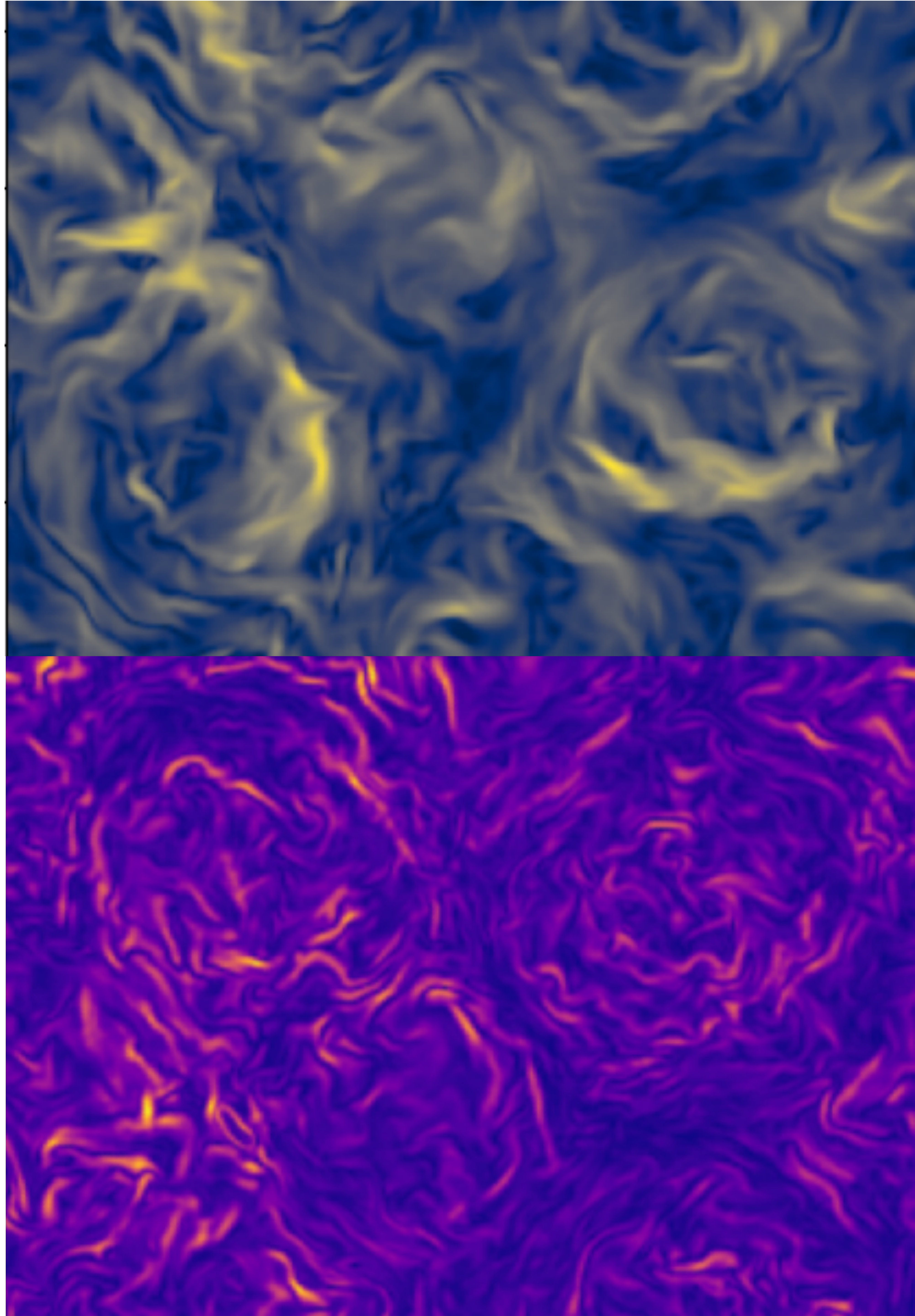
Compressible turbulence in 1D and 3D solar wind flux tubes

