Magnetic Fields in the Universe

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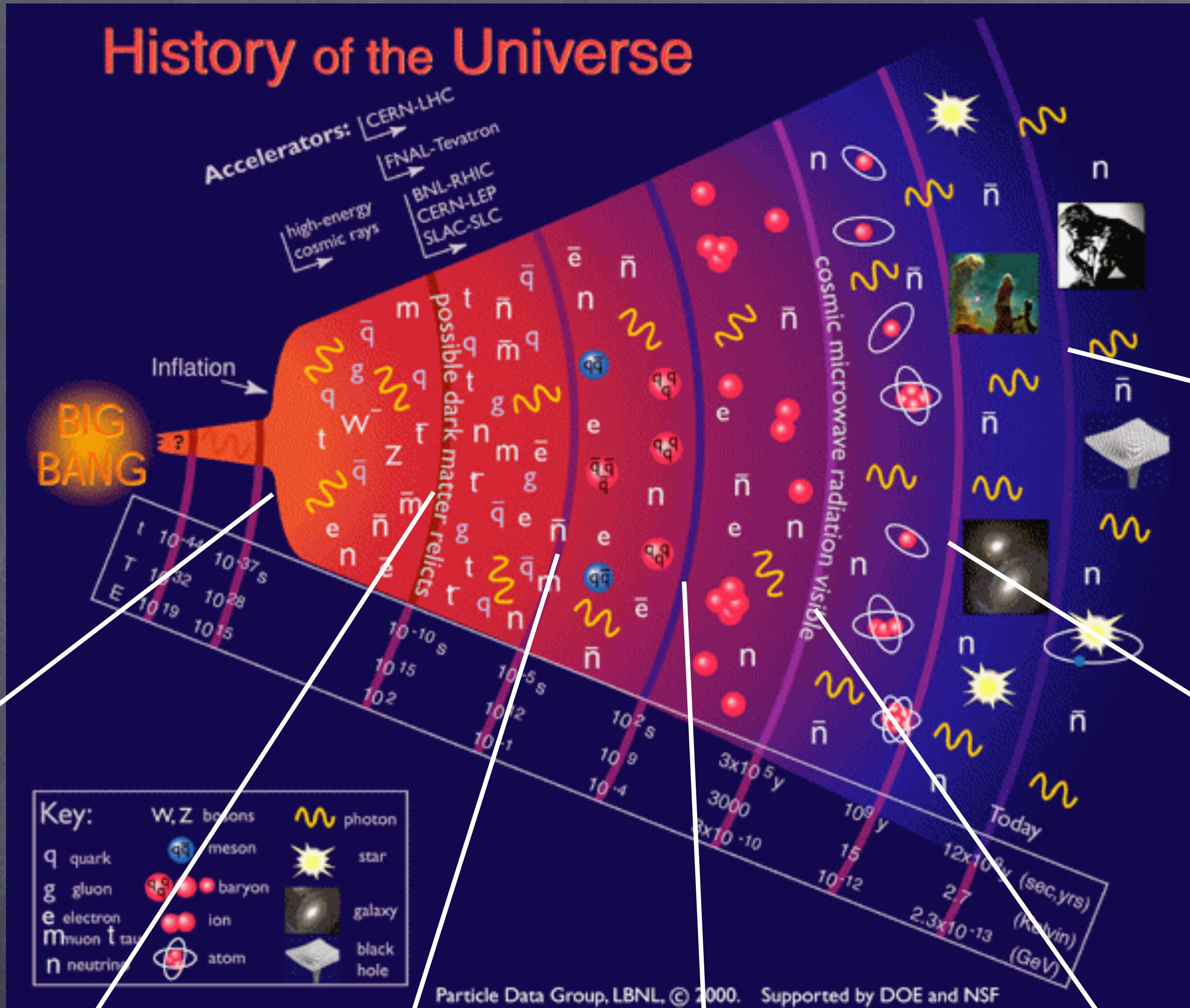


