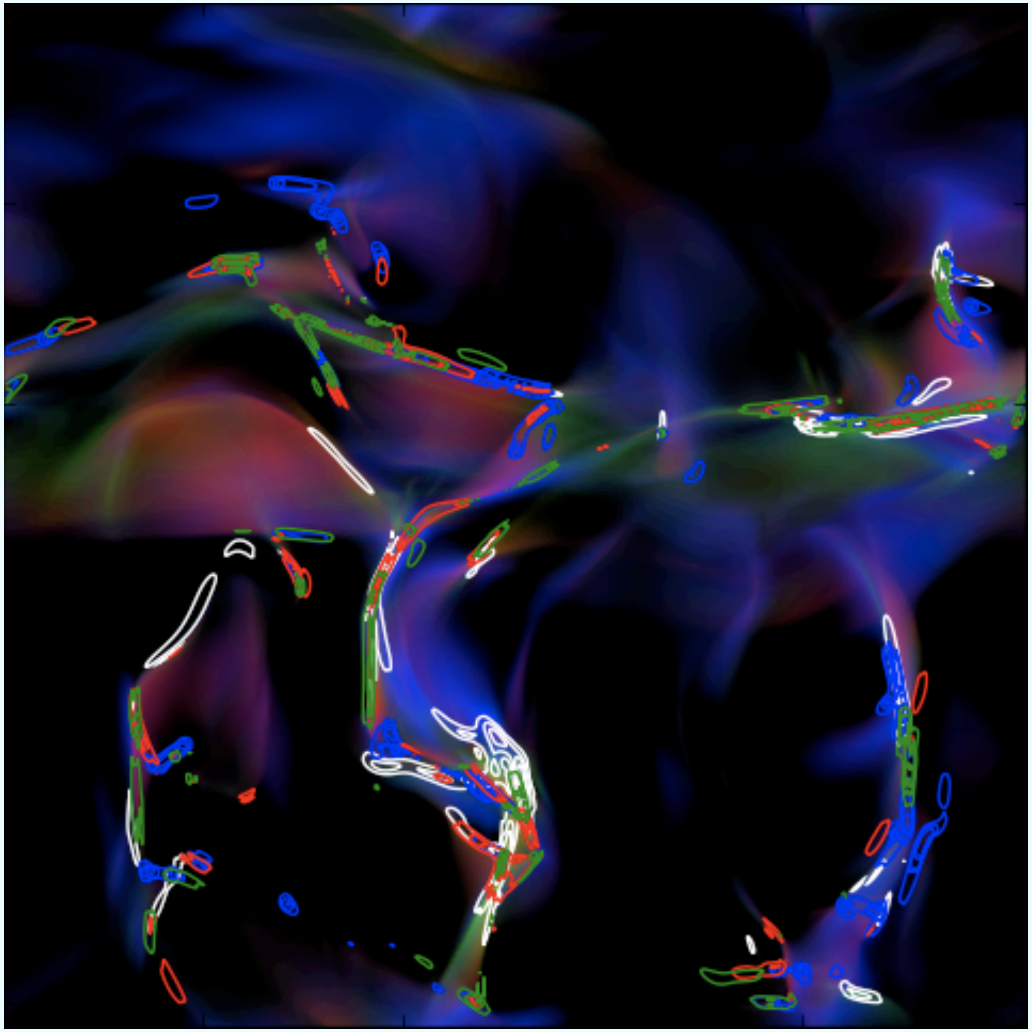
Ohmique Viscous AD

- Observables

= Increments of integrated:

- LOS velocity (white)
- Stokes Q (green)
- Stokes U (red)
- POS magnetic field direction (blue)

