The role of shocks in the InterStellar Medium

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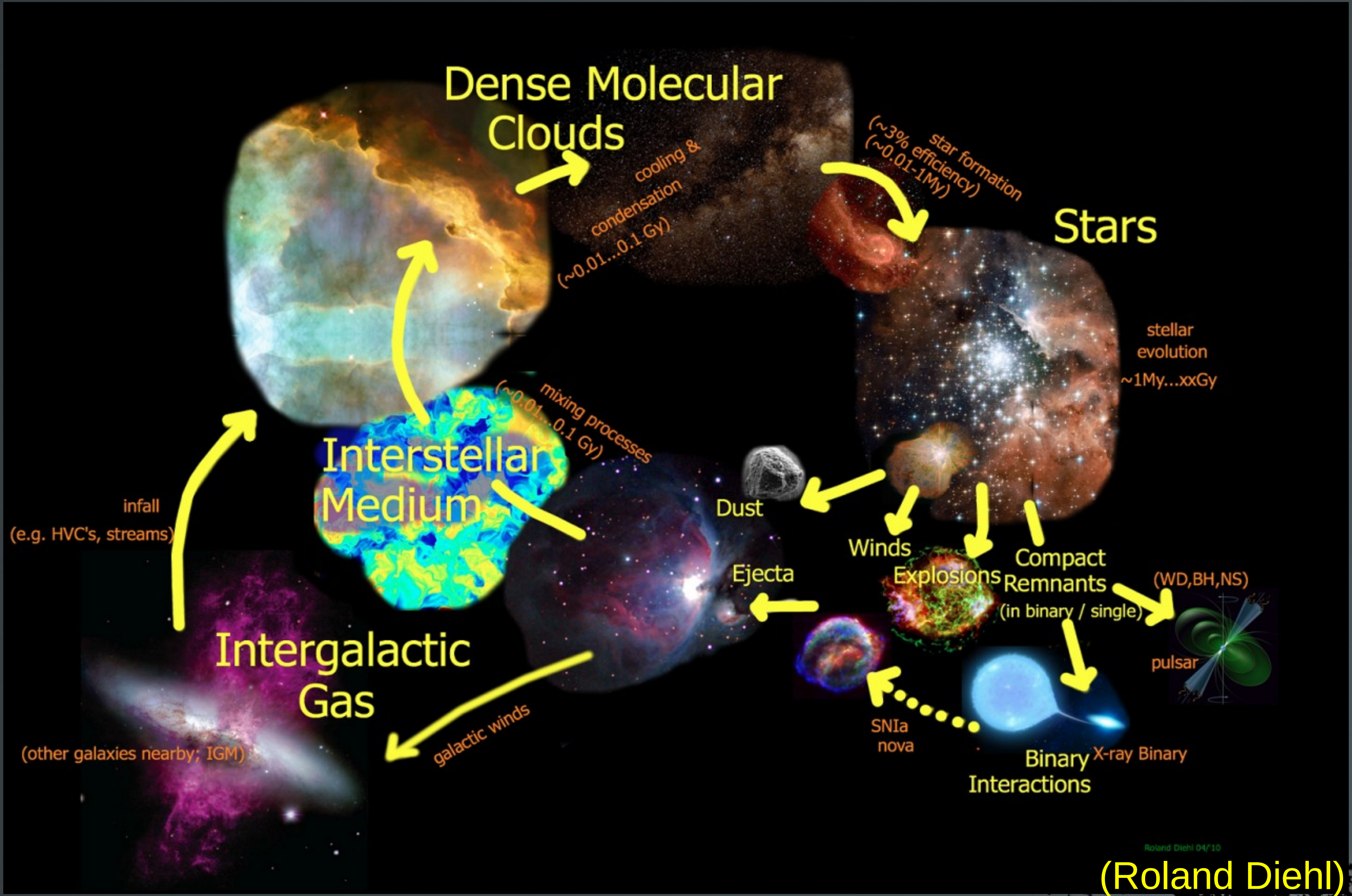
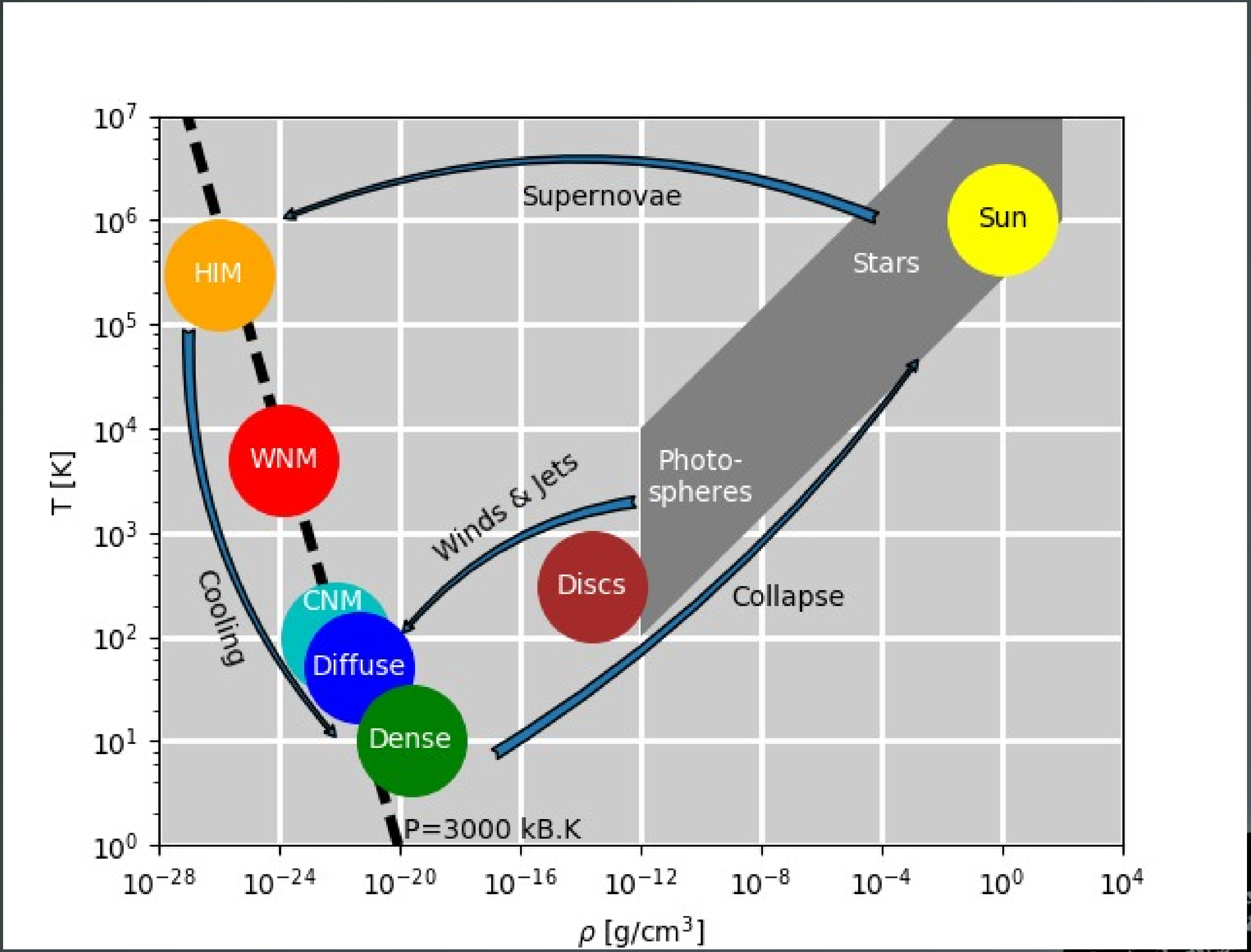
The matter cycle in the galaxy



(Roland Diehl)

Quantitative view of the galactic cycle

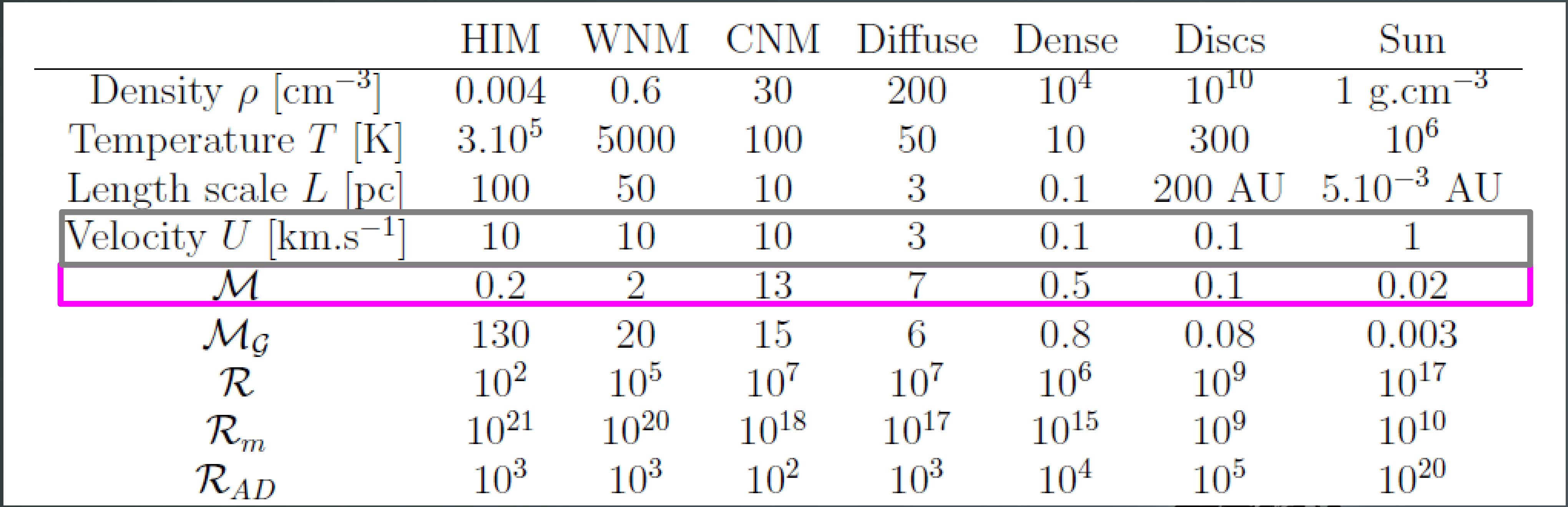


(HDR Lesaffre 2018
Values by Draine)

Typical values

- Velocities are ~ trans-sonic

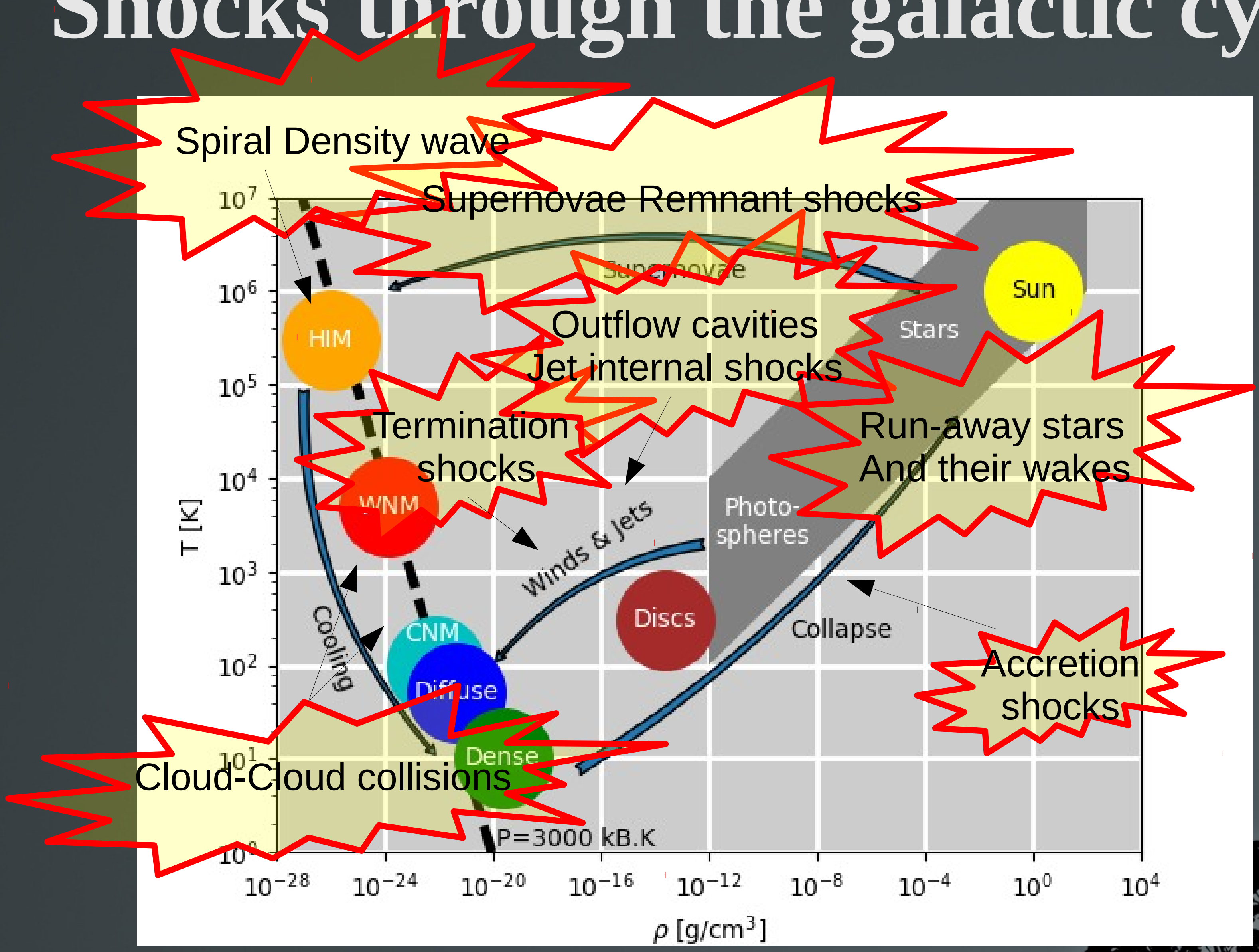
  => Shocks are likely to form



	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}

(HDR Lesaffre 2018
Values by Draine)