today

inflation

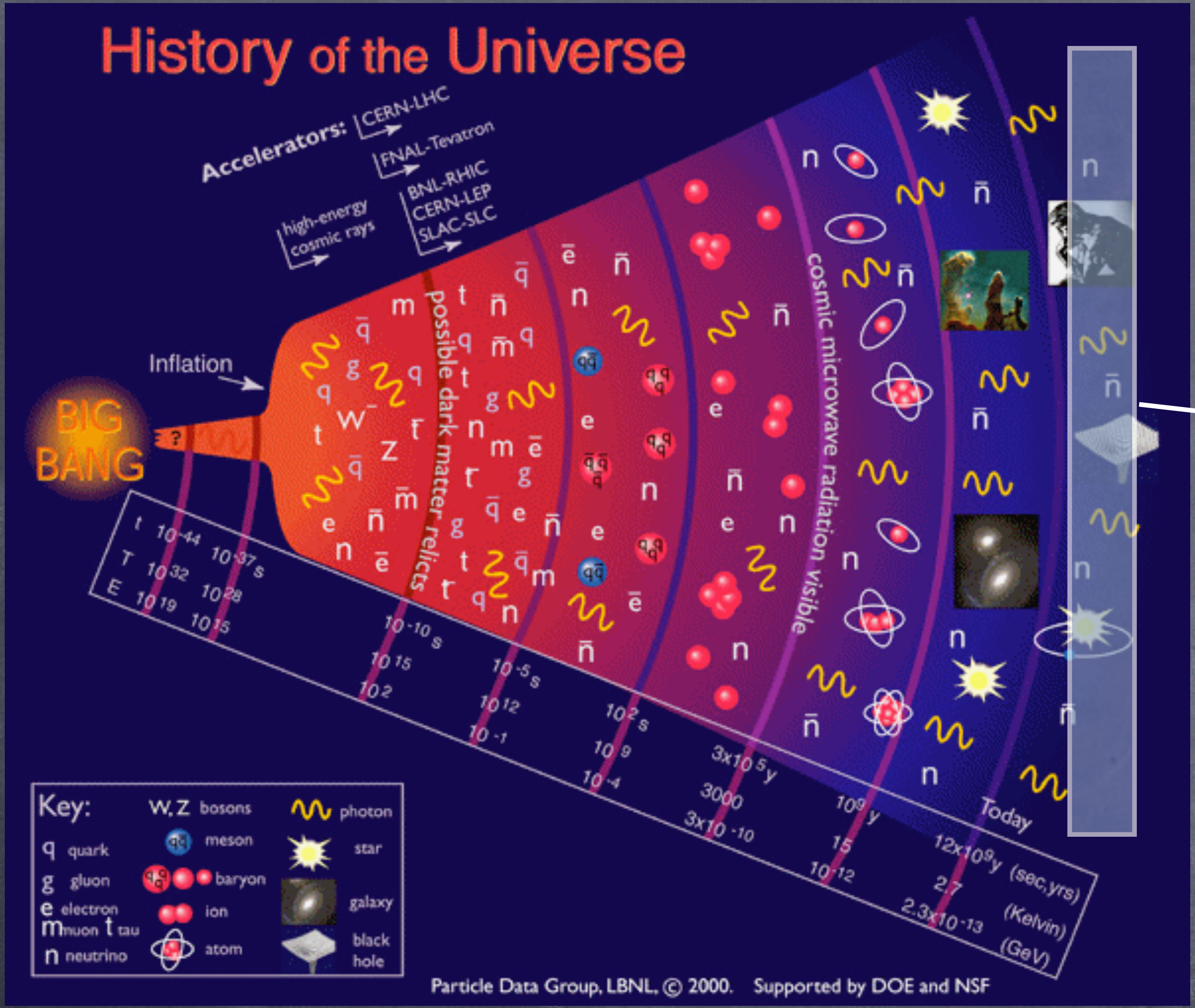
structure formation reionisation

EW phase transition

QCD phase transition

nucleosynthesis
neutrino decoupling
electron non relativistic

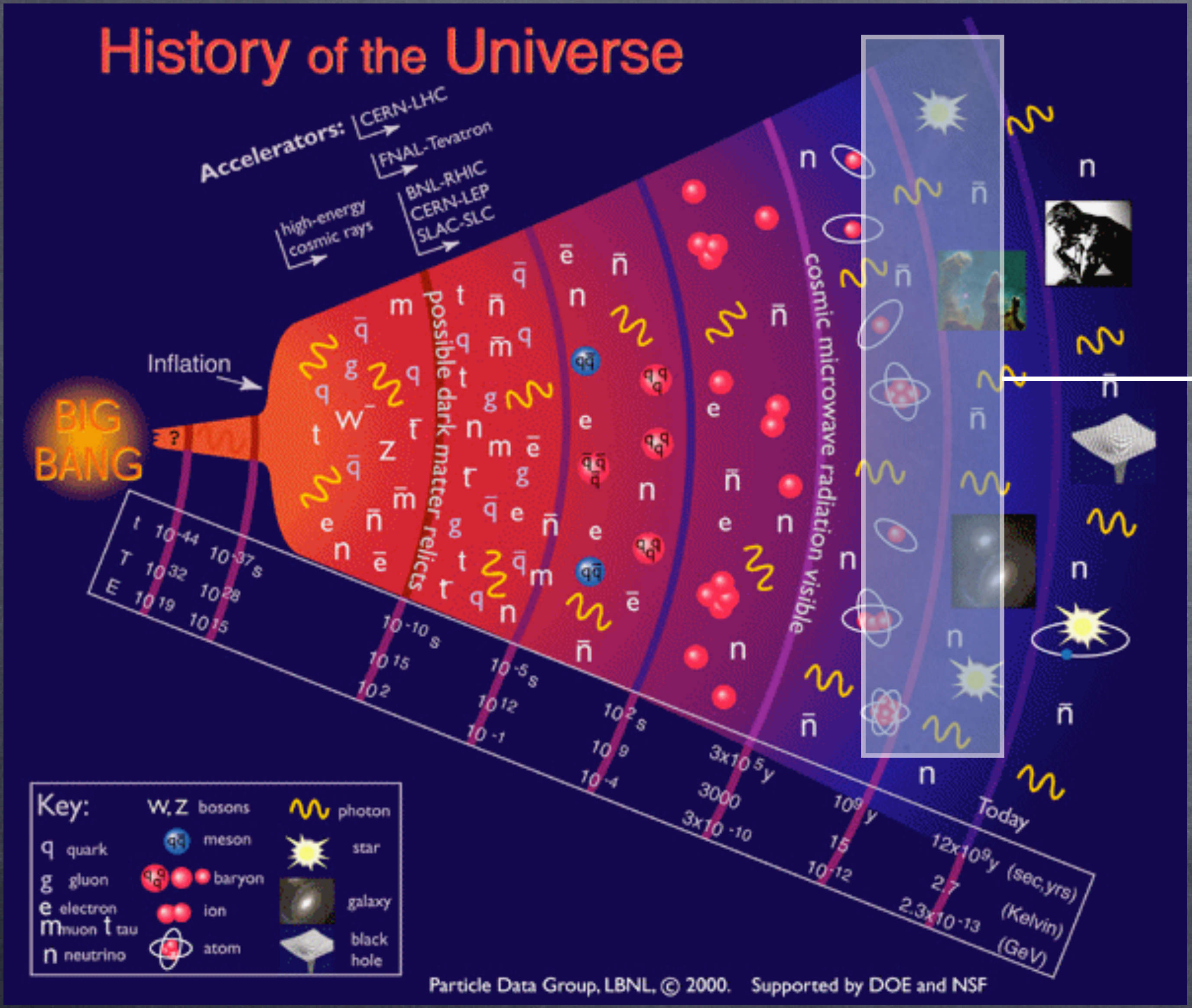
equality
recombination
formation of the CMB



