Evolution of Primordial Magnetic Fields

Robi Banerjee

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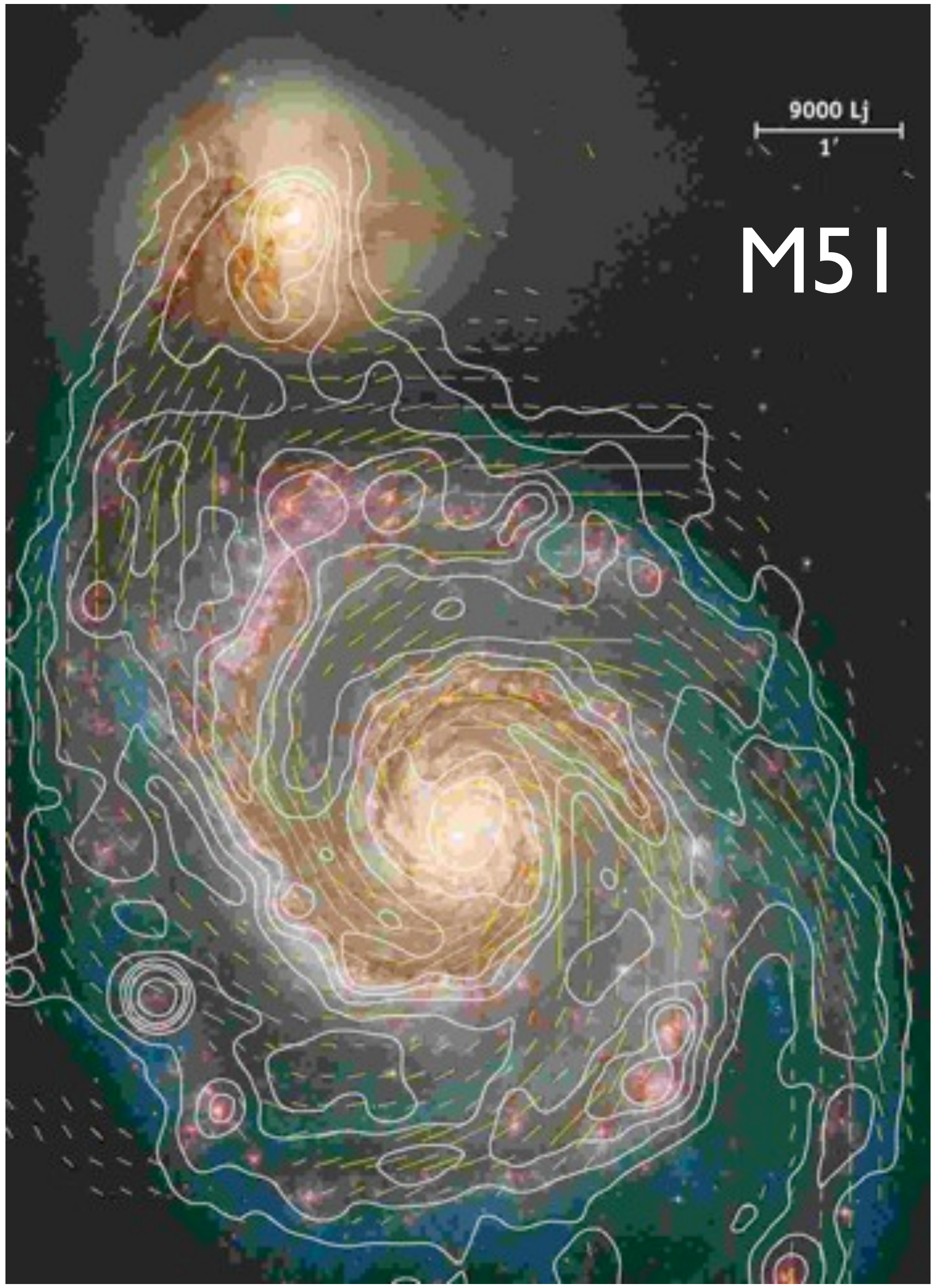
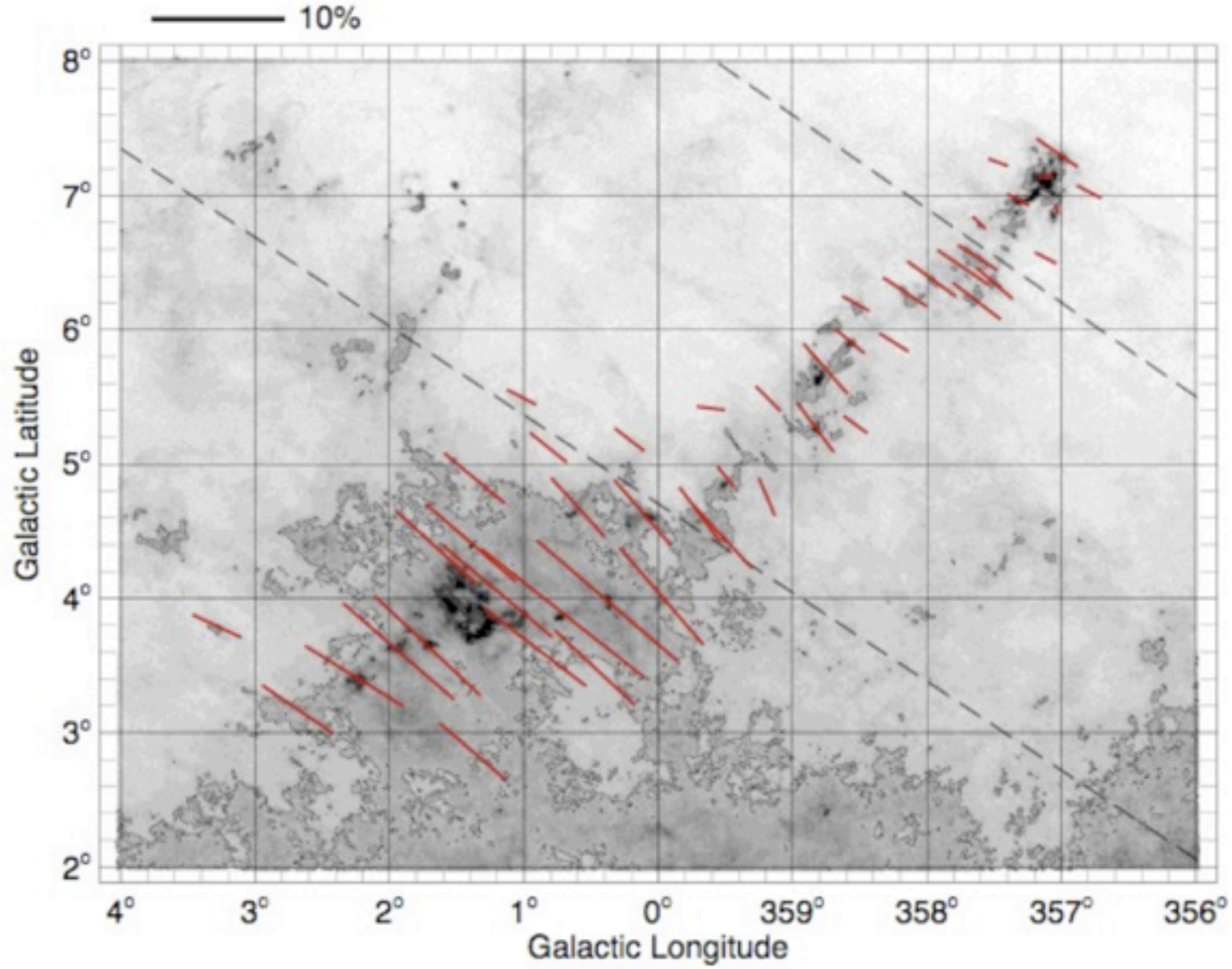
Observed Magnetic Fields



galactic B-fields (e.g. *R.Beck 2001*)
large scale component: ~ 6μG
total field strength: ~ 10μG

Magnetic fields are observed on all scales



magnetic polarization measurements in the Pipe nebula
F.O.Alves, Franco, Girart 2008

Cosmic Magnetic Fields

- Observations:
  - Galactic fields ~ 10 μG

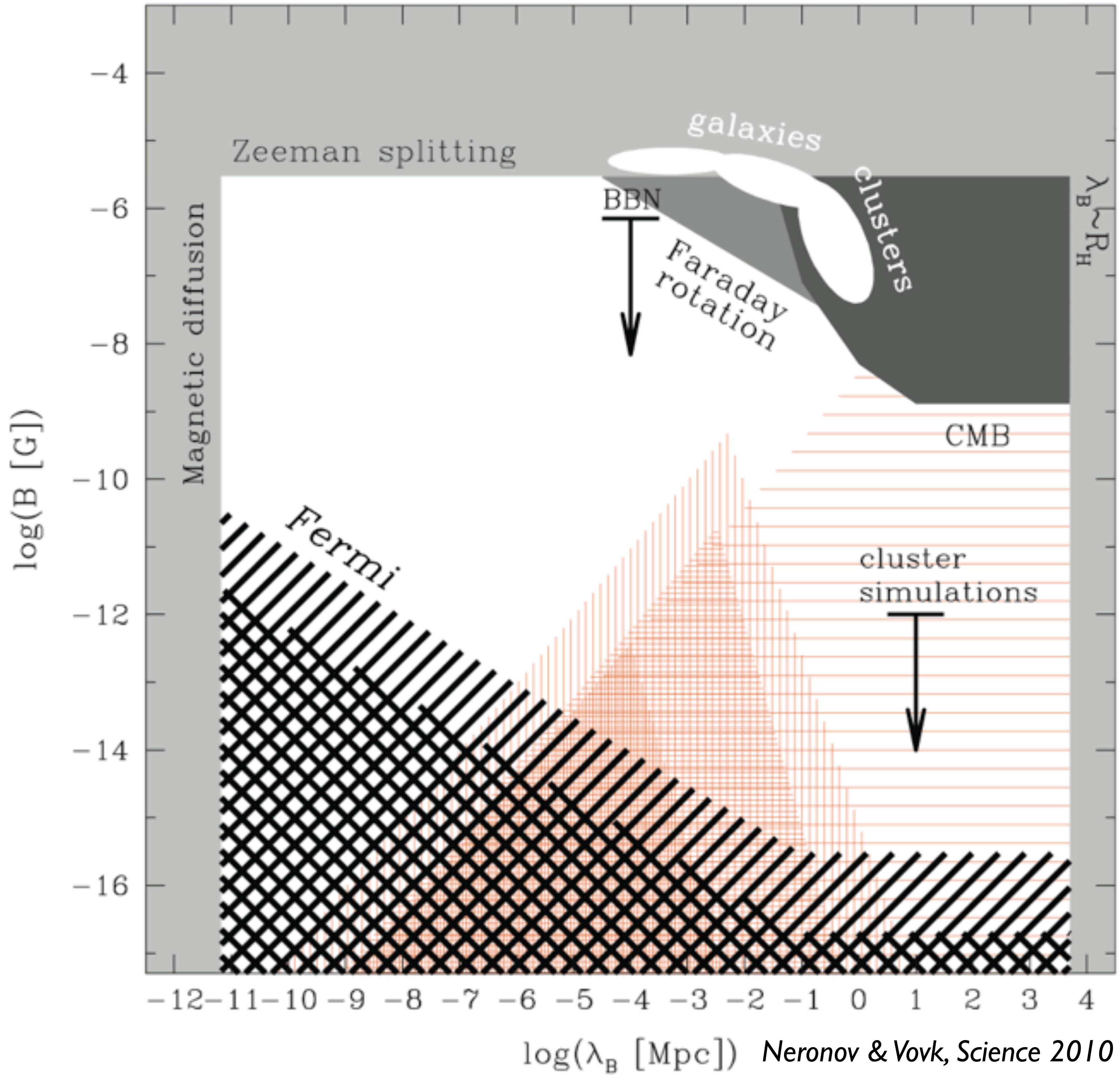
    (e.g. Beck 1999)
  - Cluster fields ~ μG

    (e.g. Bonafede et al. 2010)
- Upper limits:
  - BBN ~ 10^{-7} G

    (Grasso & Rubinstein 2001)
  - CMBR ~ 10^{-9} G
  - Reionization ~ 10^{-9} G

    (Schleicher et al. 2008)
- **Lower** limits ~ 10^{-15} G (?)

  (FERMI obs. e.g. Neronov & Vovk 2010;
  Taveccio et al. 2010)



Neronov & Vovk, Science 2010

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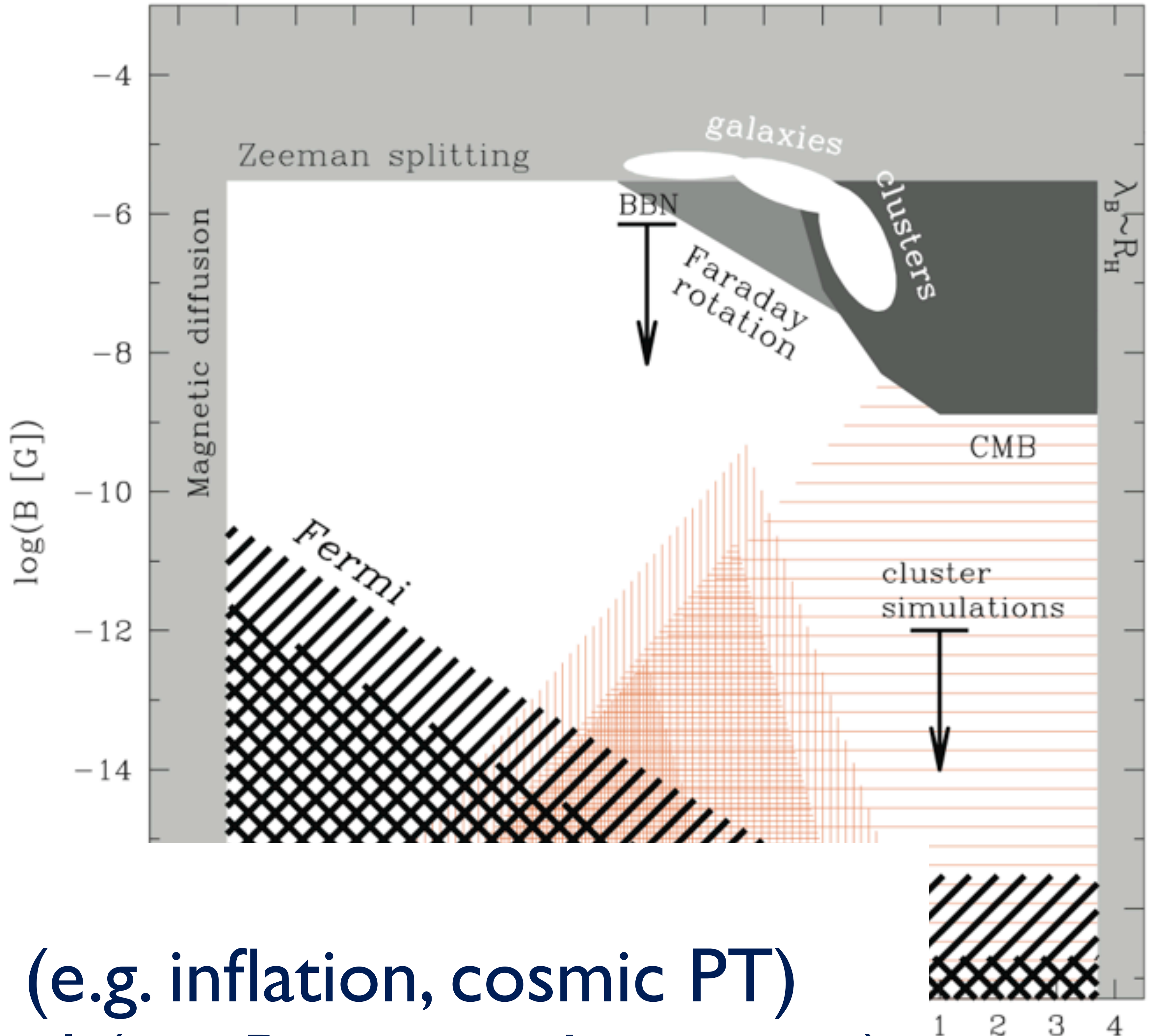

'ovk, Science 2010

Origin?

- primordial (e.g. inflation, cosmic PT)
- astrophysical (e.g. Biermann battery, ...)

