Baryogenesis, Primordial Magnetic Fields & CMB Polarization

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Introduction and Motivation

- Cosmology has matured into a precision science with a wealth of data: CMB anisotropies, Lensing, Type Ia Suernovae,Large Scale Structure, soon to come SNAP. . .
- The interplay between cosmology and particle physics holds the promise to address unresolved observational problems.
- Today we focus on three observational and theoretical mysteries.

Common Issues in Particle-Cosmology

- Baryogenesis: Why on largest observed distances, is there virtually no anti-matter (anti-galaxies) observed?
- Primordial Magnetic Fields: All spiral galaxies have a magnetic dynamo that plays role for star formation and cosmic ray physics.
- Who is the Inflaton?

Key Insights

- Model independent Anomaly (quantum mechanical violation of a classical symmetry) cancelling interactions, that arise from string theory contribute to the standard model can source magnetic fields and matter asymmetry.
- Inflation works together with these anomalies to amplify an otherwise small effect.
- After Inflation magnetic fields are necessarily generated in a surprising way from the anomaly.

Lofty idea, but can we test it?

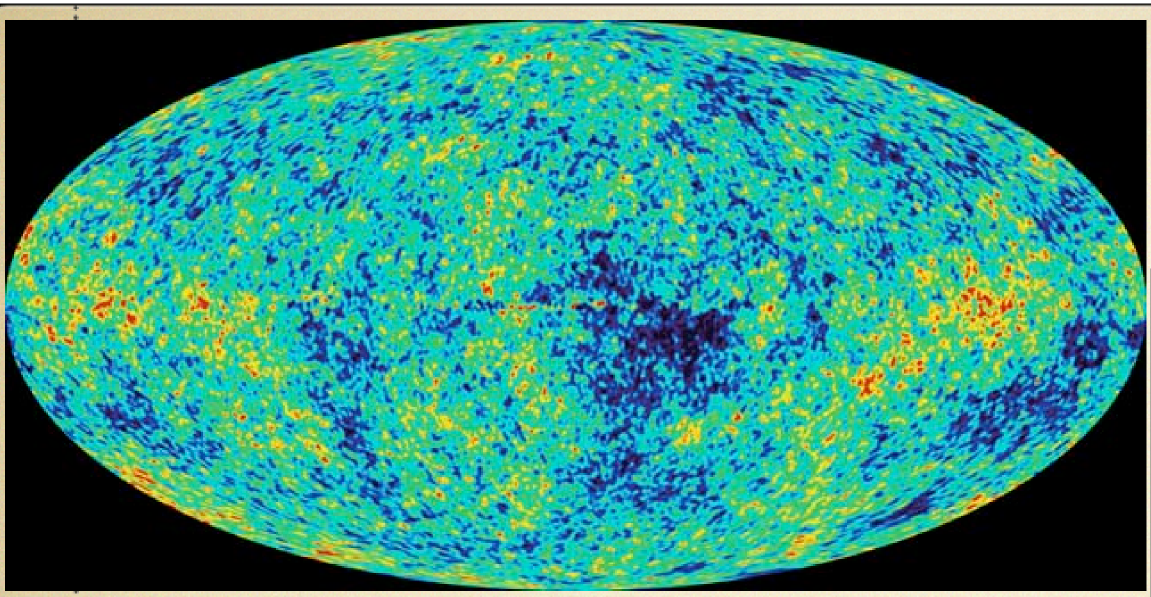
Yes, these models predict:

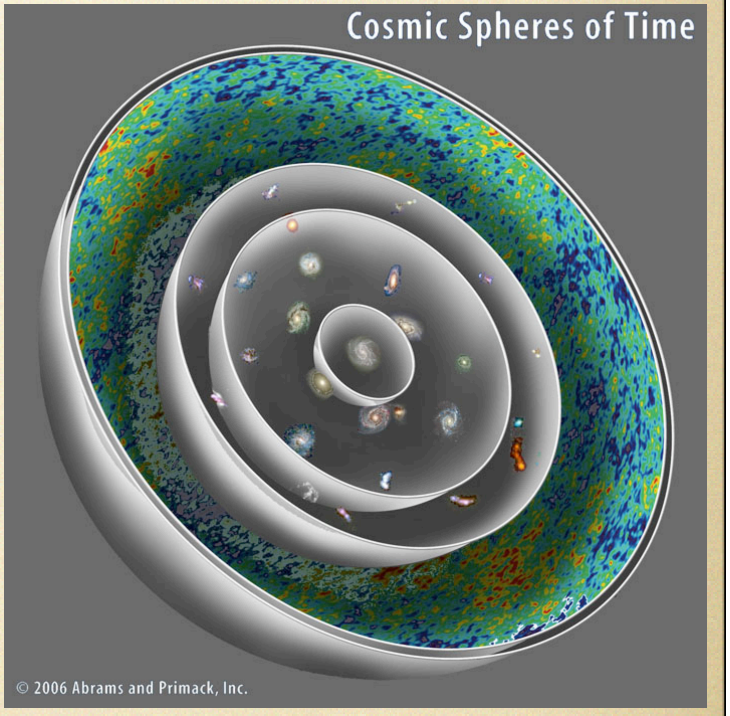
1) New PPN Parameter.
2) Possible circular polarization signal in CMB anisotropy!

Part I
Baryogenesis

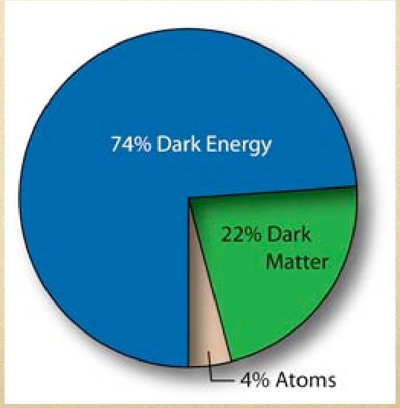
The Baryon Asymmetry Problem

- WMAP and BBN : $$\frac{n_b}{s} \simeq (6.5 \pm 0.4) \times 10^{-10}$$
- Why this number? Where does it come from?
- Our Standard Model Makes Wrong Prediction in the context of SBB!
- What is missing?





Baryon asymmetry is measured in the CMB anisotropies



Sakharov's Dream

- Sakharov realized the 3 necessary conditions for Baryogenesis

Baryon number Violation

CP and C VIOLATION

Departure from Equilibrium

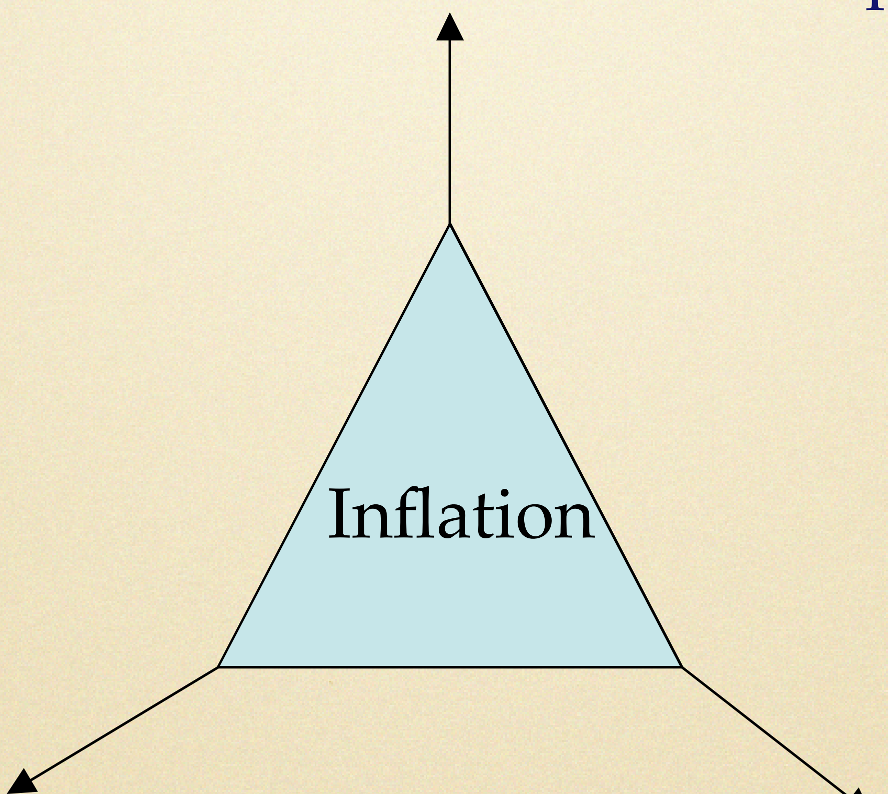
The Past Mechanisms

- The Sakharov conditions were not unified by a simple physical process. (This of course is our (APS) prejudice)
- CP & B usually come from non-perturbative and finite temperature effects in the Standard Model and its extensions.
- Baryogenesis usually thought to occur after inflation. We show that it can happen during inflation naturally and economically.