Today: large scale magnetic fields are observed in structures

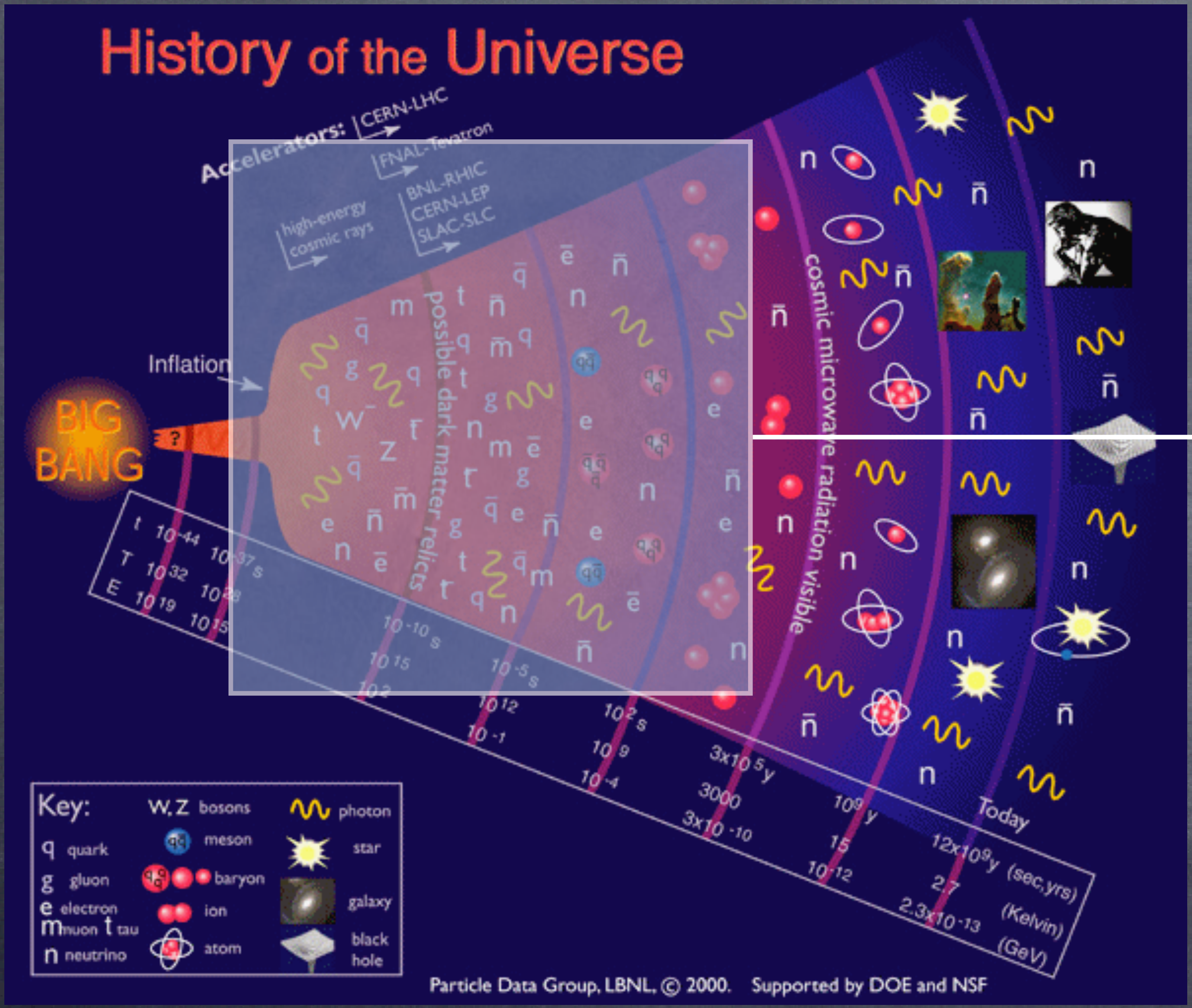
PROBLEM: WHAT IS THE ORIGIN OF THESE MAGNETIC FIELDS ?

