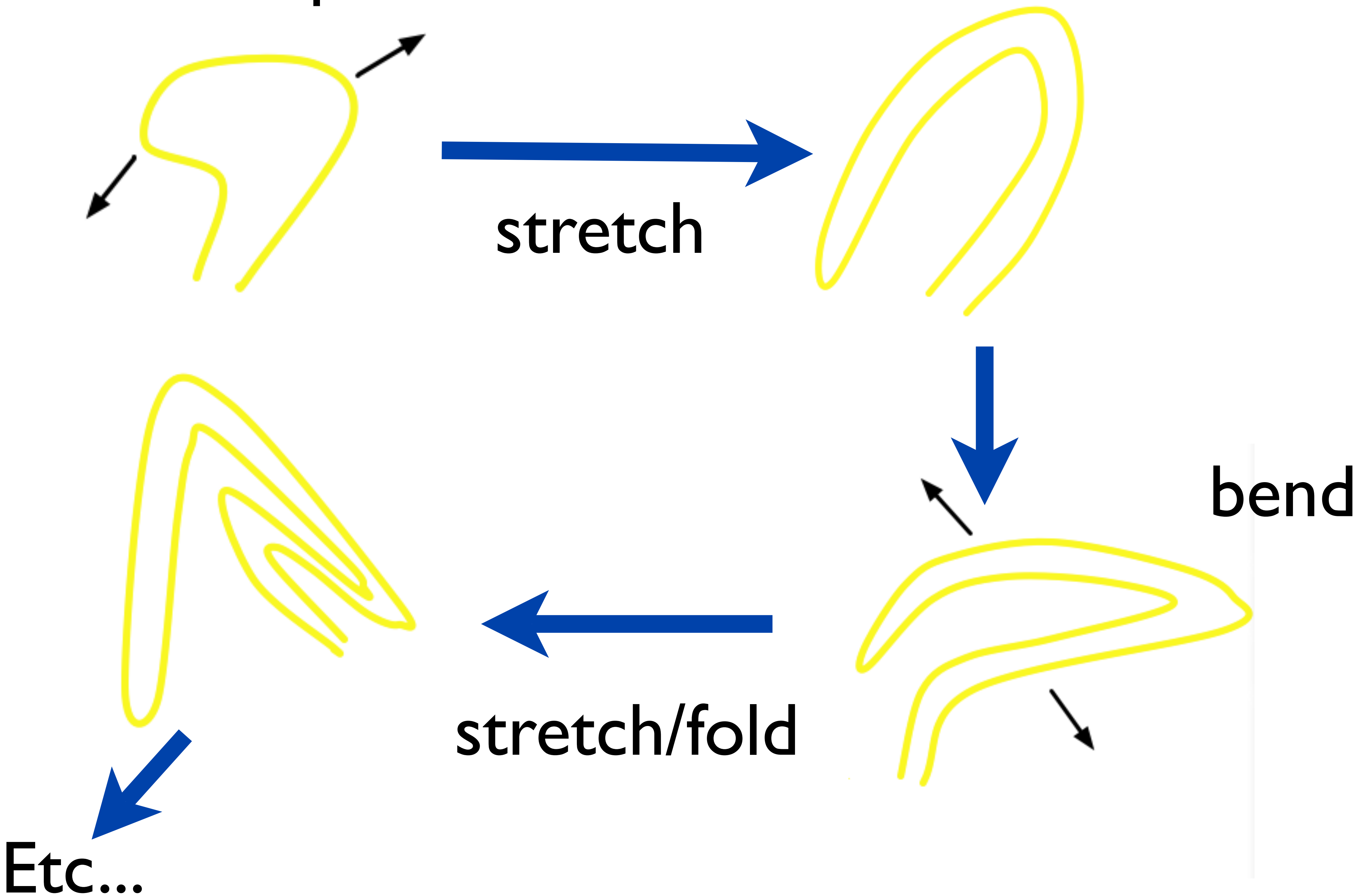
Magnetic field amplification by the small-scale dynamo: Implications for the SKA

Dominik Schleicher
Institut für Astrophysik,
University of Göttingen

Collaborators:
T. Arshakian (Bonn), R. Banerjee (Hamburg), R. Beck (Bonn), C. Federrath (Lyon), R. Klessen (Heidelberg), T. Peters (Heidelberg/Zürich), J. Schober (Heidelberg), S. Sur (Heidelberg)

The small-scale dynamo:

Turbulent amplification



Amplification via stretch-and-fold

originally suggested by Kazantsev (1968)

The small-scale dynamo:

General concepts

Split velocity field into mean-field & fluctuation component:

$$\mathbf{v} = \langle \mathbf{v} \rangle + \delta \mathbf{v}$$

Correlation function:

$$\langle \delta v_i(\mathbf{r}_1, t) \delta v_j(\mathbf{r}_2, s) \rangle = T_{ij}(r) \delta(t - s)$$

Define transversal and longitudinal component:

$$T_{ij}(r) = \left(\delta_{ij} - \frac{r_i r_j}{r^2} \right) T_{\mathrm{N}}(r) + \frac{r_i r_j}{r^2} T_{\mathrm{L}}(r)$$

Note: Helicity is neglected.

