Title: Antimatter from nonperturbative field configurations and magnetic fields

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Abstract: Observations of the Milky Way by the SPI/INTEGRAL satellite have confirmed the presence of a strong 511 KeV gamma-ray line emission from the bulge, which require an intense source of positrons in the galactic center. These observations are hard to account for by conventional astrophysical scenarios, whereas other proposals, such as light DM, face stringent constraints from the diffuse gamma-ray background. I will describe how light superconducting strings could be the source of the observed 511 KeV emission. The associated particle physics, at the ~ 1 TeV scale, is within reach of planned accelerator experiments, while the scenario has a distinguishing spatial distribution, proportional to the galactic magnetic field. I will also discuss how cosmic magnetic fields of nano-Gauss strength today could have been created at the time of baryogenesis. In addition to being astrophysically relevant, such magnetic fields, which are helical, can provide an independent probe of baryogenesis and CP violation in particle physics.

Antimatter from nonperturbative field configurations and magnetic fields

Francesc Ferrer

Case Western Reserve University

Perimeter Institute, June 2008

Outline

1. The 511 KeV line
2. Superconducting cosmic strings
3. Magnetic fields from Sphaleron decays

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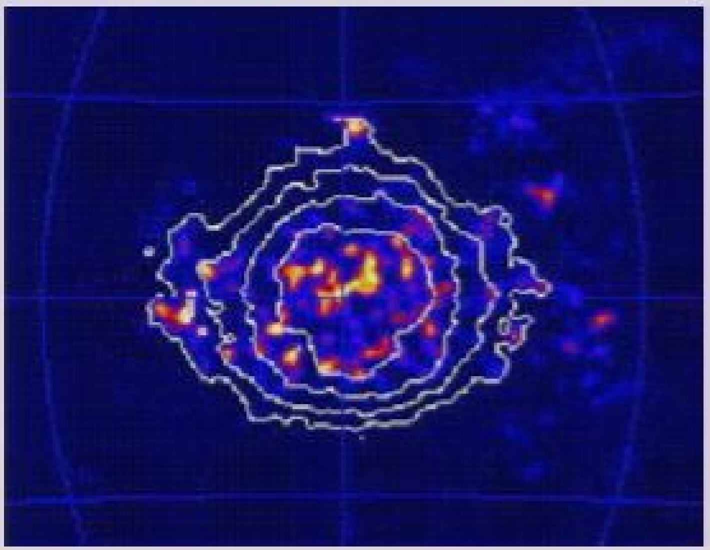
511 KeV emission from the Galactic Center



INTEGRAL results

- The SPI experiment observes a diffuse flux of $\sim 10^{-3}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 511 KeV from the GC `Knödlseder et. al. 05`
- Difficult to generate $10^{43} e^{+}/s$

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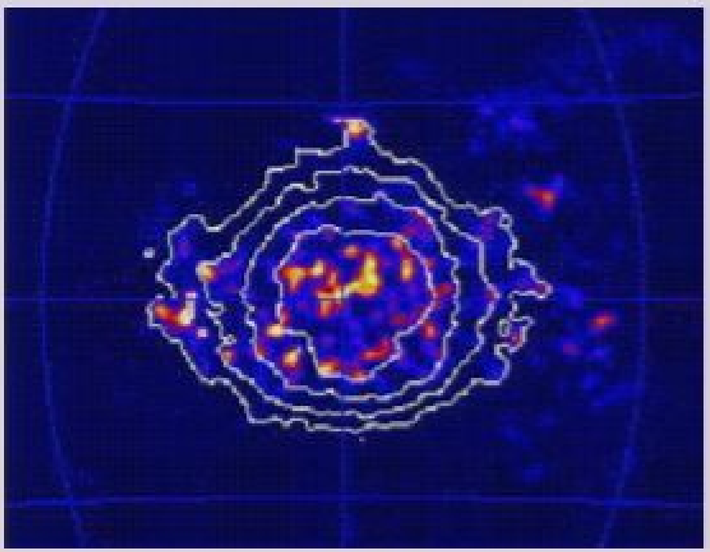

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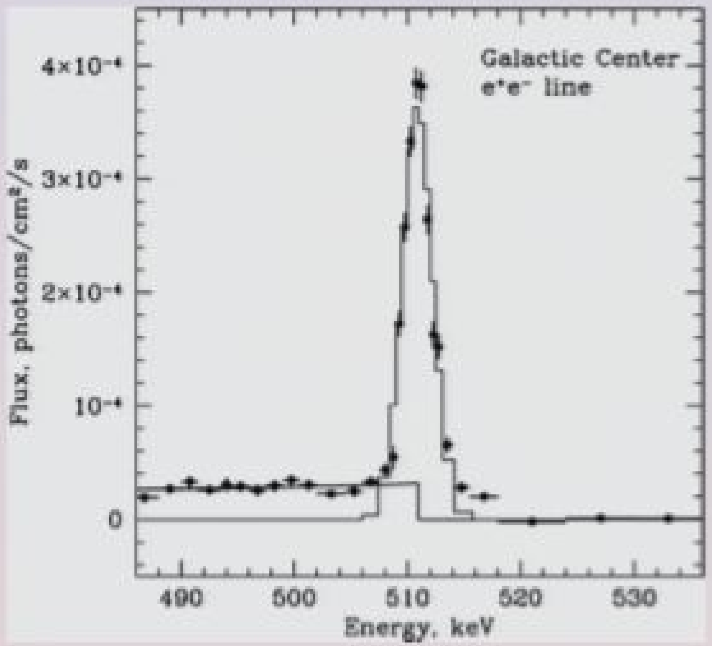

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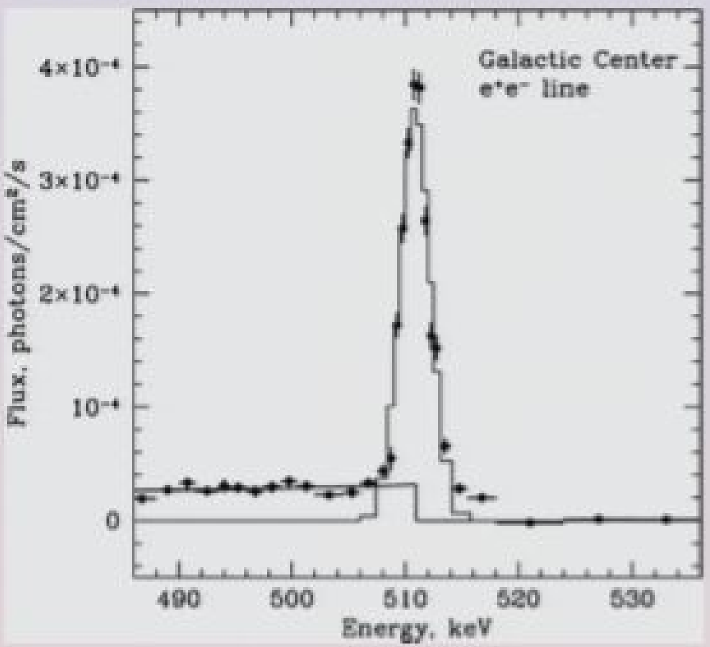