TWO POSSIBILITIES FOR THE ORIGIN:



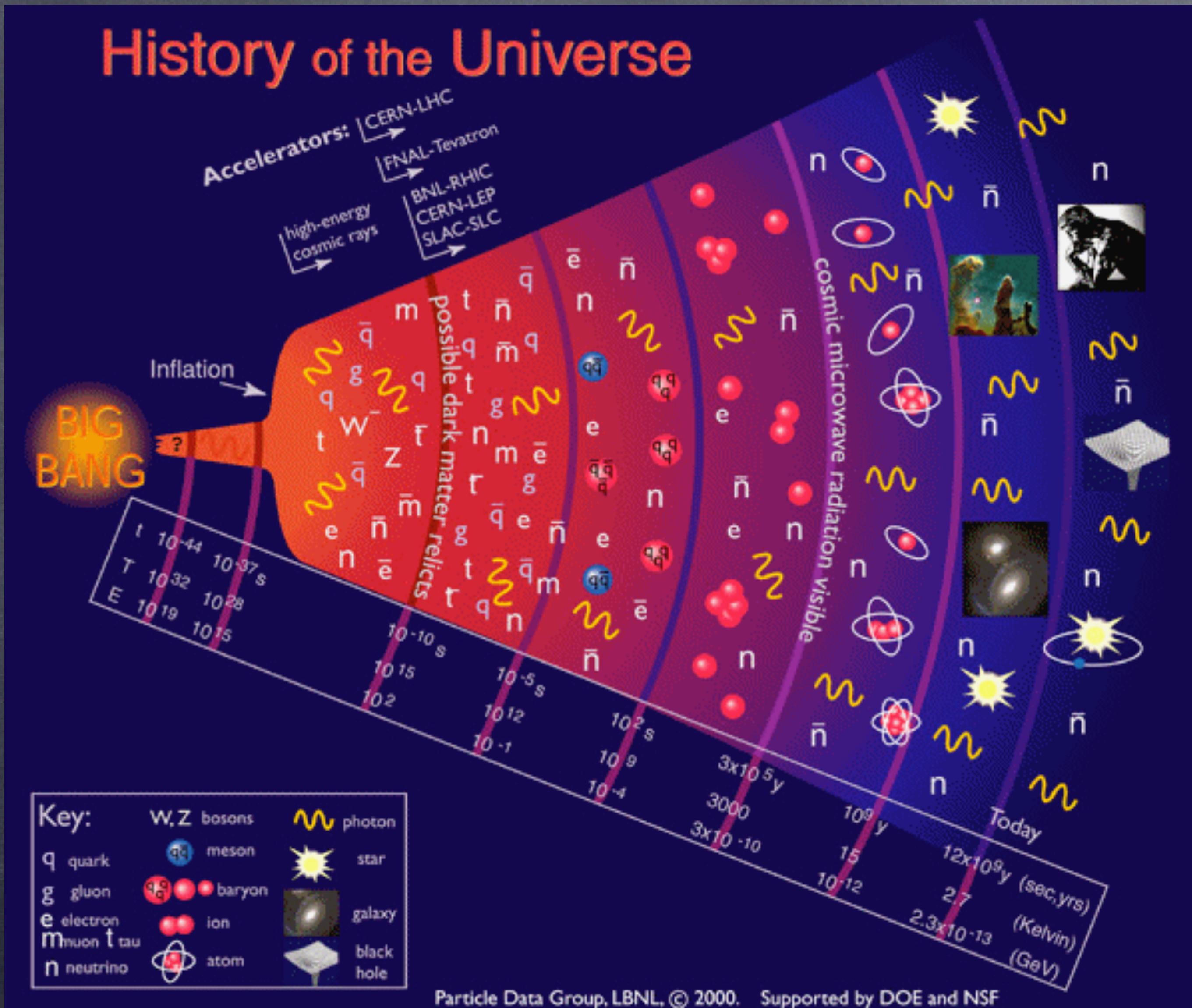
GENERATED DURING THE FORMATION OF STRUCTURES

TWO POSSIBILITIES FOR THE ORIGIN:



GENERATED IN THE PRIMORDIAL UNIVERSE

TWO POSSIBILITIES FOR THE ORIGIN:



both recent and primordial generation mechanisms have difficulties in explaining the observations

OBSERVATIONS

- Techniques: Zeeman splitting, Synchrotron radiation, Faraday rotation

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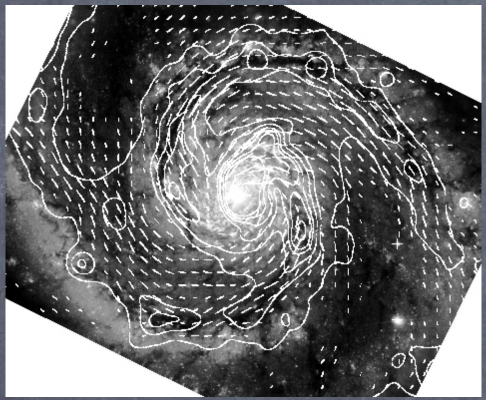
  $B_{\rm r} \simeq$ several $\mu{\rm G}$