Shocks through the galactic cycle



Spiral Density wave

Supernovae Remnant shocks

Outflow cavities
Jet internal shocks

Termination
shocks

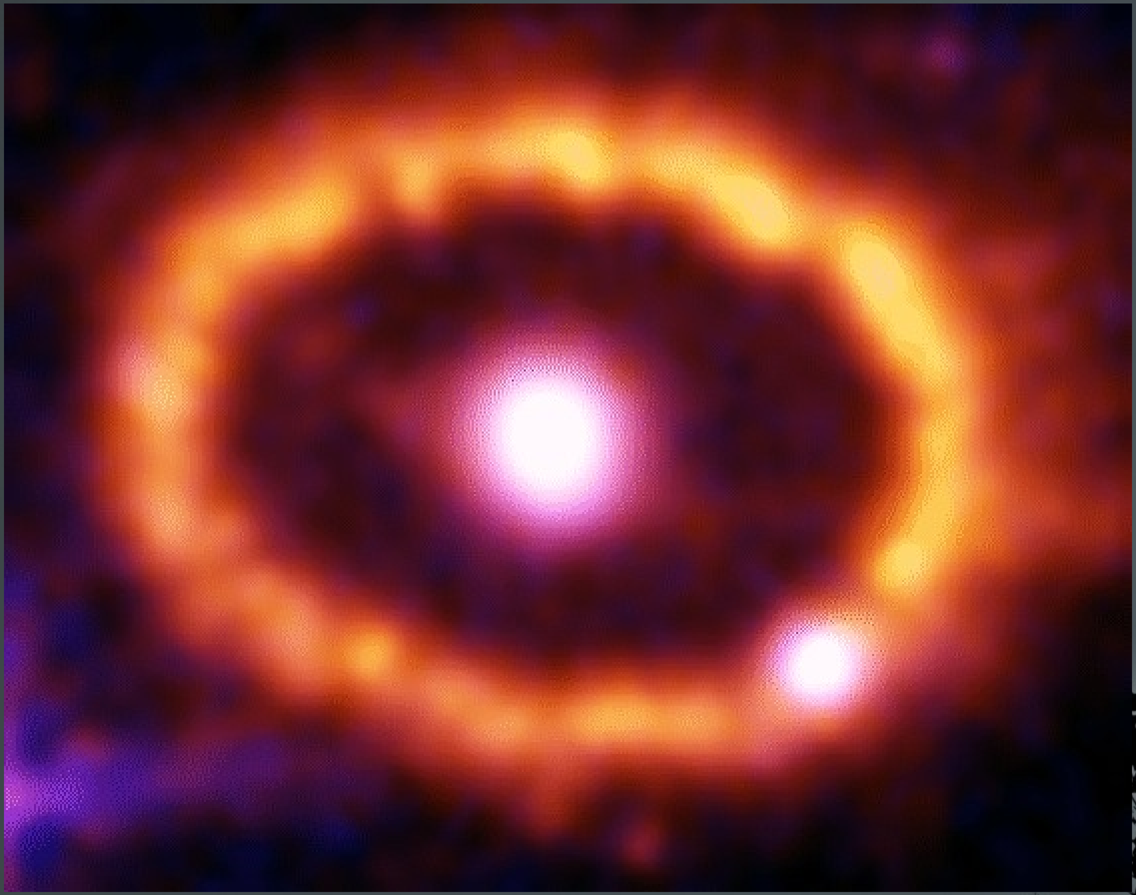
Run-away stars
And their wakes

Accretion
shocks

Cloud-Cloud collisions

Shocks as probes of the cosmic cycle

Like a photographic developer, shocks uncover details of a medium otherwise cold, diffuse and sterile.



SN 1987A, HST

Outline

- Introduction on shocks physics

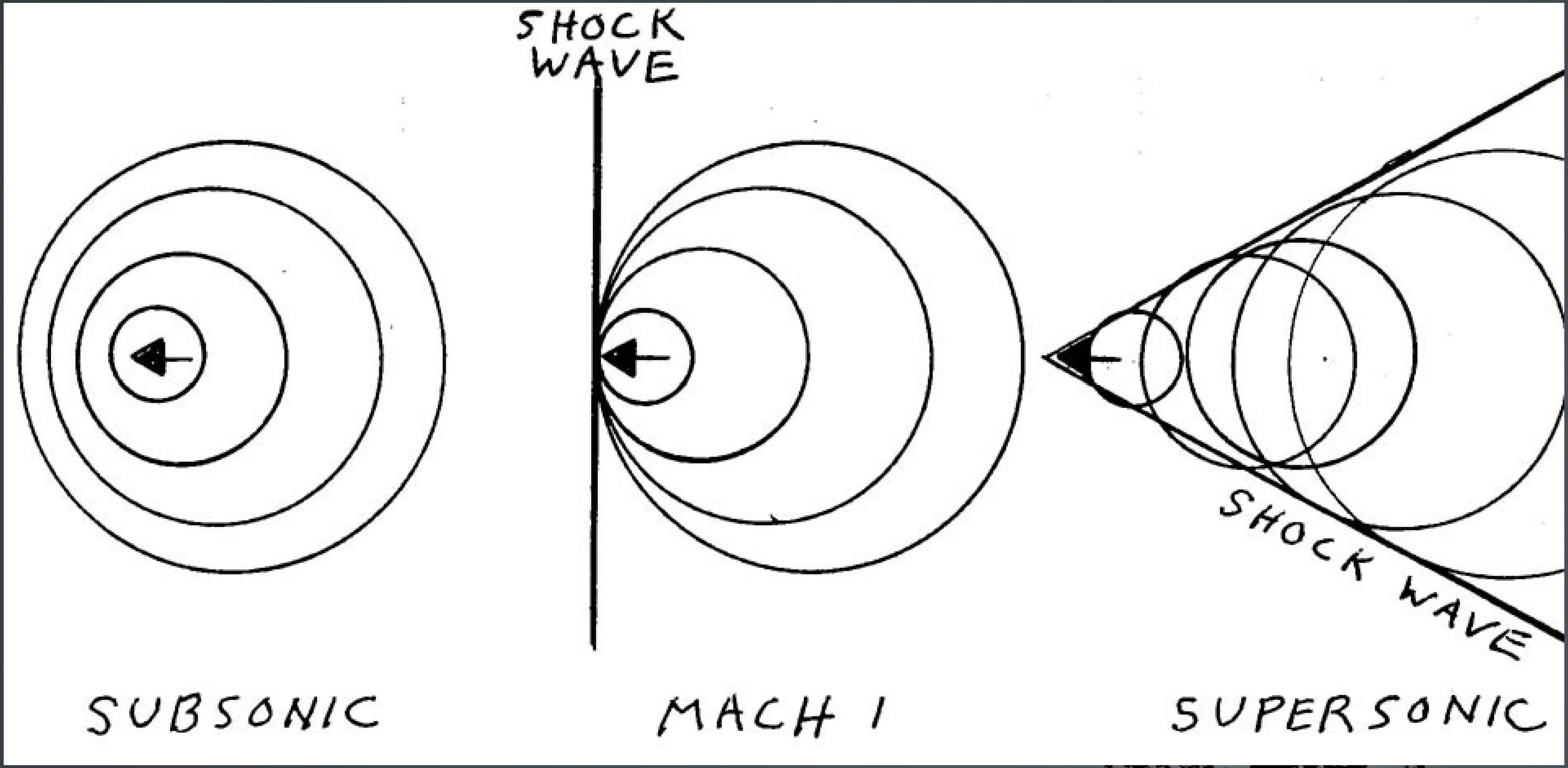
The role of shocks for:

- Dissipative heat production
- Diffuse ISM chemistry
- Magnetic fields shaping

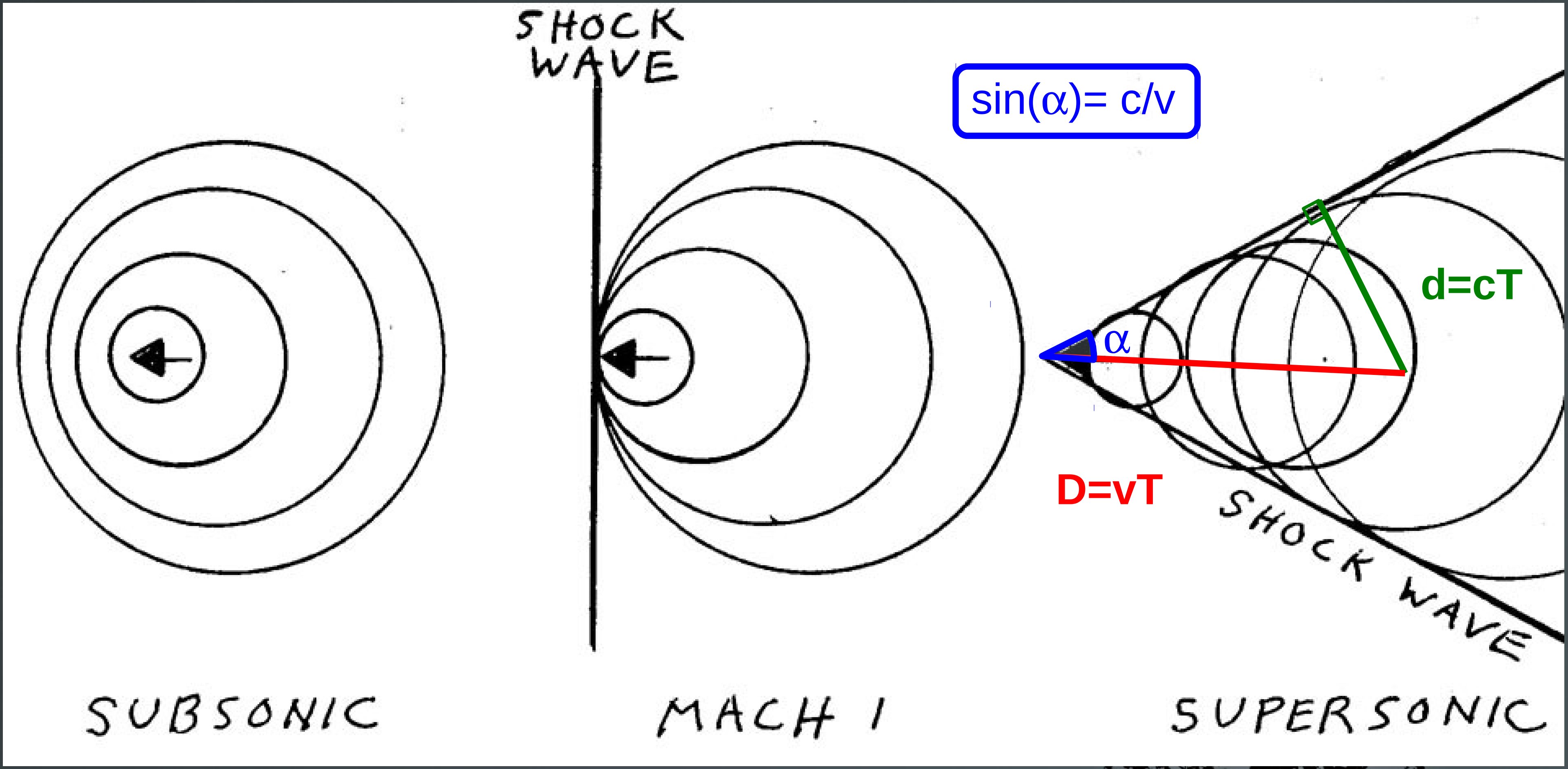
I will skip: CR acceleration, dust processing

