Towards efficient, resistive, multi-fluid merger simulations

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arXiV:1906.03150

Non-ideal MHD is needed

MHD misses out on:

- correct EM fields (interior/exterior);
- magnetic reconnection;
- accretion;
- entrainment.

So far:

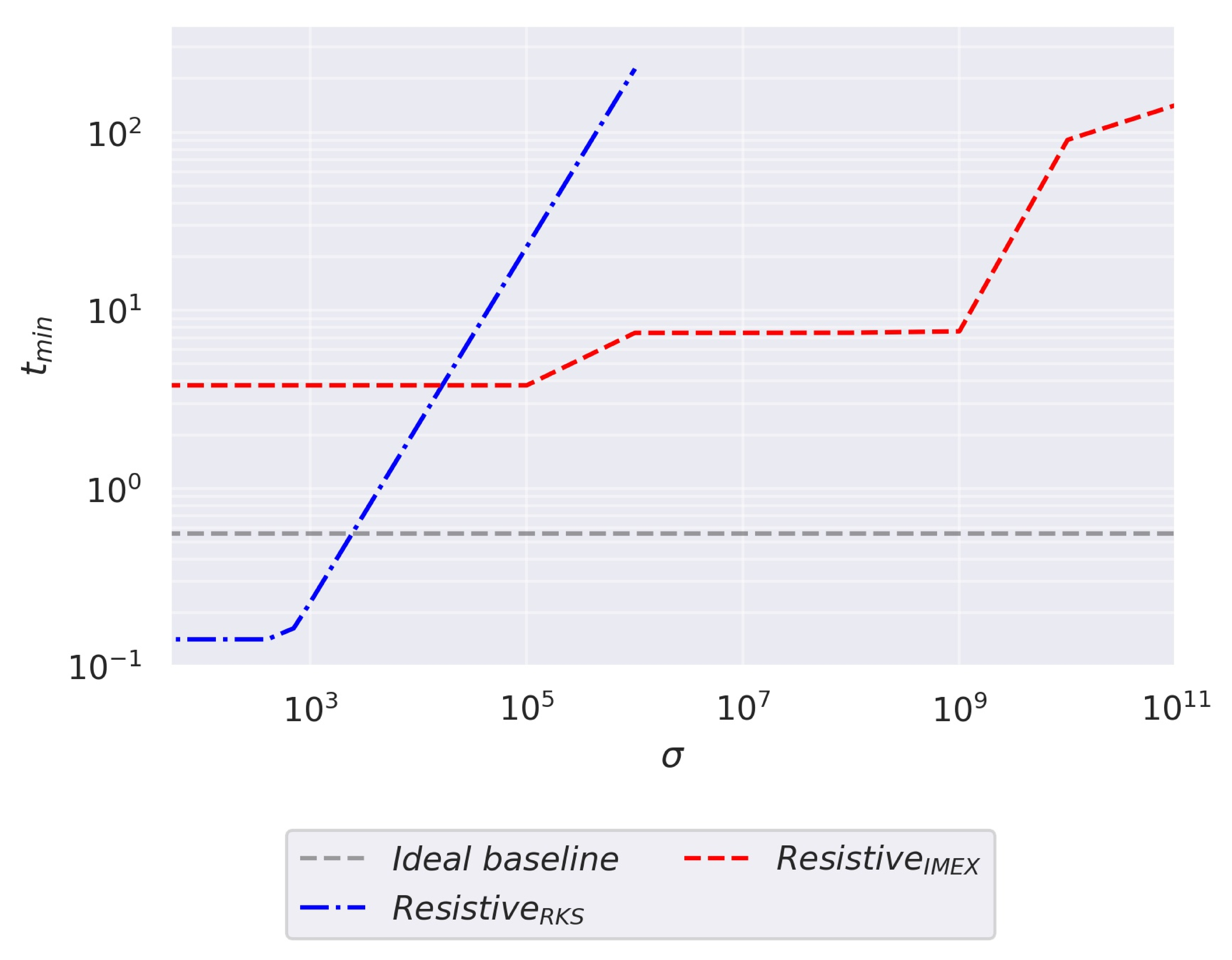
- Resistive GRMHD by Dionysopoulou (2013), Palenzuela (2009), Qian (2016);
- Charged multi-fluid by Andersson (2017), Amano (2016).

