Magnetogenesis from cosmic string loops

Diana Battefeld
Helsinki Institute of Physics

with

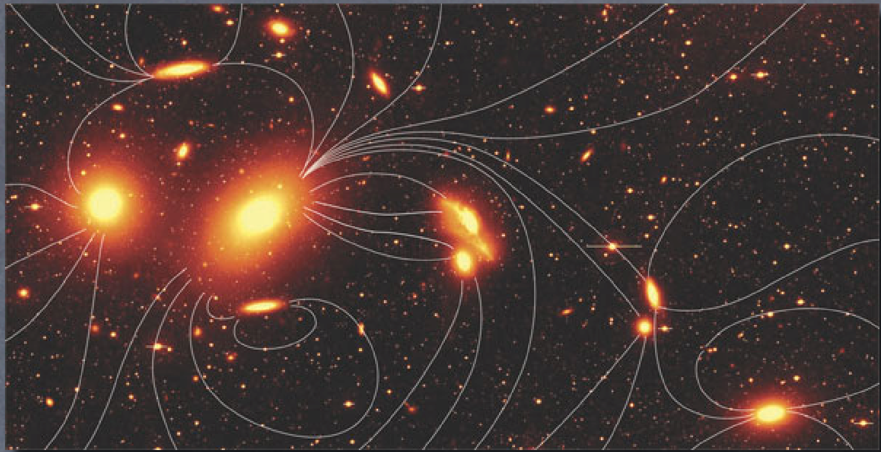
T. Battefeld (Princeton), M.Wyman (PI), D.Wesley (DAMTP)

arXiv:0708.2901, arXiv:0709.0735
(New Scientist, September 15th 2007 edition)

Outline

- Problem: How to explain large scale magnetic fields?
- Proposal: Loops in string networks cause vortices, which in turn cause magnetic seed fields.
- Predictions (implementing different network models and loop dynamics): magnetic field strength, coherence length, horizon coverage, ...

Observations



C.Mihos, P.Harding, J.Feldmeier, H.Morrison; field lines: P.Huey

- Magnetic fields in Galaxies today:

$$B_0 = 10^{-6}\,\mathrm{G}$$

Reviews: Giovannini 06; Widrow 03; Grasso, Rubinstein 01

On larger scales too, but focus on Galaxies in this talk

Proposed Explanations

Usually primordial seeds + dynamo

- Wakes in string networks (turbulence)
  Avelino, Shellard 95; Dimopoulos 98, Davis, Dimopoulos 05; ...
- Inverse cascade (or large scale avg.) after turbulence
  Brandenburg, Enqvist, Olesen 96; Cornwall 97; Son 99; Field ,Carroll 00; ...
- Second order perturbations, Riotto, Notari, et.al. 02; ...
- Phase transitions, Hogan 83; Quashnock, Loeb, Spergel 89; Vachaspati 91; ...
- During inflation (break conformal invariance)
  Turner, Widrow 88; ...

Problems

- Coherence length: hard to achieve by causal physics within the horizon (field strength: ok).
- On super-horizon sizes (seeded during inflation): magnetic fields are hard to produce (conformal invariance of EM) - weak field strength.

Common ingredient of many proposals:

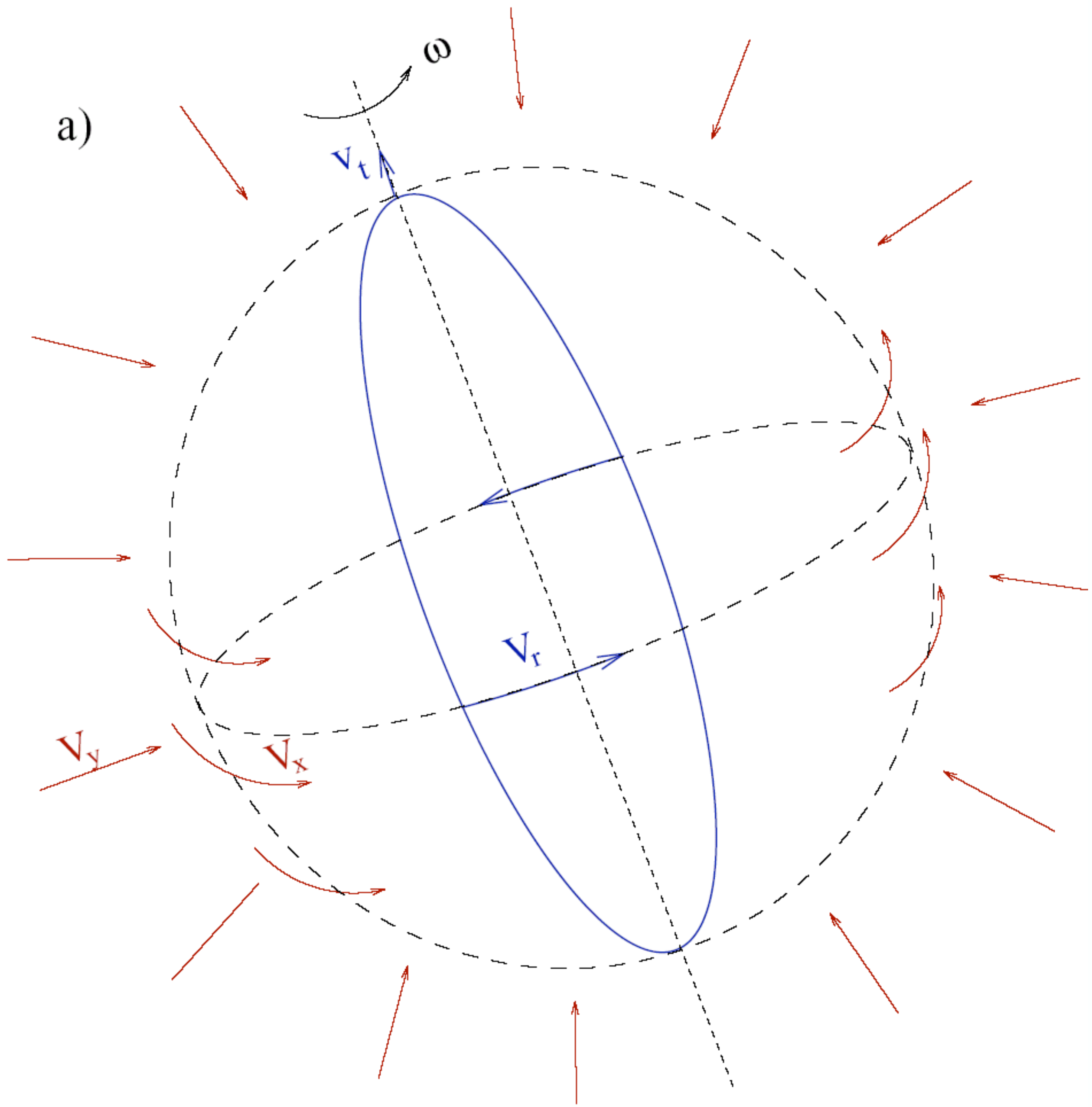
vortices causing magnetic fields (HR-mechanism).

Proposal

- Loop population in string networks causes vortices (gravitational dragging).
- HR mechanism gives rise to magnetic fields around time of decoupling, subsequent dynamo amplification.
- Coherence length: ideal for galaxies.
- Field strength: large enough if a strong dynamo is present in galaxies.

Creating Vortices

- String network: Long strings generate vorticity by dragging the plasma behind. Vachaspati, Vilenkin '91
- Rotating loop: a vortex is created as the infalling plasma accretes and drags the plasma behind it (flow is rotational).
- Not considered here: turbulent eddies (expected on small scales) – might enhance the following effects.


a)
ω
V t
V r
V y
V x

In-fall velocity

- Straight string
  Vachaspati, Vilenkin 91

$$v_y = \frac{2\pi G\lambda}{v_s\gamma_s} + 4\pi G\mu_0 v_s\gamma_s$$

effective mass per length
(average over wiggles)

$$\lambda = \mu - T$$

- Loop: non-relativistic limit, averaged over rotations

$$v_y \sim \frac{2\pi G\lambda}{v_t}$$

Dragging velocity

- Straight string
  Avelino, Shellard 95

$$v_x = \frac{v_y^2}{2v_s}$$

- Loops

$$v_x \approx \frac{v_y^2}{v_r}|\mathcal{C}_2| \sim \frac{v_y^2}{7\,v_r}$$

- Note: without turbulence, vortex is determined by the dragging velocity (not in-fall velocity).

