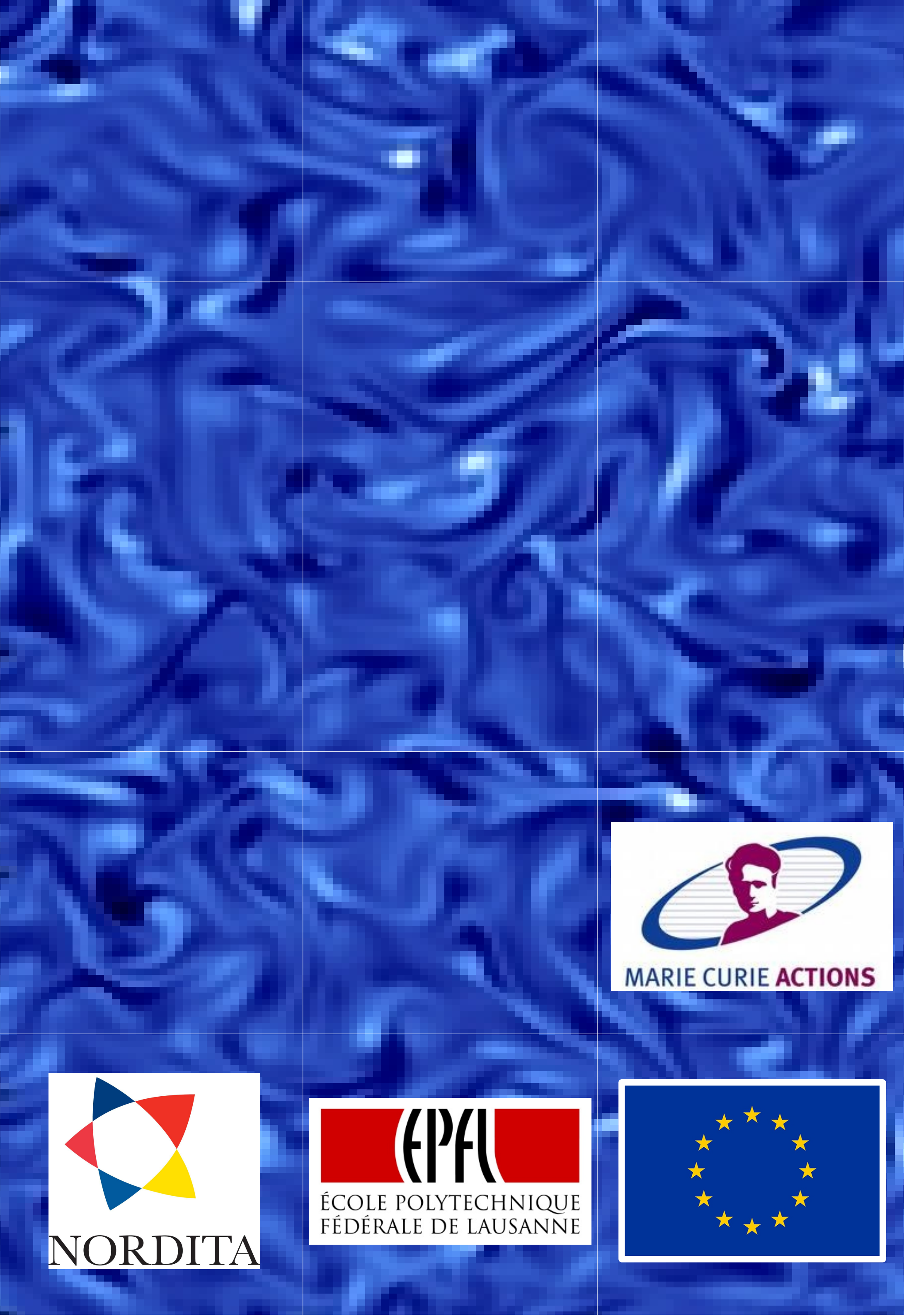


Swiss SKA Days
FHNW, Switzerland, 2018

"Chiral MHD dynamos and the origin of cosmic magnetic fields"

Jennifer Schober
& collaborators:

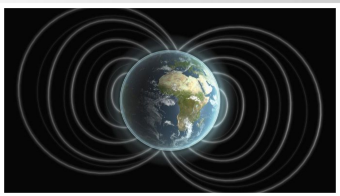
Axel Brandenburg, Igor Rogachevskii, Nathan Kleeorin, Tina Kahniashvili, Oleg Ruchayskiy, Alexey Boyarsky, Jürg Fröhlich

MARIE CURIE ACTIONS

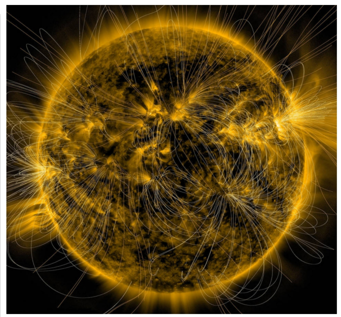
NORDITA

EPFL ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

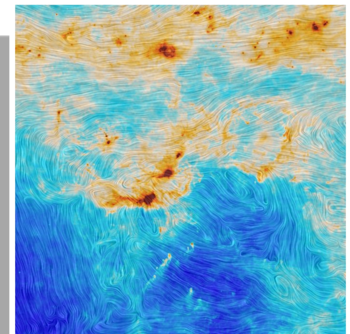
MHD dynamos and cosmic magnetic fields



Planets
[here: Earth, credit: *Science Picture Company*]

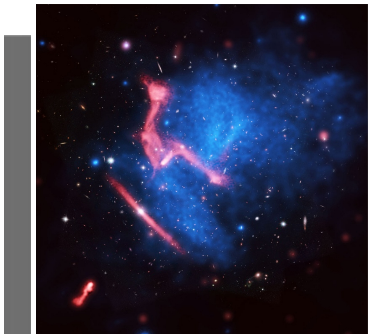


Stars
[here: Sun, credit: *NASA/SDO/AIA/LMSALe*]



Interstellar medium
[here: Orion Molecular Cloud, credit: *ESA and Planck Collaboration*]

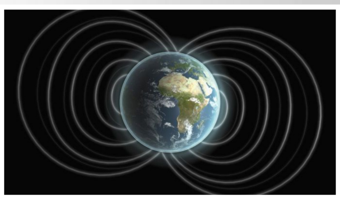
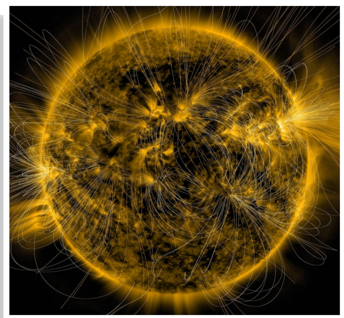
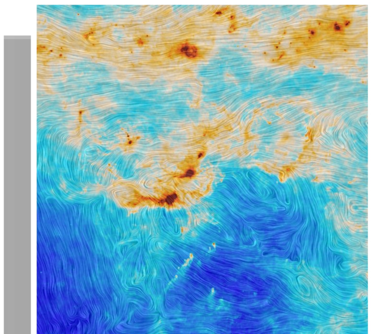
Galaxies
[here: M51, credit: *Beck 2011*]

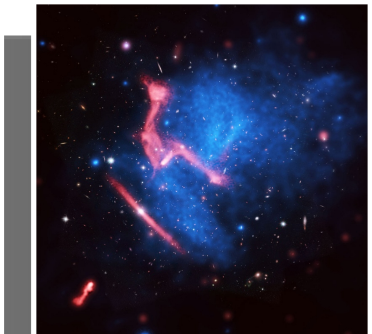


Galaxy clusters
[here: colliding clusters MACS J0717+3745 credit: *NRAO/AUI/NSF and NASA*]

Inter-galactic medium

MHD dynamos and cosmic magnetic fields

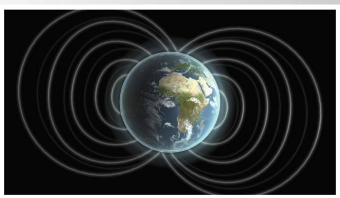
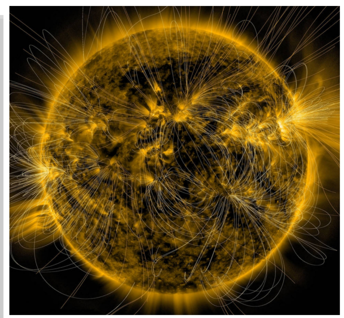
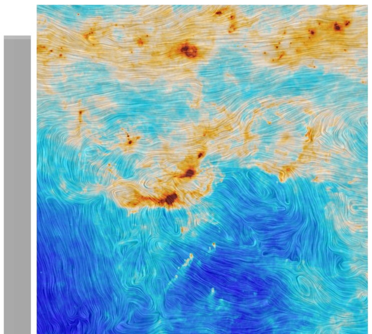


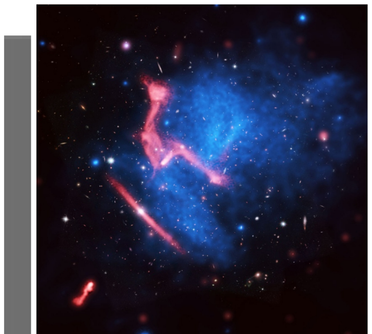
Inter-
galactic
medium

The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$

MHD dynamos and cosmic magnetic fields

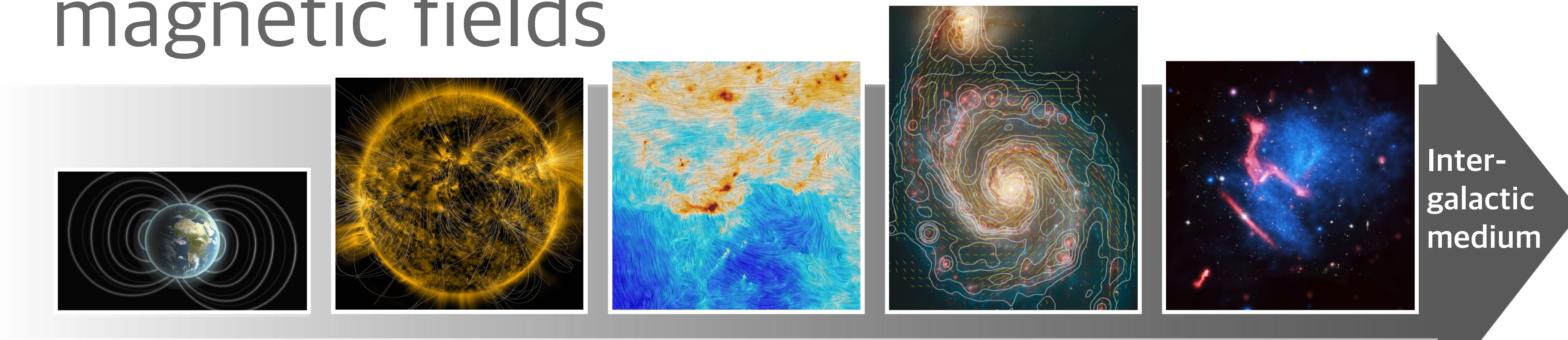


The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$

advection   dissipation

MHD dynamos and cosmic magnetic fields



The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$

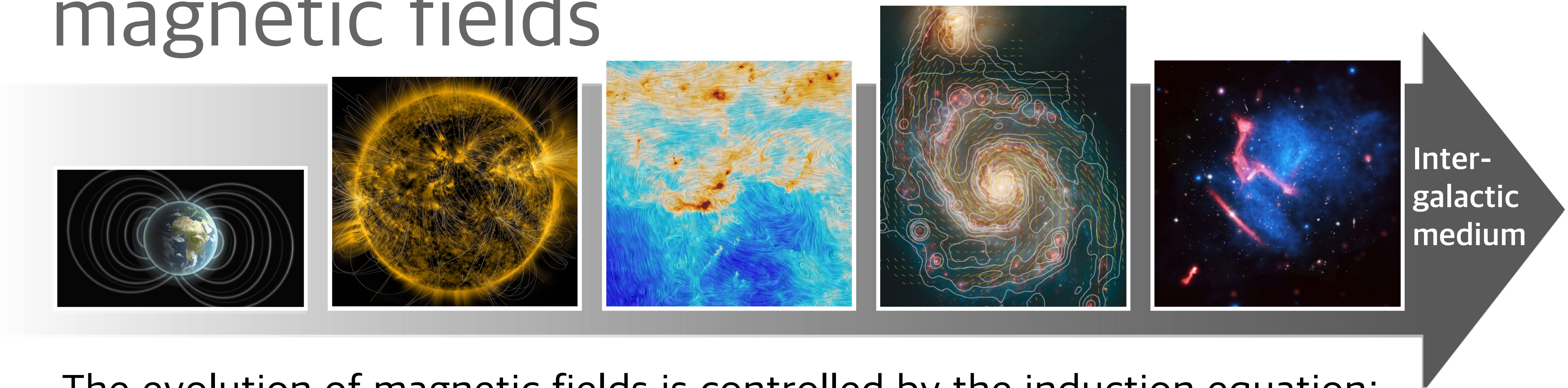
advection   dissipation

→ Magnetic field decays.

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Jennifer
Schober

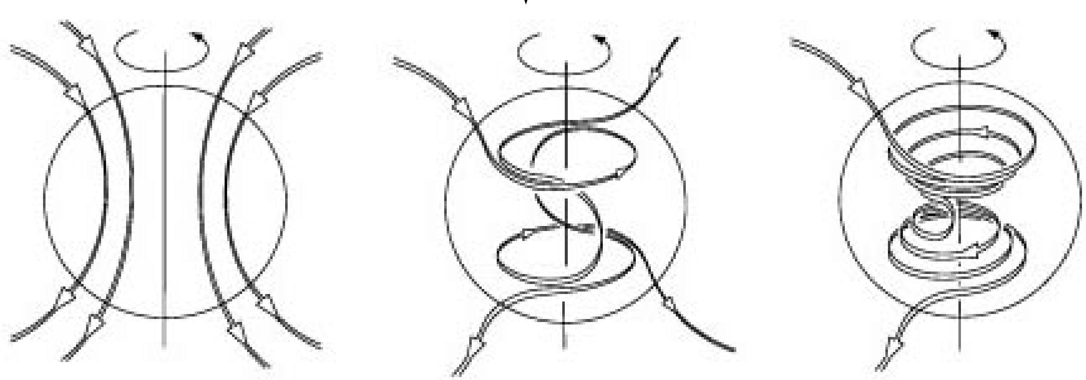
MHD dynamos and cosmic magnetic fields



The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{U} \times \boldsymbol{B} - \eta \, (\nabla \times \boldsymbol{B})]$$

e.g. large-scale rotation

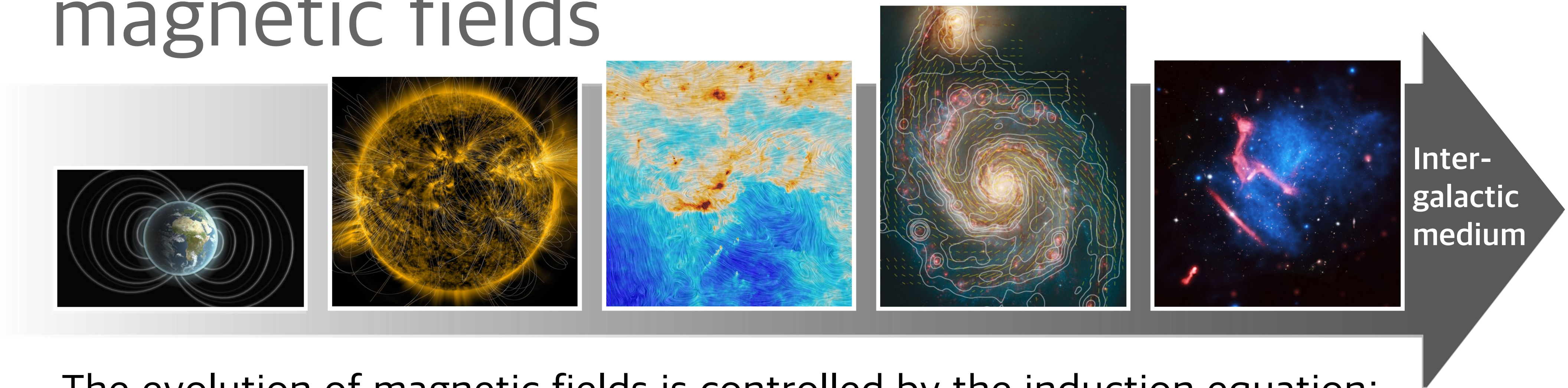


“ Ω dynamo”
[credit: *Love (1999)*]