Waves

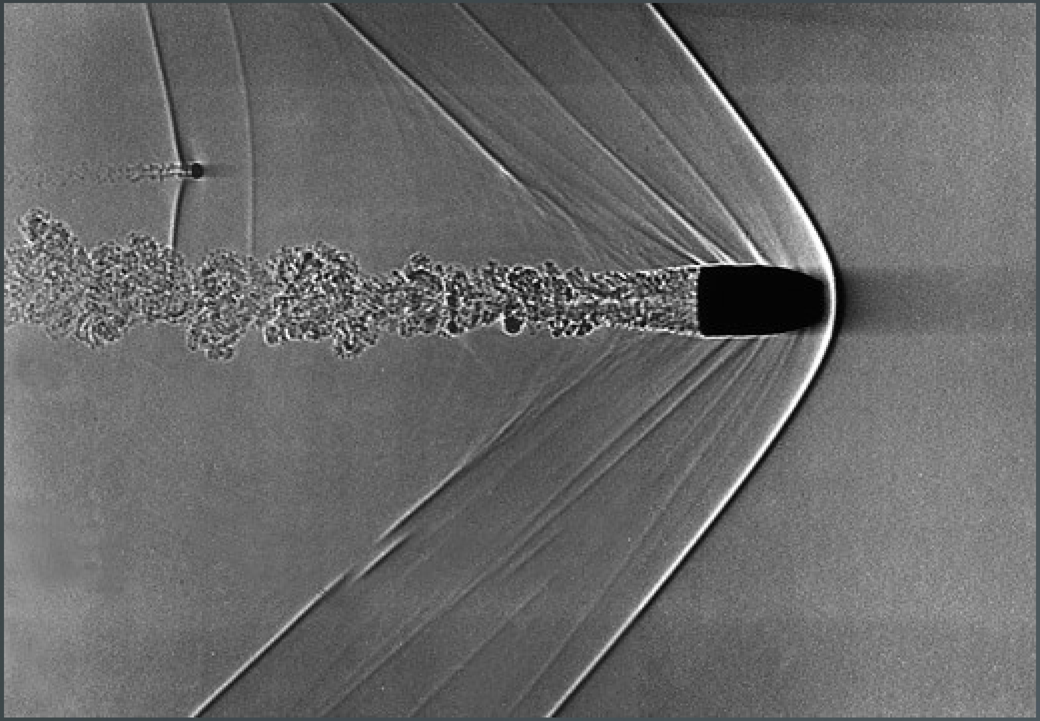
Shock wave



Shock wave

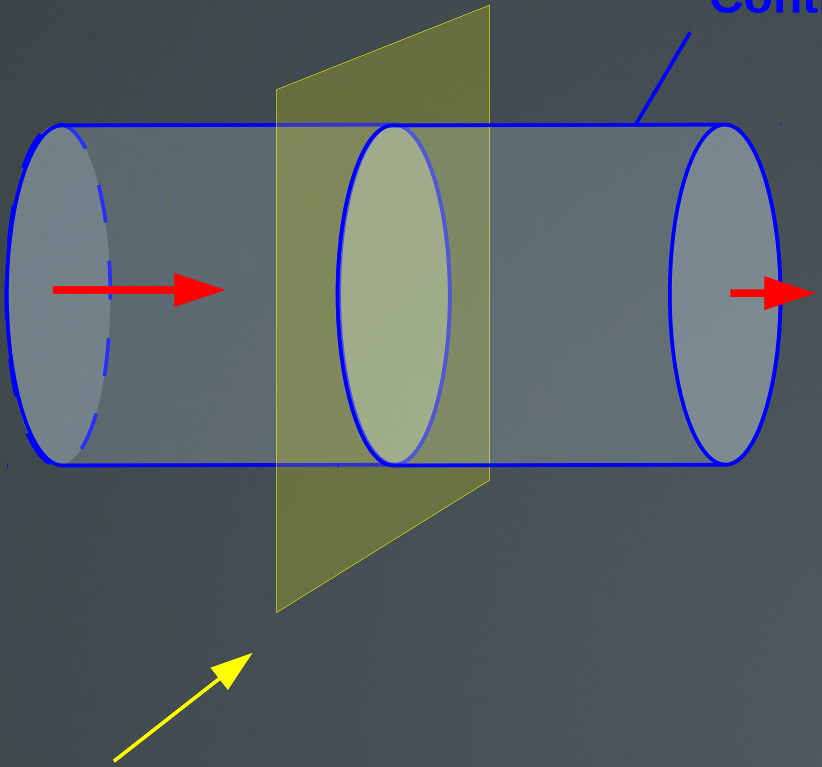

SHOCK WAVE
sin(α)= c/v
α
d=cT
D=vT
SHOCK WAVE
SUBSONIC
MACH 1
SUPERSONIC

Shocks: bullet



Rankine Hugoniot

- Flux conservation through a *steady* planar shock



Control volume

Pre-shock

Post-shock

Working surface

Rankine Hugoniot

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

$$\Big[B_x\Big]_{pre}^{post} = 0$$

$$\Big[\rho\ u_x\Big]_{pre}^{post} = 0$$

$$\Big[(B \times u)_y\Big]_{pre}^{post} = 0$$

$$\Big[(B \times u)_z\Big]_{pre}^{post} = 0$$

$$\Big[\rho u_x u_y - B_x B_y\Big]_{pre}^{post} = 0$$

$$\Big[\rho u_x u_z - B_x B_z\Big]_{pre}^{post} = 0$$

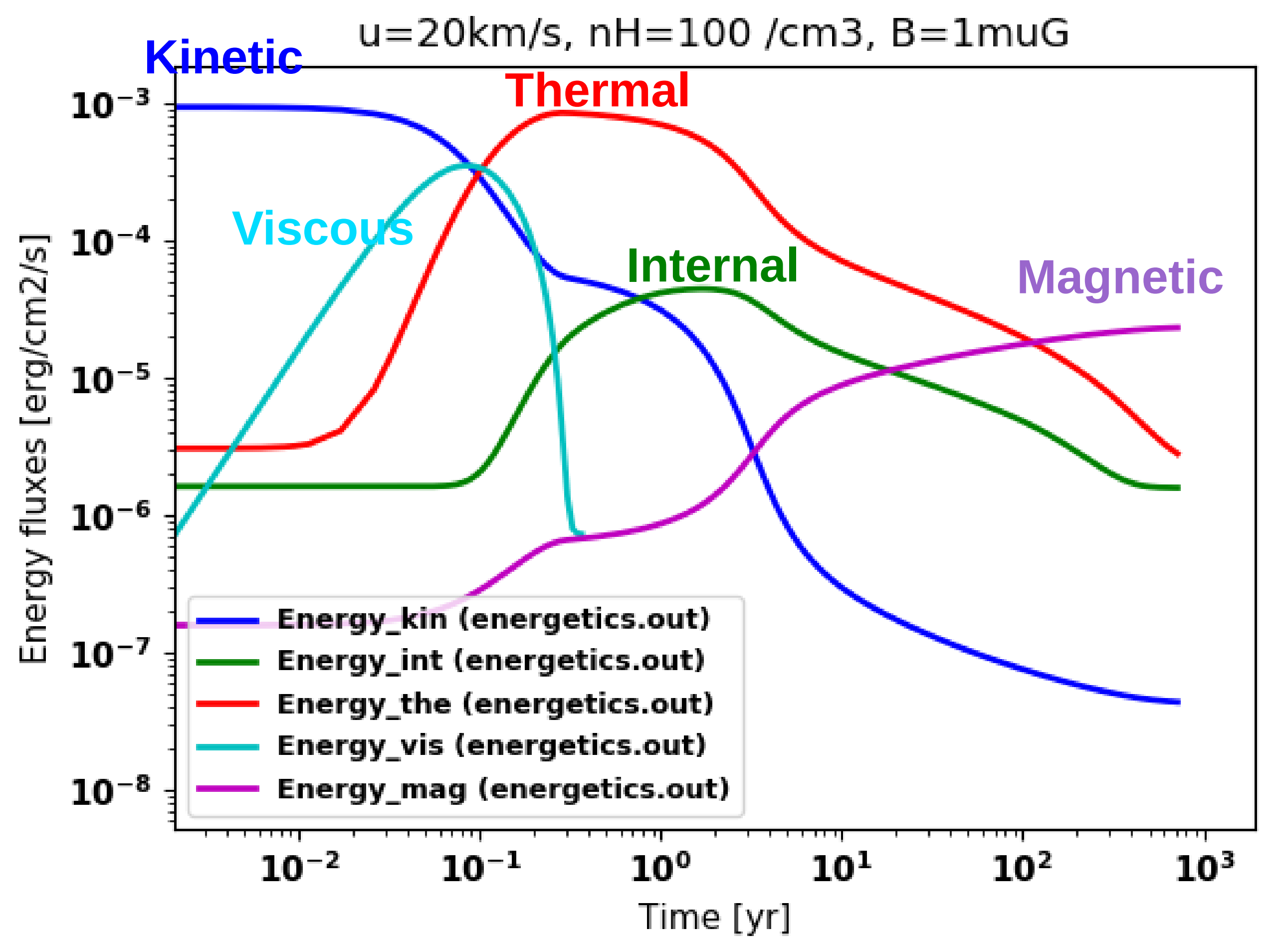
$$\Big[\rho u_x^2 + P\Big]_{pre}^{post} = 0$$

- 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: $T_{\rm max} = 53\,{\rm K}\,(u/1\,{\rm km\ s}^{-1})^2$

Energy fluxes through a viscous (“J-type”) shock in the ISM



The Paris-Durham shock code

Dissipative heating

Dissipation in the turbulent ISM

Molecules, magnetic fields and Intermittency in coSmic Turbulence

Following the energy trail...

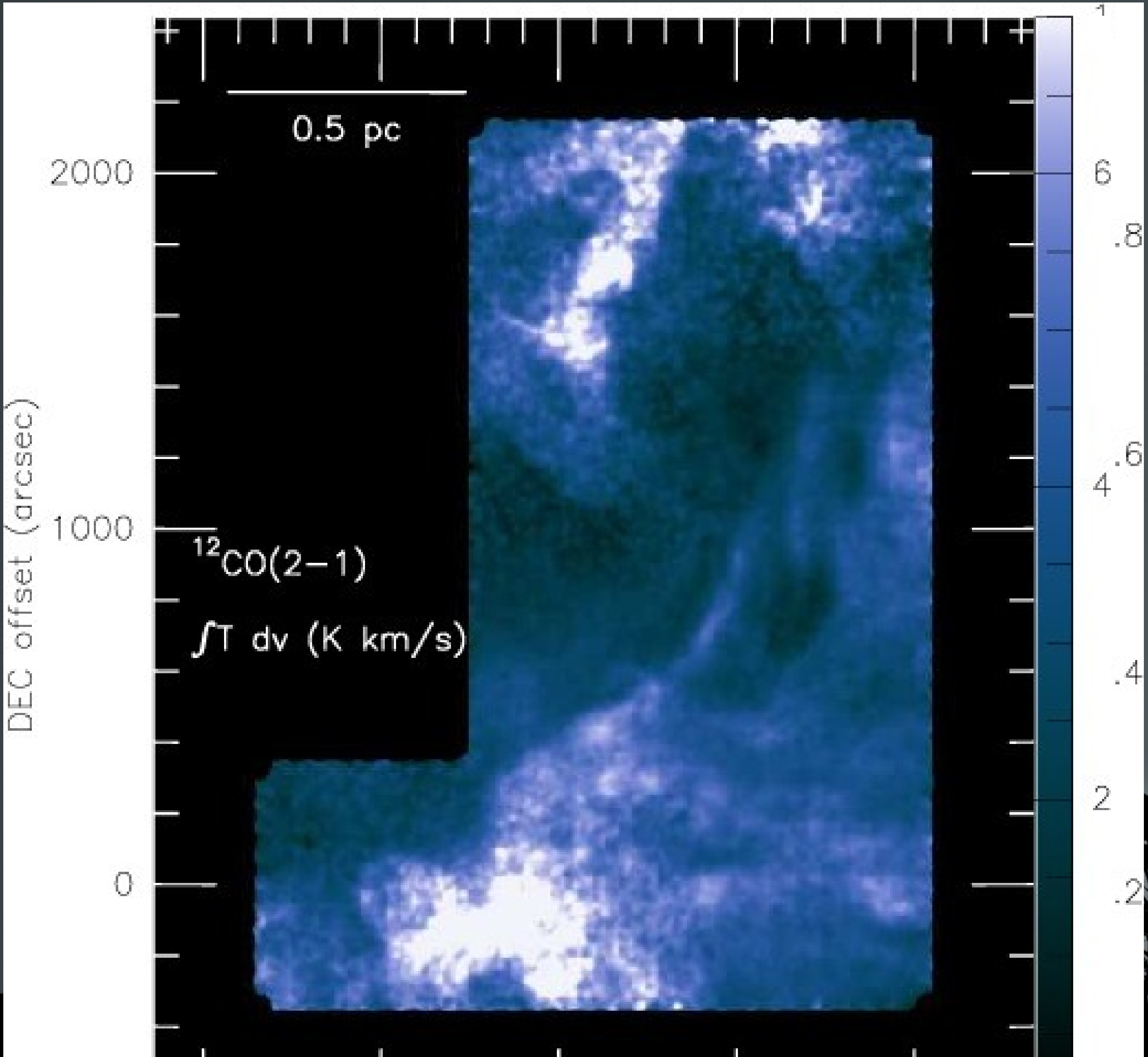
Edith Falgarone

François Boulanger, Benjamin Godard, Pierre Hily-Blant, François Levrier, Pierre Lesaffre, Guillaume Pineau des Forêts,

Andrew Lehmann, Alba Vidal García, Thibaud Richard

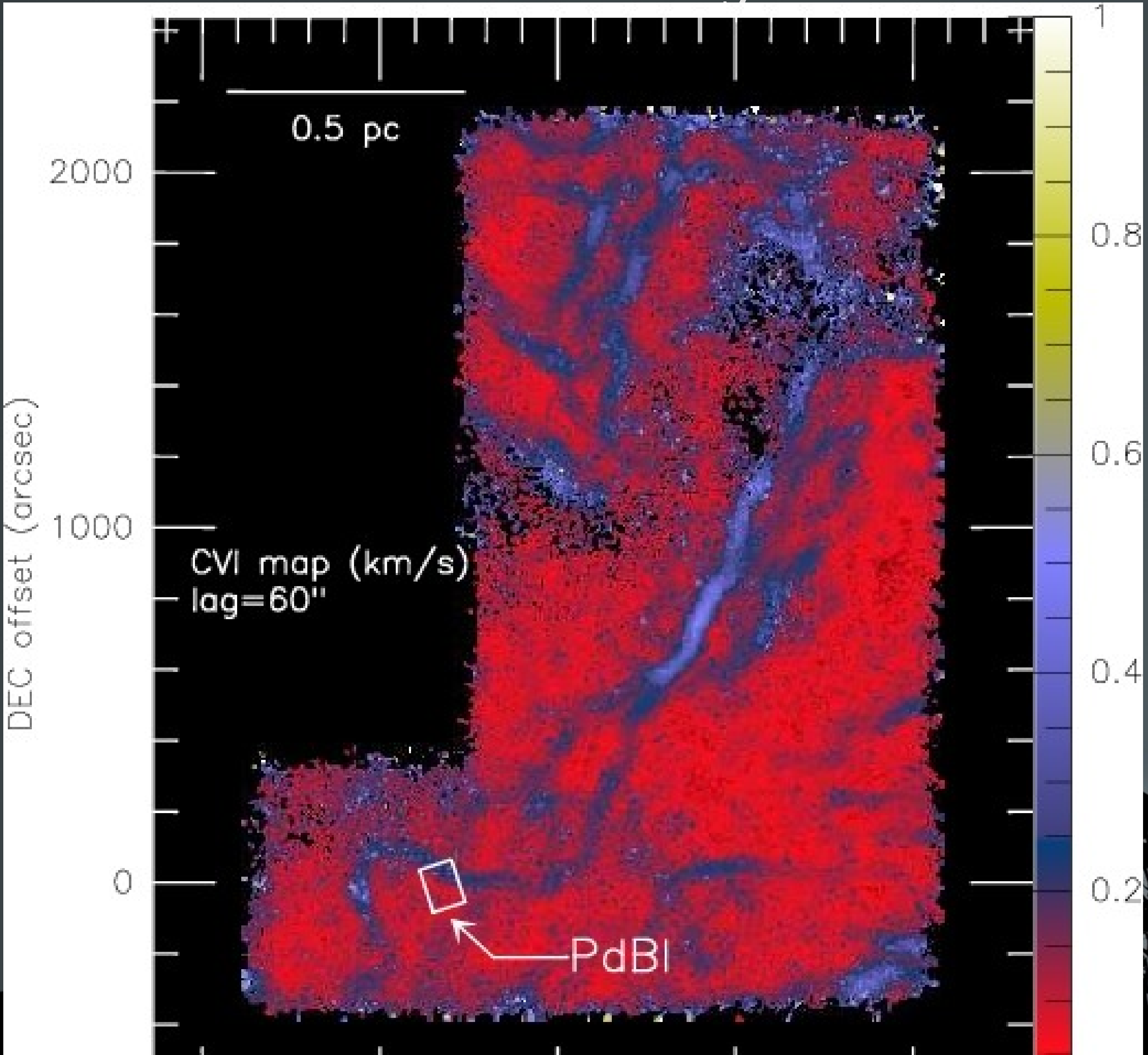
2D turbulence:
dissipation is very localised