M51

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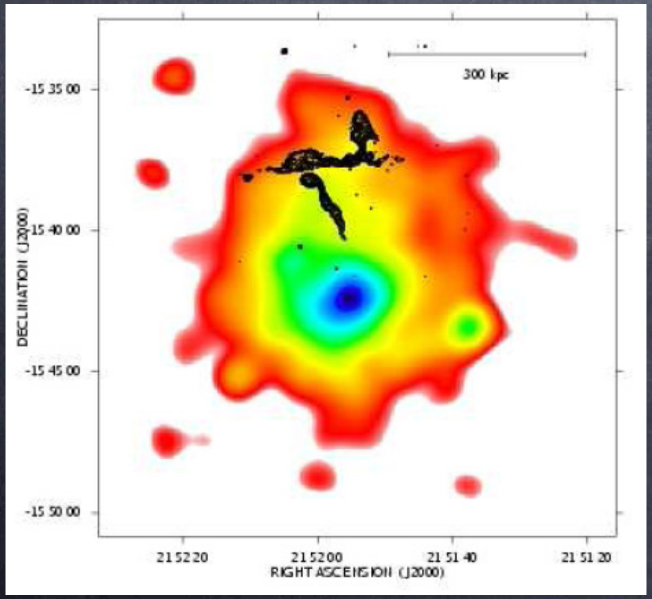
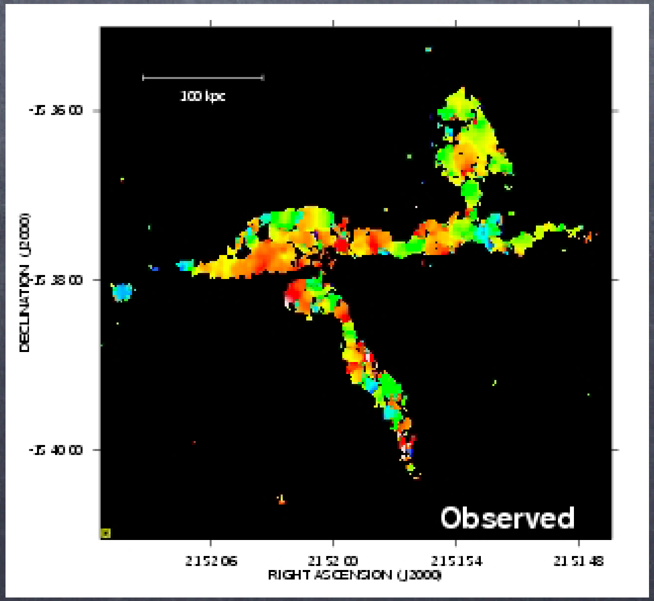
- MF in clusters: $B \simeq \mu{\rm G}$ $\quad \ell_{\rm corr} \simeq 1 - 100~{\rm kpc}$

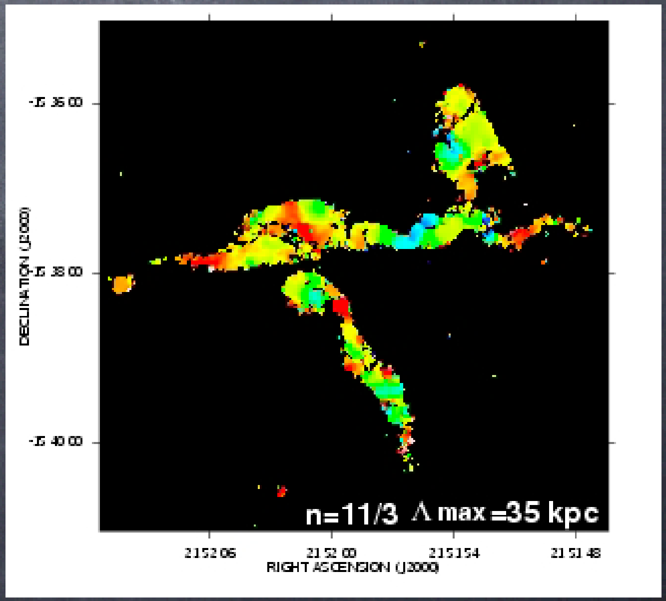
Faraday rotation of radio sources inside or behind the cluster + X-ray observation of the hot gas + simulated RM maps assuming a MF model

Abell 2382

Guidetti et al 2007







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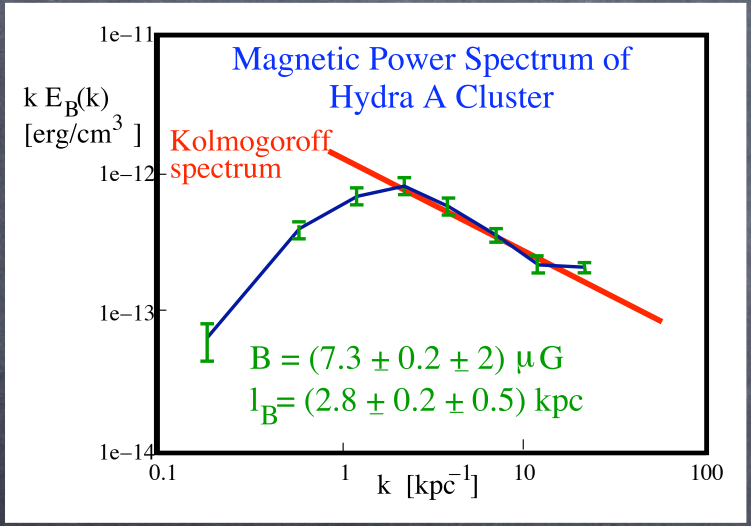
- MF in clusters: $B \simeq \mu G \qquad \ell_{corr} \simeq 1 - 100 \text{ kpc}$



Hydra A : Vogt and Ensslin 2005

$B \simeq 7\mu G \quad \Lambda_{max} \simeq 3\text{kpc}$

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- MF in protogalactic clouds around high redshift quasars, 2<z<4

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- MF in low density filaments and shocks

  $B \simeq 10\,{\rm nG}$ $\ell_{\rm corr} \sim {\rm few\ \ Mpc}$ Battaglia 2009, Giovannini 2010...