The Mechanism

(CP)

Inflaton sourced GW production:
CP Violation in Inflaton's phase



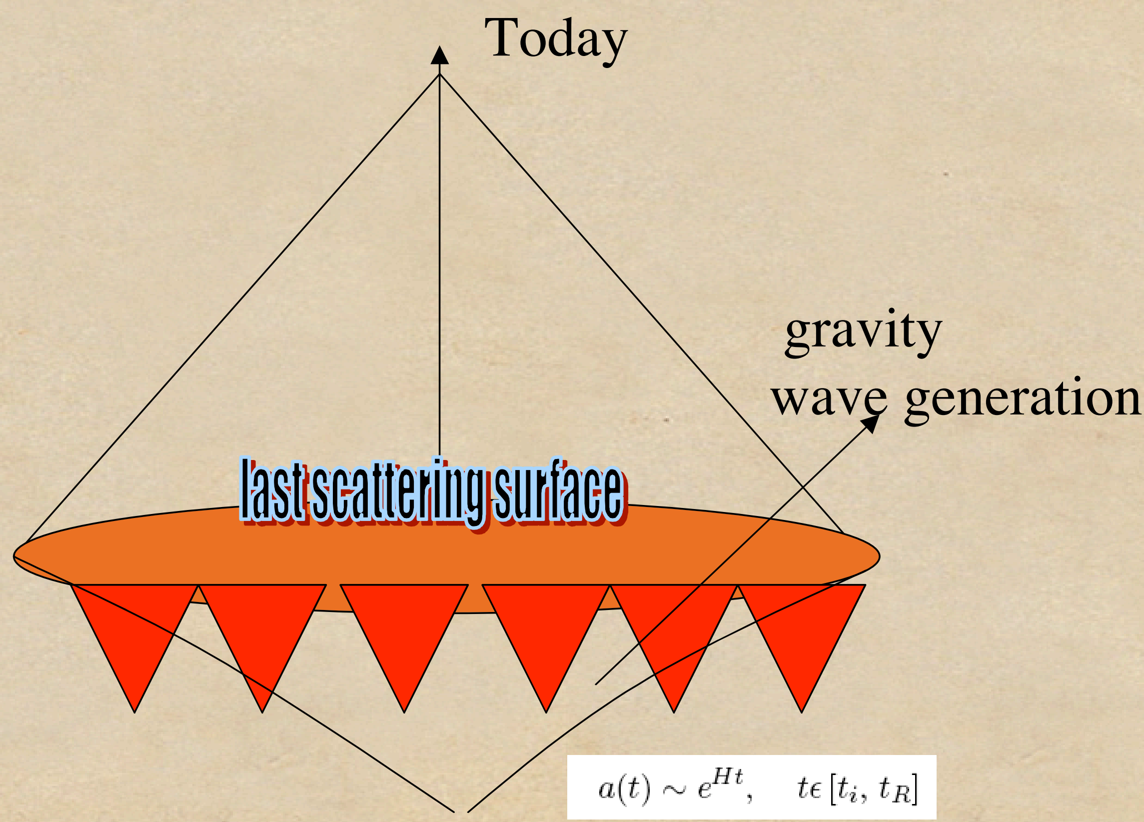
(EQ)

Rapid Expansion:
out of equilibrium

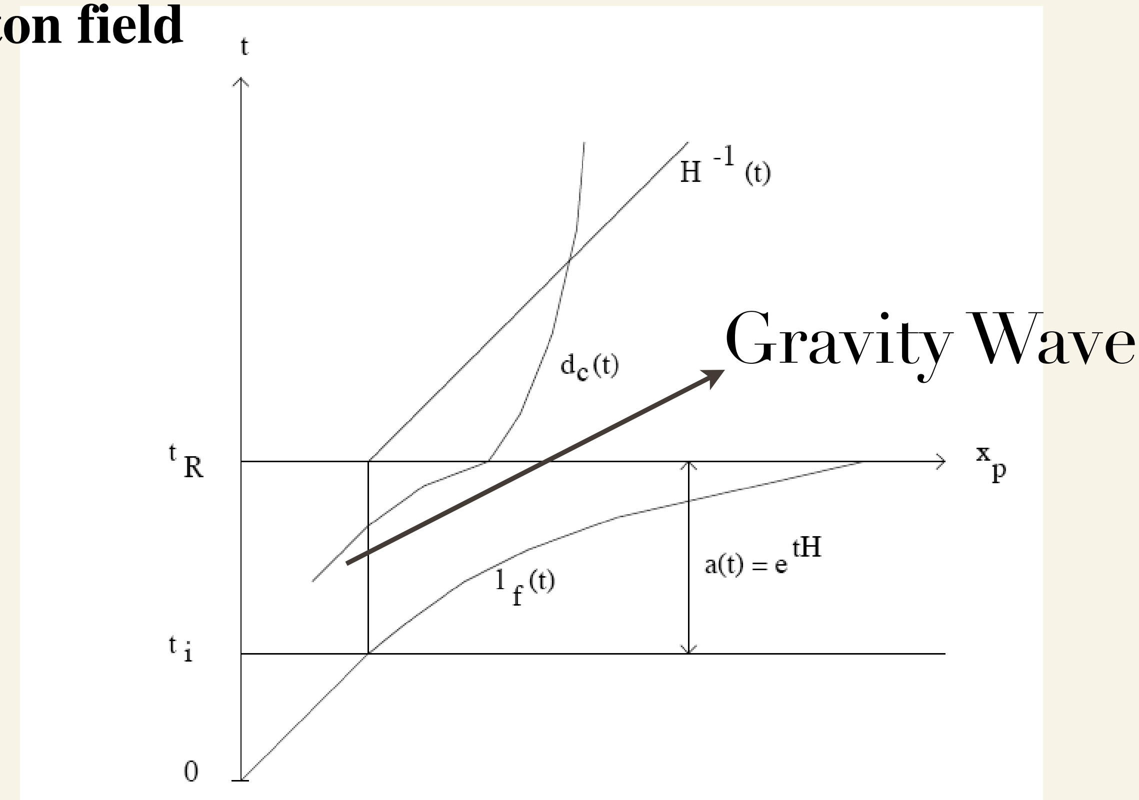
(B)

Gravitational Anomaly
-> lepton production

Inflation is an epoch wherein
The scale factor has positive acceleration



Idea: During inflation gravity waves can generate Lepton number if they are sourced by the phase of the Inflaton field



Imbalance of handedness in GW spectrum
(Circular Dichroism)

Gravitational Chiral Anomaly

In the interaction the global lepton current is classically conserved

$$\partial_\mu J_{\mu 5} = \partial_\mu \bar{\Psi} \gamma_\mu \gamma_5 \Psi = 0$$

However, this is not the case quantum mechanically
The expectation value up to 2nd order in coupling

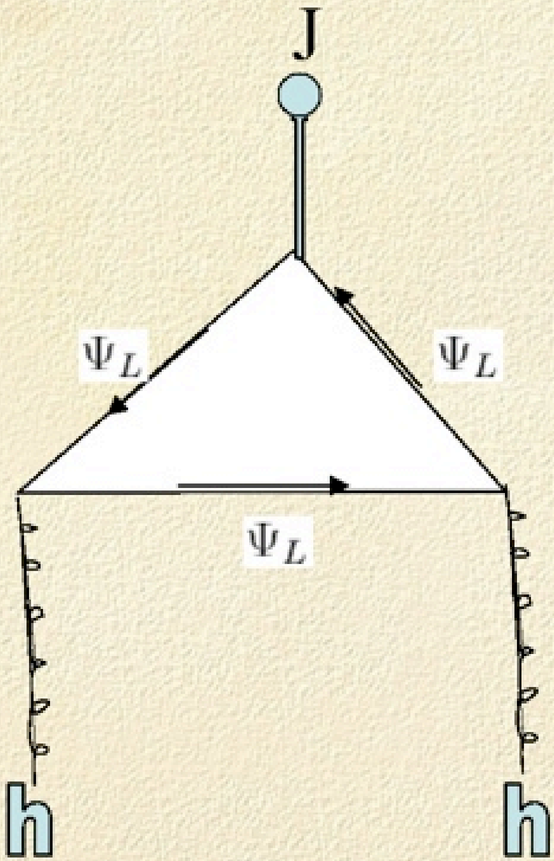
$$\langle J_5^\mu \rangle = \langle J_5^\mu \mathcal{L}_{int} \mathcal{L}_{int} \rangle$$

Chiral-Current Anomaly

Duff, Deser, Isham 88; Alvarez-Gaume, Witten. 90

Alvarez-Gaume, Nelson, '85

Cardoso, Ovrut, '91



This leads to the well known ABJ triangle anomaly

$$\partial_\mu J_l^\mu = \frac{1}{16\pi^2} R\tilde{R}$$

$$J_l^\mu = \bar{l}_i \gamma^\mu l_i + \bar{\nu}_i \gamma^\mu \nu_i \qquad R\tilde{R} = \frac{1}{2}\epsilon^{\alpha\beta\gamma\delta} R_{\alpha\beta\rho\sigma} R_{\gamma\delta}{}^{\rho\sigma}$$

$$< \partial_0 J_{05} >= \frac{dn}{dt}$$

- This current vanishes in FRW backgrounds so at first sight it is not useful for cosmology.
- However for Gravity Waves the lepton number can be non vanishing. Let us explore this possiblitiy

Perturbed FRW metric:

$$ds^2 = -(1+2\varphi)dt^2 + w_i dt dx^i + a^2(t)\left[((1+2\psi)\delta_{ij} + h_{ij})\, dx^i dx^j\right]$$

$$R\tilde{R} = \frac{4i}{a^3}\left[\left(\partial_z^2 h_R\ \partial_z\partial_t h_L + a^2\partial_t^2 h_R\ \partial_t\partial_z h_L + \frac{1}{2}\partial_t a^2 \partial_t h_R\ \partial_t\partial_z h_L\right) - (L \leftrightarrow R)\right]$$

During inflation the gravity waves obey:

$$\Box h_L = -2i\frac{\Theta}{a}\dot{h}_L' \ , \qquad \Box h_R = +2i\frac{\Theta}{a}\dot{h}_R' \ ,$$

where

$$\Theta = 8\left(\frac{H}{M_{\rm Pl}}\right)^2\dot{\phi})/HM_{\rm Pl} \ ,$$

PROVE IT!