Resulting Vorticity for loops

$$\omega_{pl} \sim \frac{v_x}{\ell} \sim \frac{v_y^2}{\ell v_r} \sim \frac{(2\pi)^2 \lambda^2 G^2}{7\,\ell v_t^2 v_r}$$

- Parameters depend on
  network model (OSM/VOS) and
  loop dynamics (emission of grav. waves,
  red-shifting, gravitational dragging)

Network Models

- One Scale Model (OSM)
  Caldwell, Allen 92;
  Hindmarsch, Kibble 94;
  Vilenkin, Shellard 00

- Velocity dependent One Scale model (VOS)
  Martins, Shellard 96 & 02;
  Tye, Wasserman, Wyman 05

In either model, loops are continuously produced (both models are considered in our numerical code).

Loop dynamics

- Size $$\ell(t) = f_r \alpha l_H(t_F) - \Gamma_l G\mu_0 (t - t_F)$$

Caldwell, Allen 92;
Allen, Casper 95, 96

- Translational velocity

$$\dot{\mathbf{v}}_t = -H\mathbf{v}_t - \frac{\mathbf{v}_t \ln \theta_{min}^{-1}}{t_*} + \frac{\Gamma_p G\mu_0}{\ell}\hat{\mathbf{n}}$$

$$t_* \equiv \frac{v_t^3 t^2}{C_1}, \quad C_1 = \frac{2}{3} G\ell\lambda$$

$$\ln \theta_{min}^{-1} \approx \ln\left(\frac{3v_t^3(t_F)t_F}{2G\lambda\ell}\right) = \text{const}$$

Vachaspati, Vilenkin 85

Chandrasekhar 43;
Silk, Vilenkin 84

Loop dynamics

- Rotational velocity

$$\tau_{gr} = -\ell G \mu_0^2 \Gamma_{gr}$$

$$\tau_{drag} \approx -\frac{(2\pi)^2}{7} \frac{G^2 \lambda^2}{v_r^2} \ell^3 \rho$$

$$\dot{J} = \frac{\lambda}{4\pi} \left(2\ell \dot{\ell} v_r + \ell^2 \dot{v}_r \right)$$

Durrer 89

- Eqns. can be solved approx. analytical, but we kept the full equations in the code.

Harrison-Rees Mechanism

Harrison 70;
Rees 87

- Vortex in plasma: Compton scattering of electrons on CMB photons slow them down.
- Current (carried by ions) builds up.
- Magnetic field is created:

Avelino, Shellard 95

$$B \approx 10^{-4}\omega_{pl}$$

Field evolution after creation of seed field:

- Seed field creation $B(z_F)$
- Redshifting (flux conservation) $$B(z) = \left(\frac{1+z}{1+z_F}\right)^2 B(z_F)$$
- Amplification during galaxy collapse $$\frac{B_i}{B_{gf}} \approx 8 \times 10^3$$ Review: Widrow 03
- Dynamo amplif. (large uncertainty in rate) $$\ln \frac{B_0}{B_i} = \Gamma_{dy} (t_f - t_i)$$

