Full-f gyrofluid turbulence
and magnetic reconnection

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Research group "Nonlinear Dynamics and Complex Systems"

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FWF Der Wissenschaftsfonds. | EUROfusion | universität innsbruck

Poster Session 3:

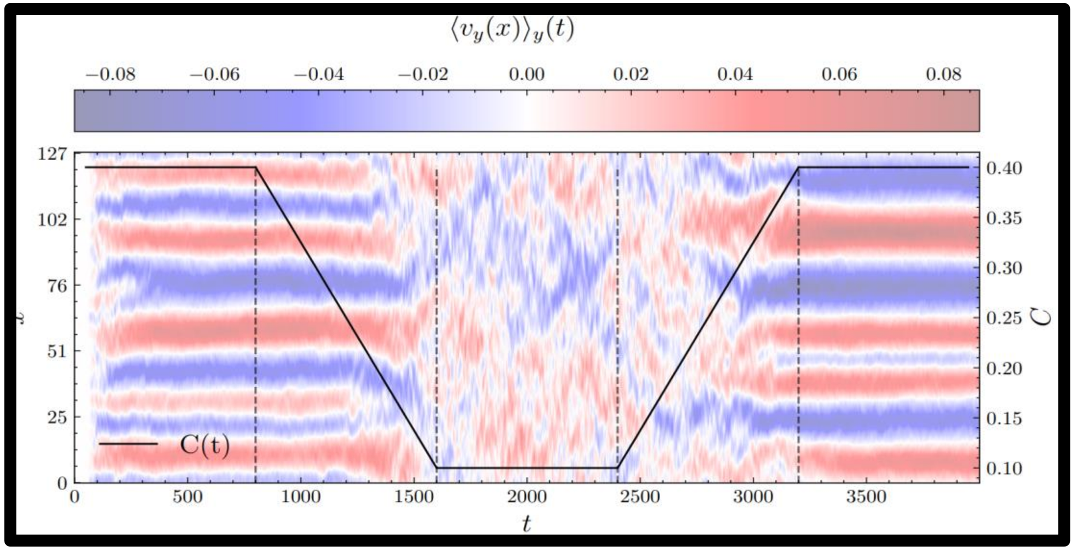
Testing approximations to the full-f polarization equation

$$\frac{\Gamma_1}{\sqrt{\Gamma_0}}(N_e - N_i) = \nabla \cdot \left(\frac{m_i N_i}{B^2} \nabla_\perp \sqrt{\Gamma_0}\phi \right)$$

$$N_i = 1$$

$$N_i = N_{initial}$$

$$N_i(x,y) = N_{i_{yavg}}(x)$$



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Gyrofluid model(s) in various implementations

FELTOR

- Library based,
  combines various different simulations.
- cuda-parallelization for HPC
- global geometry
- https://feltor-dev.github.io/

T3p,T3g

- 3D electromagnetic
- flux tube geometry
- delta-f, full-f, full-k
- thermal (work in progress)
- open field lines

Greeny

- 2D magnetic -
  reconnection Code
- delta-f, full-f, low-k, full-k
- thermal (work in progress)
- https://git.uibk.ac.at/c74413
  15/greeny

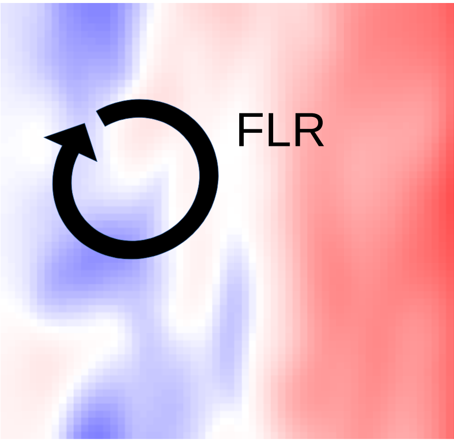
TIFF

- 2D drift wave, interchange,
  impurity,
- delta-f, full-f, low-k, full-k

Gyrofluid model(s) for magnetized plasma turbulence

Pros:

- consistent **FLR (finite Larmor radius)** effects for arbitrary $\tau = T_i / T_e$
- trans-collisional closure (but possible Braginskii amendments)
- Landau damping model (for thermal fluctuations)
- computationally efficient (**2-3 orders of magnitude faster than g.k.**)



Cons:

- can not (well) treat trapped particles (?)
- can not (well) treat ion orbit loss effects (?)
- can not (yet) reproduce g.k. zonal flow damping (?)
- can not treat kinetic sheath (energetic tails ?)
- ...

→ gyrokinetic ?
→ fully kinetic ??