Comparison to observables



$L_{box}/8$

- Dissipation rates

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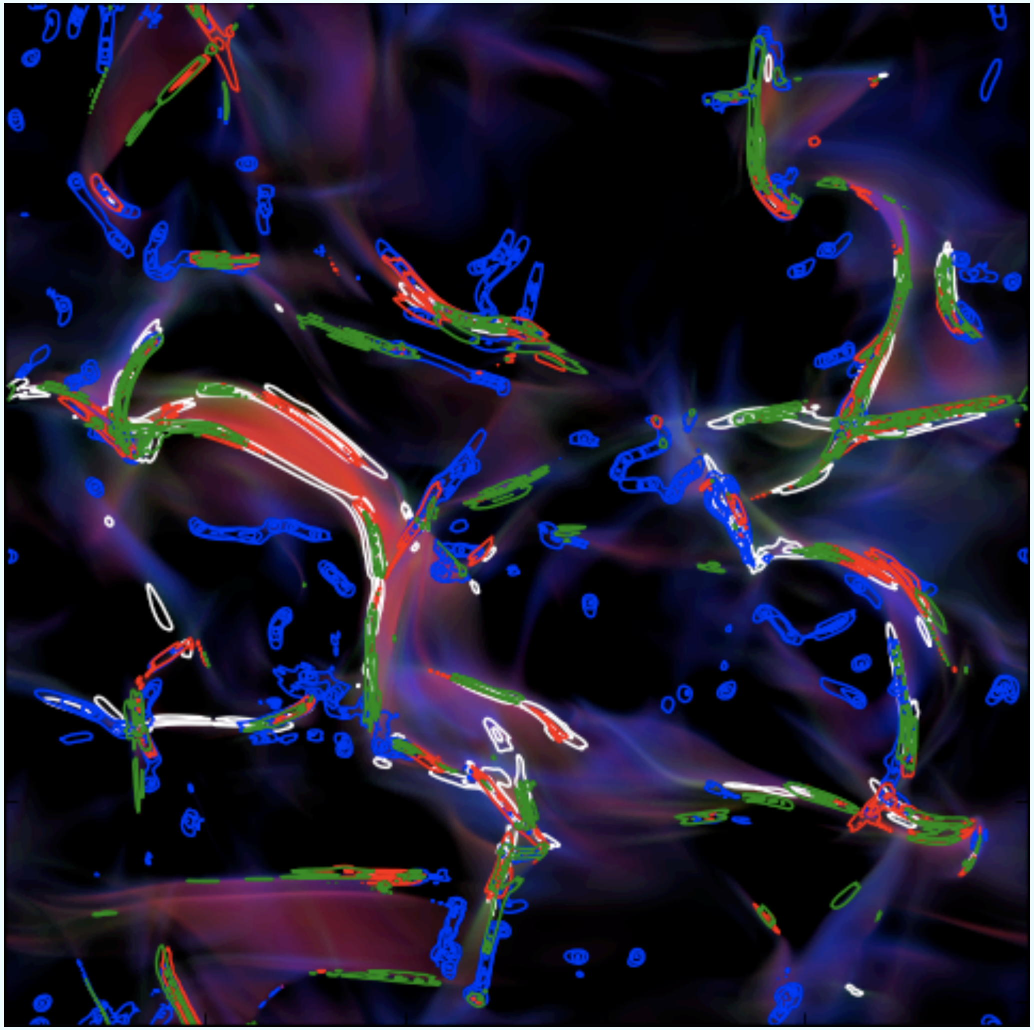
Comparison to observables



