Magnetogenesis
from Rotating Cosmic String Loops

Or, can we get a μG from a Gμ?

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with
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arXiv:0708.2901 (astro-ph)
JCAP *accepted*

Magnetogenesis

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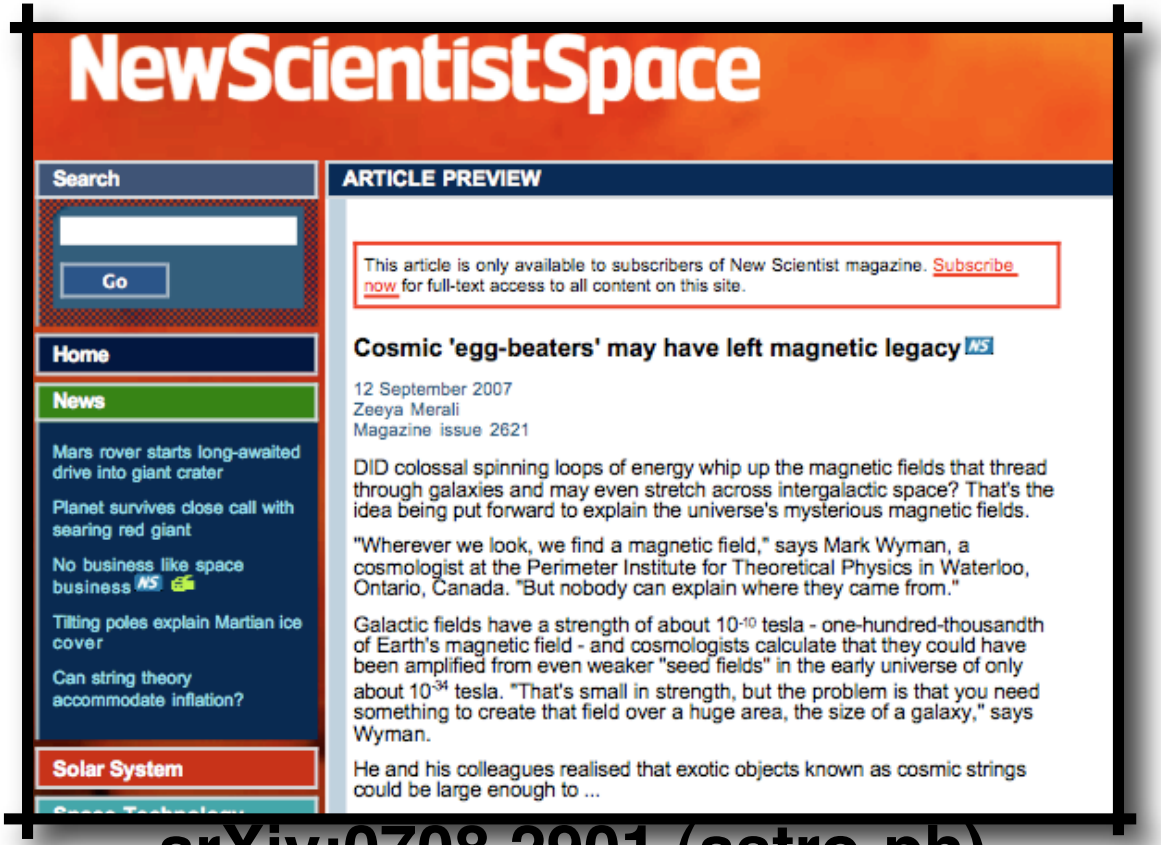

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Cosmic 'egg-beaters' may have left magnetic legacy

12 September 2007
Zeeya Merali
Magazine issue 2621

DID colossal spinning loops of energy whip up the magnetic fields that thread through galaxies and may even stretch across intergalactic space? That's the idea being put forward to explain the universe's mysterious magnetic fields.

"Wherever we look, we find a magnetic field," says Mark Wyman, a cosmologist at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada. "But nobody can explain where they came from."

Galactic fields have a strength of about 10^{-10} tesla - one-hundred-thousandth of Earth's magnetic field - and cosmologists calculate that they could have been amplified from even weaker "seed fields" in the early universe of only about 10^{-34} tesla. "That's small in strength, but the problem is that you need something to create that field over a huge area, the size of a galaxy," says Wyman.

He and his colleagues realised that exotic objects known as cosmic strings could be large enough to ...

arXiv:0708.2901 (astro-ph)

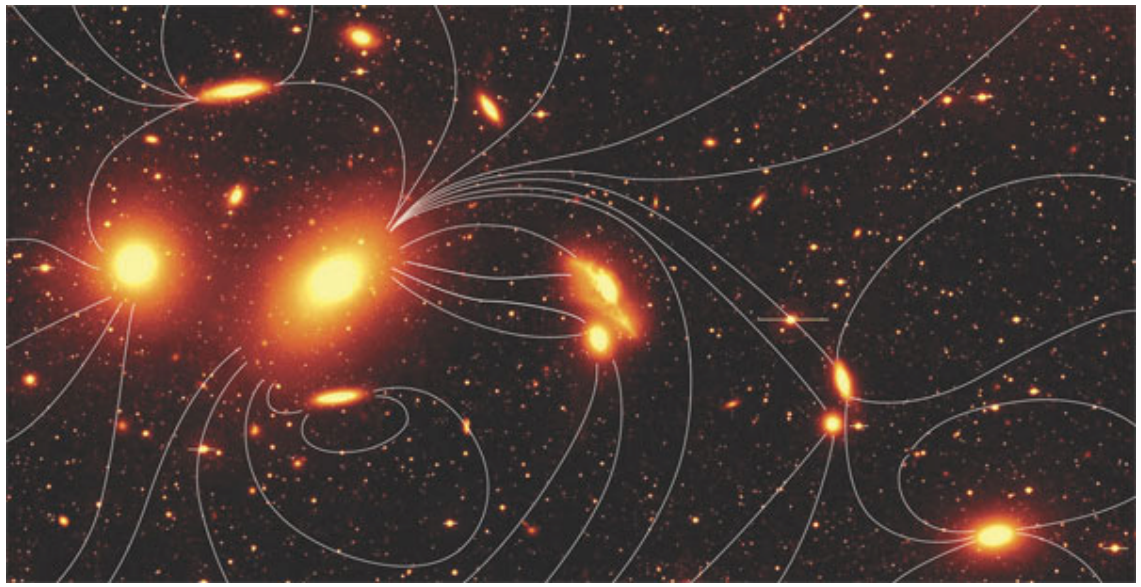
JCAP *accepted*

Plan

- Motivation: galactic and cluster magnetic fields exist today, origin unknown
- Paradigm: primordial *seed field*, dynamically *amplified*
- Competition: full-strength primordial field, produced by ...?
- Mechanism: rotating cosmic string loops

Reviews: M. Giovannini, arXiv:astro-ph/0612378.
D. Grasso and H. R. Rubinstein,
Phys. Rept. 348, 163 (2001) [arXiv:astro-ph/0009061].

Magnetic fields today



$$B_0 \sim 10^{-6}\mathrm{Gauss}$$

Present in clusters and galaxies. How do we know?

Reviews: M. Giovannini, arXiv:astro-ph/0612378.
D. Grasso and H. R. Rubinstein,
Phys. Rept. 348, 163 (2001) [arXiv:astro-ph/0009061].

MAGNETIC FIELD LINES: P. HUEY/*SCIENCE*

Synchrotron emission

- From relativistic electrons spiralling through a magnetic field
- Non-thermal polarised emission, depends on the energy spectrum of the electron population

$$W(B_\perp \nu) \sim n_0 B_\perp^{(1+\alpha)/2} \nu^{(1-\alpha)/2}$$

$$n_e(E)\mathrm{d}E = n_0 E^{-\alpha}\mathrm{d}E$$

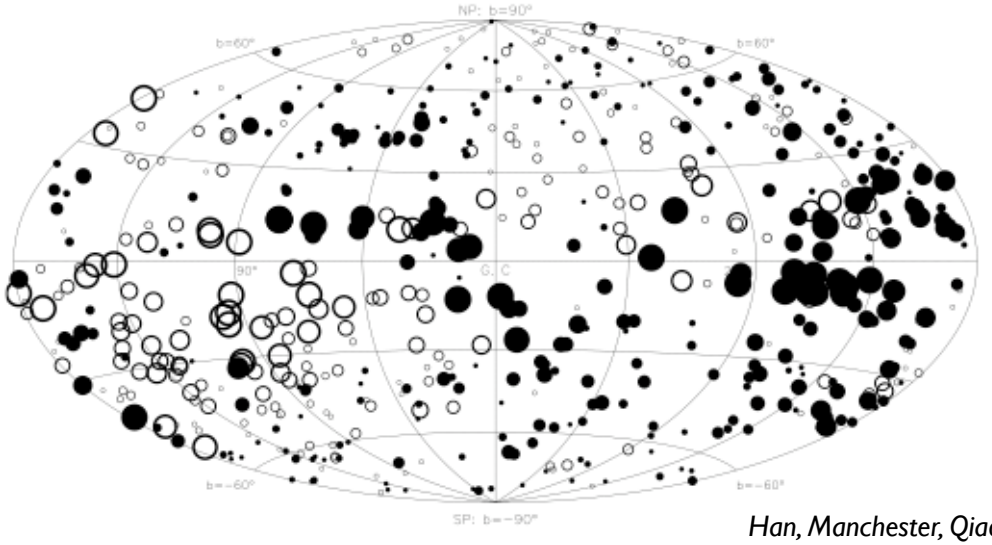
- Can be observed in galaxies beyond the Milky Way
- Depends on a combination of
  - field strength
  - electron density

so to measure the field strength requires a model or independent measurement of the electron density

