Turbulent dynamo: nonlinear and linear regimes

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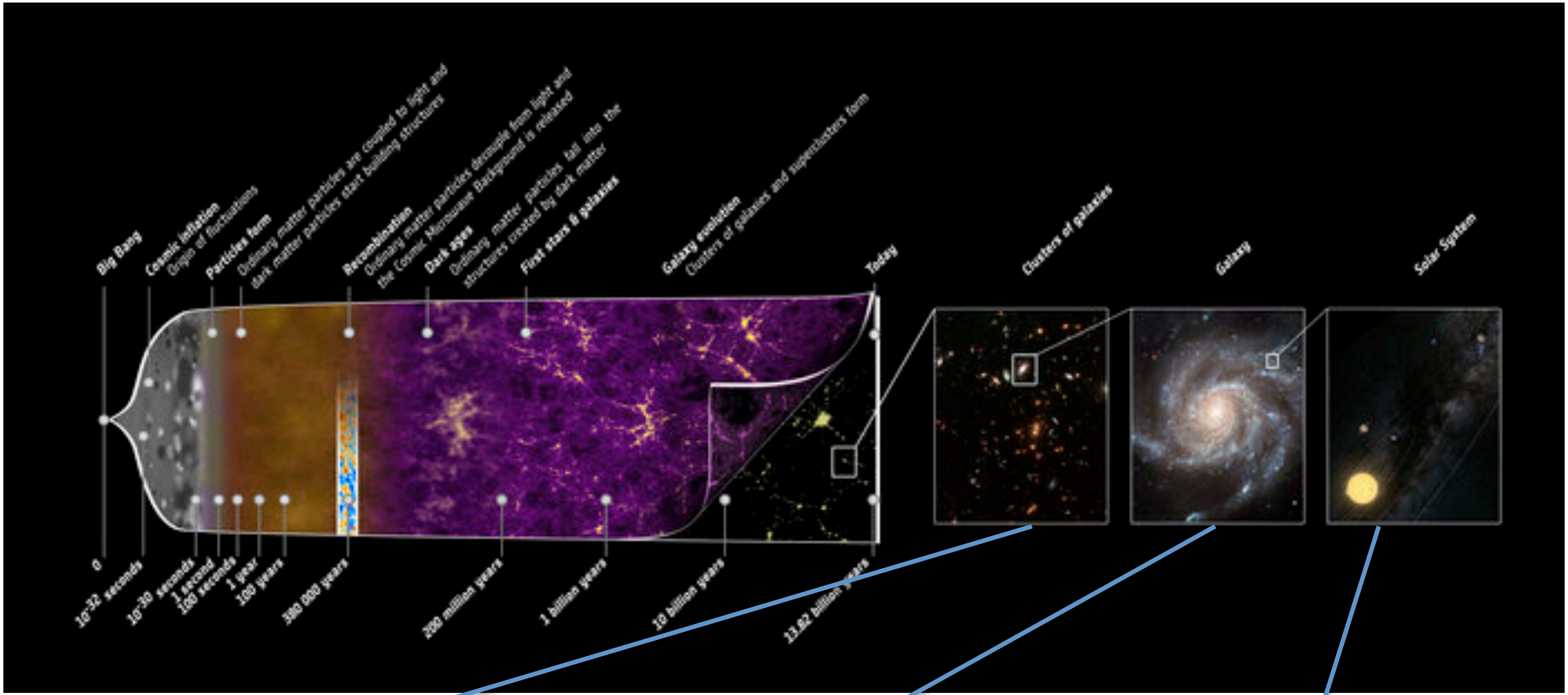
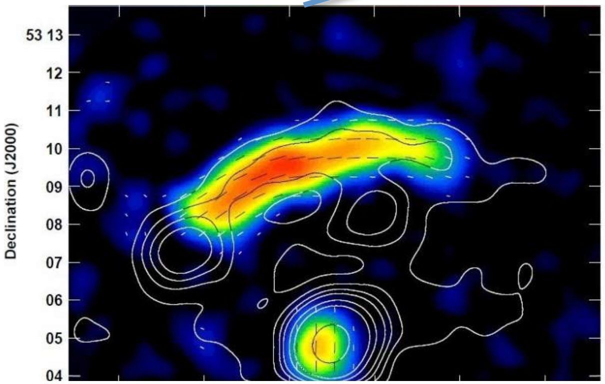
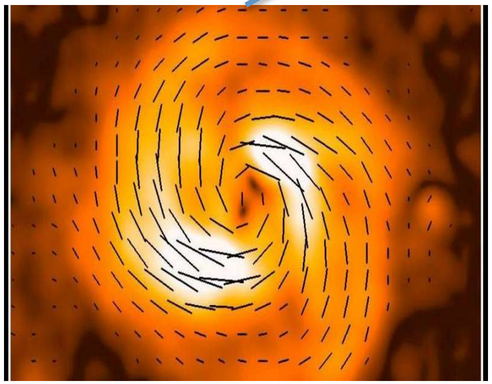


Planck



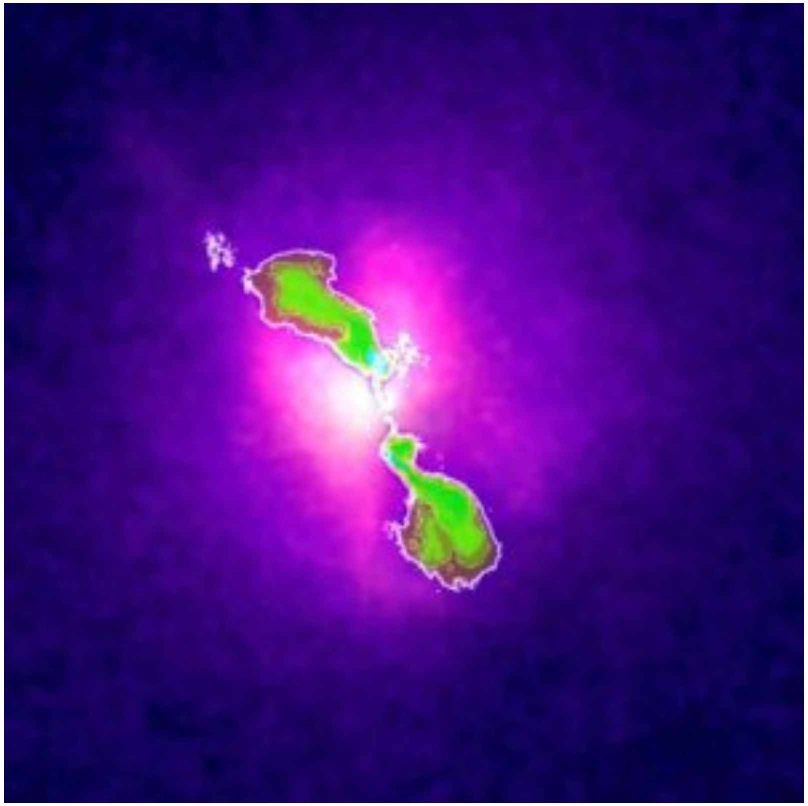
Kierdorf et al. 2017



R. Beck 2015

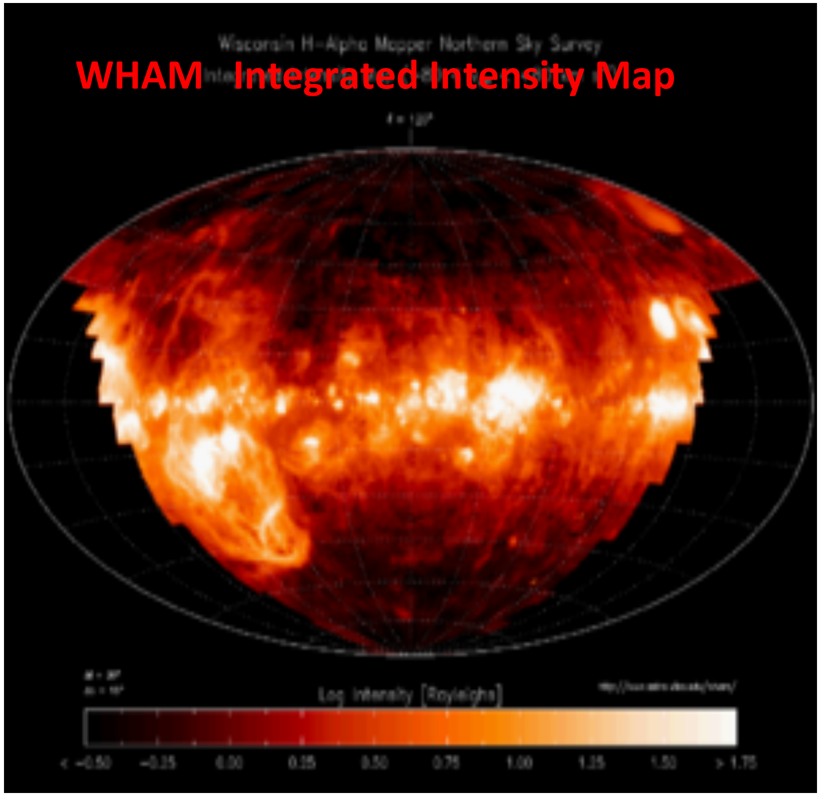
TRACE Team

Clusters of Galaxies



X-ray: NASA/CXC/SAO; Radio: Greg Taylor (NRAO).