$L_{box}/2$

- Dissipation rates

Ohmique Viscous AD

- Observables

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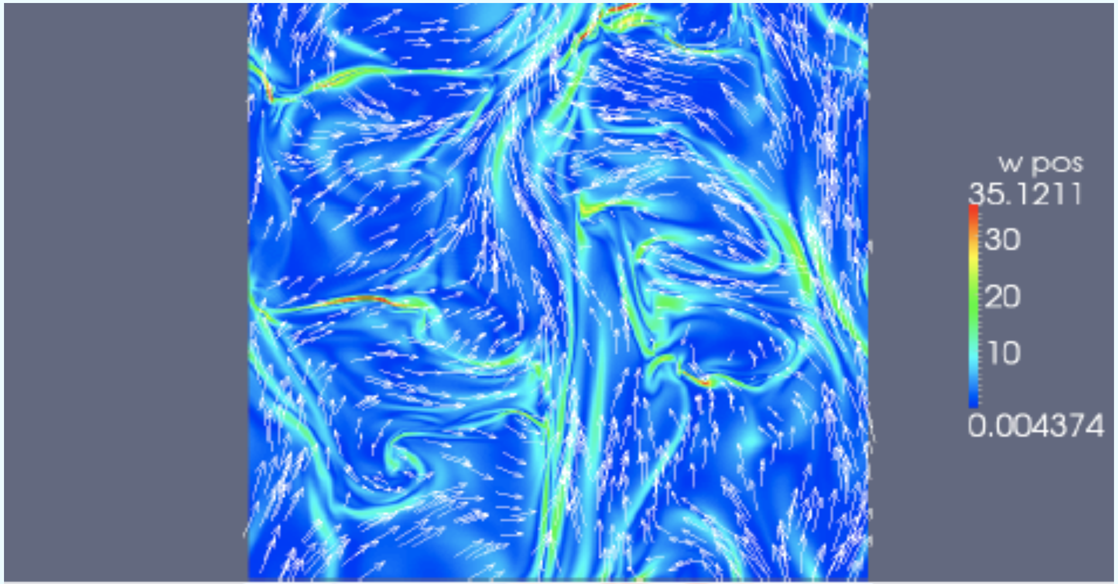
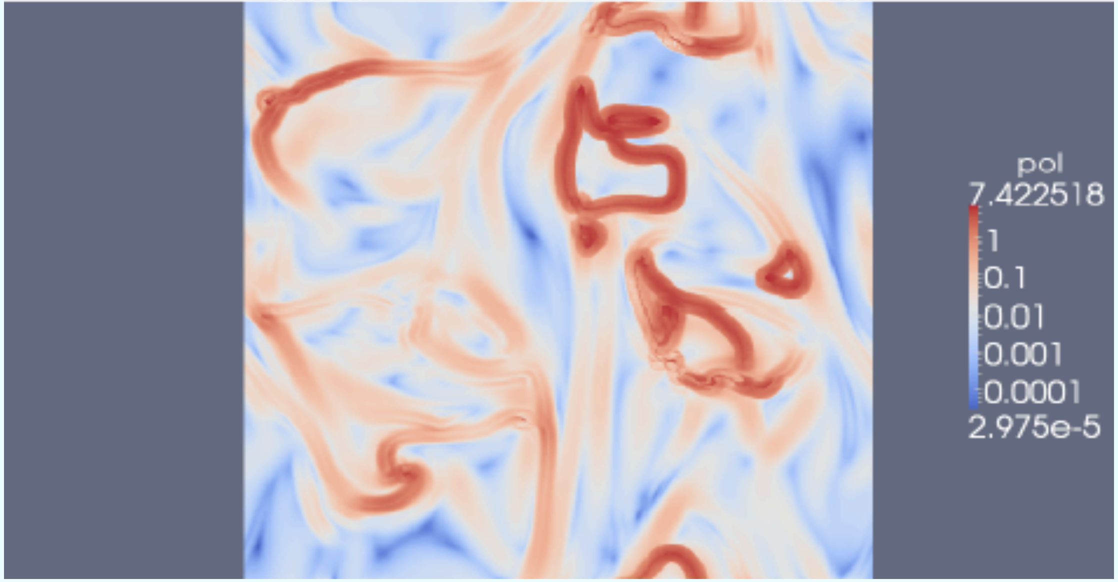
- Stokes U (red)
- POS magnetic field direction (blue)