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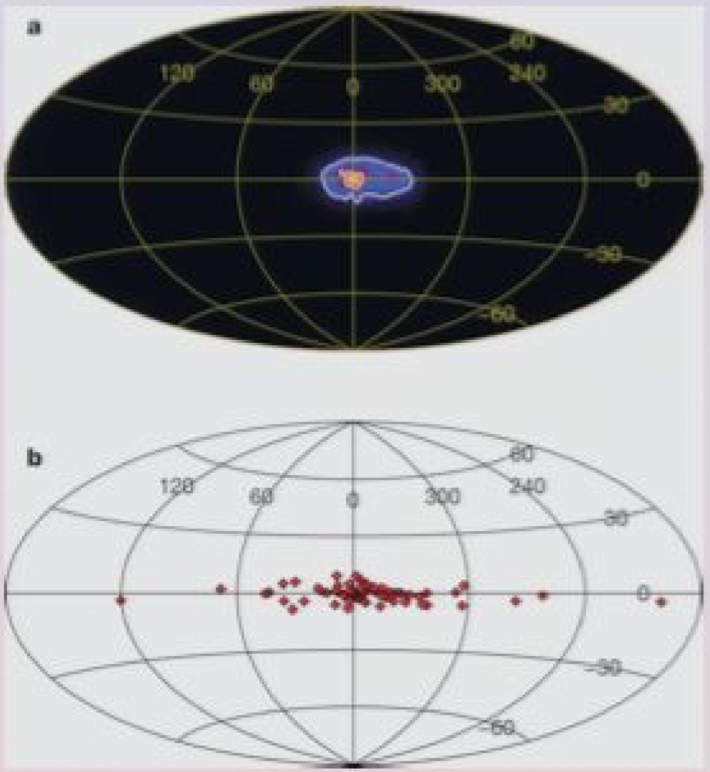
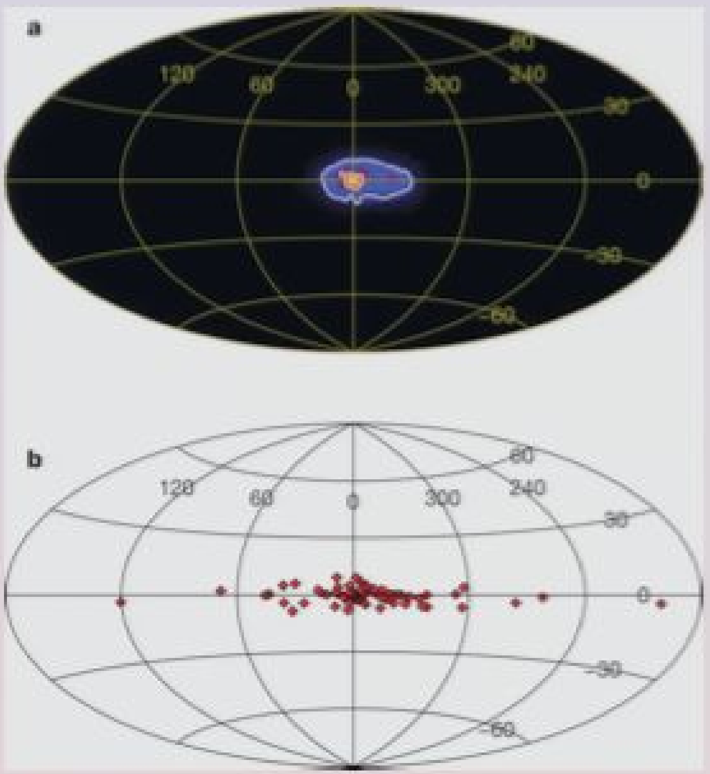
2008 update: X-ray binaries?



- The *disk* emission is asymmetric, like that of LMXBs Weidenspointner et. al. 08
- The bulge/disk luminosities are still 3-9

2008 update: X-ray binaries?



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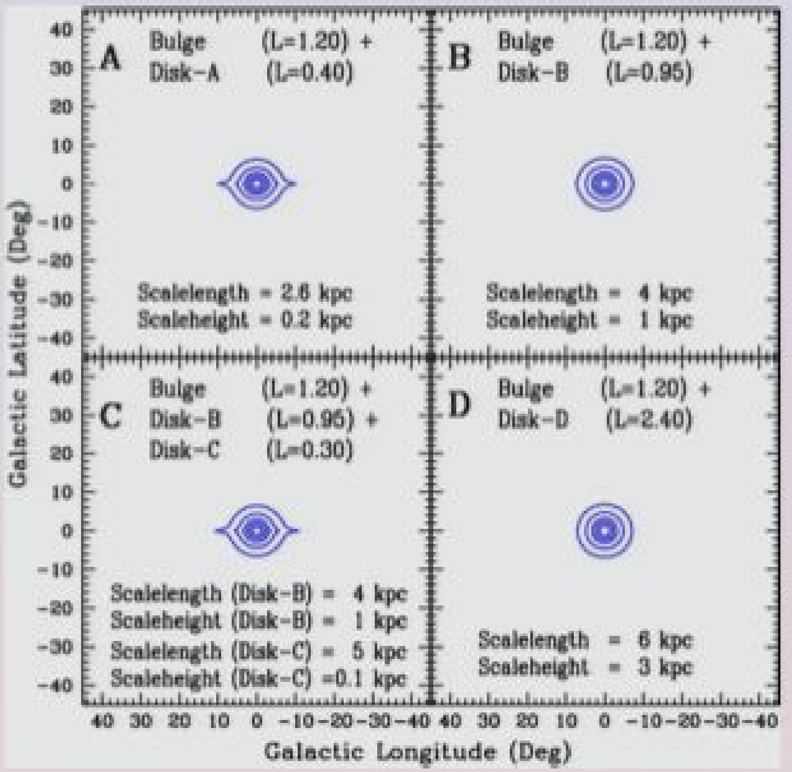
CASE

Astrophysical models



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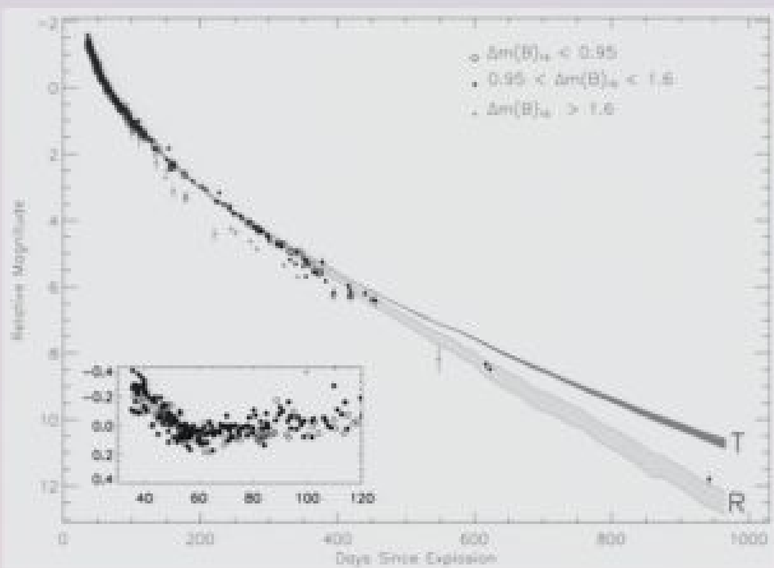

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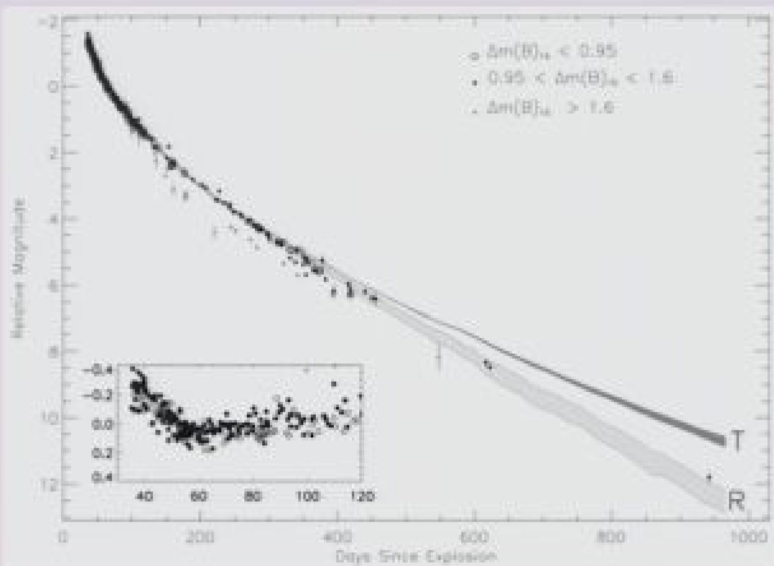