Generation of Primordial Fields

Possible generation of primordial magnetic fields
(e.g. *Grasso & Rubinstein 2001*; *Widrow 2003*; *Widrow et al. 2011*)

- during cosmic **inflation** (e.g. *Turner & Widrow 1998*)

- during cosmic **phase transitions**
  - electroweak PT ($t \sim 10^{-10}$ sec, $T \sim 100$ GeV)
    (e.g. *Baym et al. 1996*)
  - QCD PT ($T \sim 100$ MeV)
    (e.g. *Quashnock et al. 1989; Cheng & Olinto 1994; Sigl et al. 1997*)

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  - QCD PT (T ~ 100 MeV)

  (e.g. *Quashnock et al. 1989; Cheng & Olinto 1994; Sigl et al. 1997*)

⇒ causal process
⇒ coherence length limited by Hubble length
at epoch of generation

Evolution of Magnetic Fields

Subsequent evolution

- dilution by cosmic expansion:

$$B \propto a^{-2}$$

assumption: flux freezing (no dynamic damping/ amplification)

- but: damping/amplification is important

(e.g. *Jedamzik et al. 98, Subramanian & Barrow 98, RB & Jedamzik 2003/04, Schleicher et al. 2010, Sur et al. 2010, Jedamzik & Sigl 2011*)

Evolution of Magnetic Fields

MHD equations on an expanding background:

$$\frac{\partial \rho}{\partial t} + \frac{1}{a} \nabla \cdot \left((\rho + p)\, \mathbf{v} \right) + 3\, H\, (\rho + p) = \frac{6}{a} H\, \xi\, (\nabla \cdot \mathbf{v}) - \chi\, \nabla \cdot \mathbf{q}\,,$$

$$\frac{1}{a} \left(\frac{\partial}{\partial t} + \frac{1}{a} (\mathbf{v} \cdot \nabla) + H \right) \mathbf{v} + \frac{1}{a} \frac{\mathbf{v}}{\rho + p} \frac{\partial p}{\partial t} + \frac{1}{a^2} \frac{\nabla p}{\rho + p} + \frac{1}{a^2} \left(\frac{\mathbf{B} \times (\nabla \times \mathbf{B})}{4\pi\, (\rho + p)} \right) =$$

$$\frac{1}{a^3} \frac{\nu}{\rho + p} \left(\nabla^2 \mathbf{v} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{v}) \right) + \frac{1}{a^3} \frac{\xi}{\rho + p} \nabla (\nabla \cdot \mathbf{v}) - \frac{1}{\rho + p} \left(\frac{\partial}{\partial t} + 5\, H \right) \chi\, \mathbf{q}\,,$$

$$\frac{1}{a} \left(\frac{\partial}{\partial t} + 2\, H \right) \mathbf{B} = \frac{1}{a^2} \nabla \times (\mathbf{v} \times \mathbf{B})$$

- ν, ξ viscosity; χ, $\mathbf{q}$ heat conductivity/heat flux
- H, a Hubble parameter/scale factor $\Longrightarrow$ cosmic expansion

assumption: infinite conductivity $\Longrightarrow$ large Prandtl numbers

Evolution of Magnetic Fields

MHD equations on an expanding background with *super co-moving* variables* (e.g. *Enqvist 98*):

$$\begin{aligned}
\frac{\partial \tilde{\rho}}{\partial \tilde{t}} + \nabla \cdot (\tilde{\rho}\, \tilde{\mathbf{v}}) &= 0 \quad , \\
\frac{\partial \tilde{\mathbf{v}}}{\partial \tilde{t}} + (\tilde{\mathbf{v}} \cdot \nabla)\, \tilde{\mathbf{v}} + \frac{1}{\tilde{\rho}} \nabla \tilde{p} + \frac{1}{4\pi \tilde{\rho}} \tilde{\mathbf{B}} \times (\nabla \times \tilde{\mathbf{B}}) &= -\tilde{\mathbf{s}} \quad , \\
\frac{\partial \tilde{\epsilon}}{\partial \tilde{t}} + \nabla \cdot (\tilde{\epsilon}\, \tilde{\mathbf{v}}) + \tilde{p}\, (\nabla \cdot \tilde{\mathbf{v}}) &= -\tilde{\Gamma} \quad , \\
\frac{\partial \tilde{\mathbf{B}}}{\partial \tilde{t}} - \nabla \times (\tilde{\mathbf{v}} \times \tilde{\mathbf{B}}) &= 0 \quad .
\end{aligned}$$

$\Longrightarrow$ no Hubble-expansion

$\Longrightarrow$ same form than non-relativistic MHD equations

*
$$\begin{aligned}
\tilde{\rho} &\equiv \rho\, a^3 & \tilde{p} &\equiv p\, a^4 & \tilde{\mathbf{B}} &\equiv \mathbf{B}\, a^2 \\
\tilde{\mathbf{v}} &\equiv \mathbf{v}\, a^{1/2} & \tilde{\epsilon} &\equiv \epsilon\, a^4 & \tilde{T} &\equiv T\, a^2 \\
\tilde{\chi} &\equiv \chi\, a^{3/2} & \tilde{\nu} &\equiv \nu\, a^{5/2} & d\tilde{t} &\equiv dt\, a^{-3/2} \\
\tilde{\xi} &\equiv \xi\, a^{5/2} & \tilde{H} &\equiv a^{3/2}\, H & &
\end{aligned}$$

Evolution of Magnetic Fields

Further assumptions:

- incompressible MHD:

$v,\ v_A \ll c_s$

$v_A < c_s$ if $B < 5\text{x}10^{-5}$ G at recombination

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} - (\mathbf{v}_A\cdot\nabla)\mathbf{v}_A = \mathbf{f},$$

$$\frac{\partial \mathbf{v}_A}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v}_A - (\mathbf{v}_A\cdot\nabla)\mathbf{v} = \nu\nabla^2\mathbf{v}_A,$$

dissipation:

$$\mathbf{f} = \begin{cases} \eta\nabla^2\mathbf{v} & l_{\mathrm{mfp}} \ll l, \\ -\alpha\mathbf{v} & l_{\mathrm{mfp}} \gg l, \end{cases}$$

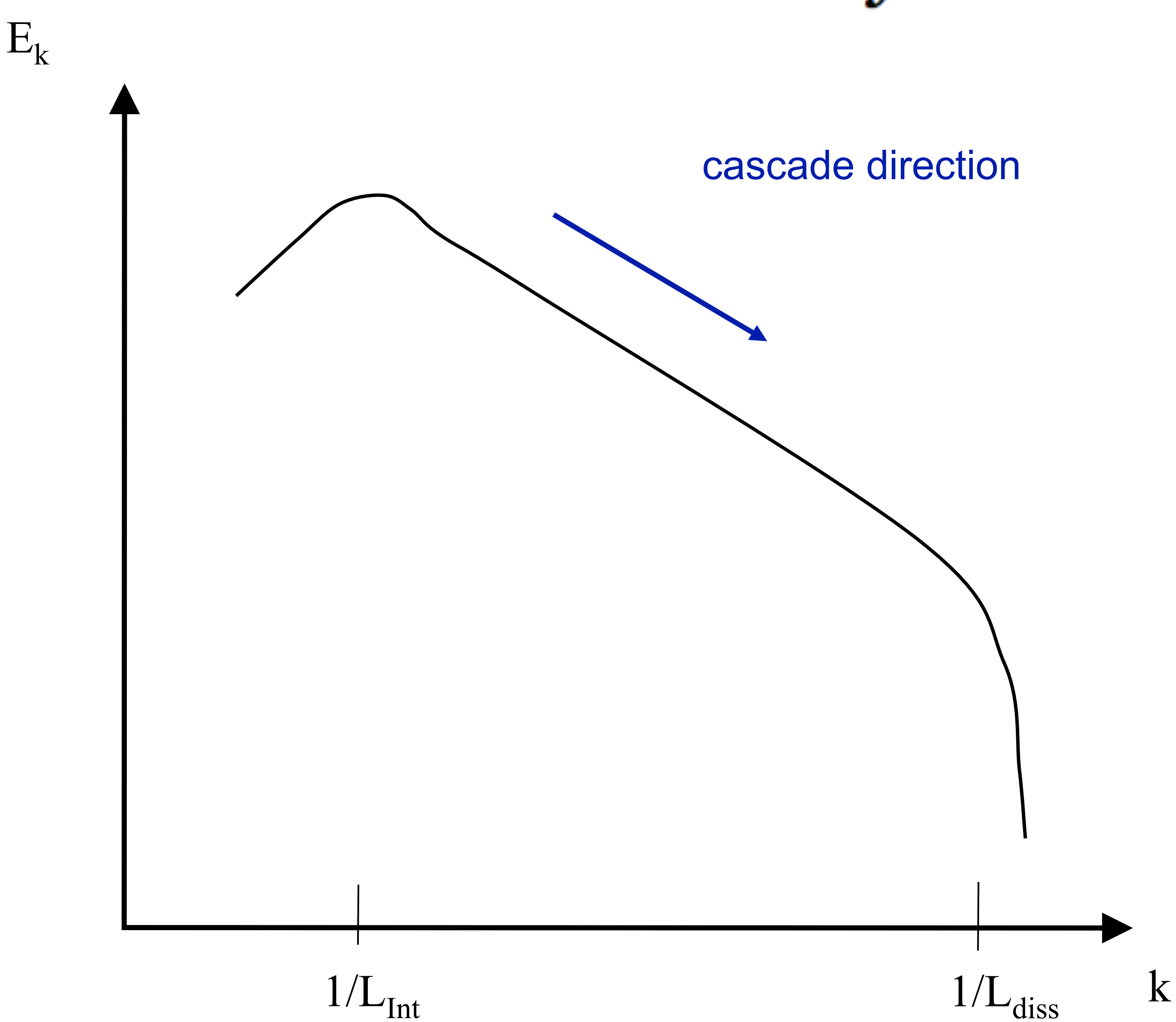
Reynolds number:

$$R_e(l) = \frac{v^2/l}{|\mathbf{f}|} = \begin{cases} \frac{vl}{\eta} & l_{\mathrm{mfp}} \ll l \\ \frac{v}{\alpha l} & l_{\mathrm{mfp}} \gg l, \end{cases}$$

Evolution of Magnetic Fields

$\mathrm{R_e} \gg 1 \quad \Longrightarrow \quad$ decay via MHD turbulence

$$E \approx \int d\ln k k^3 (\langle |\boldsymbol{v}_k|^2 \rangle + \langle |\boldsymbol{v}_{\mathrm{A},k}|^2 \rangle) \equiv \int d\ln k E_l,$$



quasi-stationary transfer of energy in *k*-space

$\Longrightarrow$ Kolmogorov Turbulence

$$\frac{\mathrm{d}E_l}{\mathrm{d}t} \approx \frac{E_l}{\tau_l} \approx \mathrm{const}(l)$$

Evolution of Magnetic Fields

spectra of turbulence

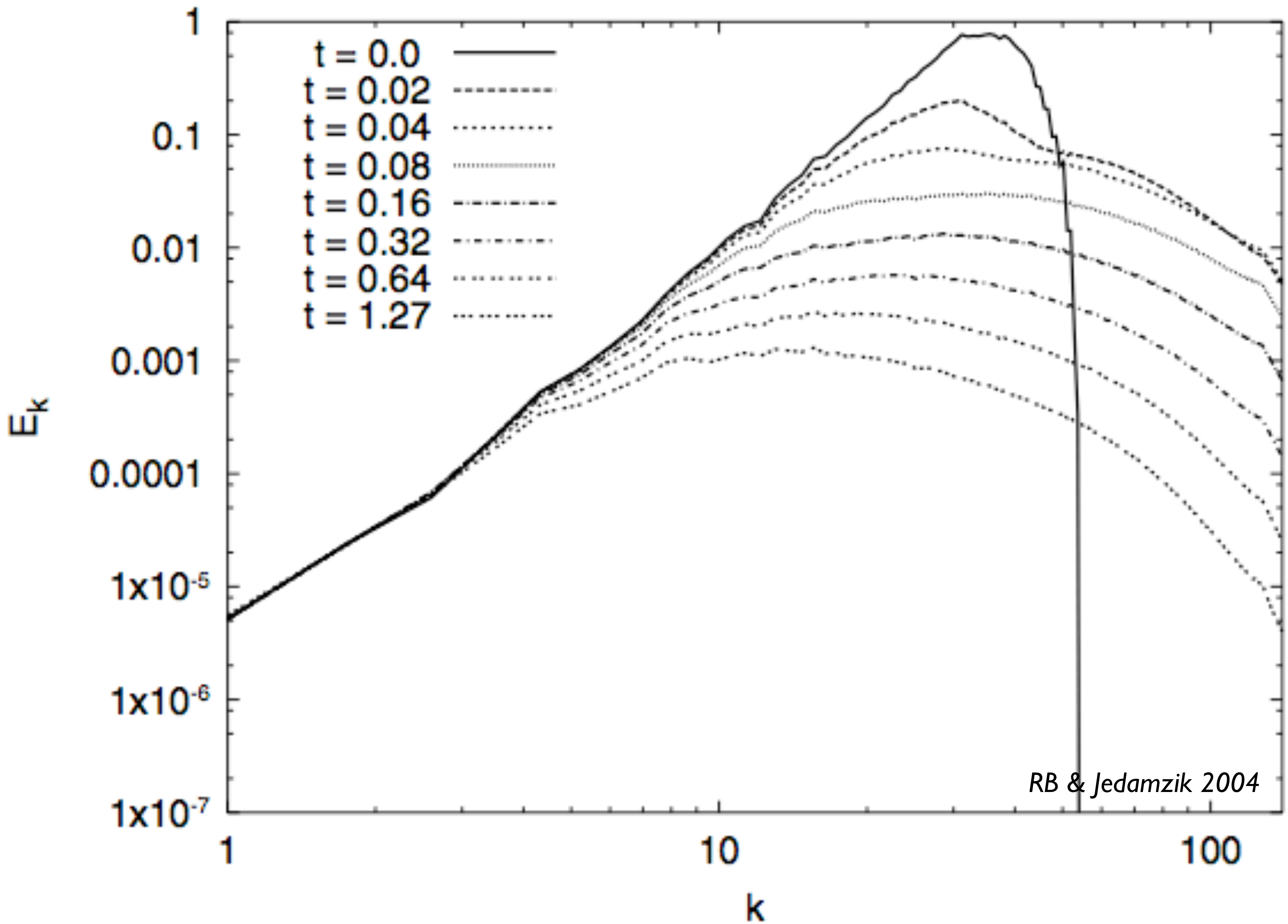
Kolmogorov ('41): $\tau_{\mathrm{K}} = l/v_l$

Iroshnikov-Kraichnan ('64/'65): $\tau_{\mathrm{IK}} = (l/v_l)\,(v_{\mathrm{A},L}/v_l)$

$$E_k/k \propto \begin{cases} k^{-5/3} & : \quad \text{unmagnetized} \\ k^{-3/2} & : \quad \text{magnetized} \end{cases}$$

Evolution of Magnetic Fields

turbulent decay: numerical simulations



Evolution of Magnetic Fields

turbulent decay laws

- Initial spectrum on large scales ($l > \mathrm{L}$):

$$E_k \approx E_0 \left(\frac{k}{k_0}\right)^n = E_0 \left(\frac{l}{L_0}\right)^{-n} \quad \text{for } l > L_0.$$

- with: $v_l = \sqrt{E_l}$:

energy decay:

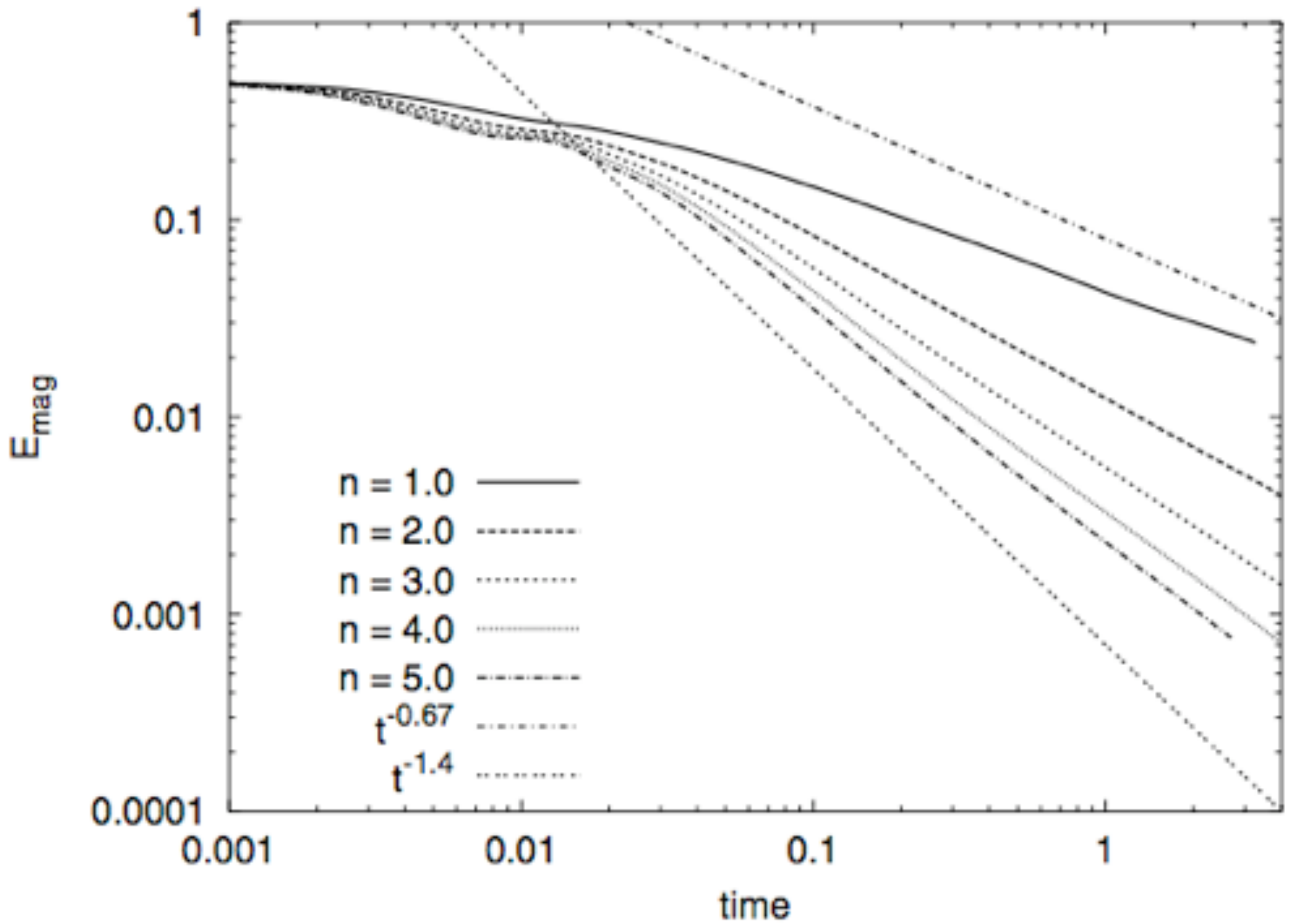
$$E \approx E_0 \left(\frac{t}{\tau_0}\right)^{-2n/(2+n)}$$