And for the magnetic field:

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}$$

Correlation function:

$$\langle \delta B_i(\mathbf{r}_1, t) \delta B_j(\mathbf{r}_2, t) \rangle = M_{ij}(r, t)$$

Define transversal and longitudinal component:

$$M_{ij}(r, t) = \left(\delta_{ij} - \frac{r_i r_j}{r^2} \right) M_{\mathrm{N}}(r, t) + \frac{r_i r_j}{r^2} M_{\mathrm{L}}(r, t)$$

e.g. Schober, Schleicher, Federrath, Klessen & Banerjee (2011).

See Talk Jennifer Schober in the high-redshift star formation session.

The small-scale dynamo:

General concepts

The induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{v} \times \mathbf{B} - \eta \nabla \times \nabla \times \mathbf{B}$$

can be used to derive

$$\frac{\partial M_{\rm L}}{\partial t} = 2\kappa_{\rm diff} M_{\rm L}'' + 2\left(\frac{4\kappa_{\rm diff}}{r} + \kappa_{\rm diff}'\right) M_{\rm L}' + \frac{4}{r}\left(\frac{T_{\rm N}}{r} - \frac{T_{\rm L}}{r} - T_{\rm N}' - T_{\rm L}'\right) M_{\rm L}$$

The Ansatz:

$$M_{\rm L}(r,t) \equiv \frac{1}{r^2\sqrt{\kappa_{\rm diff}}}\psi(r){\rm e}^{2\Gamma t}$$

leads to a Schroedinger-type equation:

$$-\kappa_{\rm diff}(r)\frac{{\rm d}^2\psi(r)}{{\rm d}^2 r} + U\psi(r) = -\Gamma\psi(r)$$

where the potential U depends on the properties of turbulence.

-> Can be solved using standard methods from quantum mechanics.

see e.g. Kazantsev (1968); Subramanian (1998);
Schober, Schleicher, Federrath, Klessen & Banerjee (2011).

The small-scale dynamo:

General concepts

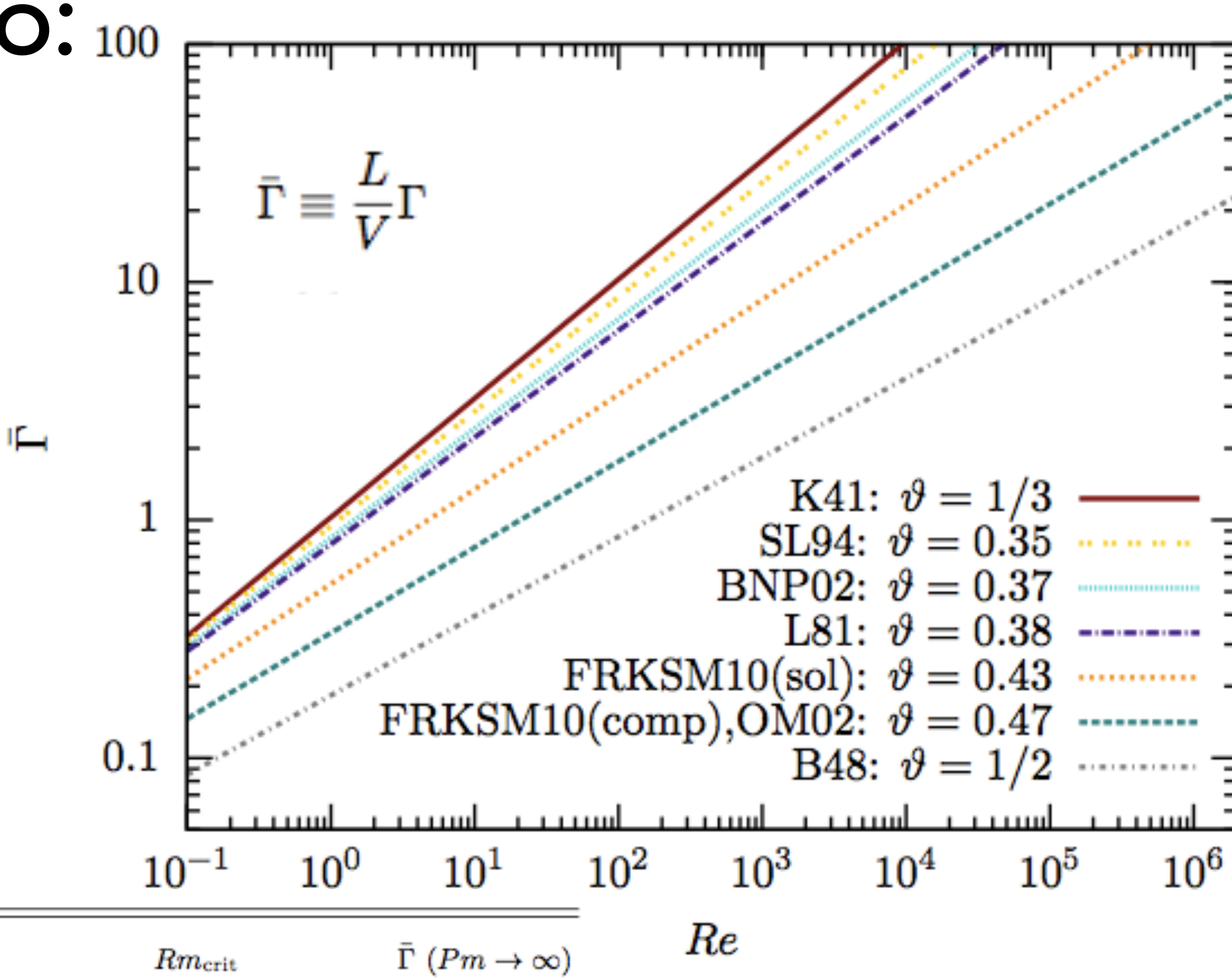
Explore turbulent spectra with

$$v(\ell) \propto \ell^{\vartheta}$$

Growth rate:

$$\Gamma = \frac{(163 - 304\vartheta)\ V}{60\ L}\ Re^{(1-\vartheta)/(1+\vartheta)}$$