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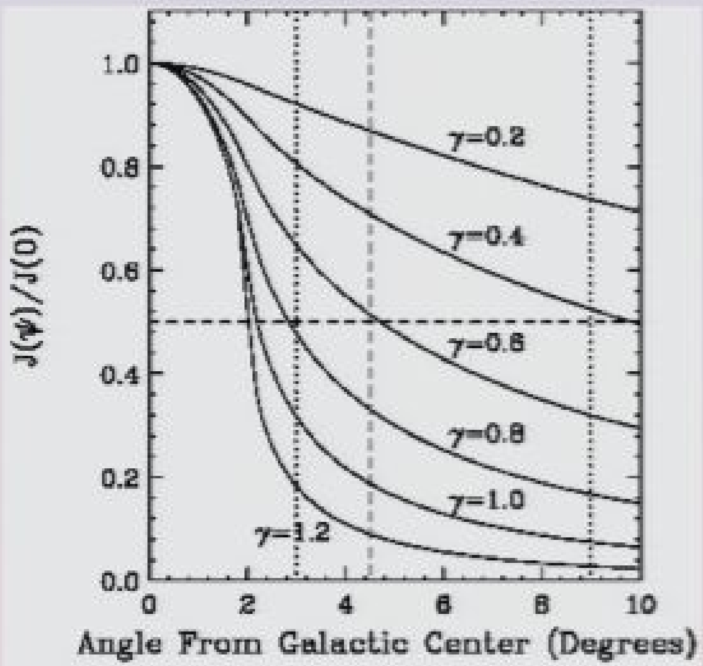

Light DM, $m_{DM} \sim 1 - 100\mathrm{MeV}$, could generate the positron flux

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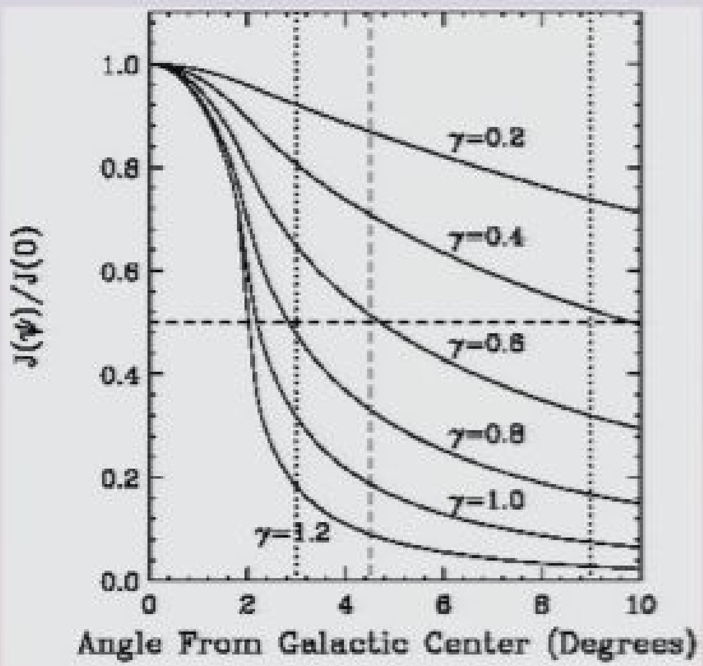

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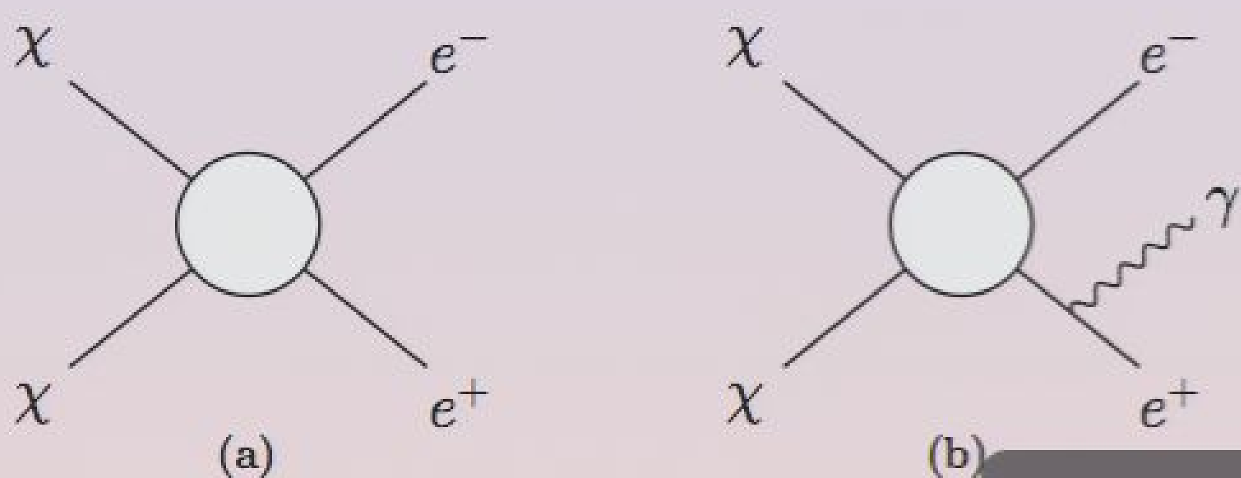
Constraints on a light DM solution

10 MeV DM

- EGRET observations require the mass to be in a narrow range $m_{DM} \sim 1 - 10\text{MeV}$ Beacom et. al. 05, 06
- Difficult to build natural PP models