We need to calculate the quantum expectation value of the lepton number during the history of inflation.

Birefringent Gravity Waves

his field will have the following gravitational coupling

$$\mathcal{L}_{\rm int} = \mathrm{f}(\theta)\mathrm{R}^{\alpha}_{\sigma\mu\nu}\tilde{\mathrm{R}}_{\alpha}^{\sigma\mu\nu}$$

NEW INGREDIENT

From Green-Schwartz Mechanism

$$f(\phi) = \frac{1}{16\pi^2 M_{Pl}}\mathcal{N}\phi$$

Later, we will derive this model independent function from Heterotic String theory.
The above is identical to the divergence of Chiral current discussed earlier, from ABJ anomaly.

But how are gravity waves affected by this term? Lets see.

Birefringent Inflationary Gravity Waves: Quantization

In The Inflationary Epoch the Gravity Wave E.O.M simplifies

$$\partial_\mu \partial^\mu h_L = -2i\frac{\dot{\Theta}}{a} h'_L$$

$$\partial_\mu \partial^\mu h_R = 2i\frac{\dot{\Theta}}{a} h'_R$$

$$M_{pl}^2 \Theta = 4(F'' \dot{\phi}^2 + 2HF'\dot{\phi})$$

Convenient to use conformal time $\eta = \frac{1}{Ha} = \frac{1}{H} e^{-Ht}$

$$\frac{d^2}{d\eta^2} h_L - 2\frac{1}{\eta}\frac{d}{d\eta} h_L + k^2 h_L = +2k\Theta \frac{d}{d\eta} h_L$$

If we ignore r.h.s we get a spherical Bessel function (note with r.h.s we have a Coloumb Wavefunction eq)

$$\frac{d^2}{d\eta^2}h_L - 2\frac{1}{\eta}\frac{d}{d\eta}h_L + k^2 h_L = 0$$

Whose solution is:

$$h_L^+(k,\eta) = e^{+ik(\eta+z)}(1 - ik\eta)$$

Lets take the ansatz

$$h_L = e^{ikz} \cdot (-ik\eta)e^{k\Theta\eta}e^{ik\eta}g(\eta)$$

Hence the quantum expectation value:

$$< R\tilde{R} >= \frac{16}{a} \int \frac{d^3k}{2\pi^3} \frac{H^2}{2k^3 M_{Pl}^2} (k\eta)^2 . k^4 \Theta$$

We pick up only the leading behavior for $k\eta >> 1$
Which corresponds to UV Sub-Horizon modes

A reminder: The above expression is non-zero because of the effect of inflation in producing CP asymmetry out of equilibrium.

WE ARE FINALLY READY TO COMPUTE LEPTON NUMBER :)

Integrating momentum up the cutoff scale μ
we obtain the number:

$$n = \int_0^{H^{-1}} d\eta \int \frac{d^3k}{(2\pi)^3} \frac{1}{16\pi^2} \frac{8H^2k^5\eta^2\Theta}{M_{\rm Pl}^2}$$

This integral represents a compromise between two effects of inflation. First, to blow up distances and thus carry us to smaller physical momenta and second to dilute the generated lepton number through expansion.

SEMI-FINAL RESULT

- We arrive at the final result for the baryon to entropy ratio. We can find μ for a range of Hubble that is acceptable by CMB constraints.

$$\frac{n}{s} \sim 1 \times 10^{-5} \cdot \left(\frac{H}{M_{\rm Pl}}\right)^{-1/2} \left(\frac{\mu}{M_{\rm Pl}}\right)^{5}$$

$$10^{-30} \lesssim H/M_{\rm Pl} < 10^{-4}$$

The range is $3 \times 10^{14} < \mu \lesssim 10^{17}$

Which is the scale of the right handed neutrino! From this we can get

$$\Rightarrow \quad \frac{n}{s} \sim 10^{-10}$$

Caveat: Still some fine tuning

Jackiw, “There are many ways to modify GR. But the Chern-Simons is well motivated by particle physics.”

Are There Ways to Test This Mofication to Gravity in the Contemporary Universe?

Yes, with the Parameterized Post-Newtonian Approximtion

The key interaction is the gravitational anomaly coupled to the complex phase of the inflaton f(ϕ)

$$S_{CS} = \frac{1}{16\pi G}\int d^4x \frac{1}{4} f \; R^{\star}R$$

This term can be tested in solar system with a new PPN parameter

We first need to introduce the Cotton -Tensor

$$D^{\alpha}C_{\alpha\beta} = \frac{\dot{f}\delta^{\beta 0}}{8\sqrt{-g}} R^{\star}R$$

Weak-Field Motion and the ABC of PPN

S.A., Yunes, PRL (2008)   Kamionkowski, PRD (2008)

Assume test-particle, $G \ll 1$, $c^{-1} \ll 1 \to$ solve EEs $\Box_\eta h_{\mu\nu} \sim T_{\mu\nu}$

But in alternative theories, EEs are modified $\to$ PPN (**Nordtvedt & Will**):

- (1) Solve the EOM in your alternative theory.
  - Expand the modified Einstein Equations about a Minkowski background to second order in the metric perturbation.
  - Assume a perfect fluid stress-energy source (binaries, Earth-Sun, etc).
  - Assume a slow-motion/weak-gravity approximation and perturbatively solve the linearized EEs: g_{00} to $\mathcal{O}(v^4)$, g_{0i} to $\mathcal{O}(v^3)$ and g_{ij} to $\mathcal{O}(v^2)$.
  - The final solution is then expressed in terms of PPN potentials (Green-function like integrals over $T_{\mu\nu}$, eg. $U \sim \int_V T_{00}/|x - x'|$.)

- (2) Construct a Super-Duper-Duper Metric
  - Based on some assumptions, construct a family of metric solutions labeled by some *PPN parameters*, eg.

$$g_{ij} = (1 + 2\gamma U)\,\delta_{ij}$$

- (3) Compare solution to new theory to super-metric and read off PPN params.

- Expand the Cotton tensor: $C_{00} = \mathcal{O}(v)^6$, C_{ij} leads to $\delta h_{ij} = \mathcal{O}(\dot{f})^2$ and

$$C_{0i} \sim -\frac{1}{4}\dot{f}\tilde{\epsilon}^{kl}{}_i \nabla^2 h_{0l,k}$$

- The only modification to the gravitational field to leading $\mathcal{O}(\dot{f})$ is then

$$\delta h_{0i} \sim 2\dot{f}\,(\nabla \times V)_i$$

where V_i is a vector PPN potential (eg, binary $V^i_A \sim m_A v^i_A / r_A + J_A / r^2_A$)

- Interpretation: Axion is like a fluid that is "dragged" by motion.
- New PPN parameter!! (such terms had not been considered before.)
- Direct effect on frame-dragging of gyroscopes:

$$\delta\Omega^i = -\sum_A \dot{f}\frac{m_A}{r^3_A}\left[3\,(v_A \cdot n_A)\, n^i_A - v^i_A\right]$$

- Detectable? (Smith, *et. al.*) used LAGEOS and GP B: $\dot{f} \lesssim 10^{-2}$ secs.

Birefringent Gravitational Wave Detection

S.A., L.S. Finn, N. Yunes, 2008

- Linearize and solve the EEs about an FRW background plus a gravitational perturbation in CS gravity (Jackiw & Pi; Alexander, Peskin, Jabbari)

$$h_{R,L} = e^{\pm F\tau} h^0_{R,L},$$

where F i the GW frequency and $\tau \sim H_0 z \theta'_0$ is the *CS timescale*.