Interstellar Medium

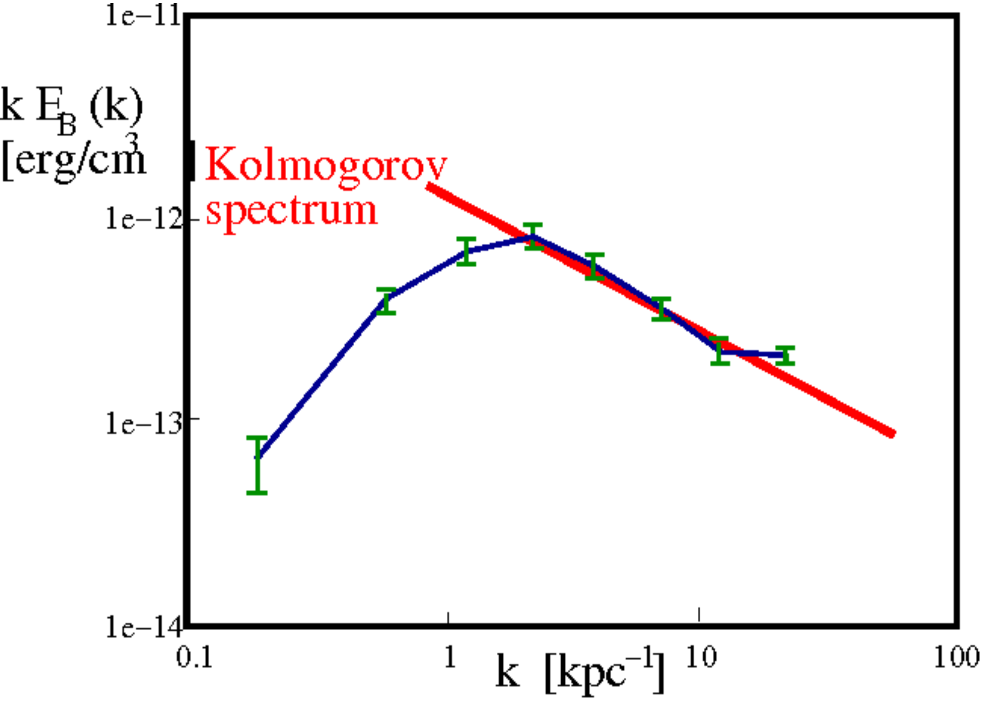

WHAM Integrated Intensity Map

Haffner et al. 2003

Clusters of Galaxies

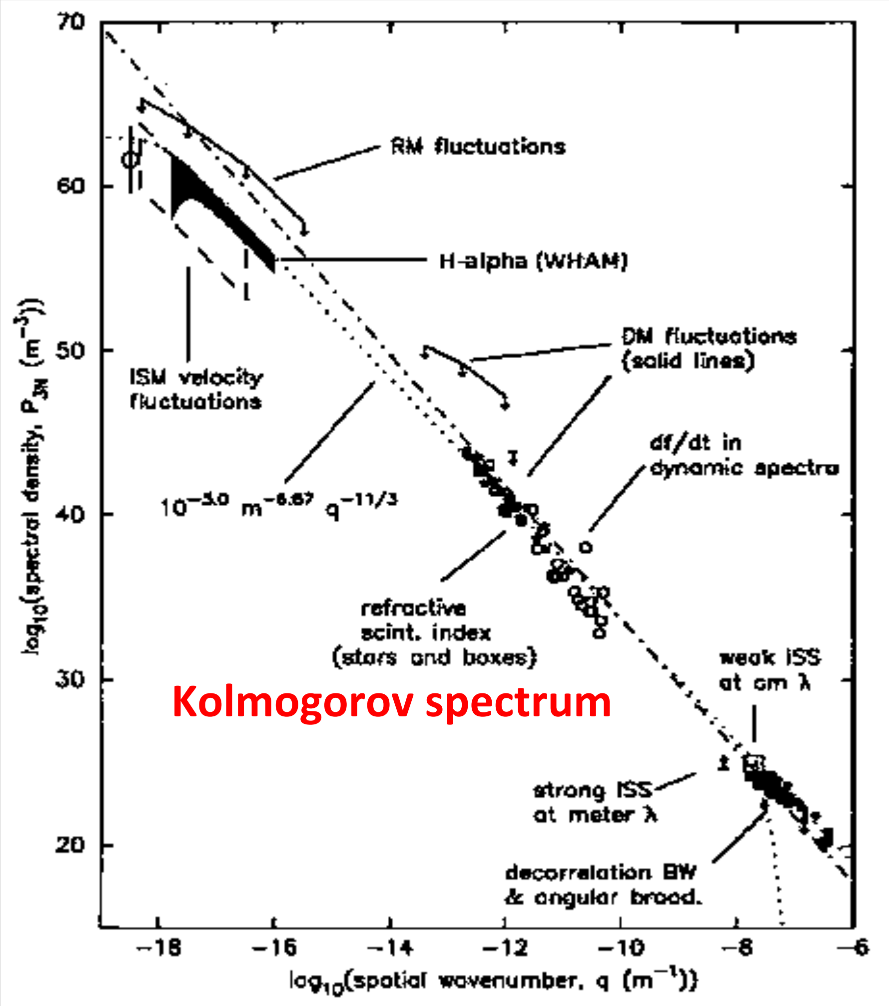
Interstellar Medium

Magnetic fluctuations



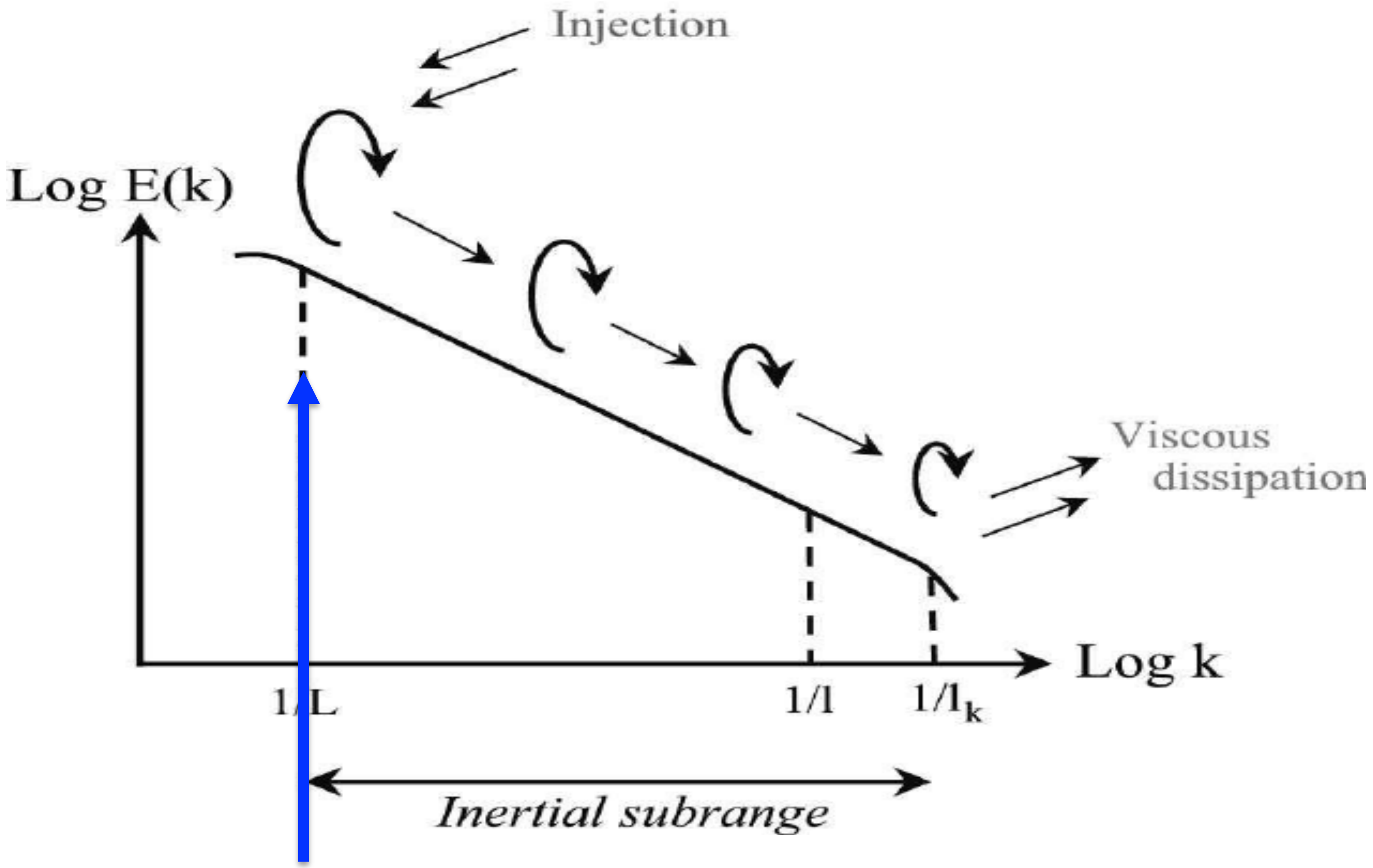
Vogt & EnBlin 2005

Density fluctuations



Armstrong+ 95; Chepurnov & Lazarian 09

Turbulent energy cascade



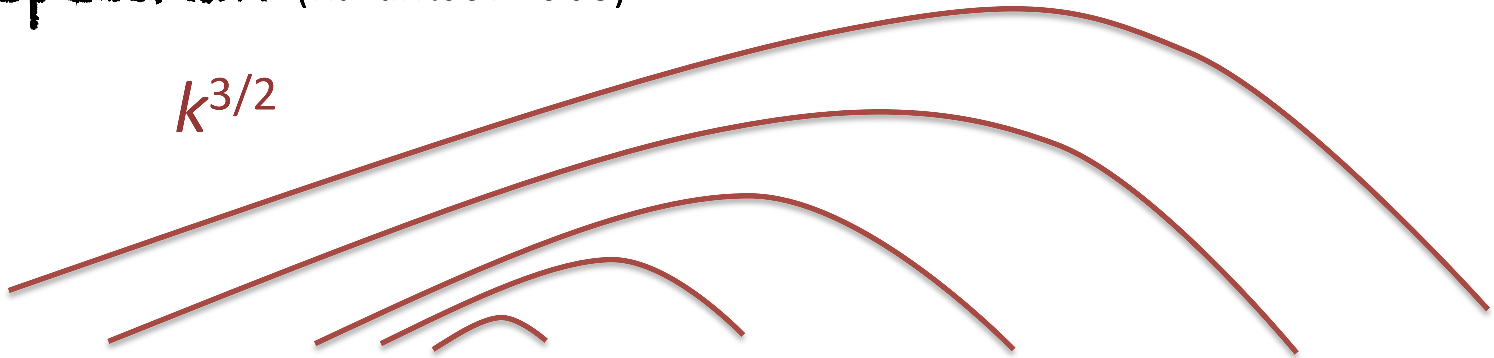
Constant turbulent energy transfer rate

https://commons.wikimedia.org/w/index.php?curid=64829708