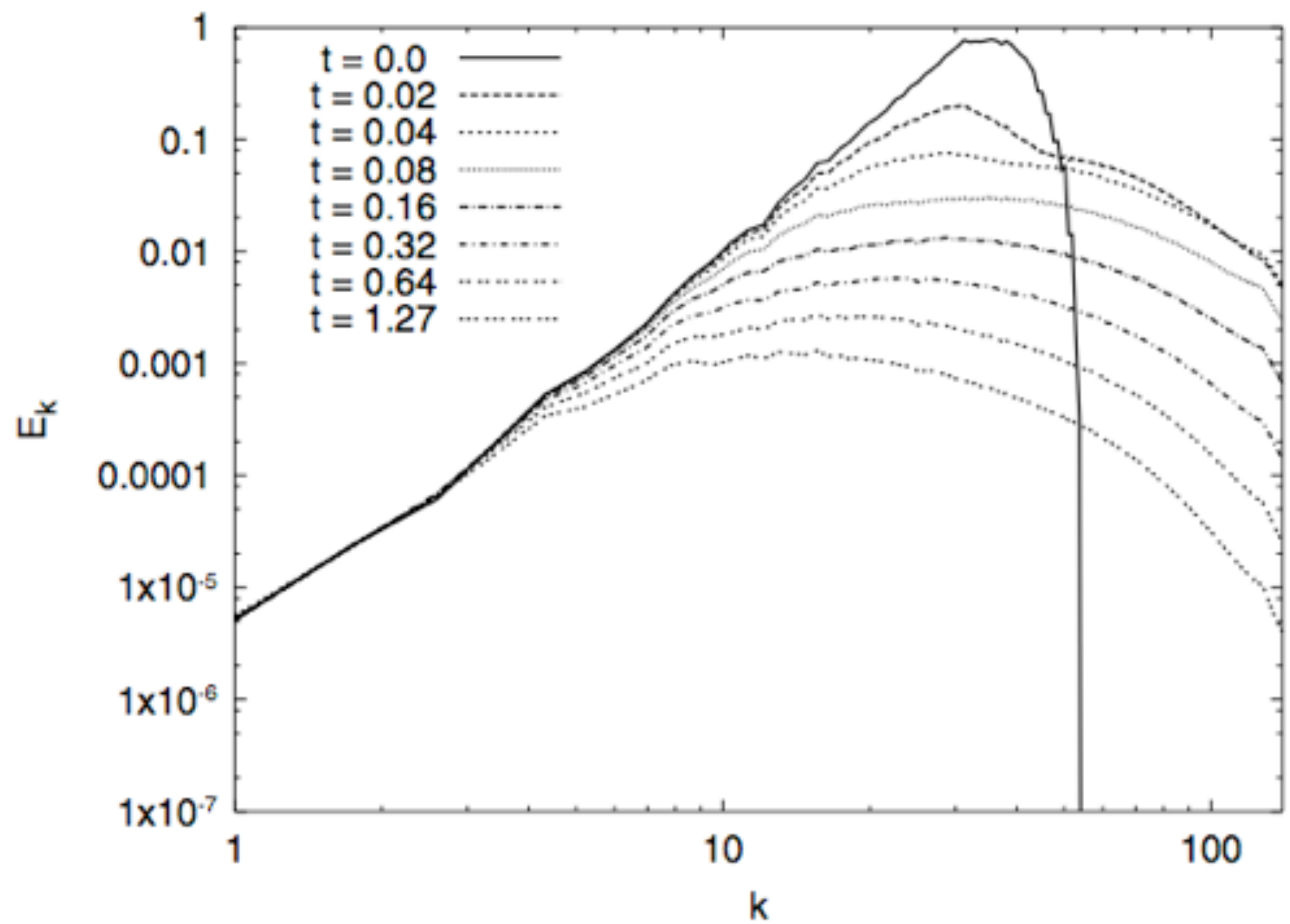
increase of coherence length:

$$L \approx L_0 \left(\frac{t}{\tau_0}\right)^{2/(2+n)}$$

Evolution of Magnetic Fields

turbulent decay laws





- decay law: $$E \approx E_0 \left(\frac{t}{\tau_0} \right)^{-2n/(2+n)}$$
- growths of coherence length: $$L \approx L_0 \left(\frac{t}{\tau_0} \right)^{2/(2+n)}$$

Helicity

Helical Fields

- Helicity (measures complexity of the field):

$$\mathcal{H} \equiv \frac{1}{V} \int_V \mathrm{d}^3x \, \mathbf{A} \cdot \mathbf{B}$$

is conserved (no resistivity)

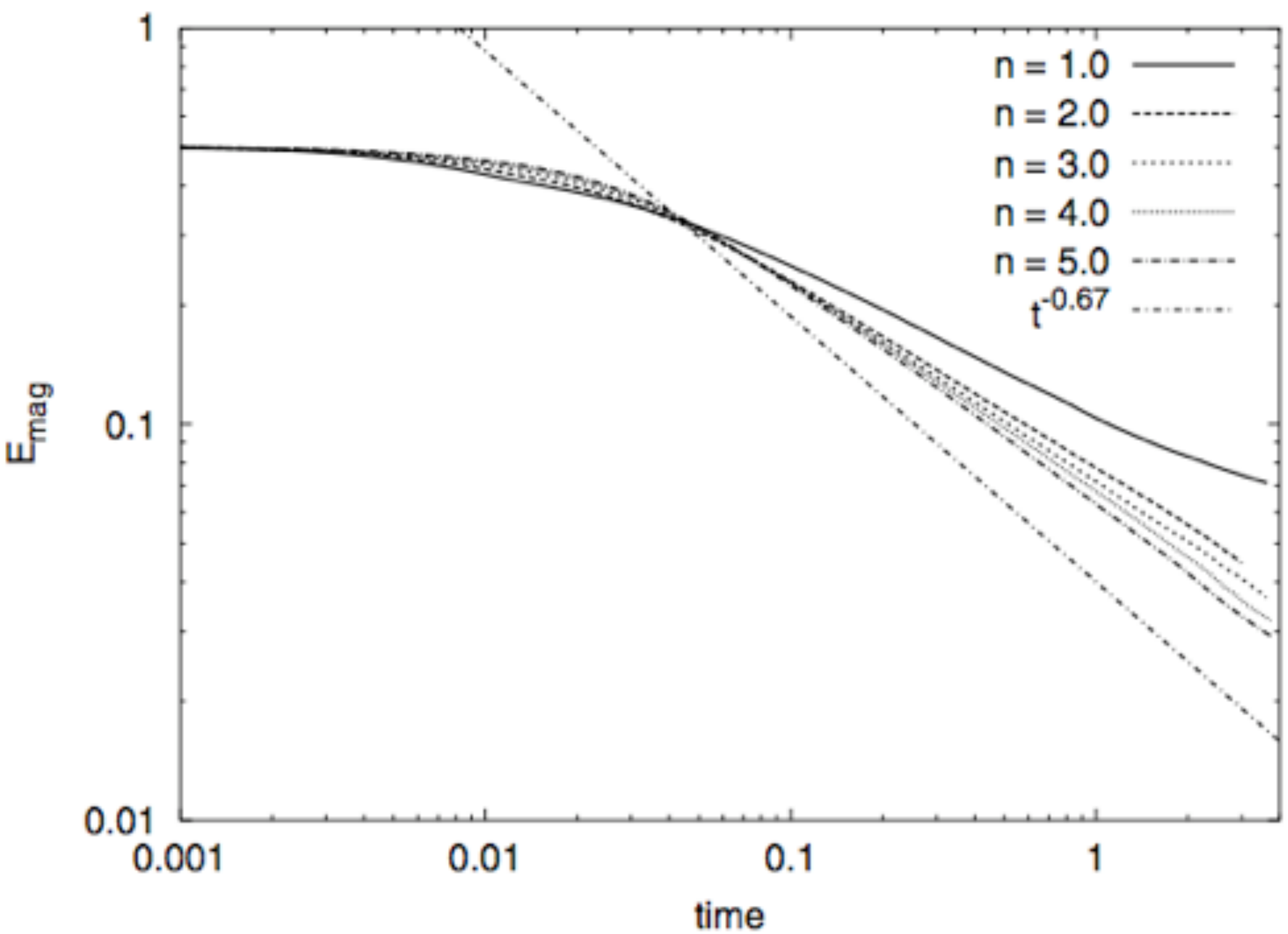
- maximal helical field: $H \sim B^2 L \approx E L$

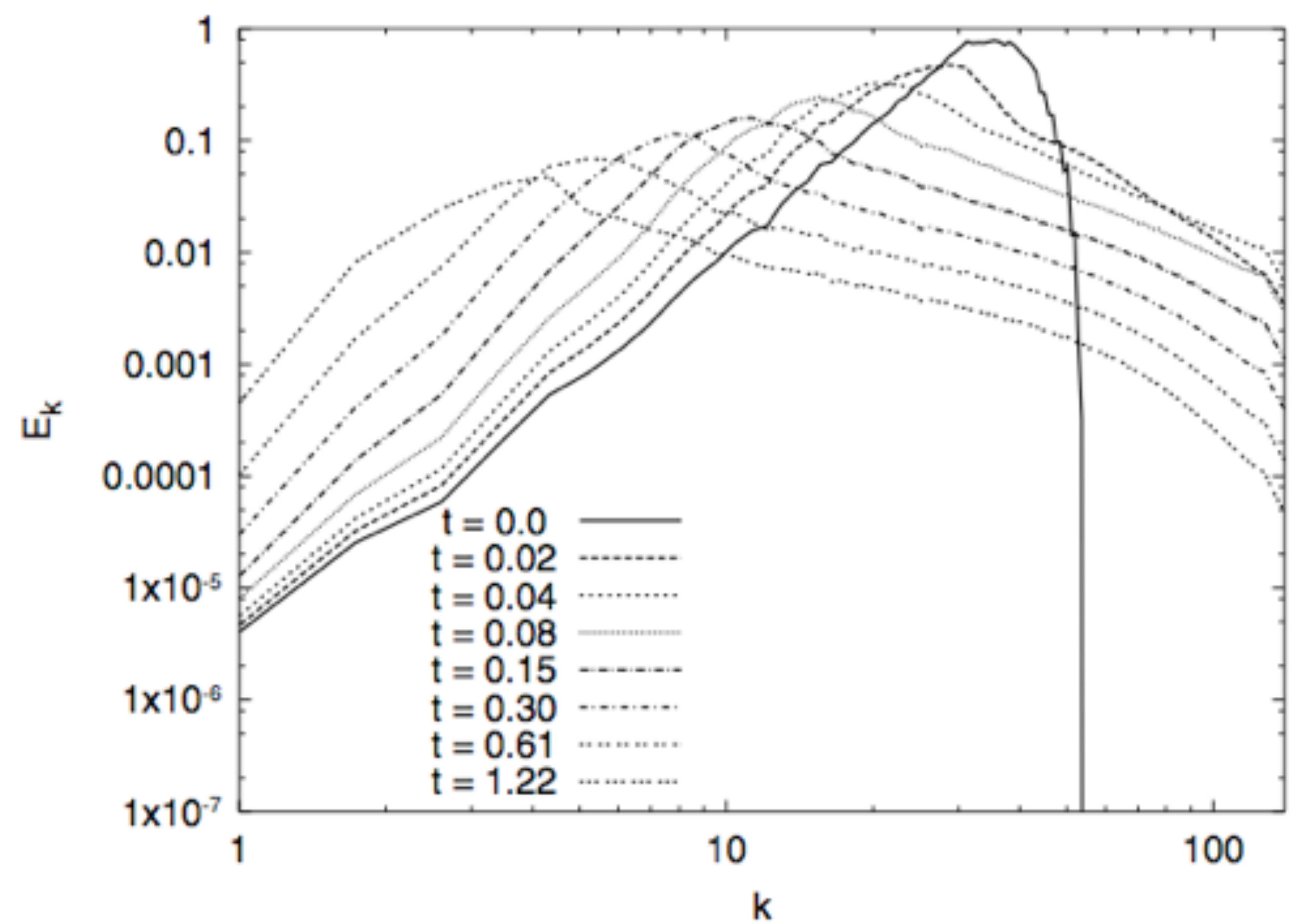
energy decay: $$E \approx E_0 \left(\frac{t}{\tau_0} \right)^{-2/3}$$

inverse cascade: $$L \approx L_0 \left(\frac{t}{\tau_0} \right)^{2/3}$$

Evolution of Magnetic Fields

- Fields with maximum helicity: $\mathcal{H}_{\max} \approx \langle B^2 L \rangle \approx (8\pi) E L$



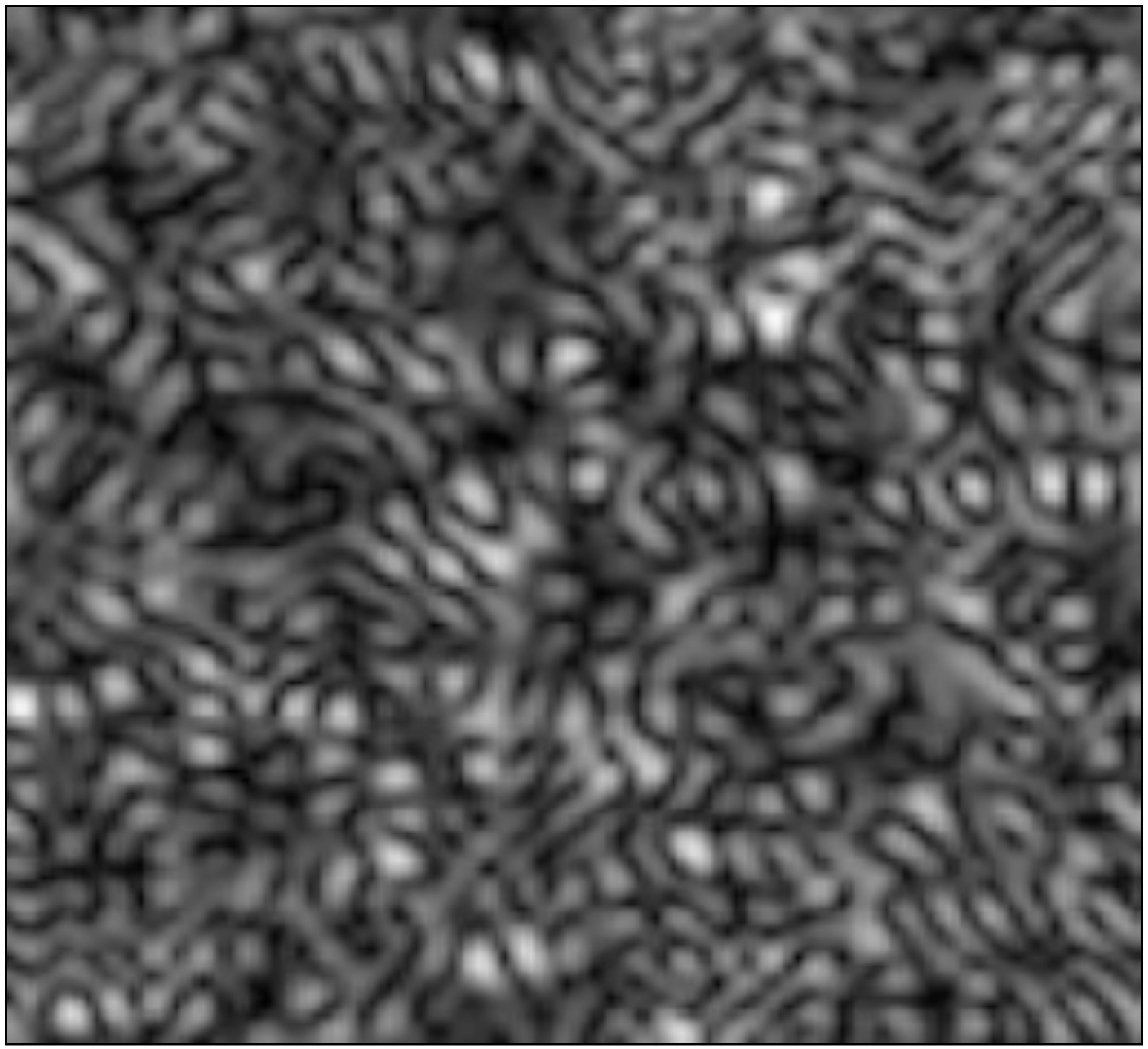


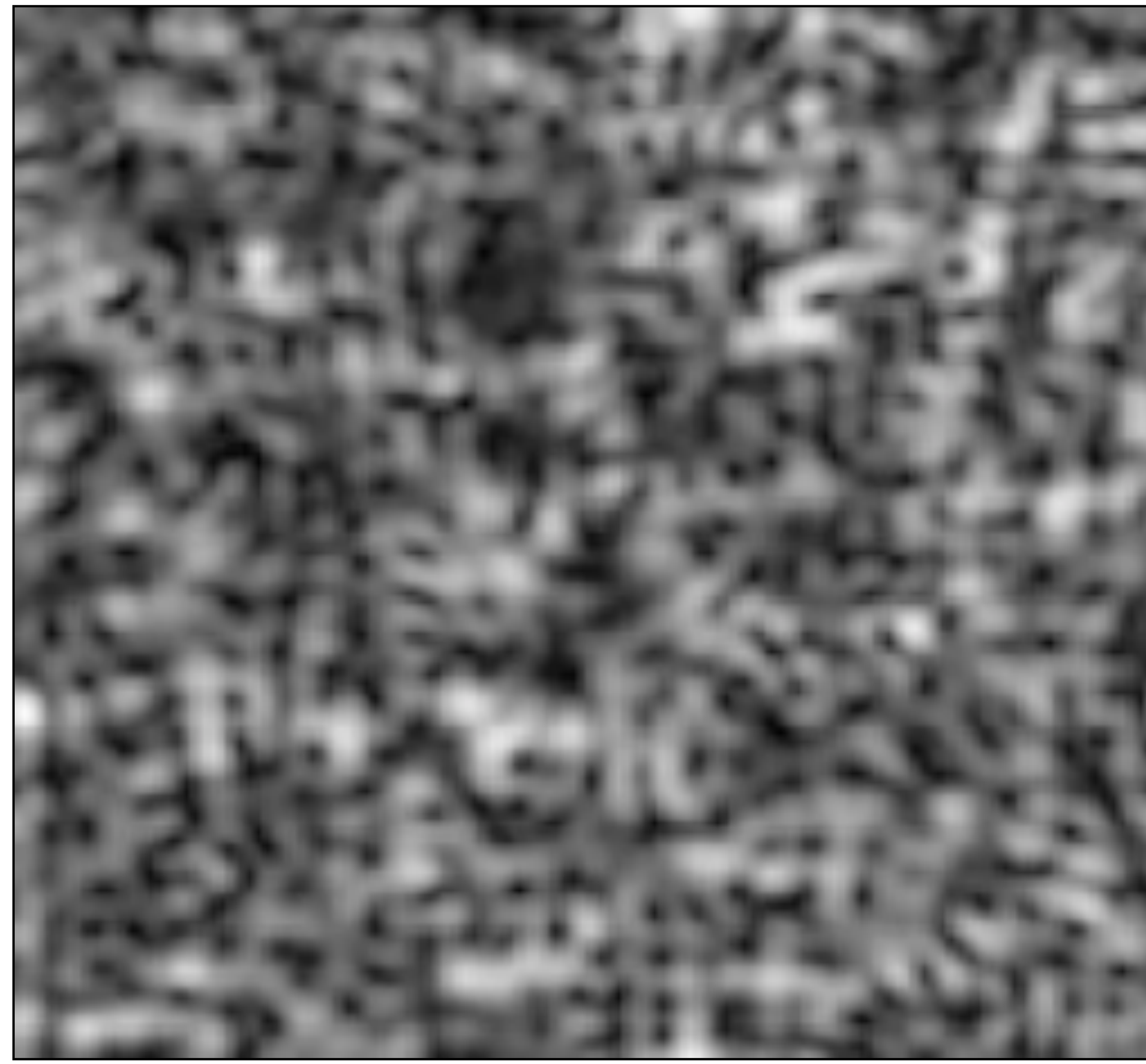
- decay law: $E \approx E_0 \left(\frac{t}{\tau_0} \right)^{-2/3}$