Integrated Observables
Line intensities in Polaris flare



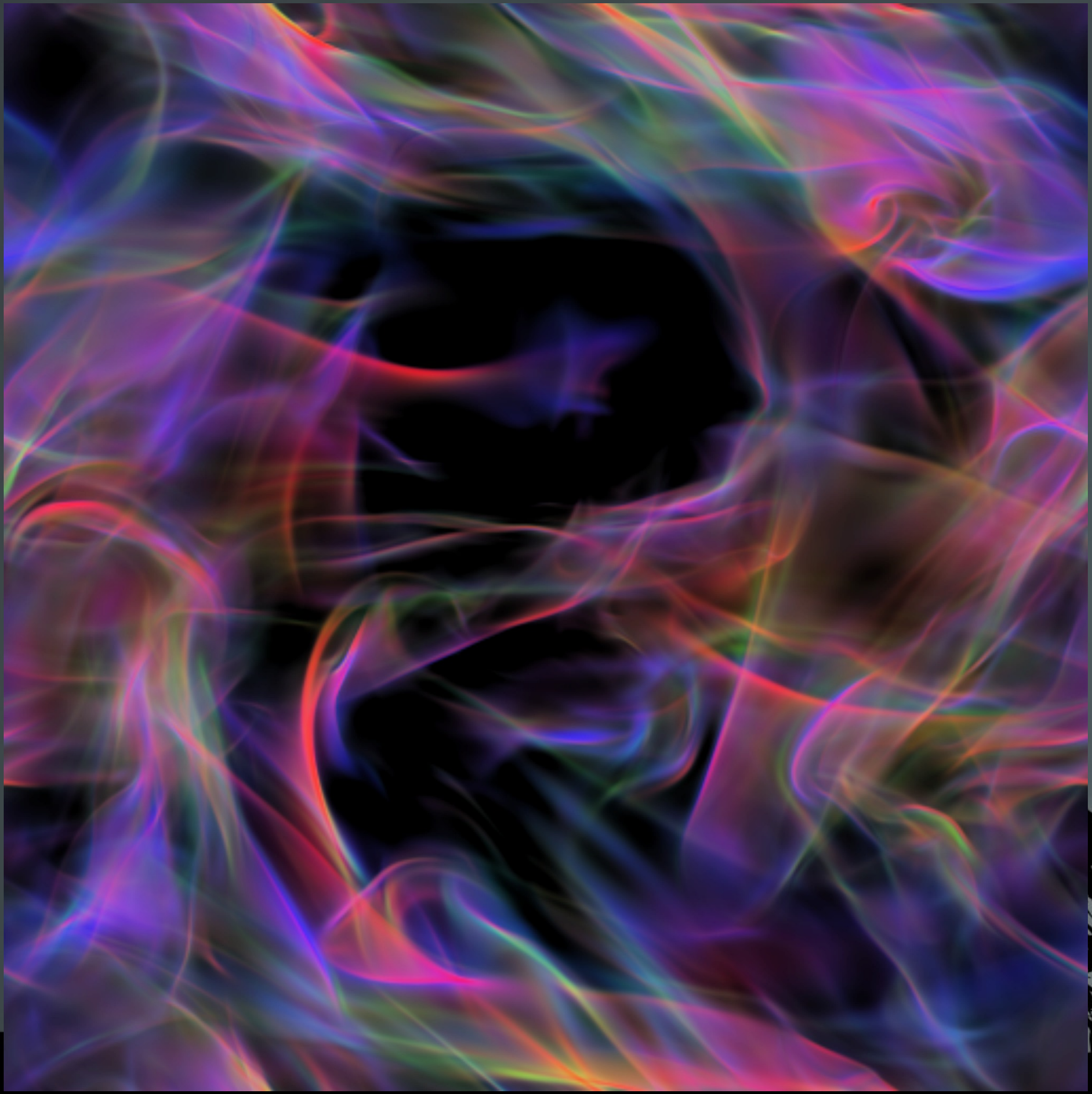
Pierre Hily-Blant,
E Falgarone

Integrated Observables
Centroid Velocity *Increments*



Pierre Hily-Blant,
E Falgarone

Shocks in 3D turbulence: dissipation is very localised



Pierre Lesaffre,
G. Momferratos

Dissipation in decaying turbulence (incompressible runs)

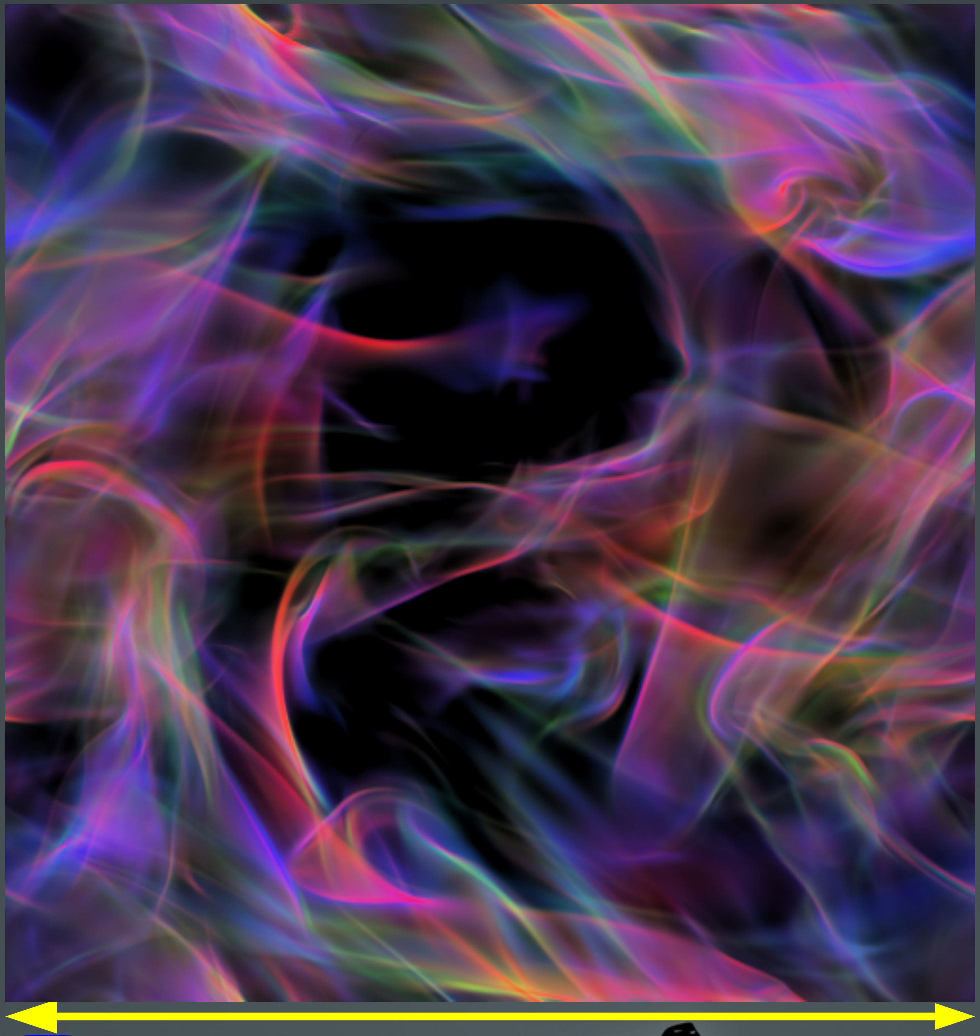
$n_H \sim 100/\mathrm{cm}^3$

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

$Re = LU/\nu \sim \cancel{2.10^7}\ 10^3$

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

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



Line of sight integrated dissipation:

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

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

Statistics of structures with strong dissipation

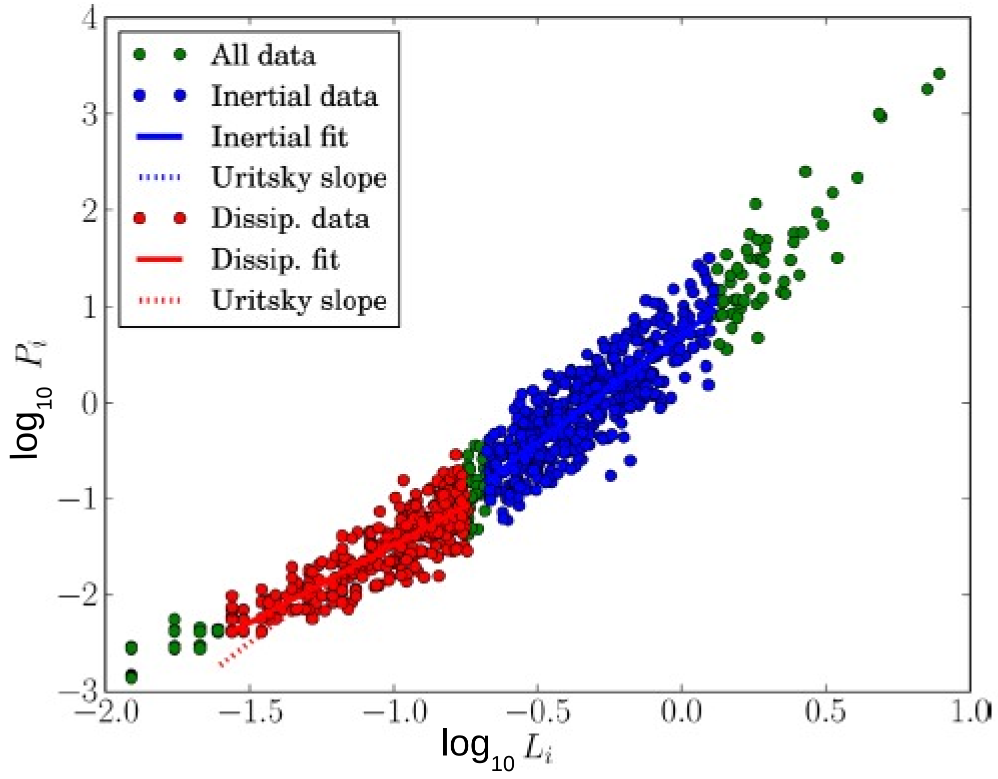


Figure 17. Scaling relations $P_i \propto L_i^{D_P}$ from run 12 (AD-OT), at the peak of dissipation, with a threshold of two standard deviations above the mean value. The dotted line shows the effect of adopting the slope found by UR10 instead of our own slope.

Momferratos *et al.* 2013

Dissipation in the diffuse ISM

(compressible runs, Mach 4, isothermal)

$n_H \sim 100/\mathrm{cm}^3$

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

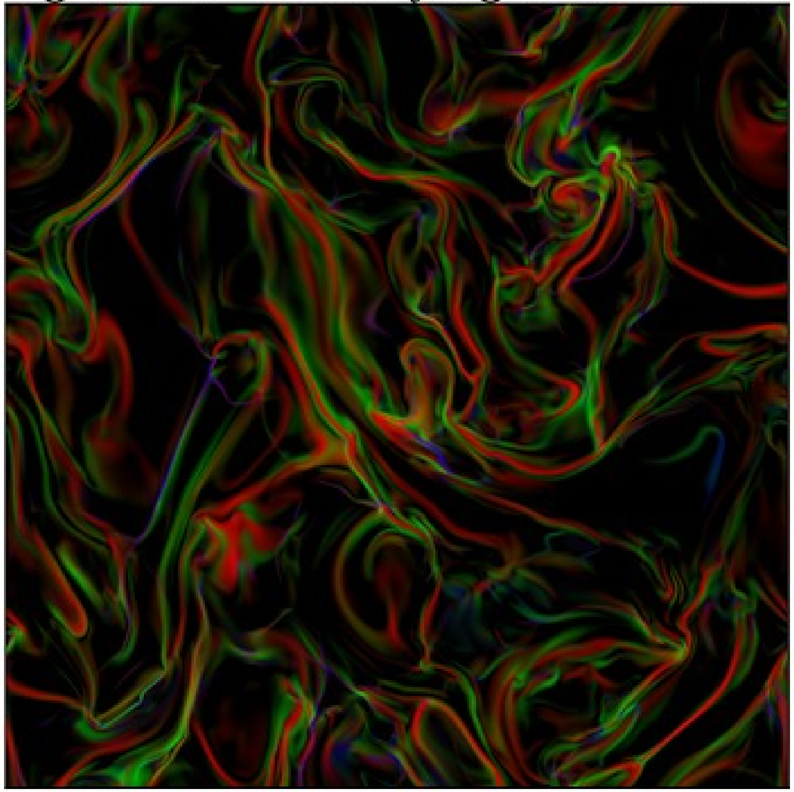
$Re=LU/\nu \sim \cancel{2.10^7}\ 10^3$

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

(1020^3 pixels)

~1 pc

Heating nature in decaying MHD turbulence



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

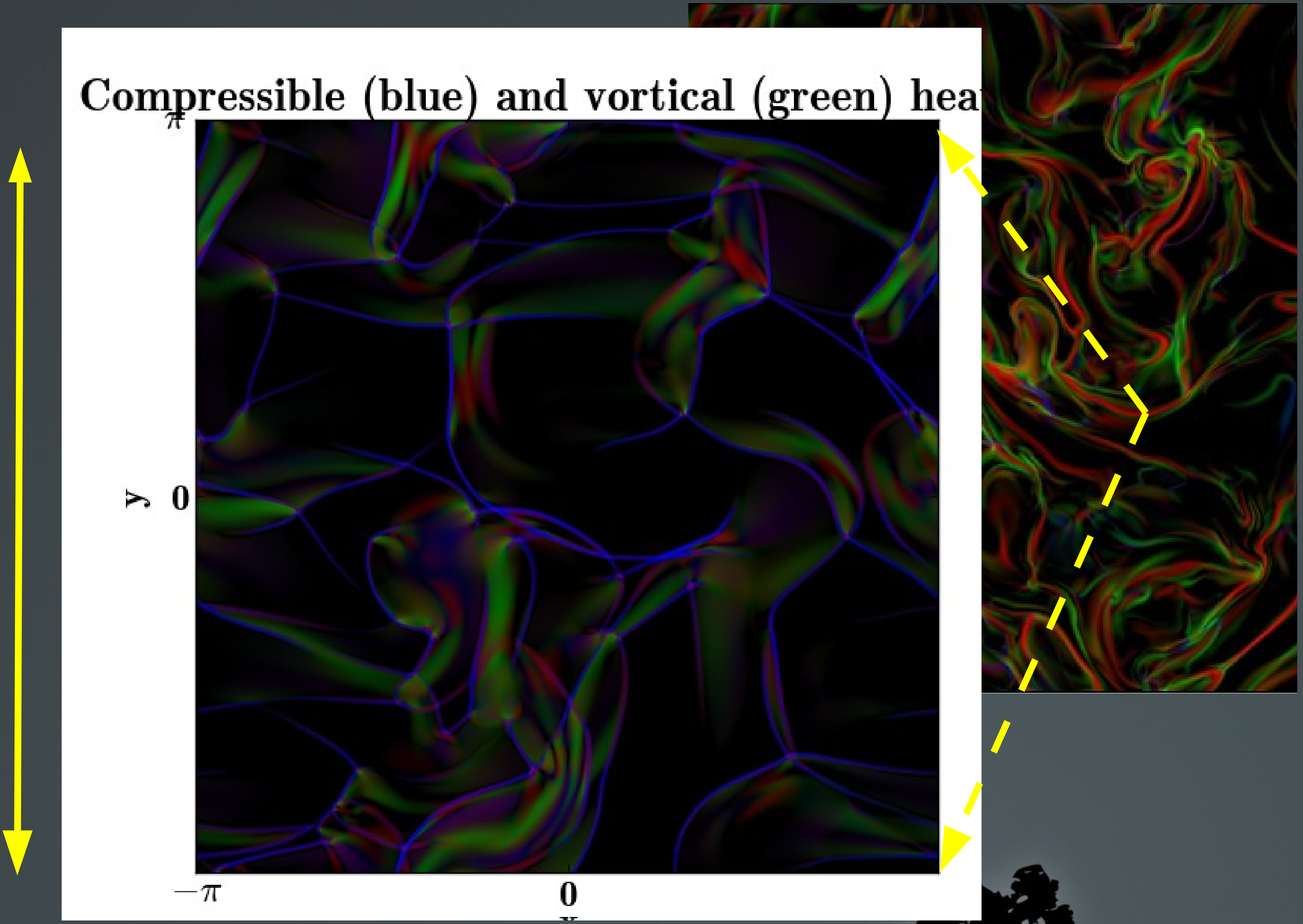
(Momferratos PhD thesis:
DUMSES simulations with careful treatment of viscous and resistive dissipation)

Decaying turbulence (2D runs)

$n_H \sim 100/\mathrm{cm}^3$

ACTUAL ν

No B field.