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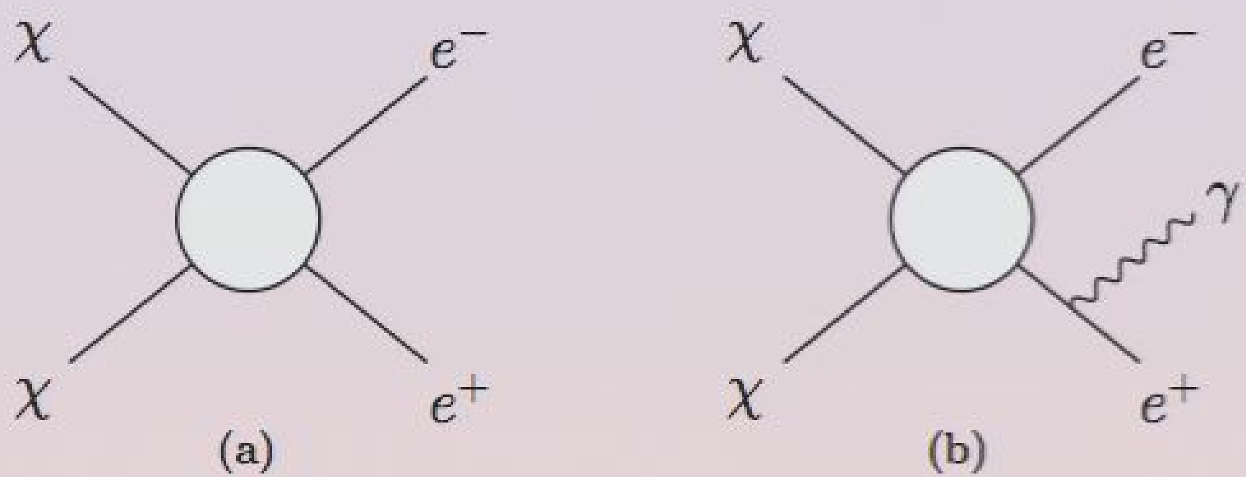
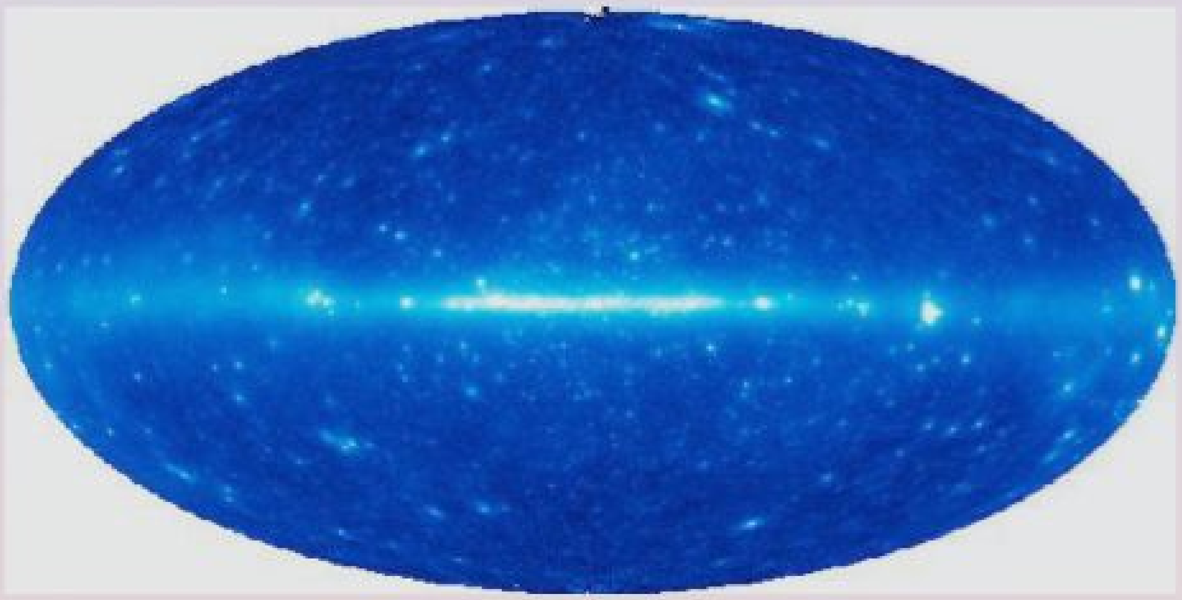


Constraints on a light DM solution

Clumps of DM should be detected Hooper, FF, et. al. 04



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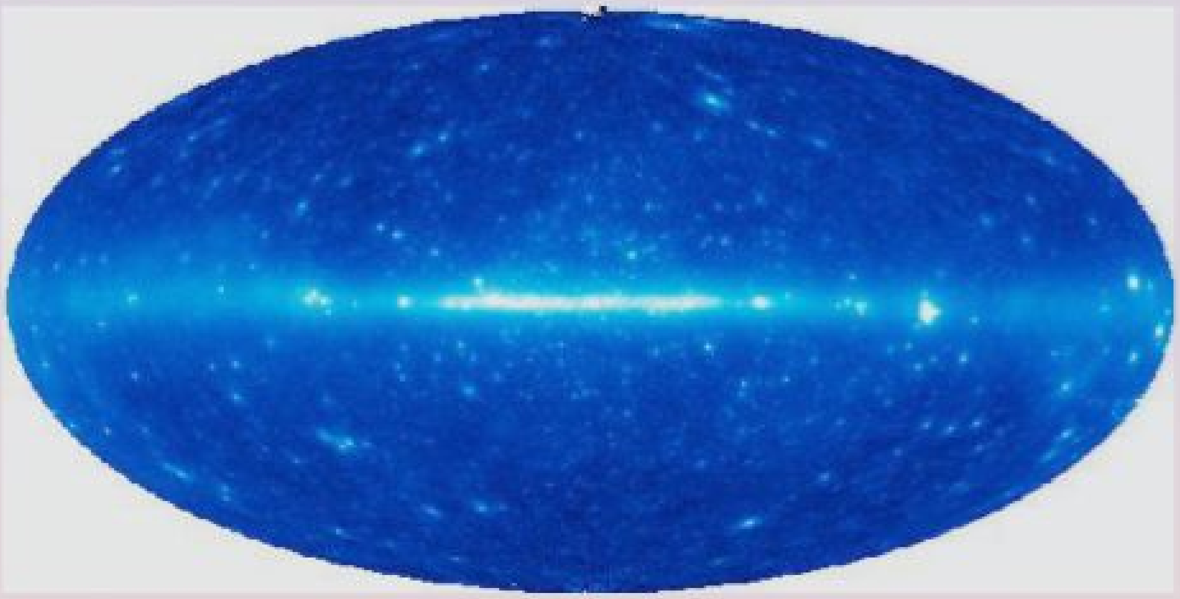
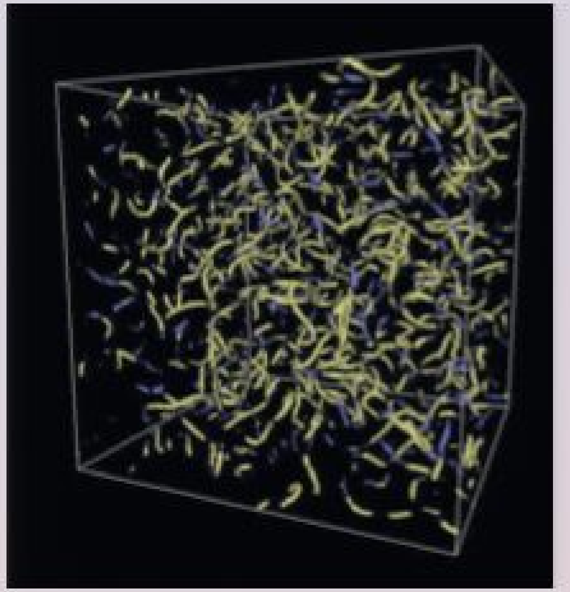
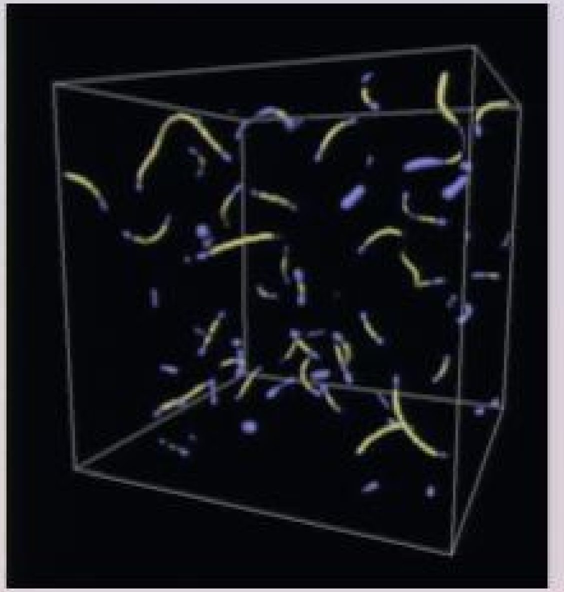


