Baryogenesis

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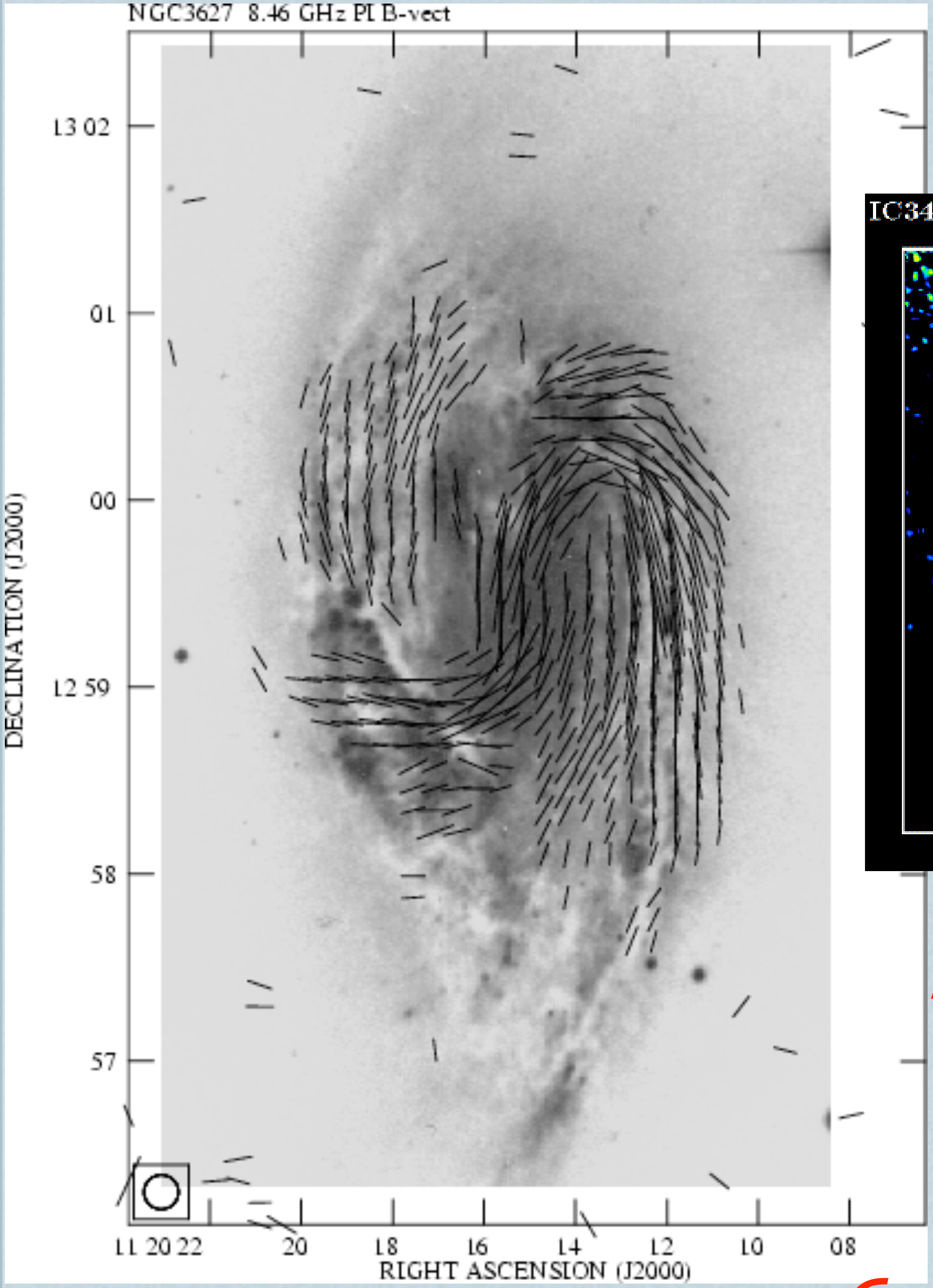