Faraday rotation

$$\mathrm{RM} = \frac{\Delta\theta}{\Delta\lambda^2} = 811.9 \int \left(\frac{n_e}{\mathrm{cm}^{-3}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\frac{\mathrm{d}\ell}{\mathrm{kpc}}$$

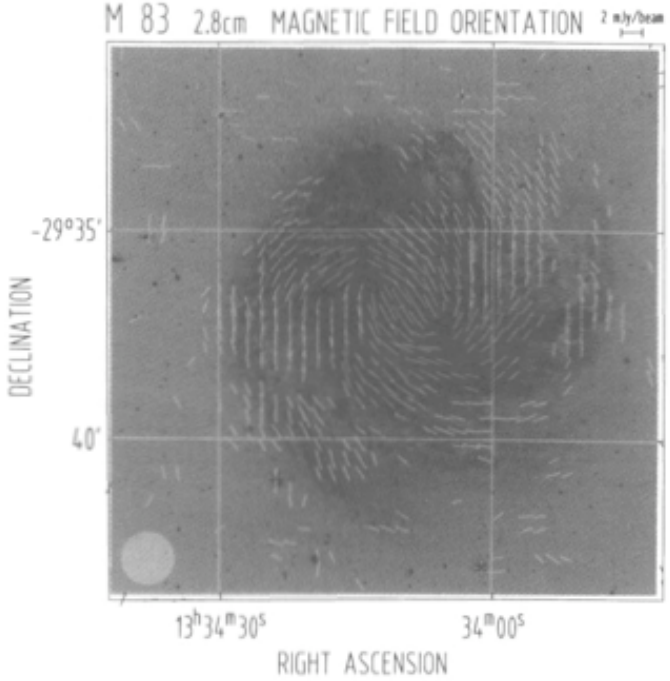
- Polarization rotates when going through plasma with magnetic field
- Rotation depends on wavelength so can be separated
- Also a combination of *B* and n_e, but in the galaxy pulsar dispersion measures can be used to independently measure n_e



Han, Manchester, Qiao. MNRAS ***306*** *(1999) 371*

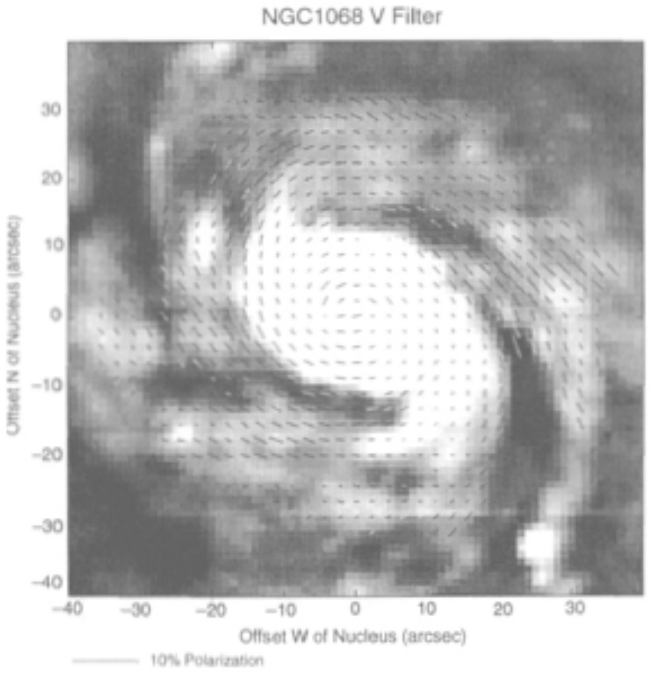
Polarized dust emission

Nonspherical dust grains align themselves with the prevailing magnetic field, and introduce polarization into scattered light



M83
2.8cm
(sync)

Neininger, Klein, Beck Wielebinski,. Nature ***352*** *(1991) 781*



NGC 1068
optical
(dust)

Scarrott, in: Kronberg,. Rept. Prog. Phys ***57*** *(1994) 163*

Dynamo or Primordial?

The primordial option

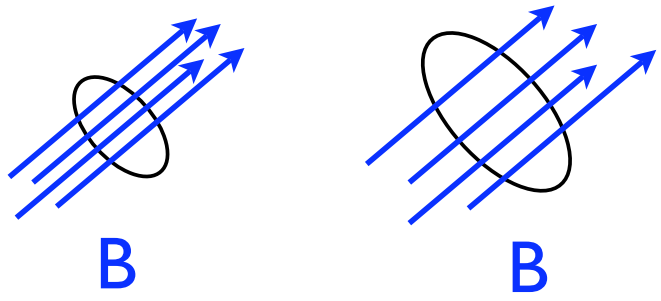
Primordial fields of the appropriate strength are present when galaxies form, then are compressed and strengthened during the galaxy formation process.

The dynamo option

Very small *seed fields* are present when galaxies form. These fields are amplified by a dynamo which operates thanks to the rotation of the galaxy.

Primordial *vs.* Dynamo

Primordial mechanism Initial fields diluted then strengthened as dictated by flux conservation $B \sim 1/a^2$



Dynamo Combination of small-scale turbulence and rotational motion amplifies field exponentially within galaxies

$$\alpha = \frac{1}{3}\tau\langle \mathbf{v}_T \cdot (\nabla \times \mathbf{v}_T)\rangle$$

$$\frac{\partial \mathbf{B}}{\partial t} = \alpha \nabla \times \mathbf{B} + \eta \nabla^2 \mathbf{B}$$

$$\mathbf{B} = (\sin kz, \cos kz, 0) e^{\gamma t}$$

The case *against* the dynamo

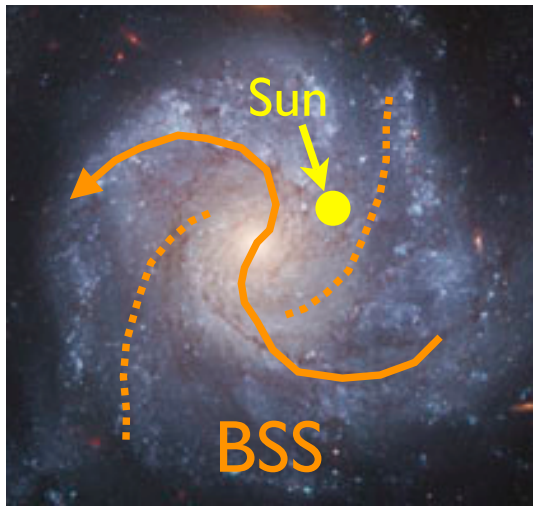
Claim: magnetic fields of the appropriate strength are already present and compressed during galaxy formation

pro-primordial

- The required seed fields (adibatically scaled to *z=0*) are roughly B ~ 10^{-10} G. Allowed by constraints.
- Rotation wraps the field into a symmetric spiral with field reversals
- This bisymmetric spiral (BSS) pattern they would produce is consistent with Milky Way observations.

anti-dynamo

- Dynamos amplify small-scale irregularities which may grow and quench the dynamo before it achieves sufficient amplification



The case *for* the dynamo

Idea: tiny seed fields are present and are amplified by a dynamo powered by galactic rotation

pro-dynamo

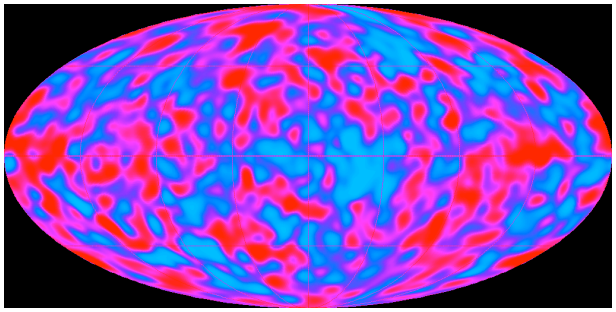
- Predicts equipartition of magnetic energy density and turbulence (Milky Way)
- Comfortably avoids constraints on primordial fields (*more on this*...)
- Accommodates polodial component of field (Milky Way)
- Predicts axisymmetric spiral, observed in some galaxies, but likely not ours.

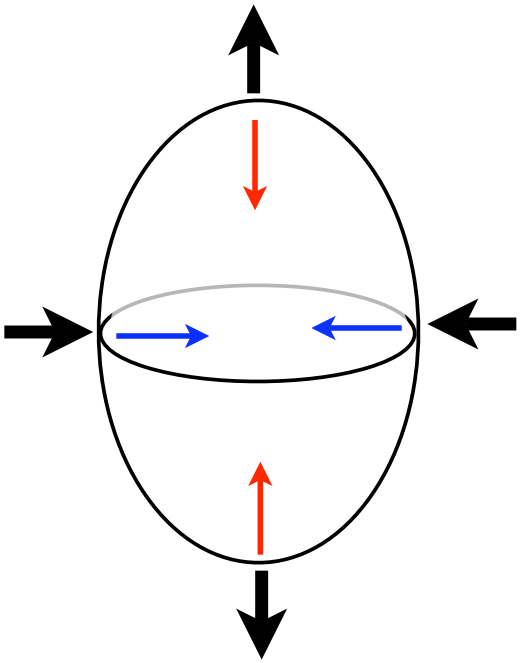
anti-primordial

- Primordial origin fields would modify structure formation significantly
- Where do the large primordial fields come from ??? (*more on this*...)