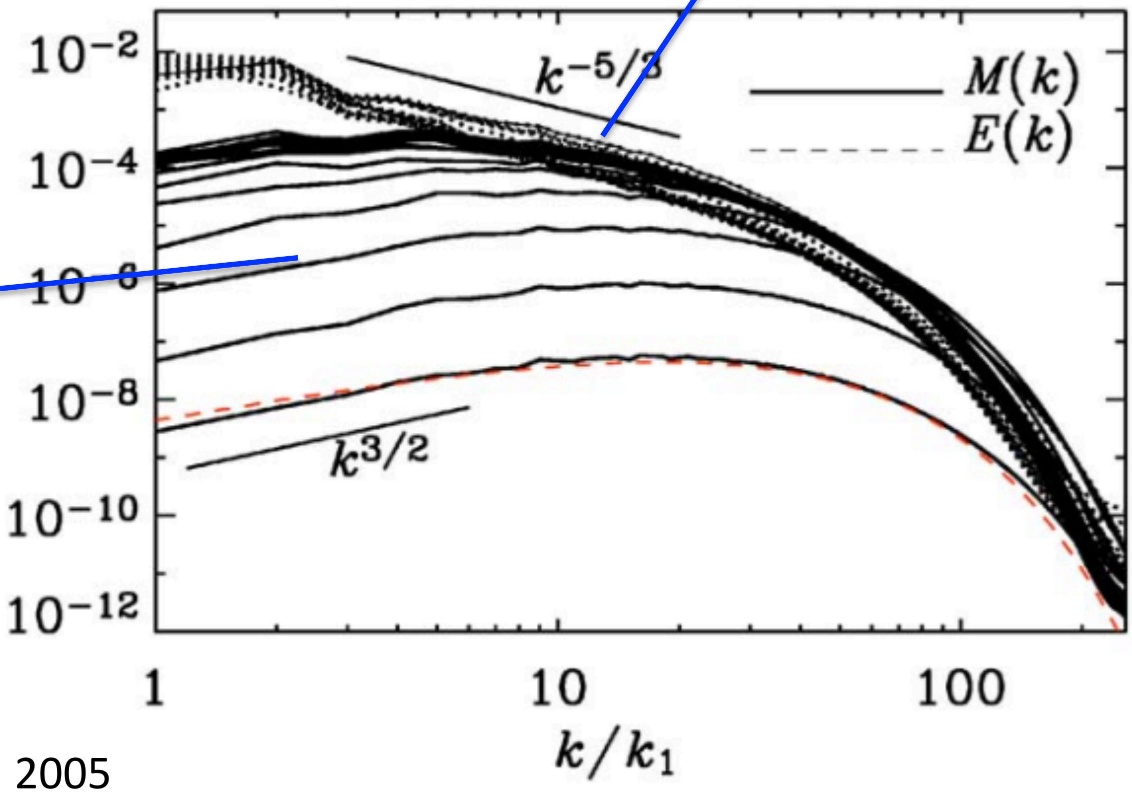
Turbulence dynamo

$$M(k,t) = M_1 \exp\left(\frac{3}{4}\int \Gamma \, dt\right)\left(\frac{k}{k_1}\right)^{\frac{3}{2}}$$

Kazantsev spectrum (Kazantsev 1968)



Turbulence dynamo



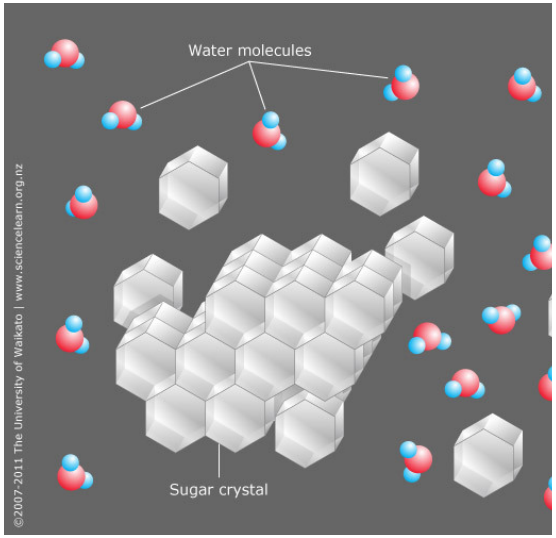
Turbulent energy spectrum

Magnetic energy spectrum

Brandenburg & Subramanian 2005

Diffusion of magnetic fields

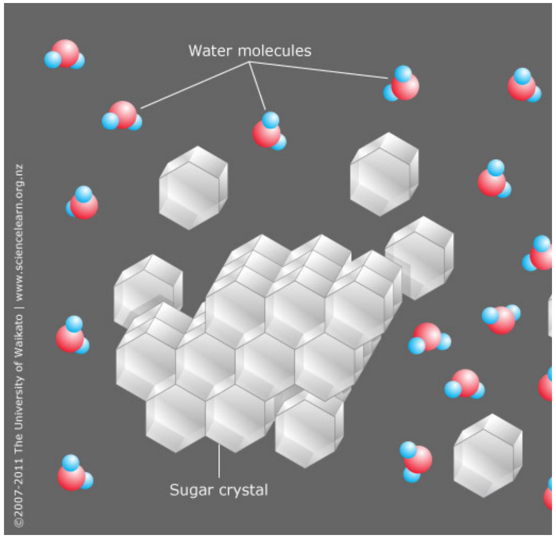
resulting in **inefficient dynamo stretching** of magnetic fields