Ruzmaikin, Sokolov, Turchaninov 80

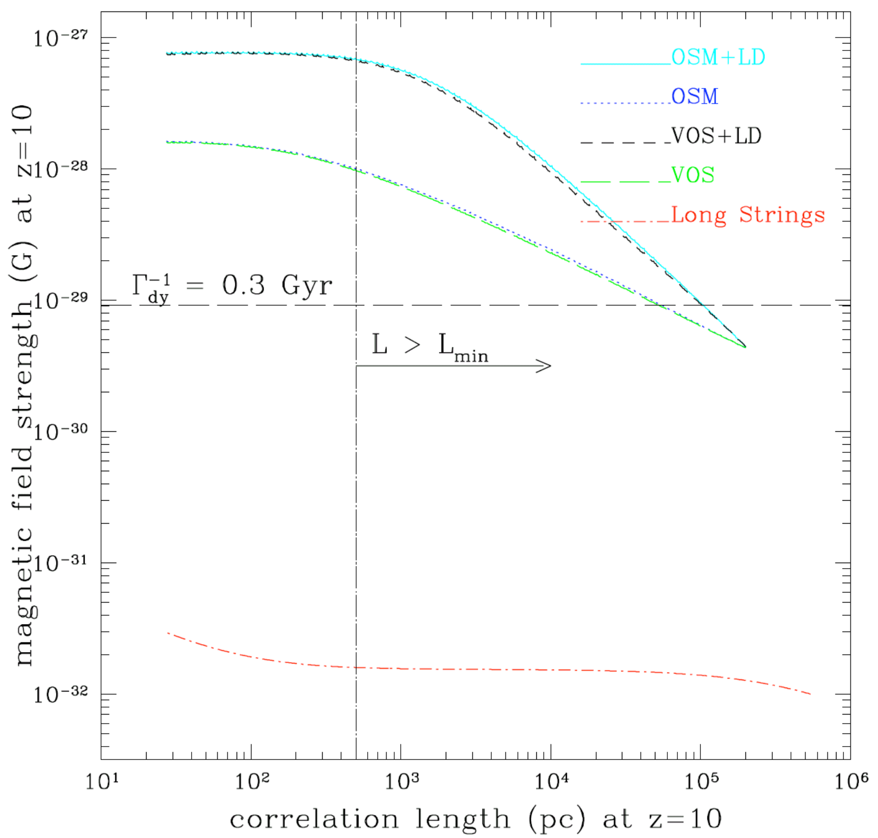
Numerical Results

- Plotted are: magnetic field strength, correlation length and horizon coverage.
- We vary: network model (VOS, OSM), w/wo loop dynamics, initial loop length, initial translational loop velocity, mass/length of strings.
- Canonical parameters if not varied:

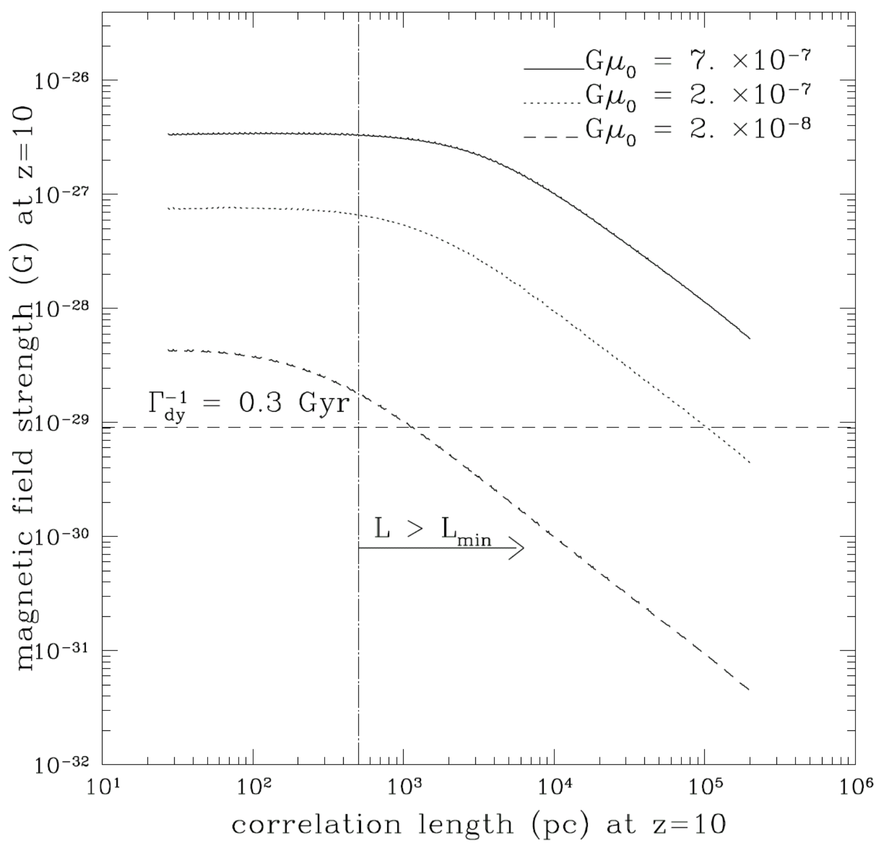
$$G\mu_0 = 2 \times 10^{-7} \quad \alpha = 0.01 \quad v_r \approx 0.4$$