CMB constraints on homogeneous fields

- Homogeneous field anisotropically distorts the Hubble flow near decoupling
- Zeldovich and Novikov (1983) showed homogeneous field of $B_0 \sim 10^{-10}$-10^{-9} G (today) would produce temperature anisotropy of 10^{-6}
- Updated by Barrow *et al.*, (1997) showed COBE constrains $B_0 < 3.5 \times 10^{-9}$ G





Whence primordial fields?

Magnetogenesis requires vector perturbations,
but a universal homogeneous would have to come
from Inflation -- which (typically) has no vector part!

Vector perturbations = a “preferred direction”

GR drives vectors down

Any vector perturbation can be written using vector harmonics

$$Q^i{}_{|i} = 0 \qquad Q_{ij} = Q_{i|j} + Q_{j|i}$$

$$\delta T_{0i} = (\rho + P)(v - B)Q_i$$
$$\delta T_{ij} = \pi_T Q_{ij}$$

$$\delta g_{\mu\nu} = \begin{pmatrix} 0 & BQ_i \\ BQ_j & H_T Q_{ij} \end{pmatrix}$$

In comoving gauge $v - B = 0$

$$kB = \dot{H}_T$$
$$\dot{B} + 2\frac{\dot{a}}{a}B = 0 \quad \Rightarrow \quad B \sim 1/a^2$$

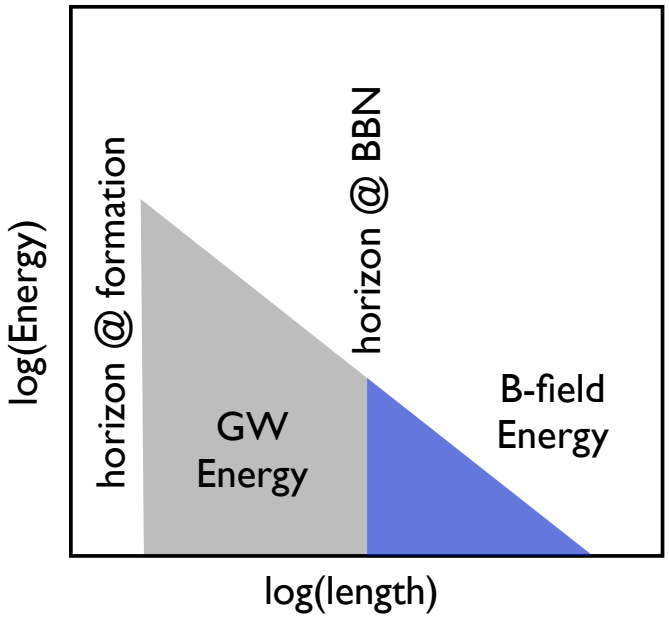
Bardeen PRD ***22*** *(1980) 1882*

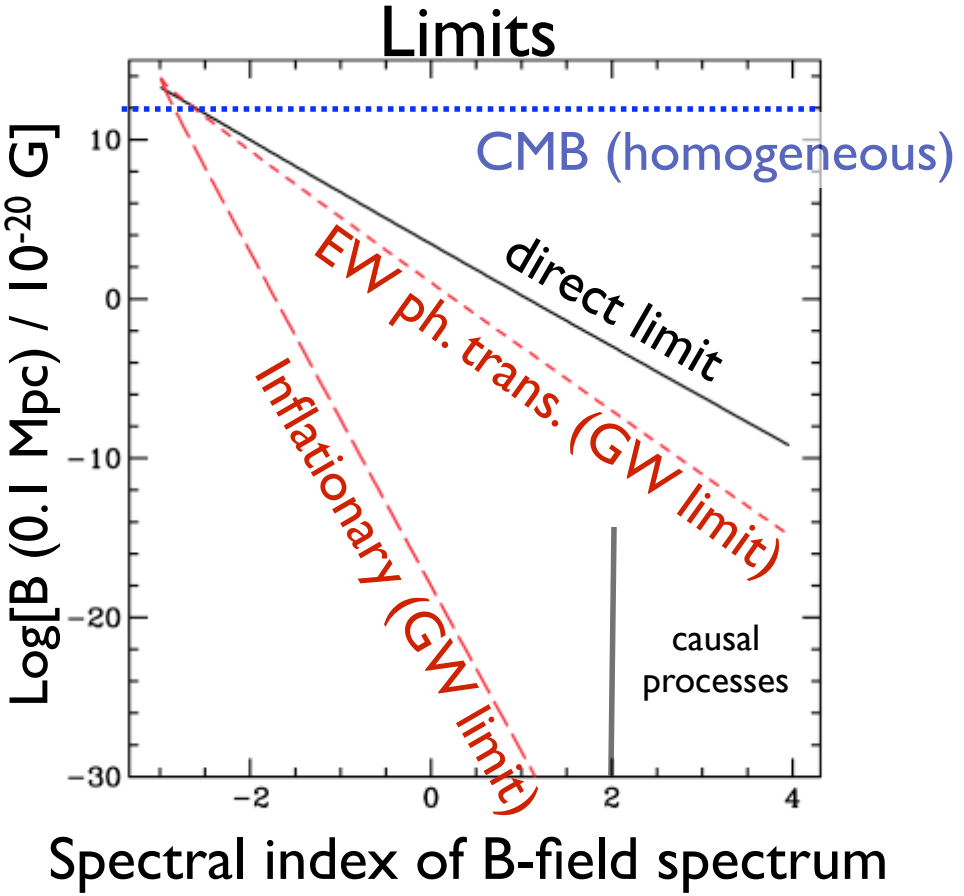
Stochastic fields from inflation and PTs

- **Electroweak phase transition T_{EW} ~ 100 GeV**
  - From 1st order bubble collisions (2nd order PT in standard model) $B_{Galaxy} \sim 10^{-20}$ - 10^{-17} G -- *Dynamo still needed*
- **QCD phase transition T_{QCD} ~ 150 MeV**
  - Electric field must form behind bubble shocks, and equation of state must be different to create pressure gradient. $B_{Galaxy} \sim 10^{-20}$ G -- *Dynamo still needed*
- **Inhomogeneous Higgs background during EWSB**
- **Heavily Modified Inflation**

BBN limits on early stochastic fields

- Too much B-field messes up BBN directly, by changing cosmology
- If B-fields source gravity waves, limits are even stricter!





Caprini, Durrer PRD ***72*** *(2005) 088301*
Caprini, Durrer PRD ***65*** *(2001) 023517*

A puzzle

- Homogeneous fields *could* work, experimentally: constraints are weak ...
- ... but *how can they be produced*? Standard inflationary models predict extremely small vector perturbations, and modified models are unsuccessful / run into Durrer bound

- Causal non-inflationary mechanisms (e.g. phase transitions) might produce a stochastic magnetic field background with some spectrum as a function of scale.
- Short correlation length of such early fields is a problem
- If produced before BBN, strength is strongly bound!

Optimal magnetogenesis mechanism

- Occur after BBN (and phase transitions)
- Operates at nearly horizon-sized length scales
- Must generate vector-type perturbations

Cosmic string network is a natural candidate

- Cosmic strings generate vector perturbations due to motion through primordial plasma
- They stretch across the horizon and can produce effects on large length scales.
- They avoid constraints on stochastic fields, and will make fields with a well defined spectrum.

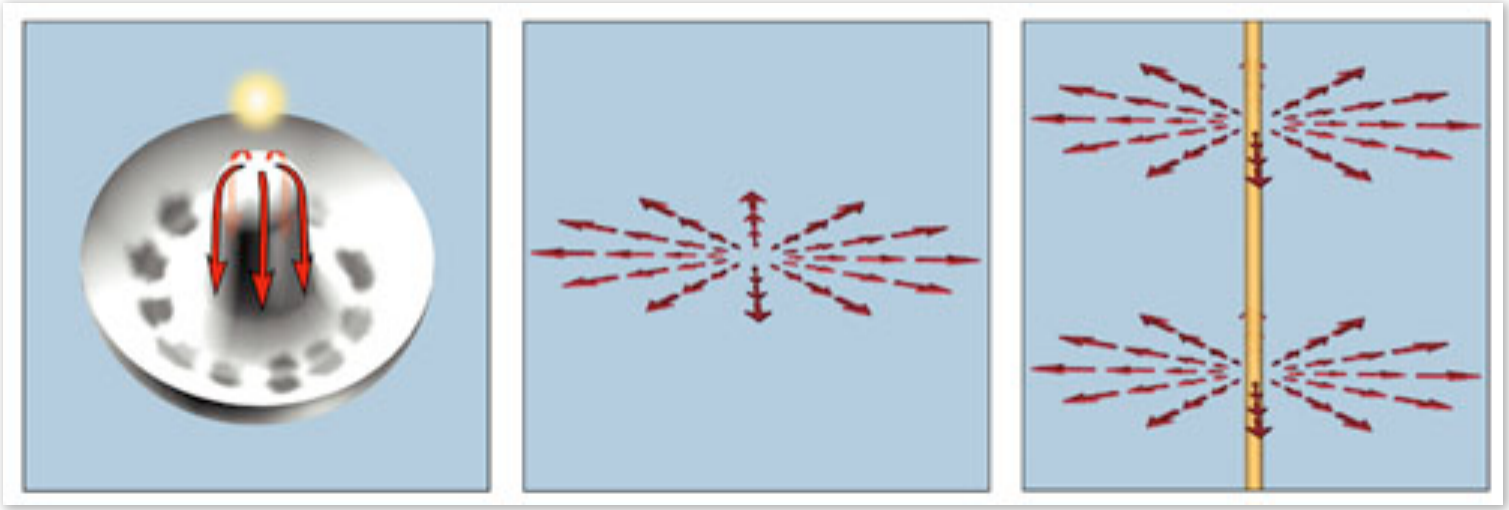
? Why cosmic strings?