Idefix days 2024, Grenoble, France

Victor Réville



Turbulence in the solar wind

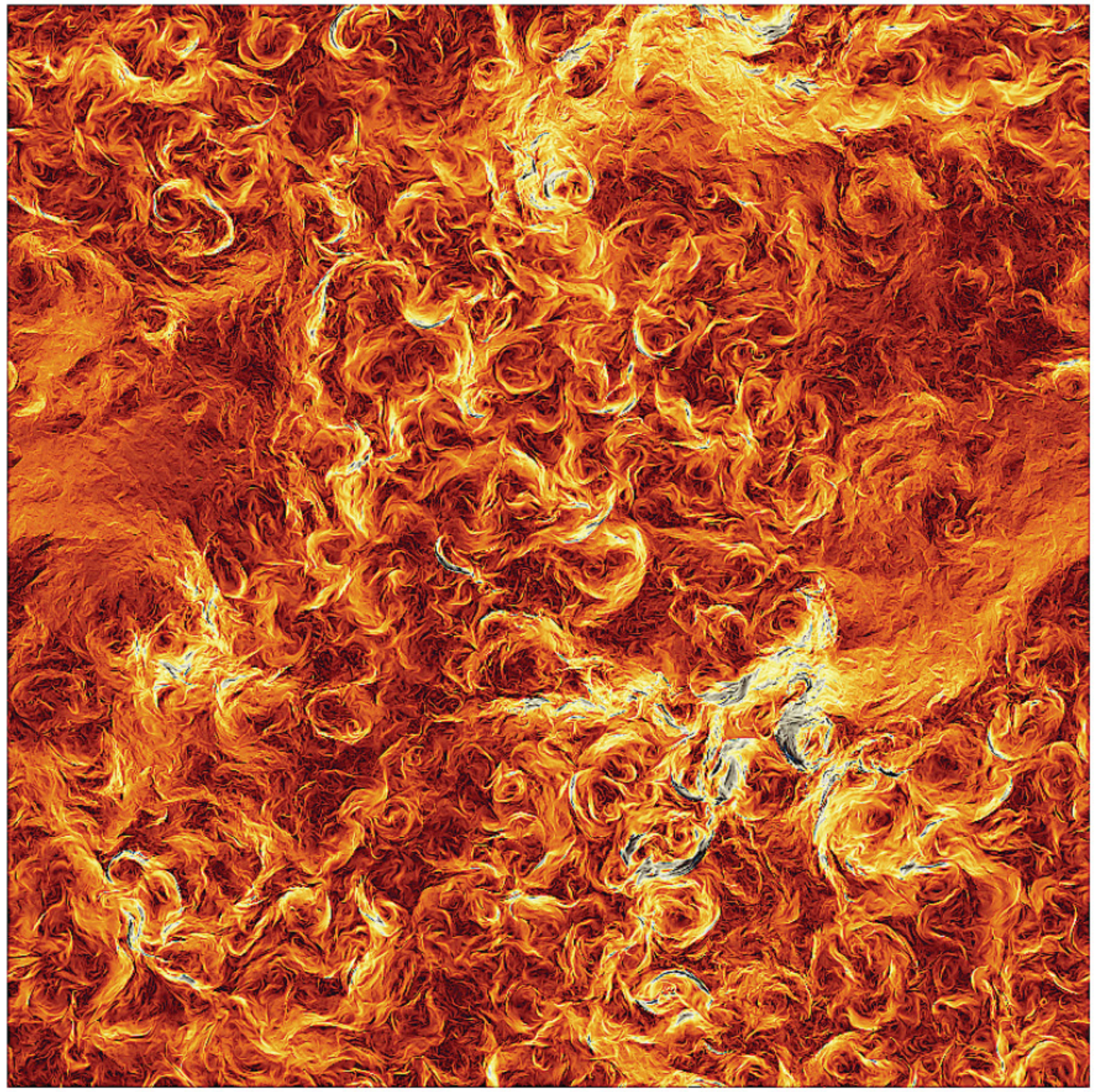
Incompressible theory

- Turbulence is believed to be the main heating source for the solar wind (and corona?)
- Theories usually consider non linear interactions of counter-propagating waves to be responsible for the cascade:

$$\mathbf{z}^{\pm} = \delta\mathbf{v} \pm \frac{\delta\mathbf{b}}{\sqrt{\mu_0\rho}} \qquad Q_w = \mathbf{z}^{\pm}\cdot\nabla\mathbf{z}^{\mp}$$

- The reflected component is created by reflection and forcing in the non-homogeneous expanding solar wind

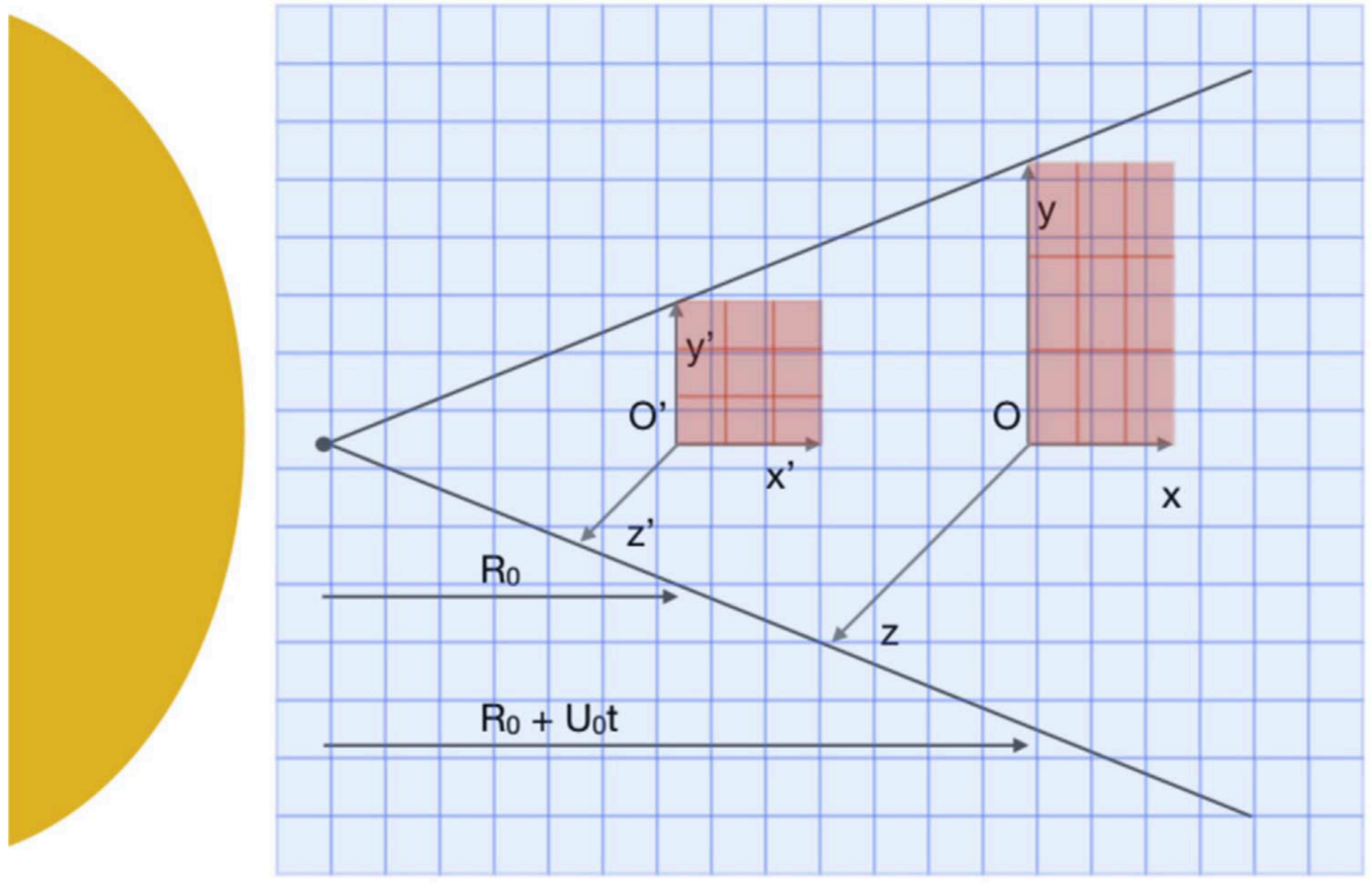
[Meyrand et al. 2024]