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

MHD dynamos and cosmic magnetic fields



The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$

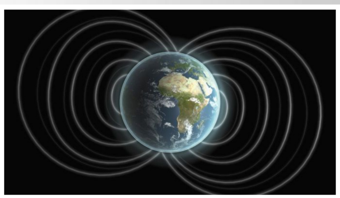
↓ mean-field theory ($\boldsymbol{B} \rightarrow \overline{\boldsymbol{B}} + \delta \boldsymbol{B}$)

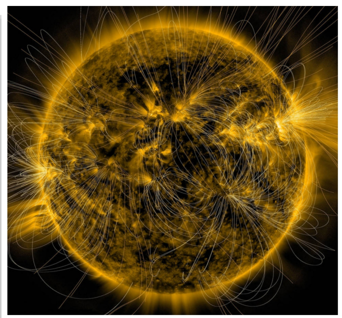
$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \nabla \times \left\{\overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \alpha \overline{\boldsymbol{B}} - (\eta + \eta_{_T}) \nabla \times \overline{\boldsymbol{B}}\right\}$$

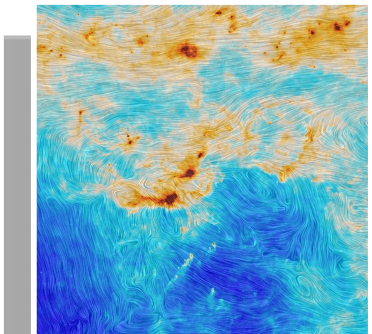
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

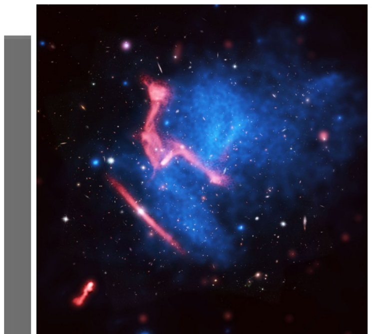
Jennifer
Schober

MHD dynamos and cosmic magnetic fields









Inter-galactic medium

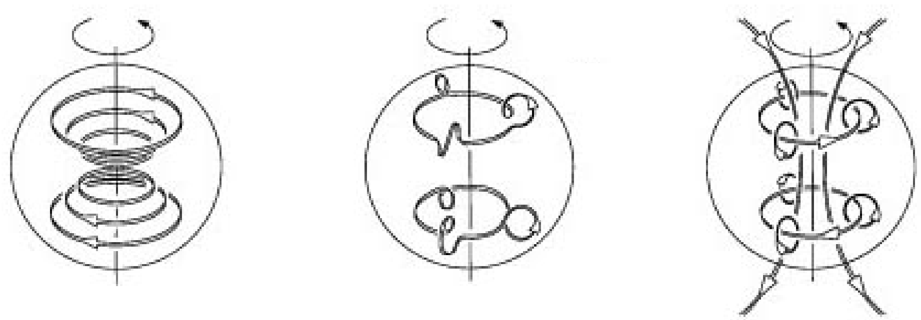
The evolution of magnetic fields is controlled by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{U} \times \boldsymbol{B} - \eta\, (\nabla \times \boldsymbol{B})]$$

mean-field theory ($\boldsymbol{B} \to \overline{\boldsymbol{B}} + \delta \boldsymbol{B}$)

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \nabla \times \left\{ \overline{\boldsymbol{U}} \times \overline{\boldsymbol{B}} + \alpha \overline{\boldsymbol{B}} - (\eta + \eta_{_T}) \nabla \times \overline{\boldsymbol{B}} \right\}$$

related to $\delta \boldsymbol{B}$ and $\delta \boldsymbol{U}$



“ α dynamo”

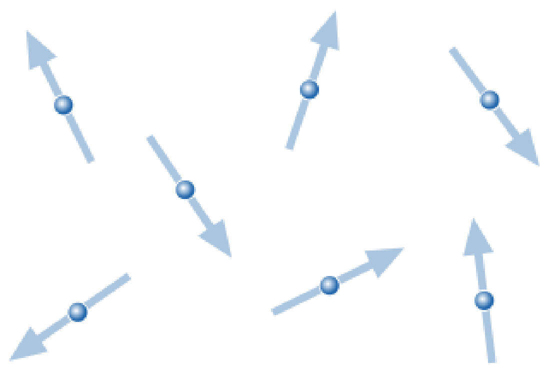
[credit: *Love (1999)*]

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

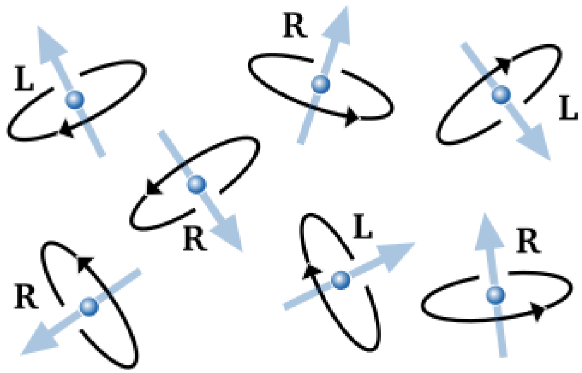
New dynamos at high energies

Chiral Magnetic Effect (CME) :



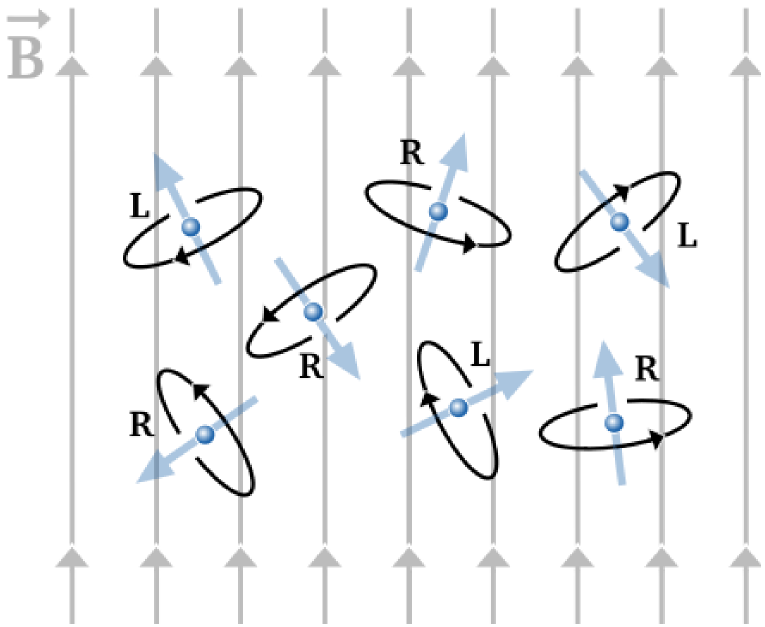
New dynamos at high energies

Chiral Magnetic Effect (CME) :



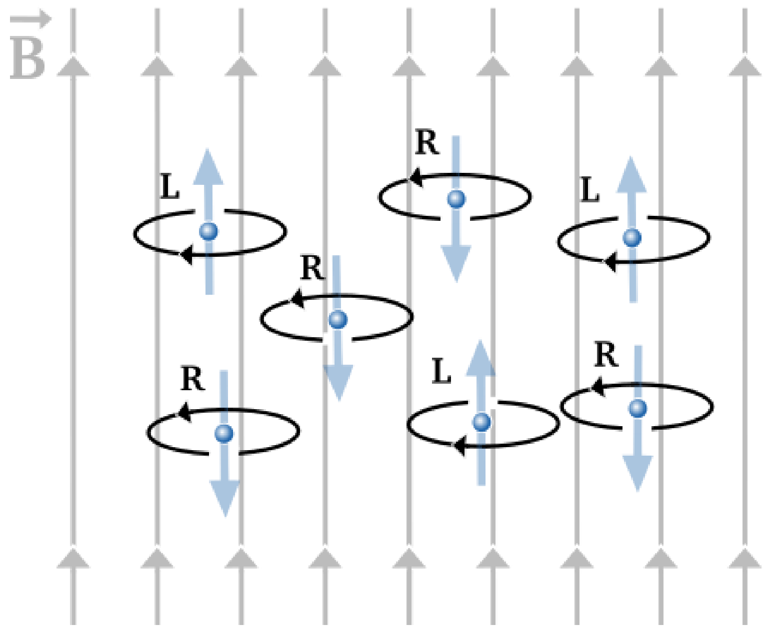
New dynamos at high energies

Chiral Magnetic Effect (CME) :



New dynamos at high energies

Chiral Magnetic Effect (CME) :

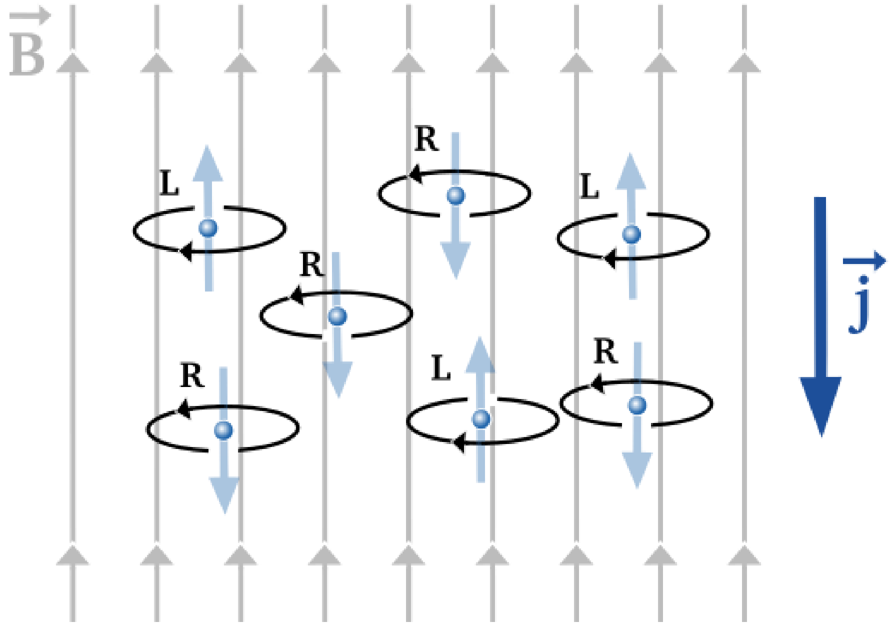


ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Jennifer
Schober

New dynamos at high energies

Chiral Magnetic Effect (CME) :

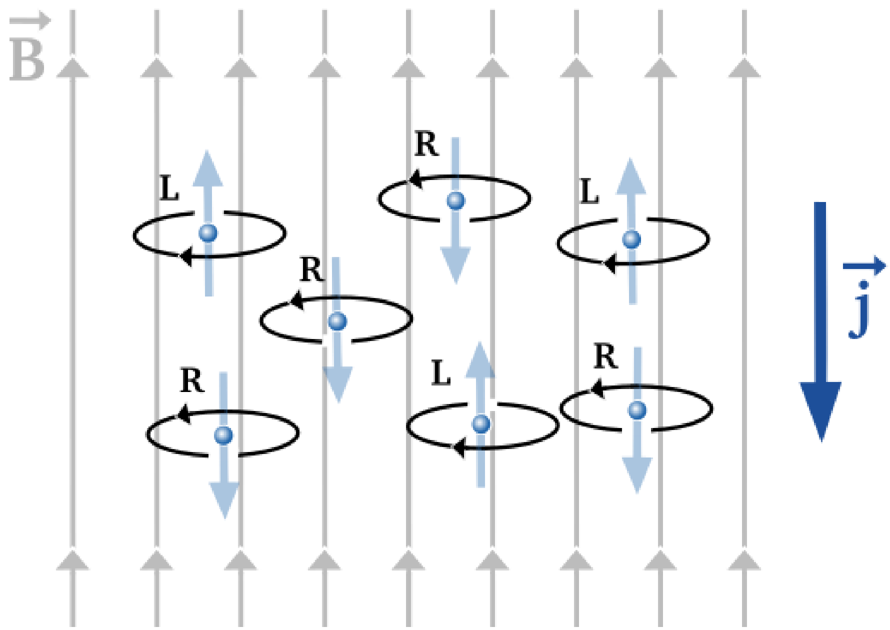


ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

New dynamos at high energies

Chiral Magnetic Effect (CME) :



For a chiral chemical potential

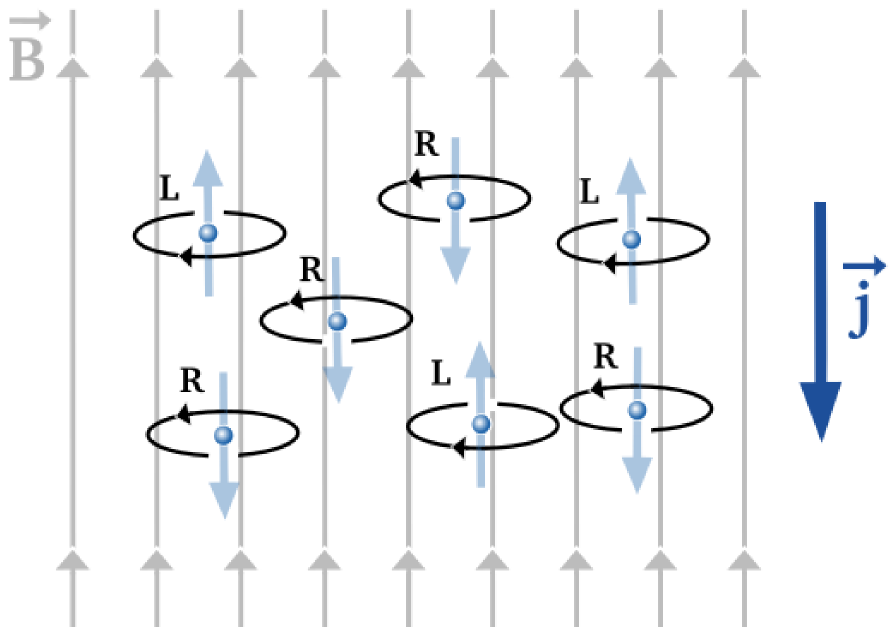
$$\mu \propto (n_{\rm L} - n_{\rm R})$$

the chiral current is

$$\boldsymbol{j} \propto \mu \boldsymbol{B}\,.$$

New dynamos at high energies

Chiral Magnetic Effect (CME) :



For a chiral chemical potential

$$\mu \propto (n_{\rm L} - n_{\rm R})$$

the chiral current is

$$\boldsymbol{j} \propto \mu \boldsymbol{B} \, .$$

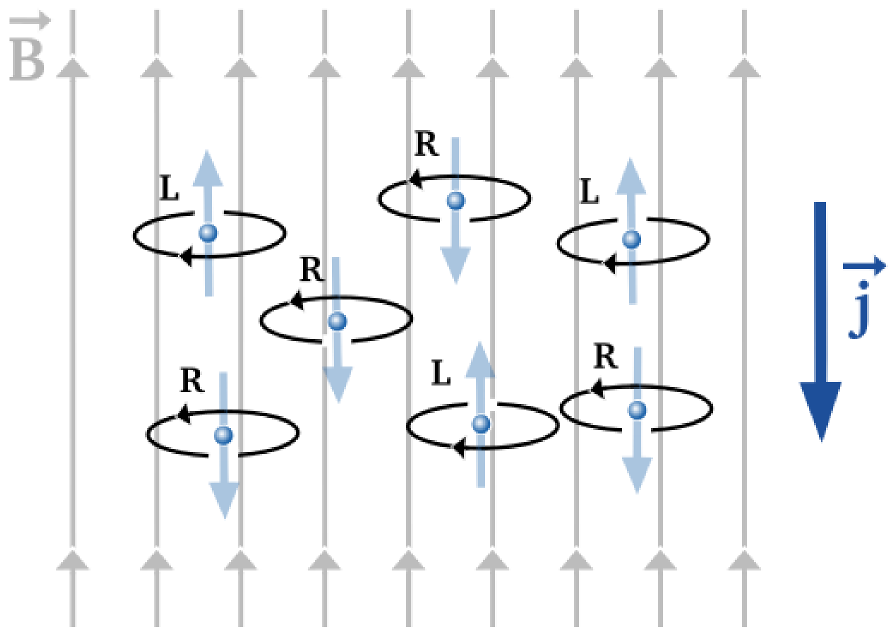
Addition to Ohmic current leads to modified Maxwell equations.