? How do strings make magnetic fields?

Cosmic strings: what are they?

Kibble mechanism for defect formation:

Regions larger than H^{-1} are out of causal contact!

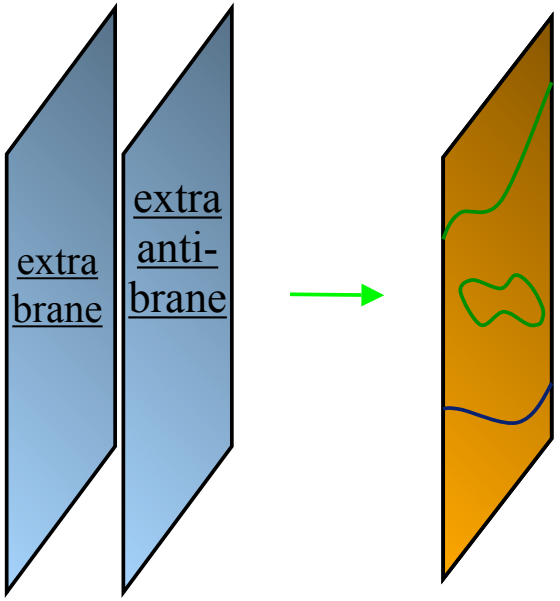


Cosmic string defect for U(1) symmetry

(Fig. From Gangui)

Brane inflation: New source for cosmic strings

(Tye and Sarangi 2002, Jones, Stoica, and Tye 2002, Copeland, Myers, and Polchinski 2004)

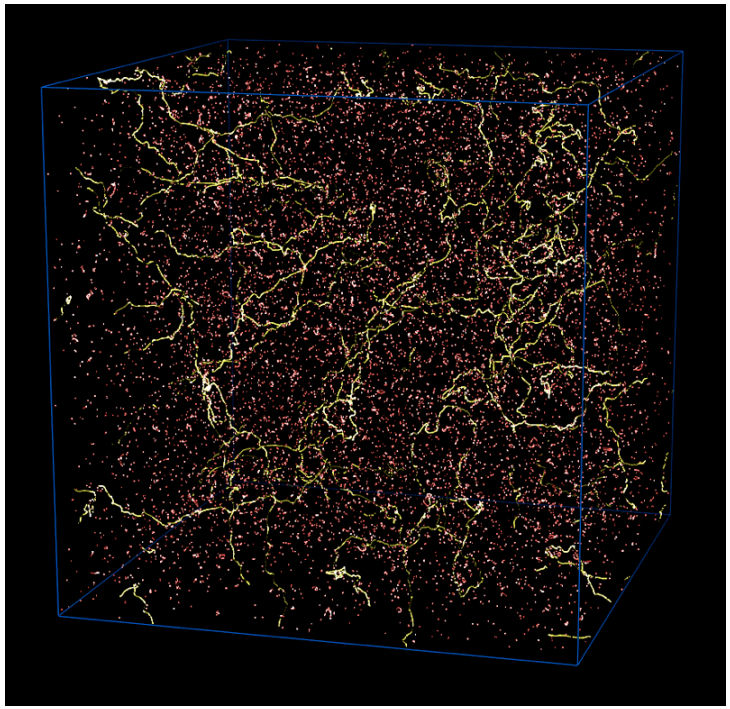


- Annihilation of inflating branes can produce strings (actual 1-D objects *or* "wrapped" higher-D objects)
- Predicts: few x $10^{-7} > G\mu > 10^{-11}$
- caveat: possible stability problems
- Not ruled out; potentially detectable

Cosmic string networks

- Cosmic string networks are typically simulated on very large computers
- Approximate as Nambu-Goto strings, or (less frequently) as "field theoretic" strings
- For Nambu-Goto strings the network contains both long strings and loops
- Key finding: during all epochs,

$$\Omega_{strings} \sim G\mu$$



String network during RD
(B. Allen and E. P. Shellard)

Scaling solution: the VOS model

- One length scale, the network correlation length L ($\sim L_H$)
- one velocity scale, v
- c_1 chopping efficiency
- c_2 momentum parameter (acceleration due to string curvature)
- Produce loops according to energy conservation

$$\rho_\infty = \frac{\mu}{L^2}$$

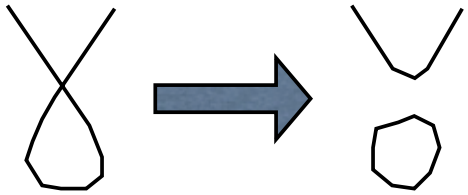
$$\frac{\mathrm{d}L}{\mathrm{d}t} = HL + c_1 v$$

$$\frac{1}{1-v^2}\frac{\mathrm{d}v}{\mathrm{d}t} = -2Hv + \frac{c_2}{L}$$

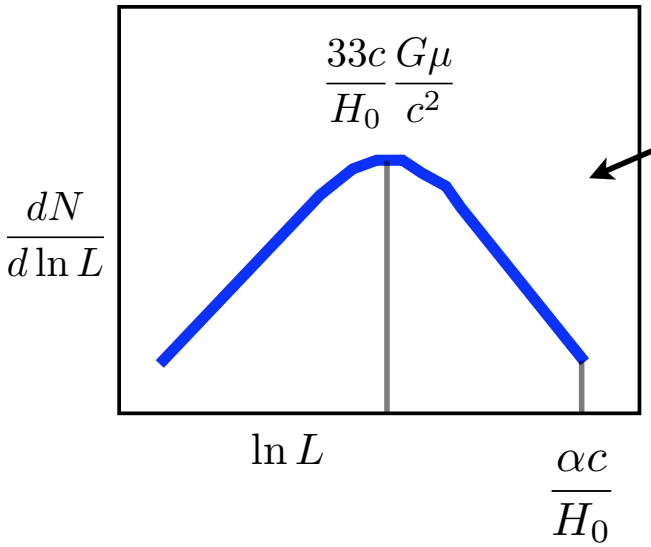
*C. J. A. P. Martins, E. P. Shellard PRD **65** (2002) 043514*
*C. J. A. P. Martins, E. P. Shellard PRD **54** (1996) 2535*

Loop production

- Lost network energy goes into loops
- *Assume* that loops are all formed at a fixed fraction of the horizon length
- Loops decay by emission of gravitational radiation



$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = -\Gamma_\ell G\mu$$

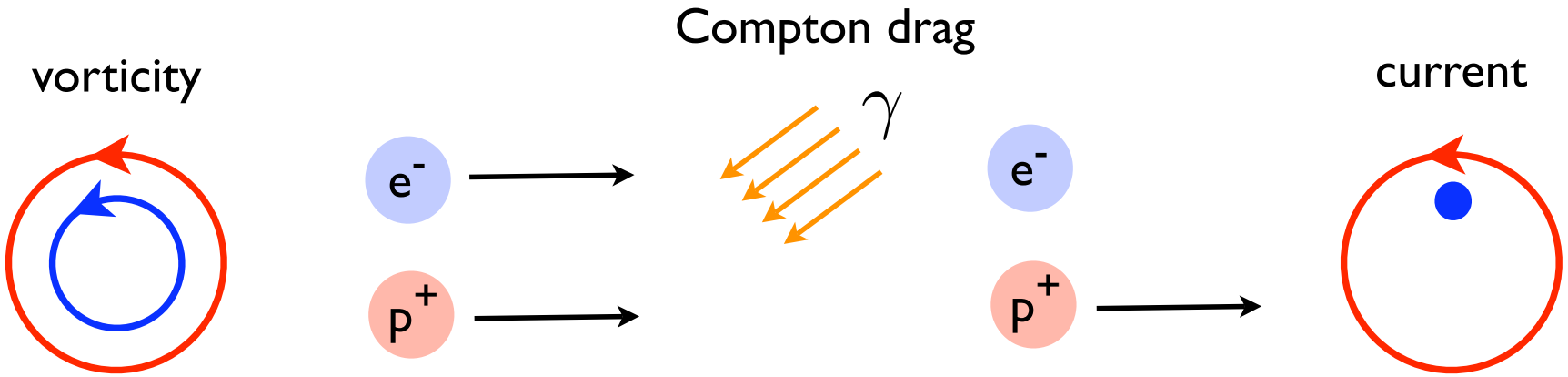


- Single creation scale + steady decay = a characteristic peaked length spectrum
- Two parameters: the string tension μ and the new loop creation length α