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- MF in low density filaments and shocks
- Lower bound on MF intensity in voids $B \gtrsim 10^{-17}\,{\rm G}$

Cascade of TeV gamma rays by a distant point source can be deflected by the extra-galactic magnetic field $\longrightarrow$ measurable effects in the shape and flux of the point source

Neronov and Vovk 2010, Tavecchio et al 2010, Dolag et al 2010, Taylor et al 2011

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FIRST DETECTION OF MF IN THE IGM
FILLING FACTOR OF ALMOST ONE

Neronov and Vovk 2010, Tavecchio et al 2010, Dolag et al 2010, Taylor et al 2011

To explain the observed fields, one needs MAGNETIC SEEDS:

amplified by structure formation up to microGauss level

$B \sim 10^{-9}$ Gauss (collapse) or 10^{-21} Gauss (galactic dynamo)

at about 100 kpc

$B \sim 10^{-17}$ Gauss in voids

at about 1 Mpc

Generation after recombination

- BIERMANN BATTERY $$\frac{\partial B}{\partial t} = \nabla \times v \times B - \frac{\Delta B}{4\pi\sigma} - \frac{\nabla n_e \times \nabla P_e}{e n_e^2}$$

galactic: shocks by SN explosions in proto-galaxies (problem: scale)
both: radiation pressure at reionisation + density fluctuations of forming structures

Hanayama et al 2005, Biermann and Galea 2003, Langer et al 2005, Colgate and Li 2000, Subramanian 2008, Schekochihin and Cowley 2005, Xu et al 2009, Miniati and Bell 2010...

Generation after recombination

- BIERMANN BATTERY

- CLUSTERS: small scale turbulent dynamo

  what generates it (mergers)?
  scale (reversal of the field, Faraday rotation)?
  saturation?

Hanayama et al 2005, Biermann and Galea 2003, Langer et al 2005, Colgate and Li 2000, Subramanian 2008, Schekochihin and Cowley 2005, Xu et al 2009, Miniati and Bell 2010...

Generation after recombination

- BIERMANN BATTERY

- CLUSTERS: small scale turbulent dynamo

- EJECTION galactic: from stars
  cluster: from galaxies and/or AGN
  (open questions: mix? amplitude? maintenance?)

Hanayama et al 2005, Biermann and Galea 2003, Langer et al 2005, Colgate and Li 2000, Subramanian 2008, Schekochihin and Cowley 2005, Xu et al 2009, Miniati and Bell 2010...

Generation after recombination

- BIERMANN BATTERY
- CLUSTERS: small scale turbulent dynamo
- EJECTION
- REIONISATION: CR propagation / radiation flux in the intergalactic medium at reionisation + return currents

$$B \sim 10^{-17}\,\mathrm{G} \qquad \text{scale?}$$

Hanayama et al 2005, Biermann and Galea 2003, Langer et al 2005, Colgate and Li 2000, Subramanian 2008, Schekochihin and Cowley 2005, Xu et al 2009, Miniati and Bell 2010...

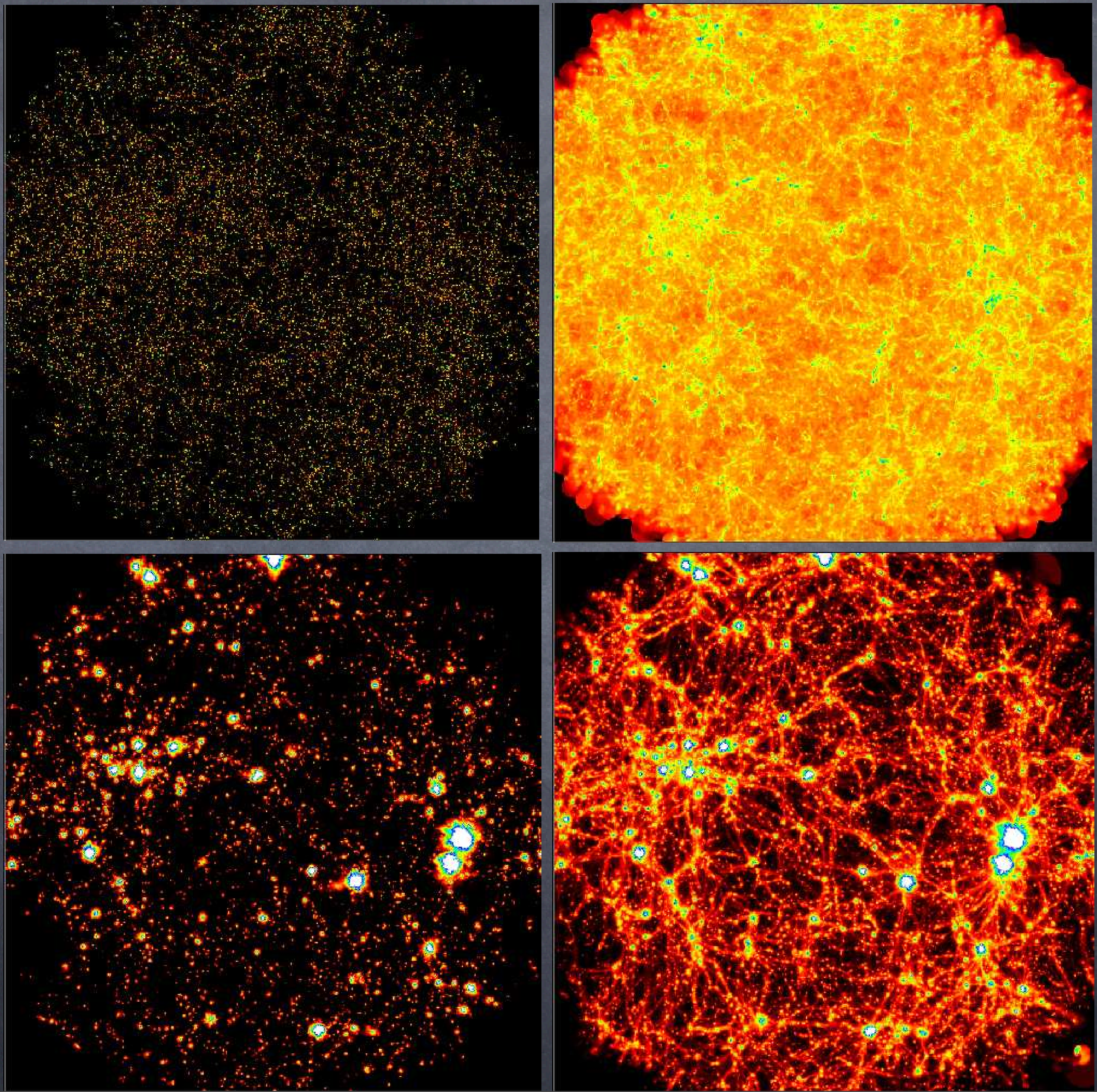
MHD simulation (Donnert et al 2008):