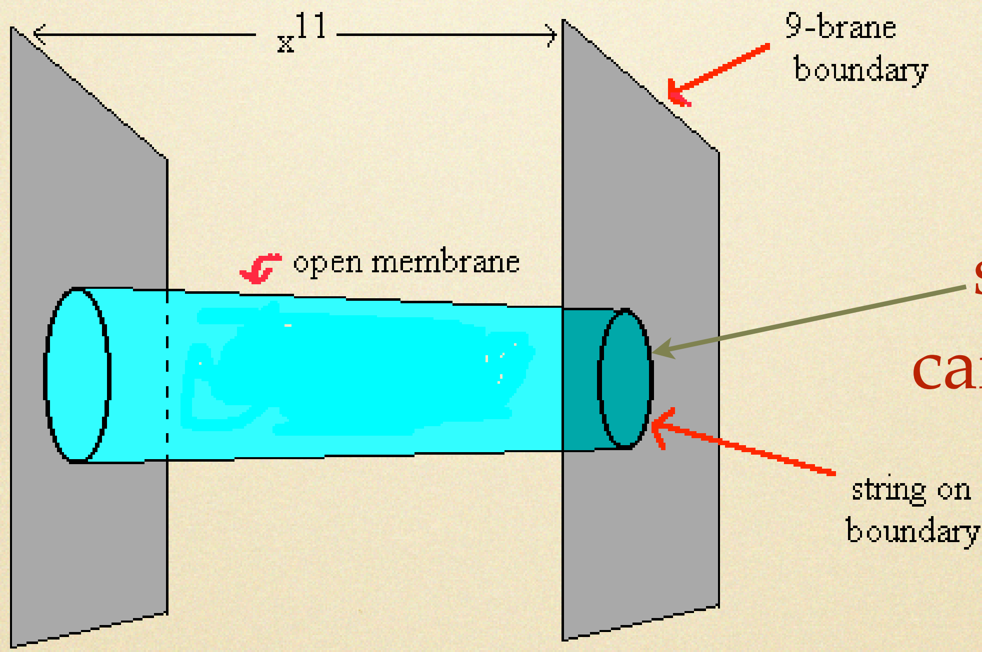
- The CS correction will modify the r$\tau \sim 10^{-4}$ on of GW detectors (eg, LIGO, LISA, etc). Given a GW detection, we estimate τ can be measured to an accuracy of (Alexander, Finn & Yunes)

$$\Delta\tau \propto \frac{\sqrt{S_0} d_L}{\mathcal{M}^{p1} F^{p2}}$$

where S_0 is the noise in the detector, d_L is the luminosity distance to the source, $\mathcal{M}$ is the chirp mass of the source (assumed to be a binary).

Bottom Line: Circularly polarized birefringent GW measurement of $\tau \sim 10^{-4}$ seconds, an order of magnitude better than solar system

We can construct the Minimally Supersymmetric Standard Model with the anomaly couplings.



In our 4D world,The strings will carry quarks in their core

This was accomplished by Ovrut et al.
Adv. Theor. Math Phys 2002

Branes and Couplings

$$\int_{M_1} A^{[1]}$$

Point particles (0D) couple
to one a one form

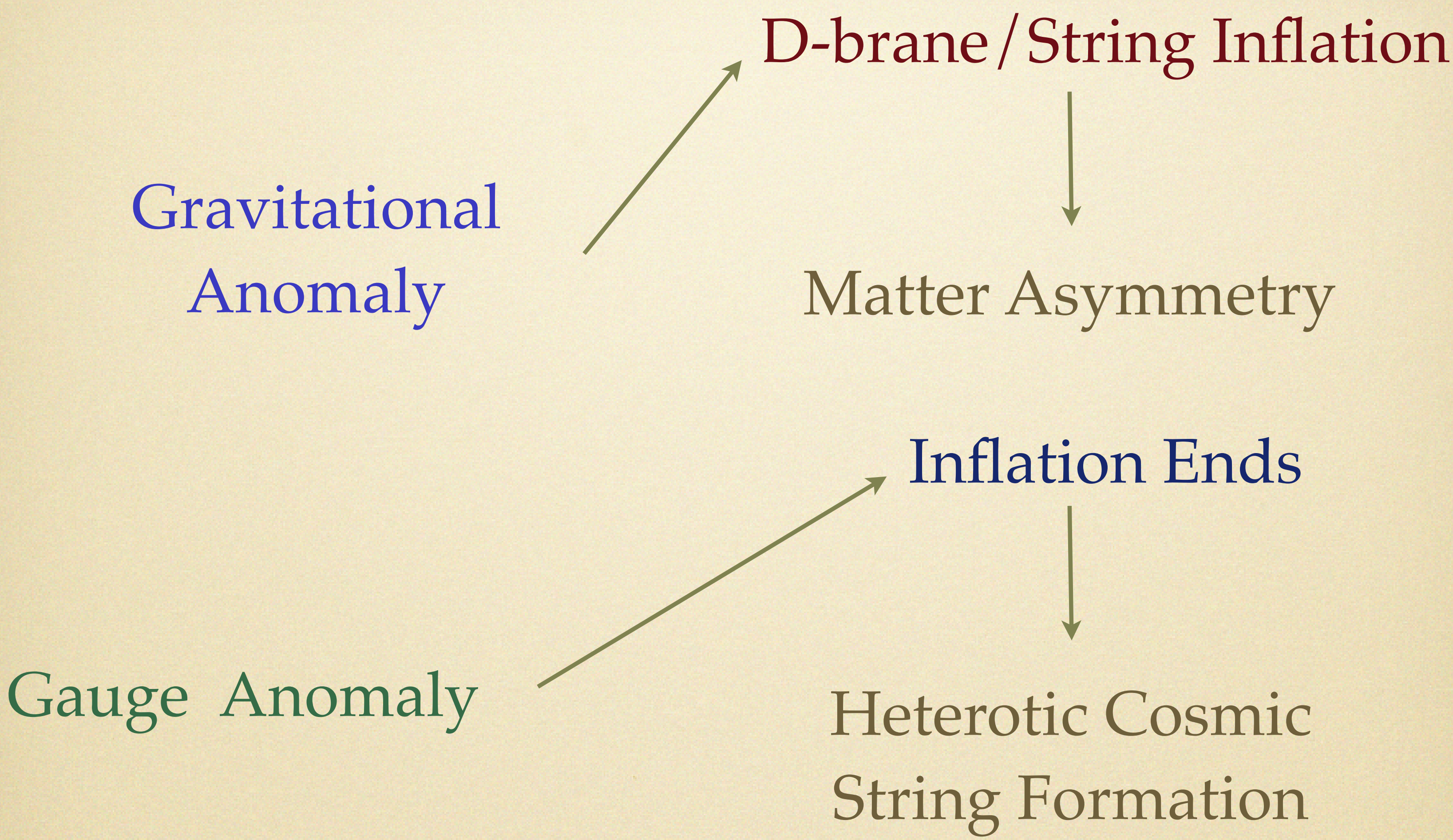
Likewise our 3-braneworld couples to
4 form potential

$$\int_{M_4} C^{[4]} \quad \Rightarrow \quad C^{[4]} = \phi F^{[2]} \wedge F^{[2]}$$

cosmic string field (ϕ)

Magnetic Field ($F^{[2]}$)