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

New dynamos at high energies

Chiral Magnetic Effect (CME) :



For a chiral chemical potential

$$\mu \propto (n_{\mathrm{L}} - n_{\mathrm{R}})$$

the chiral current is

$$\boldsymbol{j} \propto \mu \boldsymbol{B}\,.$$

Chiral induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B} - \frac{\mu}{c}\boldsymbol{B}\right)\right]$$

Addition to Ohmic current leads to modified Maxwell equations.

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

Where/When in the Universe?

→ A chiral asymmetry can only survive at $k_{\mathrm{B}}T > 10\ \mathrm{MeV}$ [*Boyarsky et al. 2012*]

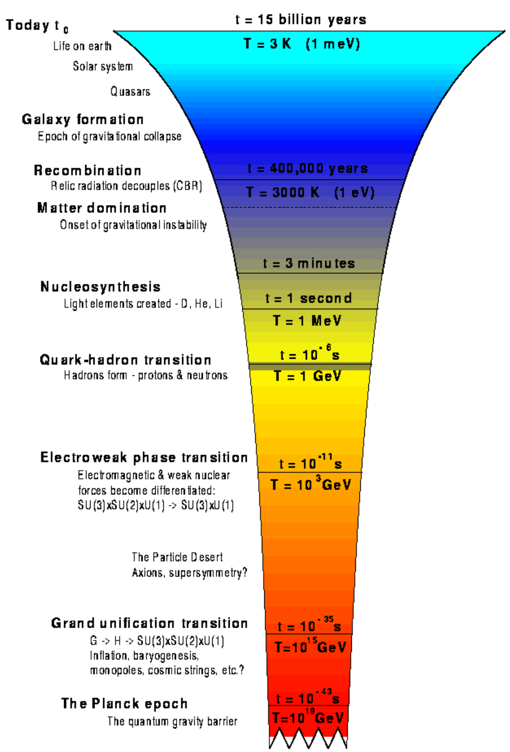
Jennifer
Schober

Where/When in the Universe?

→ A chiral asymmetry can only survive at $k_{\mathrm{B}}T > 10\ \mathrm{MeV}$ [*Boyarsky et al. 2012*]

Early Universe

[*Joyce & Shaposhnikov 1997; Fröhlich & Pedrini 2000, Semikoz & Sokoloff 2004; Pavlovic et al 2017; ...*]

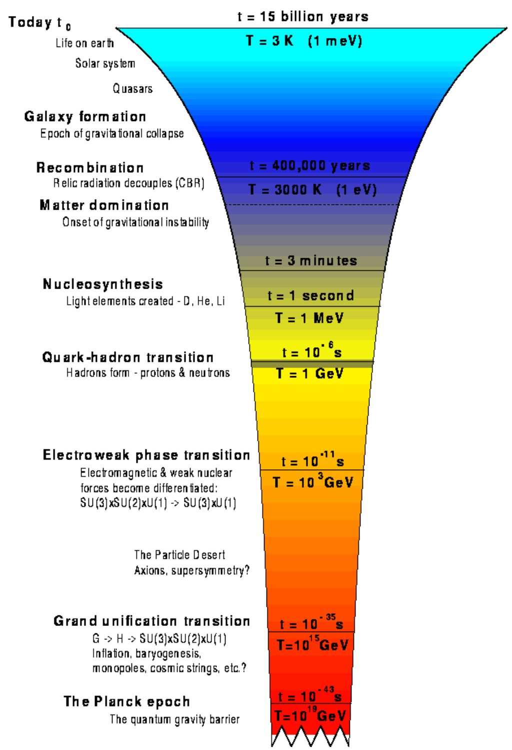


Where/When in the Universe?

→ A chiral asymmetry can only survive at $k_\mathrm{B}T > 10\ \mathrm{MeV}$ [*Boyarsky et al. 2012*]

Early Universe

[*Joyce & Shaposhnikov 1997; Fröhlich & Pedrini 2000, Semikoz & Sokoloff 2004; Pavlovic et al 2017; …*]



(Proto-) neutron stars

[*Dvornikov & Semikoz 2015; Grabowska et al. 2015; Sigl & Leite 2016; Yamamoto 2016; …*]

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

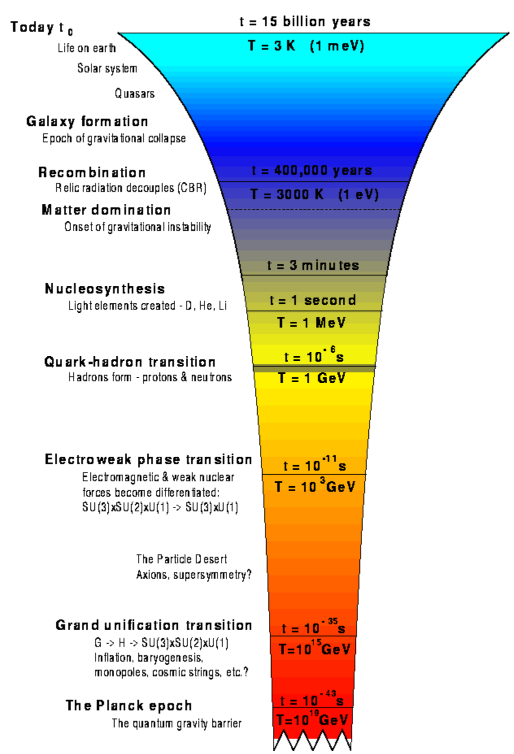
Jennifer Schober

Where/When in the Universe?

→ A chiral asymmetry can only survive at $k_B T > 10$ MeV [*Boyarsky et al. 2012*]

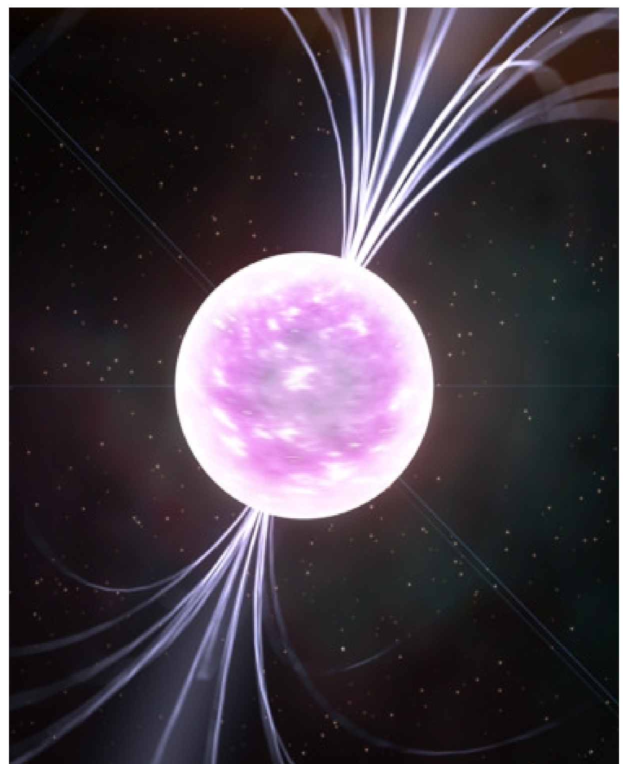
Early Universe

[*Joyce & Shaposhnikov 1997; Fröhlich & Pedrini 2000, Semikoz & Sokoloff 2004; Pavlovic et al 2017; …*]



(Proto-) neutron stars

[*Dvornikov & Semikoz 2015; Grabowska et al. 2015; Sigl & Leite 2016; Yamamoto 2016; …*]



Heavy-ion collisions

[*Abelev, et al., [ALICE Collaboration], 2013; Akamatsu & Yamamoto 2013; …*]

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

MHD with the Pencil Code

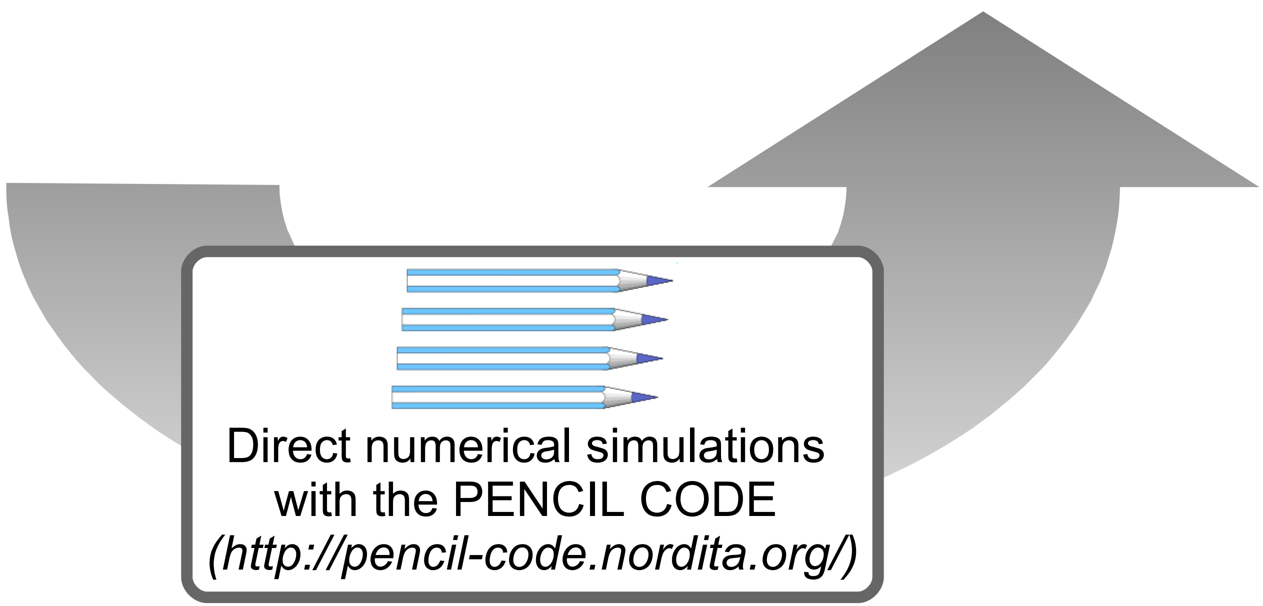
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \boldsymbol{U}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{U} \times \boldsymbol{B} - \eta \, (\nabla \times \boldsymbol{B})]$$

$$\rho \frac{D\boldsymbol{U}}{Dt} = (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p + \nabla \cdot (2 \nu \rho \boldsymbol{S})$$

MHD with the Pencil Code

$$
\begin{aligned}
\frac{D\rho}{Dt} &= -\rho\,\nabla\cdot\boldsymbol{U} \\
\frac{\partial \boldsymbol{B}}{\partial t} &= \nabla\times\left[\boldsymbol{U}\times\boldsymbol{B} - \eta\,(\nabla\times\boldsymbol{B})\right] \\
\rho\frac{D\boldsymbol{U}}{Dt} &= (\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \nabla p + \nabla\cdot(2\nu\rho\boldsymbol{S})
\end{aligned}
$$



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

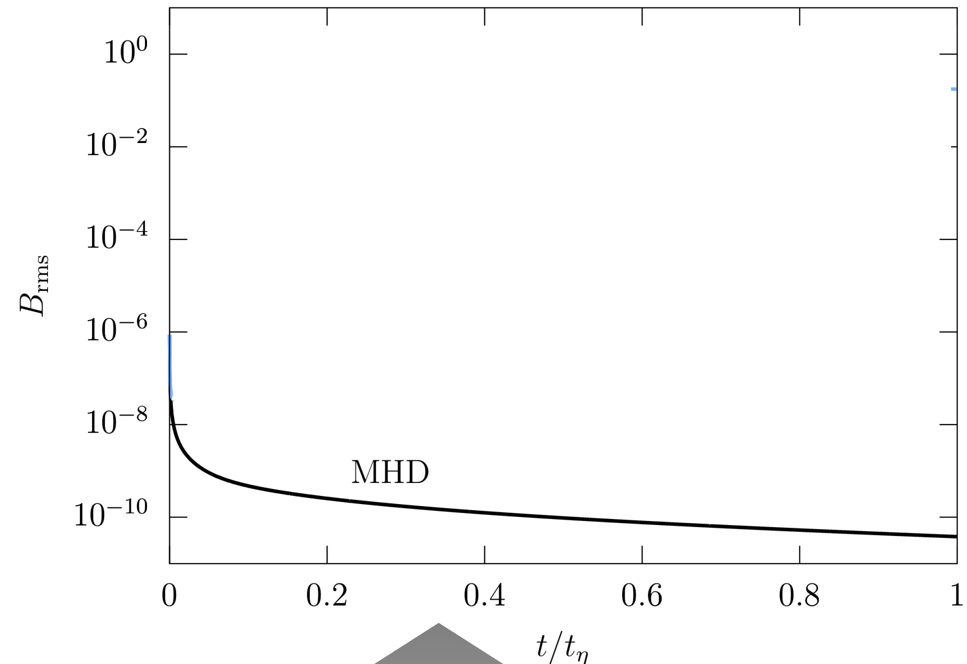
Jennifer Schober

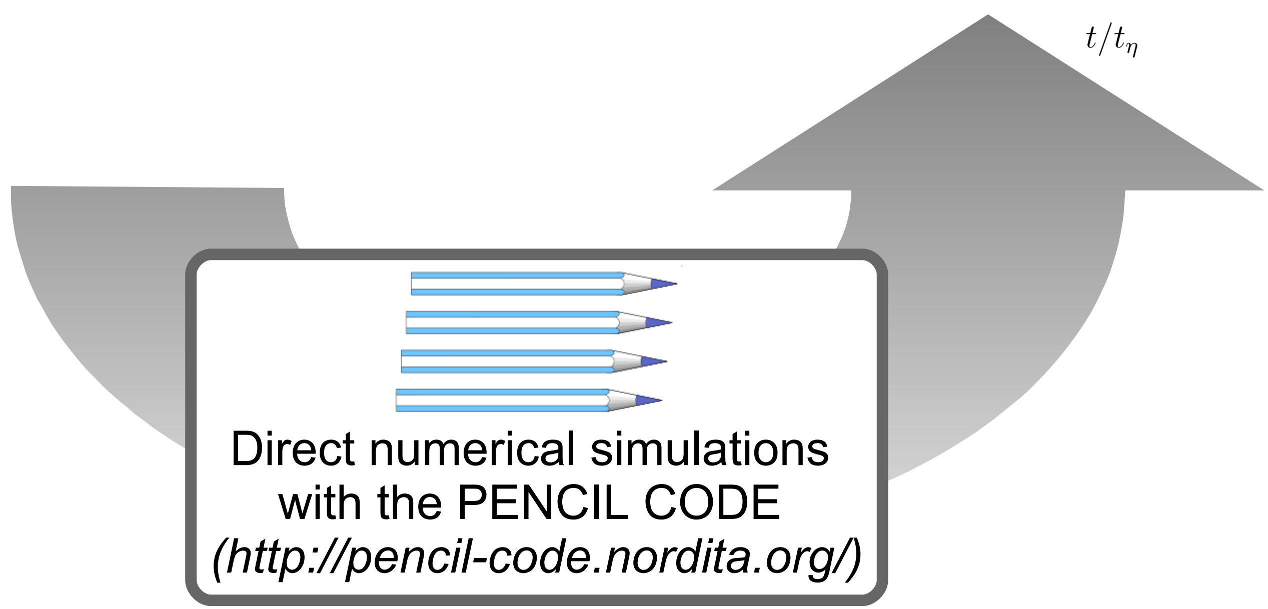
MHD with the Pencil Code

$$\frac{D\rho}{Dt} = -\rho\,\nabla\cdot\boldsymbol{U}$$

$$\frac{\partial\boldsymbol{B}}{\partial t} = \nabla\times\left[\boldsymbol{U}\times\boldsymbol{B}-\eta\,(\nabla\times\boldsymbol{B})\right]$$

$$\rho\frac{D\boldsymbol{U}}{Dt} = (\nabla\times\boldsymbol{B})\times\boldsymbol{B}-\nabla p+\nabla\cdot(2\nu\rho\boldsymbol{S})$$





ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Jennifer
Schober

Chiral MHD with the Pencil Code

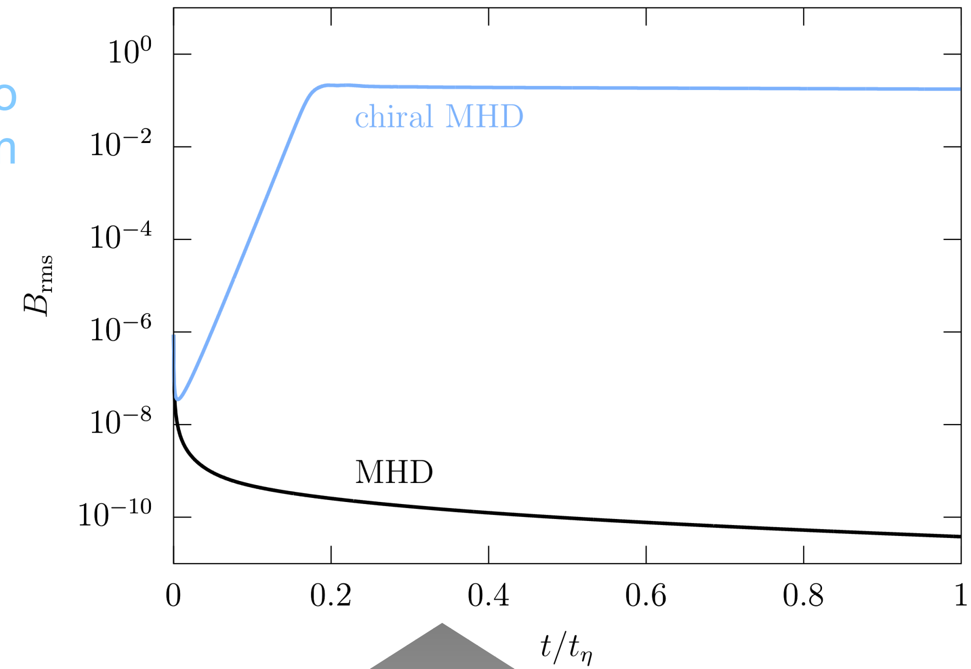
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \boldsymbol{U}$$

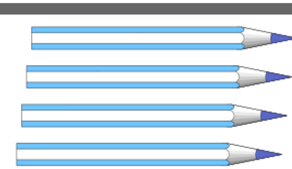
$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\boldsymbol{U} \times \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B} - \frac{\mu}{c} \boldsymbol{B} \right) \right]$$

new dynamo term ($\frac{\mu}{c}\boldsymbol{B}$)

$$\rho \frac{D\boldsymbol{U}}{Dt} = (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} - \nabla p + \nabla \cdot (2 \nu \rho \boldsymbol{S})$$

$$\frac{D\mu}{Dt} = D_5 \, \Delta \mu + \lambda \, \eta \left[\boldsymbol{B} \cdot (\nabla \times \boldsymbol{B}) - \frac{\mu}{c} \boldsymbol{B}^2 \right]$$



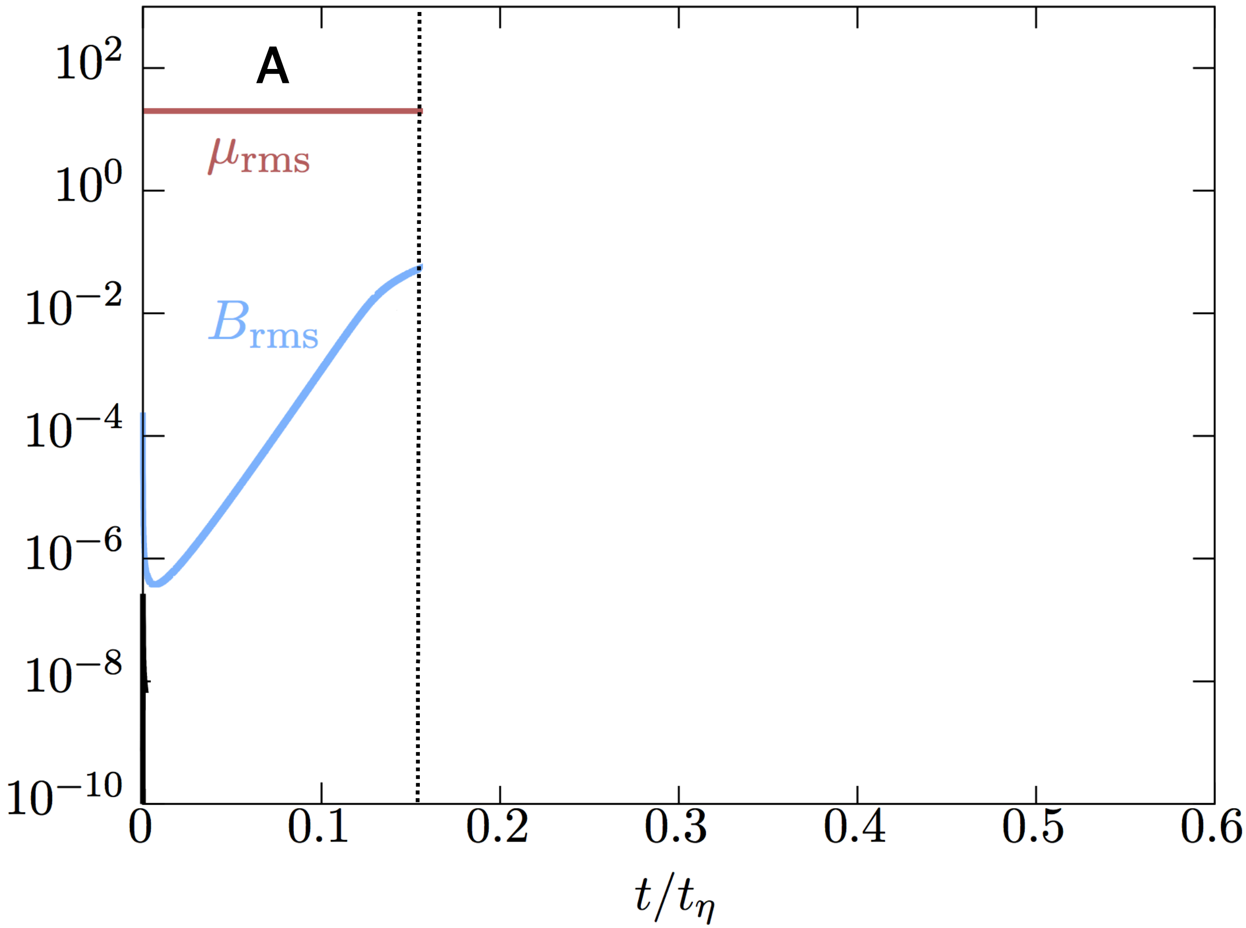


Direct numerical simulations with the PENCIL CODE
(http://pencil-code.nordita.org/)

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

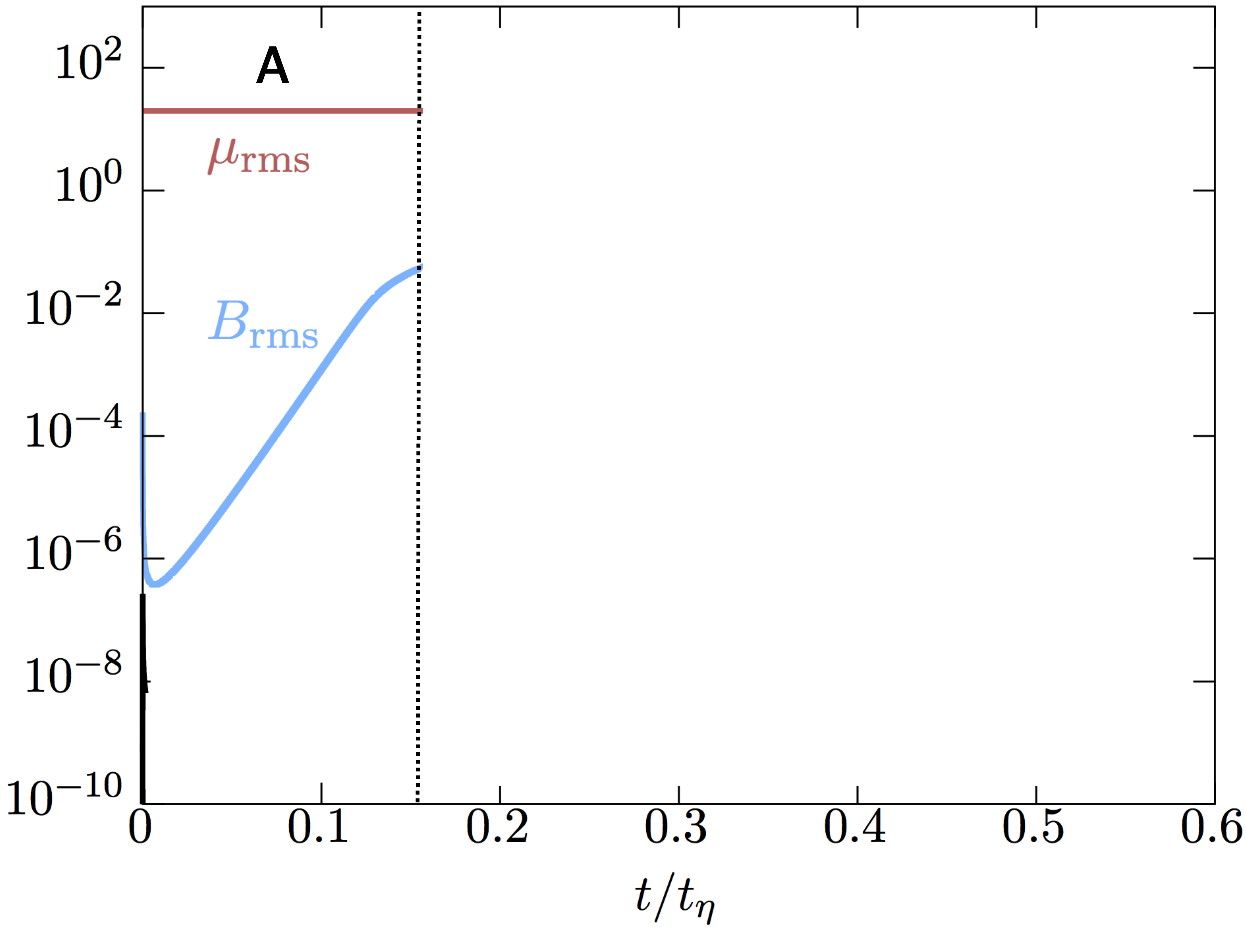
From laminar to turbulent flows



Phase A:

Laminar dynamo

From laminar to turbulent flows



Phase A:

Laminar dynamo

- Magnetic field determined by

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\eta \frac{\mu}{c} \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$

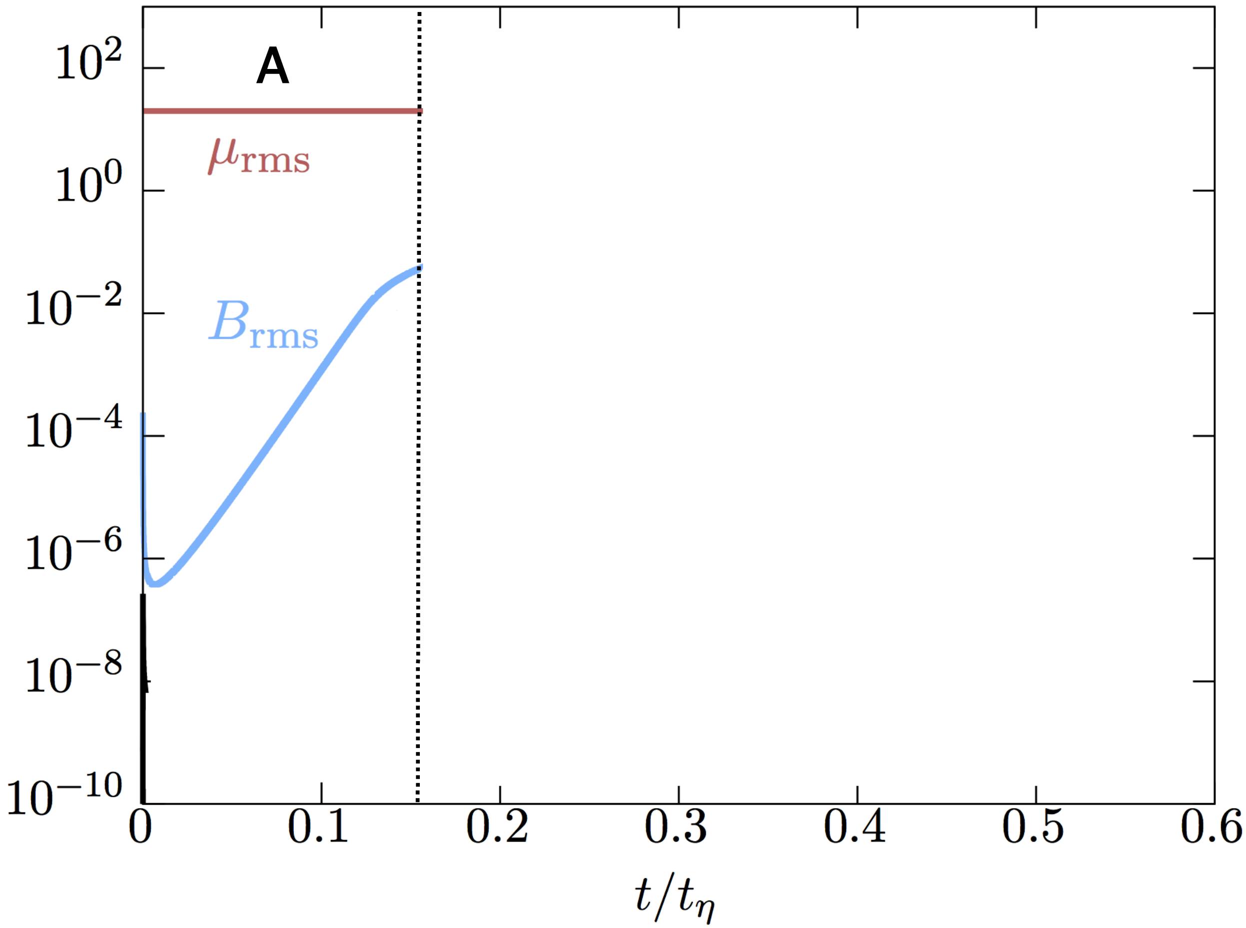
grows with

$$\gamma = \eta\mu k - \eta k^2$$

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Jennifer
Schober

From laminar to turbulent flows

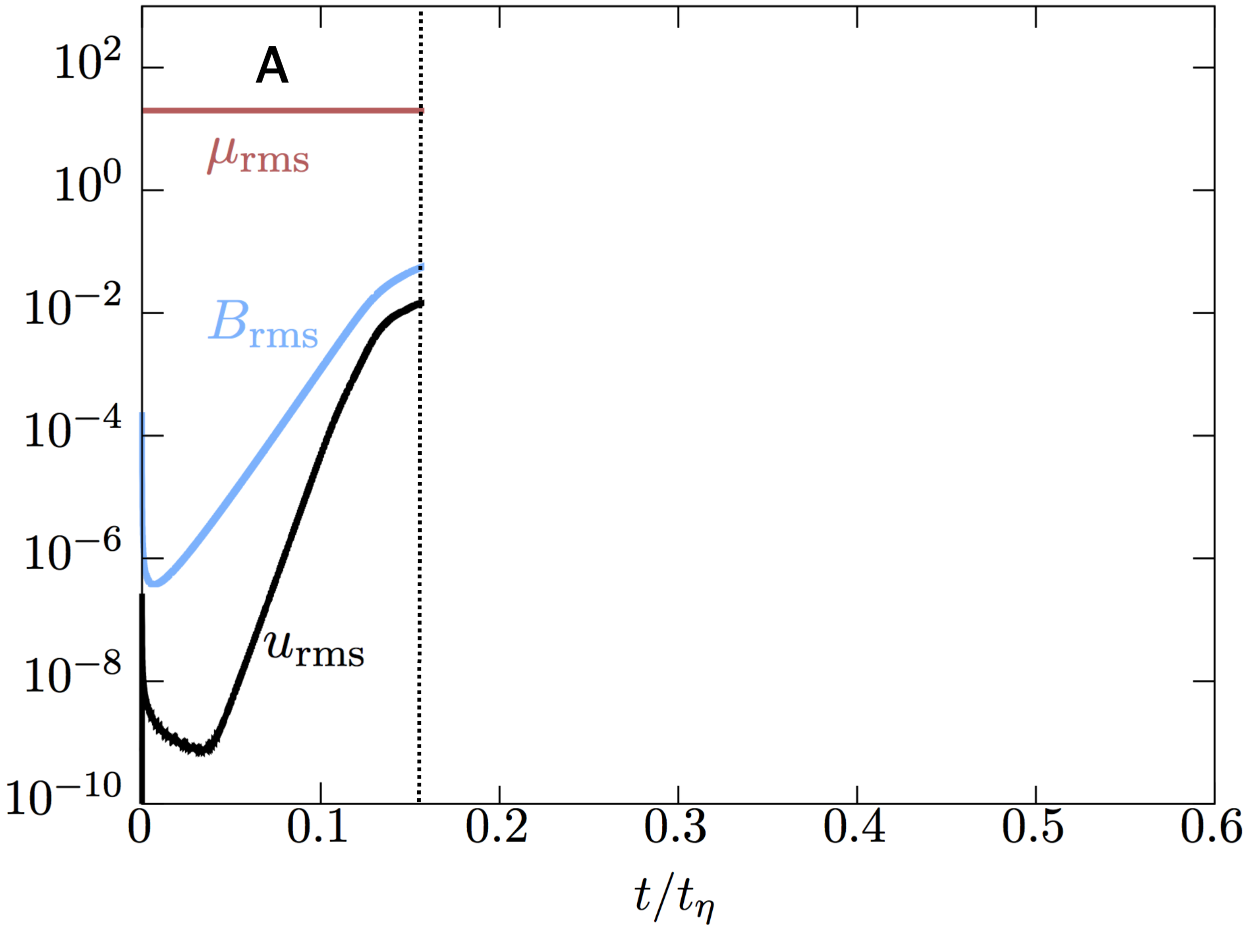


Phase A:

Laminar dynamo

- Magnetic field determined by
  $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\eta \frac{\mu}{c}\boldsymbol{B} - \eta\left(\nabla \times \boldsymbol{B}\right)\right]$$
  grows with
  $$\gamma = \eta\mu k - \eta k^2$$
- Chemical potential constant

From laminar to turbulent flows

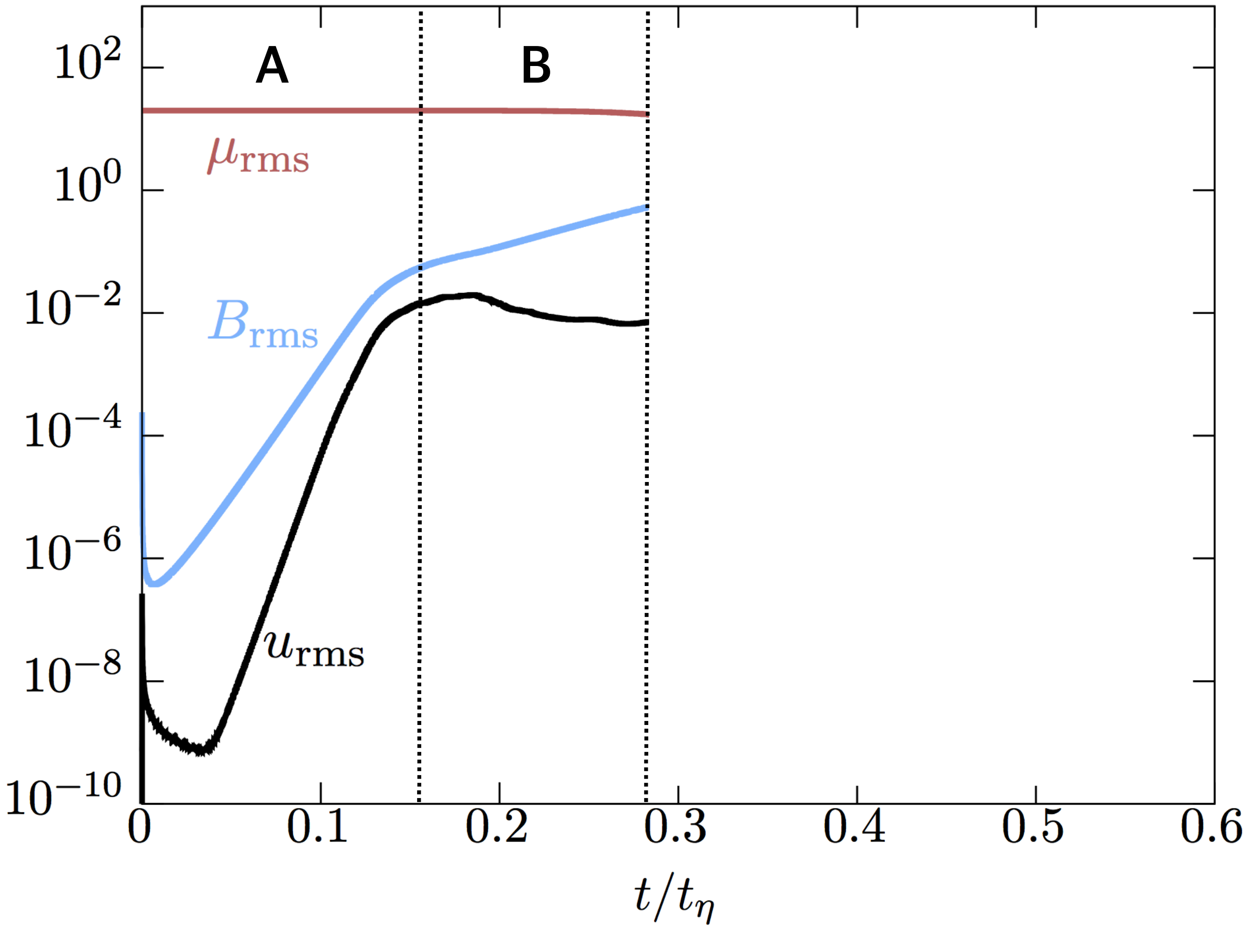


Phase A:

Laminar dynamo

- Magnetic field determined by
  $$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times \left[\eta \frac{\mu}{c} \boldsymbol{B} - \eta \left(\nabla \times \boldsymbol{B}\right)\right]$$
  grows with
  $$\gamma = \eta\mu k - \eta k^2$$
- Chemical potential constant
- Turbulence is driven by Lorentz force:
  $$\rho \frac{D\boldsymbol{U}}{Dt} = (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + ...$$

From laminar to turbulent flows



Phase B:

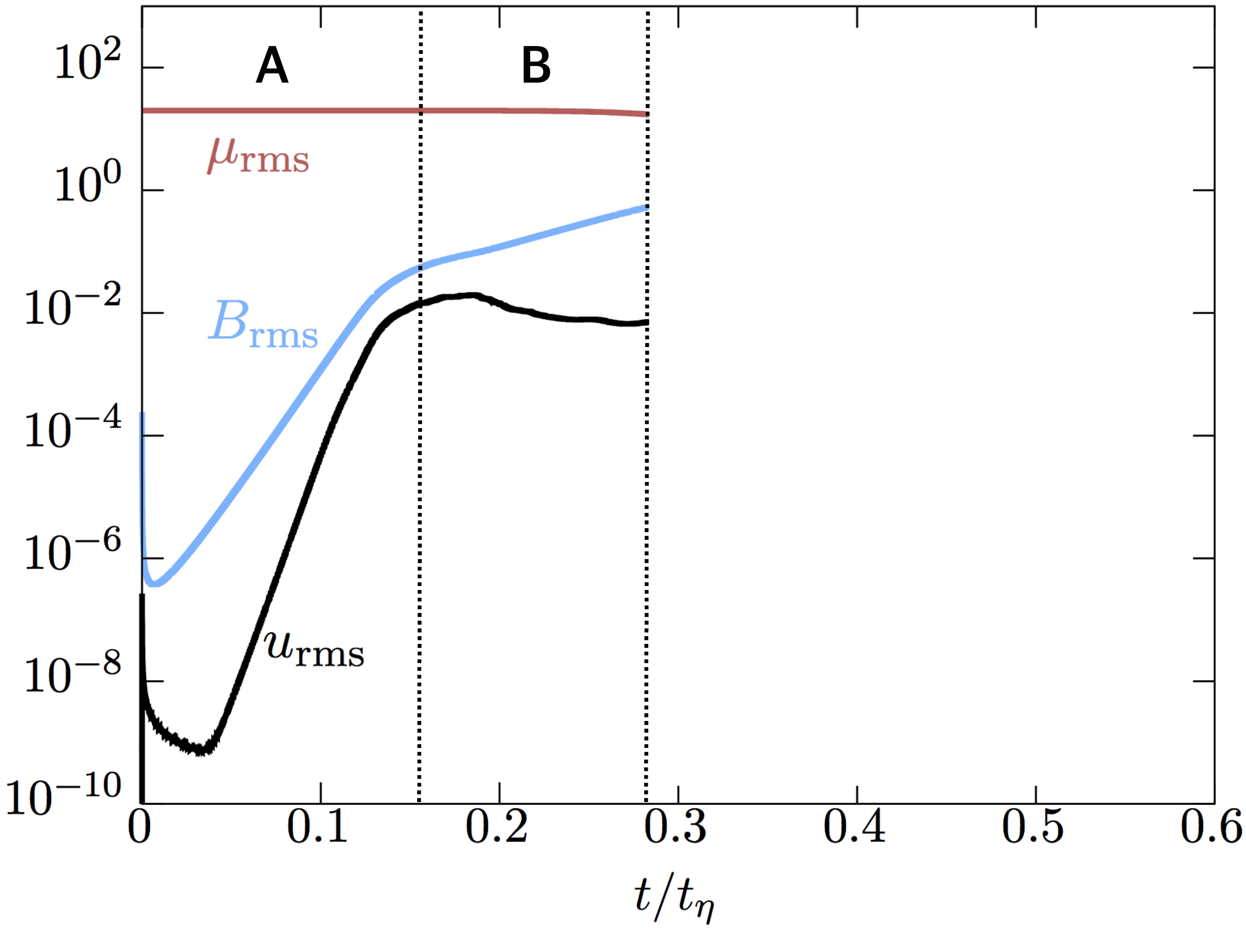
Turbulent dynamo

- Mean-field formalism can be used to explore evolution

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Jennifer Schober

From laminar to turbulent flows



Phase B:

Turbulent dynamo

- Mean-field formalism can be used to explore evolution
- Magnetic field growth rate

$$\gamma = (\eta\overline{\mu} + \alpha_\mu)k - (\eta + \eta_{\rm T})k^2$$

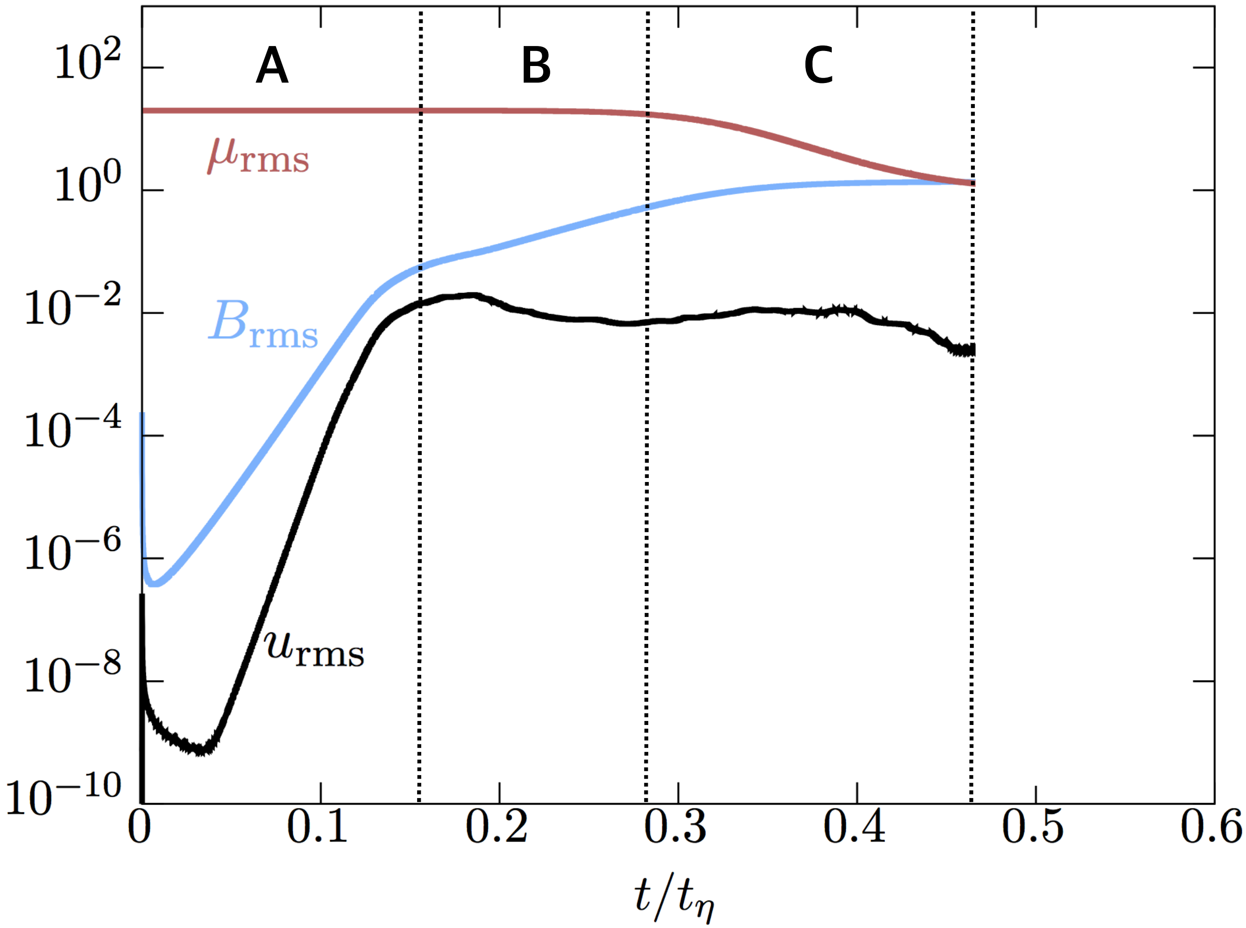
with turbulent diffusion

$$\eta_{\rm T} = \frac{u_{\rm rms}}{3\ k_{\rm f}}$$

and the chiral α_μ effect

$$\alpha_\mu = -\frac{2}{3}\eta\overline{\mu}\ \log({\rm Re})$$

From laminar to turbulent flows

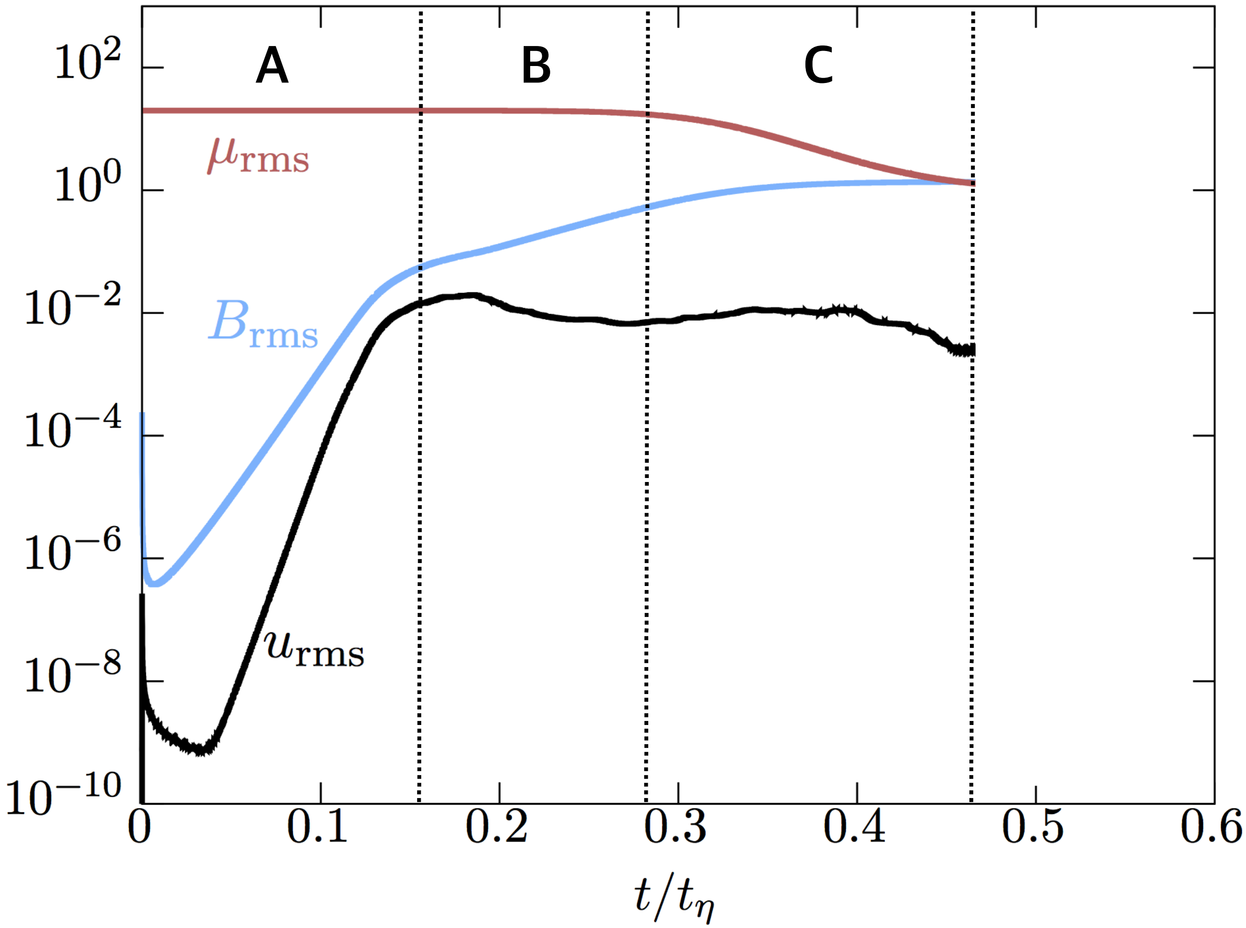


Phase C:

Saturation

- Chemical potential vanishes and dynamo saturates

From laminar to turbulent flows



Phase C:

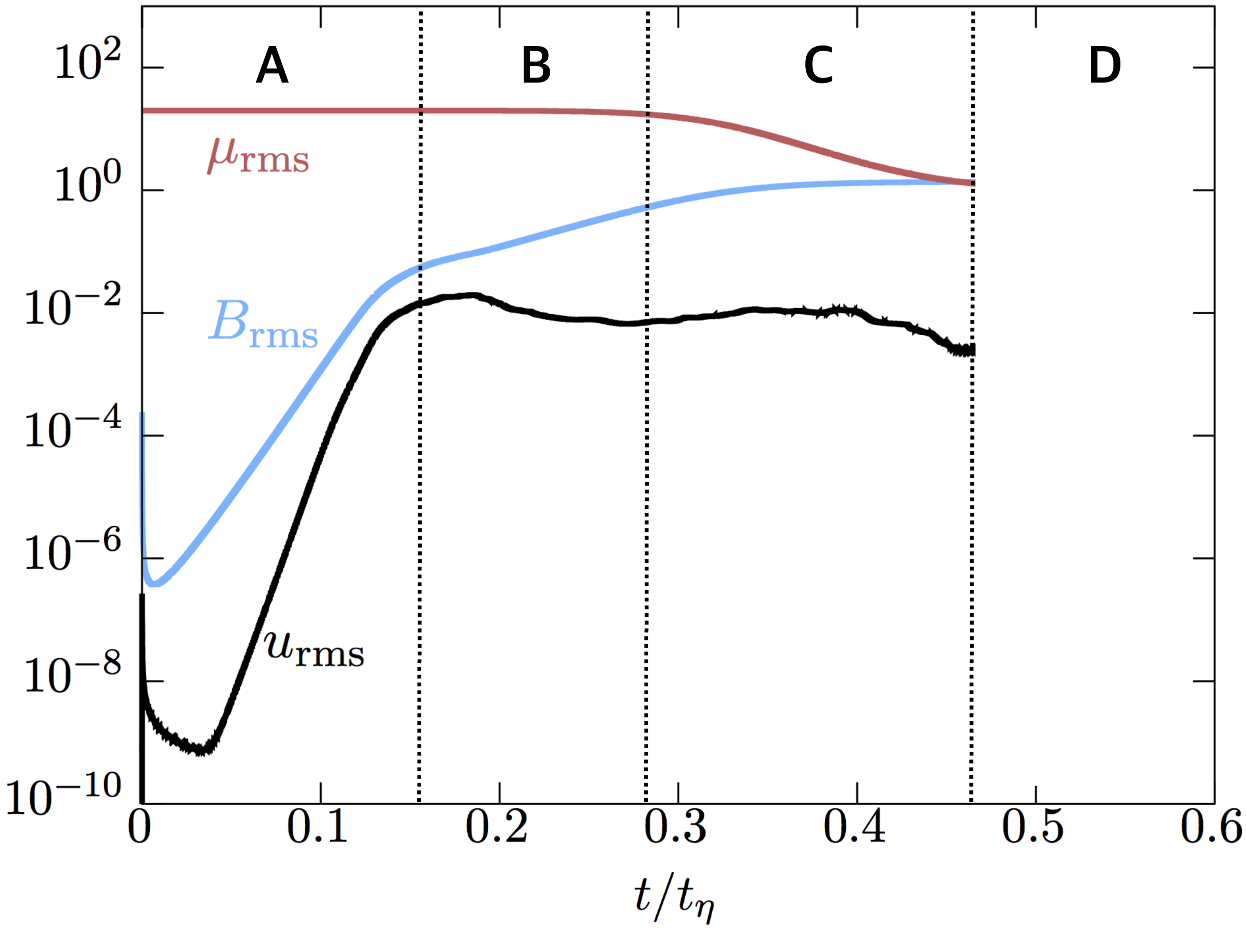
Saturation

- Chemical potential vanishes and dynamo saturates
- Controlled by conservation law of chiral MHD:

  The total chirality is conserved, or

$$\frac{2\mu_0}{\lambda} + < A \cdot B >= \text{const}$$

From laminar to turbulent flows

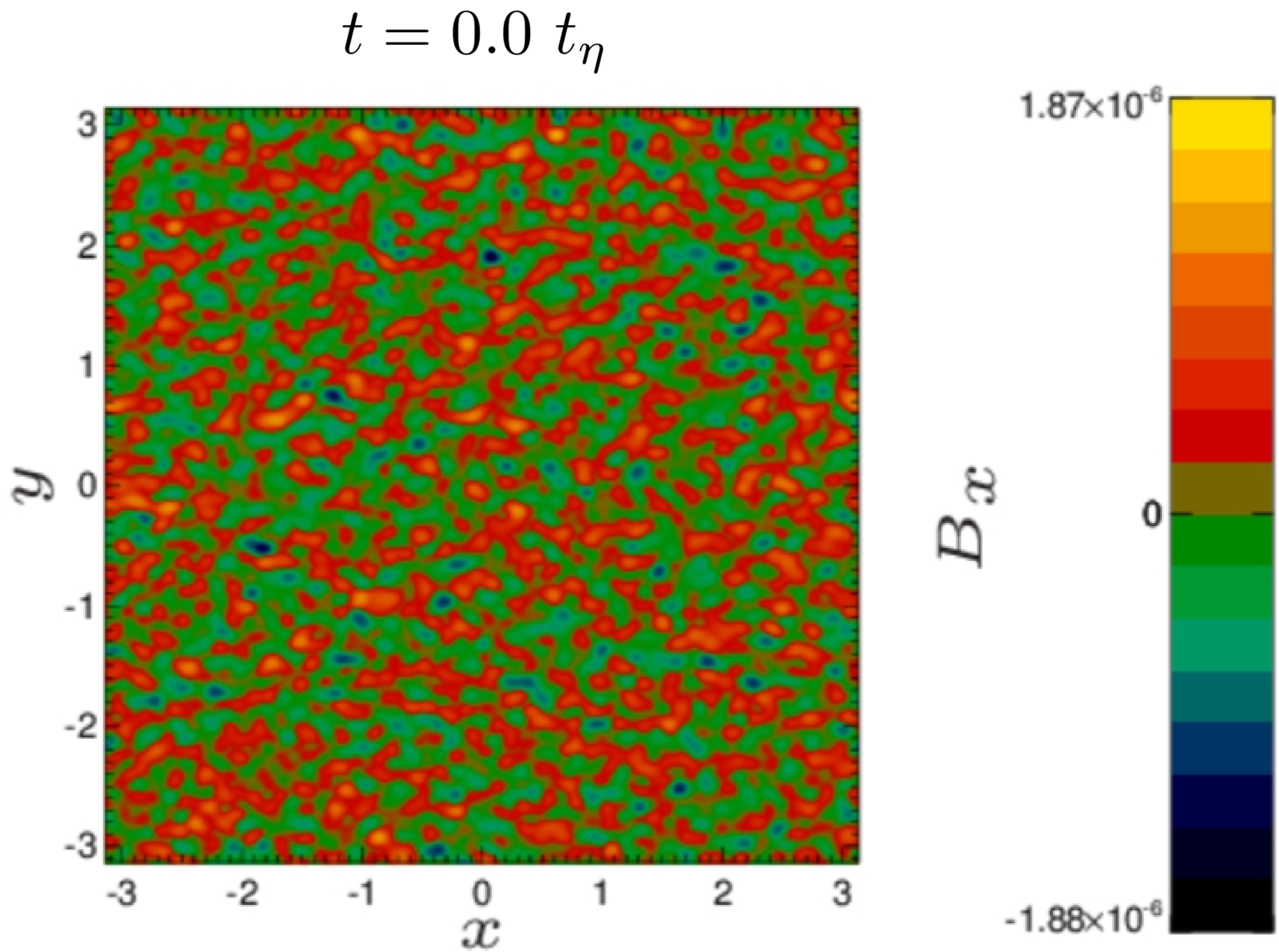


Phase D:

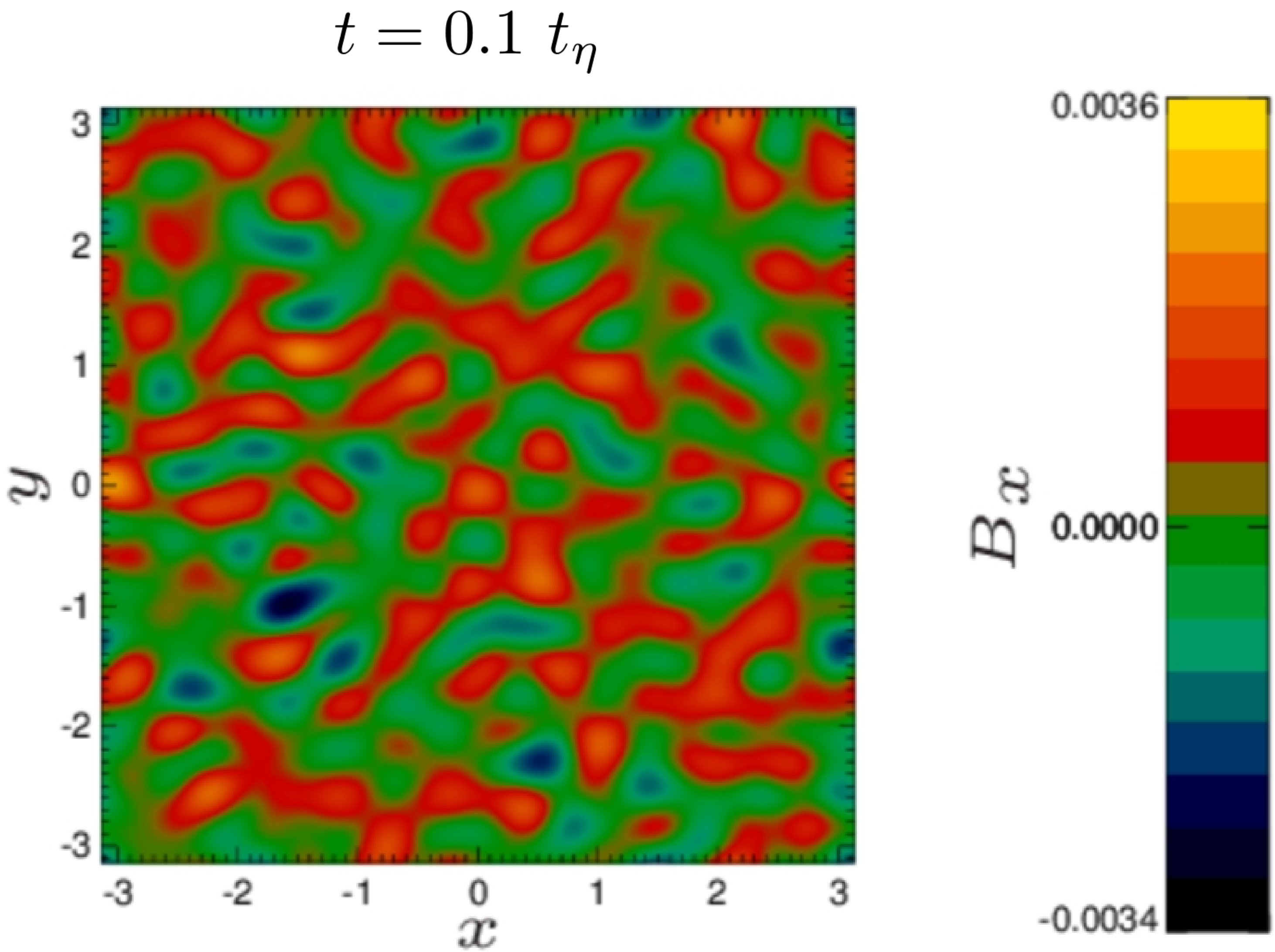
Decaying MHD turbulence

- The fully helical magnetic field decays
- Magnetic energy is transferred to larger spatial scales ("inverse cascade")