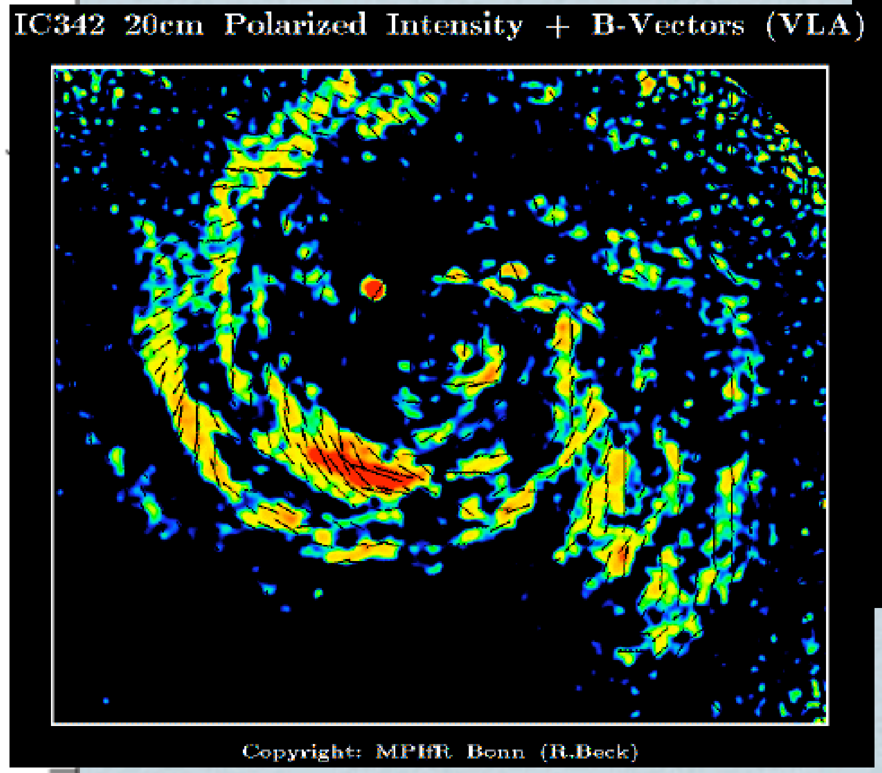
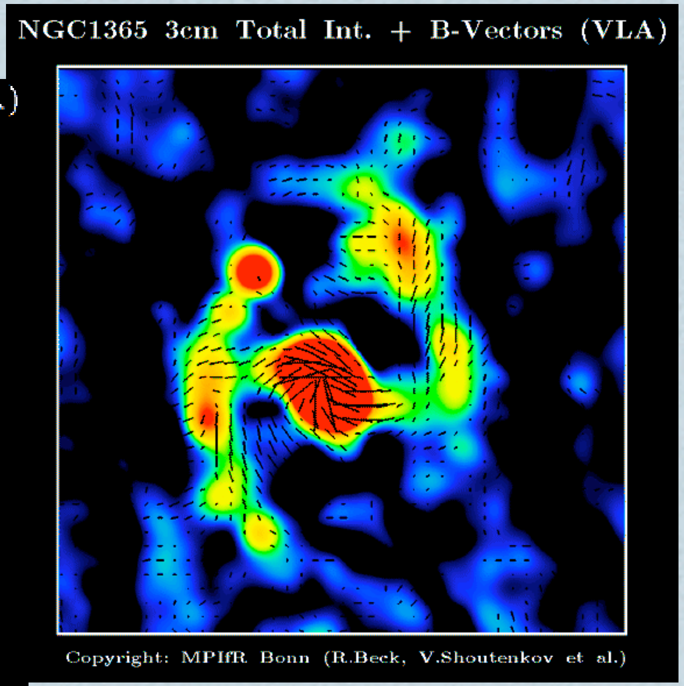
Observations