... but may be able to develop approximate **models** for missing kinetic effects
(to be critically tested by comparison between g.f. and g.k. codes)

Polarisation equation in delta-f / full-f / low-k / full-k forms

Consistent polarisation equations (i.e. quasineutral "Poisson equation" for electric potential):

→ **Recent re-derivation of full-f gyrofluid model for arbitrary wavelengths ("full-k"):**

M. Held, M. Wiesenberger, A. Kendl: *Padé-based arbitrary wavelength polarization closures for full-f gyro-kinetic and -fluid models*. Nuclear Fusion **60**, 066014 (2020).

Polarization equation: $$\sum_\alpha qN - \nabla \cdot \boldsymbol{P} = 0$$

(sum over species α)

$$\boldsymbol{P} = \boldsymbol{P}_1 + \boldsymbol{P}_2$$

$$-\nabla \cdot \boldsymbol{P}_1 = \sum_\alpha q\left(\Gamma_1^\dagger - 1\right) N$$

NEW: 2nd order full-f full-k: $$\boldsymbol{P}_2 \approx -\sum_\alpha \frac{q^2}{m} {}^{1}_{2}\check{\Gamma}_1^\dagger \frac{N}{\Omega^2} {}^{1}_{2}\check{\Gamma}_1 \nabla_\perp \phi$$ and $$\psi_2 \approx -\frac{q}{2\,m\Omega^2}\left|{}^{1}_{2}\check{\Gamma}_1 \nabla_\perp \phi\right|^2$$

→ correct delta-f full-k limit: $$-\nabla \cdot \boldsymbol{P}_2 \approx \sum_\alpha \frac{q^2 N_0}{m\Omega^2 \rho_0^2}\left(\Gamma_0 - 1\right)\phi$$

with gyro-averaging operator $$\Gamma_1 \approx \sqrt{{}^{1}_{2}\Gamma_0} = \sqrt{{}^{1}_{2}(\Gamma_1^2)} = \frac{1}{\sqrt{1-\rho^2\Delta_\perp}} =: {}^{1}_{2}\check{\Gamma}_1$$

→ **more complicated numerical solver (= extract ϕ when N_α are known)**

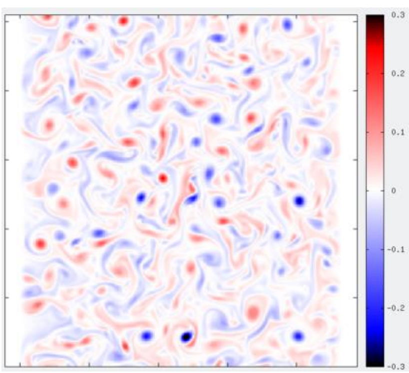
First 2-d (isothermal) gyrofluid simulations with the new full-f full-k model

Here: gyrofluid modified Hasegawa-Wakatani drift wave turbulence model

$\alpha = 0.05$, $n_0 = 0.25\text{-}1.75$, $\tau = 1$ (Pade), bath $\delta n_0 = 0.05$, $L = 96^2$, $n = 256^2$, $t = 500\ L_n/c_s$

"original" mHW:

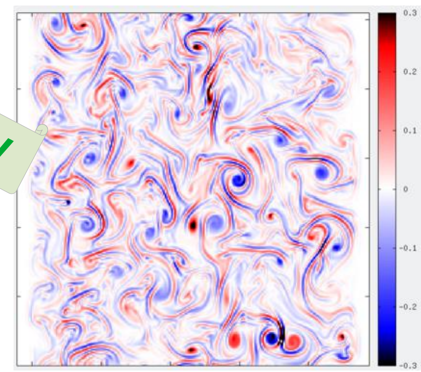
delta-f $\tau = 0$



Ω

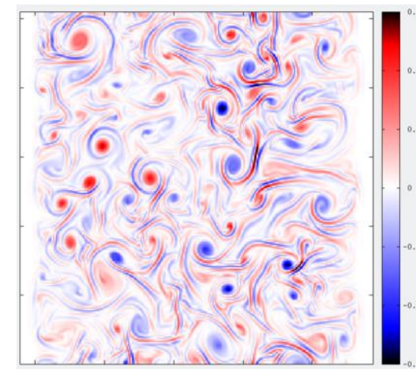
full-f full-k

NEW



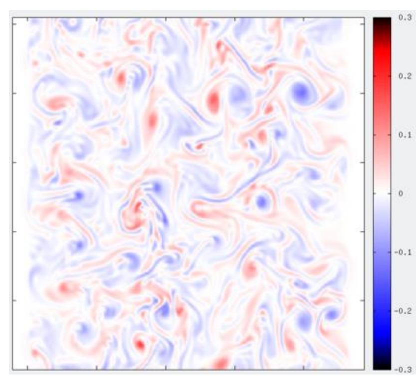
Ω

delta-f full-k



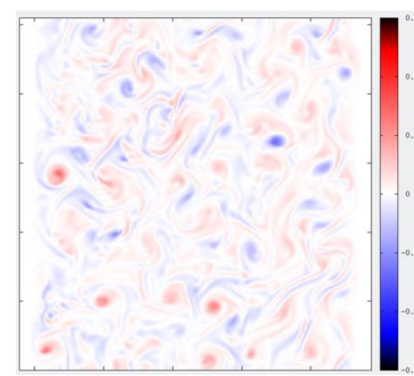
Ω

full-f low-k



Ω

delta-f low-k

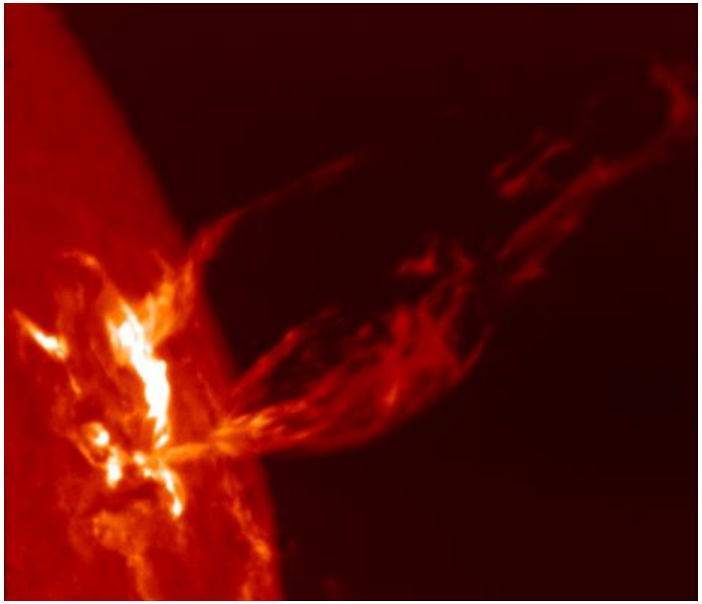


Ω

Magnetic reconnection

Where does it occur?

- Solar corona: heating and solar flares
- Earth‘s magnetosphere
- Tokamak:
  - Island formation
  - Sawtooth crashes



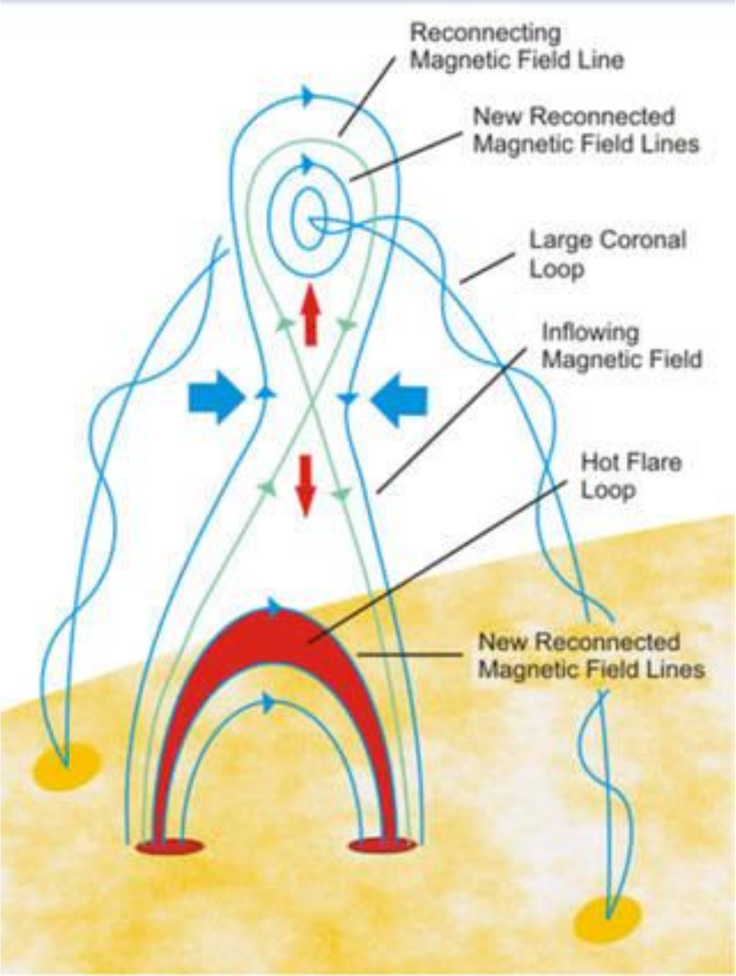


figure: https://www.nasa.gov/content/goddard/mms/nasa-to-investigate-magnetic-explosions