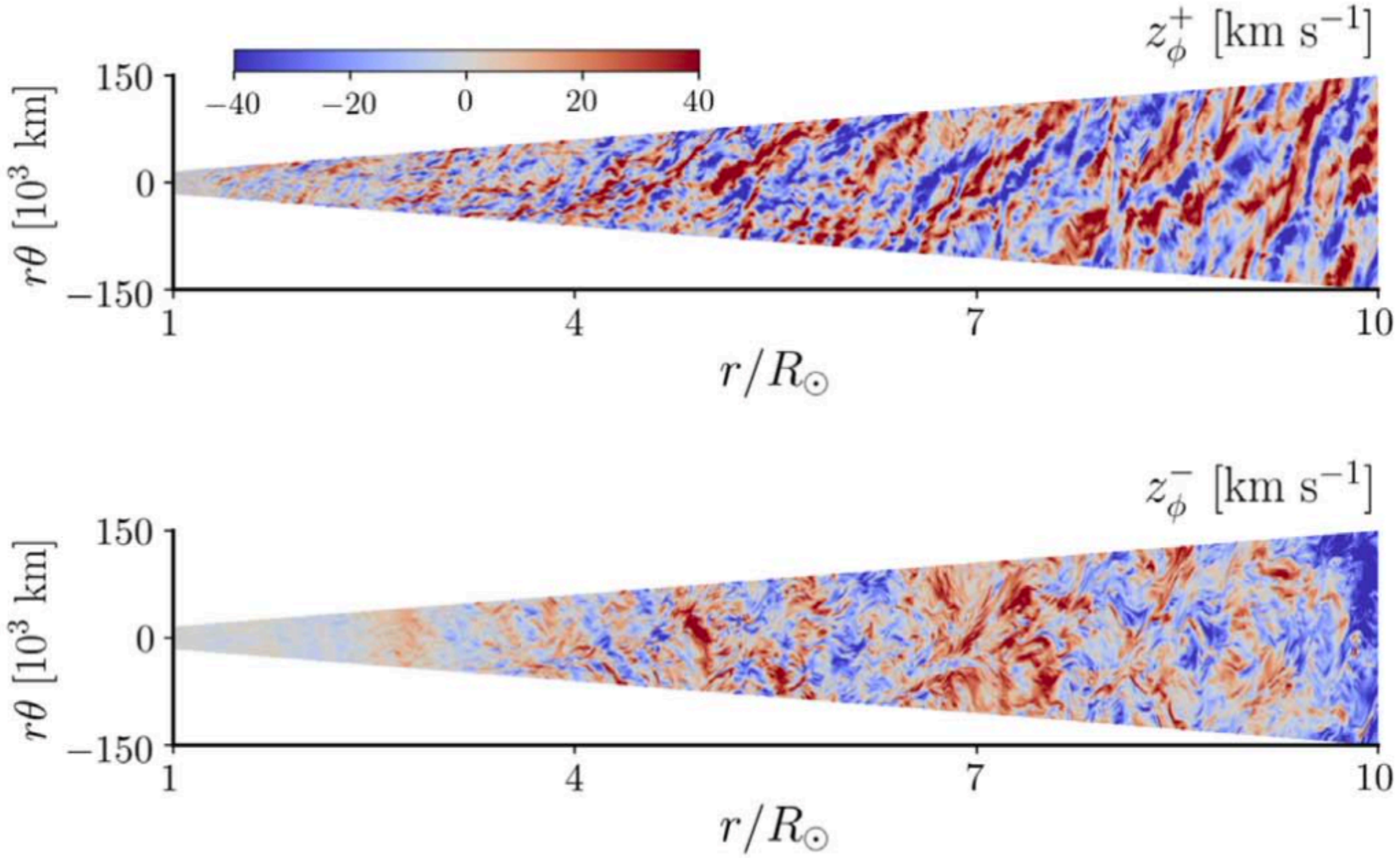


Turbulence in the solar wind

Models

- Solar wind turbulence is treated often with reduced equation (RMHD) and in periodic boxes.
- In particular the expanding box model [Grappin & Velli 1996] has been used extensively over the past few years
- This does not allow to treat the solar wind acceleration region (1-30 Rs) and the transition through the Alfvén point.
- Shoda et al. 2021 is the only work using full MHD + extended domain from the base of the solar wind