$$v_t(t = t_F) = 0.1$$

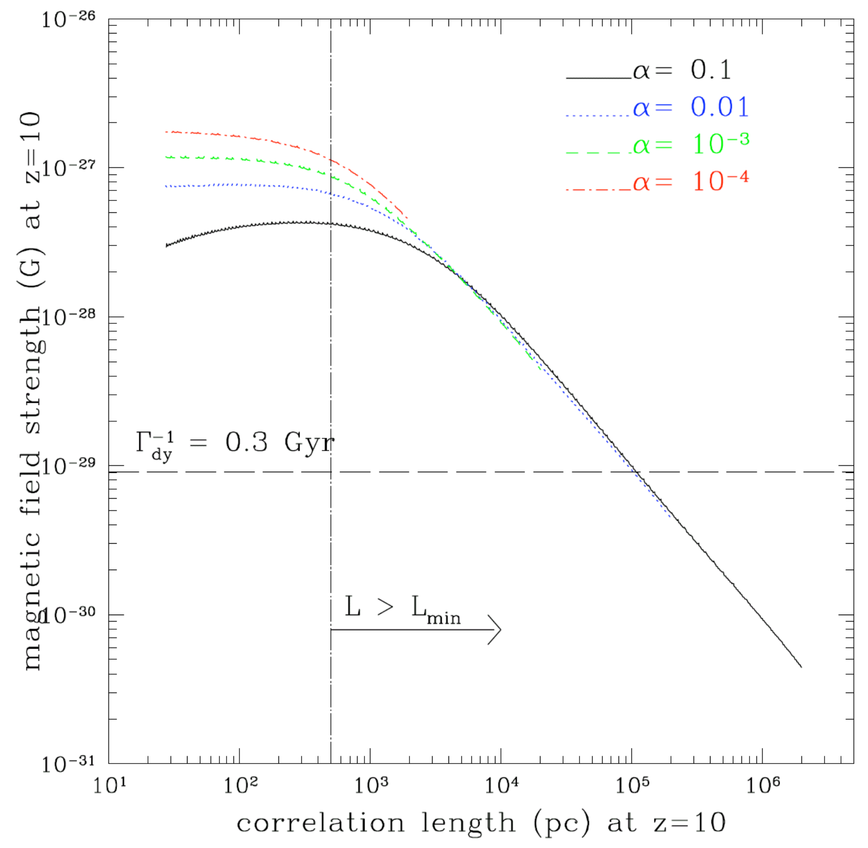
Network model and loop dynamics



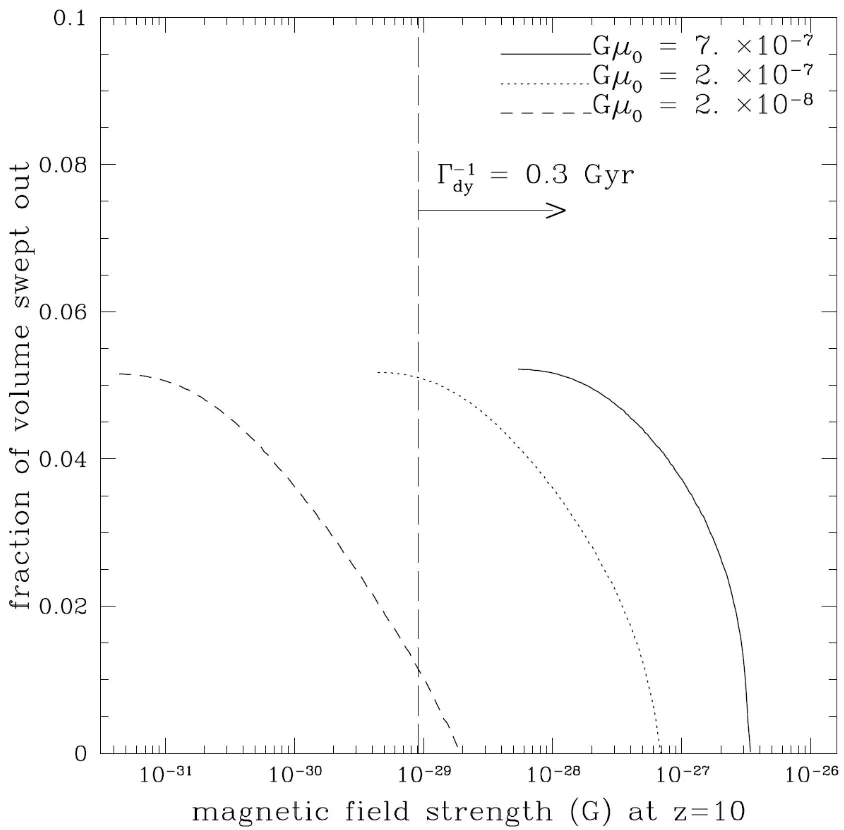
Mass density varied



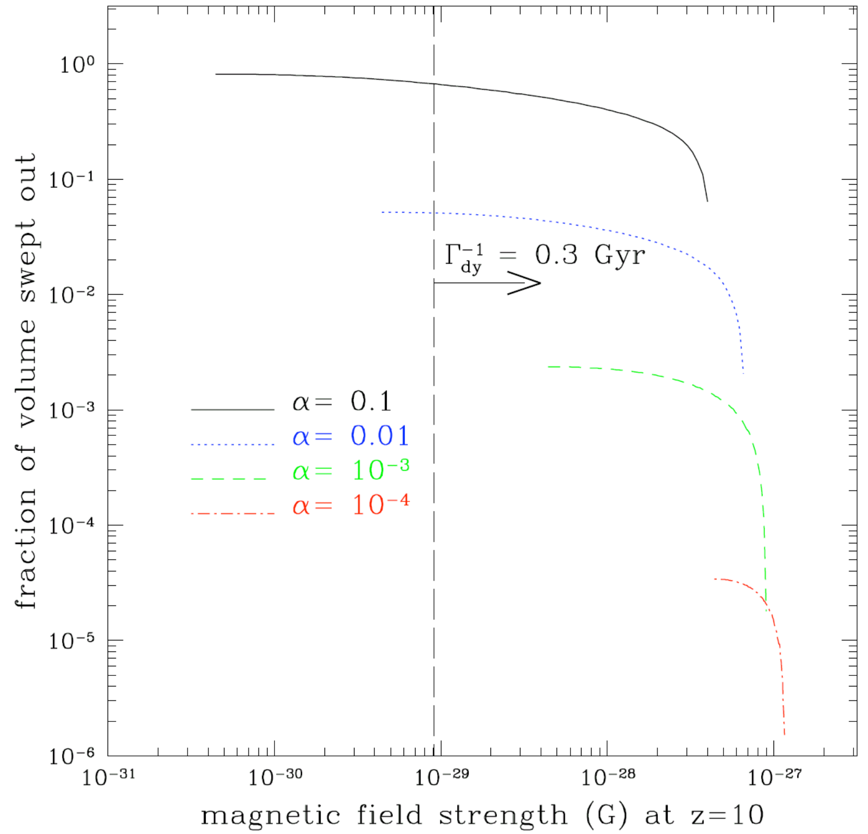
Initial loop size varied



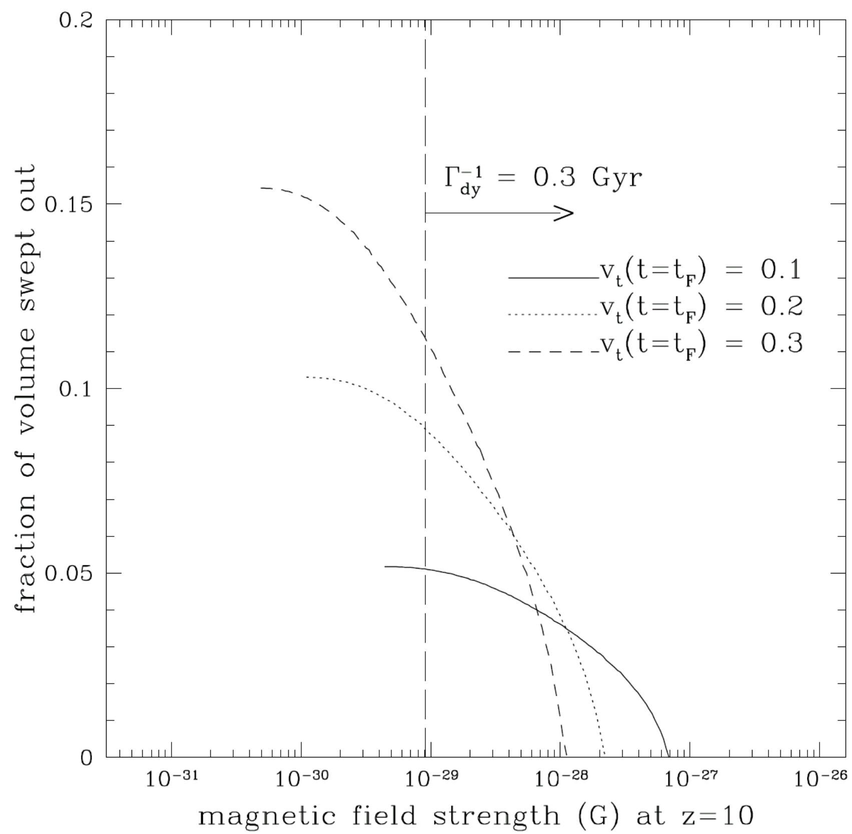
Mass density varied