Illuminating the Visible Side of Our Universe



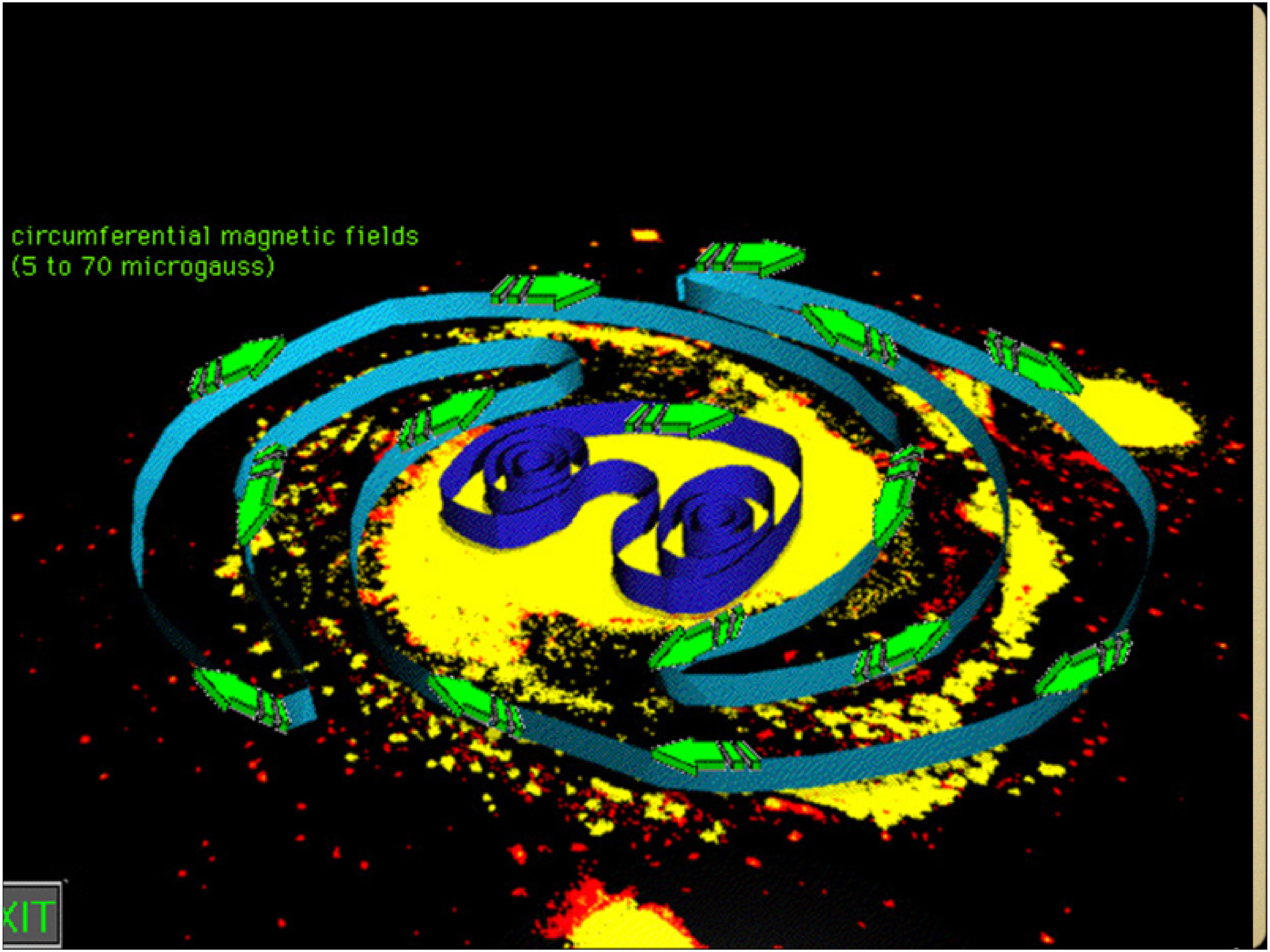
Primordial Magnetic Fields

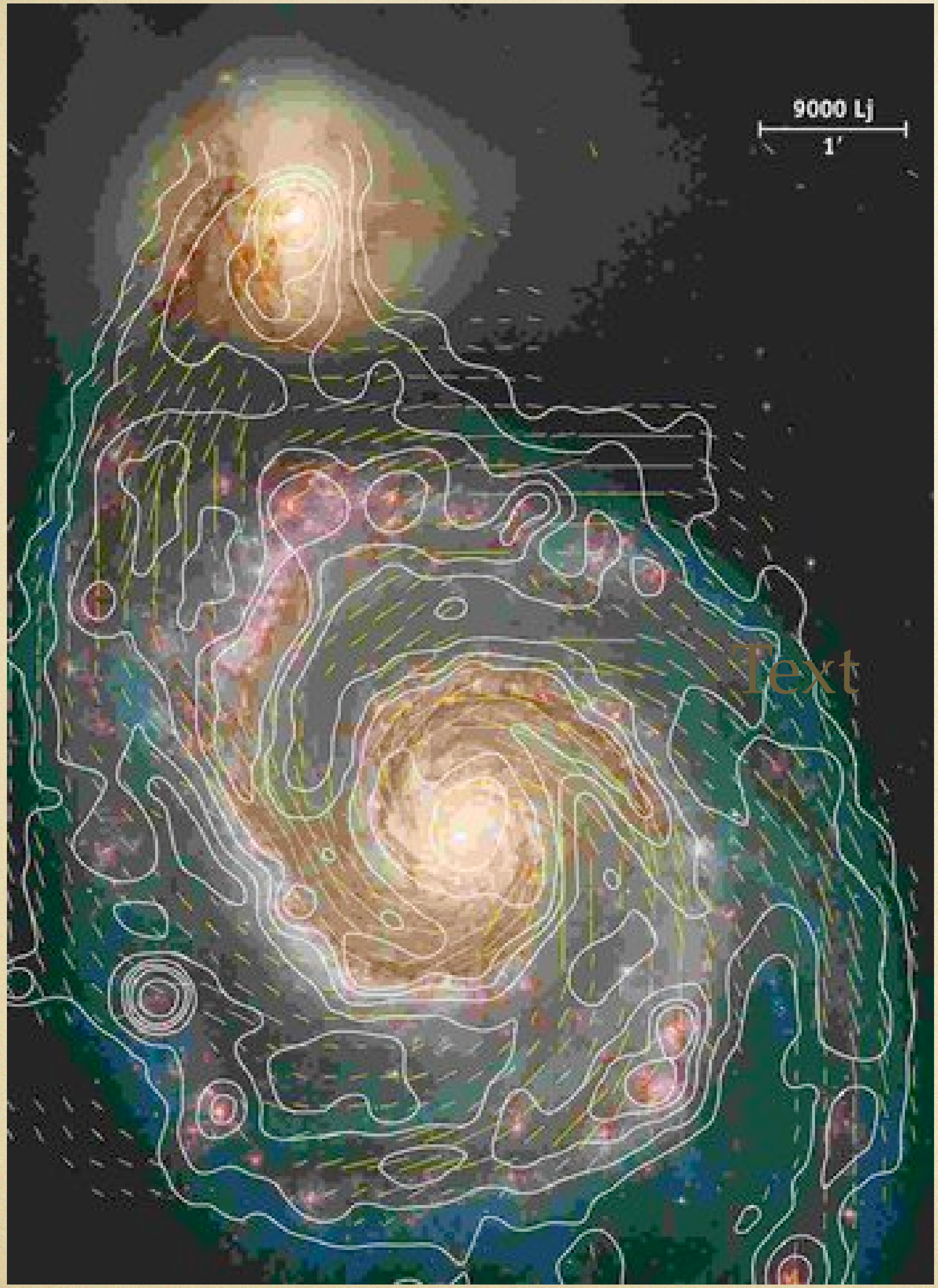
Primordial Magnetic Field Mystery

1) Most Galaxies like our Milkyway are permeated by a magnetic field on the order of a few μGauss. Clusters are observed to have same magnitude.

2) A non-linear dynamo mechanism can amplify and maintain the magnetic fields but a primordial seed is still required

The origin of this seed field is still a mystery.


circumferential magnetic fields
(5 to 70 microgauss)
XIT



Optical: M51 Spiral

B-field traces optical contours.

Part II
Primordial Magnetic Fields from Cosmic Superstrings

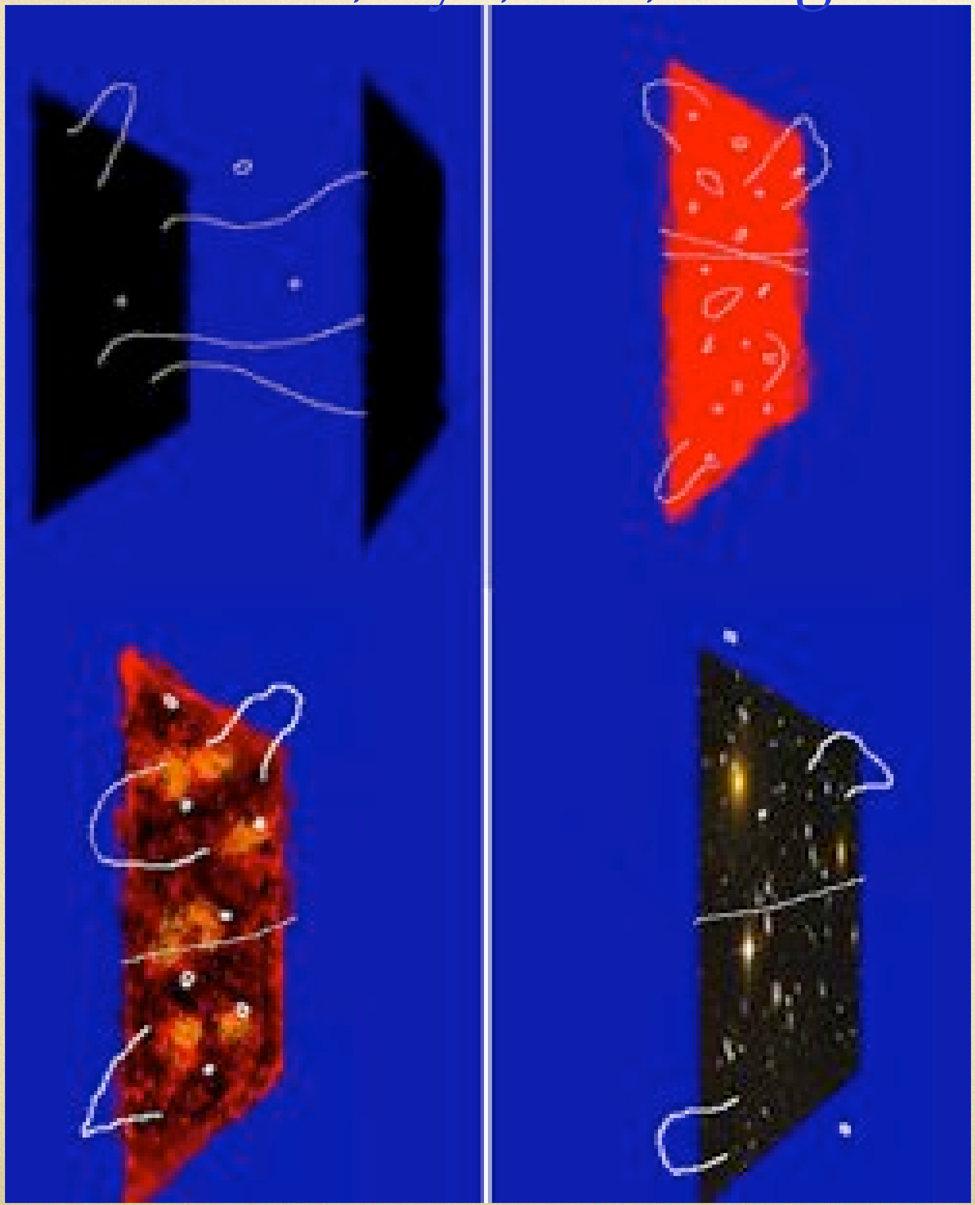
We have seen that the gravitational Chiral anomaly contributes to the standard model to possibly generate lepton asymmetry during inflation.