$$D = (4.3 \pm 0.3) \times 10^{-10}\,\mathrm{m}^2\,\mathrm{s}^{-1}$$

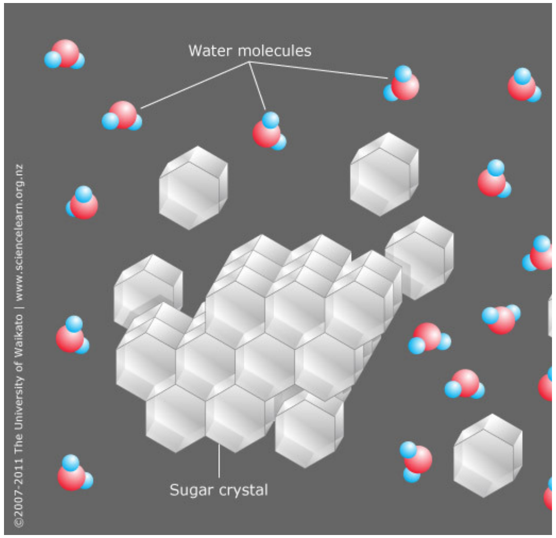
Linder et al. 1976

Molecular diffusion



Molecular diffusion

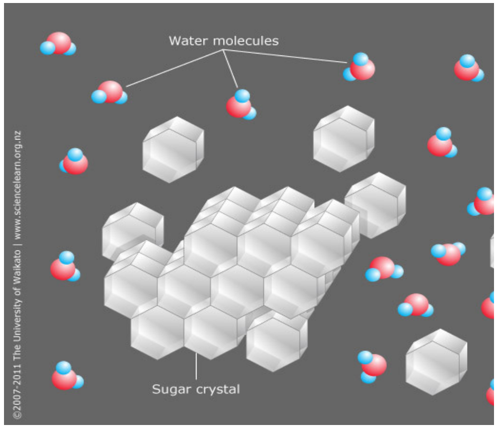
Turbulent diffusion



Molecular diffusion

Turbulent diffusion

Molecular diffusion



Turbulent diffusion

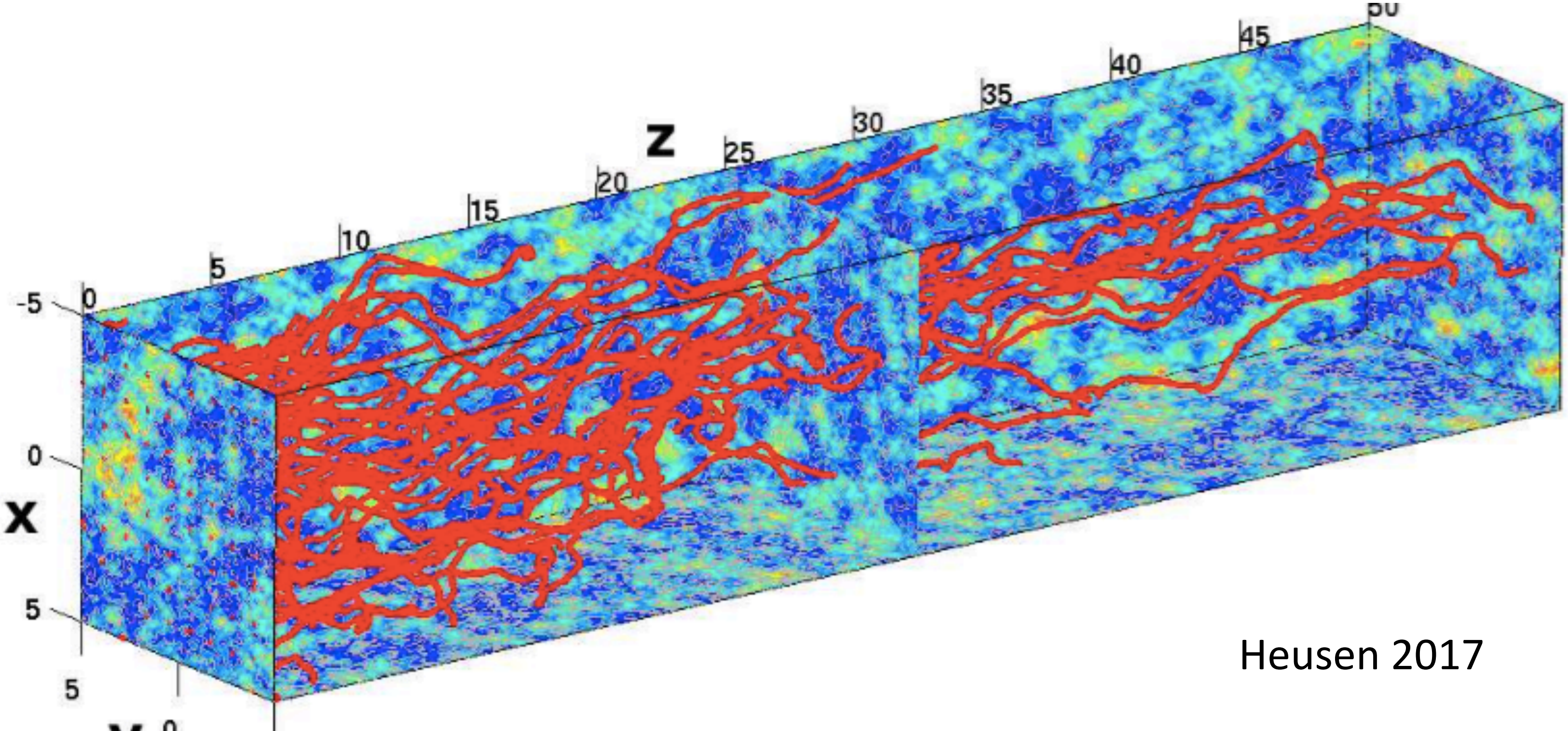
Diffusion of magnetic fields

Resistive diffusion

Ambipolar diffusion
(partially ionized medium)