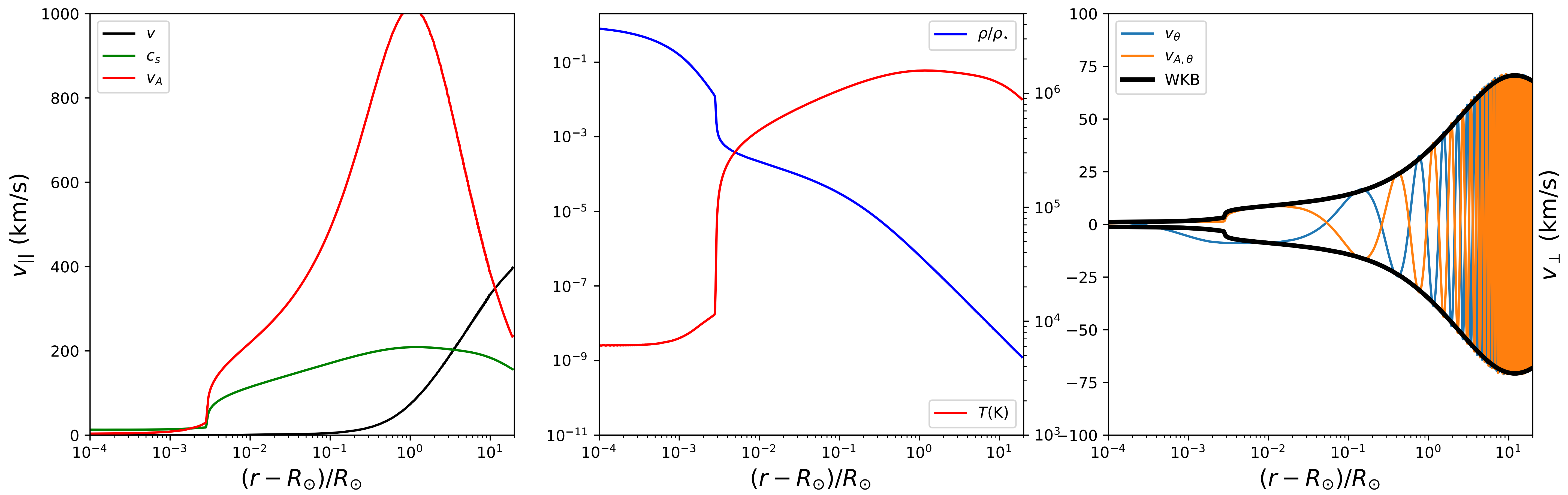


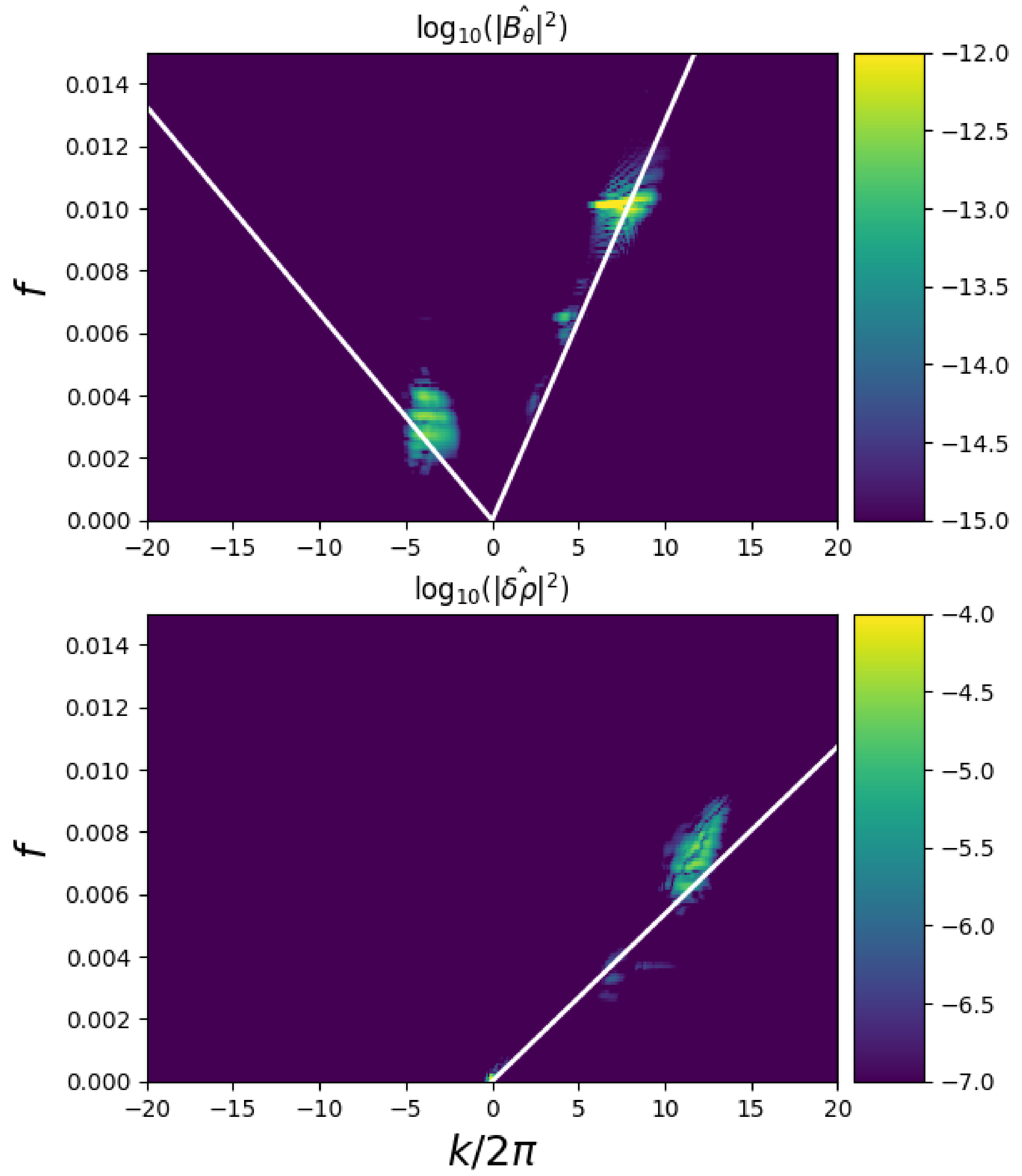
Parametric decay instability

1D setup

[Réville et al. 2018]

- PLUTO code: Godunov, HLLD, 1D/3C, Ideal MHD
- Waves injected from photosphere and through transition region





- Waves are unstable to parametric decay, a three waves resonance generating counter-propagating and sound waves (at lower frequency -> inverse cascade)
- Statistical steady state lead to balanced turbulence, with magneto-acoustic waves and shocks

3D simulations

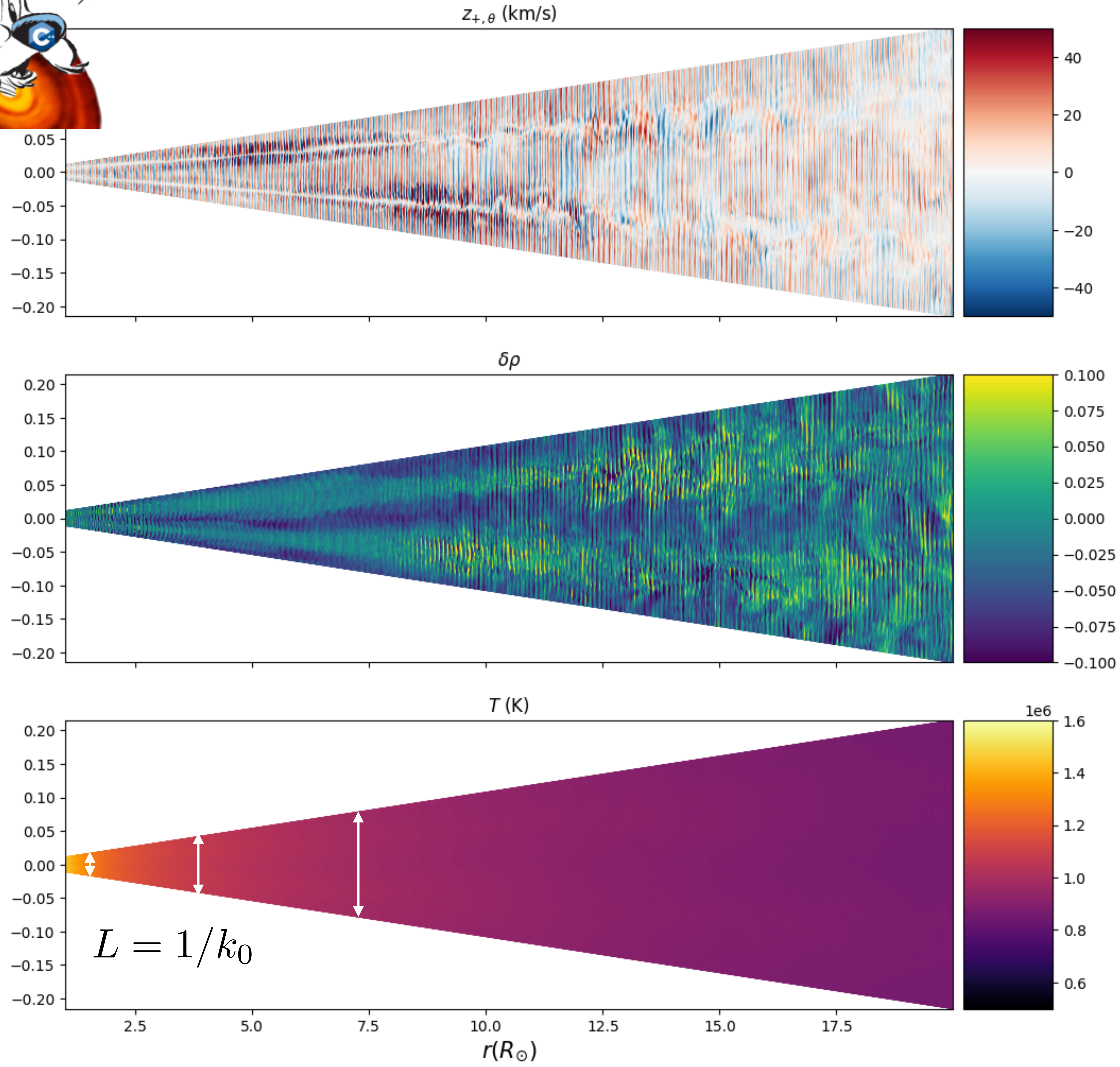
A new exascale code: Idefix

[Lesur et al. 2023]