Magnetic fields are ubiquitous in astrophysics

$\sim 10^{-6}\text{G in galaxies, clusters of galaxies}$

e.g. Kronberg review, 1994

Cosmological magnetic fields yet to be observed.

Origins of galactic $\vec{\mathbf{B}}$

astrophysical

early universe

Biermann battery

$p \neq \bar{e}$

e.g. Kulsrud et al, 1997

vorticity

Harrison, 1970
Vachaspati & Vilenkin, 1991
Battefeld et al, 2008
Hollenstein et al, 2008

inflation

Turner & Widrow, 1989
Ratra, 1992
....

phase transitions

Hogan, 1983
Vachaspati, 1991, 1994, 2001
Cornwall, 1997
...

→ seed field

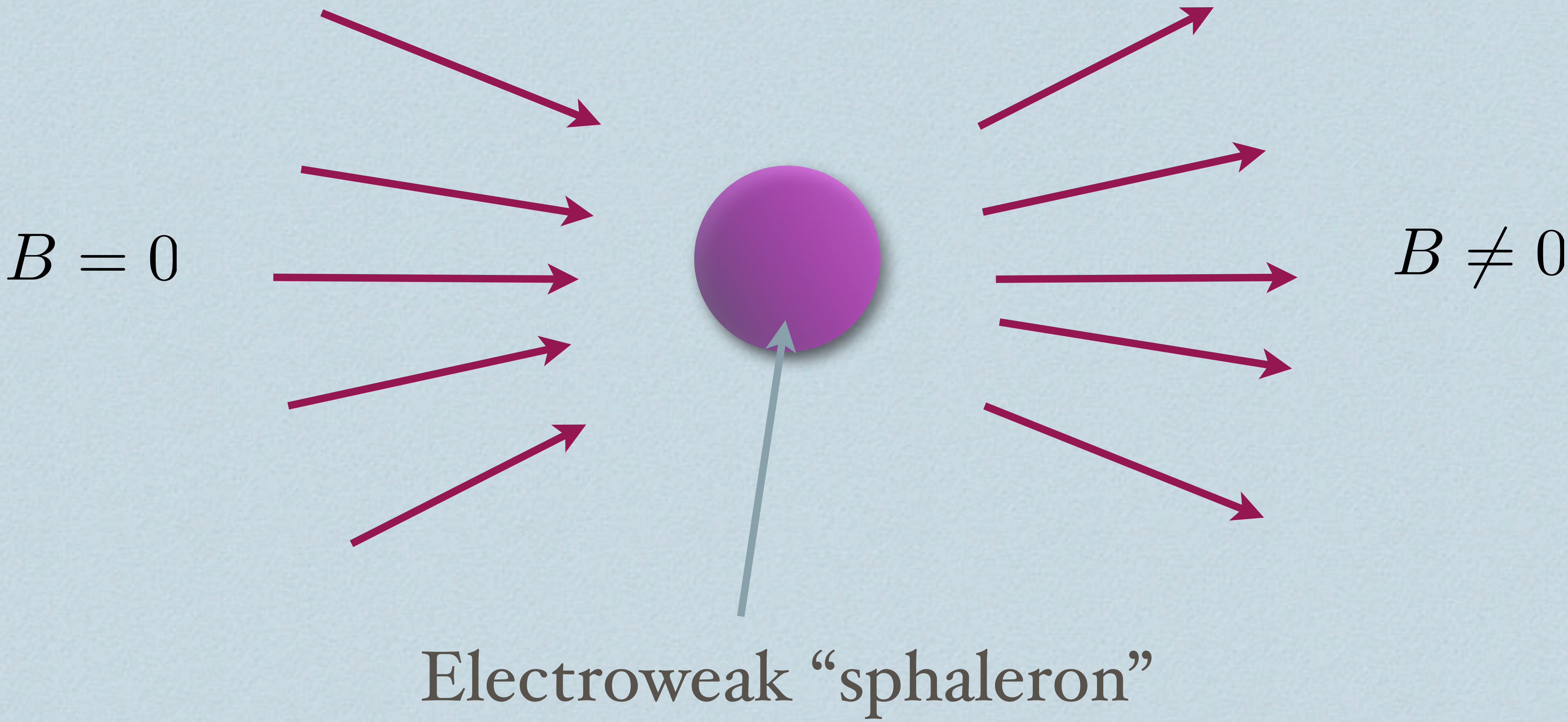
+ galactic dynamo

Inflation vs. Phase Transition

Pro: large coherence scale
Con: unconstrained models

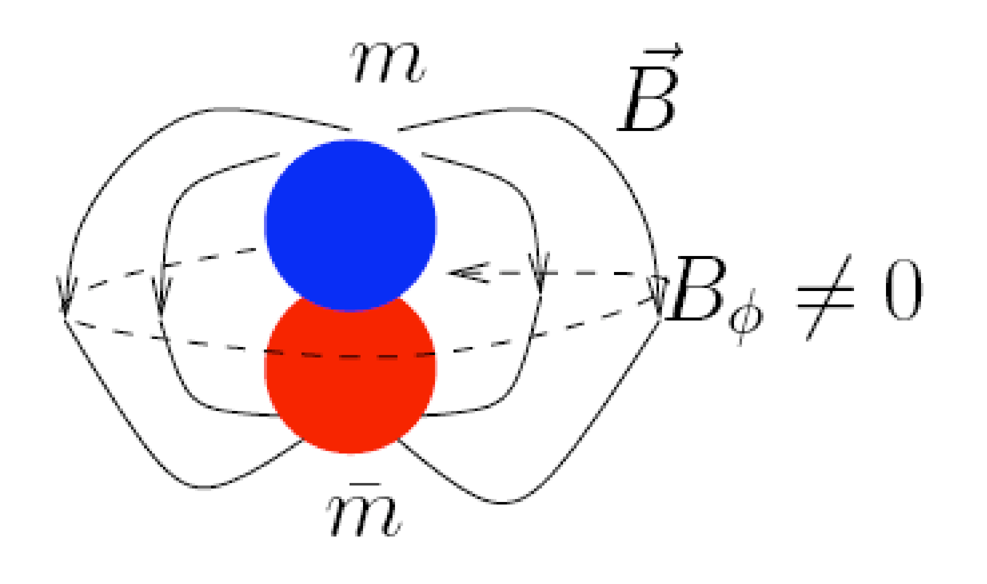
Pro: tight particle physics
Con: small coherence scale (?)