- growths of coherence length: $L \approx L_0 \left(\frac{t}{\tau_0} \right)^{2/3}$ inverse cascade

Evolution of Magnetic Fields

Evolution of small scale random magnetic fields





no initial helicity

with max. initial helicity

Evolution of Magnetic Fields

Viscous regime ($R_e < 1$):

$$v_L(T) = \frac{v_{A,L}^2(T)\, L}{\eta(T)}$$

for $l_{mfp} \ll L$

$$v_L(T) = \frac{v_{A,L}^2(T)}{\alpha(T)\, L}$$

for $l_{mfp} \gg L$

$$\Longrightarrow \qquad \tau_{\rm visc.damp} = \begin{cases} \dfrac{\eta}{V_A^2} \\ \dfrac{\alpha\, L^2}{V_A^2} \end{cases}$$

$\Longrightarrow$ overdamped modes for $t < \tau_{visc}$

(Jedamzik et al. 1998, RB & Jedamzik 2004)

$\Longrightarrow B(t) \approx \mathrm{const}$

Evolution of primordial fields

apply to cosmic evolution

$\Longrightarrow$ evolution equation:

$$\tau_L \approx \frac{L(T)}{v_L(T)} \approx \frac{1}{H(T)} \approx t_{\rm H}$$

turbulent regime ($R_e \gg 1$): $v_L(T) = v_{A,L}(T)$

viscous regime ($R_e < 1$):

$$v_L(T) = \frac{v_{A,L}^2(T)\, L}{\eta(T)}$$

for $l_{\rm mfp} \ll L$

$$v_L(T) = \frac{v_{A,L}^2(T)}{\alpha(T)\, L}$$

for $l_{\rm mfp} \gg L$

Evolution of primordial fields

viscosity η and drag α

- **neutrinos**:

$$\eta_\nu \propto l_{\mathrm{mfp},\nu} \propto T^{-5}$$
$$\alpha_\nu \propto 1/l_{\mathrm{mfp},\nu} \propto T^{5}$$

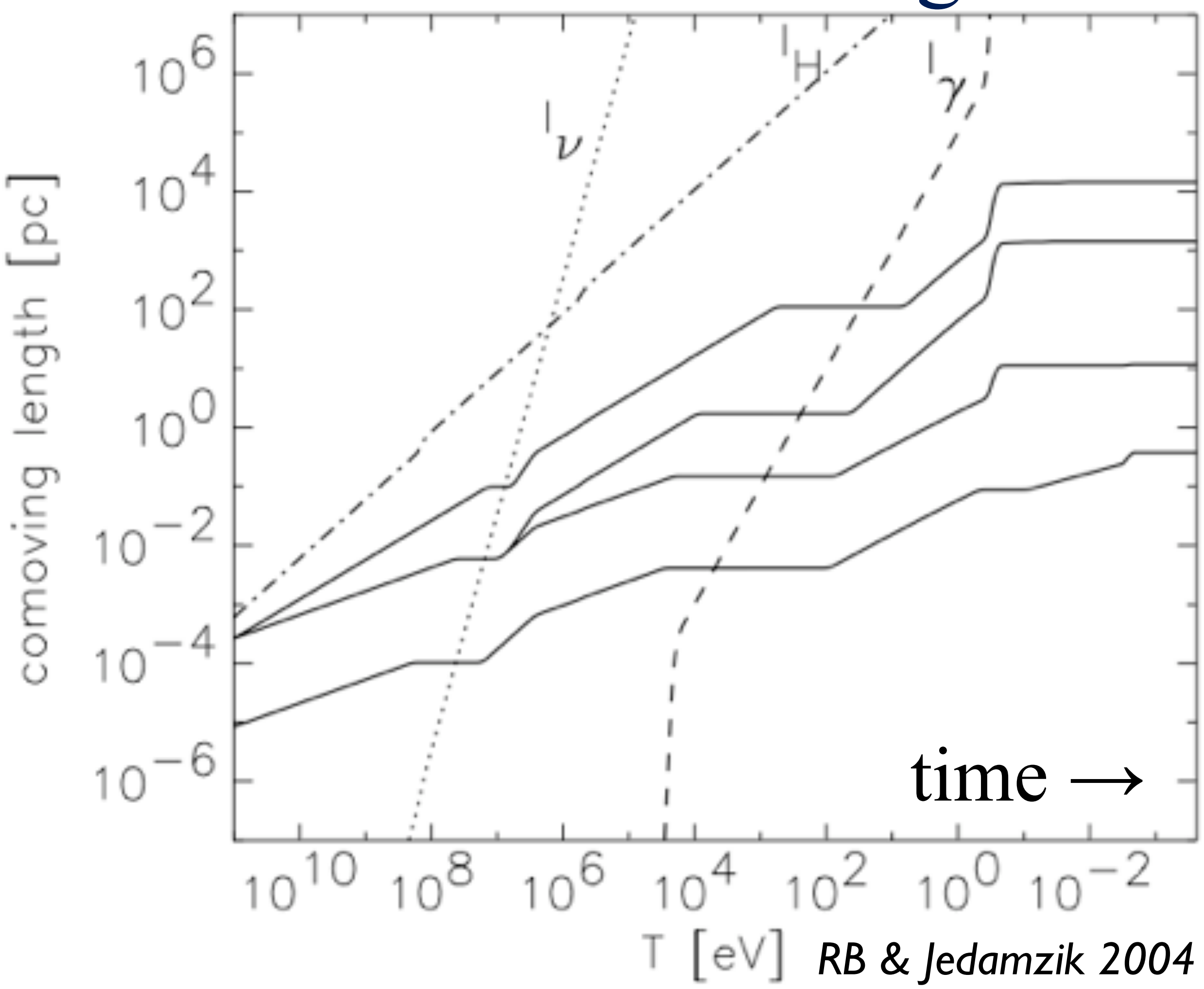
- **photons**:

$$\eta_\gamma \propto l_{\mathrm{mfp},\gamma} \propto T^{-3}$$
$$\alpha_\gamma \propto \rho_\gamma \propto T^{-4}$$

Evolution of primordial fields

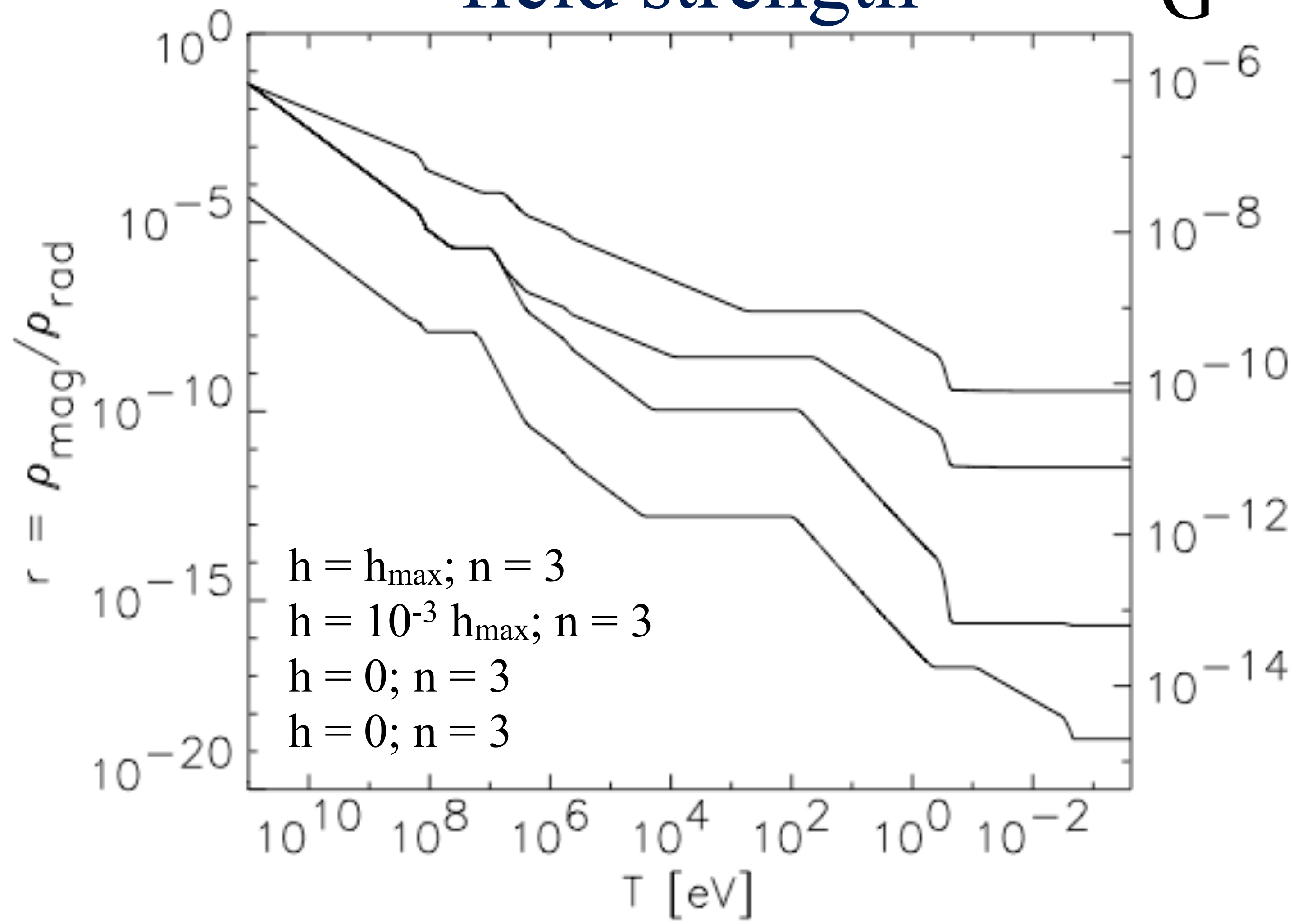
combine with cosmic evolution

coherence length



RB & Jedamzik 2004

field strength

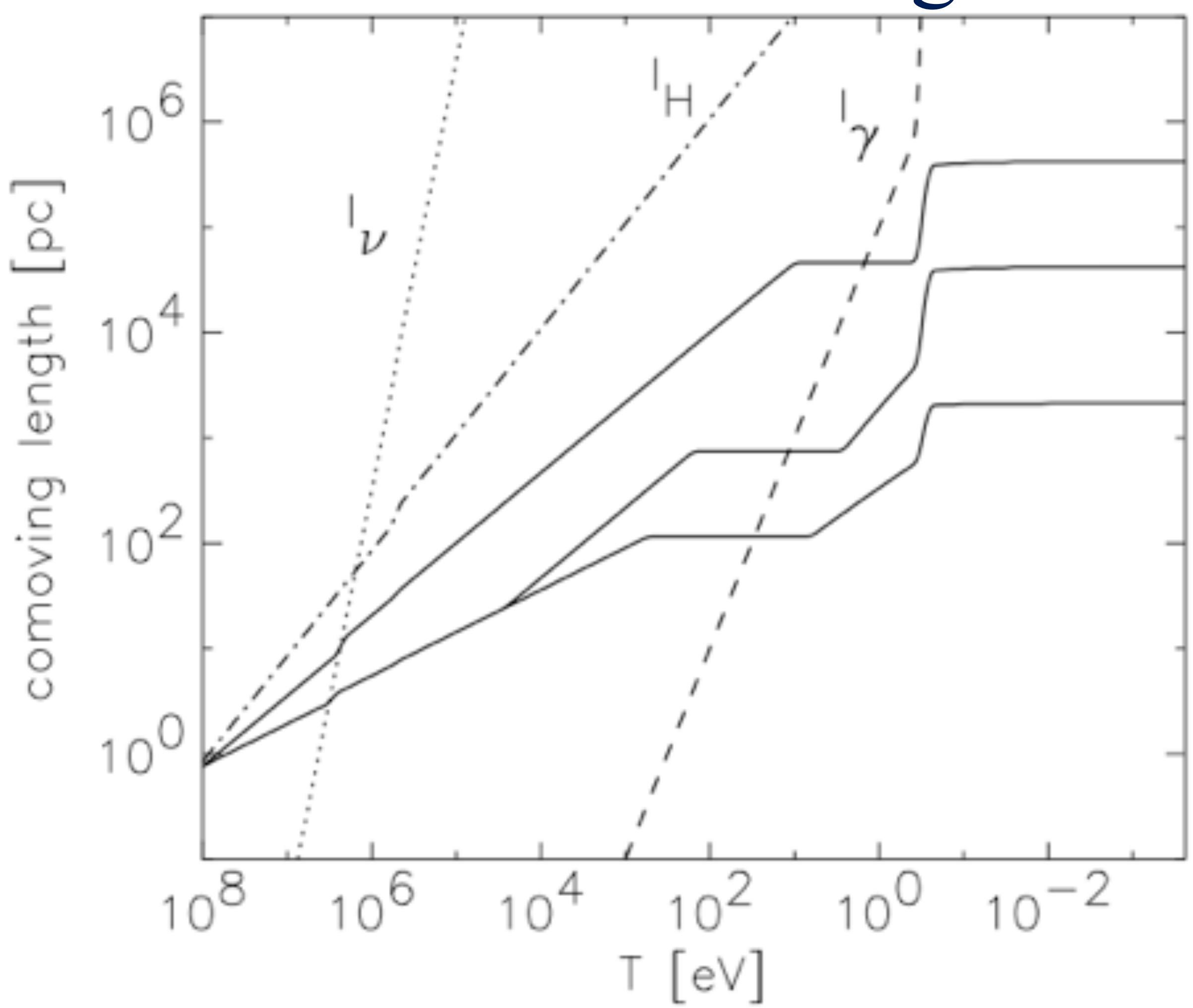


assume magneto-genesis at EW-PT ($T_{\mathrm{gen}} = 100$ GeV)