Magnetogenesis Mechanism

Harrison-Rees magnetogenesis

Converts plasma vorticity into magnetic fields



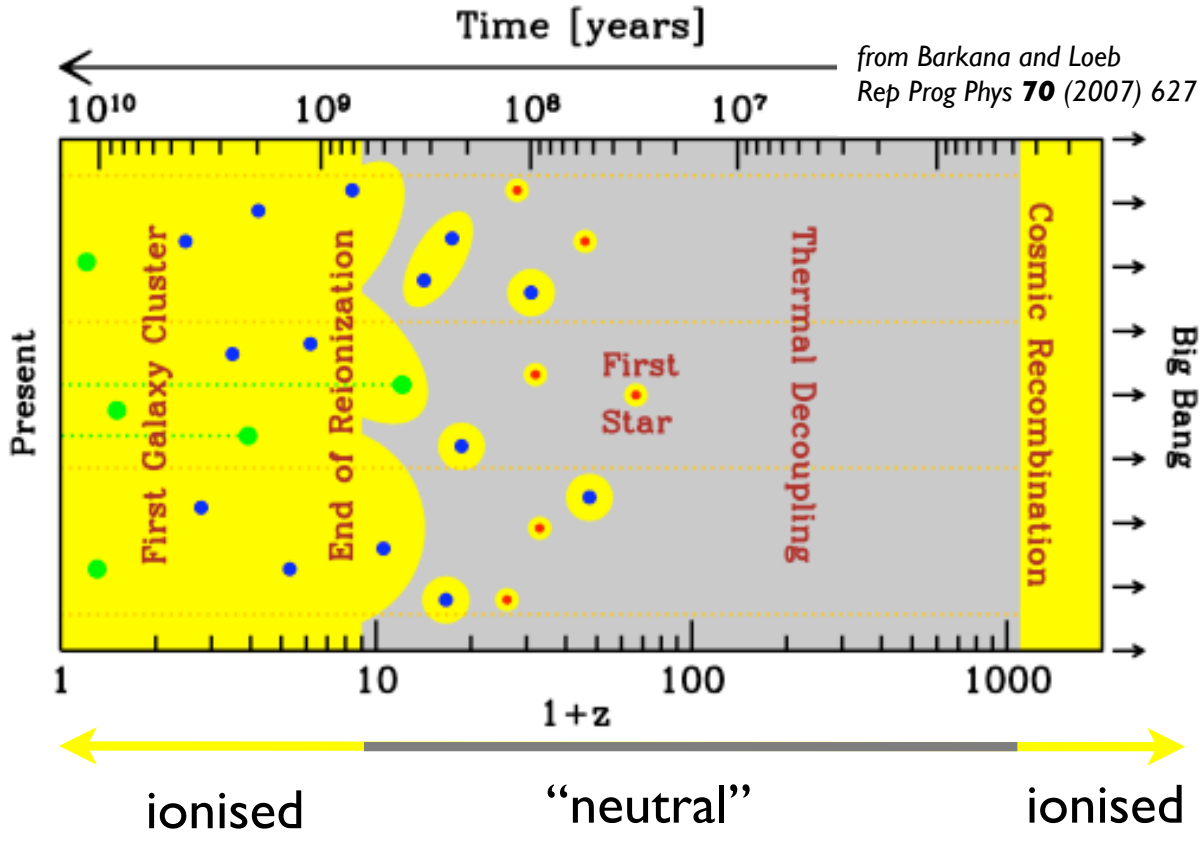
Any vorticity is converted into a circulating current and thus into a B field

$$B = \frac{2m}{e}\omega_{pl} \approx 10^{-4}\omega_{pl}$$

Requirements: {
- Universe ionised
- Compton scattering efficient

Harrison MNRAS ***147*** *(1970) 279*
Rees Q Jl R Ast. Soc. ***28*** *(1987) 197*

Ionization history



from Barkana and Loeb
Rep Prog Phys ***70*** *(2007) 627*

These conditions are met before the decoupling of the CMB at z ~ 1000

Predicting fields from the string network

Three steps:

1. Determine population of long strings and loops

2. Find vorticity and magnetic field created by a single string or loop

3. Evolve forward (adiabatically) until galaxy formation epoch

Predicting fields from the string network

Three steps:

Already discussed

1. **Determine population of long strings and loops**

2. Find vorticity and magnetic field created by a single string or loop

3. Evolve forward (adiabatically) to galaxy formation epoch

Predicting fields from the string network

Three steps:

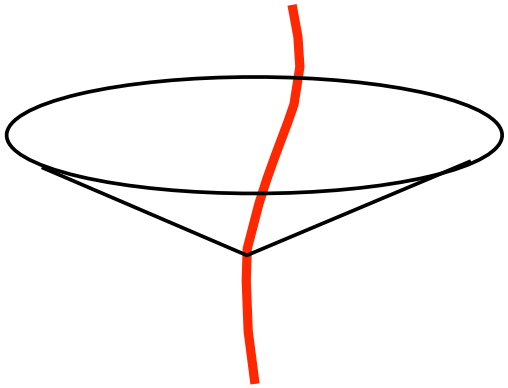
1. Determine population of long strings and loops

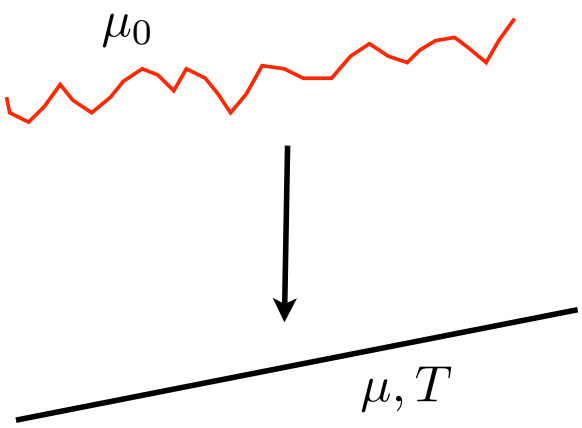
2. **Find vorticity and magnetic field created by long strings or loops**

3. Evolve forward (adiabatically) to galaxy formation epoch

Forces from long strings

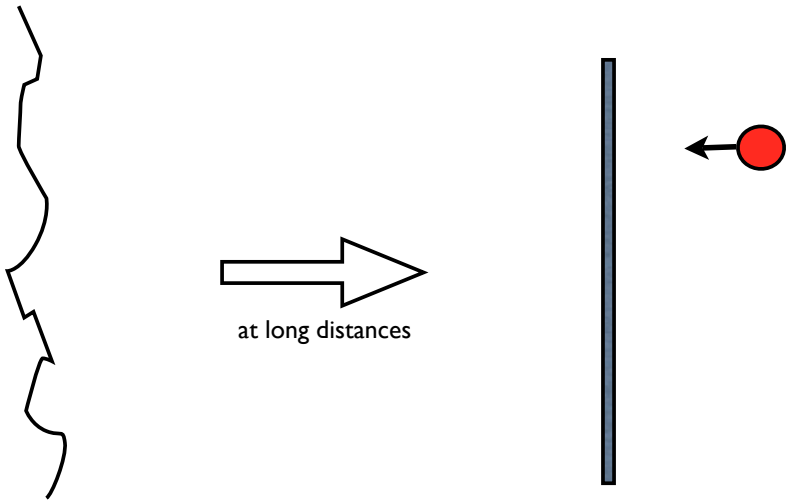
- Straight cosmic strings create a conical defect spacetime
- This spacetime is Riemann flat and so there are no forces on test particles





- Strings are wiggly and wiggles carry energy
- Averaging over wiggles creates a *Newtonian* potential around string

String Gravity



wiggly string

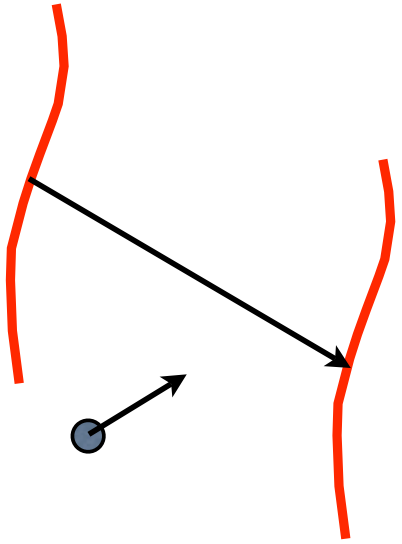
Newtonian rod

effective potential

$$\lambda = \mu - T = \mu(1 - \mu_0^2/\mu^2)$$

effective mass/length — tension — "bare" mass/length

Forces on test particles



Newtonian impulse

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

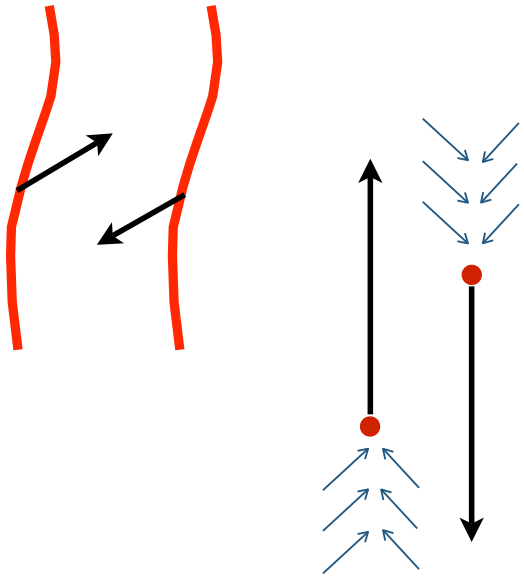
Conical defect

$$\lambda = \mu - T$$

$$\mu T = \mu_0^2$$

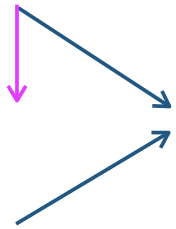
A string passing by a test particle imparts an impulse which arises from a mixture of an effective Newtonian force and the conical defect effect.