Superconducting cosmic strings





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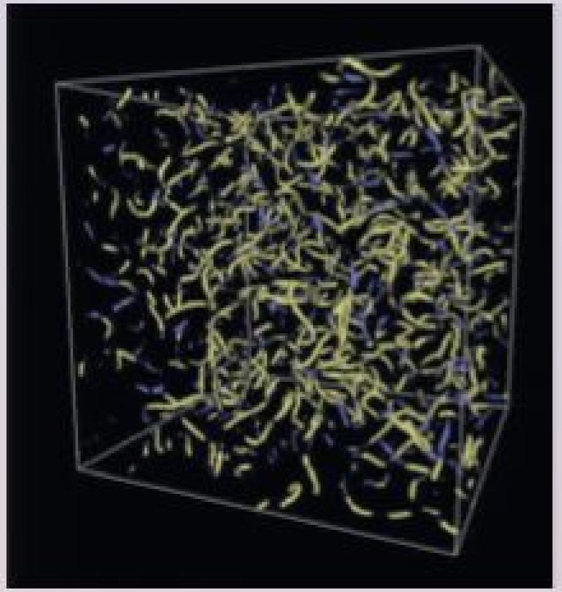

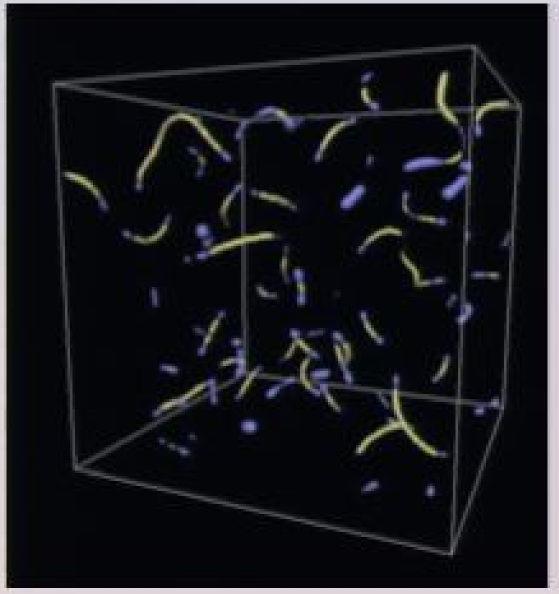

String SC

It might be energetically favorable for a bosonic field to become non-trivial within the string. If the condensate is electrically charged, the string becomes superconducting. Witten 85

$$\mathcal{L} = \mathcal{L}[\phi] + \mathcal{L}[A_\mu] + K[\chi] - V[\phi, \chi]$$

$$\mathcal{L}_{eff}(\theta) = \frac{1}{2}(\partial_\mu \theta - eA_\mu)^2 , \quad \chi = \chi_0(x) e^{i\theta}$$

Fermionic fields might be coupled to the string via Yukawa. The Dirac equation in the string background might have bound state solutions, with dispersion relation $\omega = k$, that are responsible for the fermion SC.

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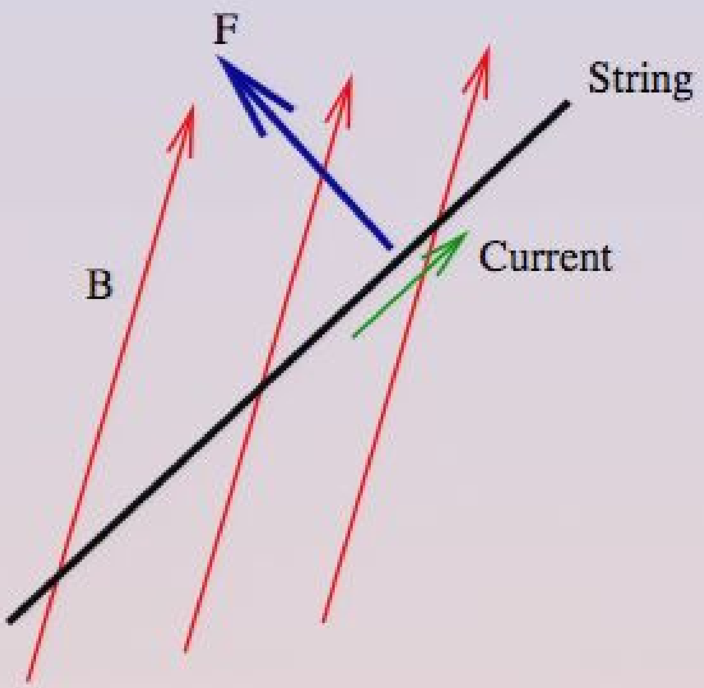
SC strings in a magnetic field `FF, Vachaspati 05`



Faraday's law

- A current composed of zero modes is created when strings cut across the MW magnetic field $\sim ev_* BR_*$
- $\frac{dN_Y}{dt} \sim ev_* B \frac{L^3}{R_*^2}$

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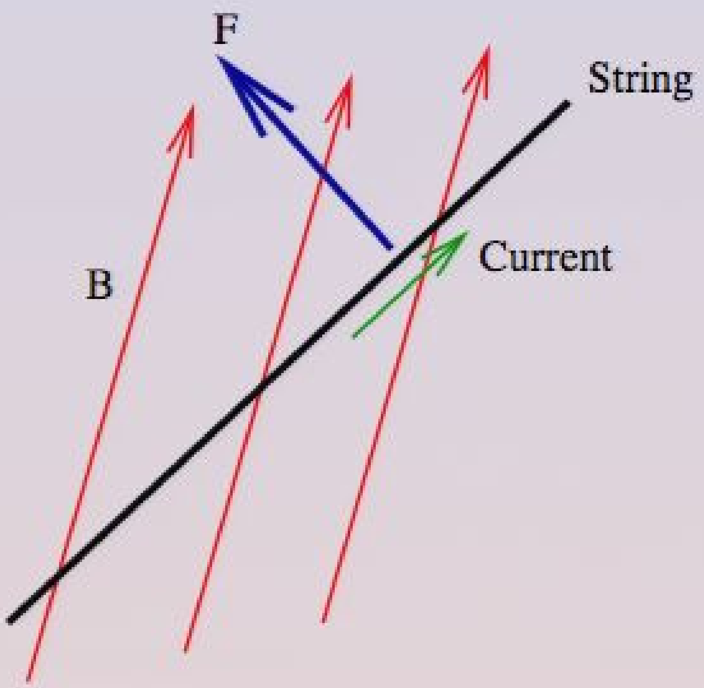

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CASE

String dynamics in a plasma Chudnovsky et. al. 86

$F_s(\mu, R) \sim F_{drag}(J, \rho)$

- $R < R_c \sim \frac{\mu}{\sqrt{\rho J}} \Rightarrow v \sim c$, decouple and annihilate
- $R > R_c \Rightarrow v_{term} \sim \frac{\mu}{\sqrt{\rho J R}}$, overdamped
- In a turbulent plasma, for $R > R_*$, strings are carried along with the plasma, $v < v_l$, and get entangled until $R \sim R_*$. The length density of strings is $\rho_l \sim \frac{1}{R_*^2}$

$$R_* \sim l \left(\sqrt{\frac{\mu}{\rho}} \frac{1}{e\kappa v_l l} \right)^{4/5} , \quad v_* \sim v_l \left(\sqrt{\frac{\mu}{\rho}} \frac{1}{e\kappa v_l l} \right)^{1/5} .$$

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Antimatter generation

Positron rate

- Faraday's law gives the rate of positron production:

$$\frac{dN_{\mathrm{V}}}{dt} \sim e v_* B \frac{L^3}{R_*^2} \sim e^{12/5} B \kappa^{7/5} \frac{L^3}{l^3} \left(\frac{\rho}{\mu}\right)^{7/10} (v_l l)^{12/5}$$