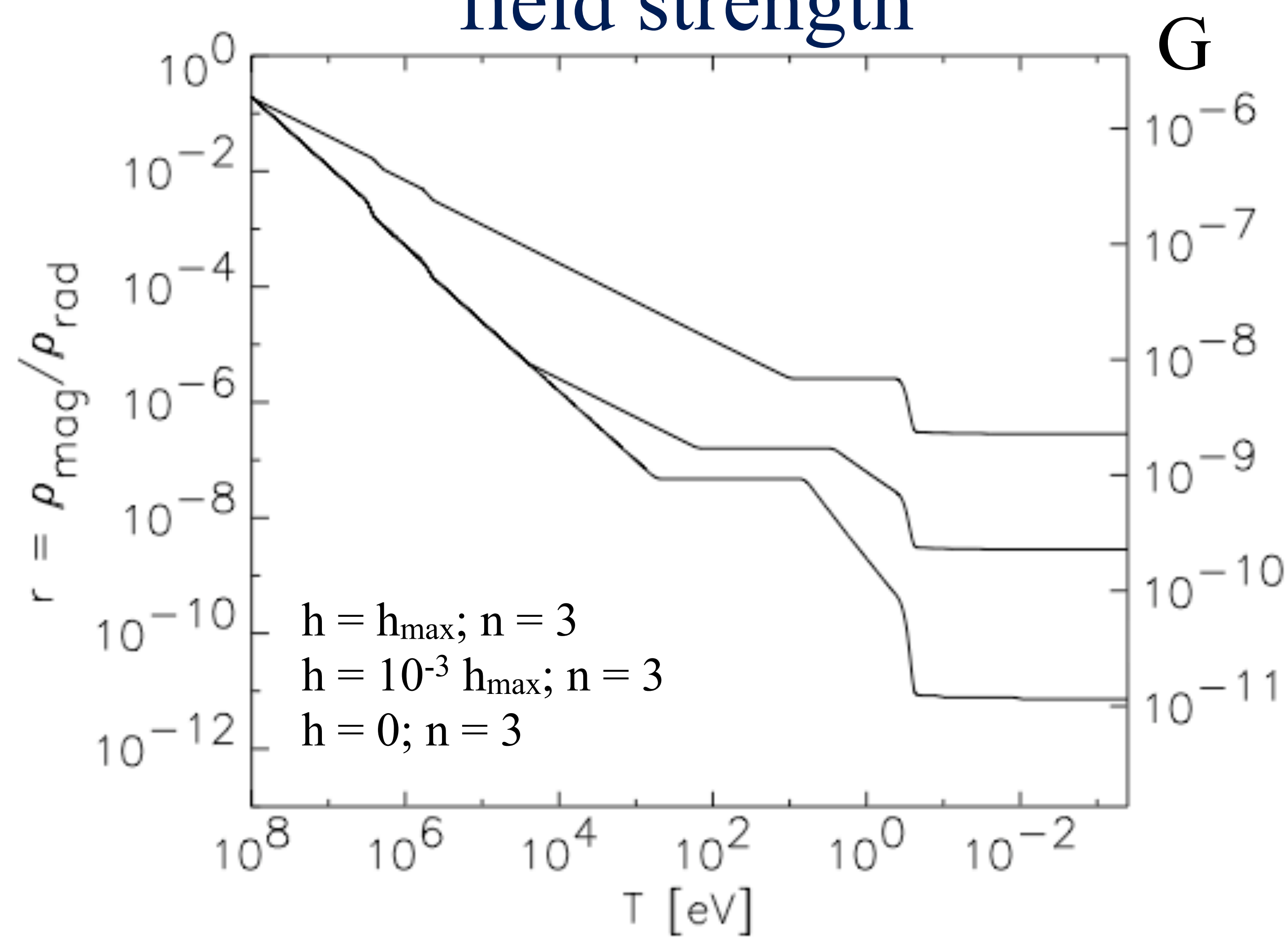
Evolution of primordial fields

combine with cosmic evolution

coherence length



field strength

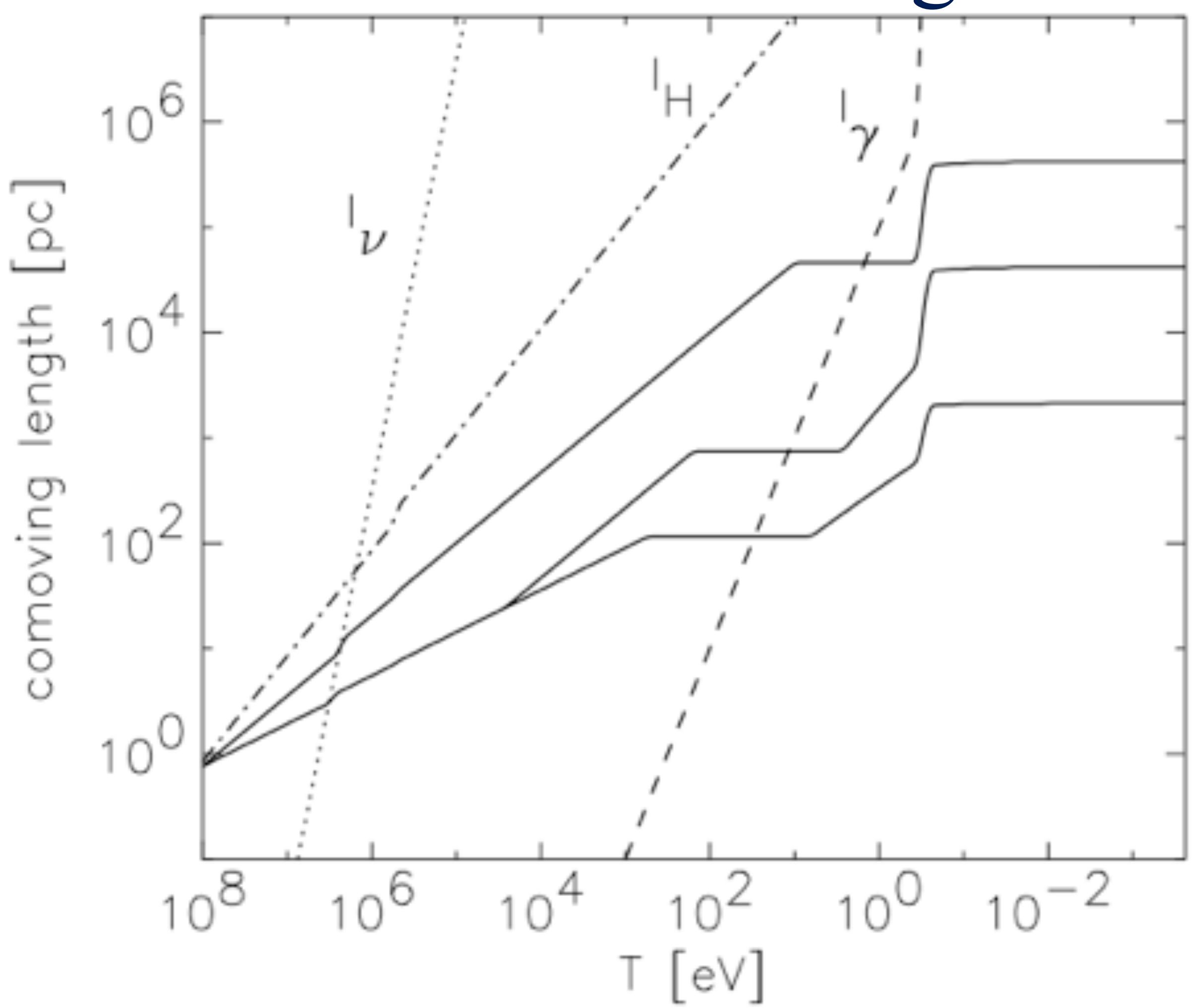


assume magneto-genesis at QCD-PT ($T_{gen} = 100$ MeV)

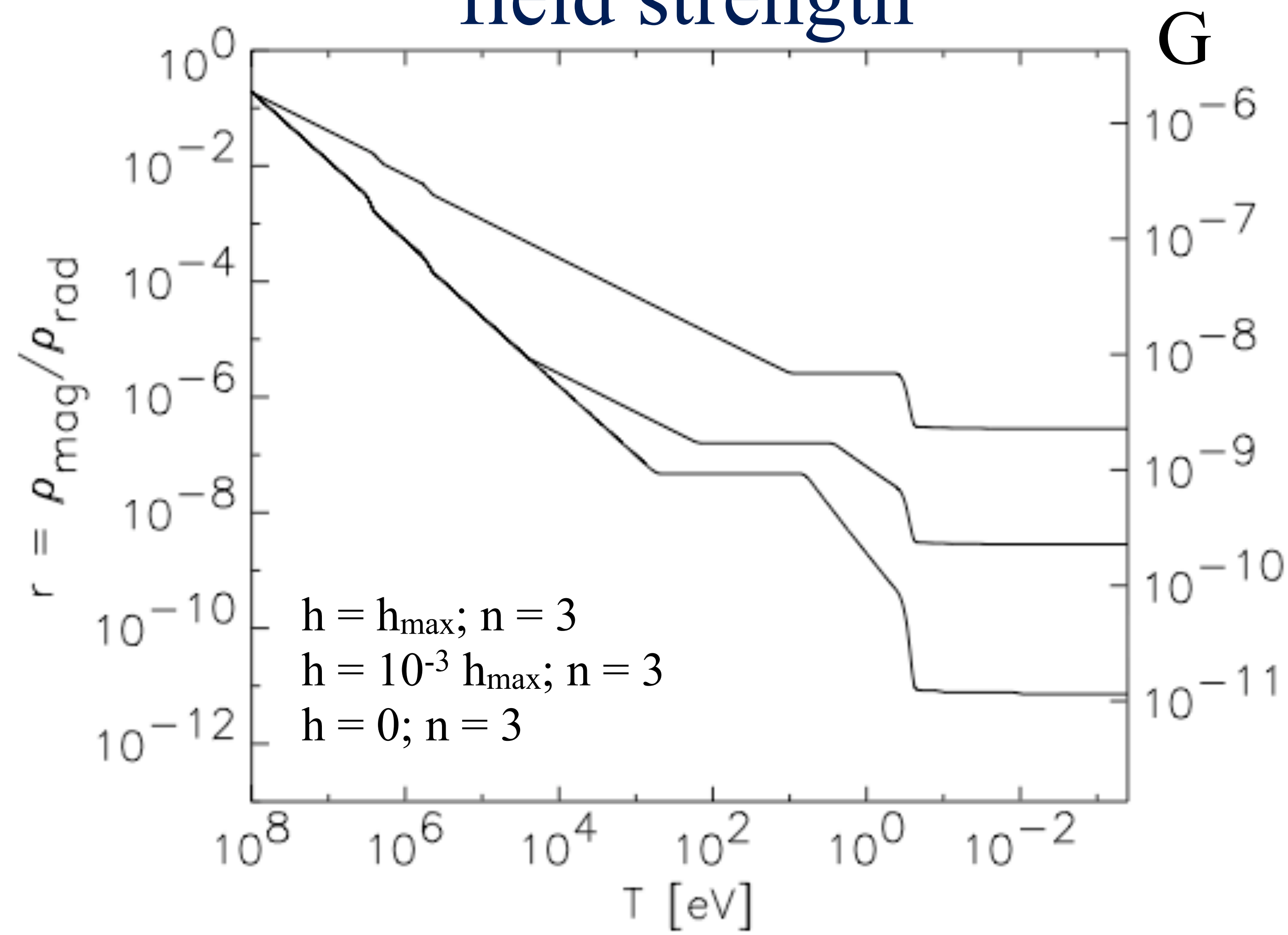
Evolution of primordial fields

combine with cosmic evolution

coherence length



field strength



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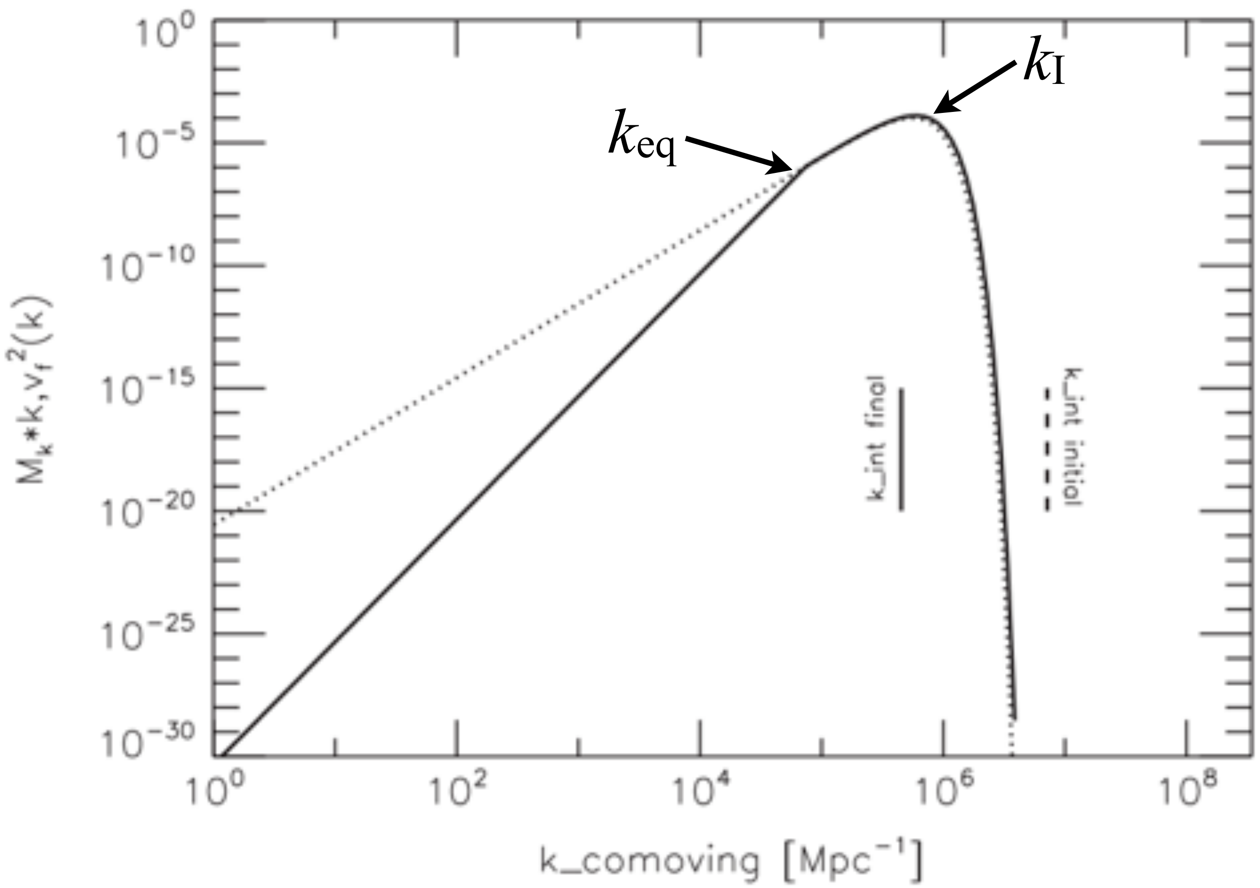
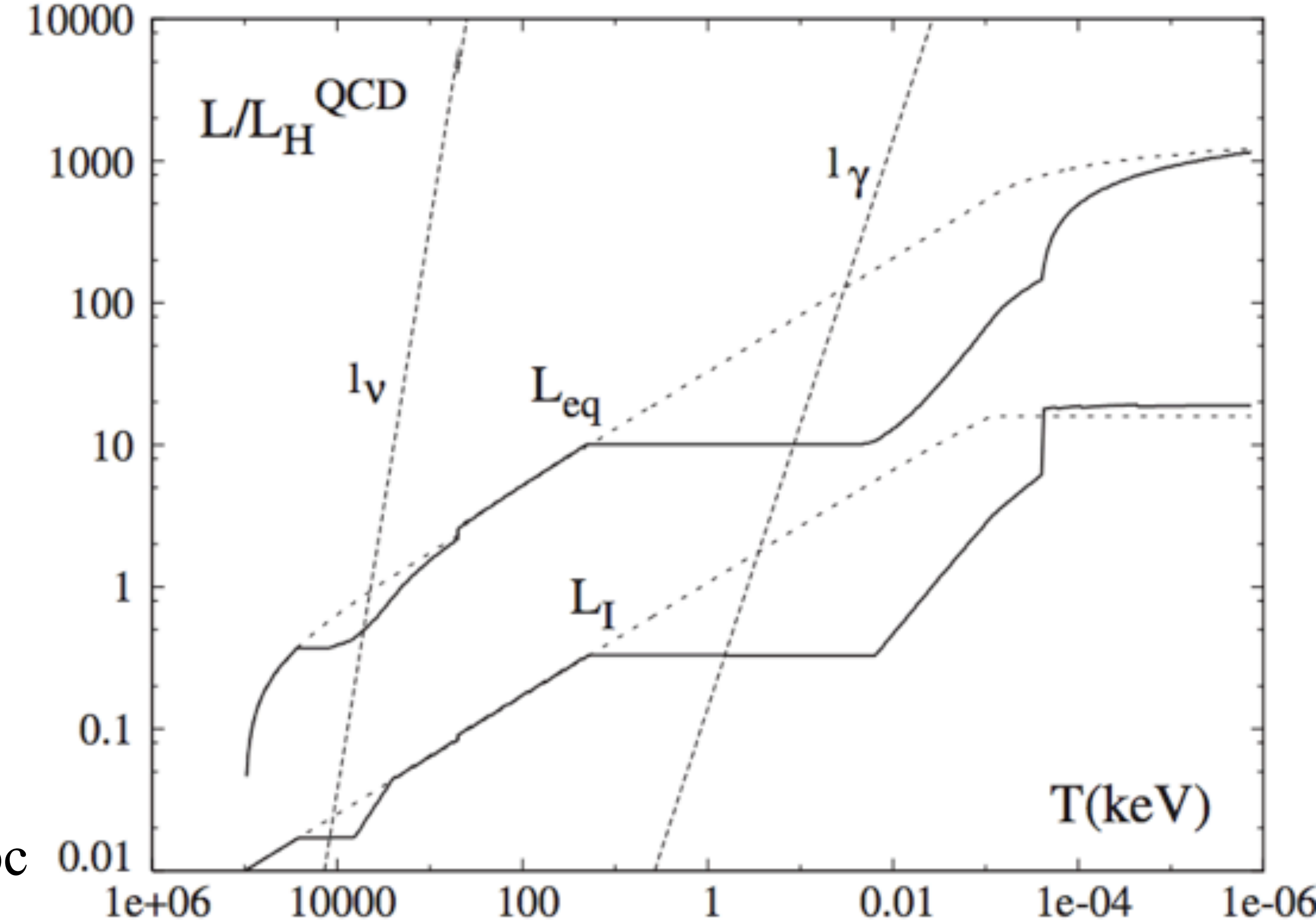
Cluster fields of primordial origin?

Evolution of primordial fields



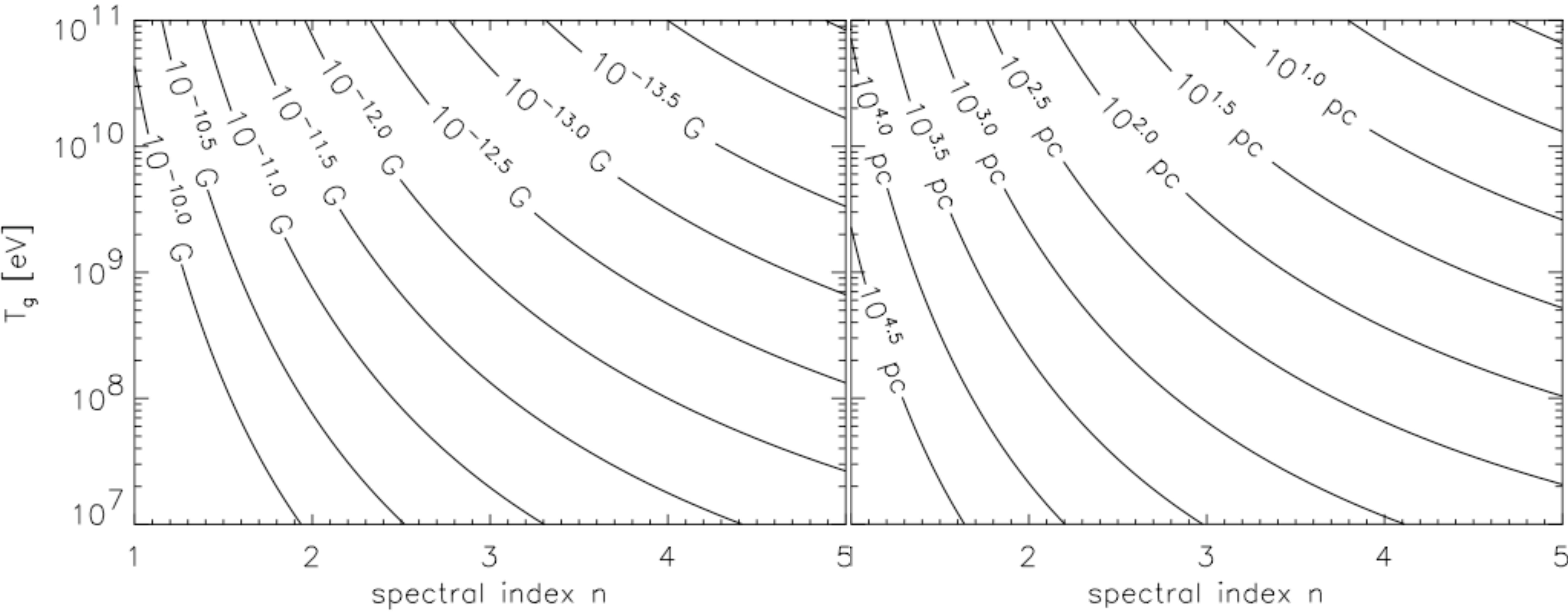


$L_H^{QCD} \approx 1$ pc

Jedamzik & Sigl PRD (2011)

Evolution of primordial fields

combine with cosmic evolution



present day field strength and coherence length

Effects of primordial fields

- Magnetic Jeans mass: $M_J^B \sim 10^{10} M_\odot \left(\frac{B_0}{3\ \mathrm{nG}}\right)^3$

  (Subramanian & Barrow 1998)

- Ambipolar diffusion heating: $L_{\mathrm{AD}} = \frac{\eta_{\mathrm{AD}}}{4\pi} \left|\left(\nabla \times \vec{B}\right) \times \vec{B}/B\right|^2$

  (Sethi & Subramanian 2005)