Magnetic reconnection in Fusion

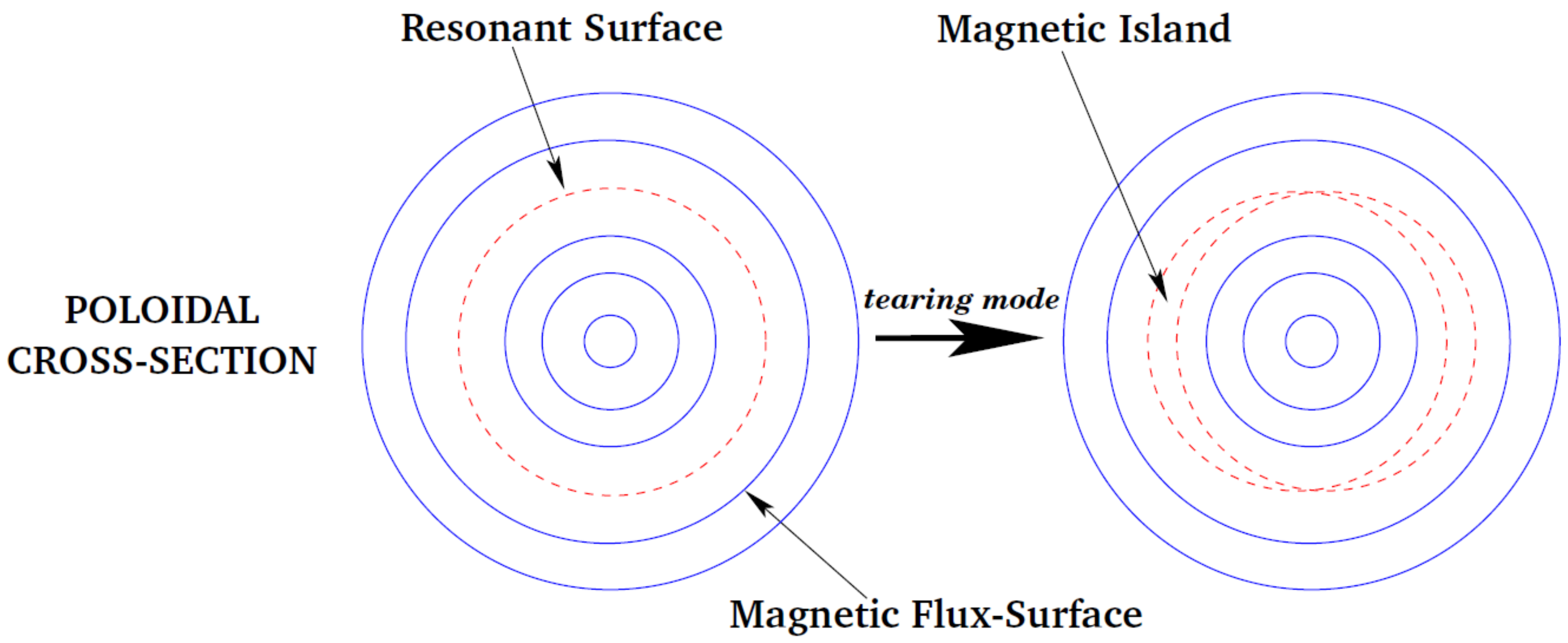


figure: Magnetic Reconnection in TokamaksRichard Fitzpatrick, Institute for Fusion Studies
University of Texas at Austin Austin TX, USA

A full-f collisioneless magnetic reconnection model (J. Madsen ,Markus Held)

$$\frac{\partial}{\partial t}n = -[\phi, n] + \boxed{[A_\parallel, n u_\parallel]}$$

$$\frac{\partial}{\partial t}N = -[\psi, N] + \boxed{[\Gamma_1 A_\parallel, N U_\parallel]}$$

$$\frac{\partial}{\partial t}\left(u_\parallel + \frac{1}{\mu_e}A_\parallel\right) = -\left[\phi, u_\parallel + \frac{1}{\mu_e}A_\parallel\right] + \boxed{\left[A_\parallel, u_\parallel^2/2\right]} - \frac{1}{\mu_e}\left[A_\parallel, \ln n\right]$$

$$\frac{\partial}{\partial t}\left(U_\parallel + \Gamma_1 A_\parallel\right) = -\left[\psi, U_\parallel + \Gamma_1 A_\parallel\right] + \boxed{\left[\Gamma_1 A_\parallel, U_\parallel^2/2\right]} + \tau_i\left[\Gamma_1 A_\parallel, \ln N\right]$$

cubic nonlinearities

+ Maxwell‘s equations

Polarization equation: $-n + \Gamma_1 N = -\vec{\nabla}\cdot\left(N\vec{\nabla}_\perp\phi\right)$