Reynolds number Re = VL/nu

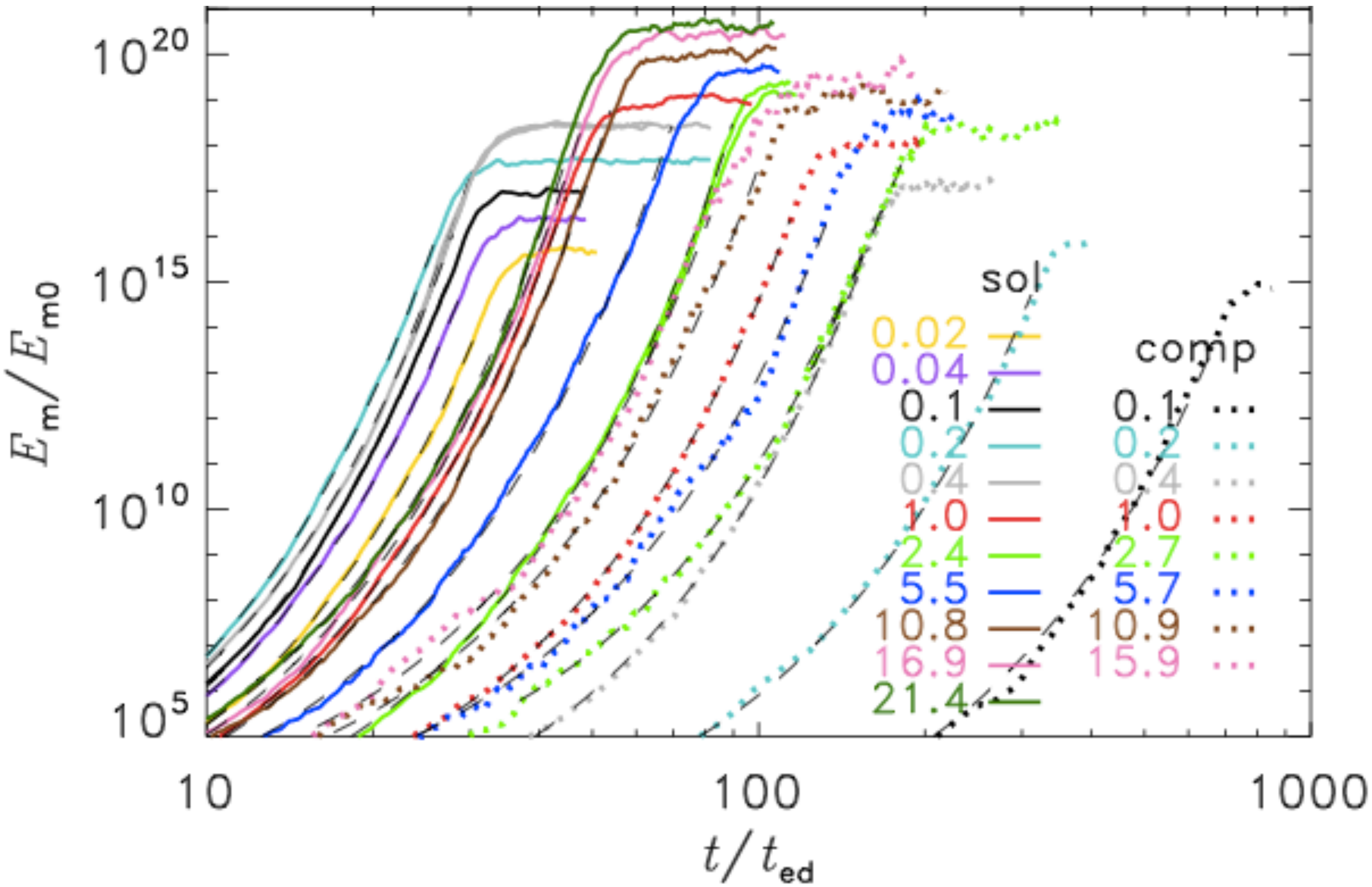


Model/Reference	ϑ	$Rm_{\rm crit}$	$\bar{\Gamma}$ ($Pm \to \infty$)
Kolmogorov [21]	1/3	≈ 107	$\frac{37}{36}\ Re^{1/2}$
intermittency of Kolmogorov turbulence (She and Leveque [23])	0.35	≈ 118	$0.94\ Re^{0.48}$
driven supersonic MHD-turbulence (Boldyrev et al.[24])	0.37	≈ 137	$0.84\ Re^{0.46}$
observation in molecular clouds (Larson [25])	0.38	≈ 149	$0.79\ Re^{0.45}$
solenoidal forcing of the turbulence (Federrath et al. [26])	0.43	≈ 227	$0.54\ Re^{0.40}$
compressive forcing of the turbulence (Federrath et al. [26]) observations in molecular clouds (Ossenkopf and Mac Low [27])	0.47	≈ 697	$0.34\ Re^{0.36}$
Burgers [22]	1/2	≈ 2718	$\frac{11}{60}\ Re^{1/3}$

Schober, Schleicher, Federrath, Klessen & Banerjee (2011).