10^{16} cm

Decaying 2D turbulence from U_{rms} ~2 km/s
(way above average, but think intermittency)

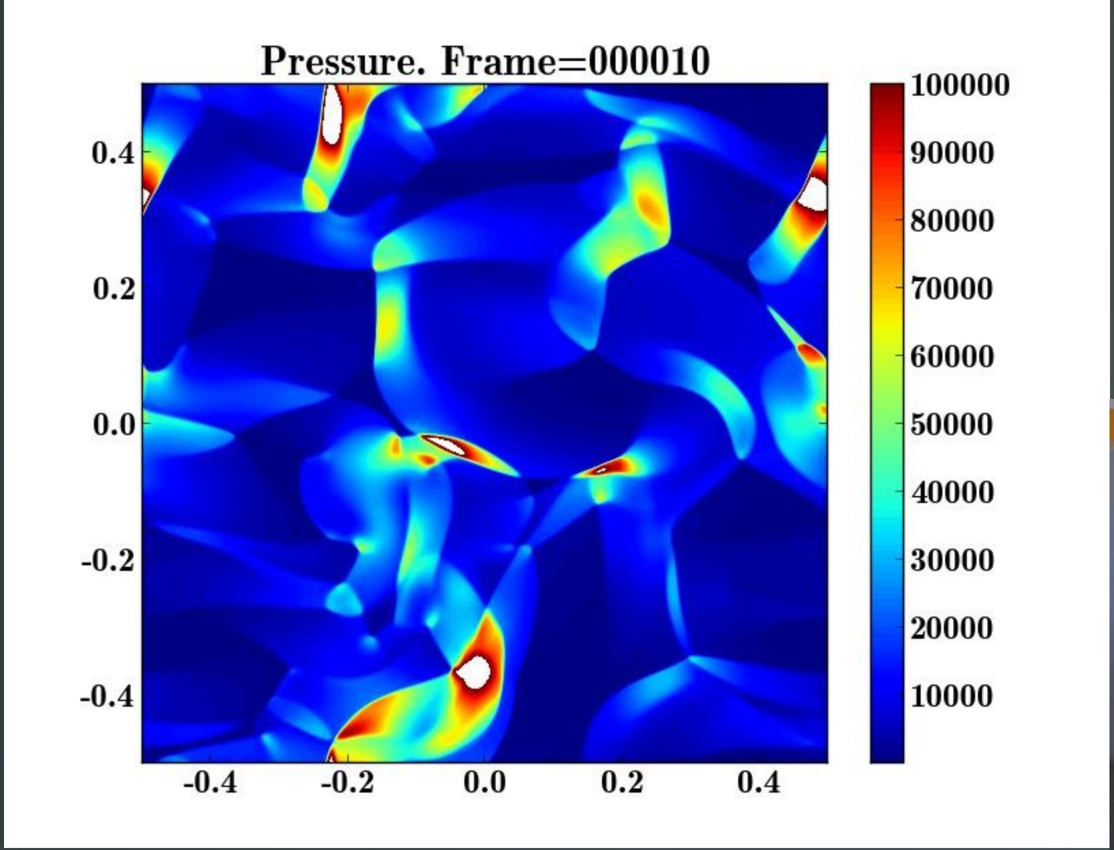
Induced chemistry

Let's shake a small piece of ISM

code CHEMSES=(RAMSES-AMR)+Paris Durham

Diffuse medium (nH=100, G_0=1), viscous length *resolved*, 32 species followed

~ 0.003 pc



CPU time:
50 000 h at IDRIS (1 day on 2000 procs)

Simulated time: 10 000 yr.

Lesaffre et al. (in prep)

Let's shake a small piece of ISM

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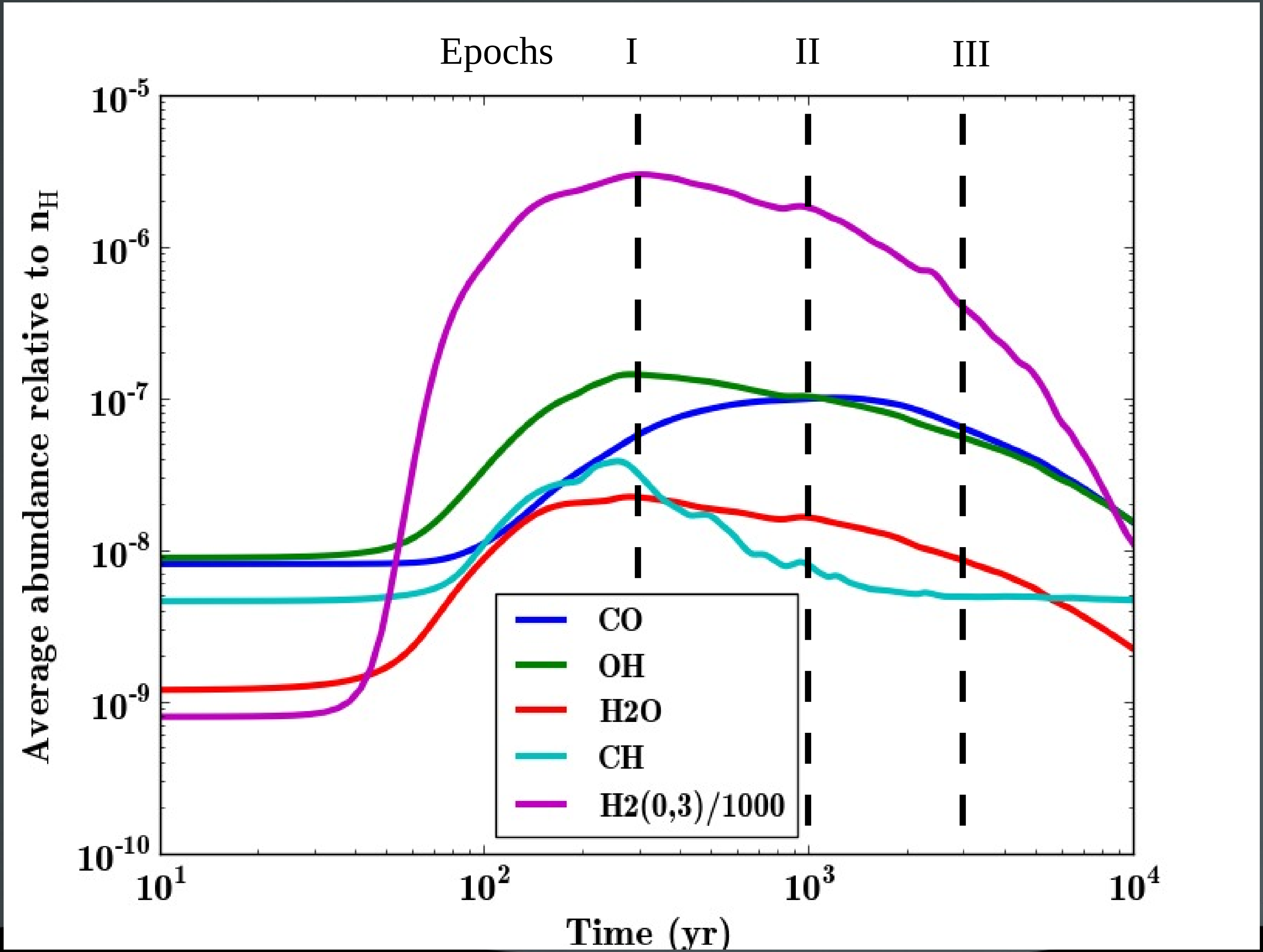
Lesaffre et al. (In prep)

H_2 excited and molecules produced by dissipation of 2D turbulence

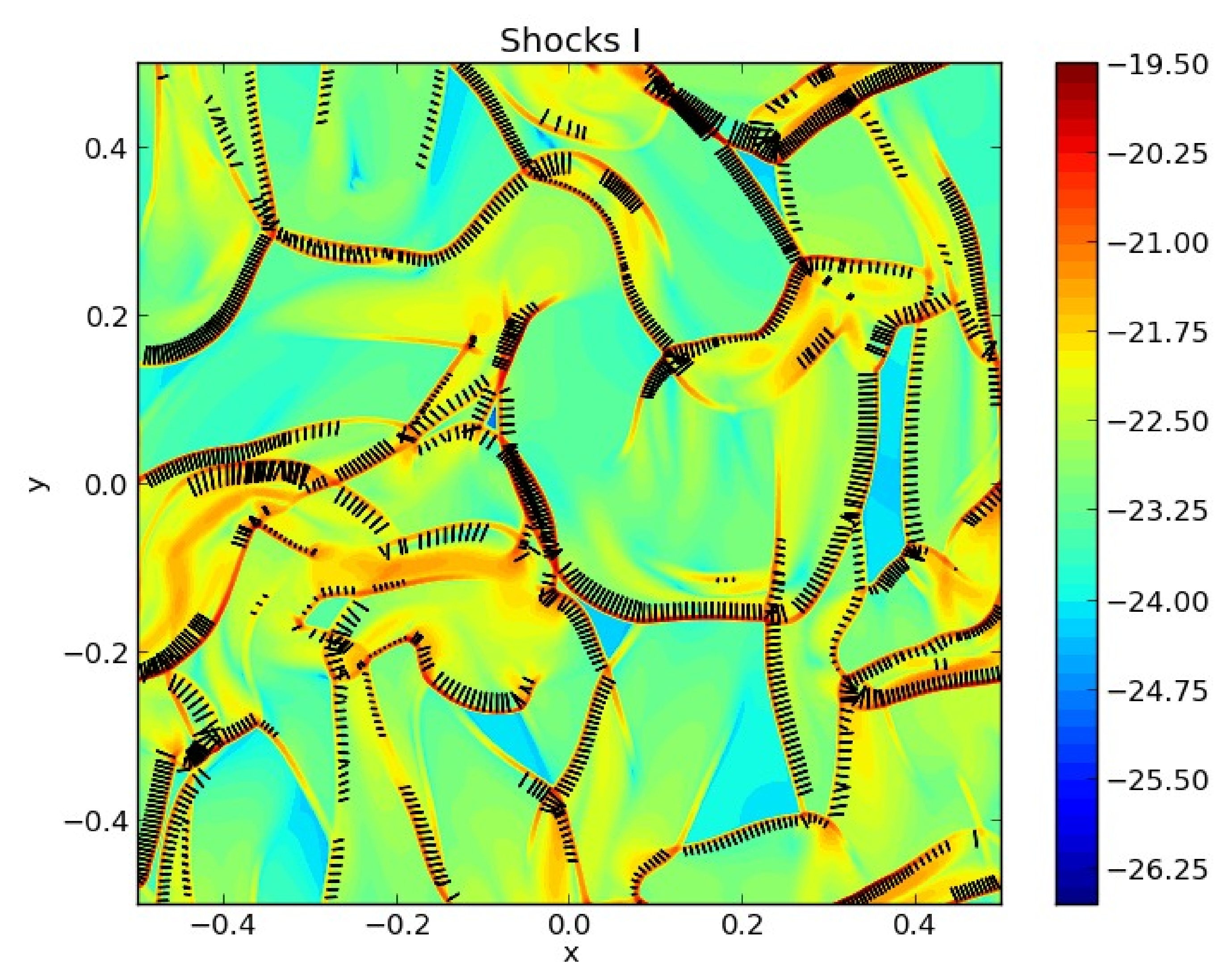
G_0=1

Av=0.1

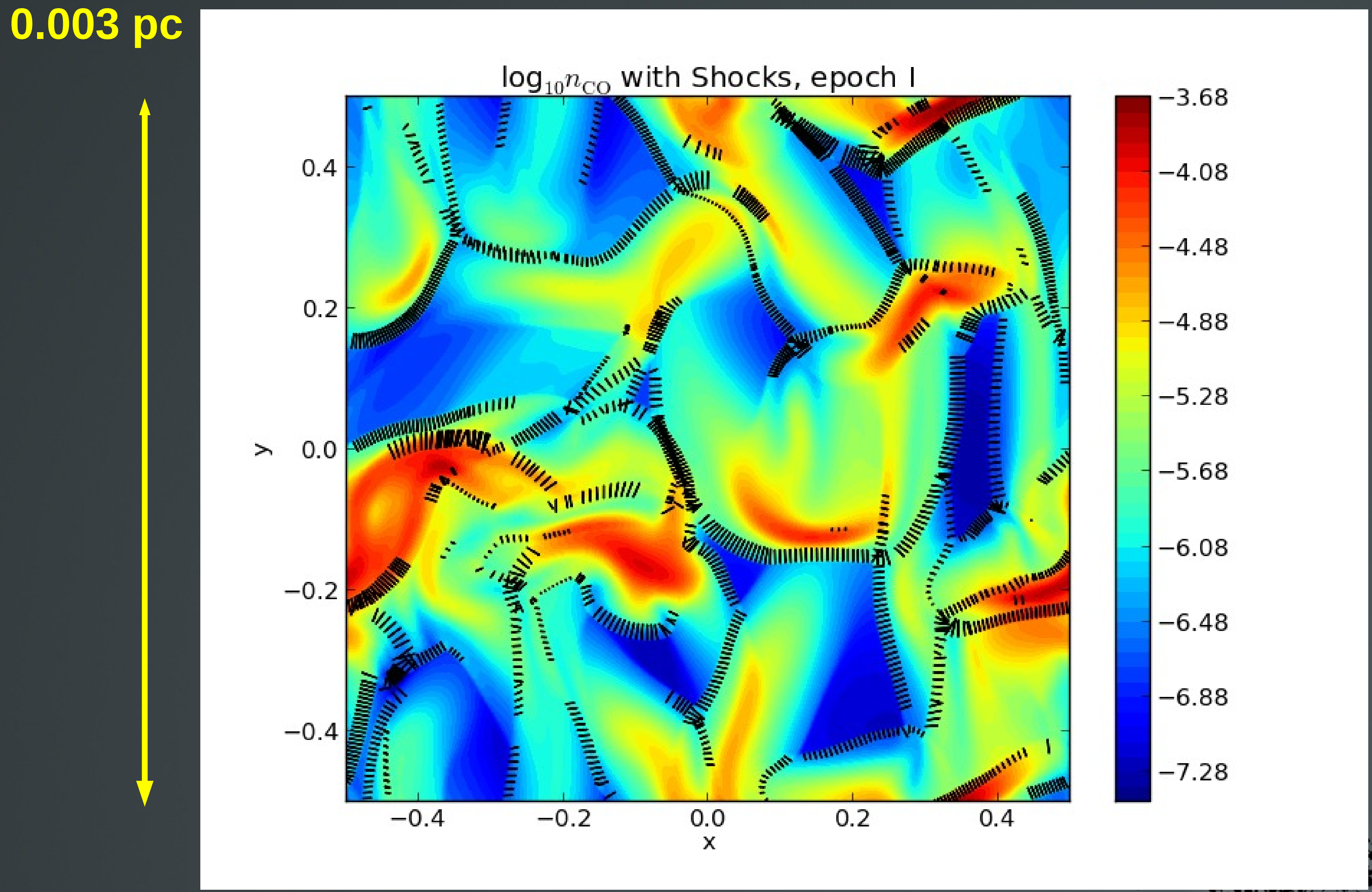


Find steady-state shocks

(local fit of adiabatic fronts)