This term is necessary for the consistency of String theory.

We now show how a similar anomaly can play a role in the generation of galactic magnetic fields.

D-brane Driven Inflation

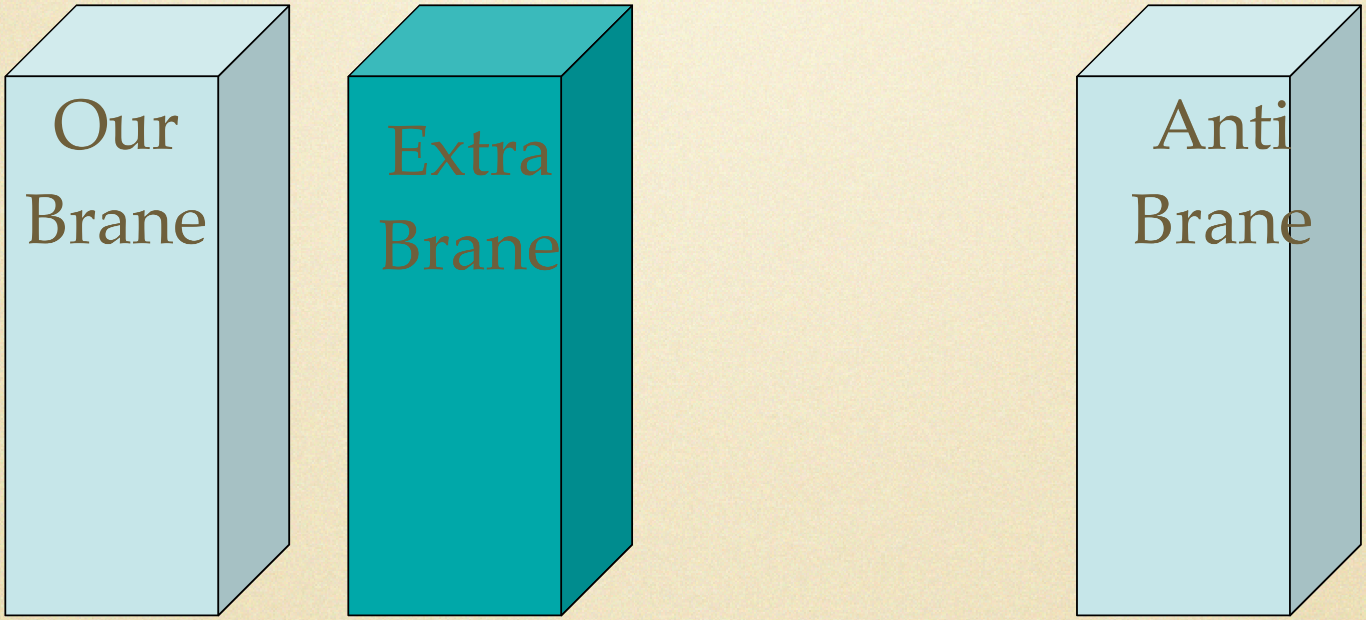
Dvali, Tye; S.A; Burgess et. al. (2001)



Annihilation of Brane-Anti Brane in Early Universe generates inflationary potential with a natural graceful exit.

D-brane Driven Inflation

Dvali, Tye; S.A; Burgess et. al.



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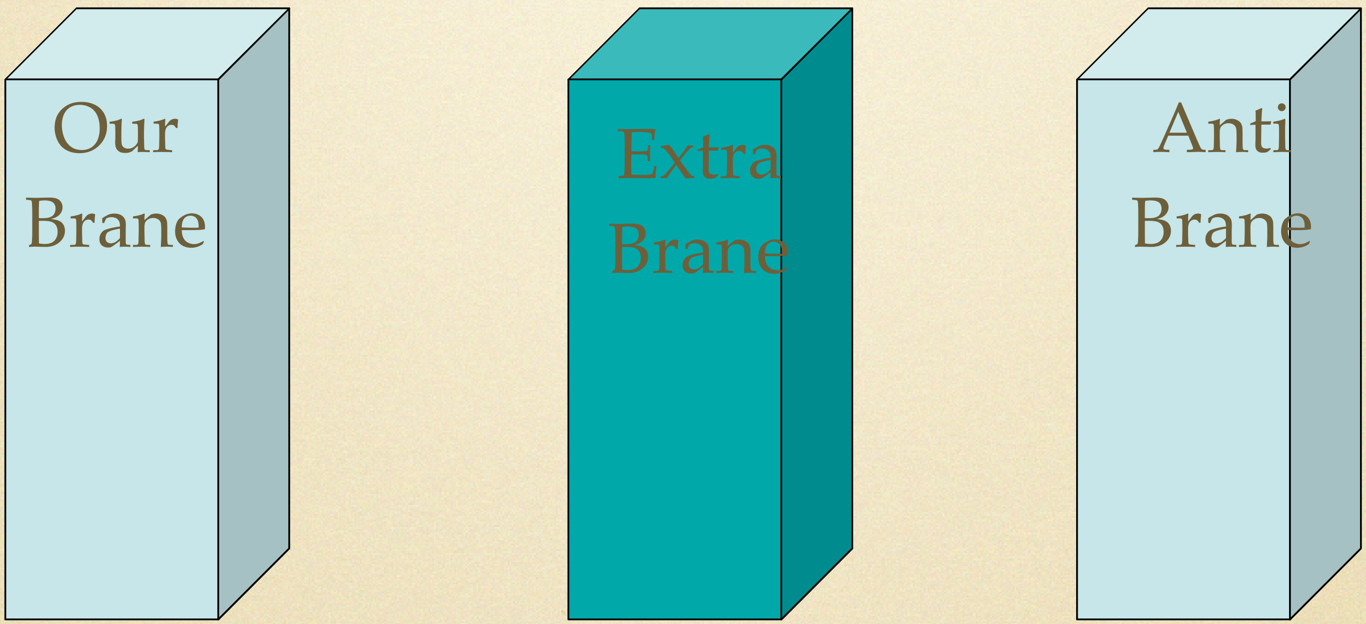

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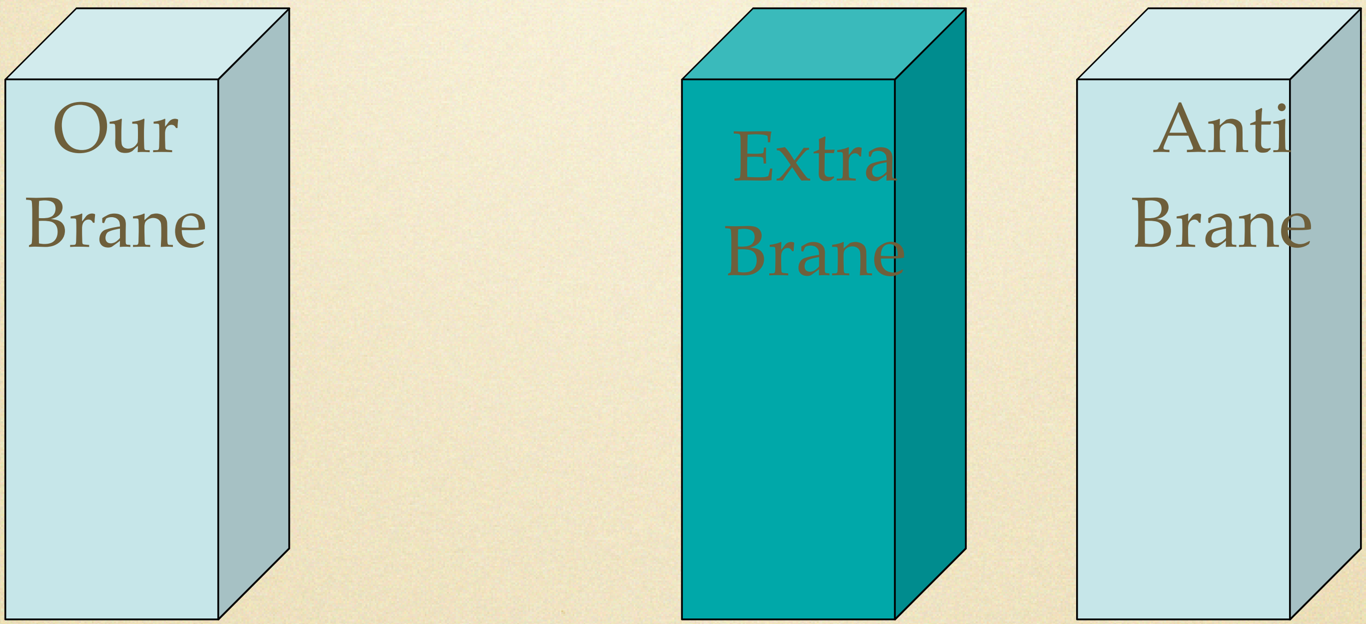
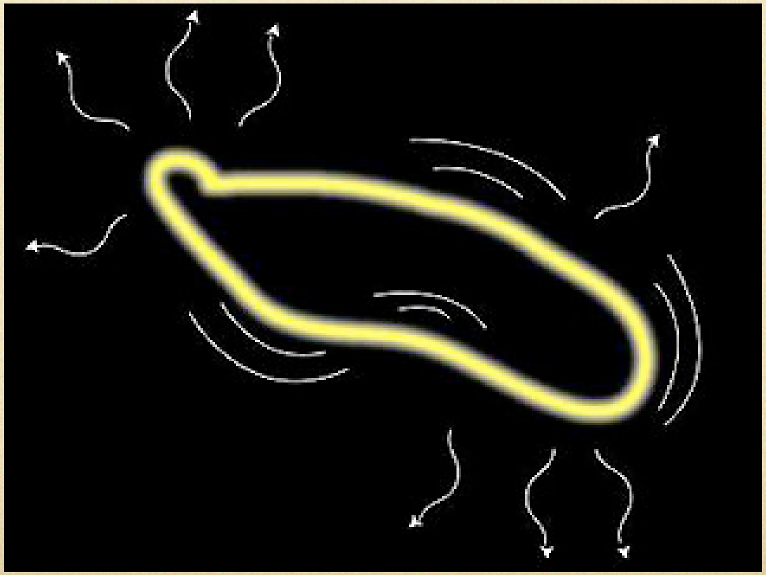