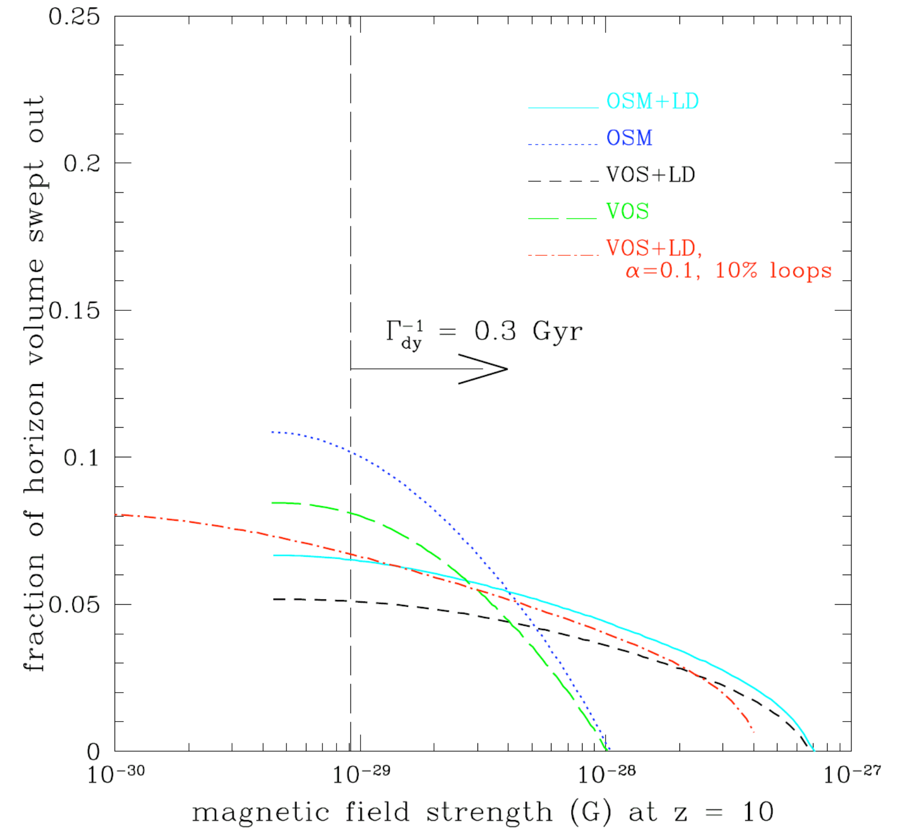
Initial loop size varied



Initial transl. vel. varied



Network model and loop dyn.



Conclusions

- Strong and coherent enough seed fields for spiral galaxies can be accounted for by considering vorticity behind rotating cosmic string loops.
- If dynamos are weaker than expected or the mass density of string decreases by a factor of 10 in future observations, our model is refuted.
- Caveat: vortices/fields could be further amplified by turbulent effects.
- Fields in clusters seem unattainable due to size and amplification barriers.