https://github.com/idefix-code/

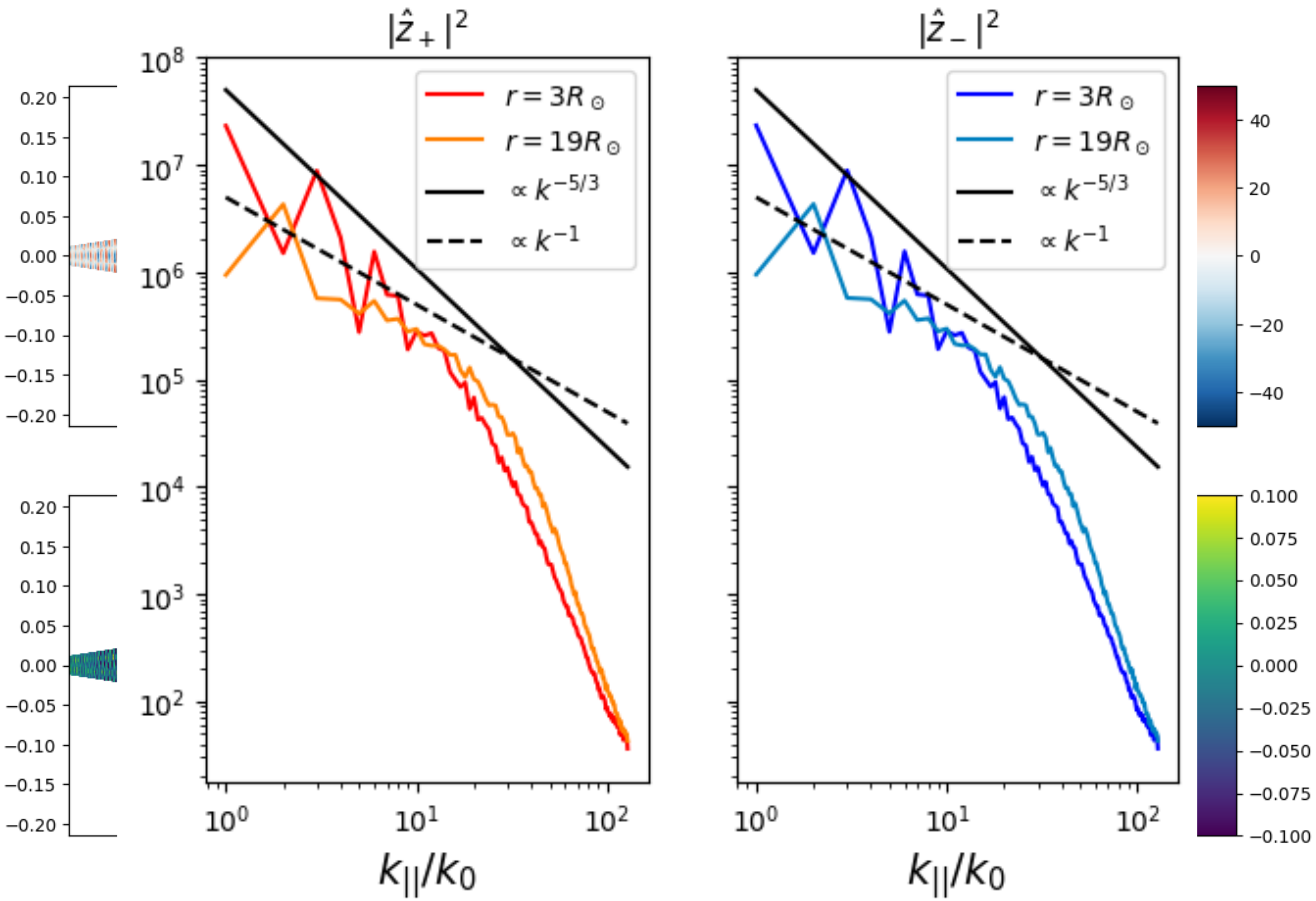
- Multi-architecture Godunov type solver based on Kokkos
- Solar wind flux tube 20 Rs x 1.2° x 1.2° [8192, 256, 256]
- Ideal MHD w/ polytropic wind initialization
- Forcing with monochromatic wave (unstable to PDI), with k0 perp modulation
- Run on 64 GPUs (v100)

[Réville 2024, in prep]