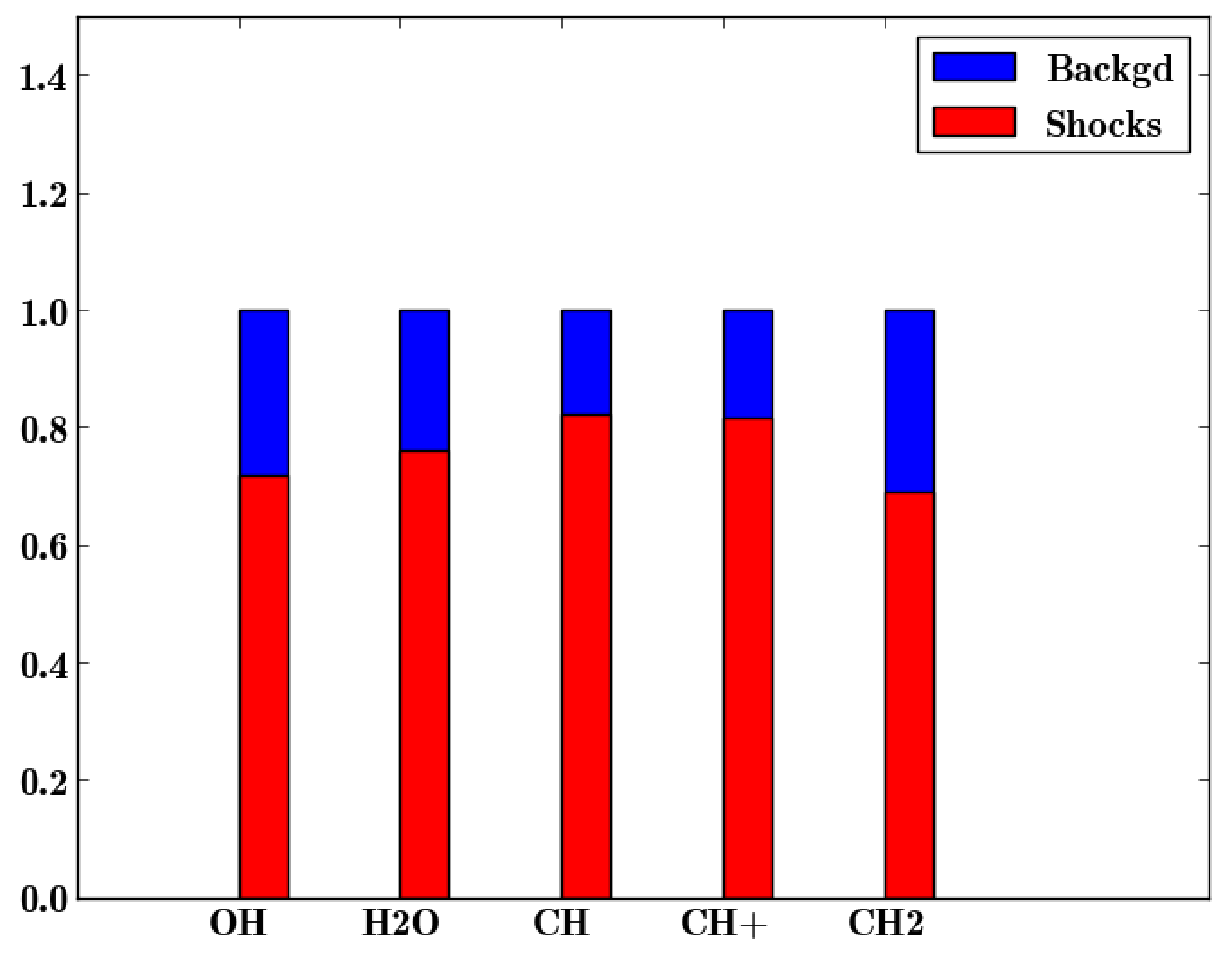
CO map produced in shocks (idem for OH, H_2O, CH, etc...)



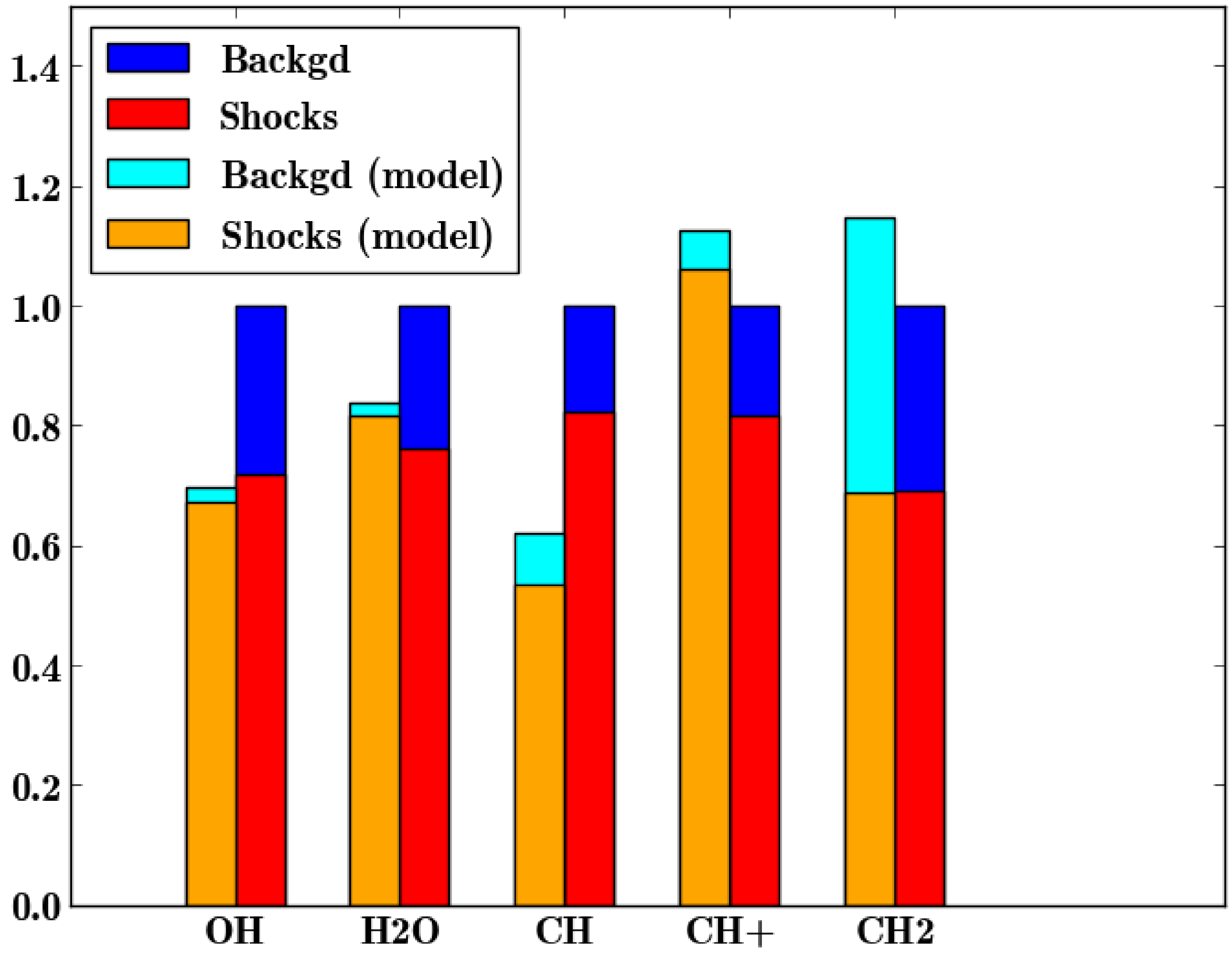
Lesaffre et al. (in prep)

Fraction of some hydrides in background and shocked region

Both regions have same volume, but shocked regions have more molecules

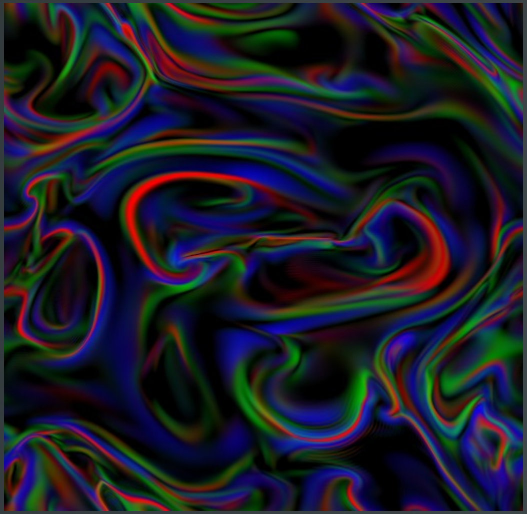


1D steady models can retrieve the molecular yields (CPU time=1h)



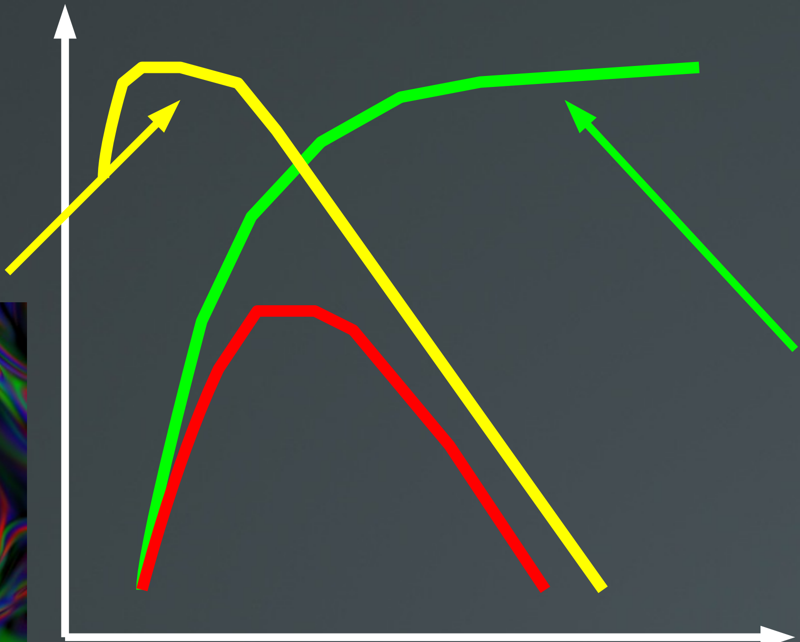
Prospects

Intermittent statistics of the dissipation

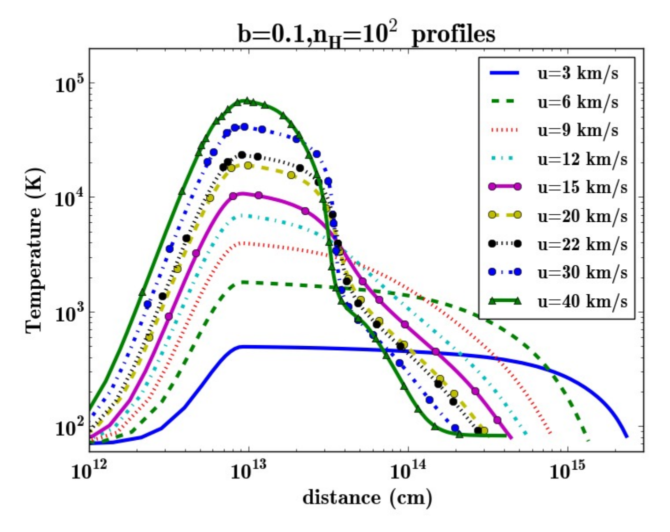


3D simulations

(cf Momferratos et al. 2013)

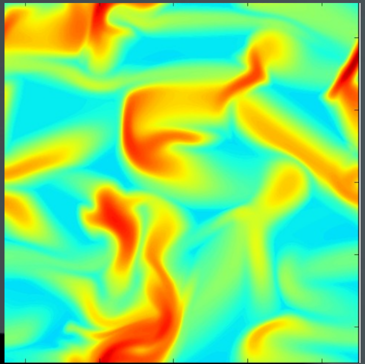


Molecular yields from Shocks (for example)