The small-scale dynamo:

Simulations

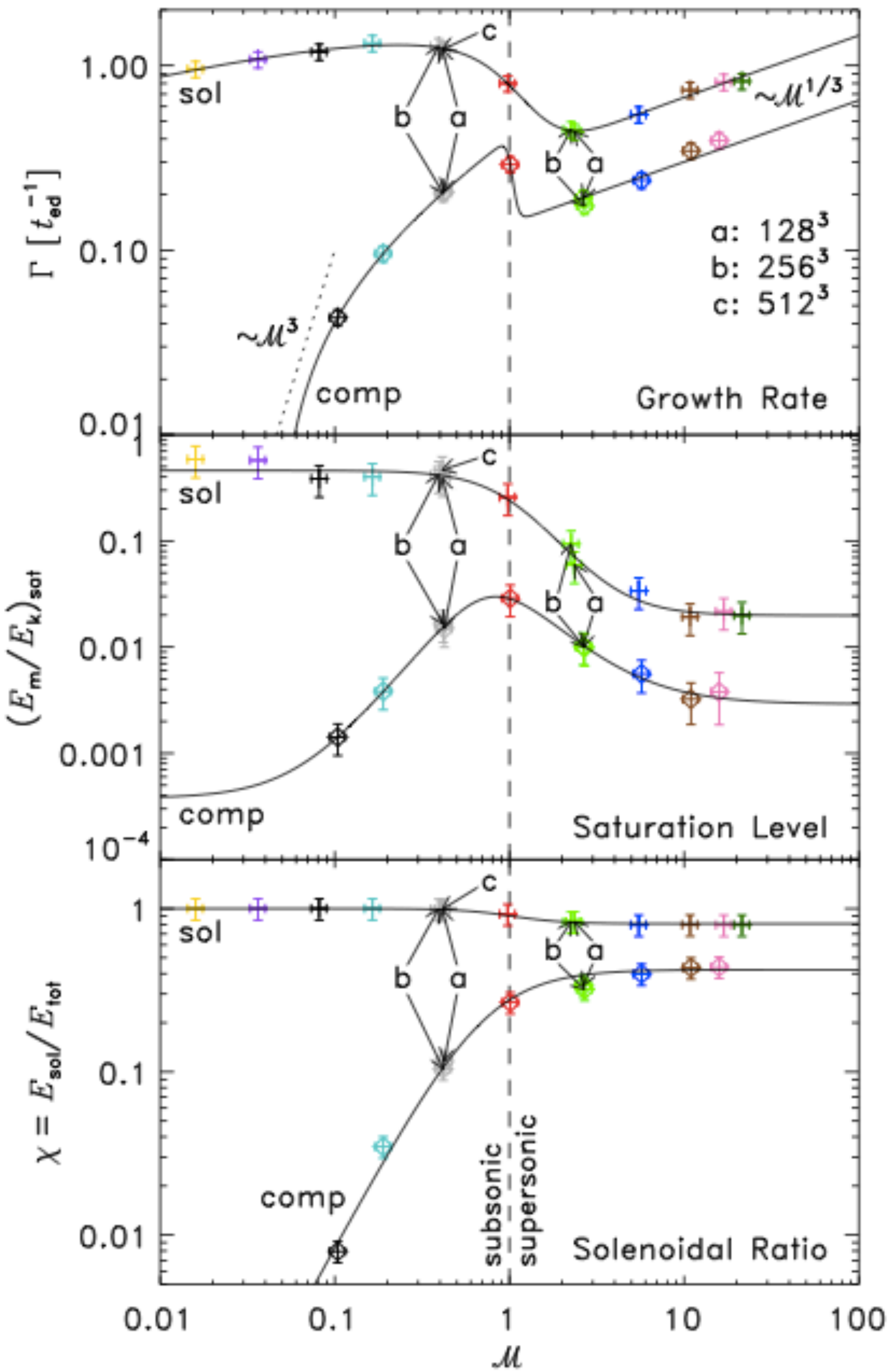


Driven-turbulence MHD simulations from Mach 0.02 to Mach 21.4, for solenoidal and compressive driving.