3D simulations

Energy transfer, cascade and dissipation

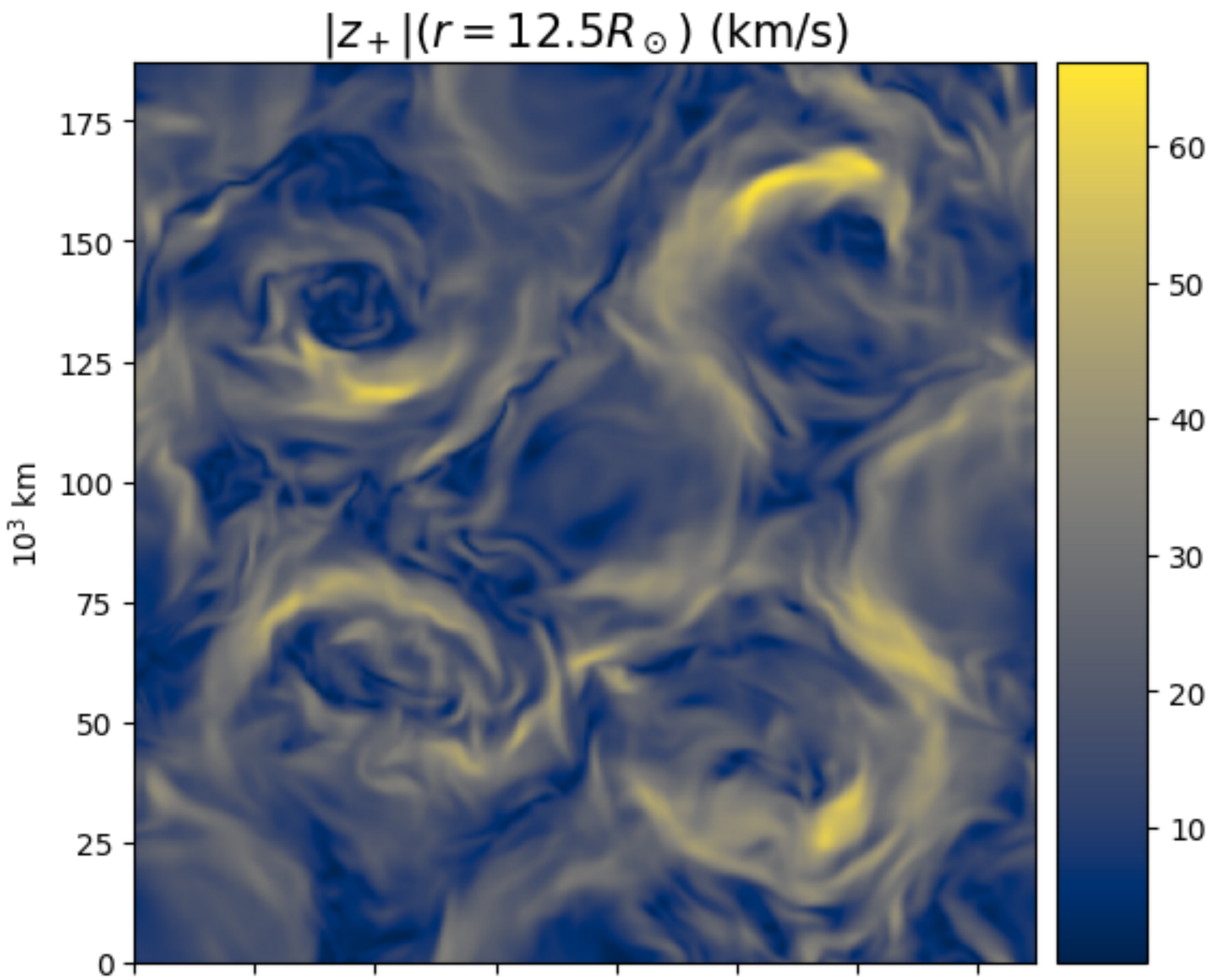


- Onset of parametric decay is clear through the density perturbations
- Balanced turbulence (z+ ~ z-)
- Slight increase in the solar wind temperature (turbulent dissipation)
- Spectra of the Elsasser variables yields the approximate level of the numerical dissipation
- Origin of this dissipation?

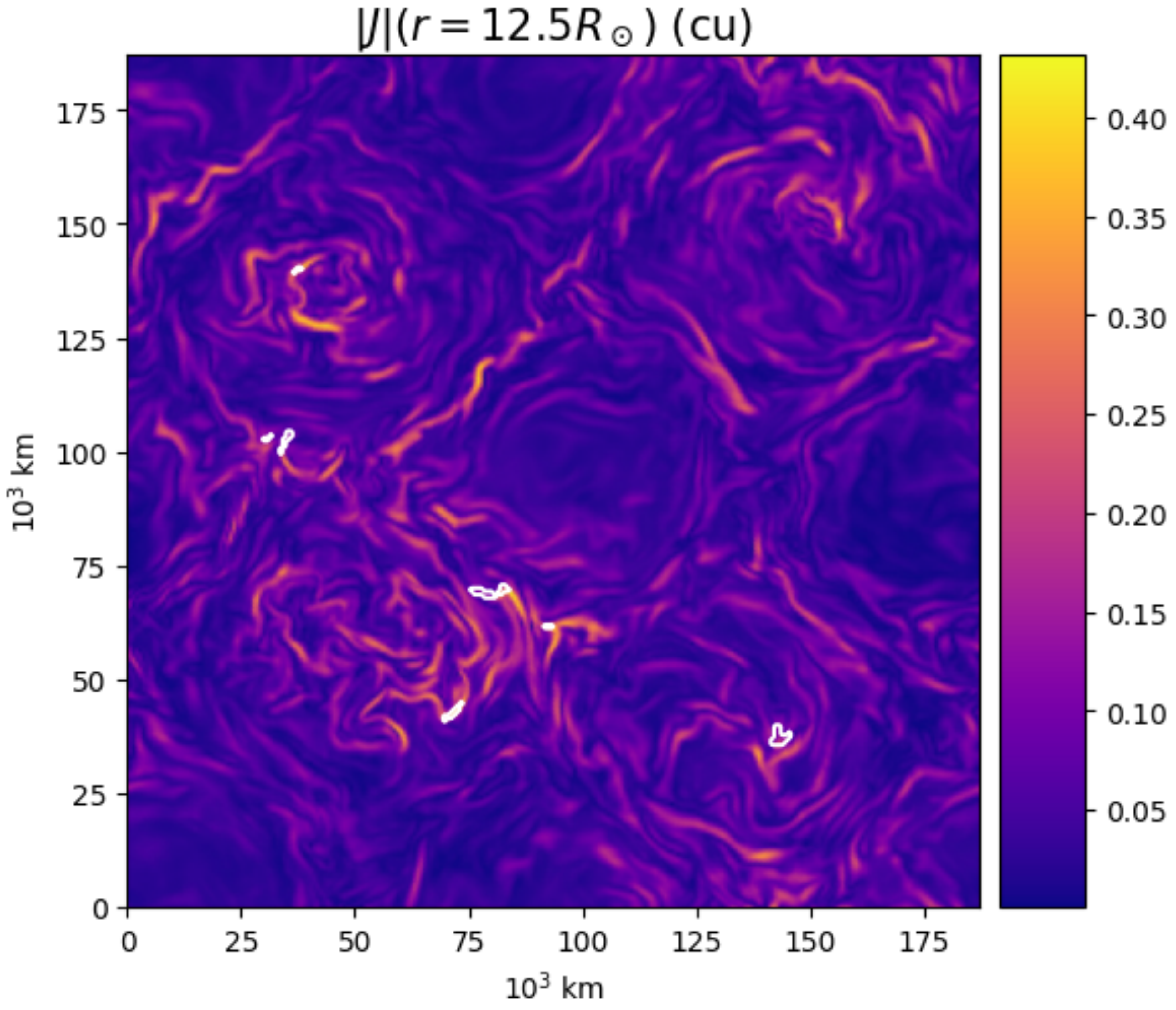
3D simulations

Energy transfer, cascade and dissipation

- Turbulent state with very few shocks (0.02%, compared to 2% of volume in 1D)
- Dissipation is likely due to numerical resistivity through currents



$|z_+|(r = 12.5R_\odot)$ (km/s)



$|J|(r = 12.5R_\odot)$ (cu)