Comparisons with B_{POS}

Plane-of-the-sky projections of vorticity and magnetic field

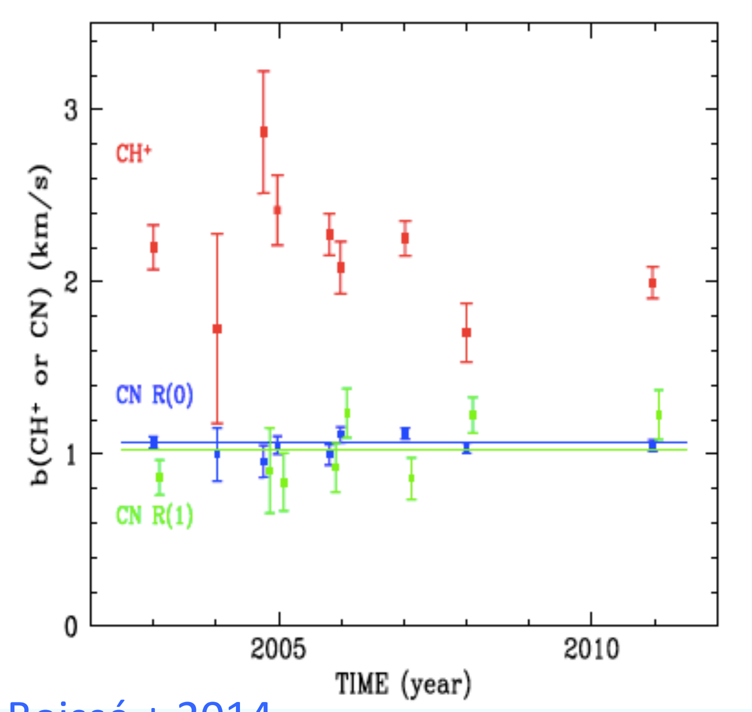


Increments of polarization orientation



Falgarone + 2015

Tiny Scale Atomic Structure



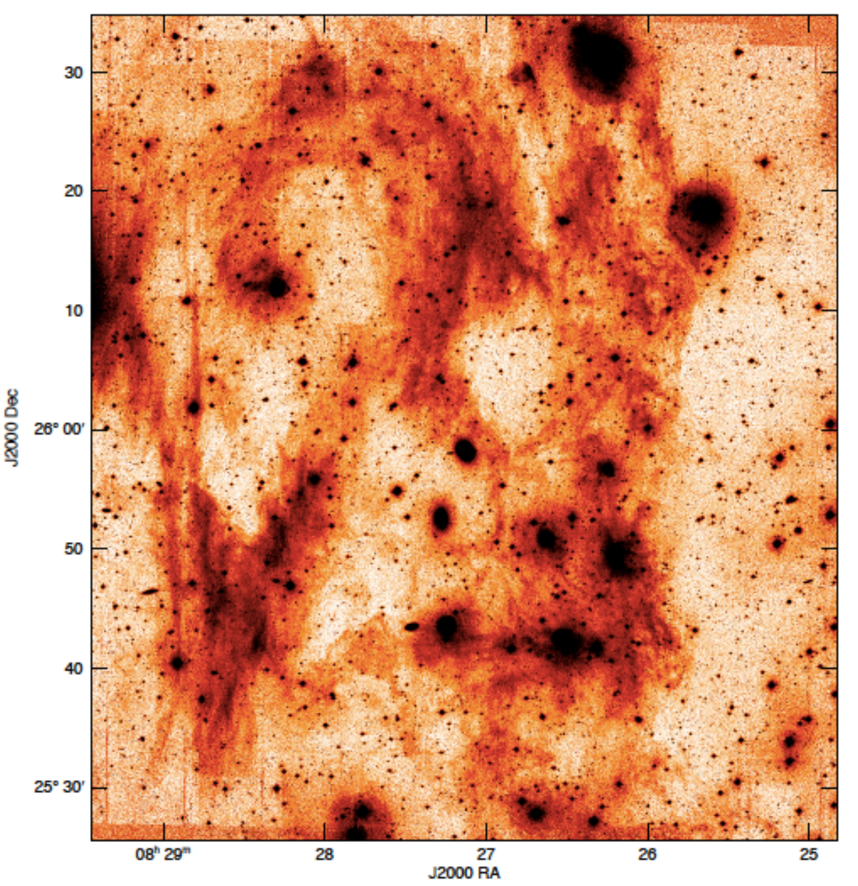
Boissé + 2014

Time variations of molecular absorption lines towards Zeta Per using proper motion
⇨ 1 -20 AU scales sampled

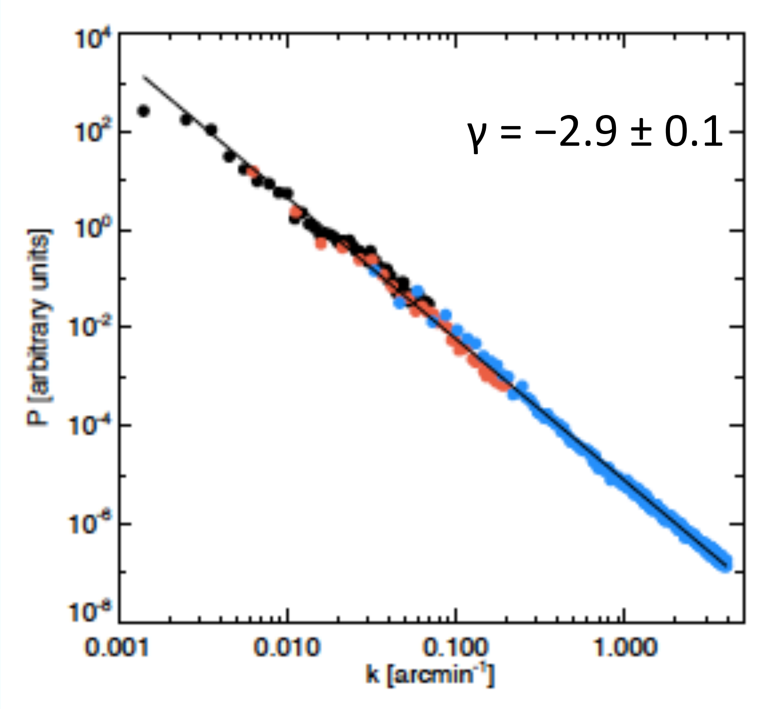
11% variations of CH$^+$ due to variations in linewidth
<6% variations for CH and CN

Validity of the fluid approximation ?
Hall MHD: kinetic effects, ion-electron decoupling, different coherent structures of current and vorticity
Stawarz and Pouquet 2015