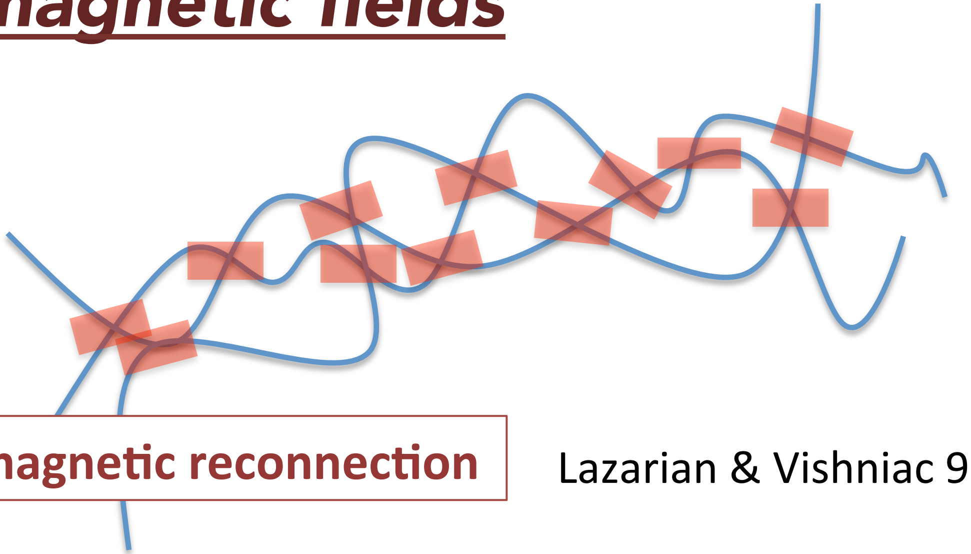
Turbulent diffusion

Turbulent diffusion of magnetic fields



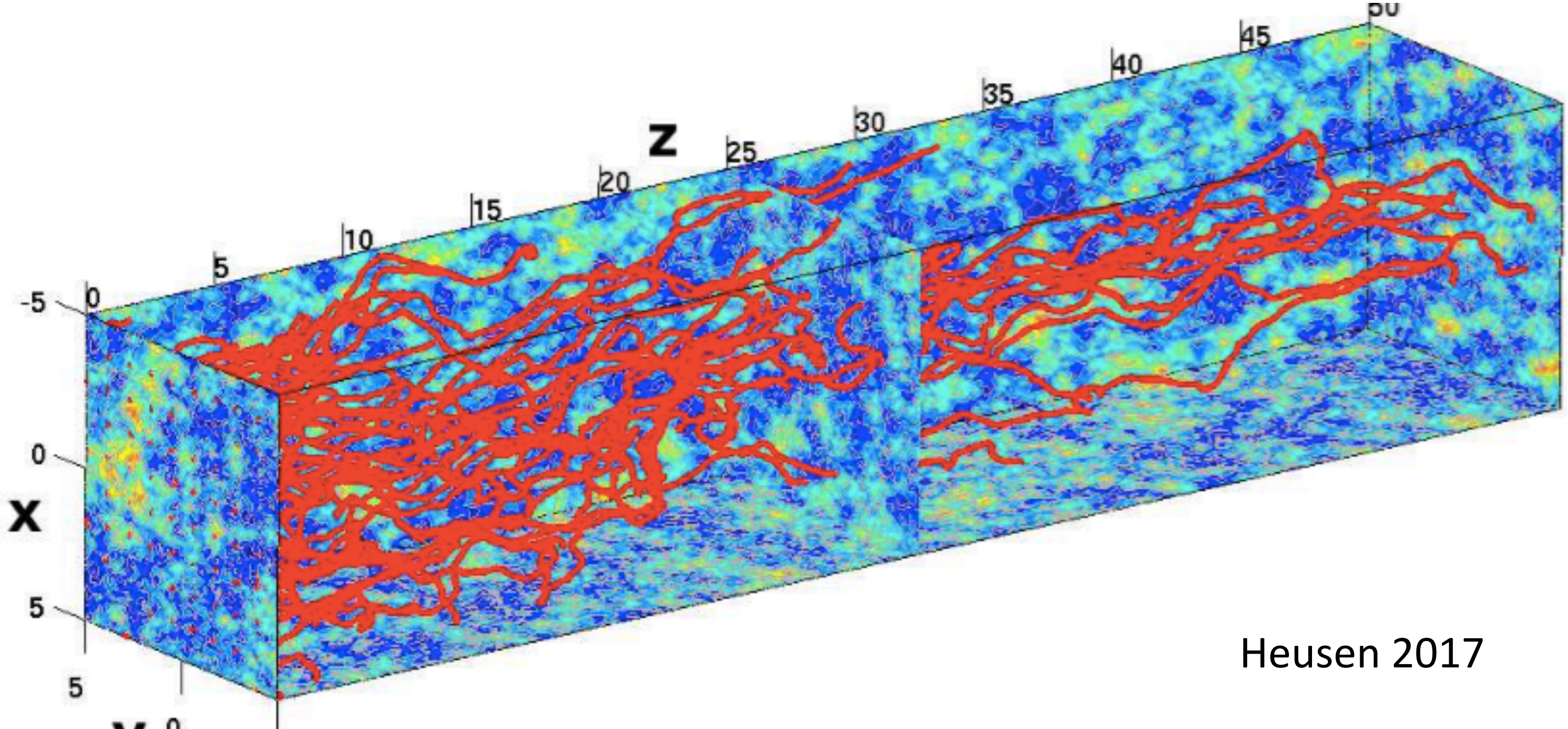
Heusen 2017

Turbulent diffusion of magnetic fields



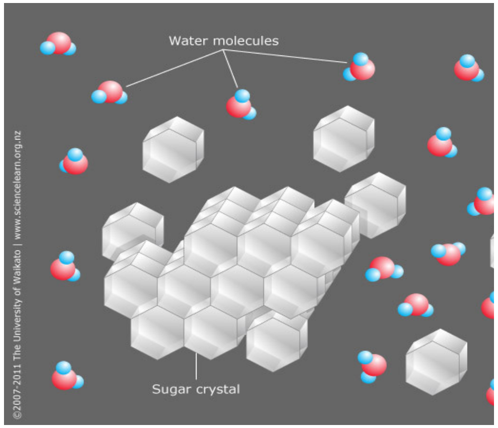
Turbulent magnetic reconnection

Lazarian & Vishniac 99



Heusen 2017

Molecular diffusion



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Turbulent diffusion

Diffusion of magnetic fields

Resistive diffusion

Ambipolar diffusion