Federrath et al., PRL, 107, 114504 (2011)

The small-scale dynamo:

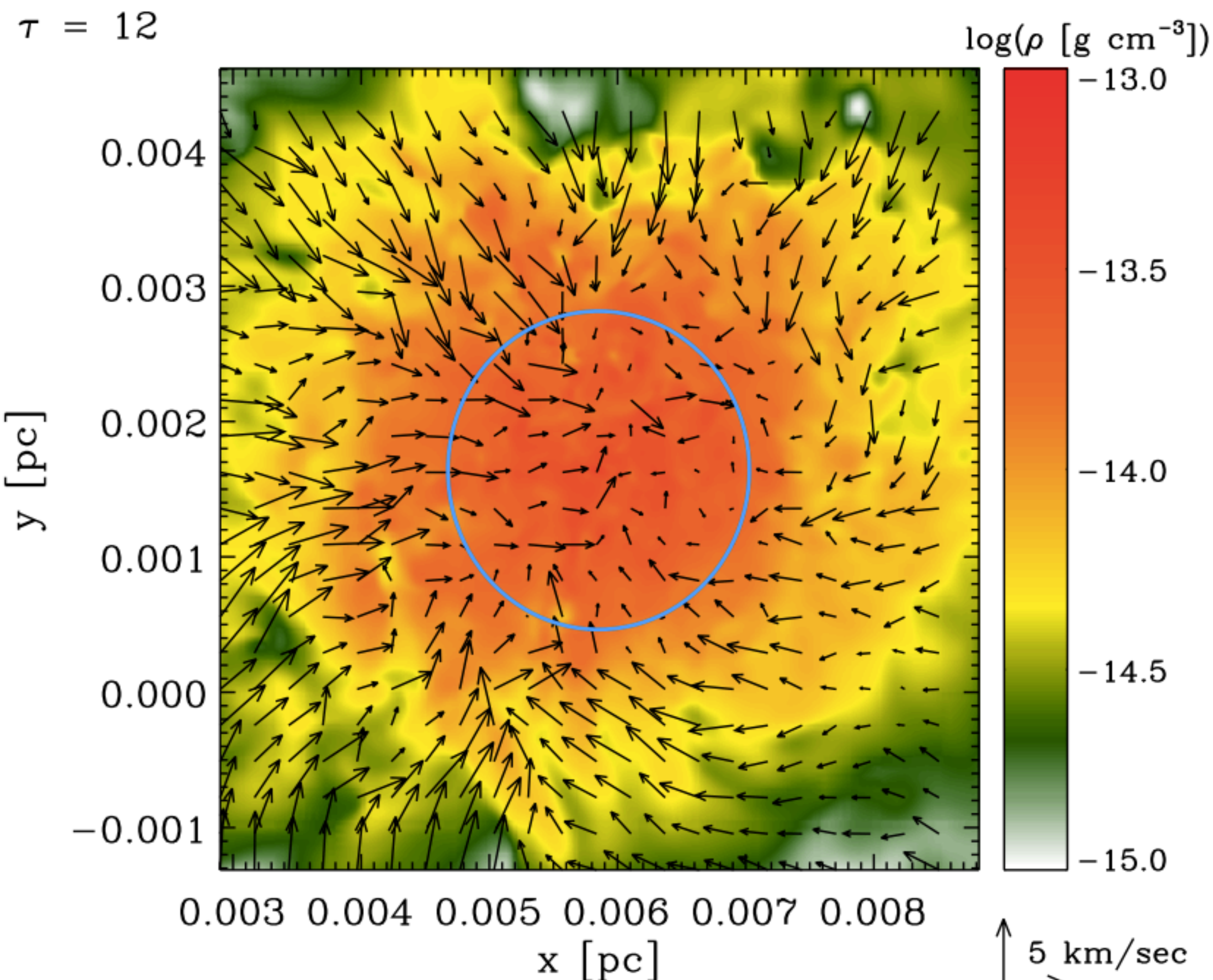
Simulations



- Low Mach numbers, solenoidal driving:
  Efficient amplification, saturation values of ~50%.
- High Mach numbers, solenoidal driving:
  Reduced amplification efficiency, saturation values <10%.
- Compressive driving:
  Reduced amplification efficiency, smaller saturation values.

Federrath et al., PRL, 107, 114504 (2011)