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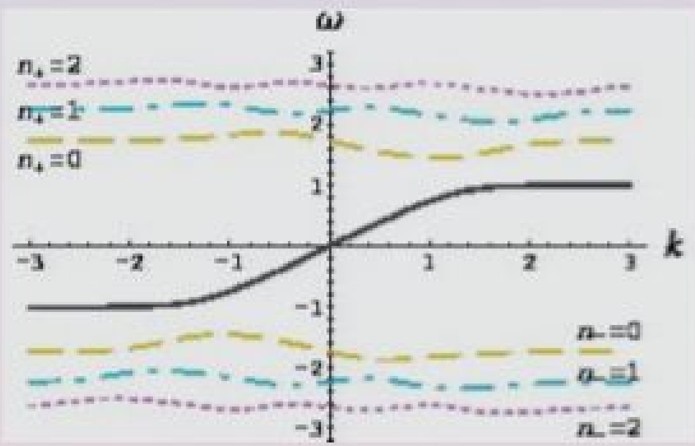
Zero modes in a B field FF et. al. 06



Landau levels on a string

- The same B field that creates the current, changes the dispersion relation of the zero modes: $\omega_k = m_{e^+} \tanh\left(\frac{k}{k_*}\right)$.
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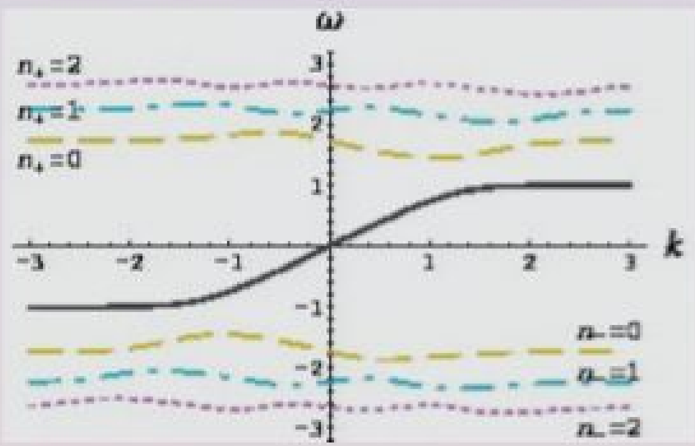

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Cosmic Magnetic Fields

Cosmic magnetic fields can be generated from primordial seeds associated with a phase transition. Processes like electroweak baryogenesis imply magnetic fields with finite helicity:

$$h = \frac{1}{V}\int_V d^3x\, \mathbf{A}\cdot\nabla\times\mathbf{A}.$$

Observation of helical primordial fields could be used as a probe of particle physics and cosmology at the epoch of baryogenesis.

Also, helicity is nearly conserved in the early universe, and fields with a very short correlation length are transformed into fields homogeneous on much longer scales.

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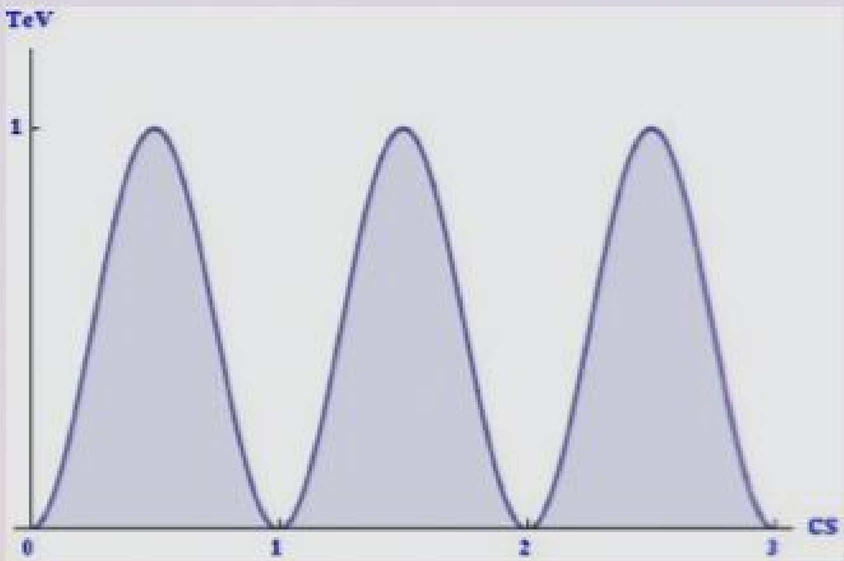
Baryon number violation, $\not{\mathcal{B}}$, is a crucial ingredient of all baryogenesis scenarios. Electroweak interactions violate $\mathcal{B}$ through nonperturbative sphaleron transitions.



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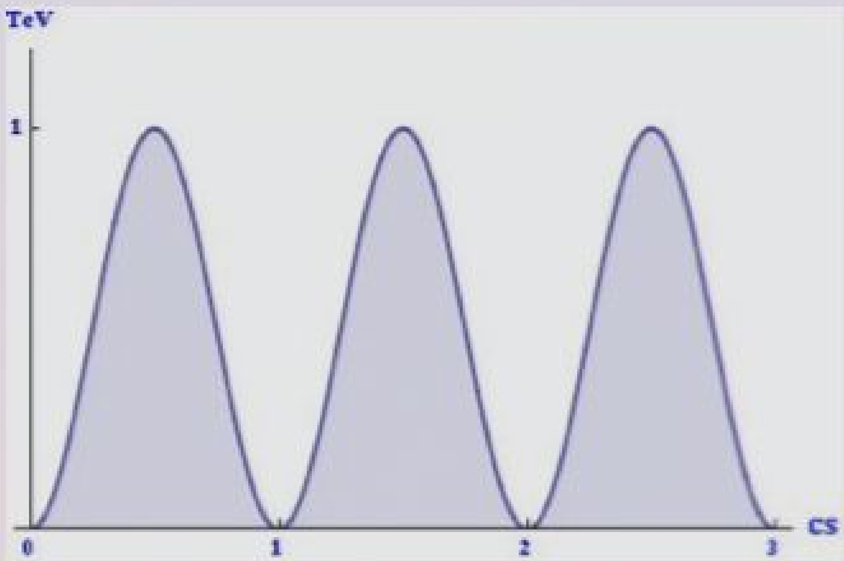

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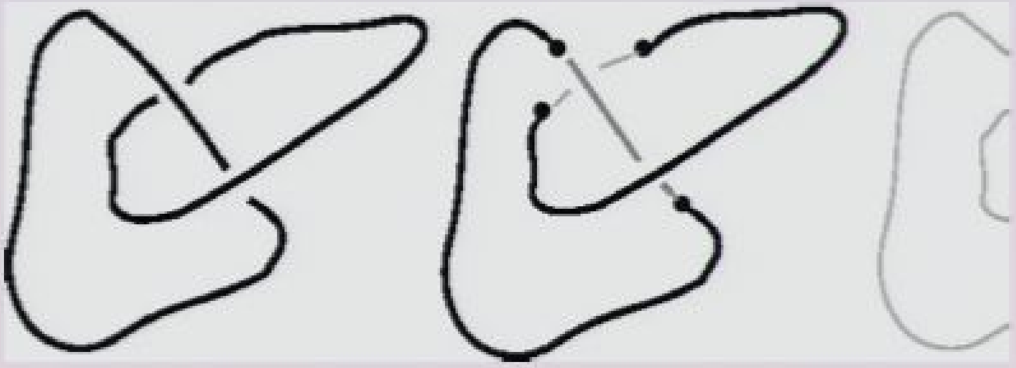

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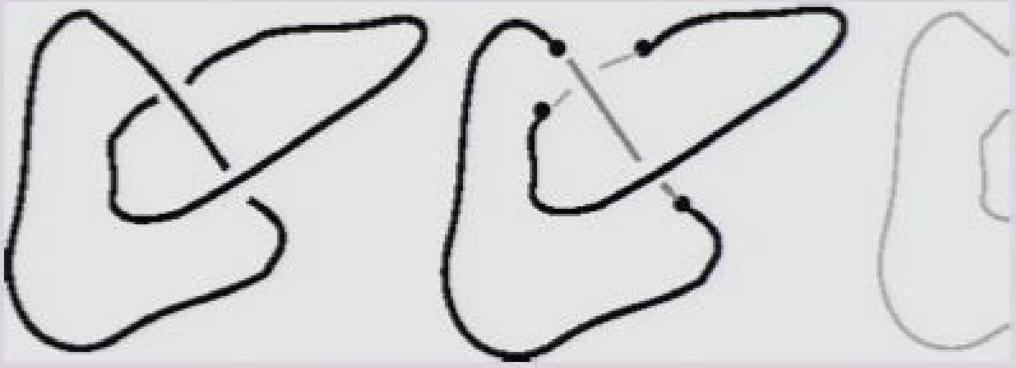