1D simulations

=> Molecules
Formation + excitation



CO map

Validation with 2D simulations

Magnetic fields processing

B orientation in oblique shocks

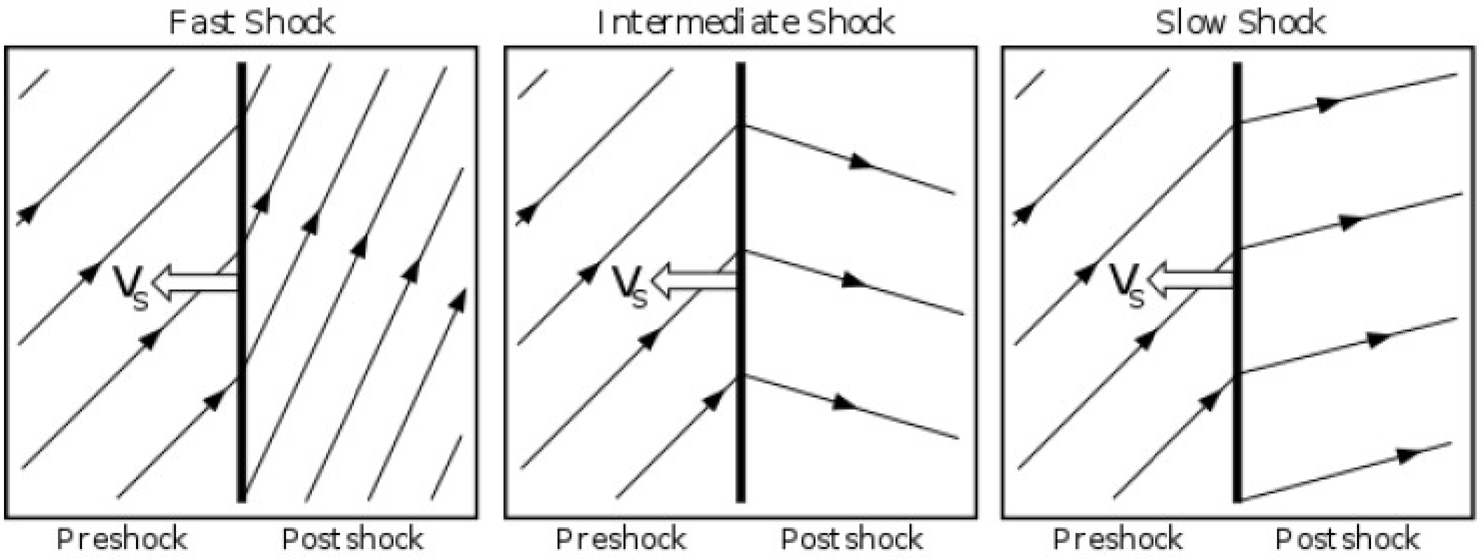
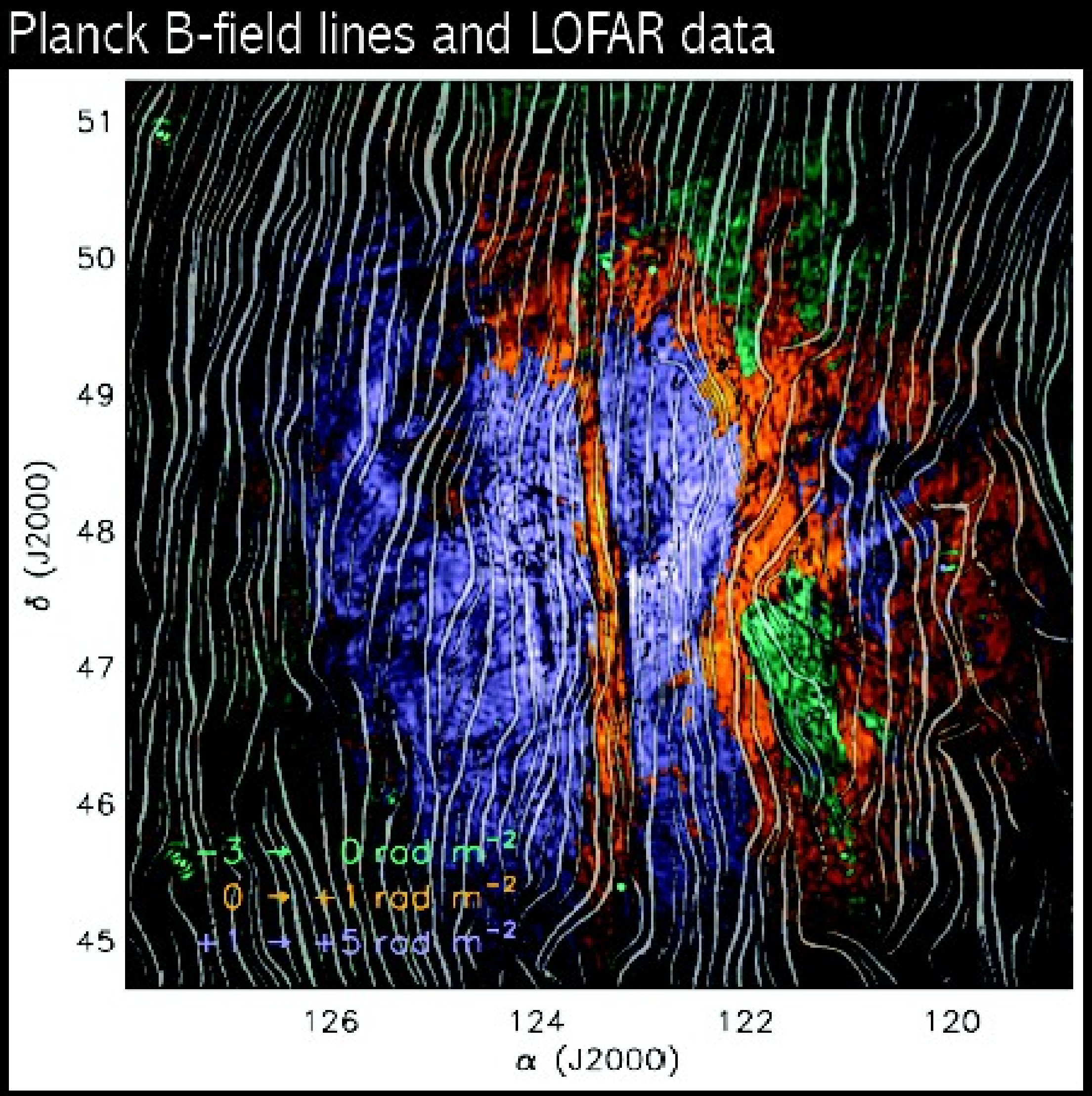


Figure 2. The effect on magnetic field orientation of the three classes of MHD shock waves. Fast shocks (left) increase the angle between the field and shock normal, intermediate shocks (middle) reverse the sign of the angle and slow shocks (right) decrease it. Hence the magnetic field strengthens across fast shocks and weakens across slow shocks.

In the 'SHOCKFIND' paper by Lehmann, Federrath, Wardle (2016)

LOFAR & Planck data

Rotation measure (Rm= Σ ne.Bz.dz) overlayed with B field direction

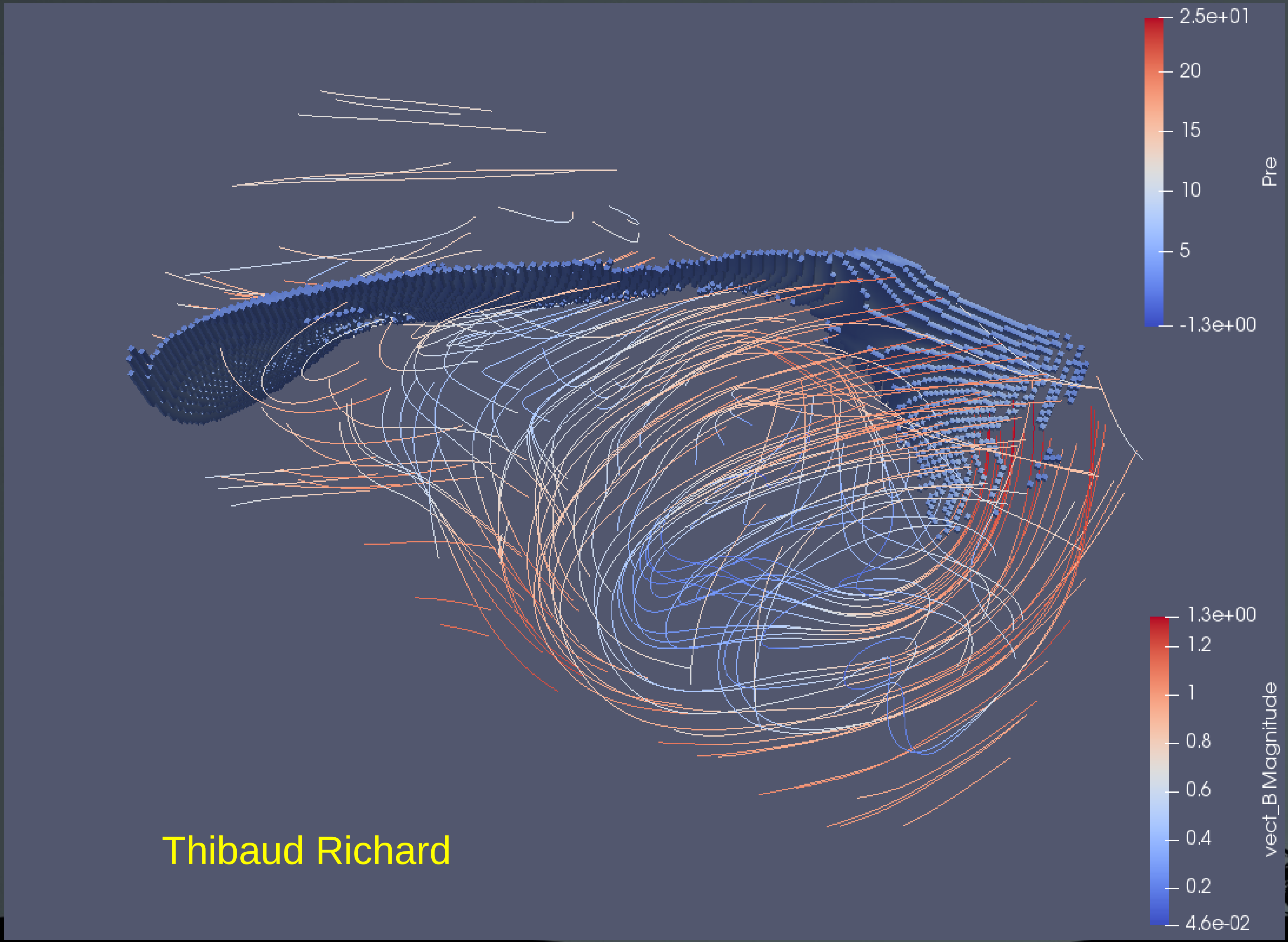


(Zaroubi et al. 2015)

Jelic et al. 2015

Dissipative structures extraction

Find connected sets where dissipation > mean + 2.standard deviations

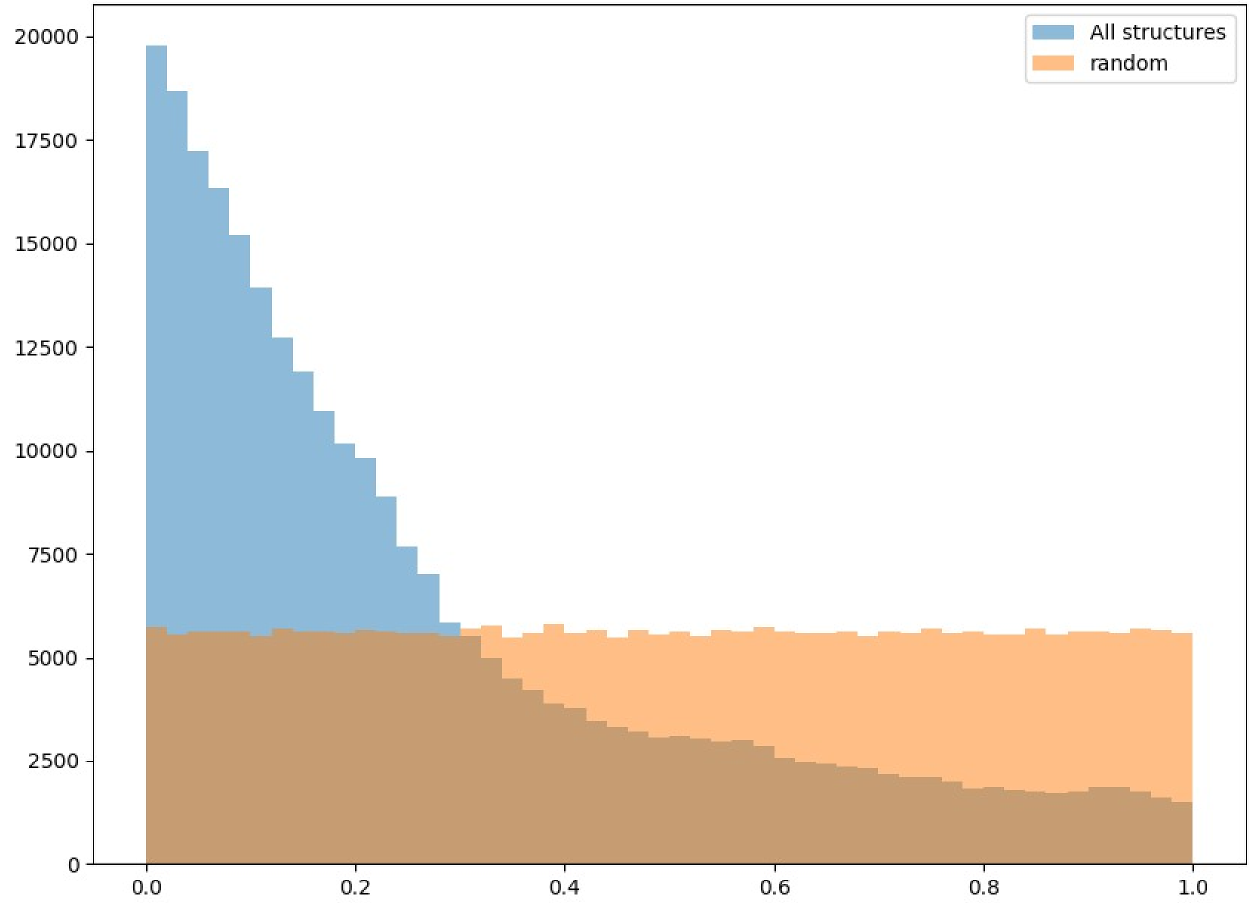


Thibaud Richard

B field is mostly parallel to structures

Thibaud Richard

Cos(B, normal to dissipative surface)