Probing interstellar turbulence in cirrus with deep optical imaging: no sign of energy dissipation at 0.01 pc scale



Dust scattered visible light (CFHT)



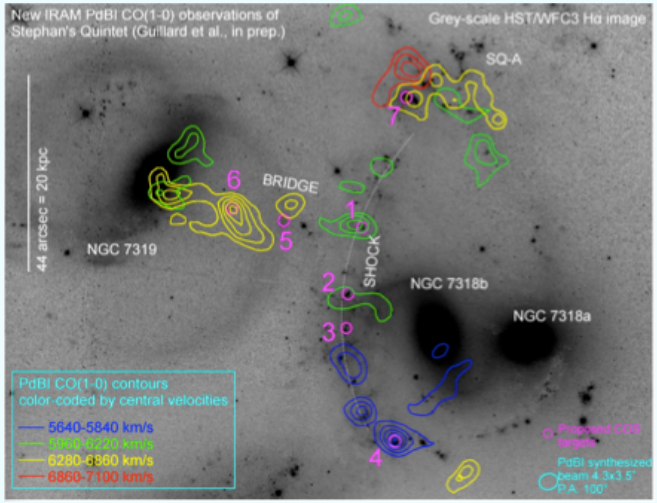
Density power spectrum: Combination of visible, Planck and WISE 12 μm data

Miville-Deschênes et al. 2016

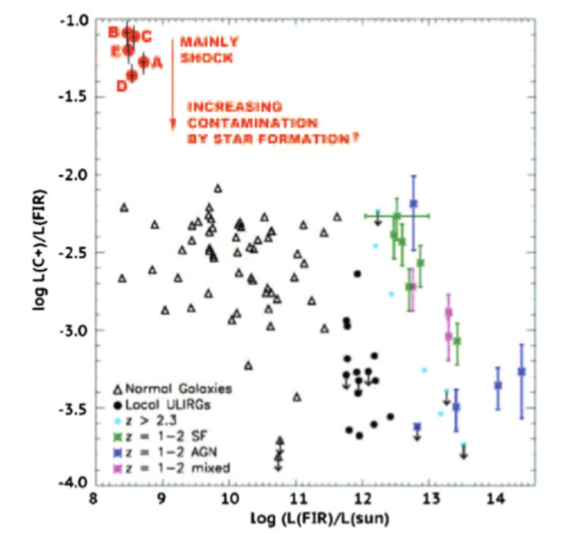
Energy cascade in mutliphase medium

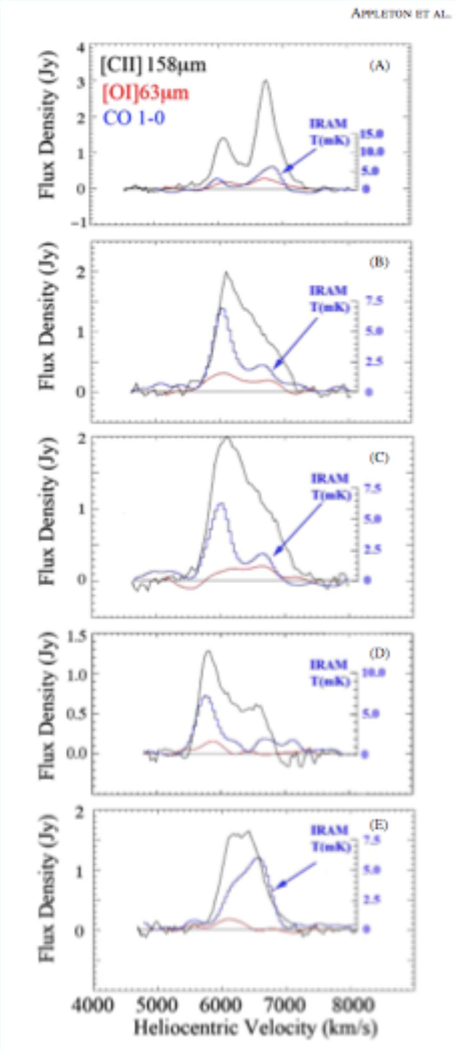
30 kpc-long shock in
Stephan's Quintet
Collision velocity
500-700 km/s

$L_X < L_{H2,\ \mathrm{rotation}}$



Cluver + 2010, Guillard + 2012





Appleton + 2013

In summary, challenges for SOFIA

Let’s learn how to follow the supra-thermal energy trail through all the ISM phases down to dissipation, with:

- Specific molecules (SH^+, redshifted CH^+ …)
- [CII] (and high-J CO) excitation, line profiles, absorption
- Pure rotational lines of H_2

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