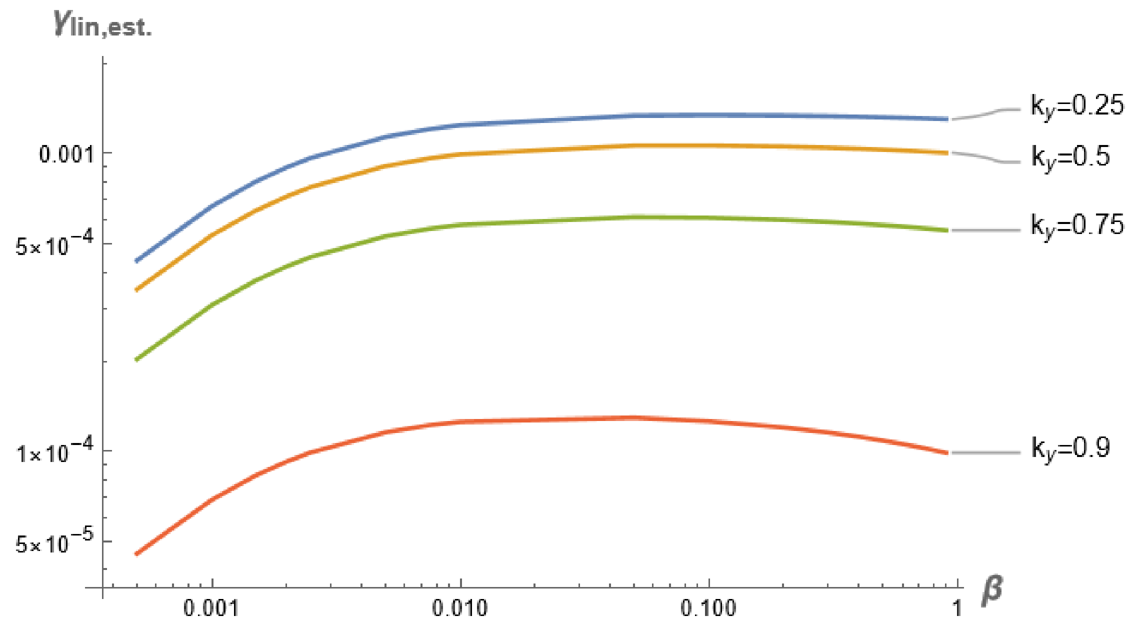
Ampère‘s law: $-\frac{1}{\beta}\vec{\nabla}_\perp^2 A_\parallel = -n u_\parallel + \Gamma_1(N U_\parallel)$

Markus Held, Two dimensional collisional reconnection model, not published, UiT The Arctic University of Norway, N-9037 Tromsø, Norway

Analytical estimate for the linear growth rate

Ansatz:

$$A_{\parallel,eq} = a \cdot \ln(\cosh(x))$$

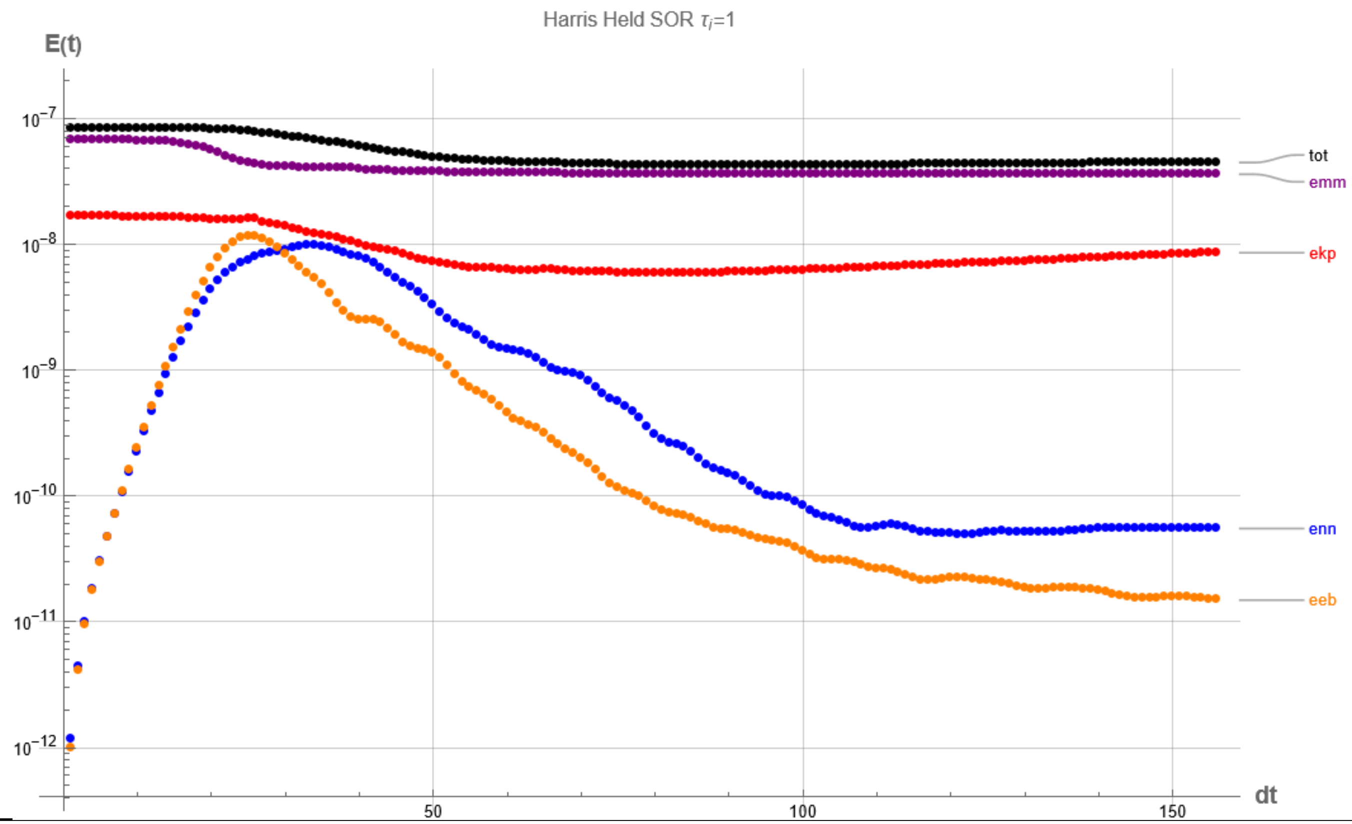


$$\Delta'_{outer} = 2\left(\frac{1}{k} - k\right) = \Delta'_{inner} =$$

$$= \beta N_0 \left(\frac{\gamma}{A_0 k}\right)^{1/2} \left[\frac{2.12}{\sqrt{\beta}} + \pi \left(\frac{\varphi^{-1} + \mu_e N_0^2}{-\mu_e N_0^2}\right) \left(\frac{\gamma}{\lambda} \frac{-\mu_e N_0^2}{A_0 k}\right)^{1/2}\right]$$