Vorticity from long-string encounter



- A single string wake cannot create appreciable vorticity, but a *two-string encounter* can
- Early estimates took the full wake velocity as the vorticity-velocity

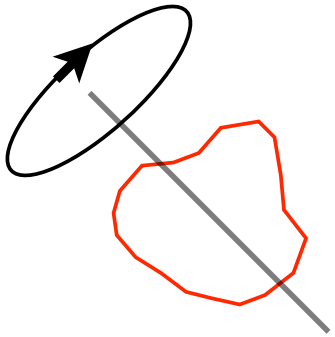
- This corresponds to all of the work done by drag going into plasma rotation
- Better estimate: the rotational velocity is set by the drag velocity



$$\omega_{pl} = \frac{(2\pi)^2 \lambda^2 G^2}{2 R_s v_s^3}$$

*Avelino, Shellard PRD **51** (1996) 5946*
*Dimopoulos PRD **57** (1998) 4629*
*Davis, Dimopoulos PRD **72** (2005) 043517*
*Vachaspati, Vilenkin Phys Rev Lett **67** (1992) 1057*
*Vachaspati PRD **45** (1992) 3487*

Vorticity from loops



- String loops around too -- $\Omega_{loops} \sim \sqrt{G\mu}$
- Loops *spin* and *translate* through the plasma.
- Spinning loops lead to rotating, vortical plasma flows

- Vortical length scale & strength set by:
  - loop size
  - translational velocity
  - rotational velocity

$$\omega_{pl} = \frac{(2\pi)^2 \lambda^2 G^2}{7 \ell v_t^2 v_r}$$

Loop dynamics

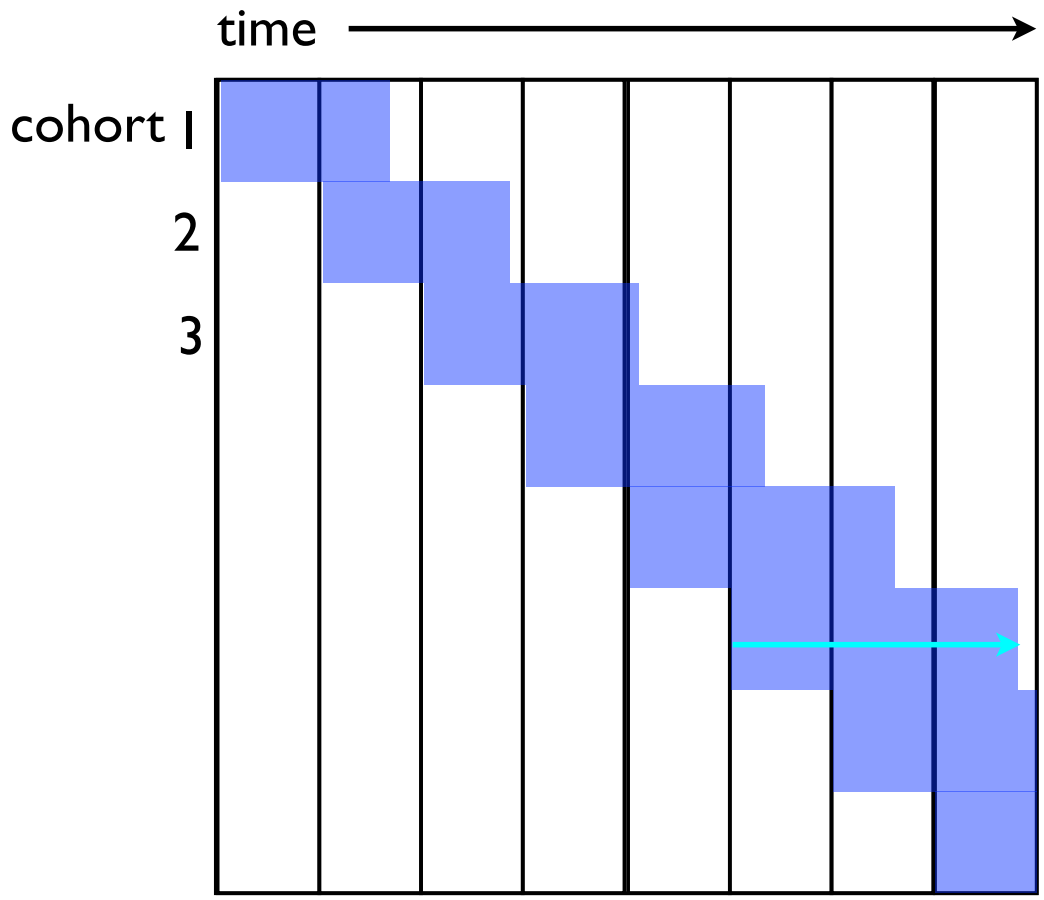
- Forces on loops:
  - Redshifting from Hubble expansion
  - Dynamical friction (drag from the plasma)
  - Preferential emission of gravitational radiation -- the "rocket effect" speeds 'em up

$$\frac{\mathrm{d}v}{\mathrm{d}t} = -Hv - v\frac{\ln\theta_{min}^{-1}}{t_*} + \frac{\Gamma_p G\mu_0}{\ell}$$

- Torques on loops:
  - Effective torque from loop shrinkage by GW emission
  - Dynamical torques (drag from the plasma)
  - Emission of gravitational radiation

$$\frac{\mathrm{d}v_r}{\mathrm{d}t} = \frac{2G\Gamma_\ell\mu_0 v_r - C_{gr}}{\ell_0 - G\Gamma_\ell\mu_0(t - t_F)}$$

Computing vorticity from the network



All loops created during a given time period are binned, and their properties evolved according to the dyn. eqs.

During the cohort lifetime it creates vorticity on different length scales as the loops shrink

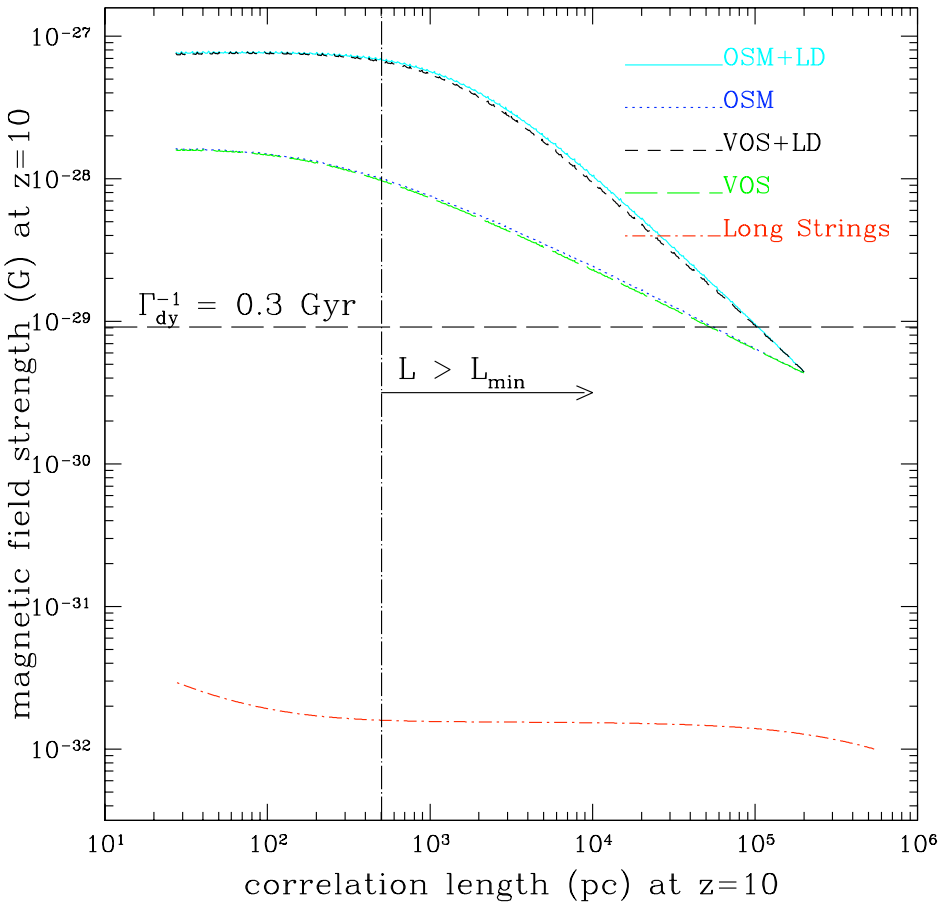
Two minimum requirements:

- Seed Field Flux $B_{seed} \gtrsim 10^{-30} G$
  (at z = z_{gf}, most optimistic dynamo)
- Correlation Length $L_{seed} > 540 \text{ pc}$
  (at z = z_{gf})

Will appear in all plots ...