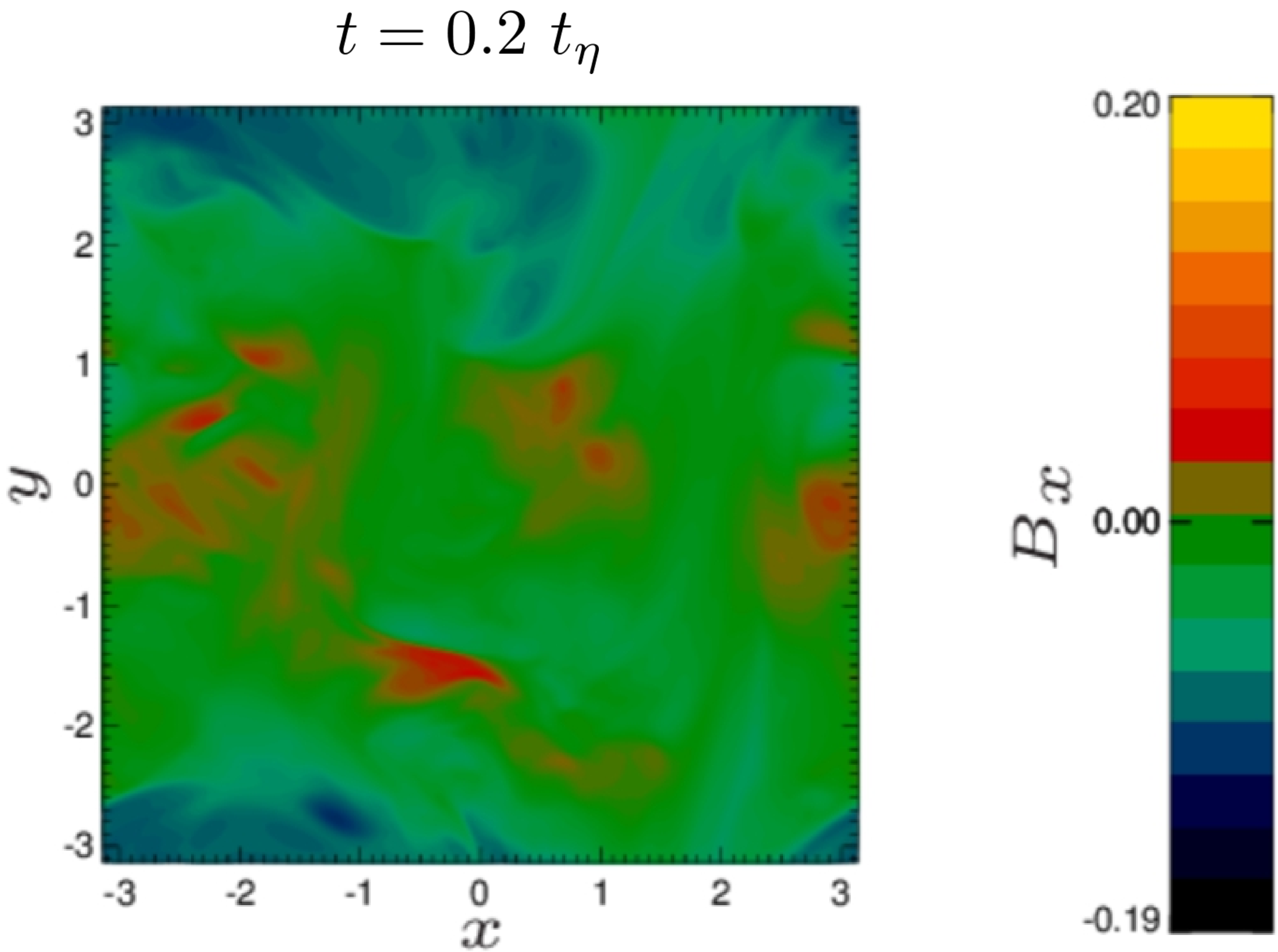
The turbulent chiral dynamo



The turbulent chiral dynamo



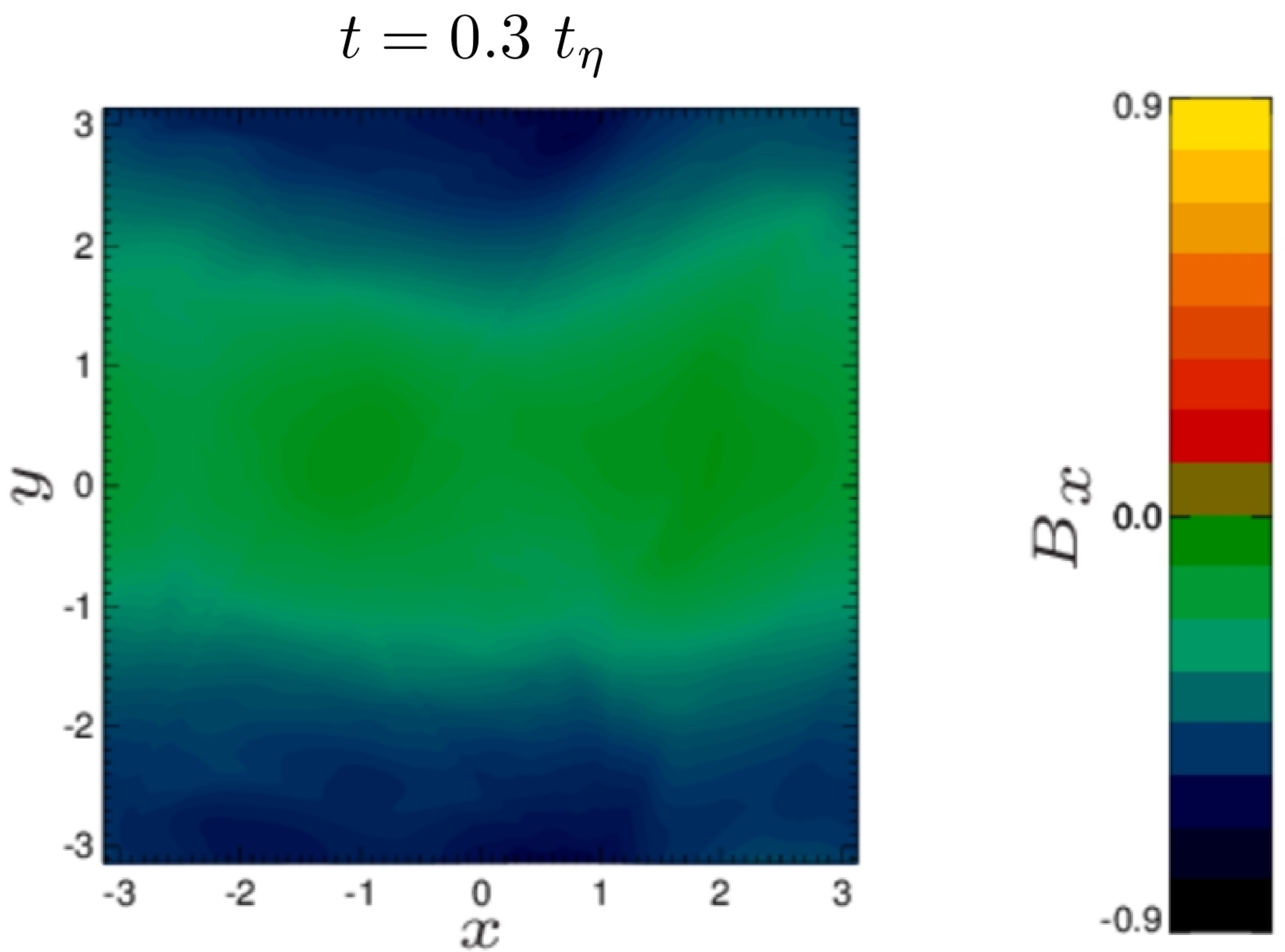
The turbulent chiral dynamo



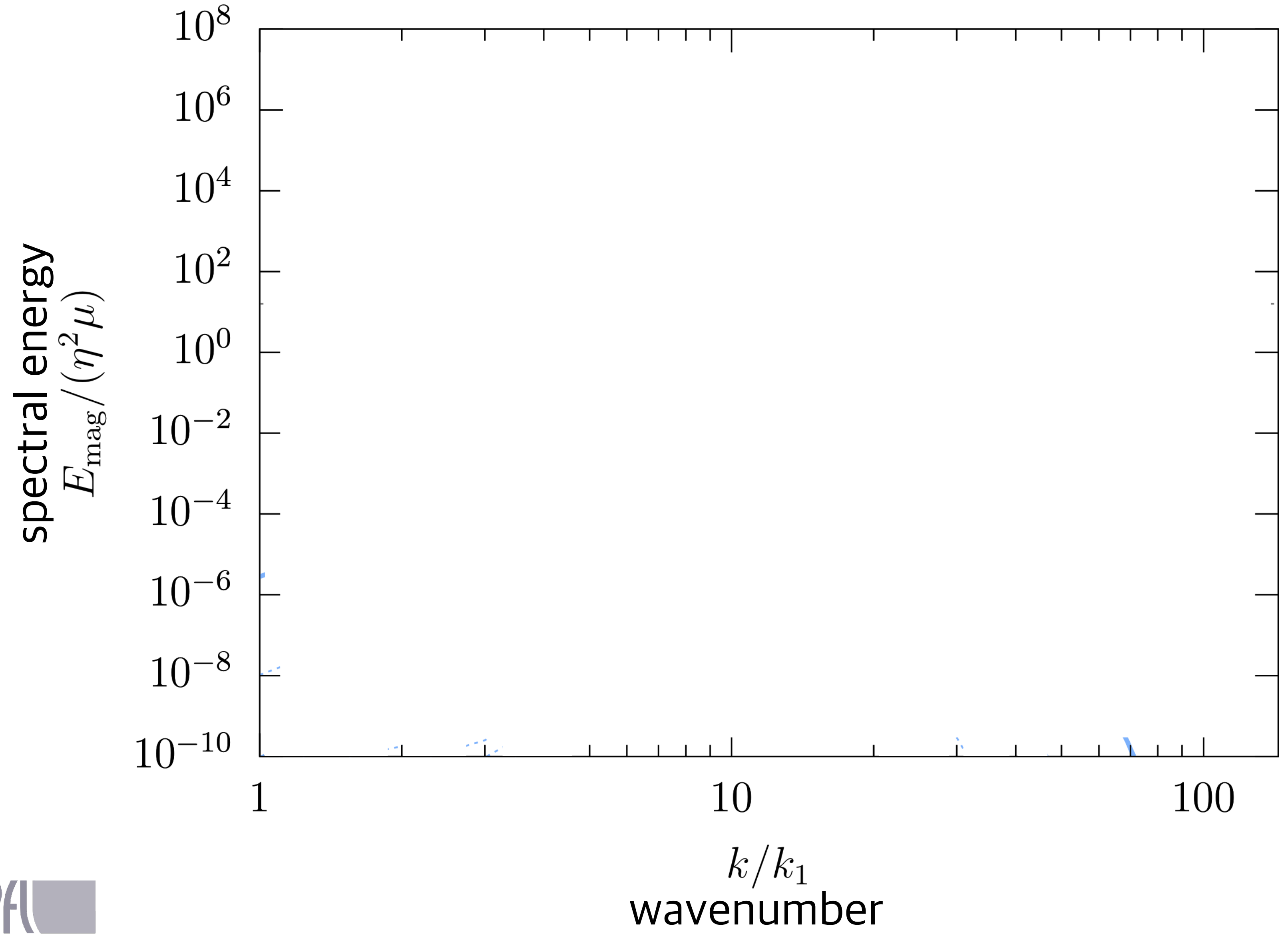
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Jennifer
Schober