D-brane Driven Inflation

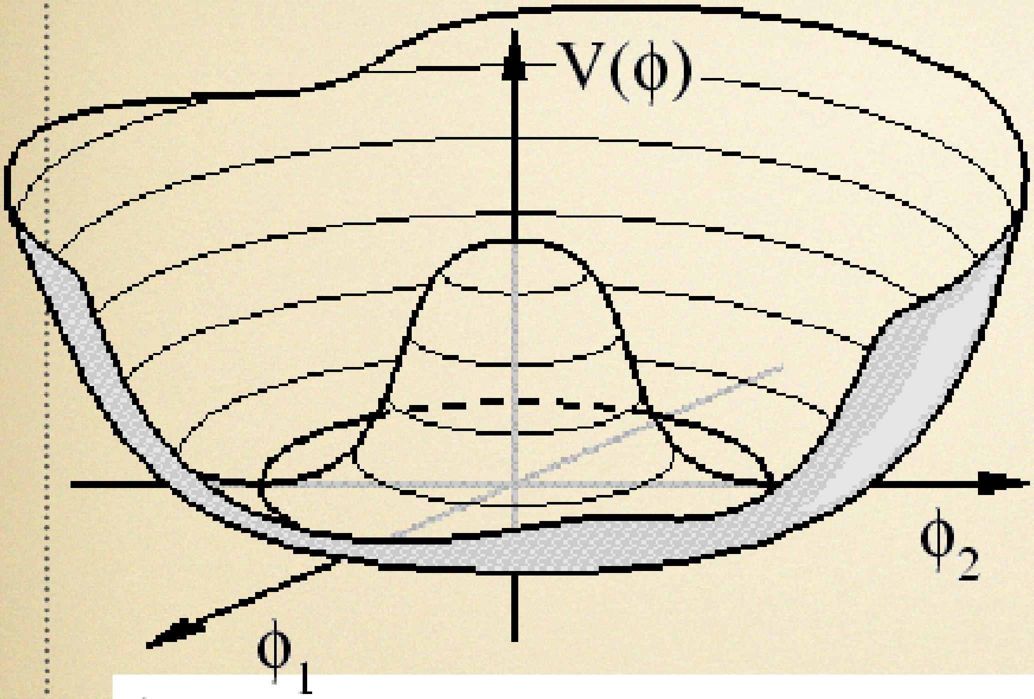
Dvali, Tye; S.A; Burgess et. al.

Cosmic Supestrings are inevitable after brane inflation

Polchinski, Copeland, Myers,S.A, Tye, Dvali, Stoica



Cosmic String Quickie



A cosmic string is a line of trapped energy density which arises whenever the field $\varphi(x)$ circles $\mathcal{M}$ along a closed path in space (*e.g.*, along a circle).

$$V(\varphi) = \frac{1}{4}\lambda(\varphi^2 - \eta^2)^2$$

Vacuum manifold: $\mathcal{M} = S^1$

$$\varphi(r,\, \vartheta) = f(r)e^{i\vartheta}$$

In 1985 Witten argued that heterotic string could exist as a cosmic string in 4D. Recall that (developed at Penn) heterotic has standard model realization (chirality)

He identified the heterotic string as an axionic cosmic string, with tension.

(nice prophetic coincidence for us)

Tension: $$G_N \mu \simeq 8 \times 10^{-4}$$

Unfortunately, the solution was unstable an violated the observational bound

$$G_N \mu \leq 8 \times 10^{-7}$$

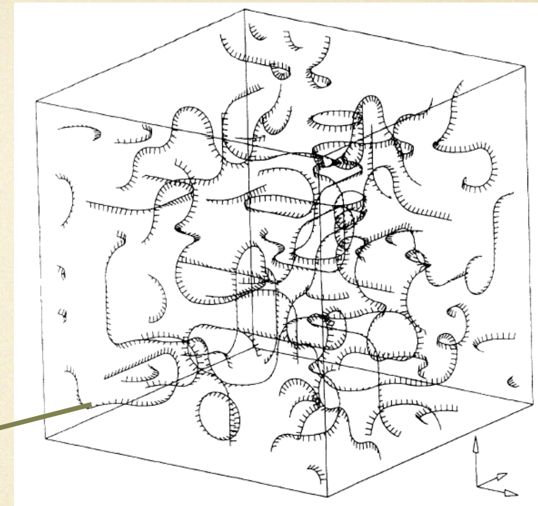
Becker, Becker and Krause '06

Found that heterotic cosmic strings which arise from strongly coupled heterotic M-theory supported by M5 branes (high tension) can satisfy bound and also be stable (which is key for magnetogenesis!).

These strings are also realized as axionic cosmic strings. We show that they have the necessary couplings to seed galactic magnetic fields at end of inflation

Brandenberger, Zhang

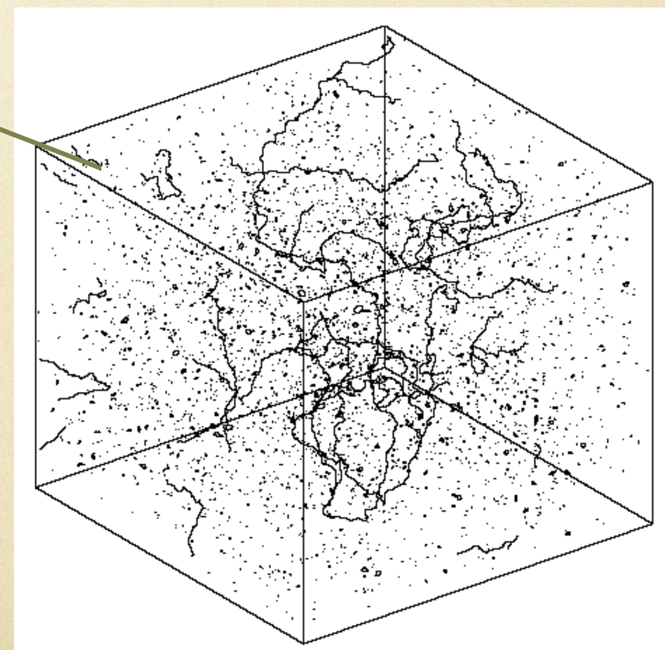
String Network After Inflation



heterotic cosmic string

Scale free network after

3×10^9 lightyears



Allen and Shellard (1990)

Cosmic Strings and Magnetic Fields

Let us consider an effective Lagrangian of cosmic string

cosmic strings will carry charged quarks currents in their core.

$$\mathcal{L} \;=\; \imath\bar{\psi}\not{D}\psi + |\partial_\mu\phi|^2 - g\phi\bar{\psi}_L\psi_R - g\phi^*\bar{\psi}_R\psi_L - \frac{\lambda}{2}\left(|\phi|^2 + f^2\right)^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$\mathcal{L} \;=\; \frac{1}{2}(\partial_\mu a)^2 - F\wedge\star A - \frac{e^2}{32\pi^2}\left(\frac{a}{f}\right)F\wedge F.$$

The above come naturally from heterotic string theory

Main Point: Charged quarks on axionic string induces a magnetic field circling the string.

From Kibble Mechanism, string network and magnetic field naturally scale with the Hubble radius soon after they form. This solves the coherence problem.

Maxwell equations get modified!