B parallel

B normal

Conclusions

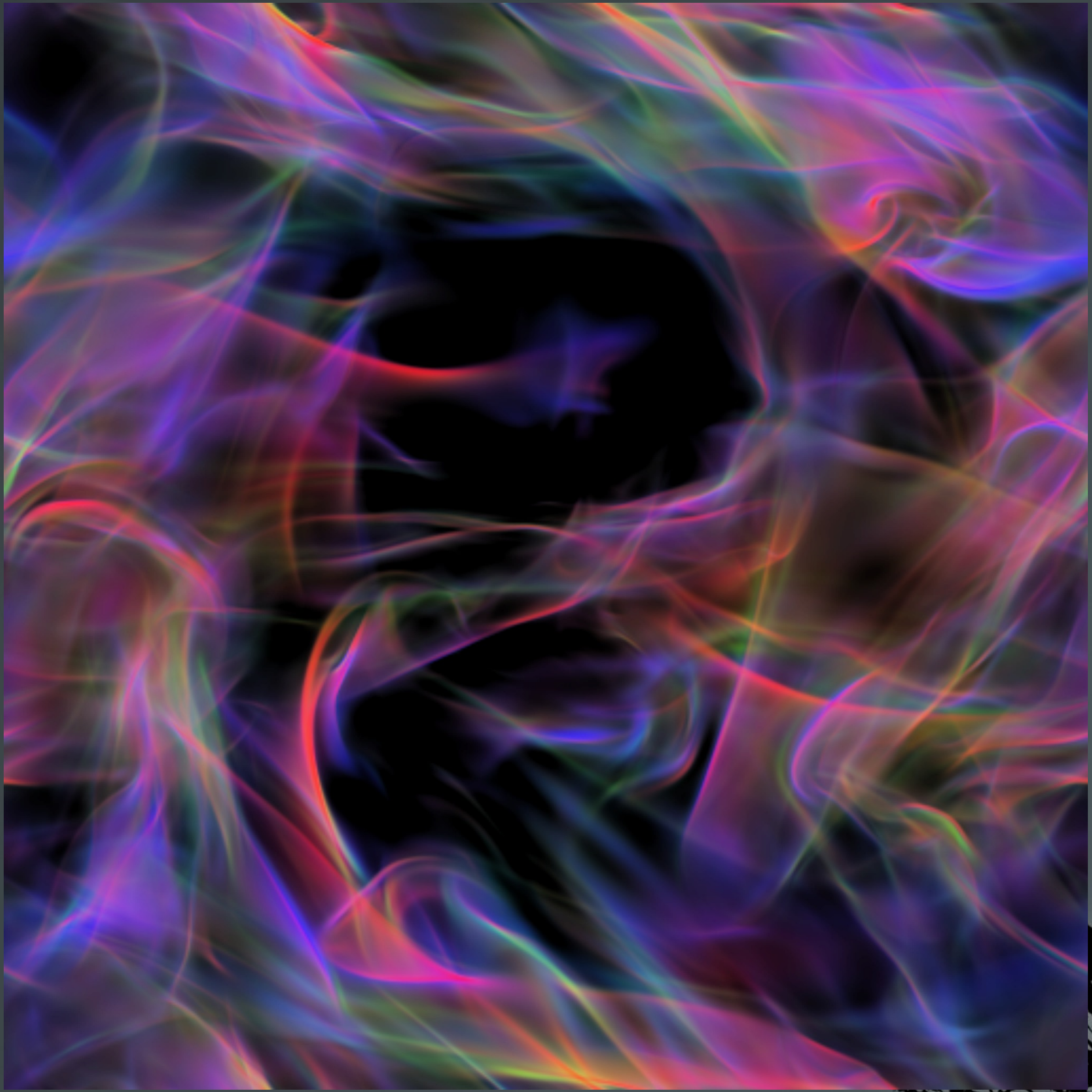
- Shocks are everywhere
- They convert kinetic energy into thermal energy
- They are good probes of the dynamics and chemistry of the gas
- They allow to make good use of up to date observational capabilities
- Still a lot of fun ahead !

Current Developments of the Paris-Durham shock code

- 3D models (Le Ngoc Tram) Tram+2018
- Stellar winds (Le Ngoc Tram) Tram+2018 in prep.
- Line post-processing (A. Gusdorf + Tram)
- Irradiated / self-irradiated shocks (A. Lehmann, B. Godard) Godard+2018 in prep.
- Oblique shocks (A. Lehmann, P.L.)

Stay Tuned !

Thanks !



Integrated Observables

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

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

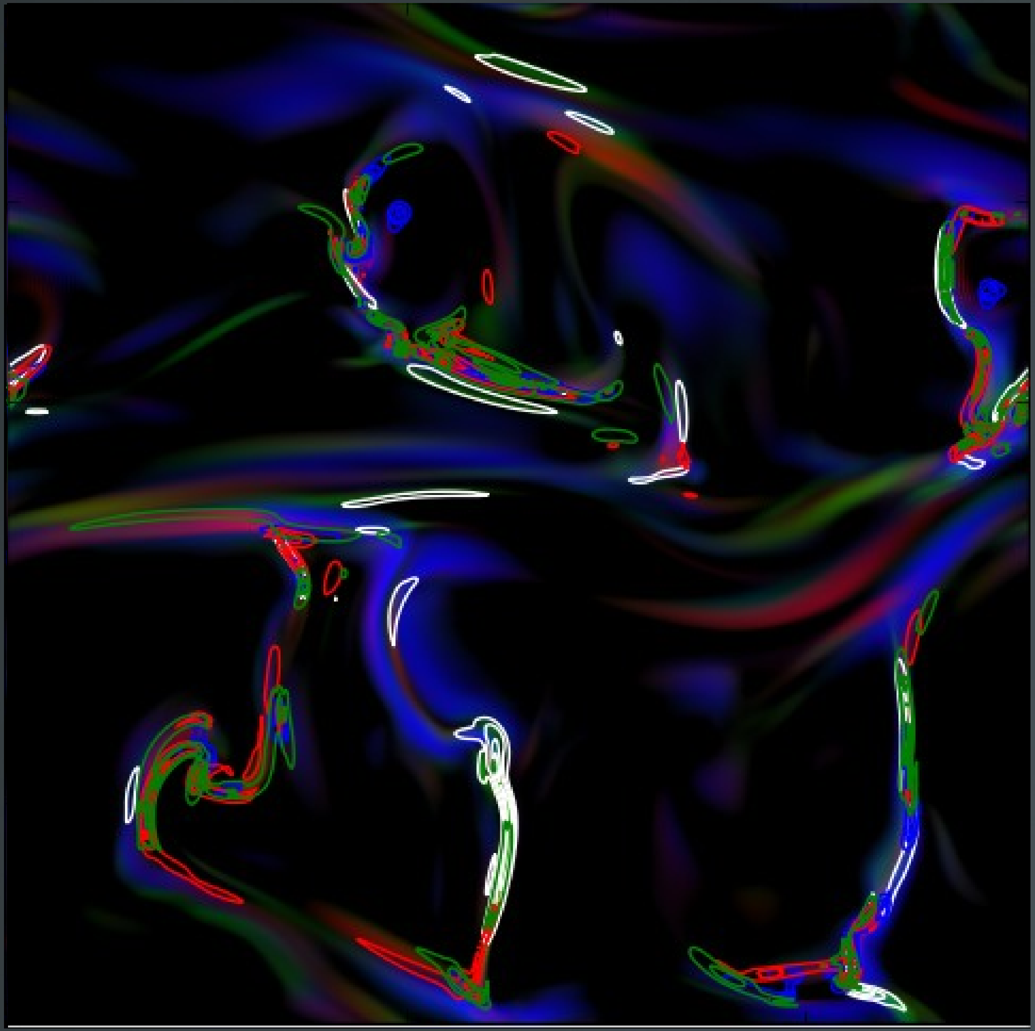
Assuming that total dissipation powers the line
(or that a chemical tracer appears right where there is heating):

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

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

Observable increments vs. dissipation

Lbox / 64



- <u>Background</u>:

Dissipation rates

Ohmic Viscous AD

- <u>Contours:</u>

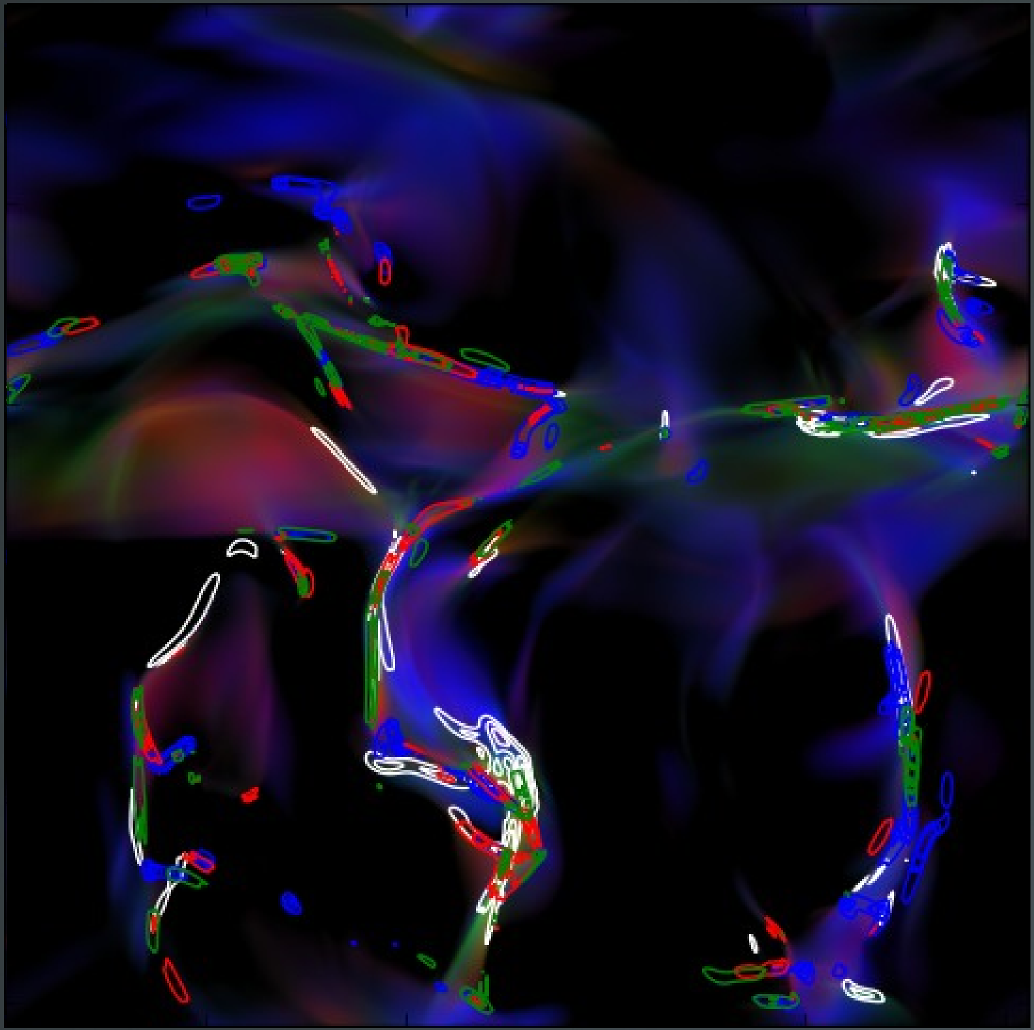
Increments of integrated observables:

- **LOS velocity (white)**
- **Stokes Q (green)**
- **Stokes U (red)**
- **POS polarisation angle (blue)**

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

Observable increments vs. dissipation

Lbox / 8



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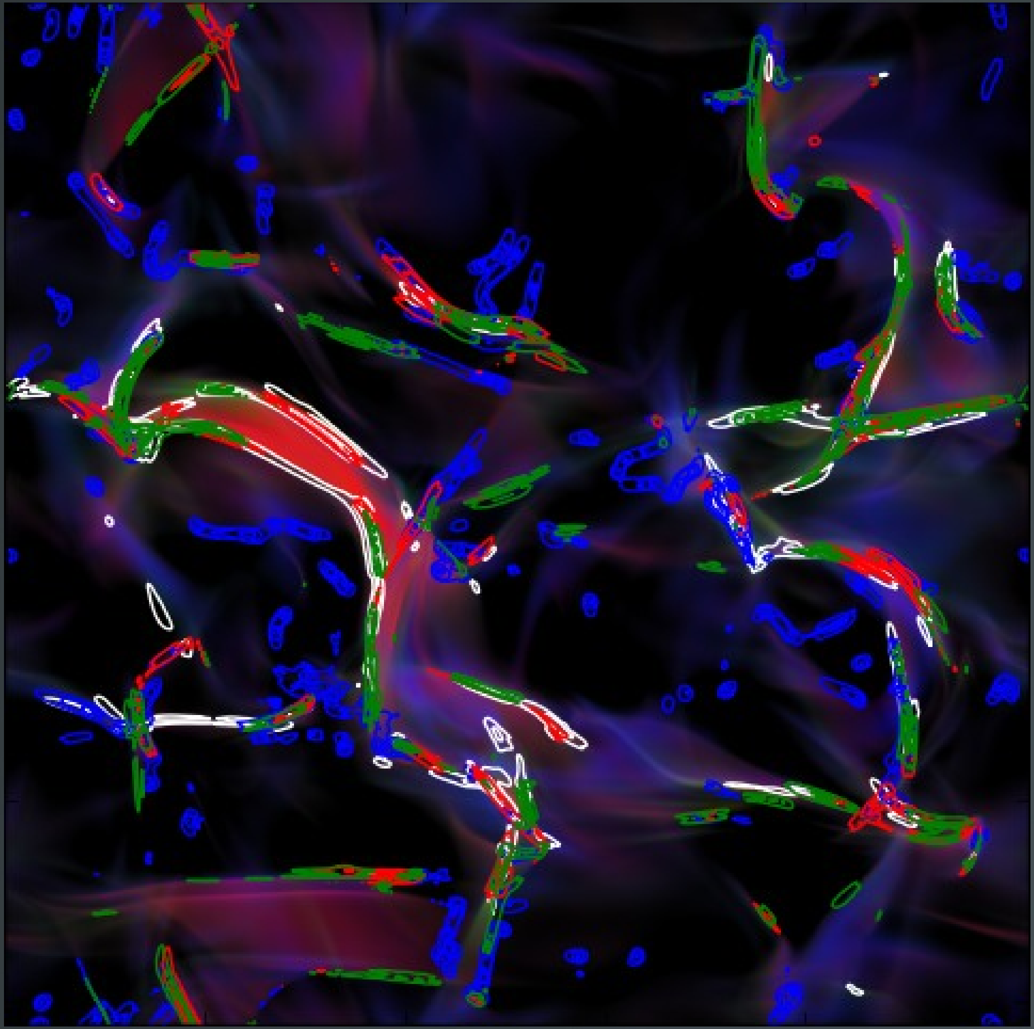
<u>NOTE:</u> increment of polarisation angle (blue contours) are less correlated to dissipation. Better use Q,U.

Observable increments vs. dissipation



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