3D simulations

Resistive simulations

- Used uniform and non uniform resistivity

$$\eta = \eta_0 \frac{r}{R_\odot}$$

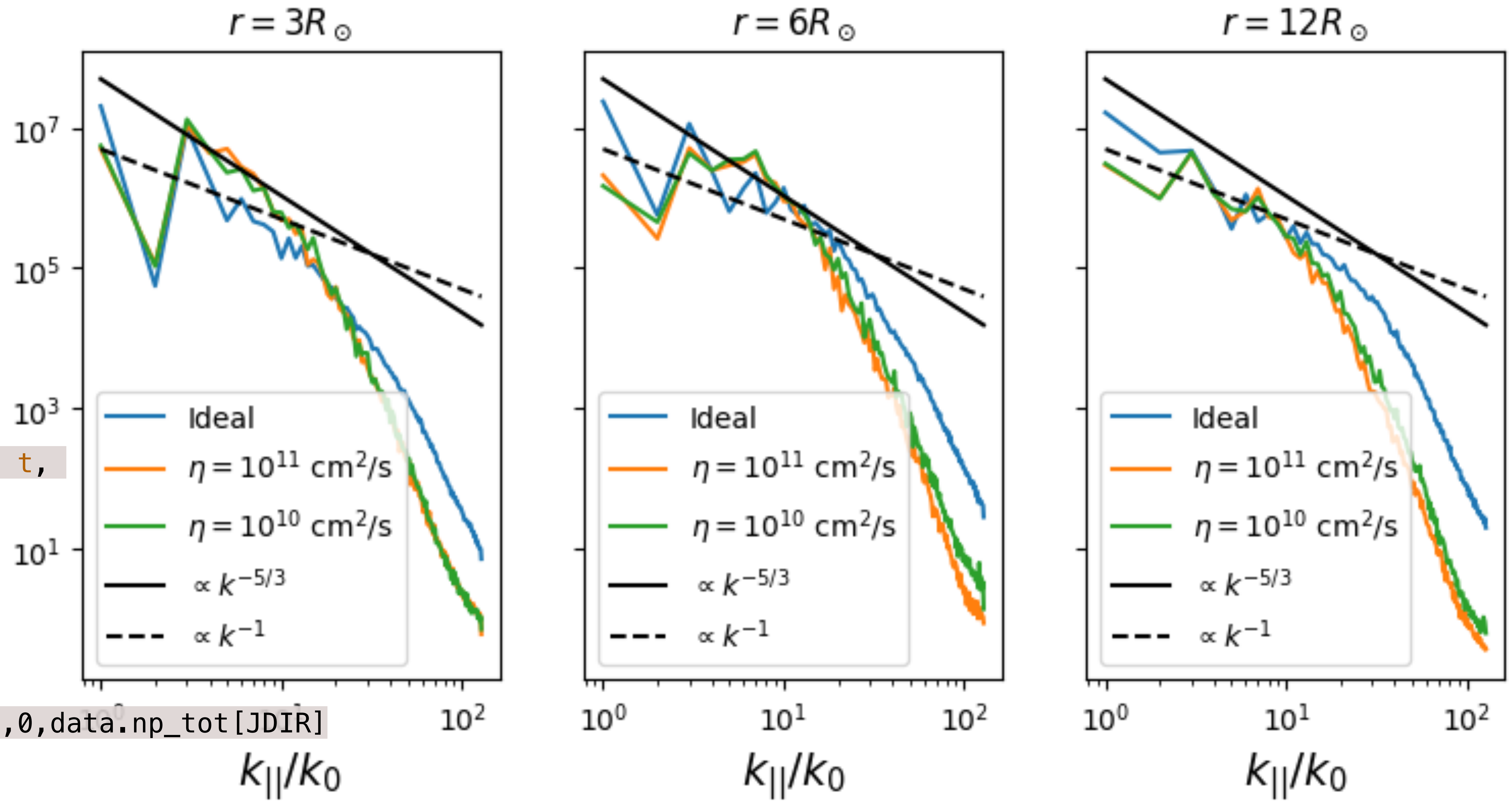
$$S = \frac{L v_A}{\eta} \sim 10^7 (\eta = 10^{11} \mathrm{cm}^2/s)$$

```
void MyOhmicDiffusivity(DataBlock &data, const real t,
IdefixArray3D<real> &Eta){

  IdefixArray1D<real> x1 = data.x[IDIR];
  real norm = ulenGlob*uvelGlob;
  real eta = eta_Glob/norm;


idefix_for("MyOhmicDiffusivity",0,data.np_tot[KDIR],0,data.np_tot[JDIR]
,0,data.np_tot[IDIR],
             KOKKOS_LAMBDA (int k, int j, int i) {
               //Eta(k,j,i) = eta;
               Eta(k,j,i) = eta*x1(i);
  });
}
```

$$|\hat{z^-}|^2$$



3D simulations

Thermal conduction

- Braginskii module by J. Kempf and F. Rincon

$$Q = \nabla \cdot q = \nabla \cdot (k_{||}(\mathbf{b} \cdot \nabla T)\mathbf{b} + k_{\perp}(\nabla T - \mathbf{b} \cdot \nabla T))$$

$$k_{||} = k_0 T^{5/2}$$ *Spitzer-Härm*

$$k_{\perp} = 0$$

```
void MyBragThermalConductivity(DataBlock &data, const real t,
IdefixArray3D<real> &kparArr, IdefixArray3D<real> &knorArr) {
  IdefixArray4D<real> Vc = data.hydro->Vc;
  IdefixArray1D<real> x2 = data.x[JDIR];
  real norm = 1.6726e-24*0.5/(udenGlob*uvelGlob*ulenGlob*1.3807e-16);
  real uTemp=0.5*uvelGlob*uvelGlob*1.6726e-24/1.3807e-16;
  real k0 = k0_Glob*norm;

idefix_for("MyThConductivity",0,data.np_tot[KDIR],0,data.np_tot[JDIR],0,data
.np_tot[IDIR],
             KOKKOS_LAMBDA (int k, int j, int i) {
               kparArr(k,j,i) = k0*Vc(RHO,k,j,i)*pow(Vc(PRS,k,j,i)/
Vc(RHO,k,j,i)*uTemp,2.5);
               knorArr(k,j,i) = 0.;
             });
}
```

- In PLUTO, this term was necessary to heat the solar wind through shocks without crashing the code