5 nG initial field, analytical model of ejection from starburst galaxies

EJECTION

PRIMORDIAL

z=4
100 Mpc



z=4

z=0

z=0

Generation prior to recombination

GENERATION BY PLASMA DYNAMICS + VORTICITY

electrons do Thomson scattering (Harrison 1973)

$$J = en(v_p - v_e) \qquad \Box B = 4\pi en(\Omega_p - \Omega_e)$$

- PROBLEM : very small amplitude, second order both in perturbation theory and tight coupling

$$B \sim 10^{-28}\,\mathrm{G}$$

Vachaspati and Vilenkin 1991, Davis and Dimopoulos 2005, Battefeld et al 2007...
Berezhiani and Dolgov 2003, Gopal and Sethi 2004, Matarrese et al 2004, Takahashi et al 2005, Fenu et al 2011...

Generation prior to recombination

PRIMORDIAL PHASE TRANSITIONS

- FIRST ORDER charge separation or currents at bubble walls + amplification by MHD turbulence (both EW and QCD)

Hogan 1983, Quashnock et al 1989, Cheng and Olinto 1994, Baym et al 1996, Sigl et al 1996, Ahonen and Enqvist 1997, Stevens and Johnson 2010...

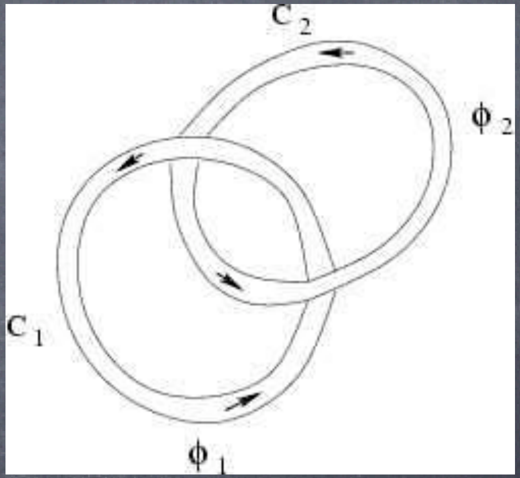
Generation prior to recombination

PRIMORDIAL PHASE TRANSITIONS

- FIRST ORDER
- SECOND ORDER EW, HELICAL FIELD

generated by the symmetry breaking connected to baryogenesis

$$h \sim -n_b/\alpha$$



Vachaspati 1991, Davidson 1996, Cornwall 1997, Grasso and Riotto 1997, Hindmarsh and Everett 1997, Tornkvist 1998, Field and Carroll 1998, Vachaspati 2001, Campanelli and Giannotti 2005, Copi et al 2008, Diaz-Gil et al 2008...