Baryogenesis



More about the sphaleron

Vachaspati & Field, 1991
Hindmarsh & James, 1992

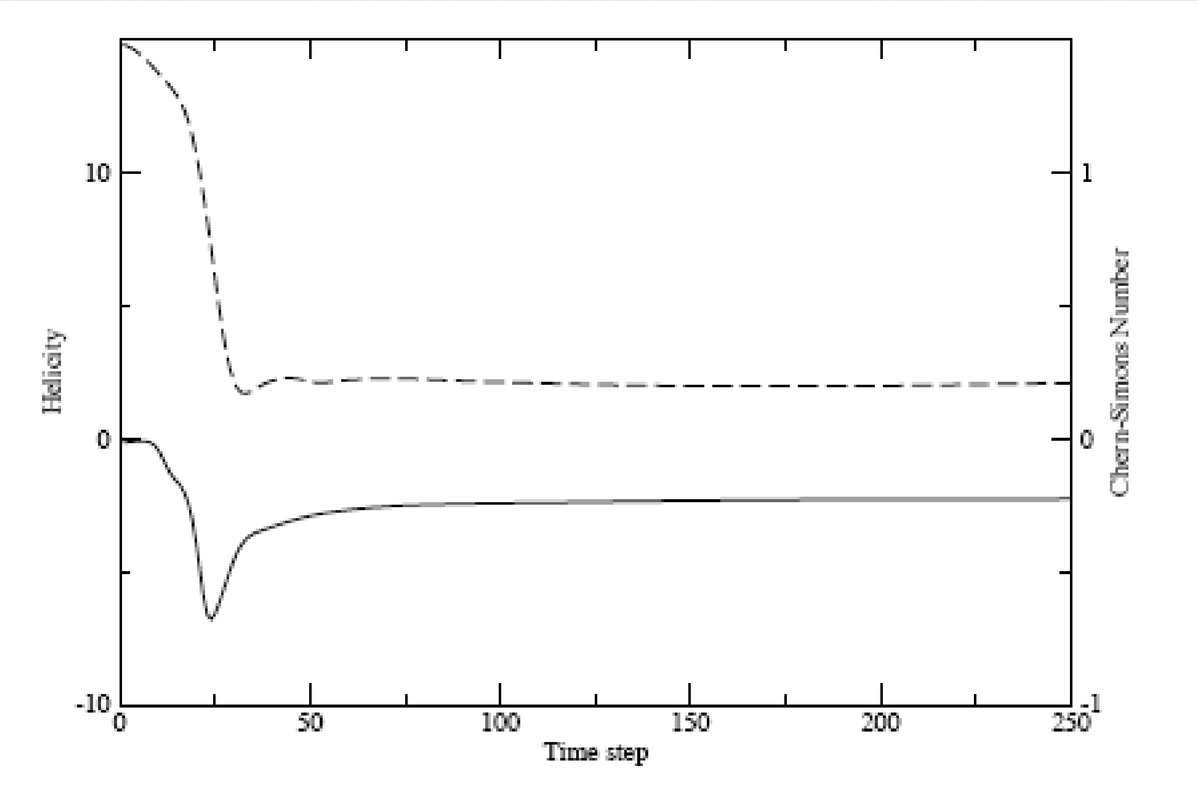


Sphaleron decay -- monopole annihilation -- produces magnetic fields with helicity.

Baryon-$\vec{B}$

A. Achucarro, C. Copi, F. Ferrer & TV, 2008

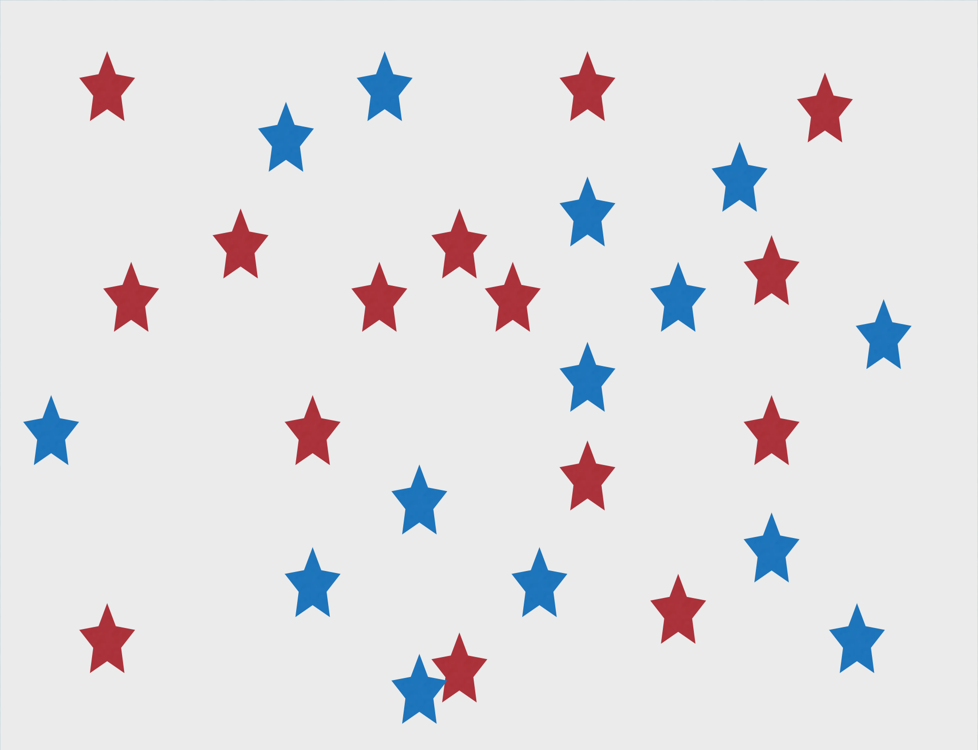
Each sphaleron decay produces magnetic fields with helicity.