- Tests are ongoing for Idefix

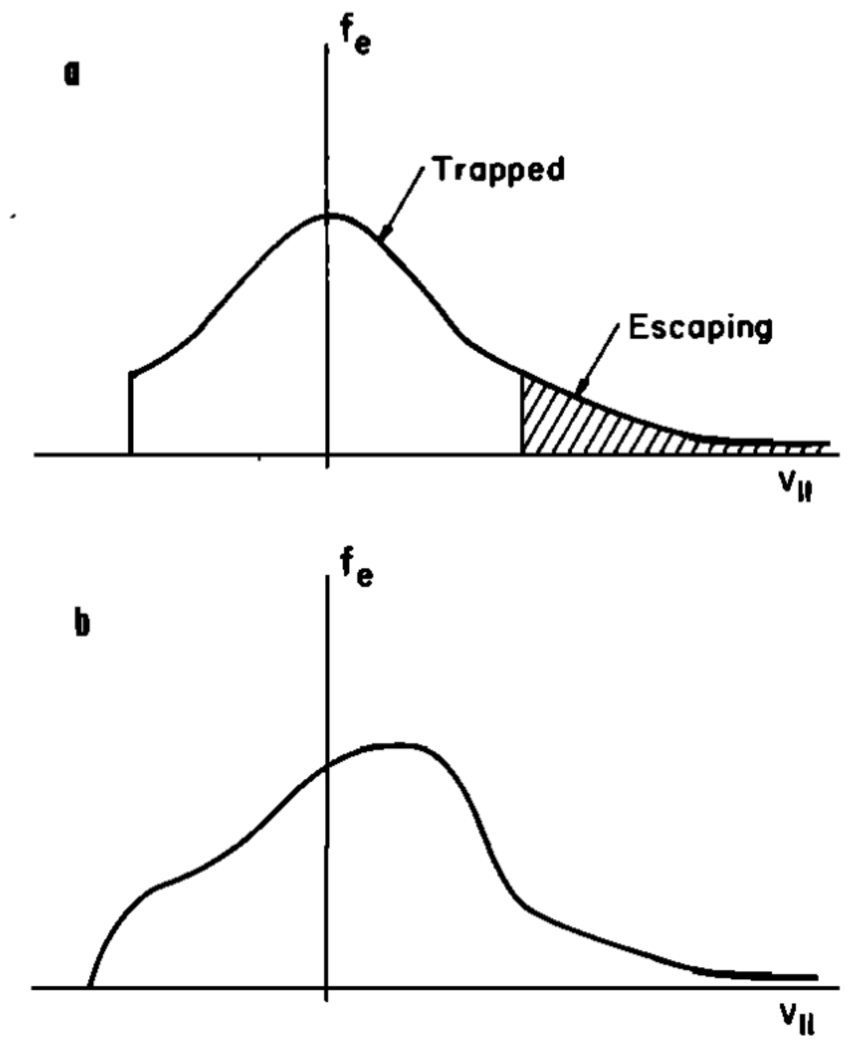
3D simulations

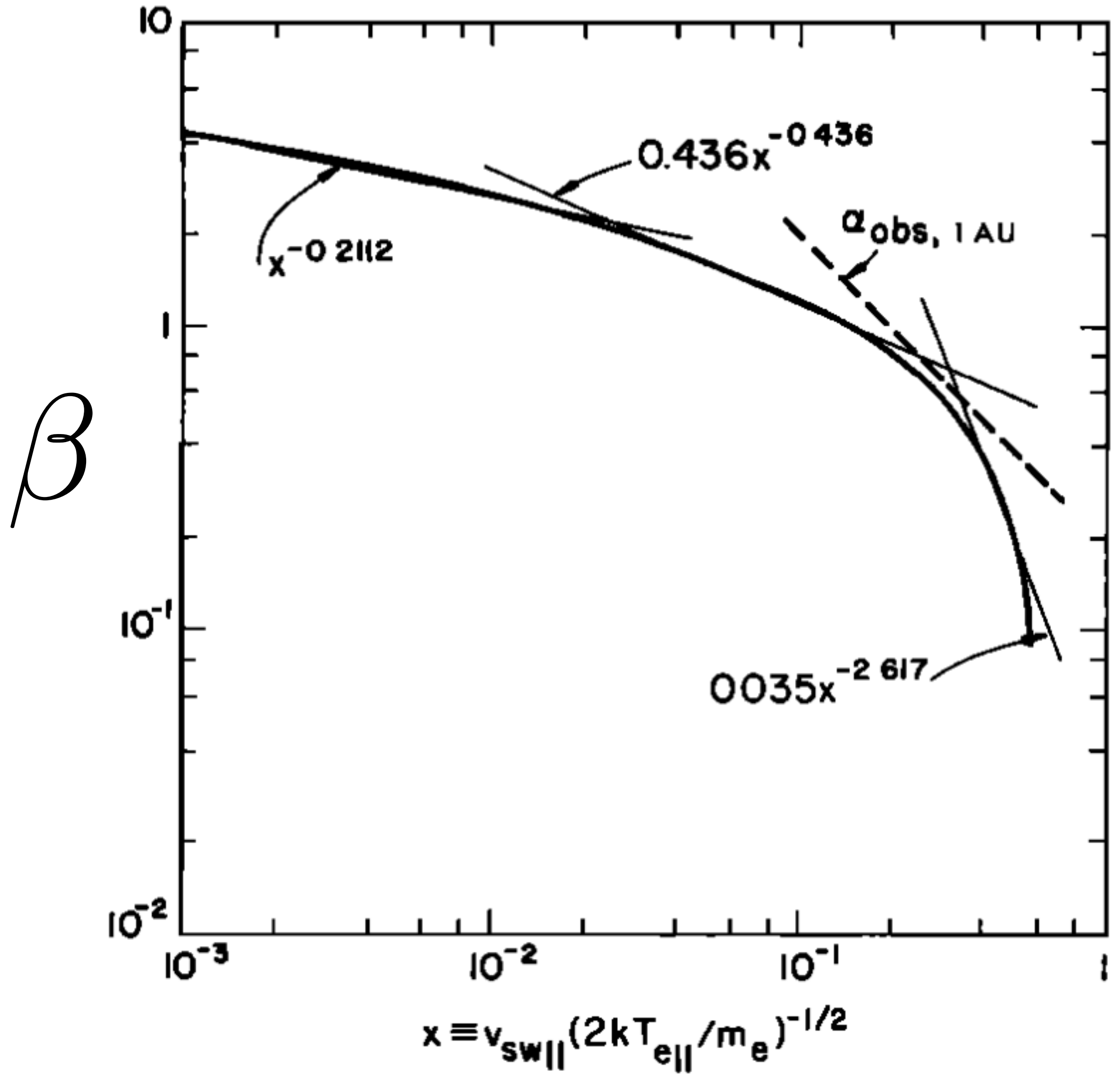
Thermal conduction

- Collisionless thermal conduction [Hollweg 1976]

Heat flux due to non thermal escaping electrons

$$q = \alpha k_{||}(\mathbf{b}\cdot\nabla T)\mathbf{b} + (1-\alpha)\beta\frac{3}{2}p\mathbf{v}$$





Two ways of modeling this:

1) Modify current Braginskii implementation to add a term k_par that does not depend on grad T

2) Allow for a variable gamma in the domain:

$$\gamma' = 1 + \frac{\gamma(\gamma-1)}{\gamma+\beta(\gamma-1)}$$

$$\gamma_{\text{eff}} = \alpha\gamma + (1-\alpha)\gamma'$$