- Smallest scale:
  (Jedamzik et al. 1998, Subramanian & Barrow 1998)

$$k_{\max} \sim 234\ \mathrm{Mpc}^{-1} \left(\frac{B_0}{1\ \mathrm{nG}}\right)^{-1} \left(\frac{\Omega_m}{0.3}\right)^{1/4} \times \left(\frac{\Omega_b h^2}{0.02}\right)^{1/2} \left(\frac{h}{0.7}\right)^{1/4},$$

Effects of primordial fields

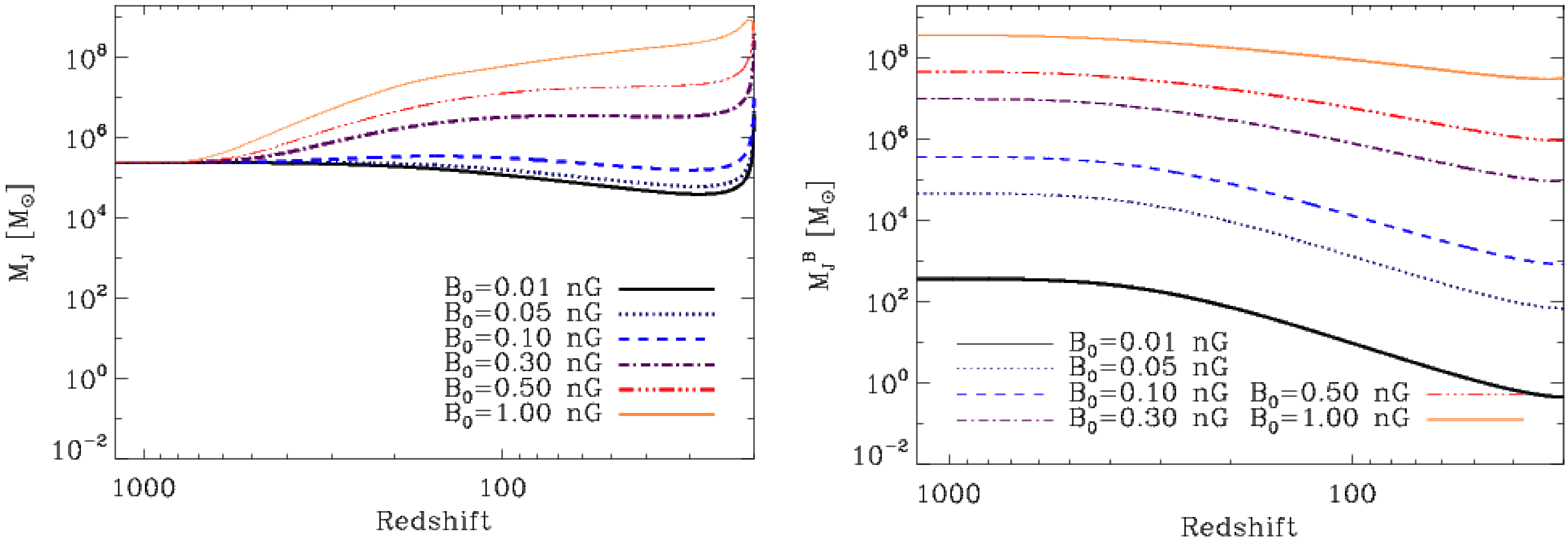
Ambipolar Diffusion

- Ions are coupled to the magnetic field.
- Neutrals are indirectly coupled to the magnetic field by collisions with the ions.
- The coupling is not perfect: partial *diffusion* through the field lines
- Magnetic energy can be dissipated by friction between ions and neutrals.

$$L_{\rm ambi} = \frac{\rho_n}{16\pi^2 \gamma \rho_b^2 \rho_i} \left| \left(\nabla \times \vec{B} \right) \times \vec{B} \right|^2$$

$$\gamma = \frac{\frac{1}{2} n_H \langle \sigma v \rangle_{\rm H^+,H} + \frac{4}{5} n_{\rm He} \langle \sigma v \rangle_{\rm H^+,He}}{m_H \left[n_{\rm H} + 4 n_{\rm He} \right]}$$

Effects of primordial fields



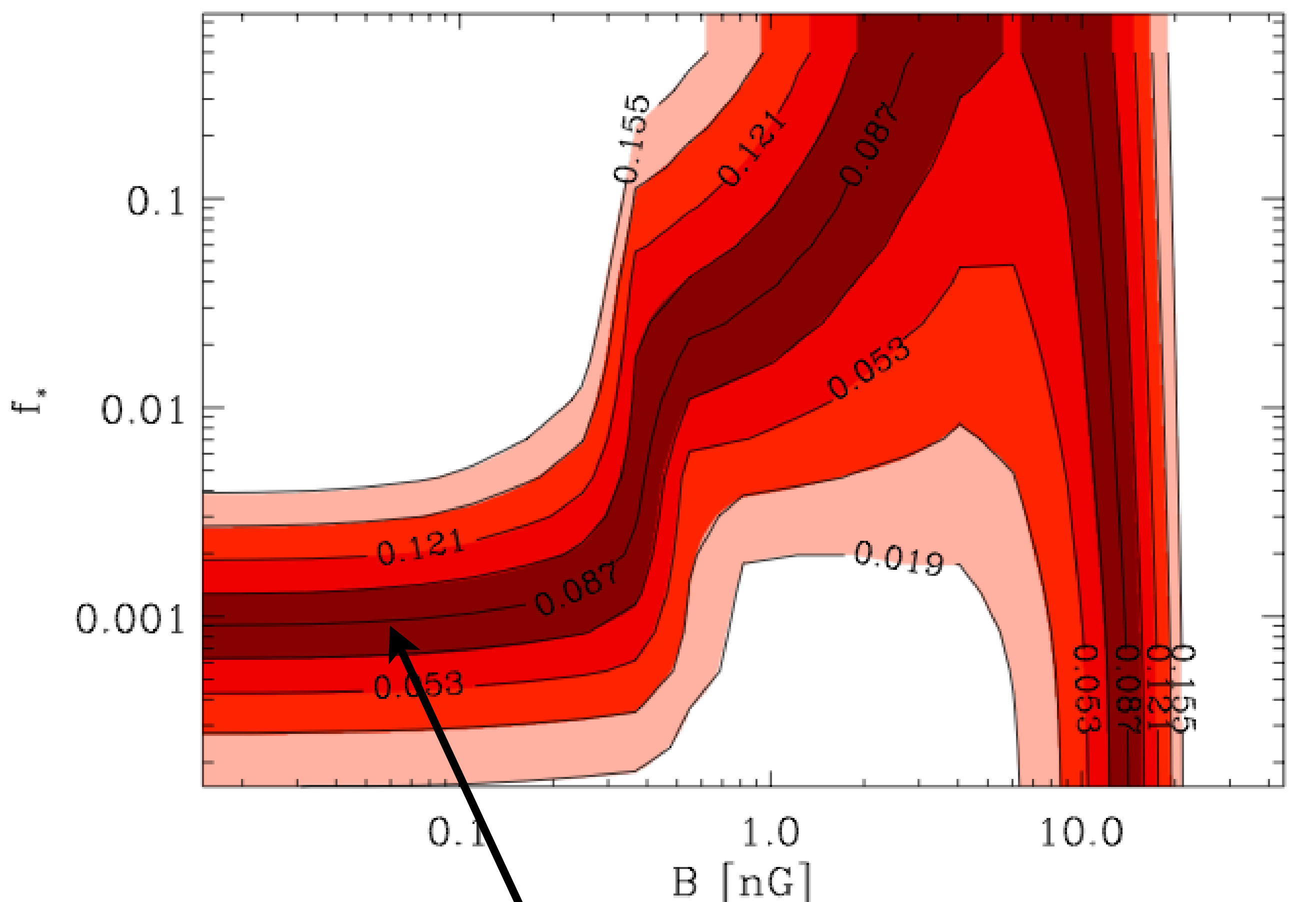
Thermal / magnetic Jeans masses: Critical mass scale for gravity to overcome thermal / magnetic pressure.

Both are significantly increased in the presence of strong magnetic fields.

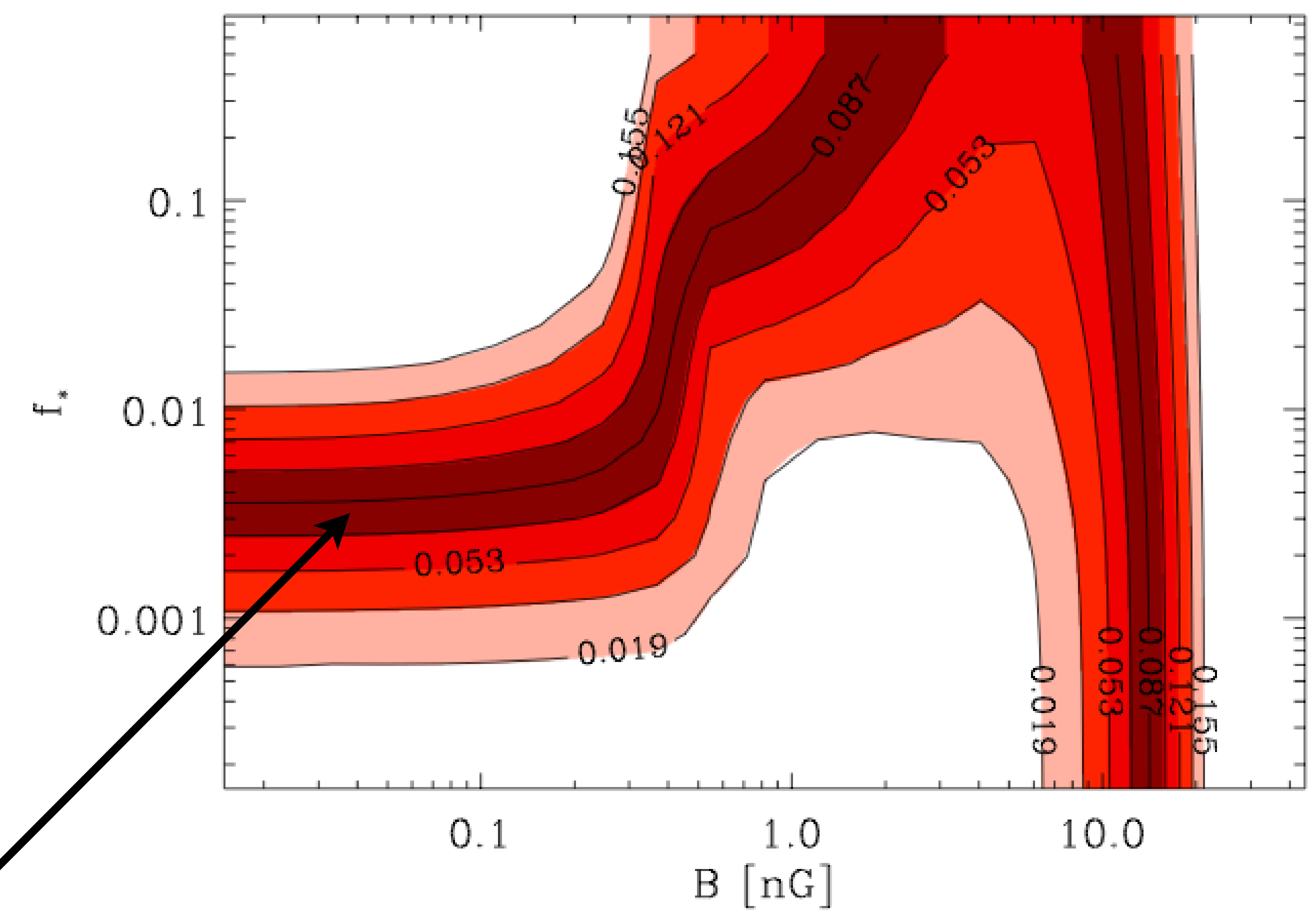
Schleicher et al. (2009)

Effects of primordial fields

Modification of primordial star formation
⟹ constraints from the optical depth



Reionization by Pop. III stars



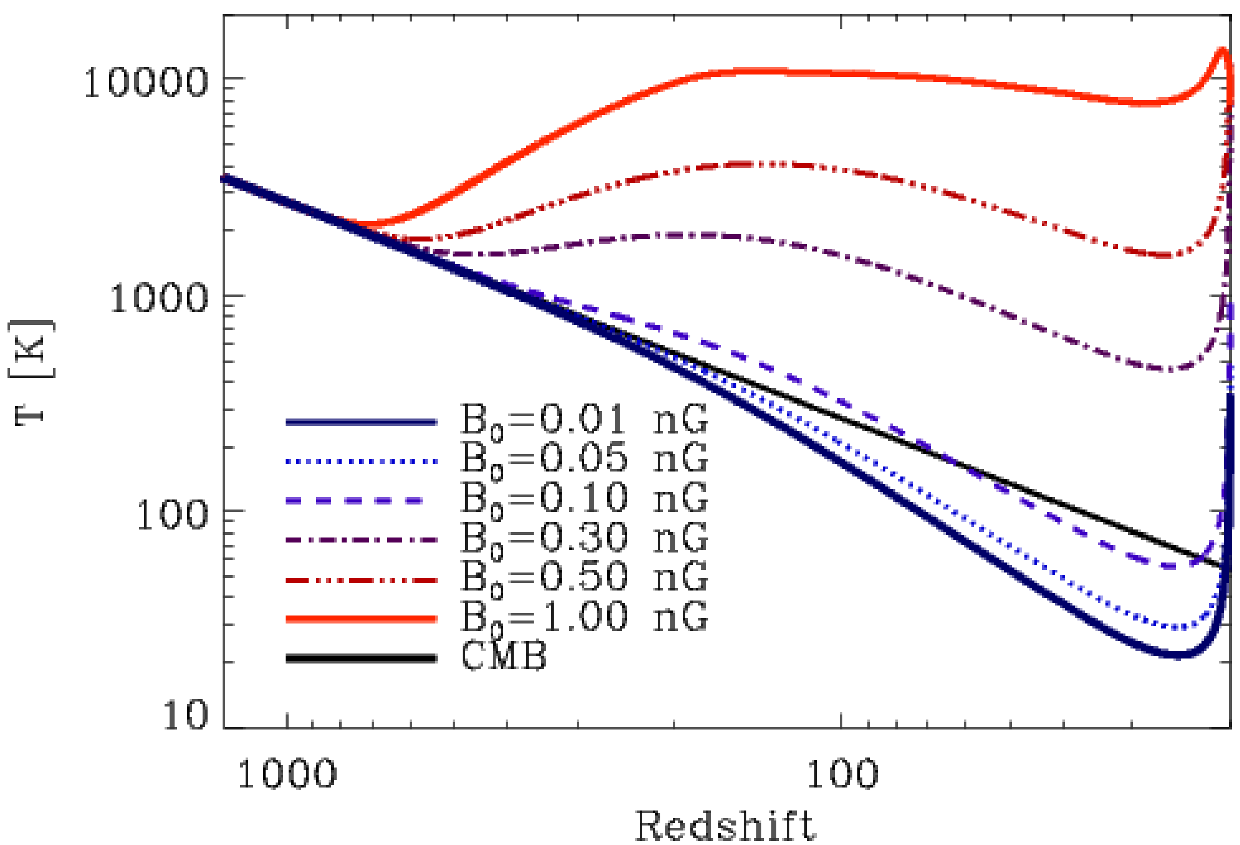
Reionization by Pop. III & Pop. II stars

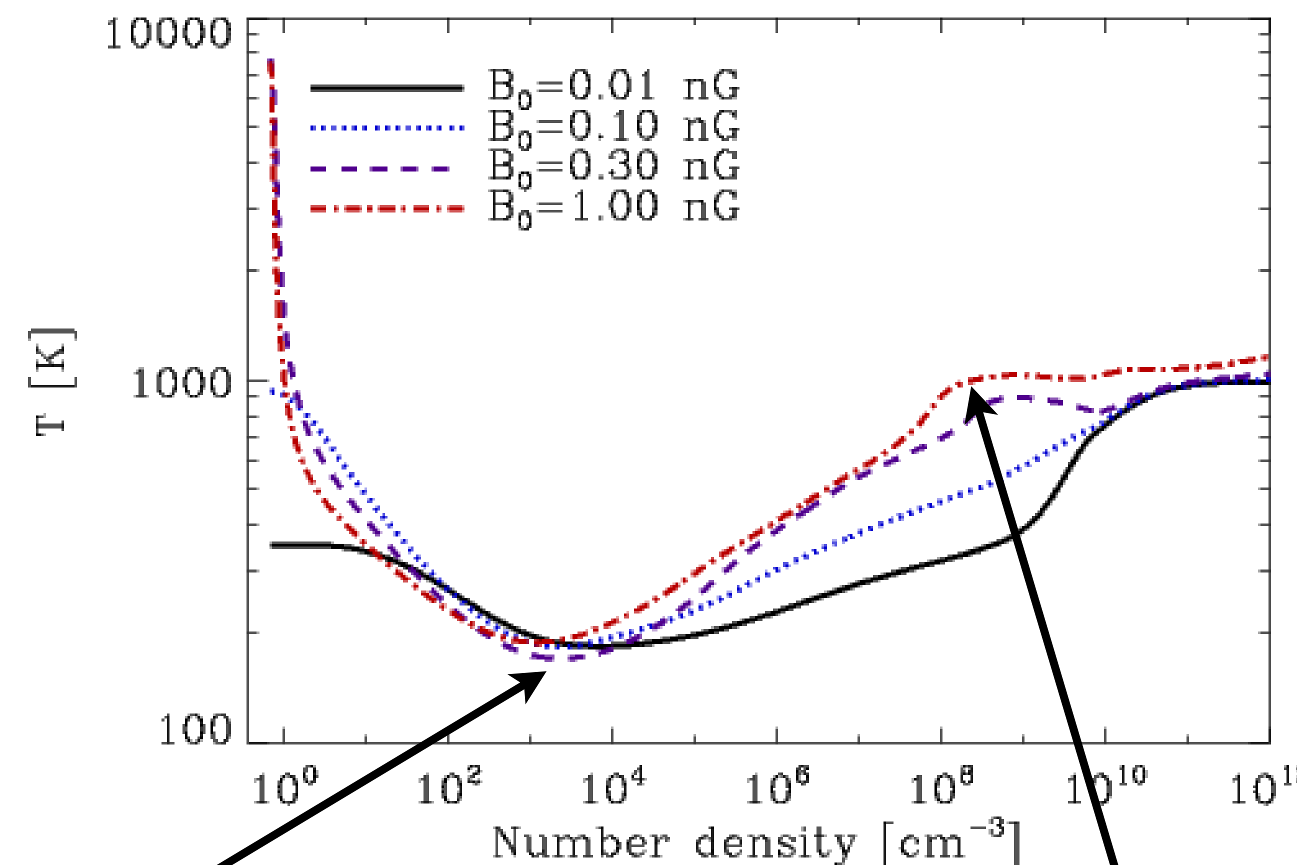
Schleicher, RB & Klessen (2008)