Note: conservation of helicity in electroweak evolution!

Baryogenesis

Baryons produced in certain sphaleron decays.
Other decays produced anti-baryons.
Slight excess of baryon producing decays.



Sphaleron-antisphaleron gas.

Baryon number & Helicity

$$h \approx \frac{n_B}{\alpha}$$

Cornwall, 1997
Vachaspati, 2001

$$h = \frac{1}{V} \int d^3x \; \mathbf{A} \cdot \mathbf{B}$$

$$n_B(t_0) \approx 10^{-6}/\mathrm{cm}^3$$

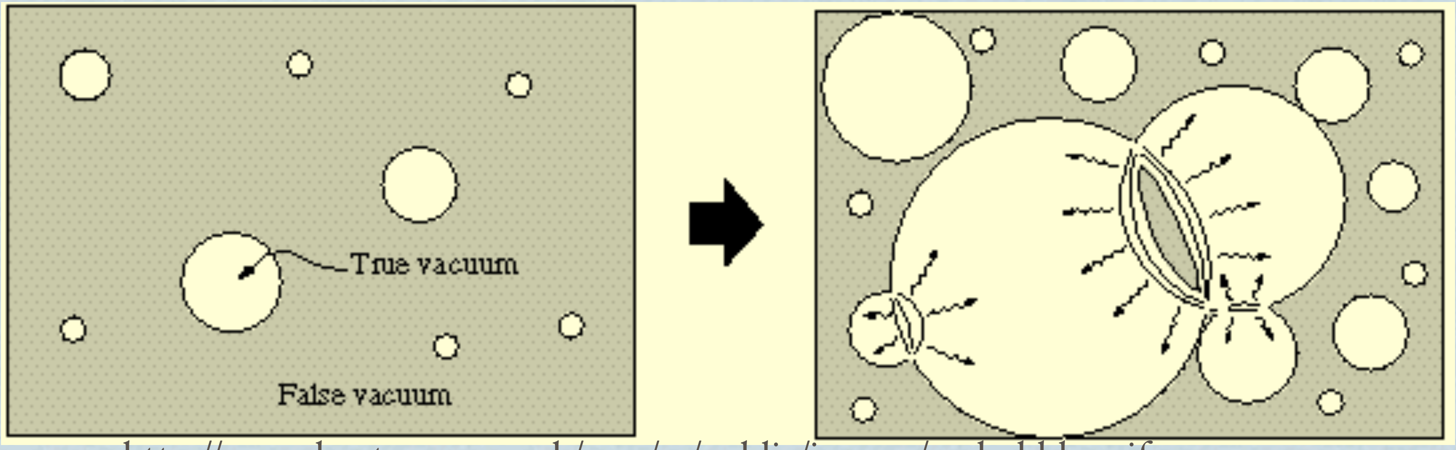
$(\alpha = e^2/4\pi\hbar c = 1/137)$

Magnetic helicity & baryon number are conserved.

So relation holds at all times.

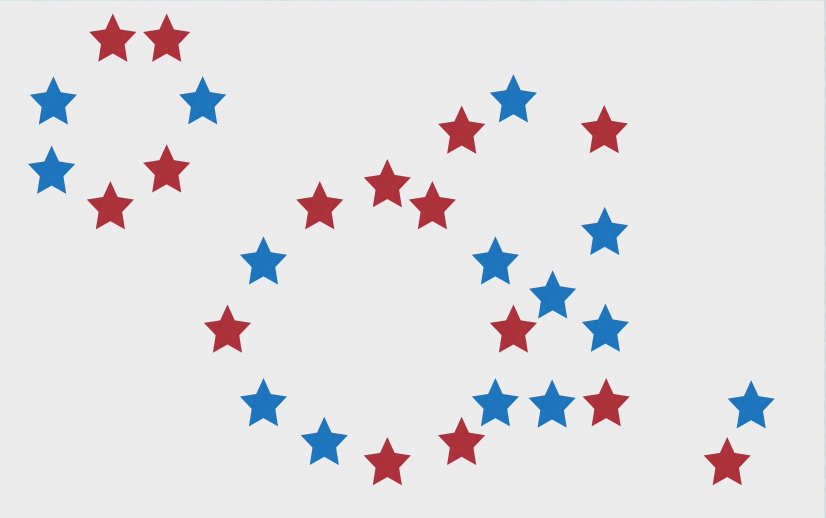
Phase Transition

Out of equilibrium during first order phase transitions.



http://www.damtp.cam.ac.uk/user/gr/public/images/cs_bubbles.gif

Several length scales.