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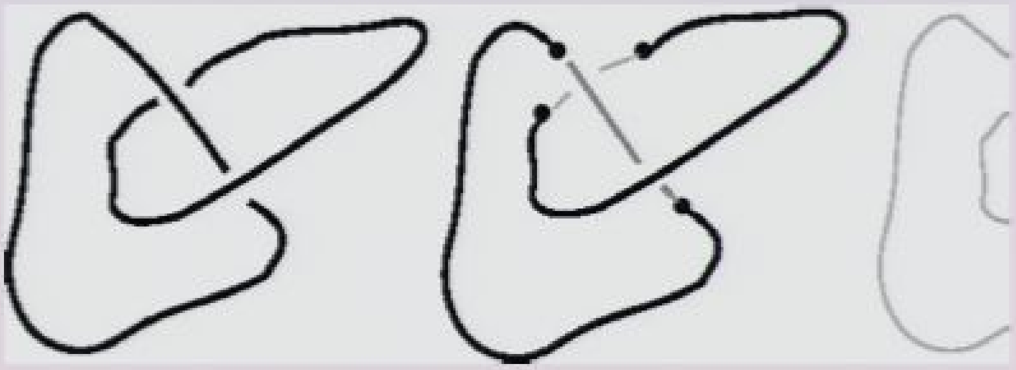

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Evolution on the lattice Copi, FF, Vachaspati, Achúcarro 08

1. Discretize the Higgs-$SU(2) \times U(1)$ equations of motion:

$$Y_\mu, W^a_\mu \to U^p_j = e^{ig' B^p_j \Delta x/2} e^{ig \mathbf{W}^p_j \cdot \boldsymbol{\tau} \Delta x/2}$$

2. Set up numerically a configuration like the ew sphaleron.
3. Go to unitary gauge to measure the electromagnetic field strength and compute helicity.

$$A_\mu = \sin\theta_W n^a W^a_\mu + \cos\theta_W B_\mu$$

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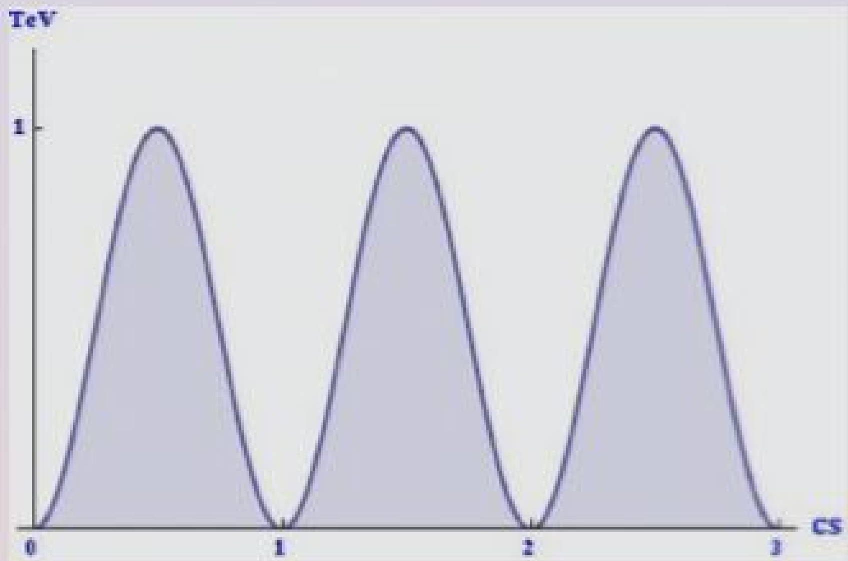

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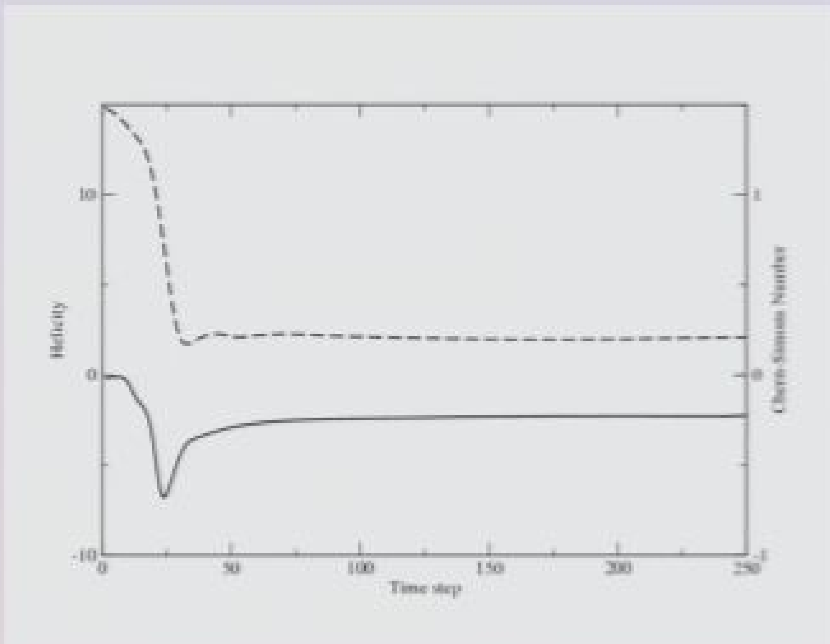

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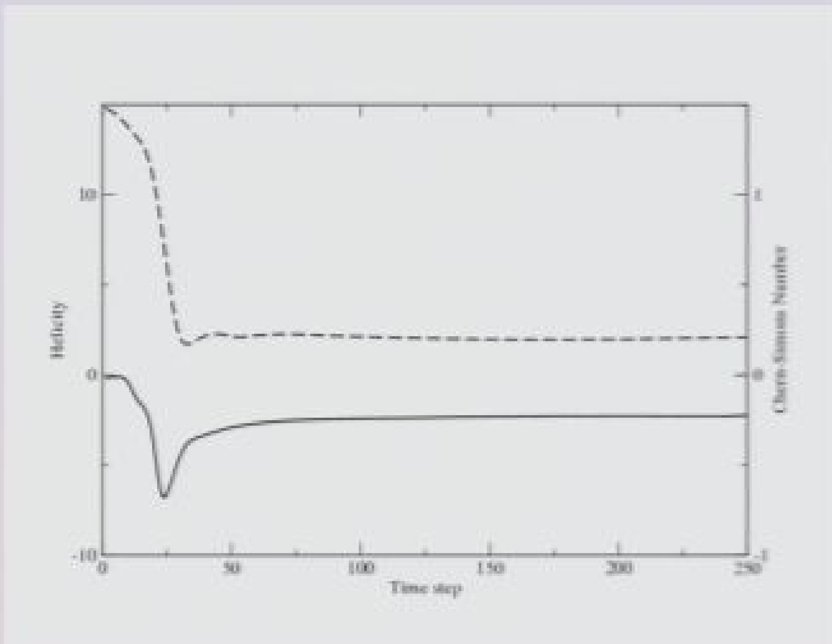

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Bound on baryogenesis from B?

We can estimate that $B_{rec} \sim 10^{-13}G$, assuming proportionality to net B, $N_b - \bar{N}_b$.