Reionization optical depth: 0.087 +/- 0.017 (WMAP 5: *Komatsu et al. 2008*)

Effects of primordial fields

Ambipolar diffusion during the collapse:





Primordial magnetic fields increase gas temperature

same fragmentation scale

higher temperature
$\Longrightarrow$ more accretion

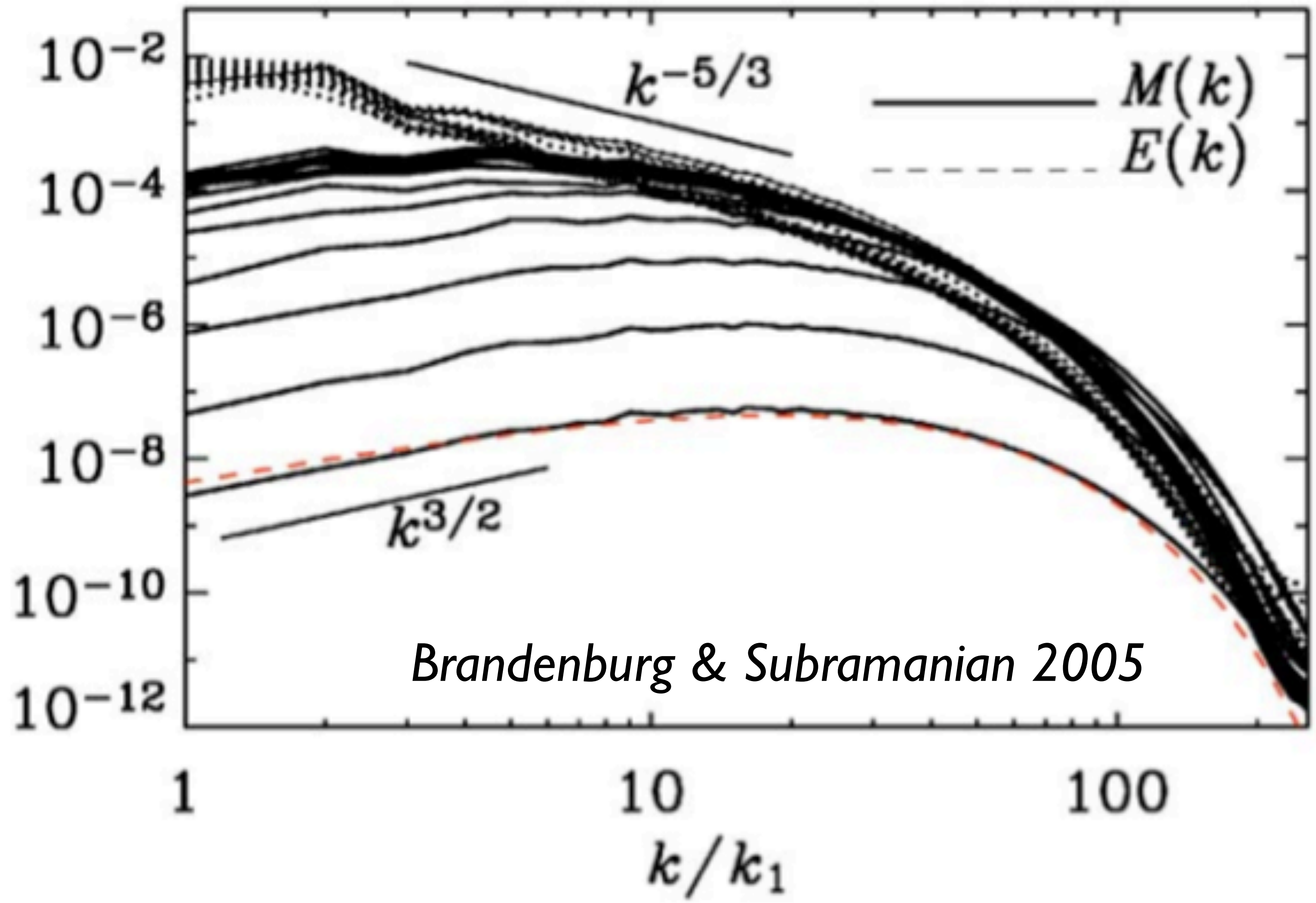
Schleicher et al. (2009)

B-Field amplification

Small-scale dynamo

(Batchelor 1950, Kazantsev 1968, see also Brandenburg & Subramanian 2005, Schober et al. 2012a,b)

- exponential growth of weak seed fields
- growth rate depends on magnetic Reynolds number: $\gamma \propto \mathrm{Rm}^{-1/2}$
- mag. spectrum: $E_{\mathrm{mag},k} \propto k^{3/2}$
- saturation at $E_{\mathrm{mag}} \sim 0.1\ E_{\mathrm{kin}}$



B-Field amplification

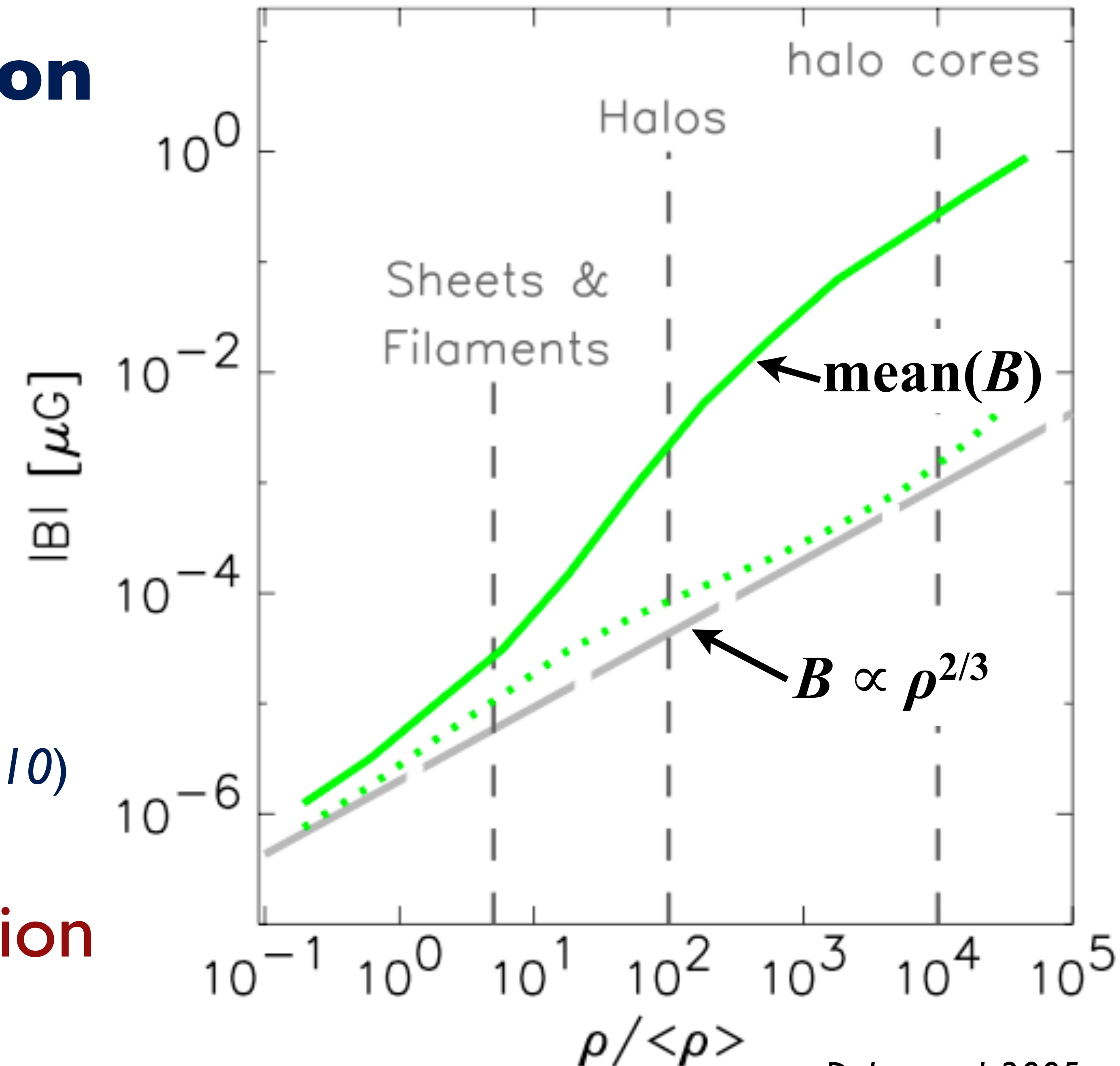
B-fields during compression

- maximum growth by adiabatic compression:
  $B \propto \rho^{2/3}$

- small-scale dynamo works in cluster forming models

  (e.g. *Dolag et al. 1999, 2000; Xu et al. 2009, 2010*)

- depends on numerical resolution

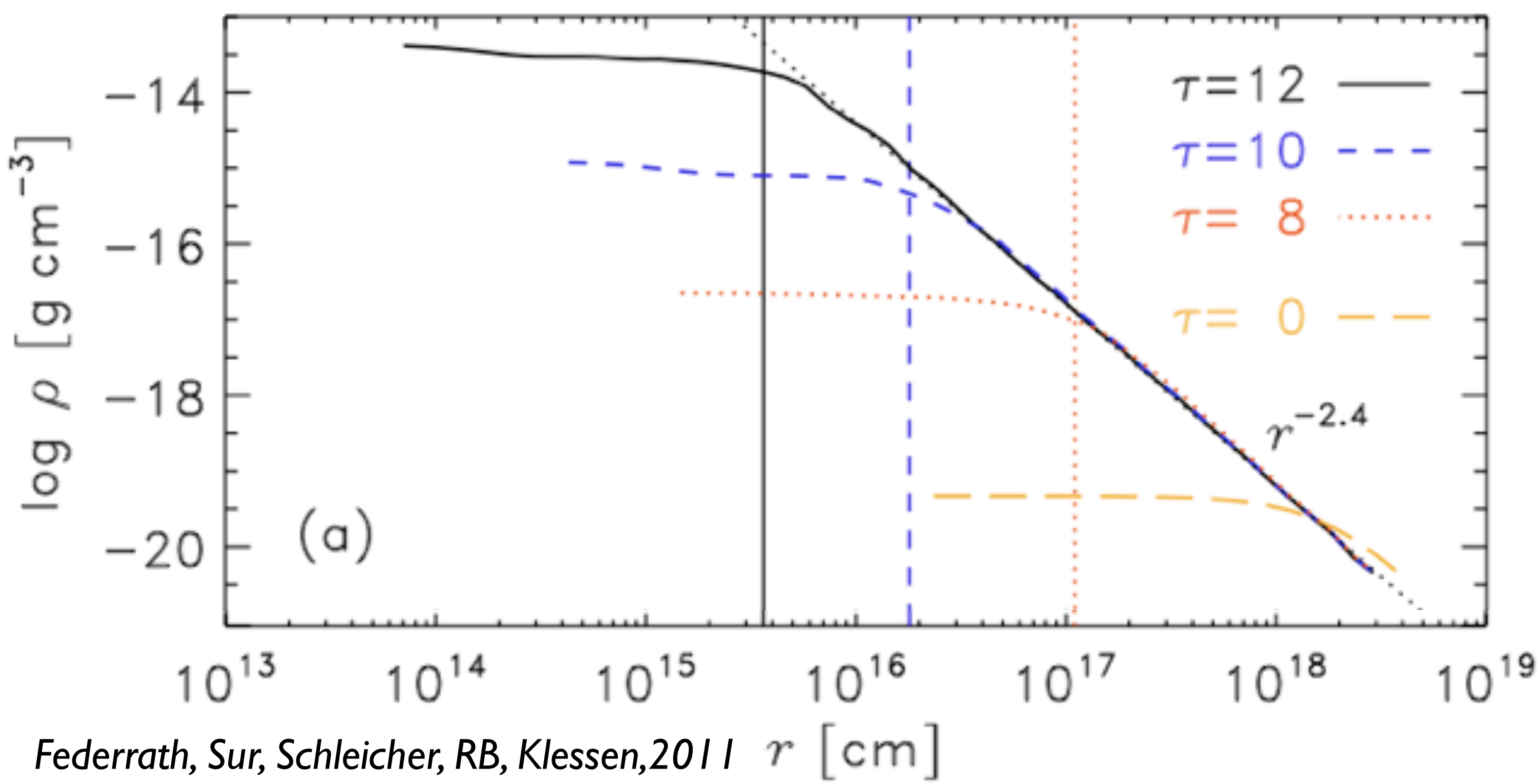


Dolag et al. 2005

Dynamo during "First Star Formation"

- turbulent infall motions (e.g. *Abel et al. 2002, Greif et al. 2008*)

- baryonic core modelled on a supercritical hydrostatic sphere:
  - $M_{\rm baryon}$ = 1500 $M_{\rm sol}$
  - $\rho_0 = 5 \times 10^{-20}$ g cm^{-3}
  - weak random field: B = 1nG, $\beta = 10^{10}$
  - transonic turbulence: $v_{\rm rms}$ = 1.1 km sec^{-1}



Federrath, Sur, Schleicher, RB, Klessen, 2011

characteristic length: **Jeans length**: $\lambda_J = \left(\frac{\pi c_s^2}{G \rho} \right)^{1/2}$

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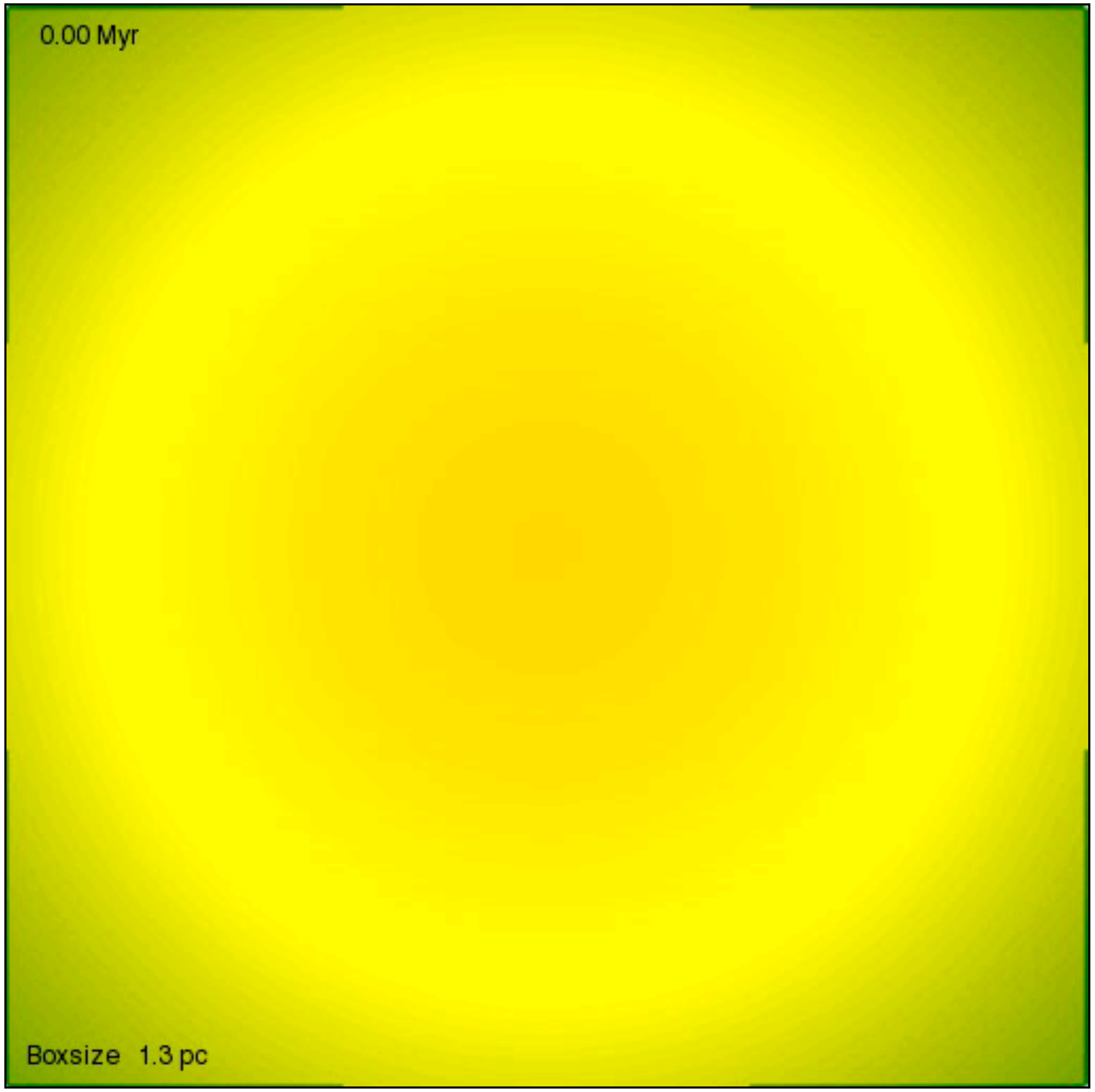
  - weak random field: $\mathrm{B} = 1\mathrm{nG},\ \beta = 10^{10}$
  - transonic turbulence: $v_{\mathrm{rms}} = 1.1\ \mathrm{km\ sec^{-1}}$



characteristic length: **Jeans length**: $\lambda_J = \left(\frac{\pi\, c_s^2}{G\, \rho}\right)^{1/2}$

Dynamo during "First Star Formation"

- analyse data within decreasing Jeans volume:

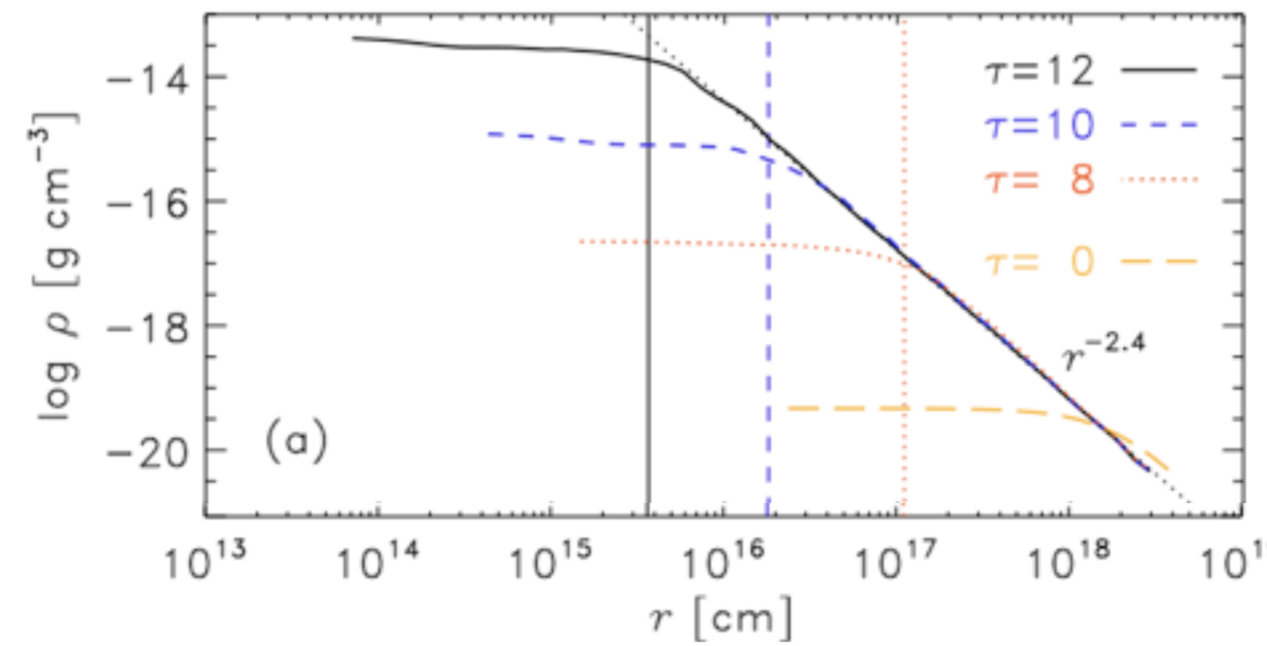
$$V_\mathrm{J} = 4\pi(\lambda_\mathrm{J}/2)^3/3$$

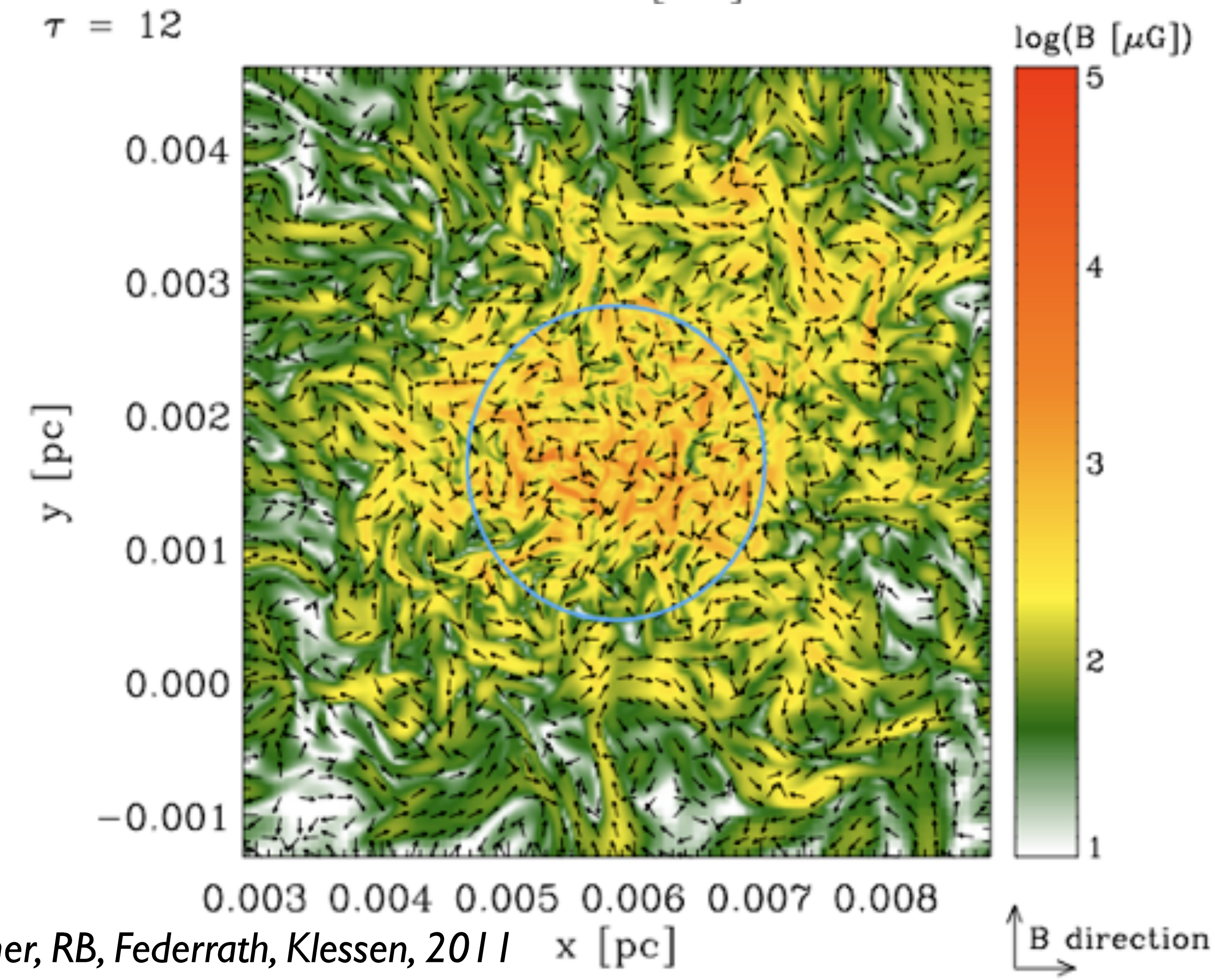
- use dimensionless time:

$$\tau = \int \frac{1}{t_\mathrm{ff}(t)}\, dt$$

- free fall time

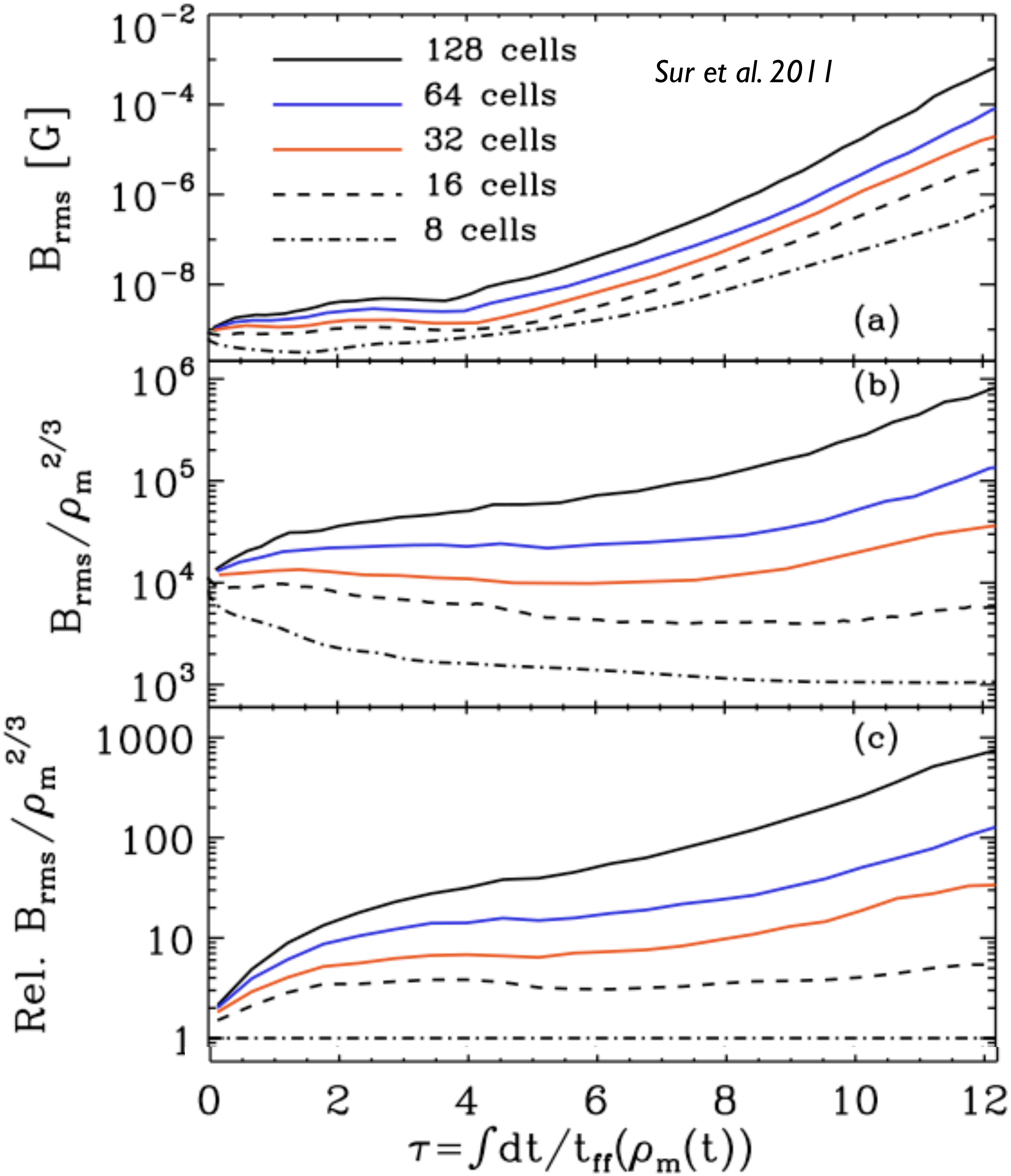
$$t_\mathrm{ff} = (3\pi/32\, G\, \langle\rho(t)\rangle)^{1/2}$$





Sur, Schleicher, RB, Federrath, Klessen, 2011

Dynamo during "First Star Formation"



- growth rate depends on R_m, i.e. resolution:

$$R_m \propto N_J^{4/3}$$ (e.g. *Haugen et al. 2004*)

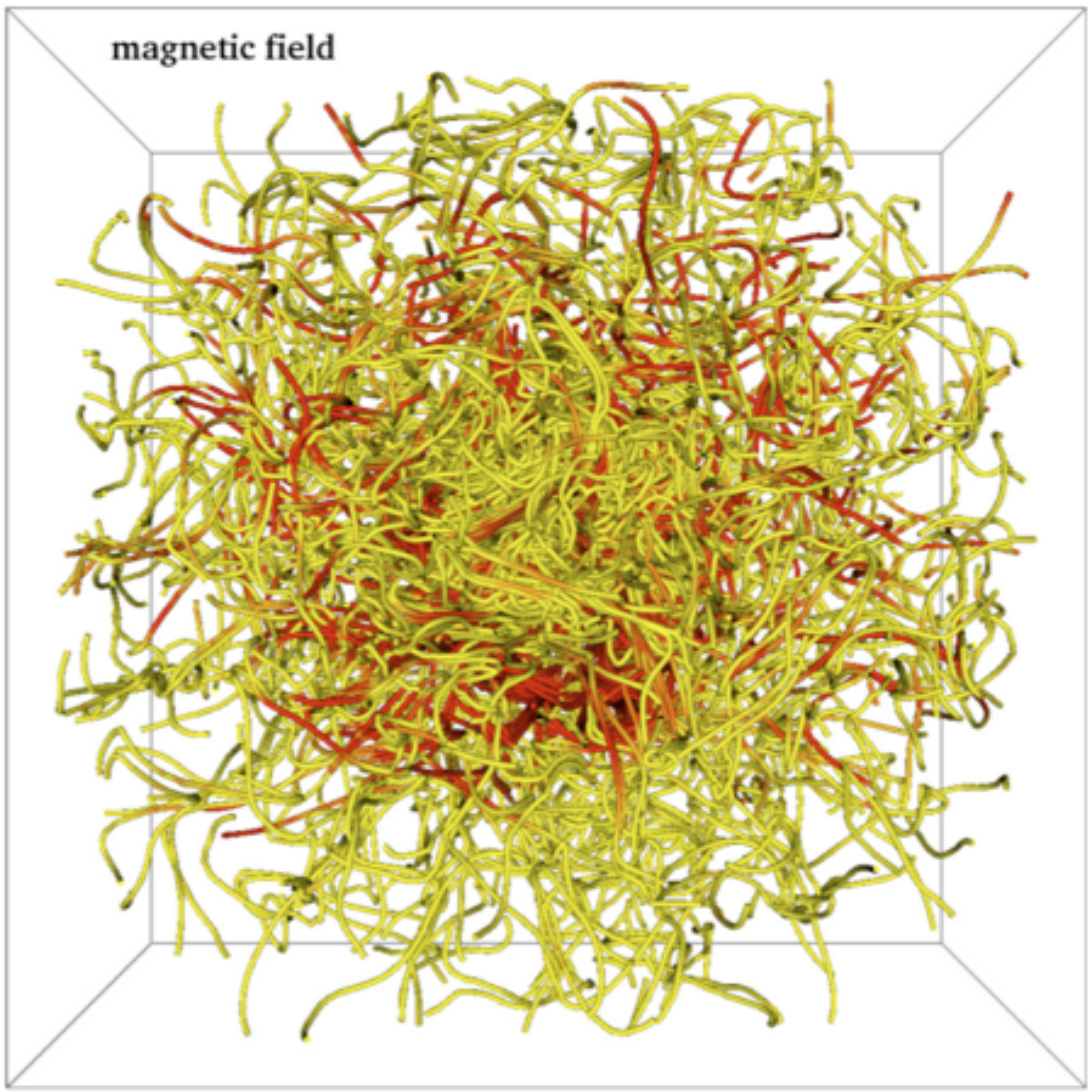
N_J: number of grid cells per local Jeans length;
realization with adaptive mesh refinement (AMR)

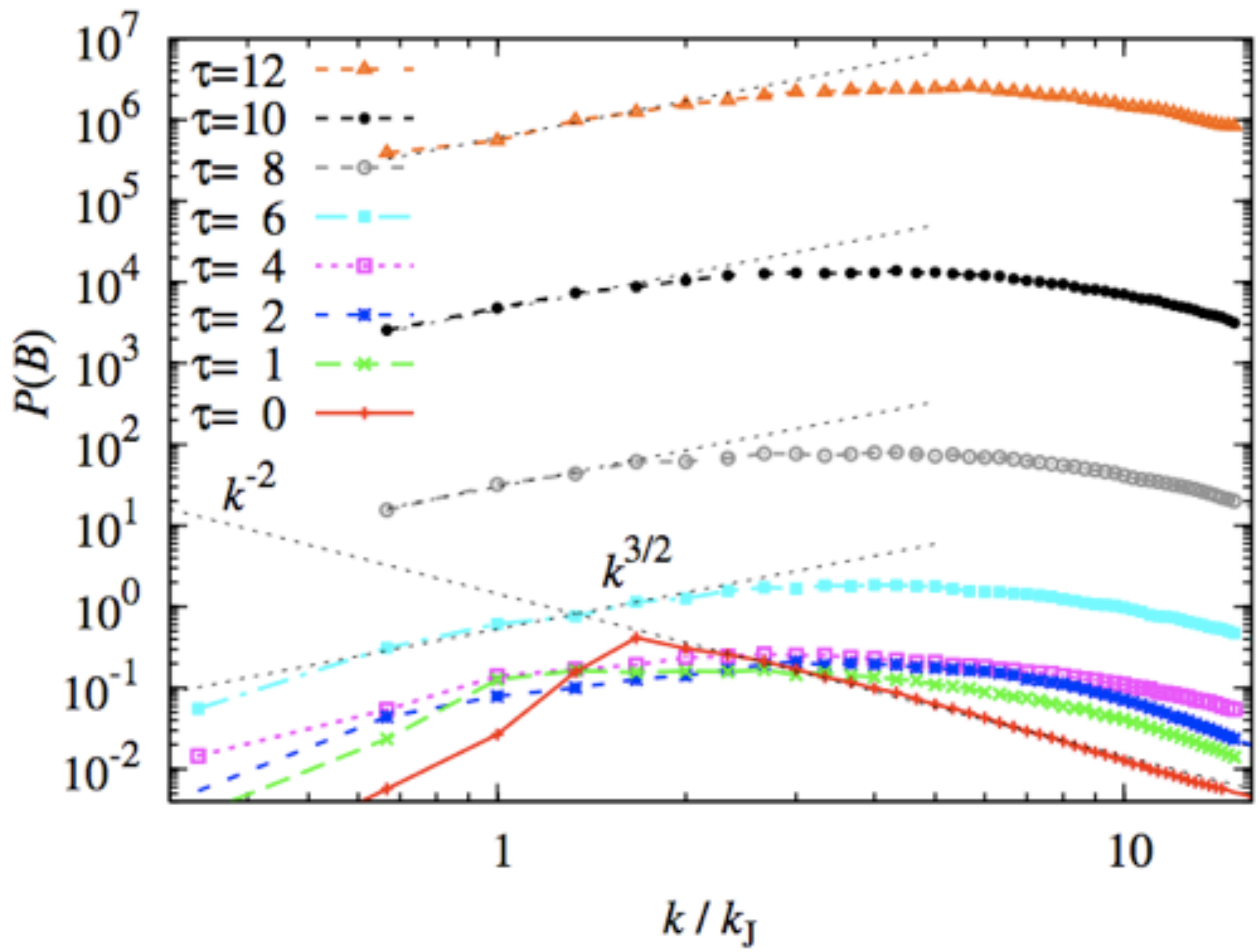
- minimum resolution: ~ 30 grid cells per Jeans length

Dynamo during "First Star Formation"

Magnetic field structure

Federrath et al.,2011





- spectra from numerical simulation follow Kazantsev theory

Summary

- **Primordial Magnetic Fields** undergo strong dynamic evolution (not only $B \propto a^{-2}$)

- damping in the turbulent regime where $v_A \sim v$
- frozen-in in the viscous regime

- turbulent dynamo: efficient amplification of weak fields

- strong fields ($\sim$ nG) change cosmic evolution

- Cluster/Galactic magnetic fields are of primordial origin?