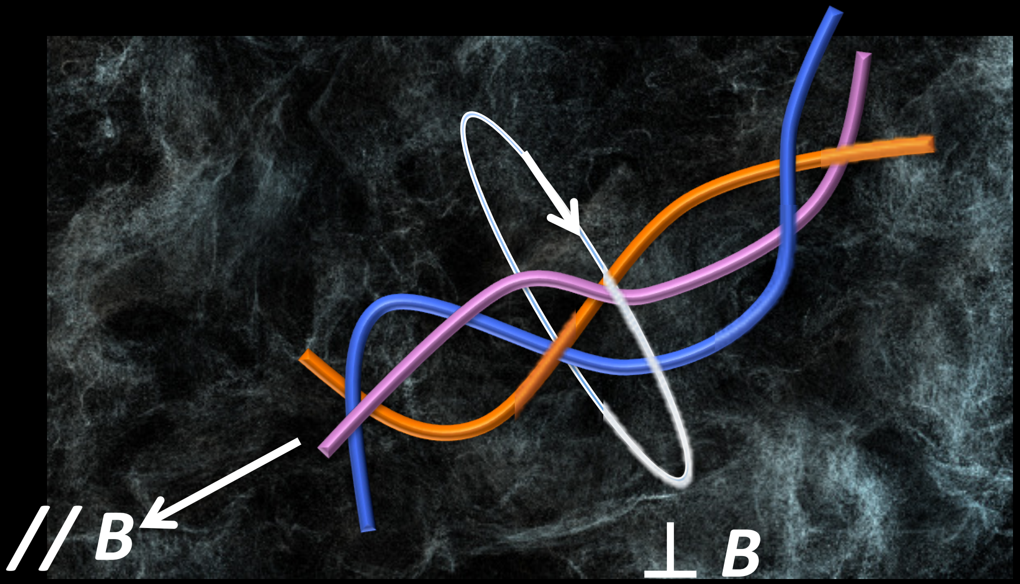
Linear dynamo

Turbulent diffusion

Nonlinear dynamo

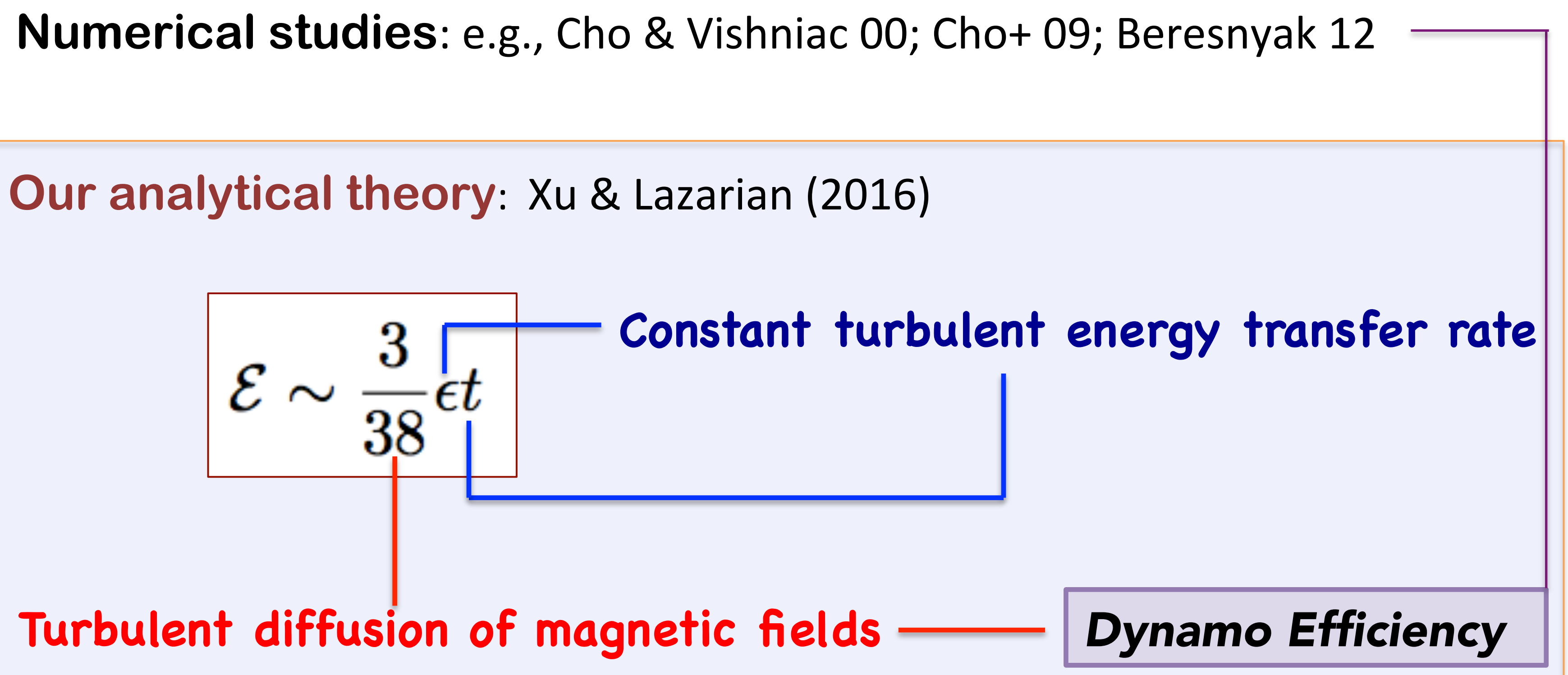
Nonlinear Turbulent Dynamo

Nonlinear turbulent dynamo



Goldreich & Sridhar 1995; Lazarian & Vishniac 1999

Nonlinear turbulent dynamo



Numerical studies: e.g., Cho & Vishniac 00; Cho+ 09; Beresnyak 12

Our analytical theory: Xu & Lazarian (2016)

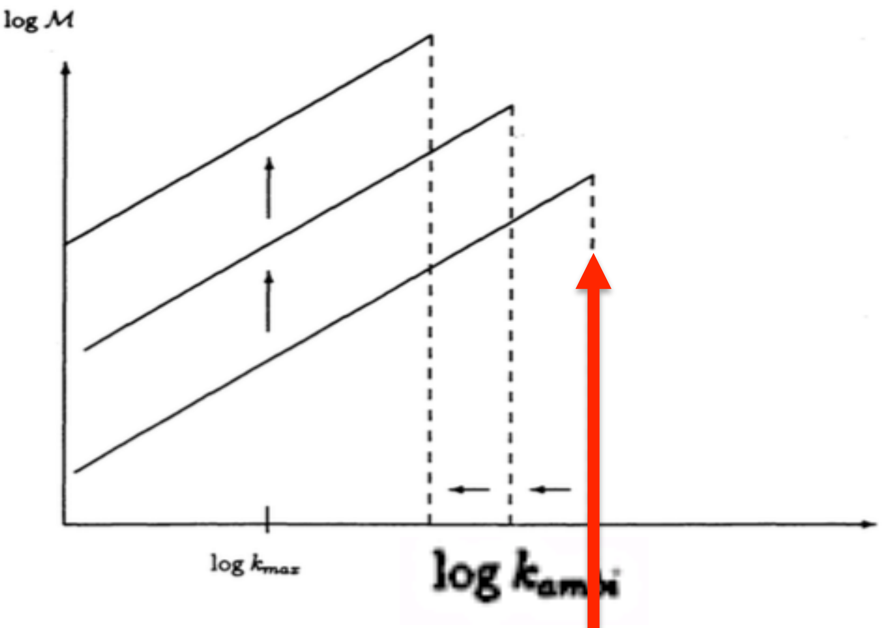
$$\mathcal{E} \sim \frac{3}{38}\epsilon t$$