Difficulties

- More realistic models can be stiff;

$$\partial_t q = \mathcal{F}(q) + \frac{1}{\epsilon}\mathcal{S}(q)$$

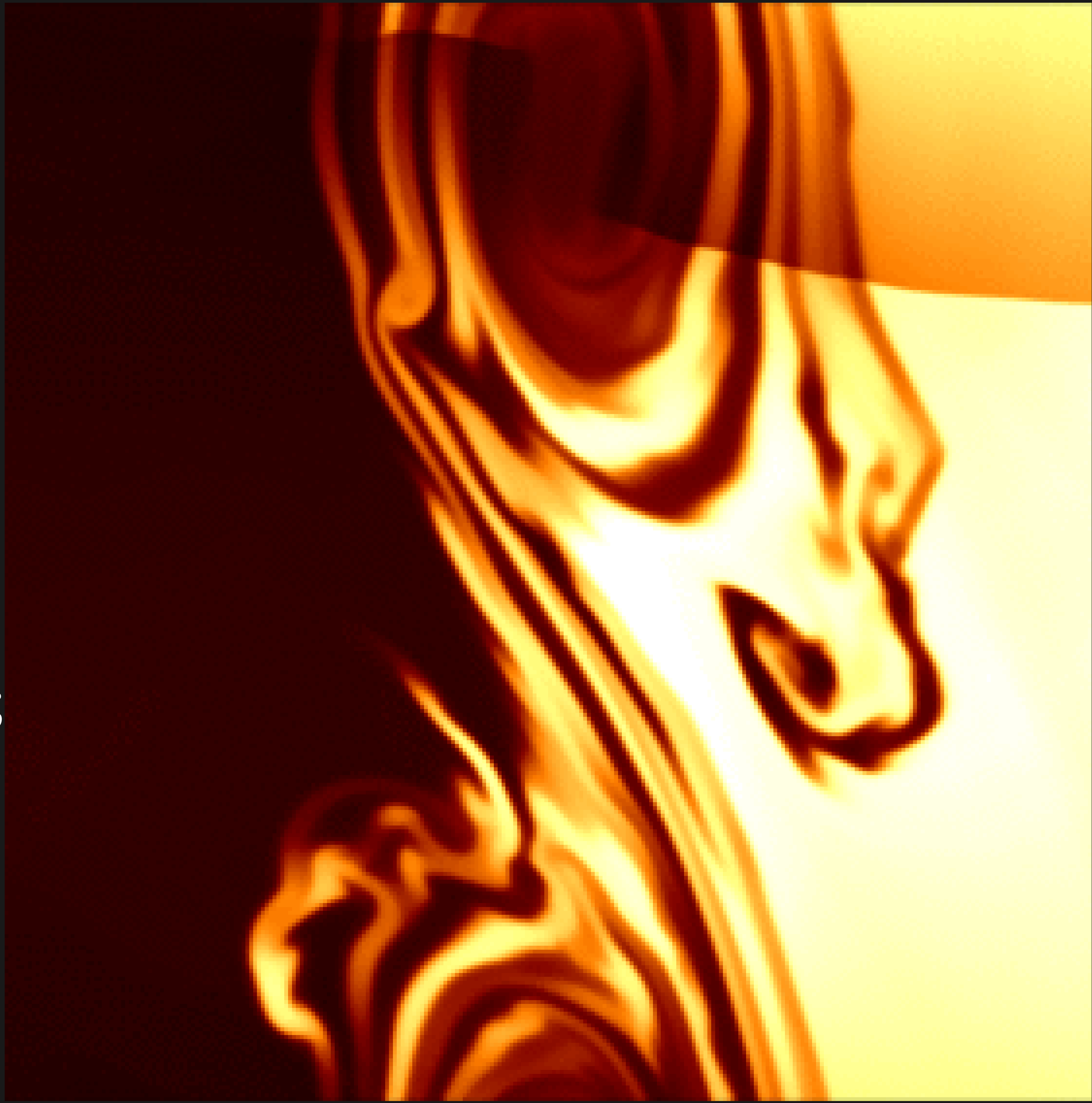
- Require implicit schemes for stability, e.g. IMEX (Pareschi & Russo 2004).