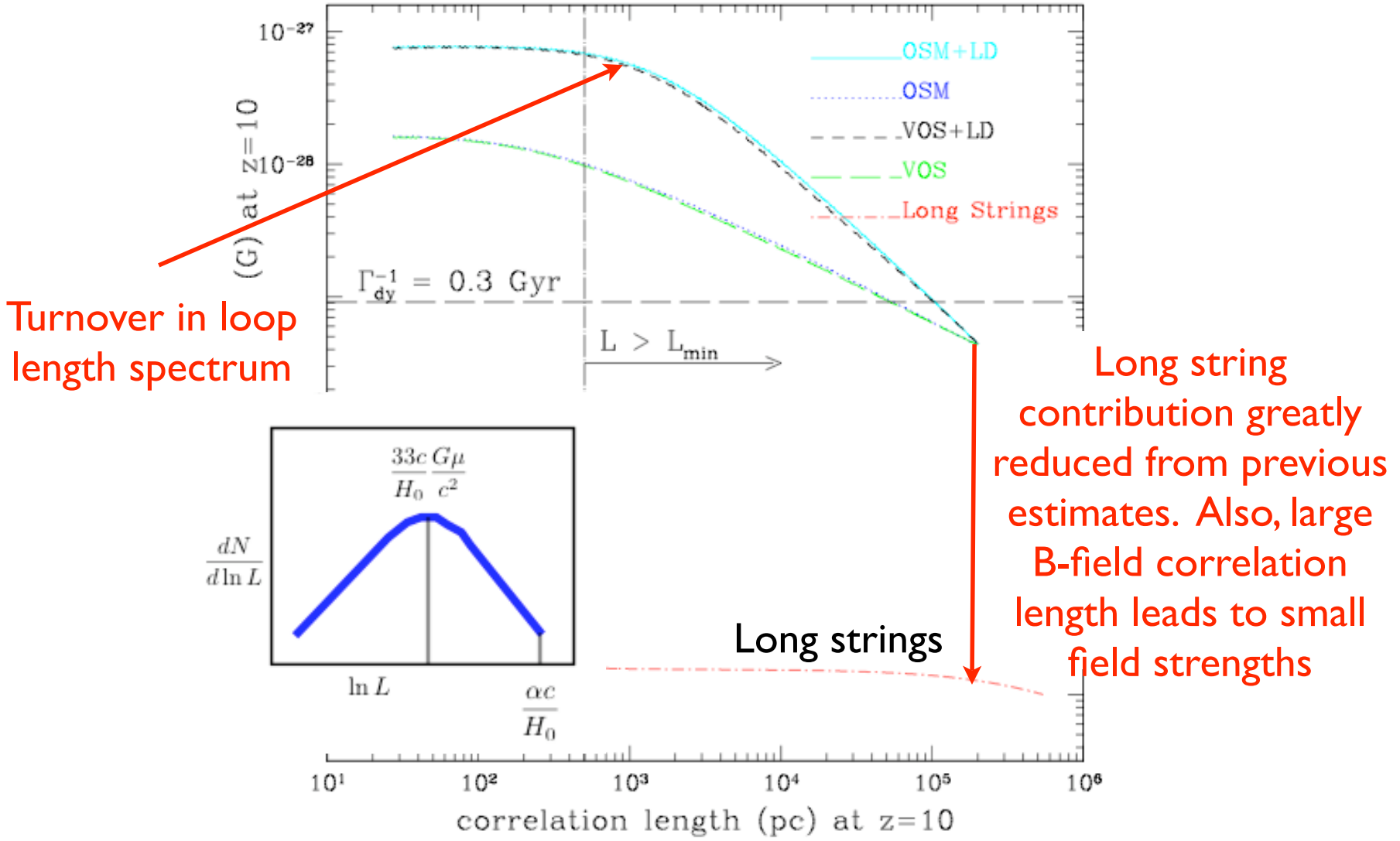
Long strings *vs.* Loops

B-field in Gauss at z=10



Correlation length in parsecs

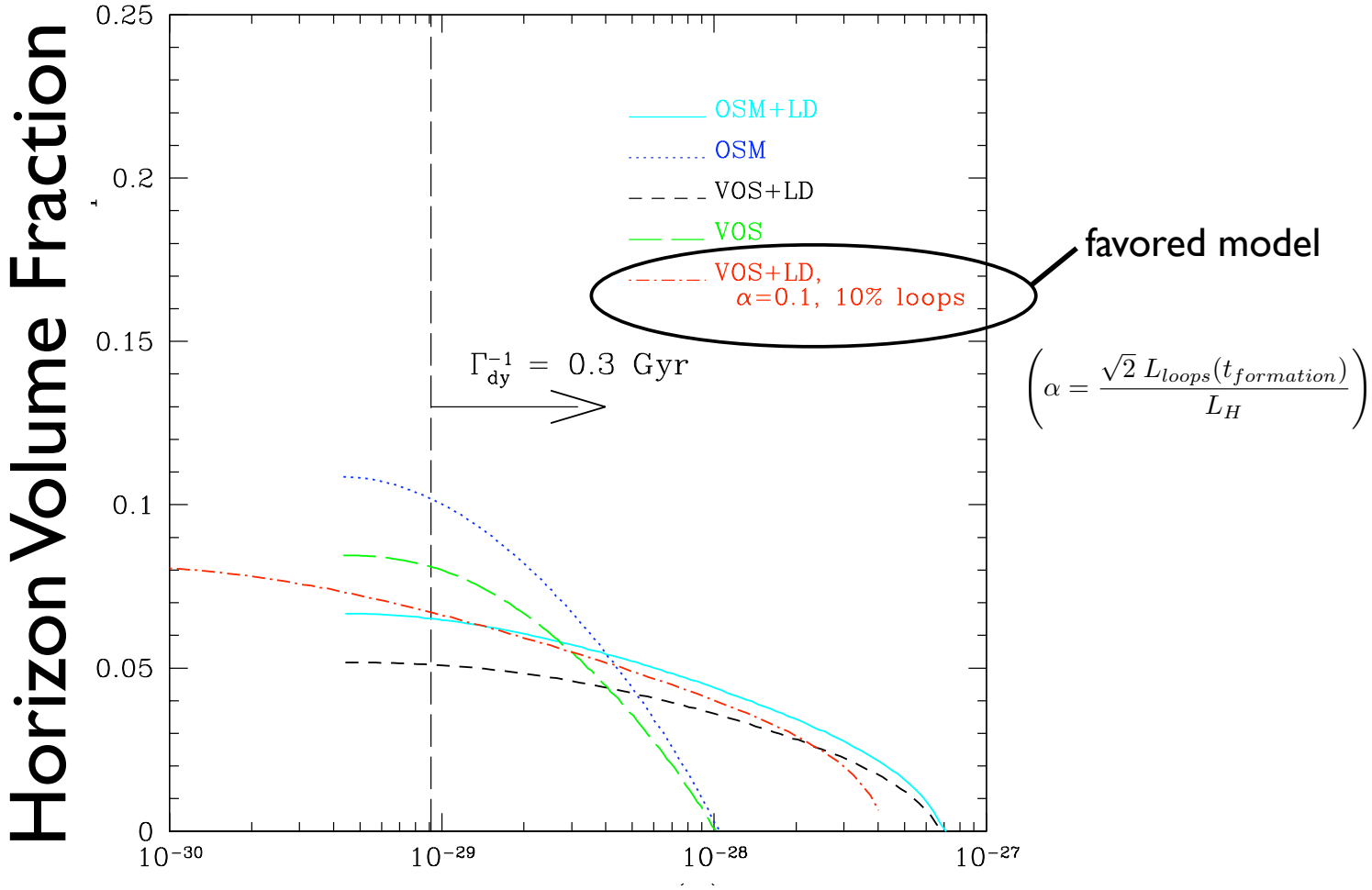
Long strings *vs.* Loops



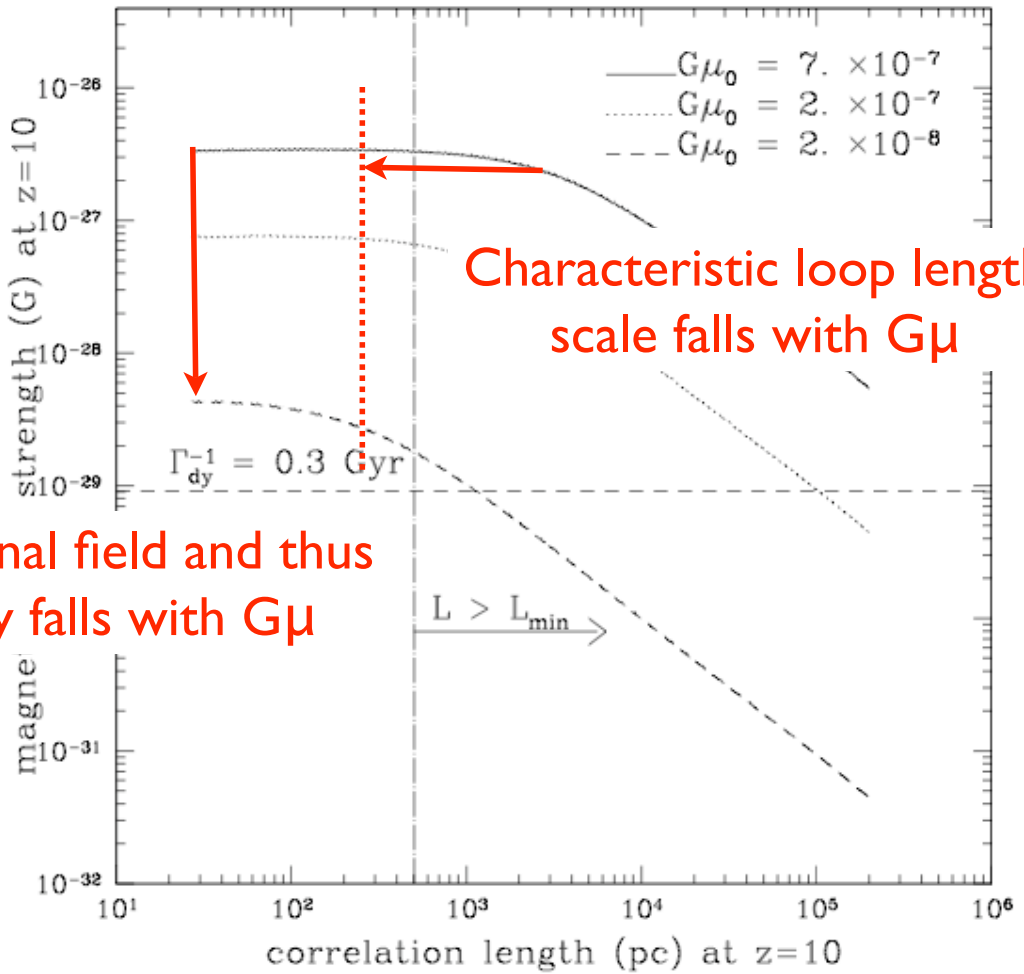
Turnover in loop length spectrum

Long string contribution greatly reduced from previous estimates. Also, large B-field correlation length leads to small field strengths

Volume coverage?



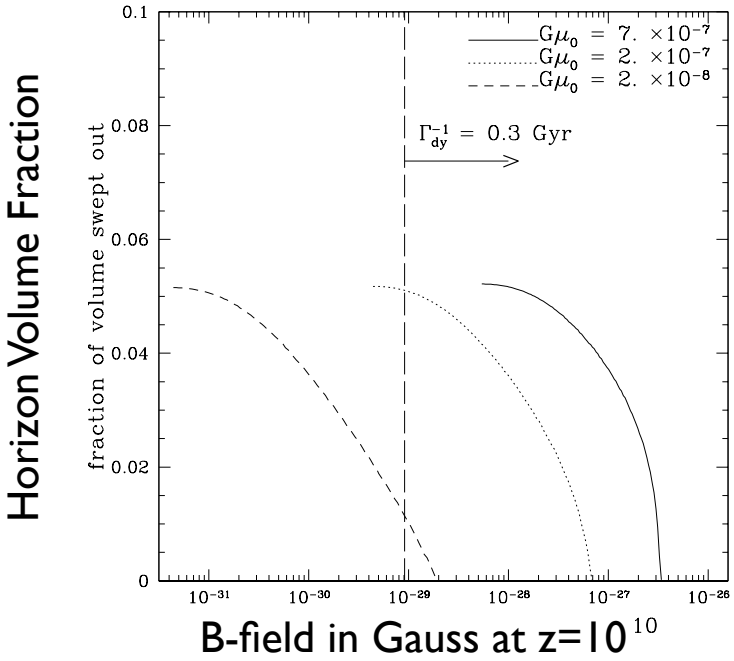
Varying Gμ

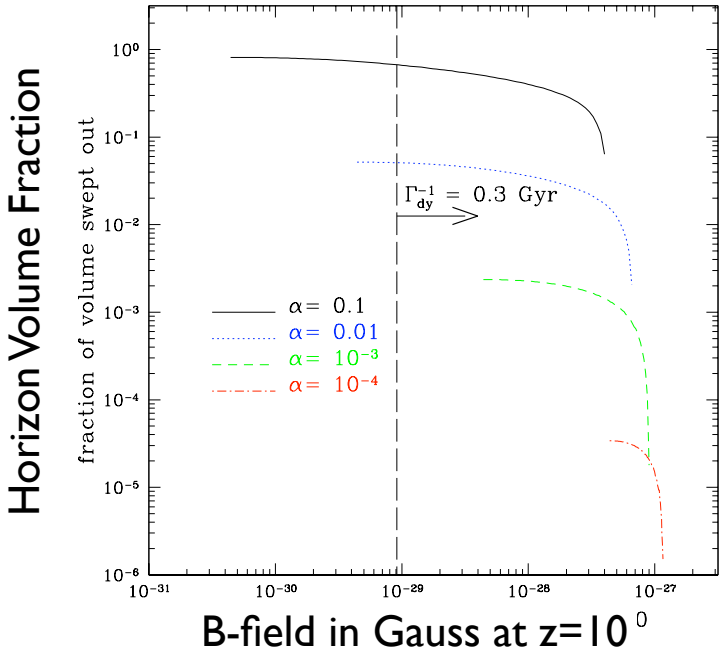


Characteristic loop length scale falls with Gμ

Gravitational field and thus vorticity falls with Gμ

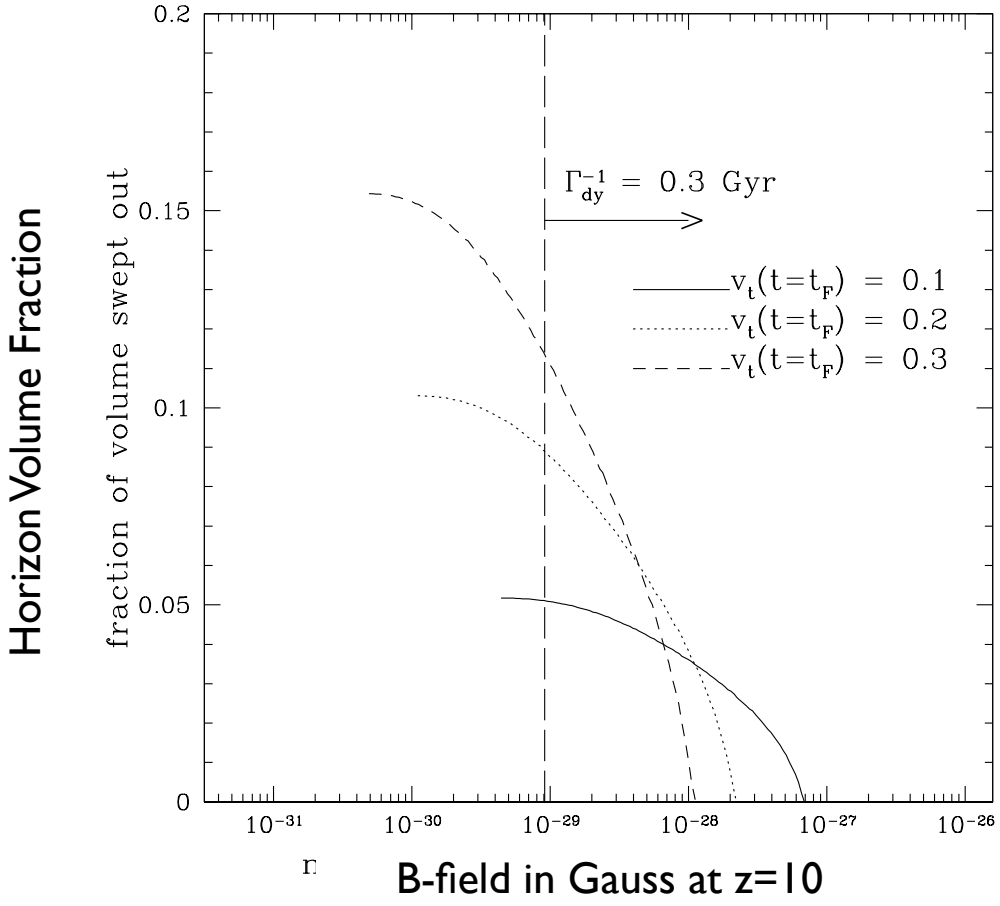
Other combinations





$$\left(\alpha = \frac{\sqrt{2}\, L_{loops}(t_{formation})}{L_H} \right)$$

Varying initial loop velocity



v_t loop transverse velocity at formation

Conclusions

- Observations and theory imply magnetic fields were created at weak values and then amplified through a dynamo
- Mechanism of generation is still mysterious!
- A cosmic string network can source magnetic fields
- Previous estimates have overestimated the long string contribution, and neglected the loops: in fact, the loops should dominate
- Still, this mechanism requires a very efficient galactic dynamo, and volume coverage could be a problem.
- Observing cosmic strings another way would be the biggest boon to this mechanism

CMB B-modes from Strings