B from EW at reheating studied by A.Diaz-Gil, J.Garcia-Bellido, M.G.Perez & A.Gonzalez-Arroyo, 2008.

Estimates

Vachaspati, 2001
Copi et al, 2008

$$B(t_0) \approx 10^{-9}\ \mathrm{G}$$

For uniformly distributed sphalerons: $\xi(t_0) \sim 0.1\ \mathrm{pc}$

For sphalerons on bubble walls: $\xi(t_0) < 10\ \mathrm{Mpc}$

... uses inverse cascade of helical fields and with a model of superposition.

Detection of cosmic $\vec{B}$

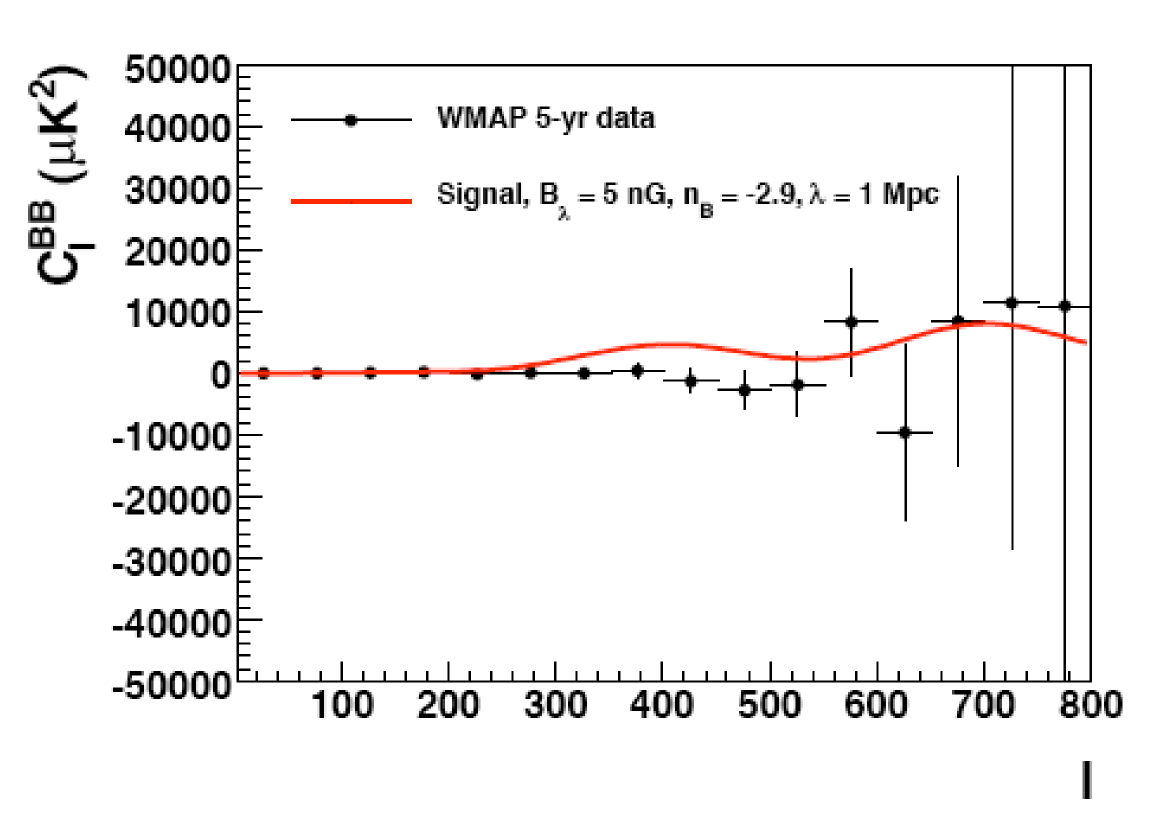
Signatures in CMB would unambiguously imply a primordial magnetic field.