However, *every* baryon number violating reaction produces magnetic fields, which should be proportional to $N_b + \bar{N}_b = 2N_b - \epsilon$. Some of the magnetic fields might cancel out, but an enhancement could be in place, $B_{rec} \sim r10^{-13}G$.

BBN bounds $r < 10^{13}$.

For the SM, $\frac{N_b+\bar{N}_b}{N_b-\bar{N}_b} \sim 10^{20}$, which results in $r \sim 10^{10}$ for Brownian evolution, or $r \sim 10^{20}$ if the magnetic field is conserved!

Summary

- The e^+ source at the GC is not known. Bulge/disk ratio hard to explain in astrophysical scenarios and light DM solution is very constrained.
- SC strings can explain the observed emission. The flux tracks the B field, and other zero modes could produce correlated signals ($\bar{p}$ at GeV, HEAT excess, ...). Related to new (non-perturbative) physics at the EW scale.
- Helical magnetic fields are generated by baryon violating processes at the electroweak scale. It may be possible to derive constraints on particle physics from limits on cosmic magnetic fields.

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- Helical magnetic fields are generated by baryon violating processes at the electroweak scale. It may be possible to derive constraints on particle physics from limits on cosmic magnetic fields.

String SC

It might be energetically favorable for a bosonic field to become non-trivial within the string. If the condensate is electrically charged, the string becomes superconducting. Witten 85

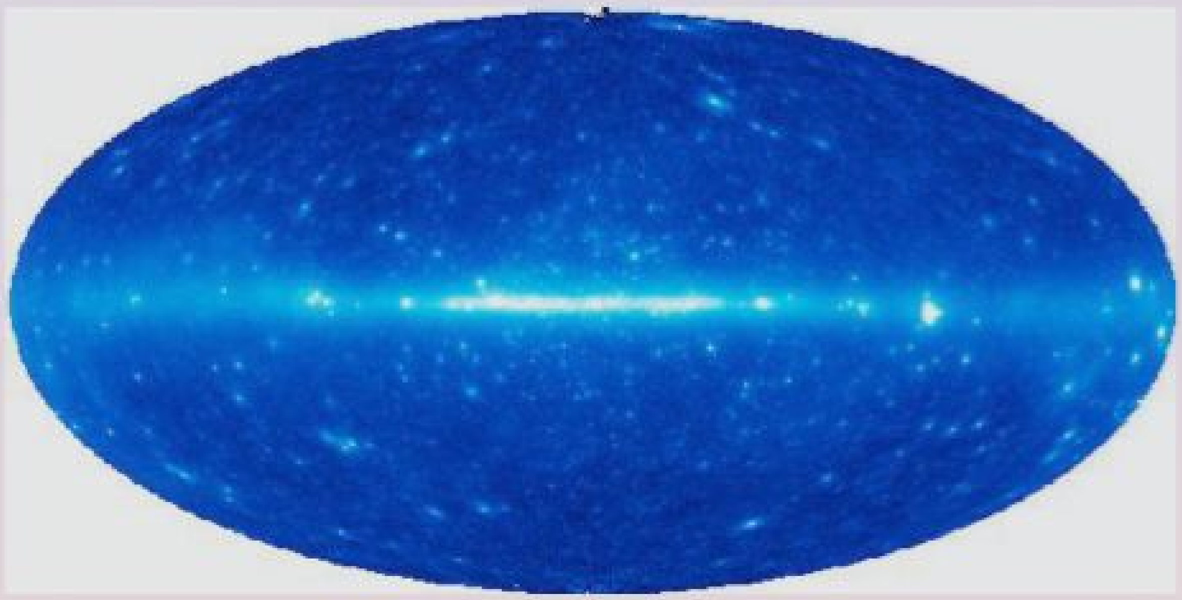
$$\mathcal{L} = \mathcal{L}[\phi] + \mathcal{L}[A_\mu] + K[\chi] - V[\phi, \chi]$$

$$\mathcal{L}_{eff}(\theta) = \frac{1}{2}\left(\partial_\mu \theta - eA_\mu\right)^2, \quad \chi = \chi_0(x)e^{i\theta}$$

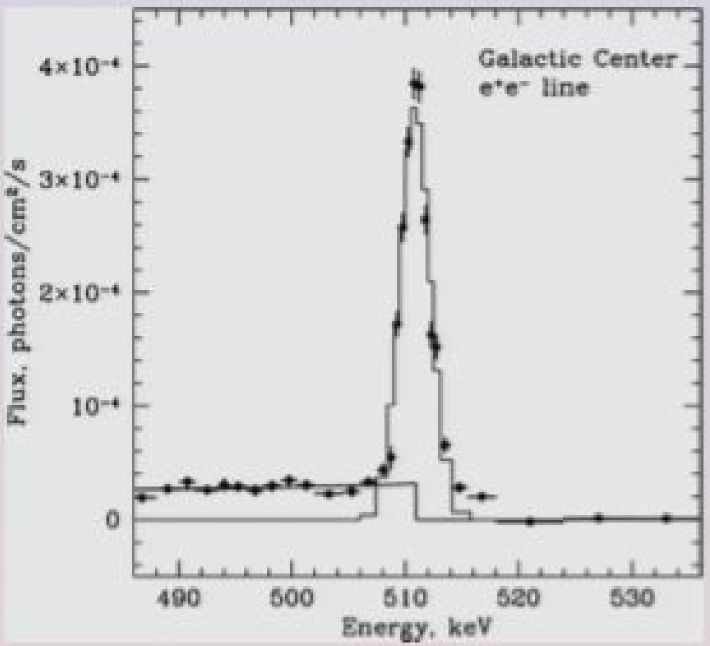
Fermionic fields might be coupled to the string via Yukawa. The Dirac equation in the string background might have bound state solutions, with dispersion relation $\omega = k$, that are responsible for the fermion SC.

Constraints on a light DM solution

Clumps of DM should be detected Hooper, FF, et. al. 04



511 KeV emission from the Galactic Center



INTEGRAL results

- The SPI experiment observes a diffuse flux of $\sim 10^{-3}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 511 KeV from the GC `Knödlseder et. al. 05`
- Difficult to generate $10^{43} e^{+}/s$

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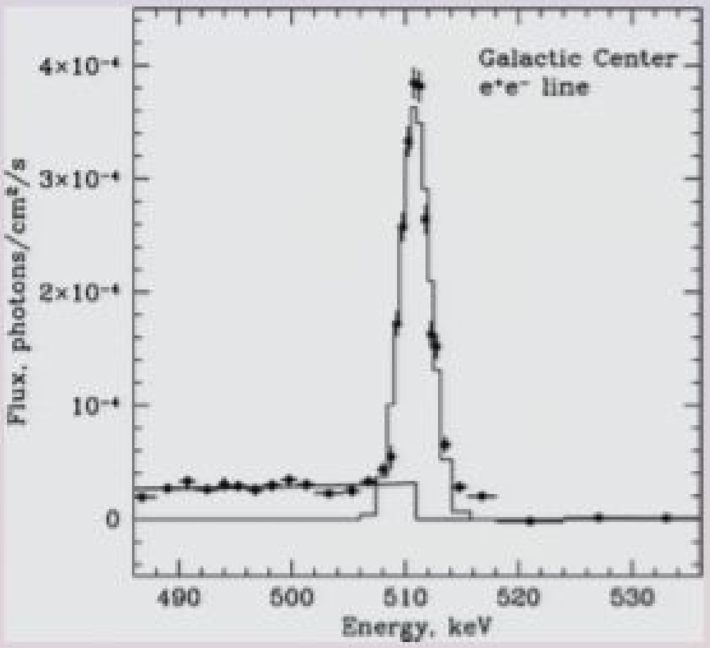

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