METHOD:

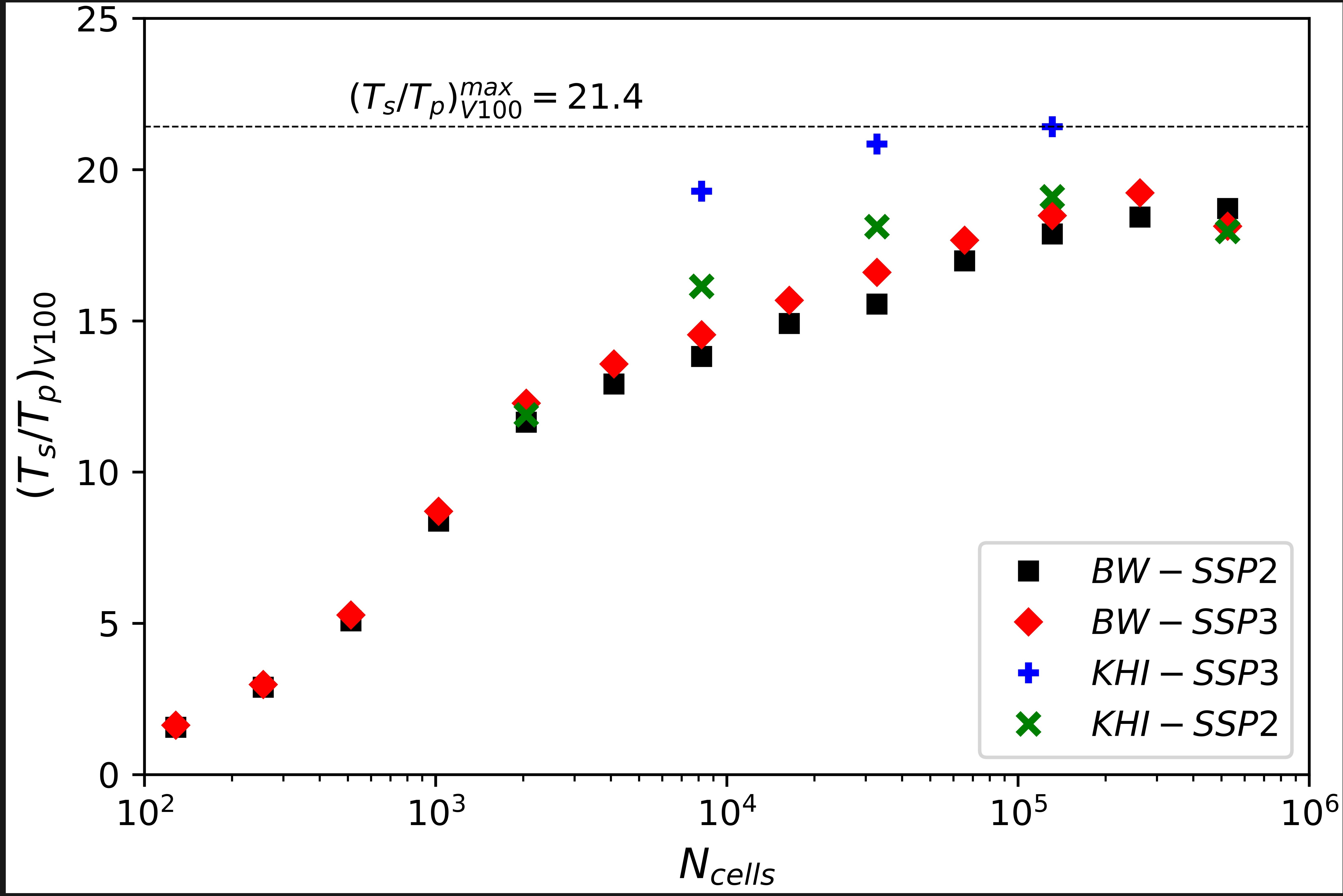
- Lightweight, multi-physics MHD code;
- Ideal and resistive single and two-fluid models;
- Explicit or implicit integration;
- GPU capable.

github.com/AlexJamesWright/METHOD



Performance

- Parallel speed up of $21\times$ versus CPU;
- Further optimisations possible;
- Wright & Hawke arXiV:1808.09721 DOI:10.3847/1538-4365/aaf1b0.



Model extensions

Examples from:

- Classical turbulence simulations (LES)
- Radiative/reactive flows
- Radice (2017) - GRLES
- Giacomazzo (2015) - subgrid source

Source terms allow:

- Easy way to add additional physics
- Computationally cheaper than solving full model

REGIME:

A resistive extension to ideal MHD*

*arXiV:1906.03150

- Start from resistive MHD, $\overline{q}$ stiff:

$$\partial_t q + \partial_x f(q, \overline{q}) = s(q, \overline{q})$$
$$\partial_t \overline{q} + \partial_x \overline{f}(q, \overline{q}) = \frac{1}{\epsilon}\overline{s}(q, \overline{q}).$$