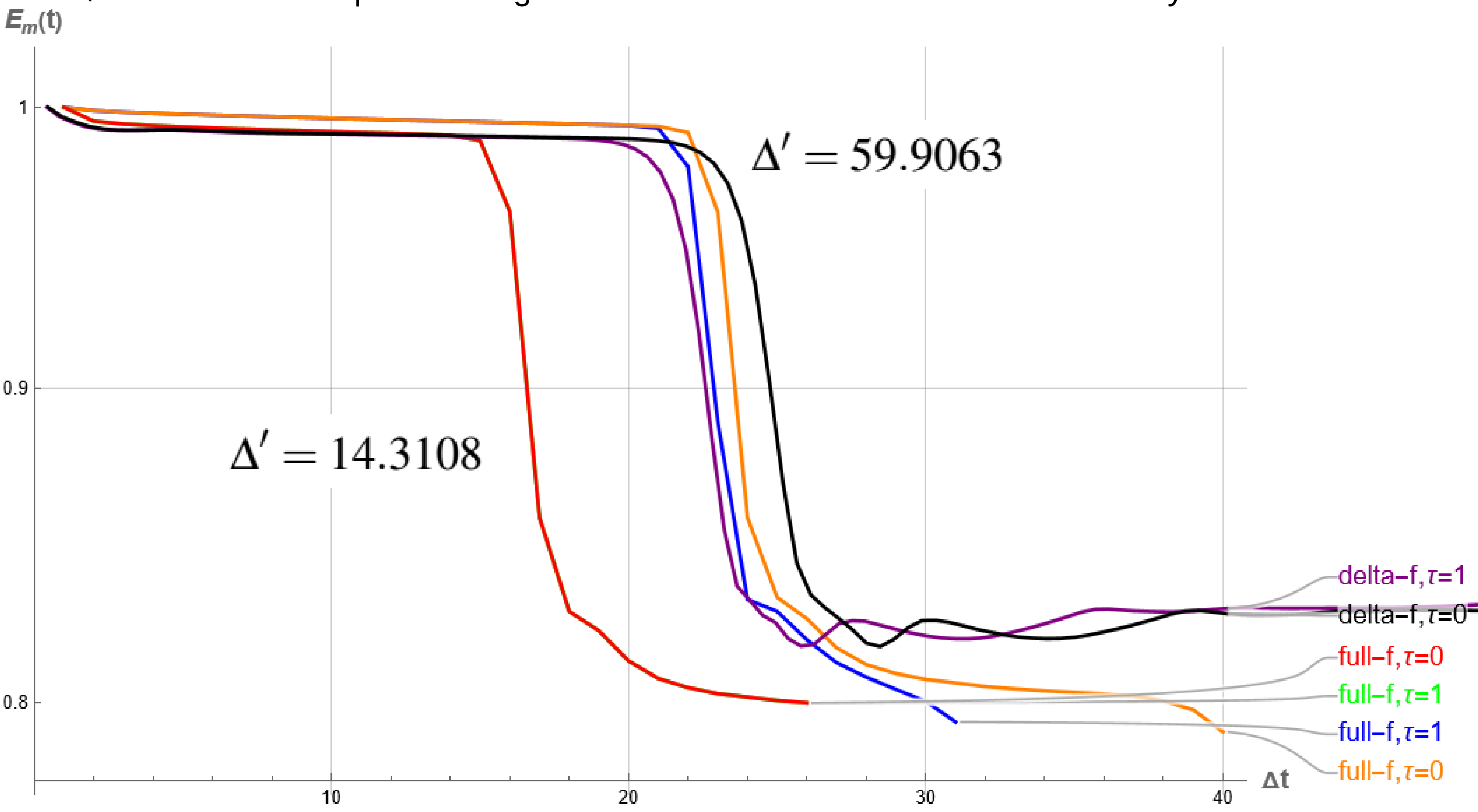
Energetics

→ energy (emm) stored in the initial magnetic configuration is transferred into thermal free energy (enn), ExB advection (eeb)
→ cold/warm ions probably dont change the qualitative behaviour but might still have a an influence on the dynamics (Tassi 2014, Biancalani & Scott 2011)
→ this surely will change after introducing temperature dynamics -> Micro Tearing



Explosive Reconnection

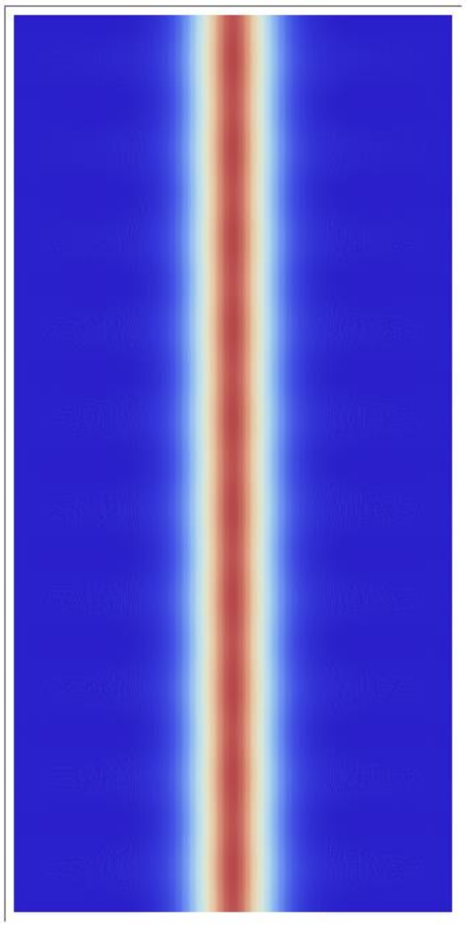
→ we observed explosive magnetic reconnection in both Feltor and Greeny



Explosive reconnection

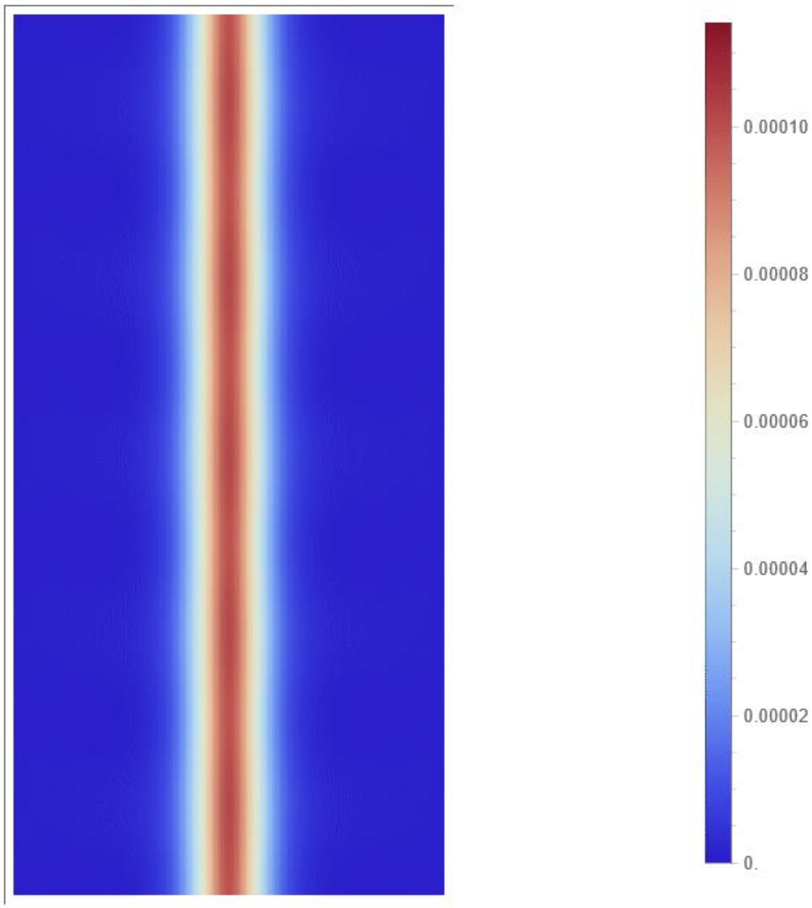
$$\mu_e = -0.000544662 \;\; \Delta' = 59.9063 \;\; \beta_e = 10^{-3}$$