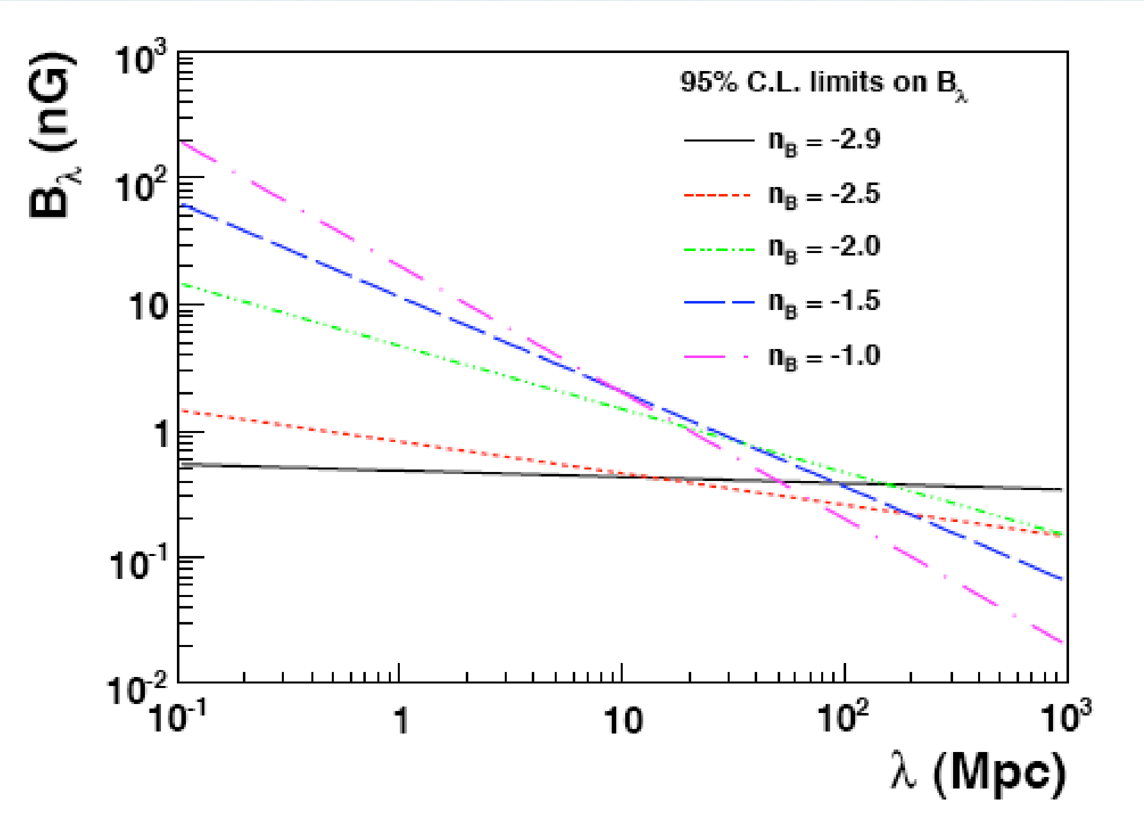
Primordial magnetic field gives:

1. $C_l^{(BB)} \neq 0$.
2. Faraday rotation of CMB polarization.