- Chapman-Enskog expansion around ideal MHD:

$$\overline{q} = \overline{q}_0 + \epsilon \overline{q}_1 + \mathcal{O}(\epsilon^2)$$
$$\rightarrow \quad \partial_t q + \partial_x f = s + \epsilon \partial_x (D \partial_x q).$$

Extension

To first order in ϵ:

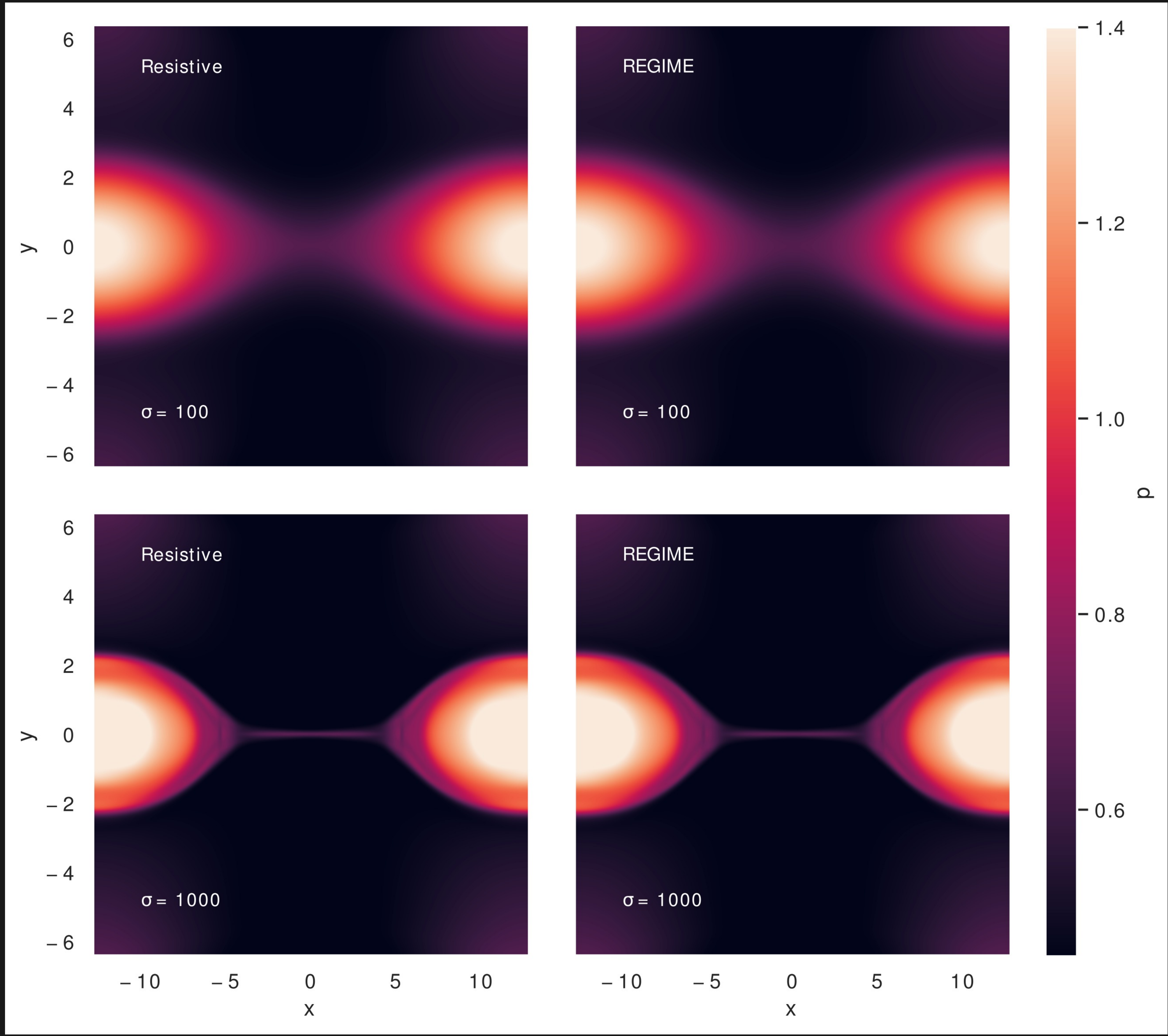
$$\partial_t q + \partial_x f = s + \epsilon \partial_x (D \partial_x q).$$

Features:

- New system extends ideal MHD;
- Stiff in opposing limit to resistive MHD as $\epsilon \propto 1/\sigma$;
- Small contribution near ideal MHD limit.