Varying our Lagrangian:

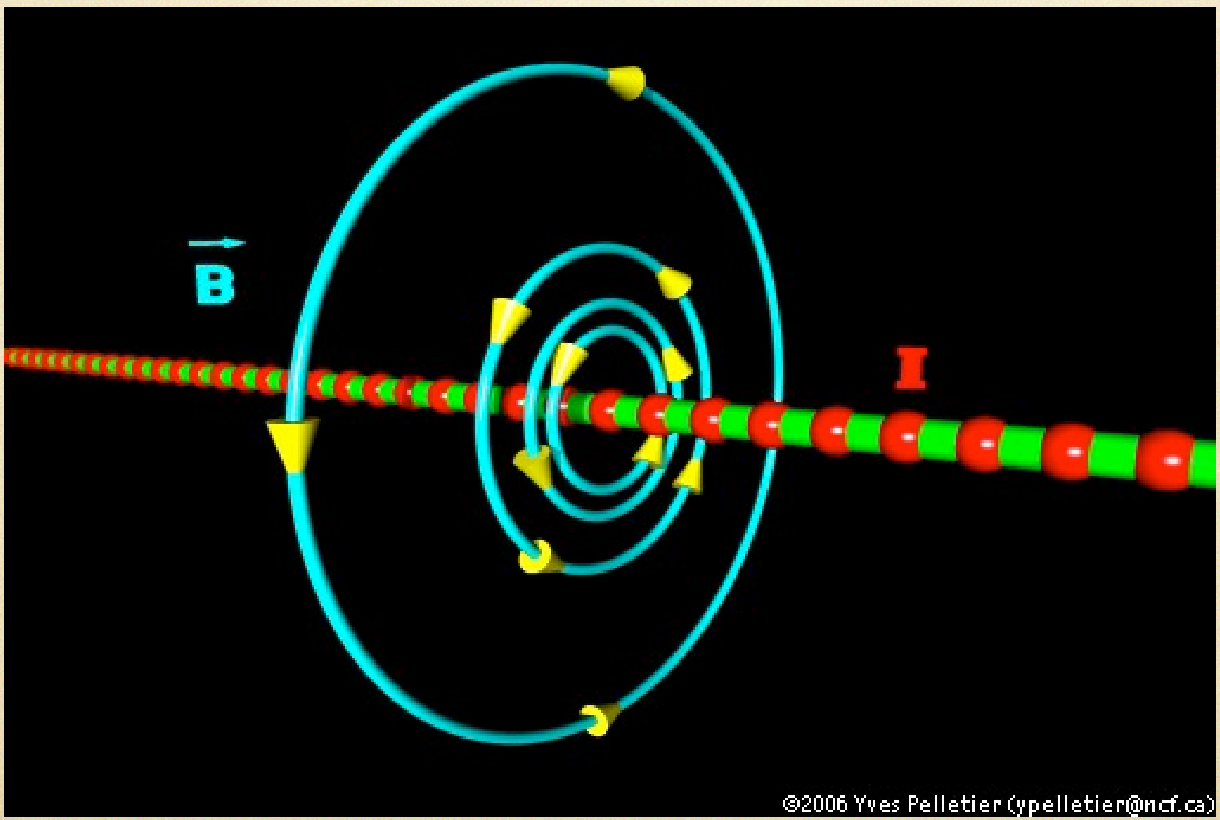
$$\partial_\mu F^{\mu\nu} = \frac{e^2}{32\pi^2}\partial_\mu \theta(x)\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$

string solution:

$$\phi = \frac{f_\pi}{\sqrt{2}}\rho(r)e^{i\theta}$$

The string will source a magnetic field -> Magnetic Induction

Analogy: Magnetic field generated by current moving along a wire (string)



Kaplan, Manohar, '88

"Fermion current is sourced by electromagnetic anomaly in string"

$$\partial_\mu J^\mu = F \wedge F$$

1) String interacts with photons and quarks.

2) Quark supercurrent along string:

a) stabilizes string.

b) generates magnetic field

The quark current generates coherent B-field outside string.

From solving the field equations, we finally obtain the magnetic field!

$$B = N_c \frac{en}{2\pi} \left(\frac{r}{r_0}\right)^{\alpha/\pi} \frac{1}{r}$$

n=number density of charge carriers on string

r=distance from string

The string network eventually aprroaches a scaling solution

$$\xi(t) \sim t^p \longrightarrow \xi(t) \sim t$$

The magnetic field will be coherent on the scale of the correlation length (Hubble Radius at End of Inflation).

$$T_c \sim 1\text{GeV}, T_d \sim 1\text{MeV}$$

After some algebra

$$B(t_0) \sim 10^{-14} \frac{T_c}{1\text{GeV}} r_{\text{kpc}}^{-1} \left(\frac{T_d}{T_c}\right)^p (rT_c)^{\alpha/\pi} \left(\frac{T_0}{T_d}\right) \text{Gauss}$$

$$B(t_0) \sim 10^{-26} (rT_c)^{\alpha/\pi} \text{Gauss}$$

In the heterotic cosmic string case:

1) The strings are stable.

2) The phase transition temperature can be larger.

This means a larger magnetic field.

Part III

Circular Polarization in the CMB and Chern-Simons

The Chern-Simons term
will produce circularly polarized
GW's

Why should we expect this?

The CMB photons are expected to be linearly polarized as there are no sources for circularly polarization in Thompson scattering.

But now the anomaly term sources circular polarization!

Anomaly Interaction:

$$\mathcal{H}_{int} = g : A \wedge T \wedge F :$$

Boltzmann Eq for photon:

$$\frac{d\rho_{ij}^{(1)}}{dt} = \frac{\partial \rho_{ij}^{(1)}}{\partial t} + \frac{\partial \rho_{ij}^{(1)}}{\partial x^i}\frac{\hat{k}^i}{a} - \frac{\partial \rho_{ij}^{(1)}}{\partial k}\frac{\dot{a}k}{a} = C$$

where

$$\frac{d}{dt}\triangle_V = 2(2g)^2\frac{a}{q}T^x T^x\Big\{\Big[(cos^2\theta+1)sin(2\phi) - cos\theta sin\theta\big(cos\phi + sin\phi\big)\Big]\triangle_U - \Big[cos\theta cos(2\phi) + sin\theta\big(sin\phi - cos\phi\big)\Big]\triangle_Q\Big\}$$

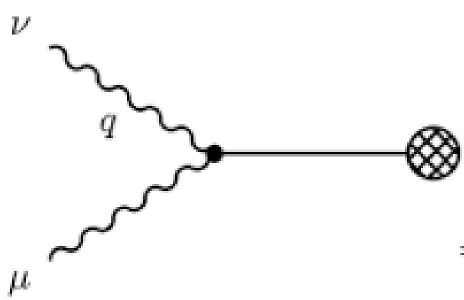
$$\triangle_V \equiv -i\Big[\frac{q}{4}\frac{\partial \rho_{11}^{(0)}(q)}{\partial q}\Big]^{-1}(\rho_{12}^{(1)} - \rho_{21}^{(1)})$$

Linear -> Circular

Our interaction term is of the form

$$\mathcal{H}_{int} = g : A \wedge T \wedge F :$$

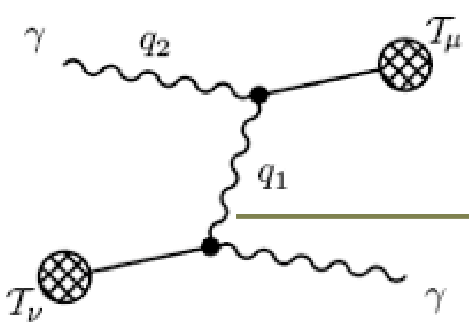
This corresponds to a vertex rule which is of the form



$$= (-ig)\epsilon^{\mu\alpha\beta\nu} T_\alpha(p)(-iq_\beta)$$

Where q_β is the momentum flowing into the labeled photon line resulting from the derivative coupling in the interaction Hamiltonian.

Now the processes which have resulted in the coupling of the V Stokes parameters with the other I, Q, and U parameters are of second order in the interaction Hamiltonian density above and of the form:



Source for Circular Polarization

Where all the diagrams are obtained by permuting the q_1 and q_2 on the available photon lines.

Soon to come...

A Direct Source of Circular Polarization in the CMB

S.A, A. Kosowsky, J. Ochoa

Future Mission

In 2367, the USS *Enterprise*-D was nearly destroyed after an encounter with a cosmic string fragment approximately one hundred and seven kilometers in length. The ship inadvertently became trapped by a group of two-dimensional lifeforms who lived in the string and were attempting to return home. In order to escape, the *Enterprise* used its parabolic dish to simulate the vibrations of the string long enough to confuse the lifeforms and disrupt their hold on the *Enterprise*. After the *Enterprise* was freed, the lifeforms continued on course to the string.

Conclusion & Outlook

- Baryon asymmetry and origin of primordial magnetic field mystery combine cosmological dynamics with model independent modifications of GR and standard model from string theory.
  - Potential for new observations in circular polarization in future CMB missions (POLARBEAR telescope with Keating and Lee)
  - Could these ideas be implemented in Ekpyrotic scenario of Khoury, Ovrut and Steinhardt?
- What is the effect of these anomalies on Lensing?
- What about the dark sector (dark matter and dark energy)?