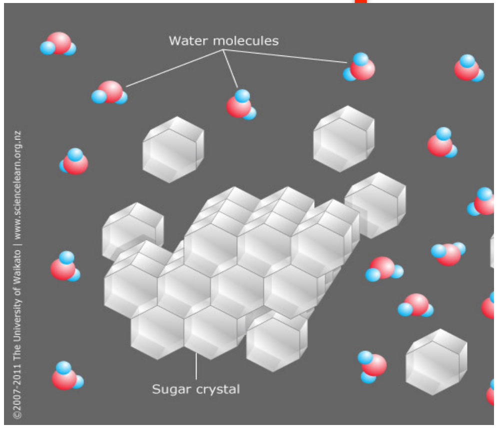
Constant turbulent energy transfer rate

Turbulent diffusion of magnetic fields

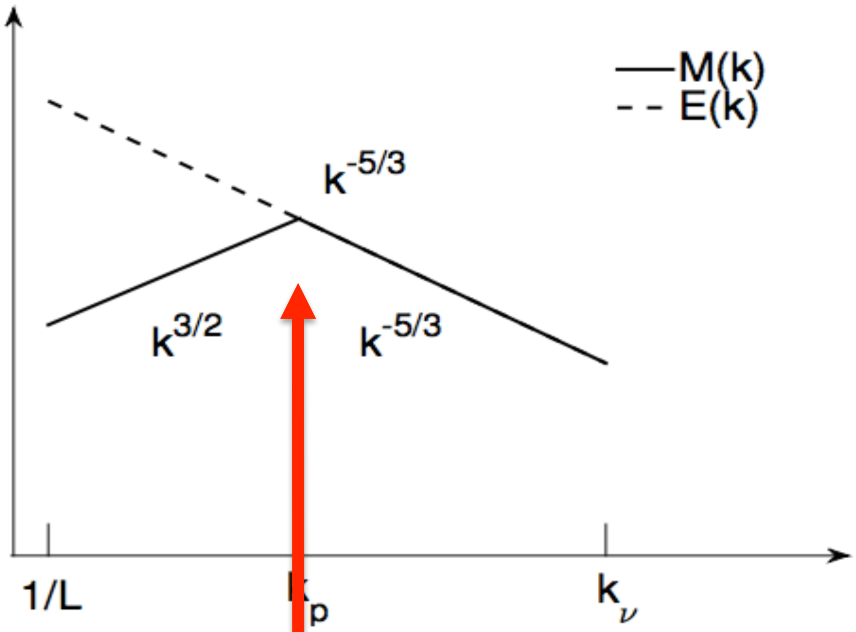
Dynamo Efficiency

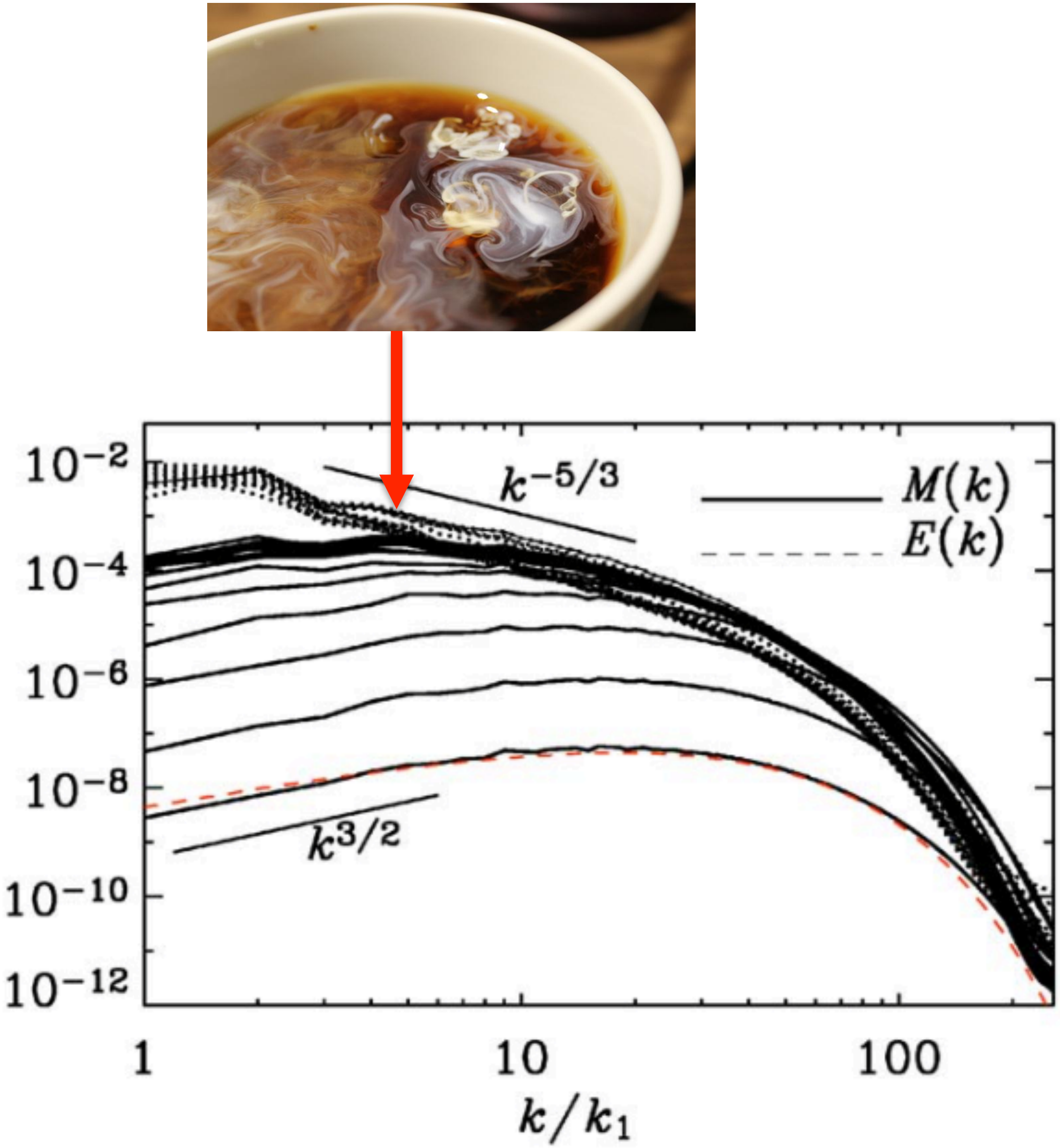
Kulsrud & Anderson 1992





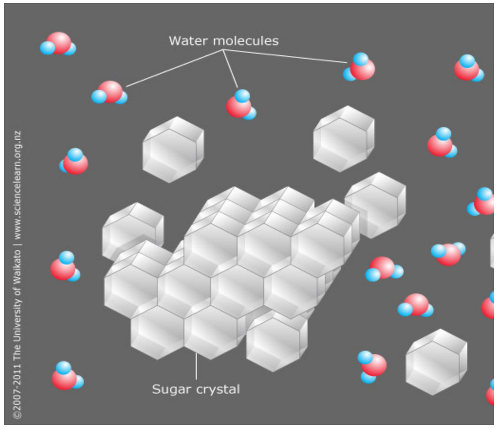
Xu & Lazarian 2016





Brandenburg & Subramanian 2005

Molecular diffusion



Turbulent diffusion

Diffusion of magnetic fields

Resistive diffusion

Ambipolar diffusion

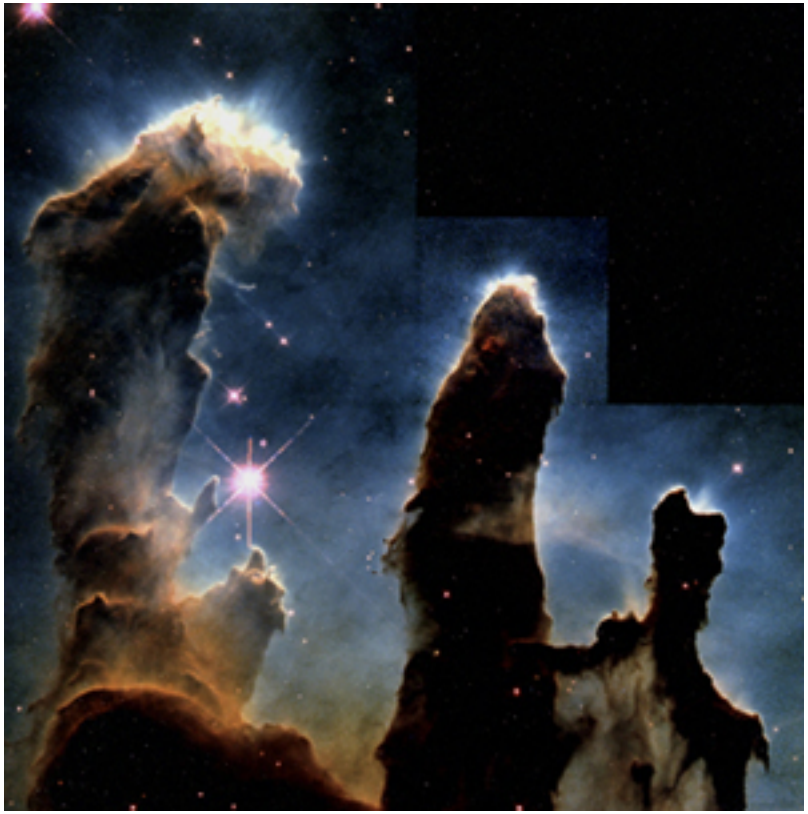
Turbulent diffusion

Linear dynamo

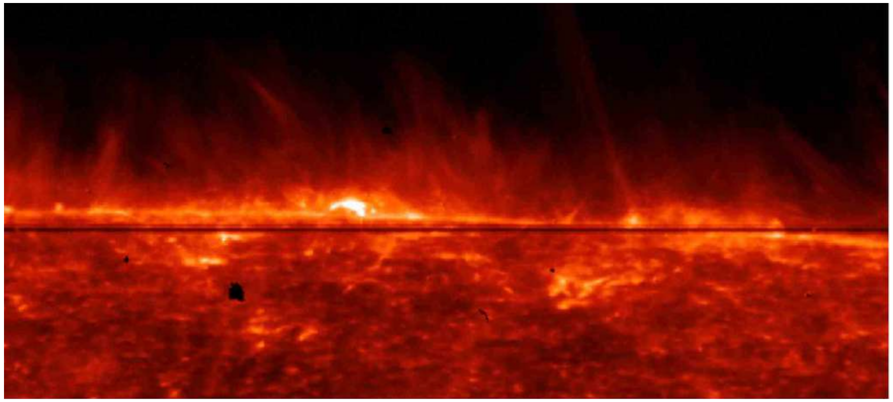
Nonlinear dynamo

Linear Damping Dynamo

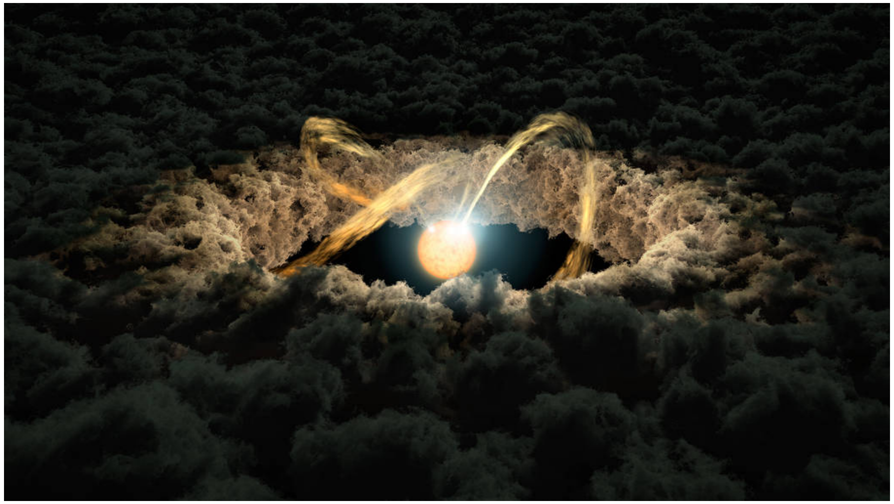
Turbulent dynamo in a partially ionized medium



NASA, Hester and Scowen



NASA/IRIS



NASA/JPL-Caltech

Turbulent dynamo in a weakly ionized medium

Neutral-ion collision frequency $\nu_{ni} = \gamma_d \rho_i$

$\nu_{in} >> \nu_{ni}$

Ion-neutral collision frequency $\nu_{in} = \gamma_d \rho_n$

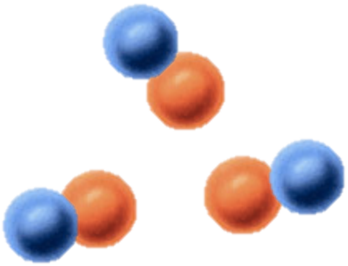
Turbulent dynamo in a weakly ionized medium