The small-scale dynamo:
Collapsing gas clouds



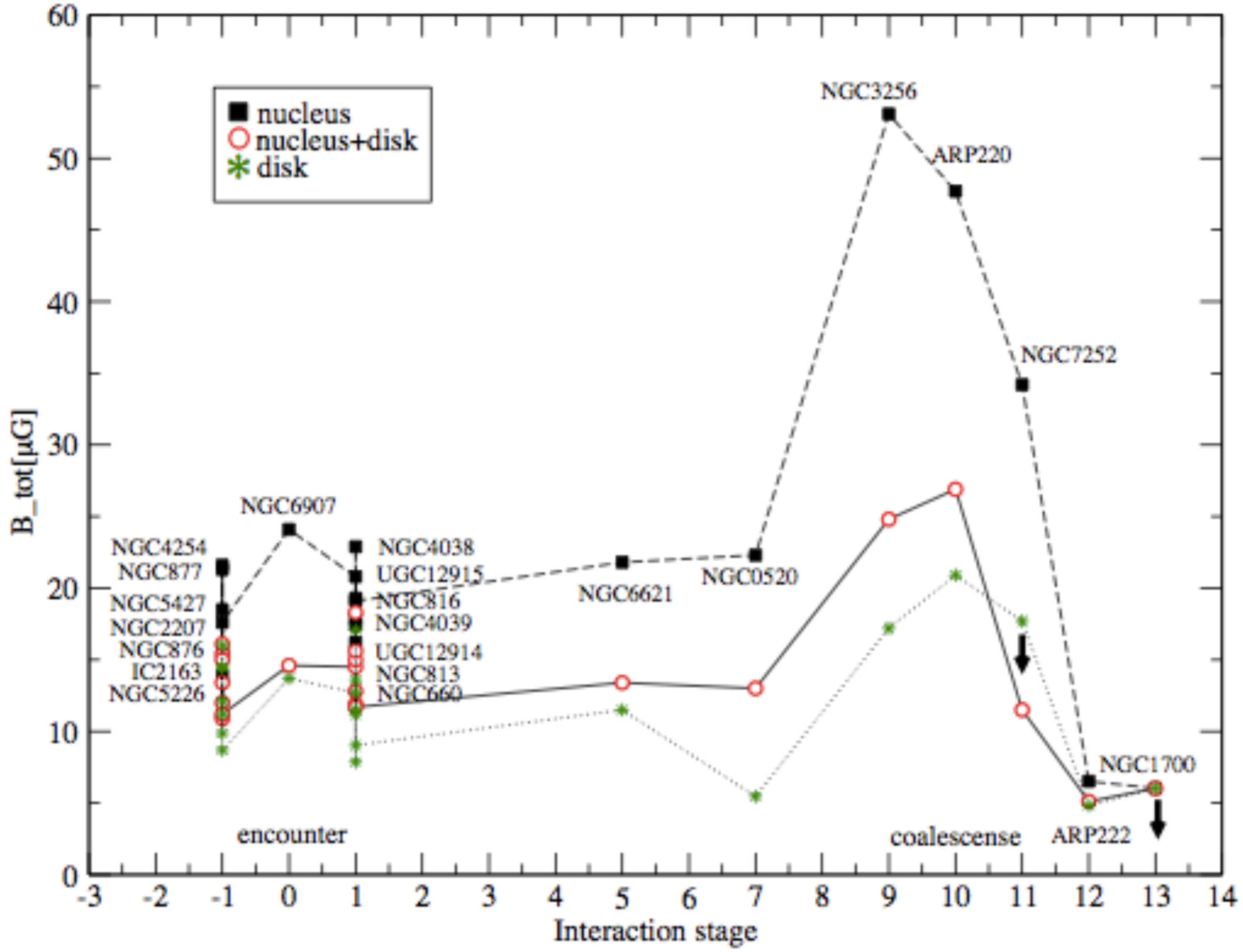
- Motions dominated by infall on large scales.
- Formation of a turbulent core in the center.
- Core size comparable to Jeans length.

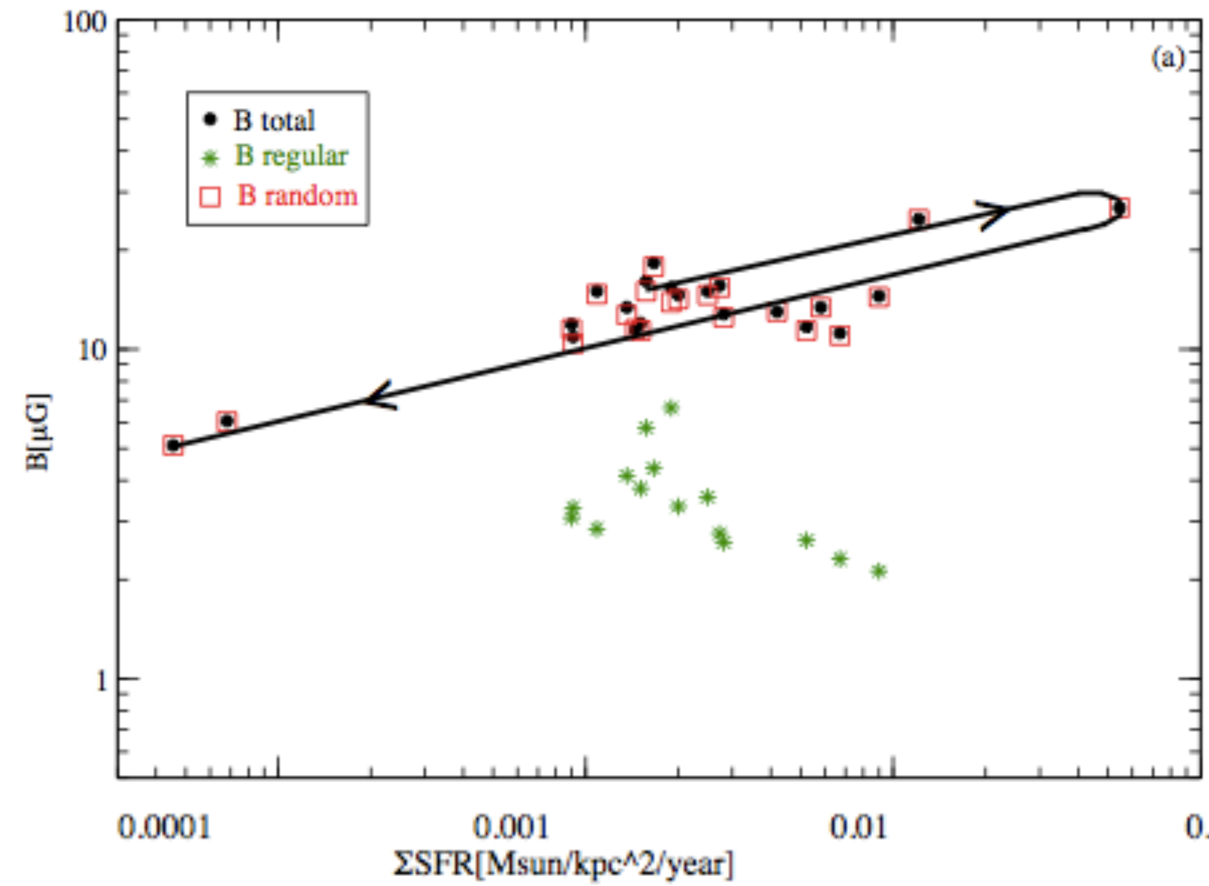
Sur et al. (2010), Federrath et al. (2011)

See Talk Robi Banerjee in the high-redshift star formation session.