$\tau_i = 1$



$A_{\parallel}(x, y)$

$\tau_i = 0$



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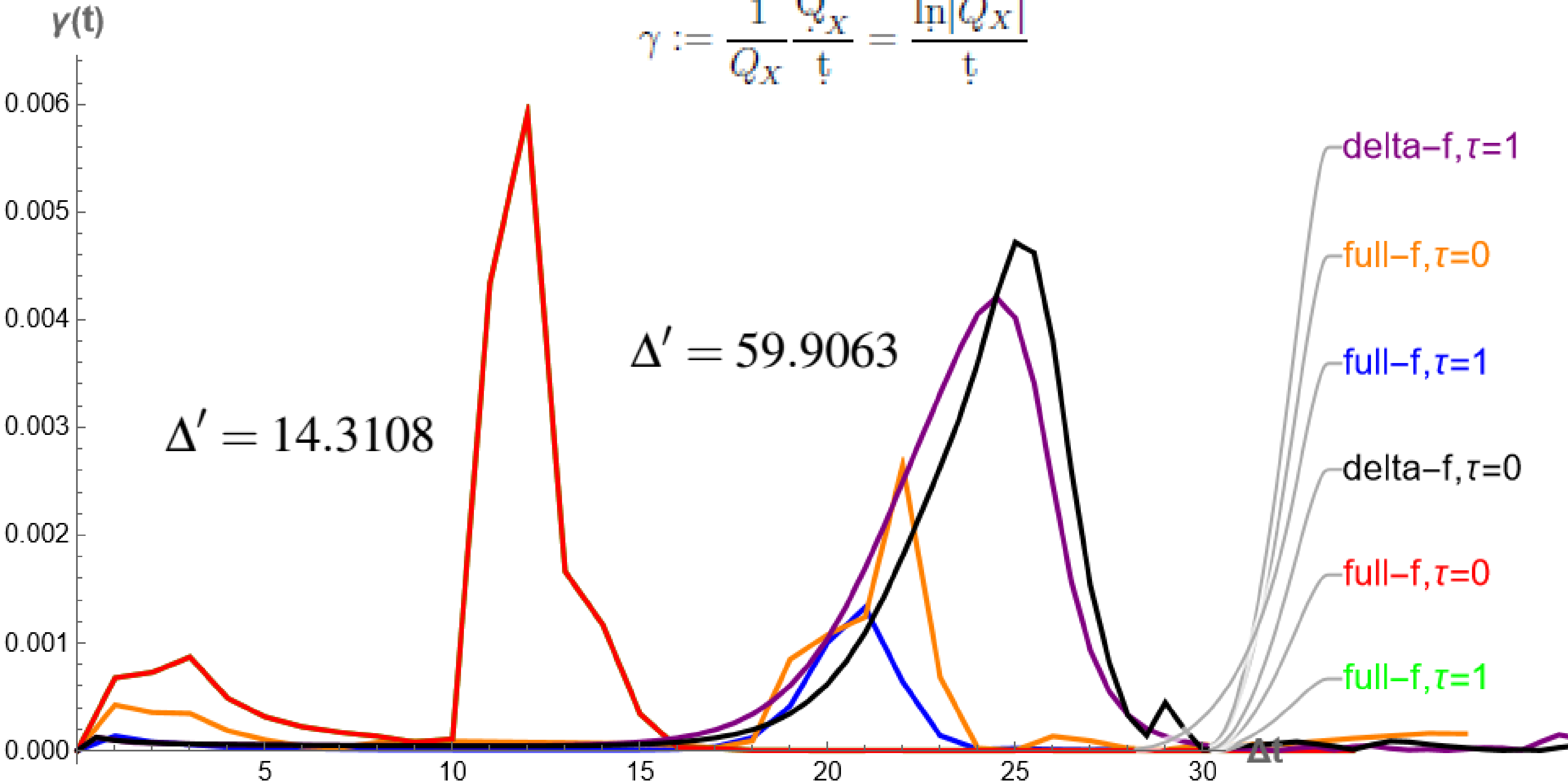
Measurement of the instability growth rate

$$Q_X := A_{\|}(\vec{x}_X, t) - A_{\|}(\vec{x}_X, 0)$$

$$\gamma := \frac{1}{Q_X}\frac{\dot{Q}_X}{t} = \frac{\ln|Q_X|}{t}$$



Conclusions & Goals

→ **First full-f full-k gyrofluid models show significant differences**

→ **Investigate role of hyperviscosity in Tearing-Reconnection**

→ **Combine with other effects (drift waves, curvature, impurities, KH-Instab.)**

→ **Investigate reconnection in a turbulent environment and look into its influence on transport**

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- Dr. Matthias Wiesenberger (Danish Technical University DTU

(former PhD researchers and postdocs in our group)

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- and many more…