Neutral-ion collision frequency $\nu_{ni} = \gamma_d \rho_i$

$\nu_{in} \gg \nu_{ni}$

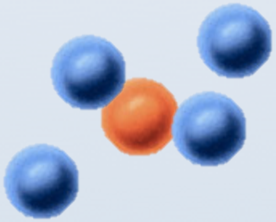
Ion-neutral collision frequency $\nu_{in} = \gamma_d \rho_n$

Strongly coupled



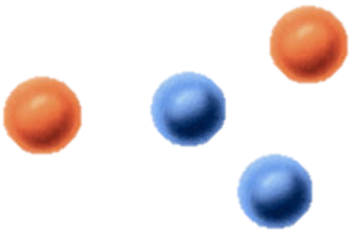
$\Gamma < \nu_{ni}$

Weakly coupled



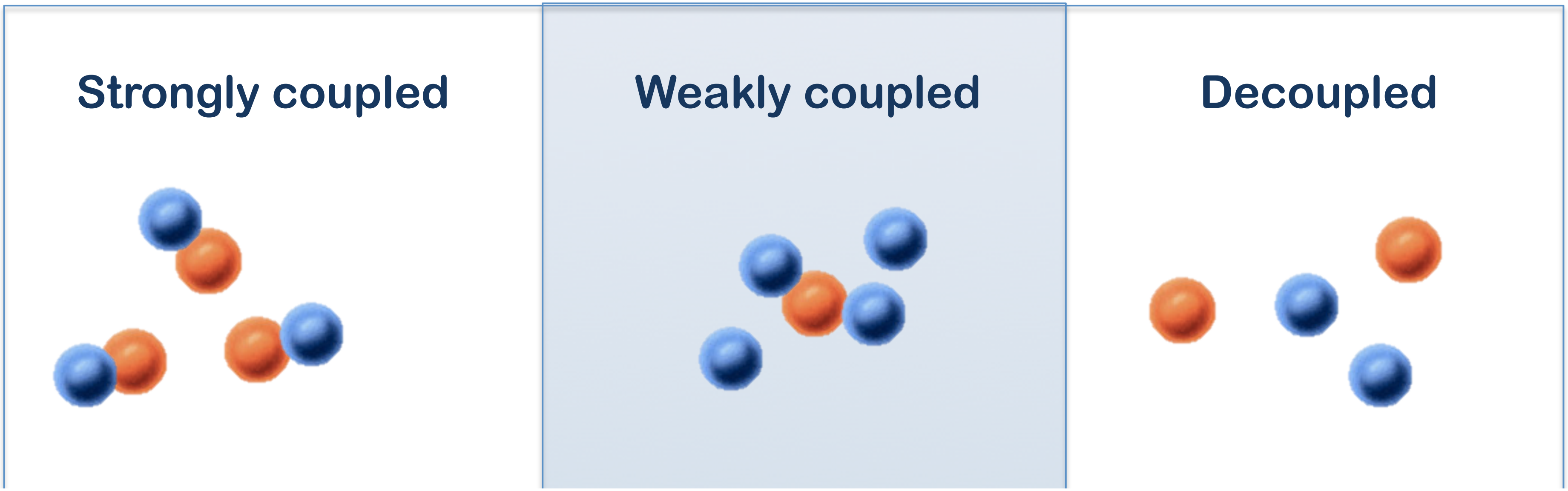
$\nu_{ni} < \Gamma < \nu_{in}$

Decoupled



$\Gamma > \nu_{in}$

MHD turbulence in a weakly ionized medium



Strongly coupled

Weakly coupled

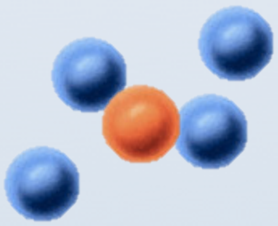
Decoupled

Coupling state	Strong coupling	Weak coupling	Decoupling
MHD turbulence	$\omega_A < \nu_{ni}$	$\nu_{ni} < \omega_A < \nu_{in}$	$\omega_A > \nu_{in}$
Turbulent dynamo	$\Gamma < \nu_{ni}$	$\nu_{ni} < \Gamma < \nu_{in}$	$\Gamma > \nu_{in}$

Xu et al. 2015; 2016; Xu et al. in prep

Damping stage of dynamo

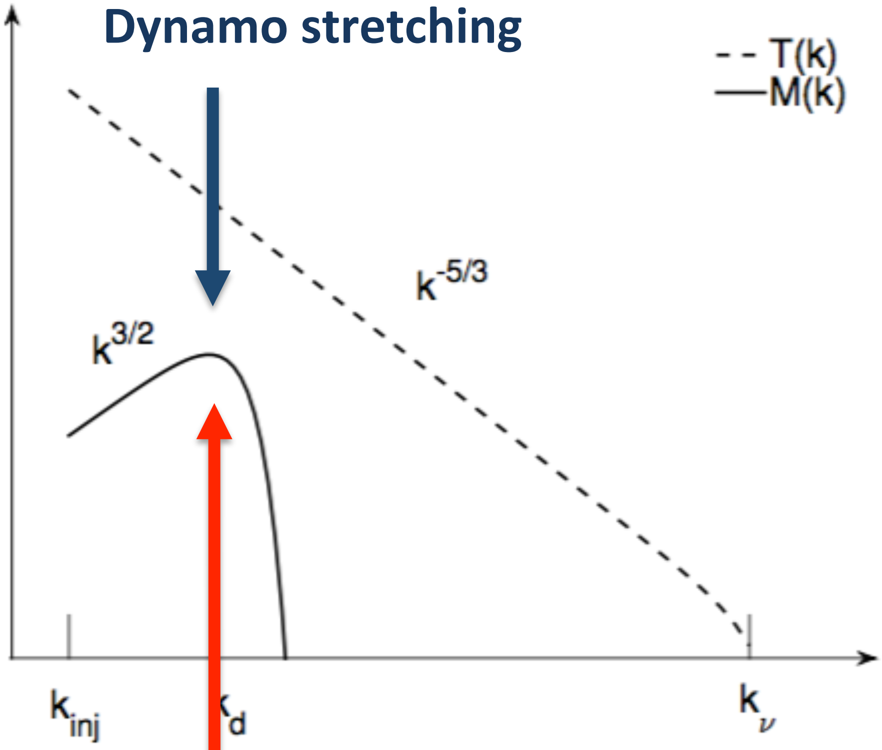
Weakly coupled



$\nu_{ni} < \Gamma < \nu_{in}$

Damping rate:

$$\omega_{\text{IN}} = C l^{-2} \mathcal{E}_M$$



Dynamo stretching

Xu et al. in prep

Damping stage of dynamo

$$M(k,t) = M_1 \exp\left(\frac{3}{4}\int \Gamma_d dt\right)\left(\frac{k}{k_1}\right)^{\frac{3}{2}}$$

Magnetic energy:

$$\mathcal{E}_M(t) = \frac{1}{2}\int_0^{k_d} M(k,t)dk.$$

Dynamo stretching rate:

$$\Gamma_d = \frac{v_d}{l_d} = L^{-\frac{1}{3}} V_L l_d^{-\frac{2}{3}}$$

Damping rate:

$$\omega_{\mathrm{IN}} = \mathcal{C} l^{-2} \mathcal{E}_M$$

Strong Damping

Xu & Lazarian (2016)

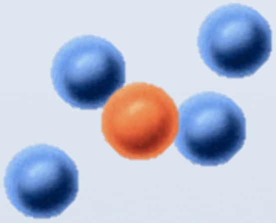
Damping stage of dynamo

Our analytical theory: Xu & Lazarian (2016)

$$\sqrt{\mathcal{E}_M} = \sqrt{\mathcal{E}_{M1}} + \frac{3}{23}\underbrace{\mathcal{C}^{-\frac{1}{2}}}_{\text{ionization fraction}}\underbrace{L^{-\frac{1}{2}}V_L^{\frac{3}{2}}}_{\text{turbulence driving condition}}(t-t_1),$$

$$\boxed{B \sim t}$$

Weakly coupled



$$\nu_{ni} < \Gamma < \nu_{in}$$

Most turbulent energy carried by neutrals cannot be converted to the magnetic energy.

Numerically tested dynamo theories:

Ambipolar diffusion

Damping dynamo

Turbulent diffusion

Nonlinear dynamo

Our analytical theory: Xu & Lazarian (2016)

Numerical tests: Cho & Vishniac 00; Cho+ 09; Beresnyak 12; Xu et al. in prep

Astrophysical applications:

- Formation of first stars
- Interstellar magnetic fields
- Magnetic field amplification and CR acceleration at shocks