The small-scale dynamo:

Enhanced magnetic field strength in interacting galaxies



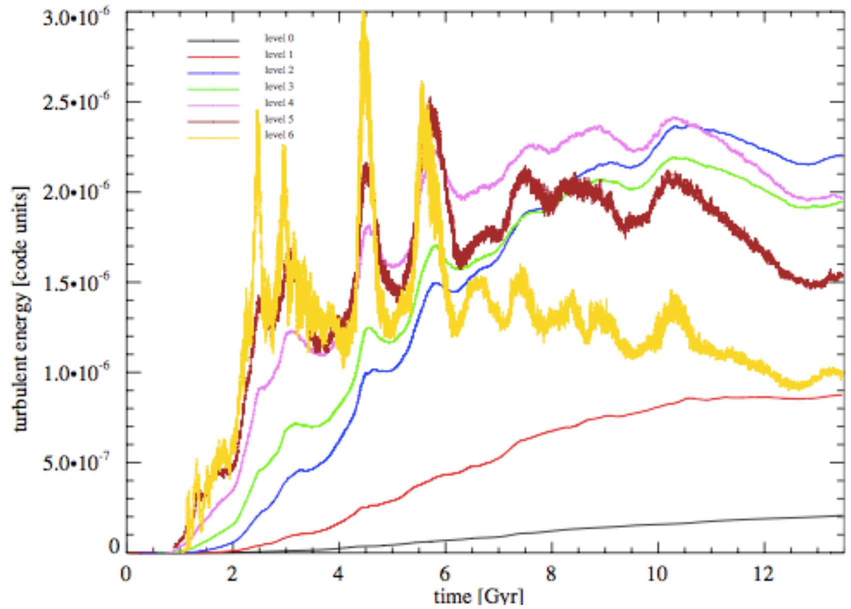


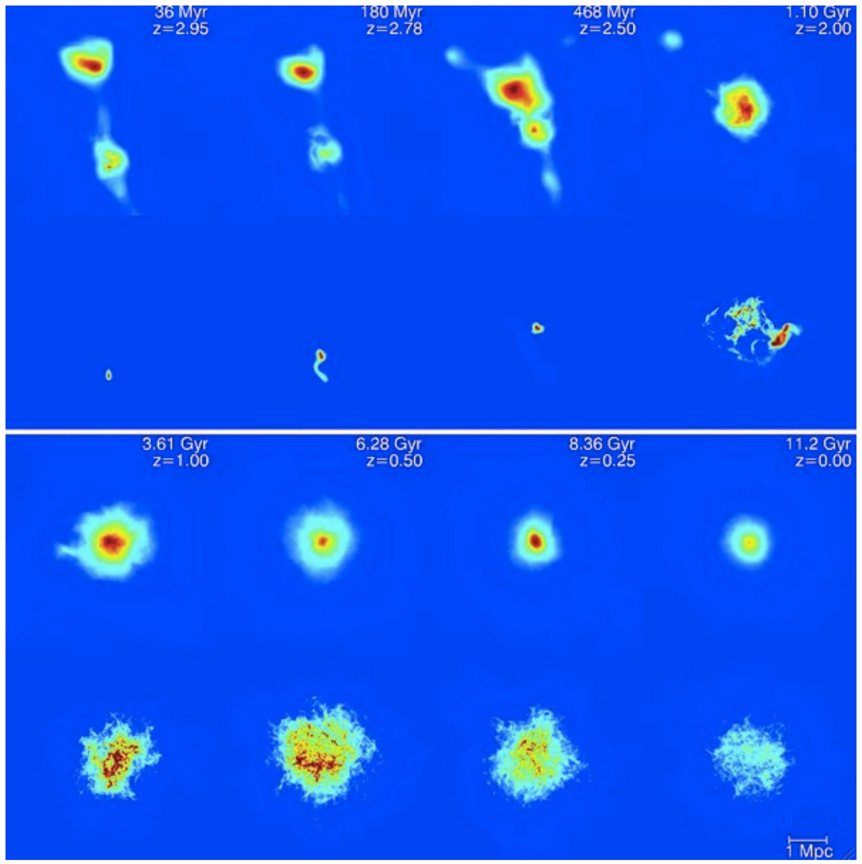
Field strength peaks at stage of strongest interaction.
Correlation with turbulence and star formation.