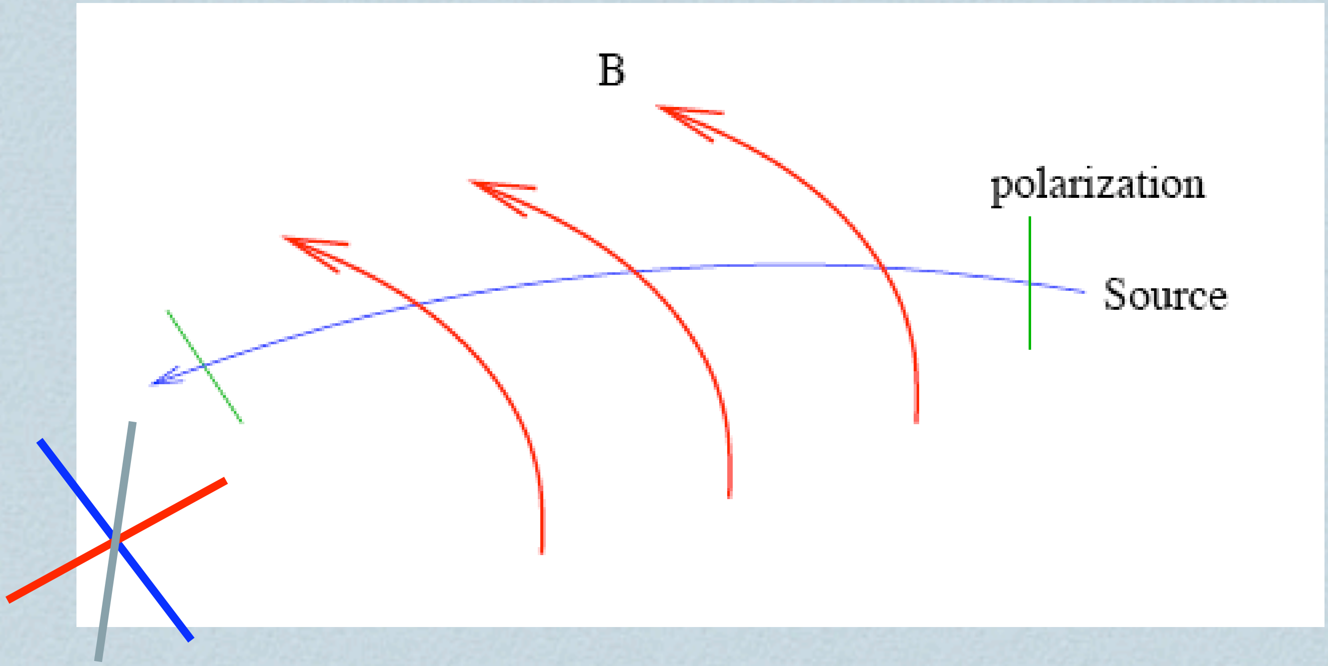
Recent WMAP Constraints

Kahniashvili, Maravin & Kosowsky, 2008





Faraday Rotation



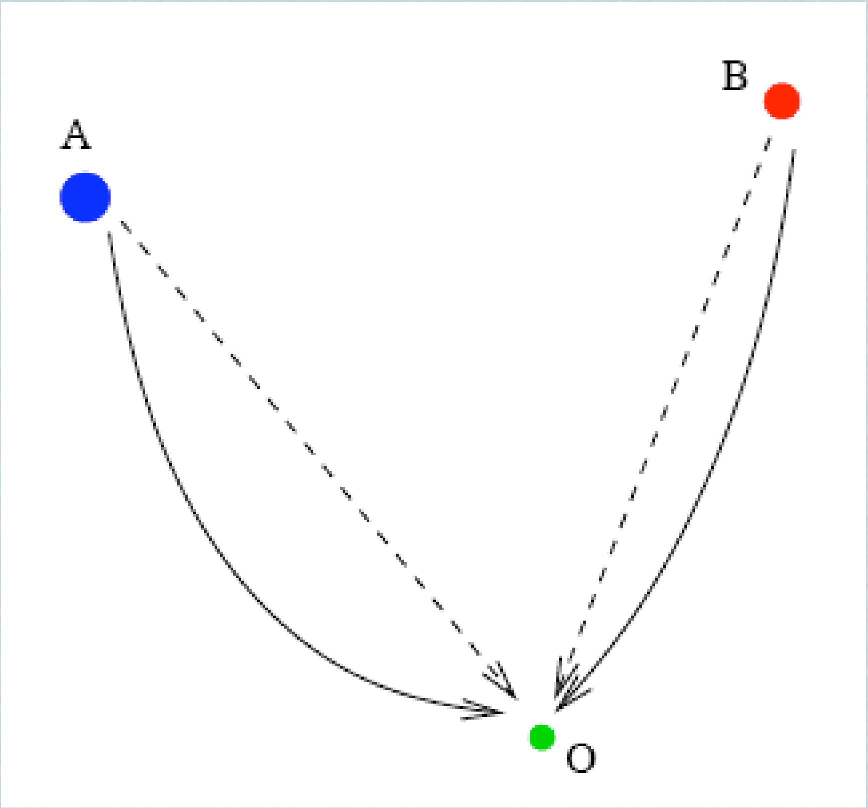
$$\Delta\theta = \lambda^2 \, \mathrm{RM} = \frac{3\lambda^2}{2\pi e} \int \dot{\tau}(\mathbf{x}) \mathbf{B} \cdot d\mathbf{l}$$

$$\mathrm{RM}_{\mathrm{gal}} \approx 10^3 \, \frac{\mathrm{rad}}{\mathrm{m}^2} \left(\frac{B_{\mathrm{gal}}}{\mu G}\right) \left(\frac{\xi}{\mathrm{kpc}}\right) \qquad \Delta\theta_{\mathrm{gal}} \sim 10^{-3} \ \mathrm{rad\ for}\ \lambda = 10^{-3}\ \mathrm{m}$$

$$\mathrm{RM}_{\mathrm{rec}} \approx 10^{10} \, \frac{\mathrm{rad}}{\mathrm{m}^2} \left(\frac{B_{\mathrm{rec}}}{G}\right) \left(\frac{\xi}{\mathrm{kpc}}\right) \qquad \Delta\theta_{\mathrm{rec}} \sim 10^{-2} \ \mathrm{rad\ for}\ \lambda_0 = 10^{-3}\ \mathrm{m}$$

Detecting Helicity

T. Kahniashvili & T. Vachaspati, 2006



Statistics to detect helicity:

$$\mathcal{P}_{\mathcal{H}}(\Delta) = \frac{1}{N} \sum_{\alpha=1}^{N} (\mathbf{n}_\alpha \cdot \mathbf{P}_\alpha)(\mathbf{e}_\alpha \cdot \mathbf{P}'_\alpha)$$

$\Delta =$ source pair separation

α labels source pairs

$\mathbf{n}_\alpha =$ normal to plane

$\mathbf{e}_\alpha =$ vector in plane

$\mathbf{P}$ denotes arrival momentum

Need identified sources.

Summary

- There is a remarkable connection between baryogenesis and helical primordial magnetic fields.
- The resulting magnetic field strength can be quite large (nanoGauss) requiring no further dynamo action. The coherence scale can also be kpc or Mpc scales.
- Detecting primordial magnetic fields and helicity is a challenge. More sensitive probes are crucial.