The turbulent chiral dynamo

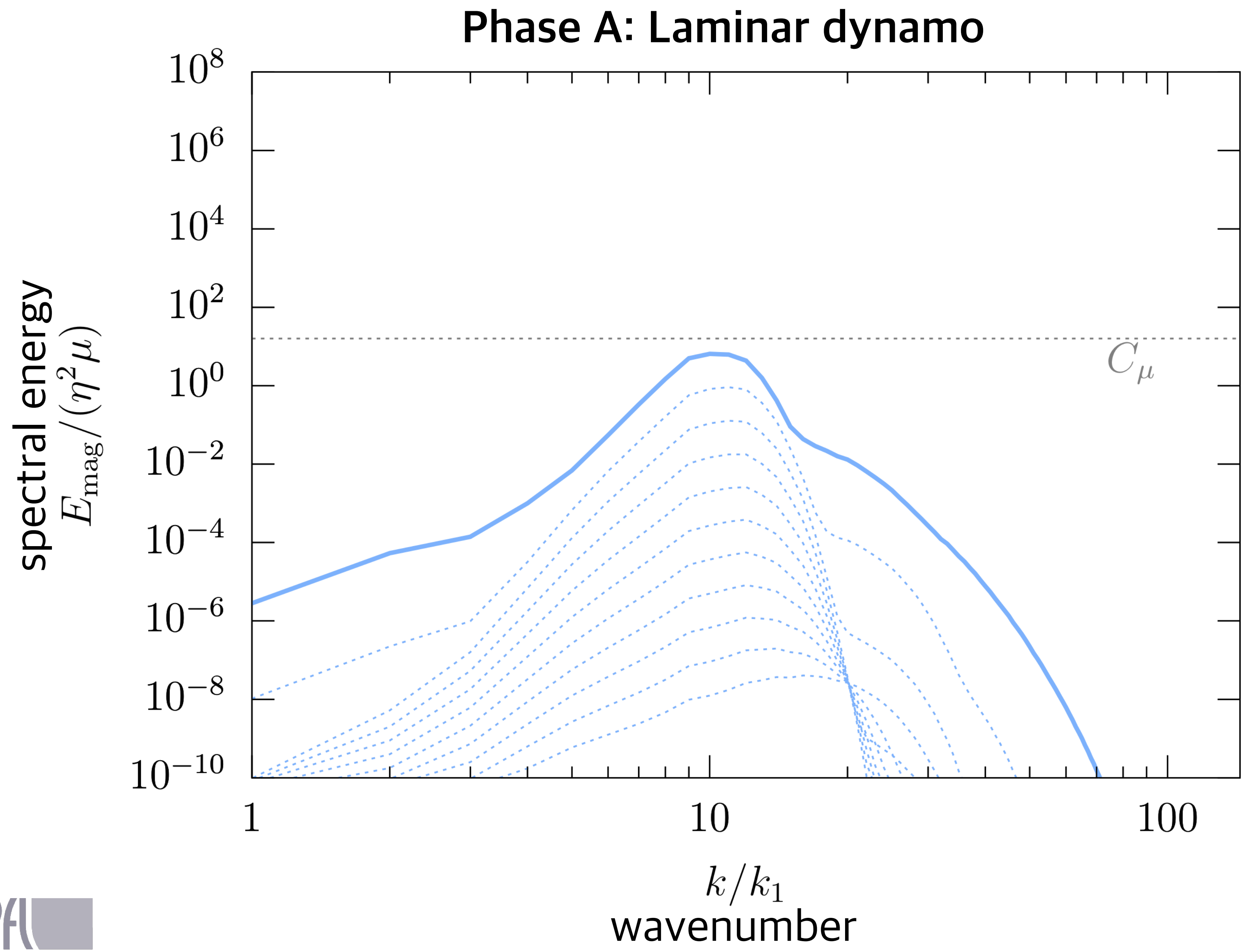


Evolution of energy spectra



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

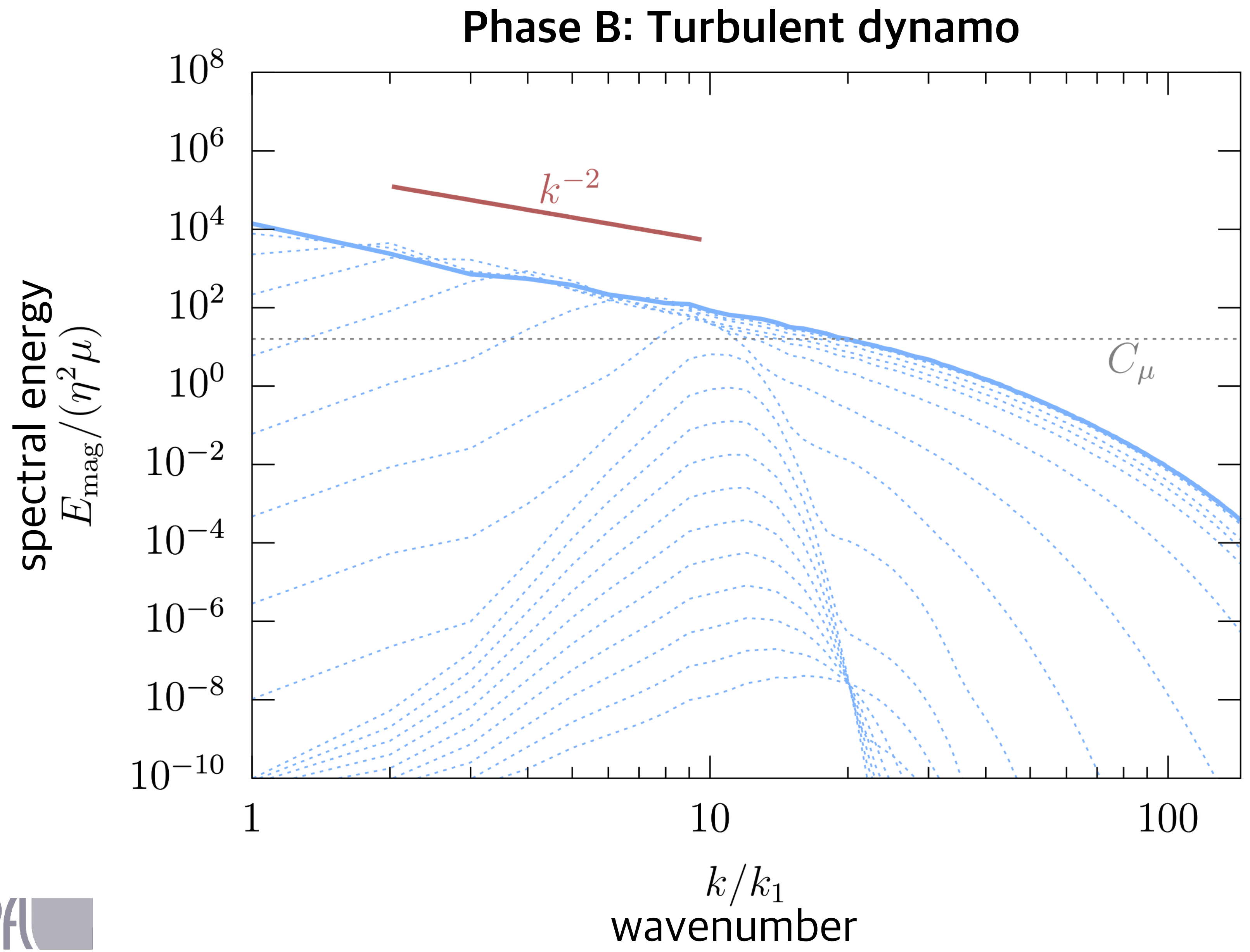
Evolution of energy spectra



École Polytechnique Fédérale de Lausanne

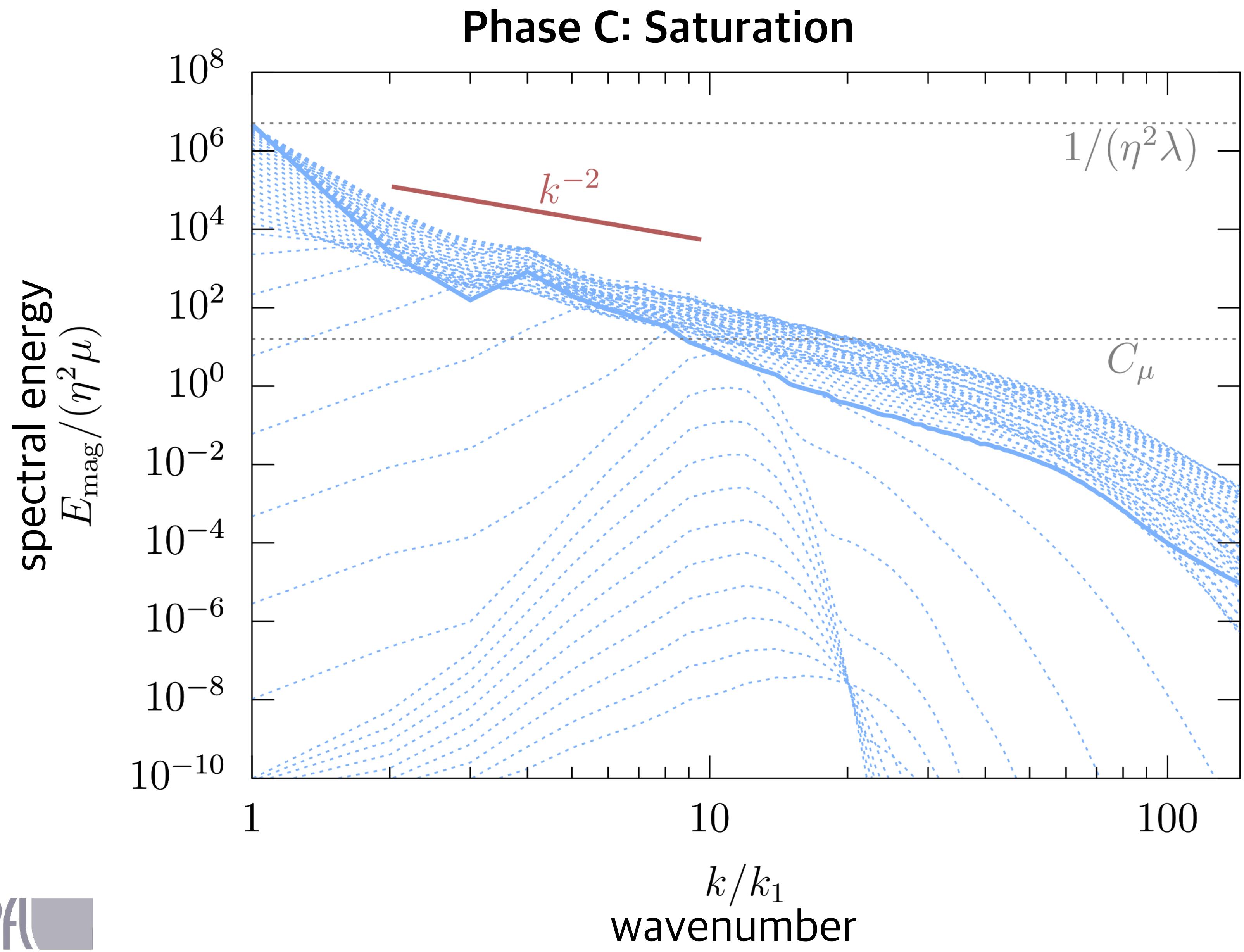
Jennifer Schober

Evolution of energy spectra



Jennifer Schober

Evolution of energy spectra



Jennifer Schober

Saturation magnetic field strength

Saturation magnetic field strength

- **Conservation law:** Fermion chirality + magnetic helicity = const

$$\frac{2\mu_0}{\lambda} + < A \cdot B >= \mathrm{const}$$

Saturation magnetic field strength

- **Conservation law:** Fermion chirality + magnetic helicity = const

$$\frac{2\mu_0}{\lambda} + < A \cdot B >= \mathrm{const}$$

- **Example:** Assume chiral chemical potential equals thermal energy density:

  $\boldsymbol{B}^2 \xi_\mathrm{M} \approx 5 \times 10^{-38} \mathrm{G}^2 \mathrm{Mpc}$ (today)

  (lower limit from Fermi observations of IGM: $\boldsymbol{B}^2 \xi_\mathrm{M} \gtrsim 10^{-36} \mathrm{G}^2 \mathrm{Mpc}$
  Neronov & Vovk 2010, Dermer et al. 2011, Durrer & Neronov 2013)

Saturation magnetic field strength

- **Conservation law:** Fermion chirality + magnetic helicity = const

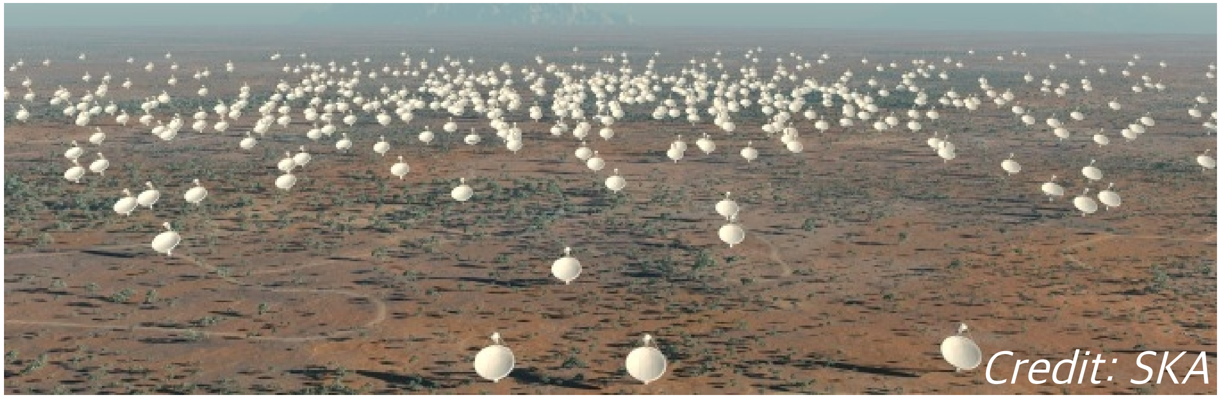
$$\frac{2\mu_0}{\lambda} + < A \cdot B >= \mathrm{const}$$

- **Example:** Assume chiral chemical potential equals thermal energy density:

$$\boldsymbol{B}^2 \xi_{\mathrm{M}} \approx 5 \times 10^{-38} \mathrm{G}^2 \mathrm{Mpc} \quad \text{(today)}$$

(lower limit from Fermi observations of IGM: $\boldsymbol{B}^2 \xi_{\mathrm{M}} \gtrsim 10^{-36} \mathrm{G}^2 \mathrm{Mpc}$
Neronov & Vovk 2010, Dermer et al. 2011, Durrer & Neronov 2013)

- **Outlook:** With detections of the IGM magnetic field, we can better understand fundamental physics in the Early Universe.



ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

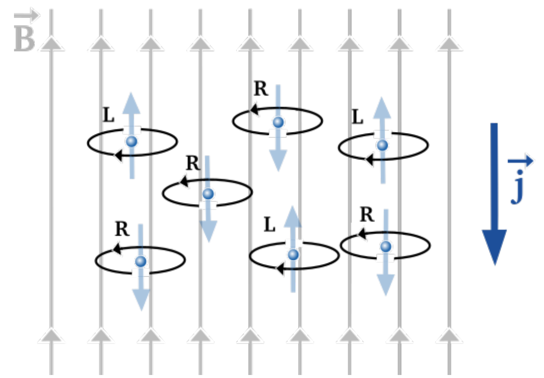
Jennifer Schober

Conclusions

Thanks for your attention!

Conclusions

The chiral magnetic effect produces new currents.

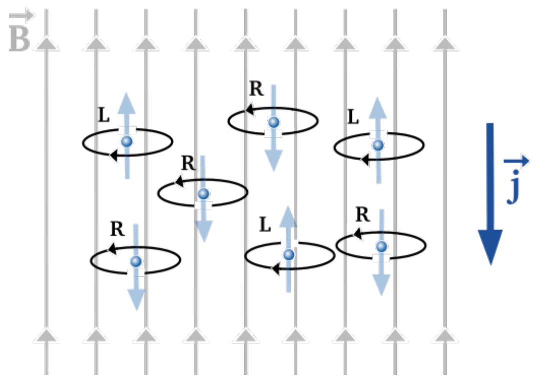


→ new dynamos and source for turbulence

Thanks for your attention!

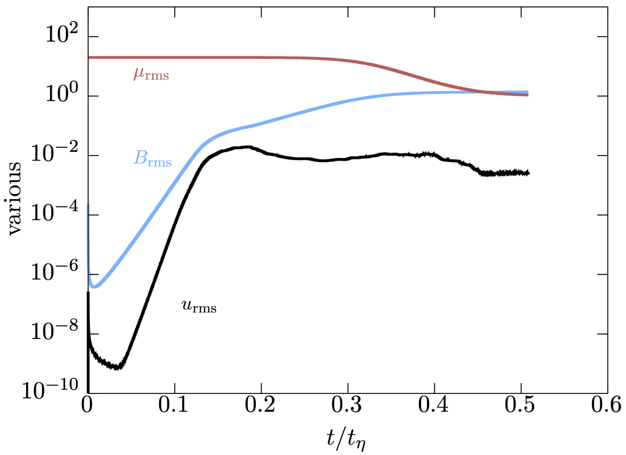
Conclusions

The chiral magnetic effect produces new currents.



→ new dynamos and source for turbulence

Magnetic field evolution:



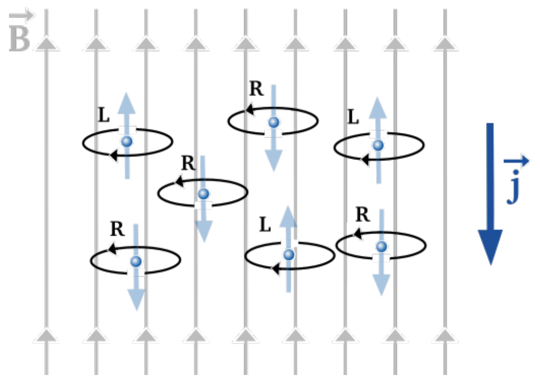
→ simulation and mean-field theory consistent

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Thanks for your attention!

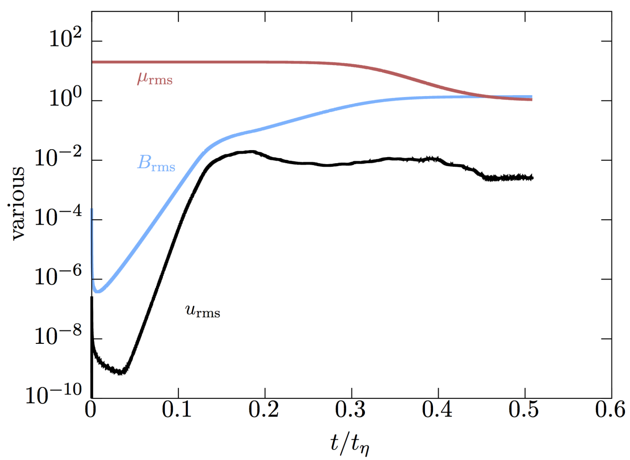
Conclusions

The chiral magnetic effect produces new currents.



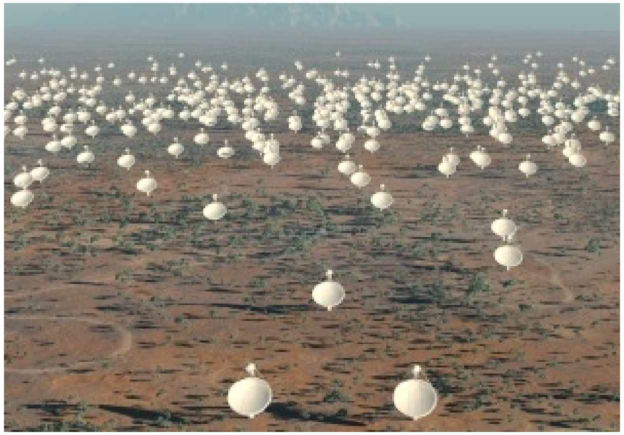
→ new dynamos and source for turbulence

Magnetic field evolution:



→ simulation and mean-field theory consistent

Non-thermal production mechanisms for chiral asymmetry needed to explain IGM magnetic fields.



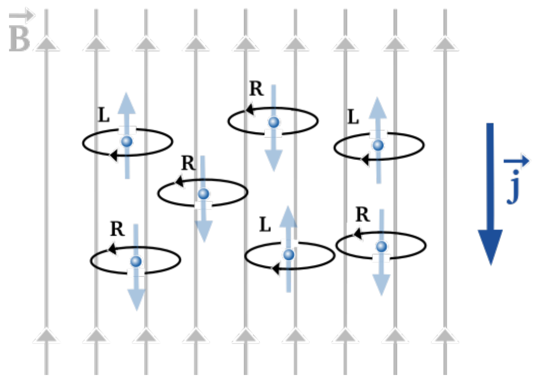
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Thanks for your attention!

Jennifer Schober

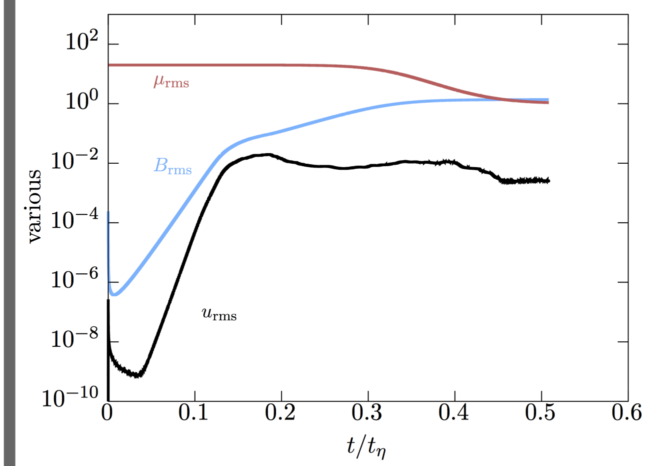
Conclusions

The chiral magnetic effect produces new currents.



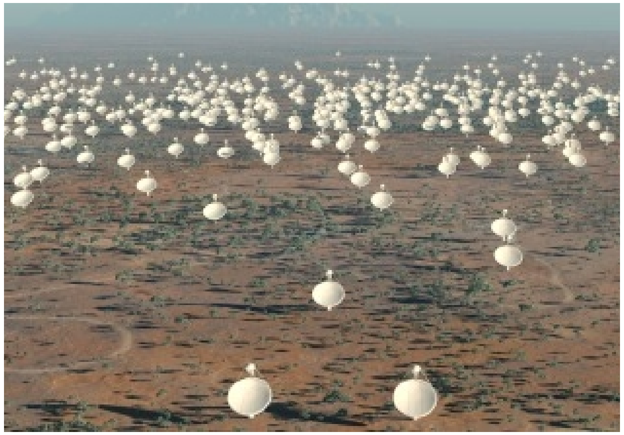
→ new dynamos and source for turbulence

Magnetic field evolution:



→ simulation and mean-field theory consistent

Non-thermal production mechanisms for chiral asymmetry needed to explain IGM magnetic fields.



For more details:

- **Schober et al. 2018** (ApJ, 858,124) → numerical simulations of chiral dynamos
- **Rogachevskii et al. 2017** (ApJ, 846, 153) → mean-field theory of chiral MHD
- **Brandenburg et al. 2017** (ApJL,845, L21) → turbulence in chiral MHD

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Thanks for your attention!

Jennifer Schober