Drzazga et al. (2011)

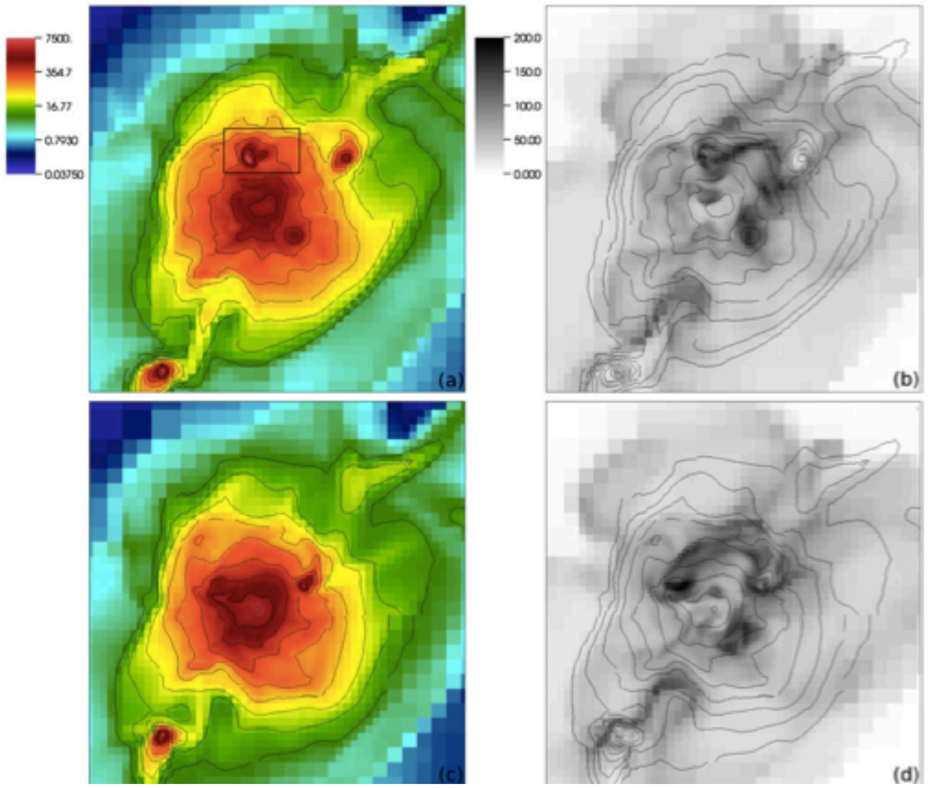
The small-scale dynamo:

Implications in galaxy clusters

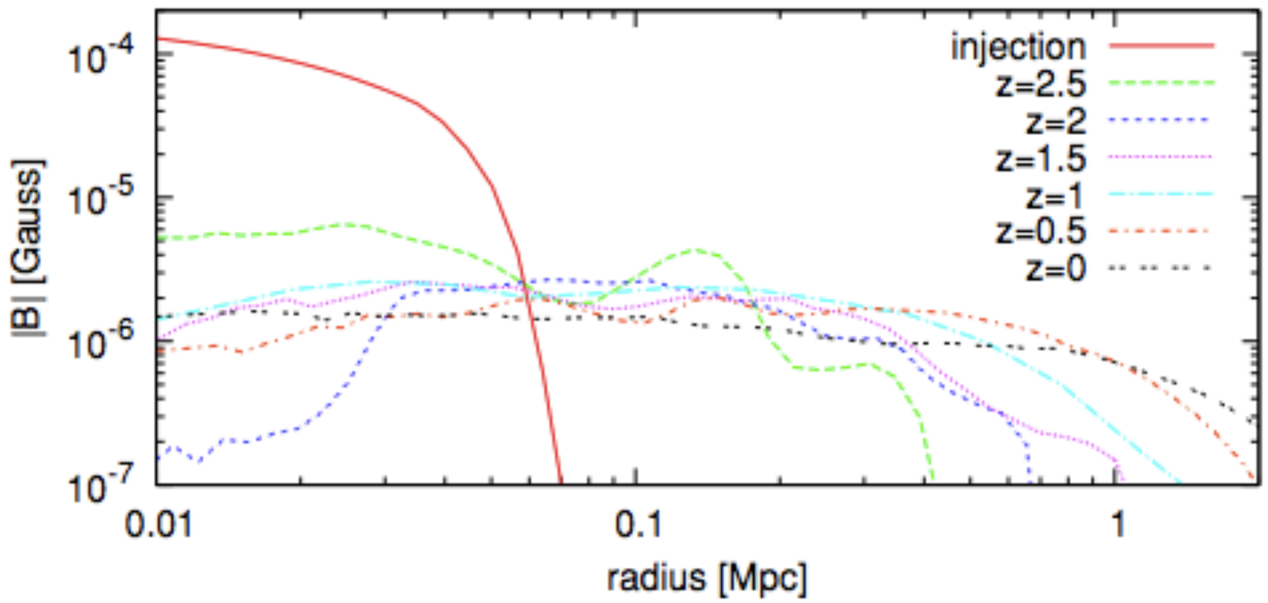




Maier et al. 2009: Evolution and distribution of turbulence



Xu et al. (2009): Magnetic field amplification in clusters



The small-scale dynamo:
Implications for the SKA

- Efficient means of magnetic field amplification
  -> Expect strong tangled magnetic fields at high redshift.

- Amplification by turbulence:
  -> Expect enhanced magnetic fields in turbulent environments (interacting galaxies, clusters, etc).

- SKA: Spatial resolution increased by an order of magnitude -> potential to study small-scale magnetic fields.