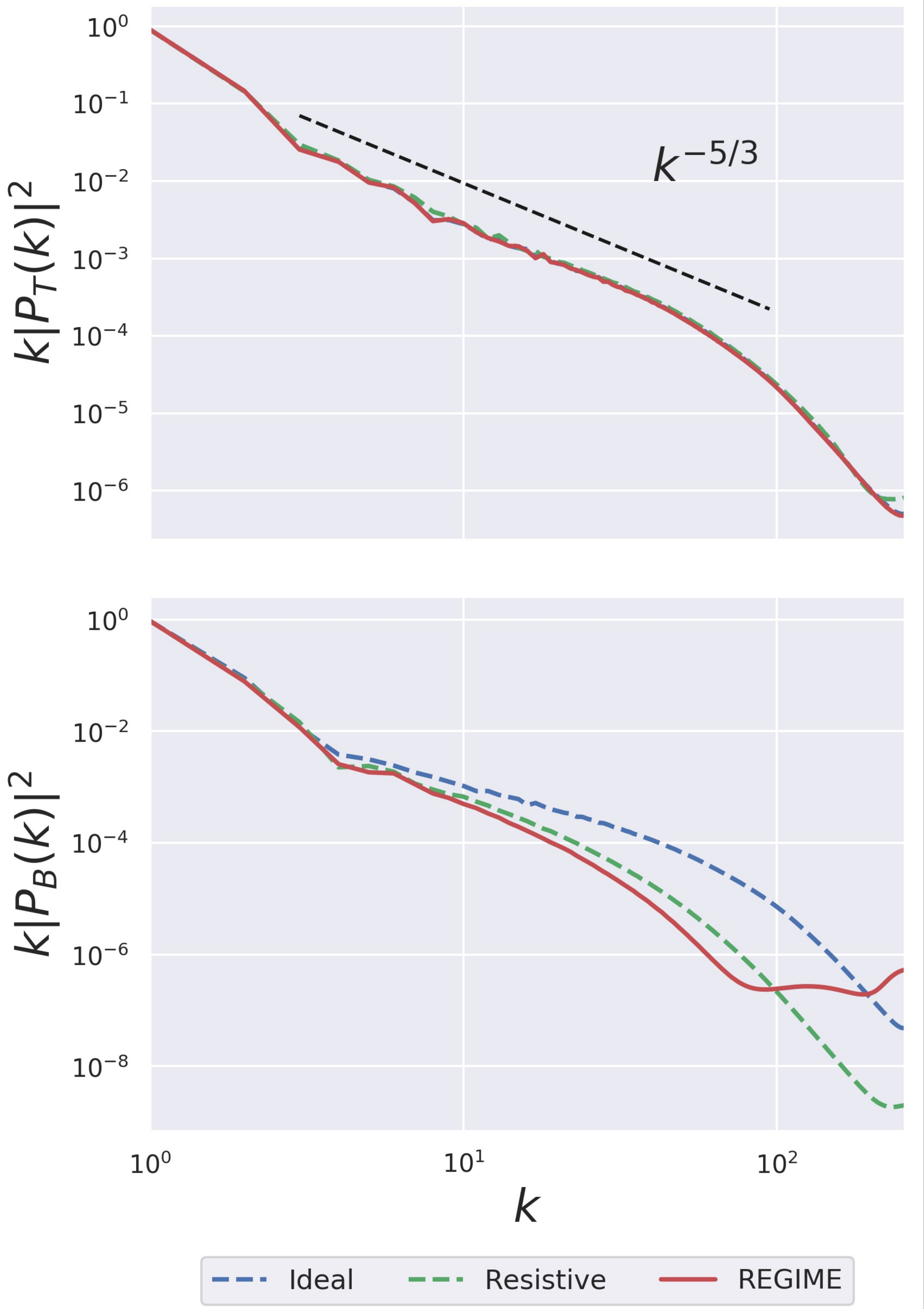
Reconnection

- Extremely good agreement with resistive MHD;
- Expected convergence with conductivity.



Kelvin-Helmholtz Instability

- Magnetic energy cascades to all scales;
- Good agreement with resistive MHD at larger scales;
- The source term approach is *not* capturing subgrid behaviour.



Performance

Many factors faster than full model.

Summary

- Resistive extension to ideal MHD
  - completed in SR with encouraging results (arXiV:1906.03150);
  - in progress in GR;
  - results match full model in a fraction of the time;
  - application to GRMHD will allow merger, accretion and MRI studies;
  - method could be useful for multi-fluid and radiative models.