Generation prior to recombination

PRIMORDIAL PHASE TRANSITIONS

- FIRST ORDER
- SECOND ORDER EW, HELICAL FIELD
- PROBLEM : CAUSAL GENERATION

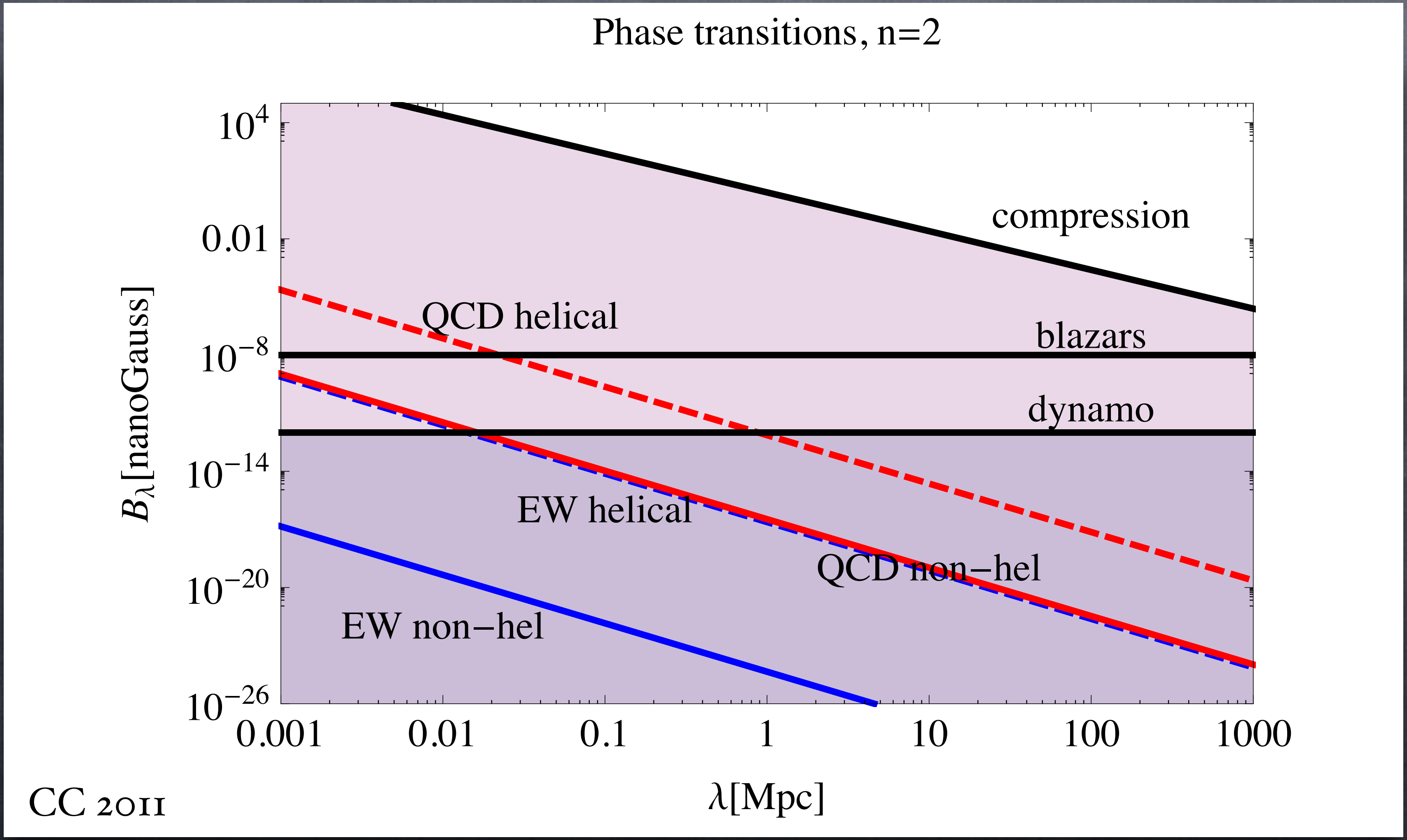
1. very small initial correlation scale $L \leq \eta_{EW} \simeq 10^{-4}\text{pc}$
2. blue spectrum, suppressed at large scales $\rho_B(k) \propto k^4$

strong constraints also simply from

$$\rho_B^* \lesssim \rho_{\text{rad}}^*$$

Constraints for generation at a phase transition

$$\rho_B^* \lesssim \rho_{\rm rad}^*$$



time evolution might help, MHD cascades for helical fields

Generation prior to recombination

INFLATION

- A-CAUSAL : generated at all scales

Generation prior to recombination

INFLATION

- A-CAUSAL : generated at all scales
- PROBLEM : need to break conformal invariance $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
  otherwise vacuum fluctuations not amplified

Generation prior to recombination

INFLATION

- A-CAUSAL : generated at all scales
- PROBLEM : need to break conformal invariance $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$
- coupling of em field to the metric, to the inflaton (also in string theory context), assuming a massive photon, by parametric resonance during preheating, introducing a charged scalar field, via axial coupling to a pseudoscalar....

$$RF_{\mu\nu}F^{\mu\nu} \qquad f(\phi)F_{\mu\nu}F^{\mu\nu} \qquad \frac{1}{4}f(\phi)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$m^2 A_\mu A^\mu \qquad (D_\mu\phi)^* D^\mu\phi - m^2\phi^*\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

Turner and Widrow 1988, Ratra 1992, Giovannini and Shaposhnikov 2000, Dimopoulos et al 2002, Bamba and Yokoyama 2004, Martin and Yokoyama 2007, Campanelli et al 2008, Demozzi et al 2009, Anber and Sorbo 2006, Durrer et al 2010...

Generation prior to recombination

INFLATION

- A-CAUSAL : generated at all scales
- PROBLEM : need to break conformal invariance $\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
- PROBLEMS: some lead to too small results, some have ghosts, some give blue spectra...

$$f(\phi) F_{\mu\nu} F^{\mu\nu}$$

Turner and Widrow 1988, Ratra 1992, Giovannini and Shaposhnikov 2000, Dimopoulos et al 2002, Bamba and Yokoyama 2004, Martin and Yokoyama 2007, Campanelli et al 2008, Demozzi et al 2009, Anber and Sorbo 2006, Durrer et al 2010...

Constraints for generation at inflation

$$S = -\int d^4x\,\sqrt{-g}\,\frac{f^2(\phi)}{4}F^{\mu\nu}F_{\mu\nu} \qquad\qquad f(\eta) = f_1\left(\frac{\eta}{\eta_1}\right)^{\gamma}$$

EM field does not affect the background
gauge field satisfies wave equation with time dependent mass term

$$\mathcal{A}'' + \left(k^2 - \frac{f''}{f}\mathcal{A}\right) = 0$$

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spectrum of EM fluctuations $\qquad P_B = \frac{k^2}{f^2 a^4}|\mathcal{A}(k,\eta)|^2$

MF amplitude today $\qquad B \simeq 10^{-10}\mathrm{G}\left(10^5\frac{H}{m_{PL}}\right)$

$$\gamma = -2$$

Constraints for generation at inflation

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EM field does not affect the background
BUT it generates first order metric perturbations

Bonvin, CC and Durrer 2011

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EM field does not affect the background
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At large scales the main contribution is due to the MF anisotropic stress

$$\Psi_{\rm inf} \propto \frac{\Omega_\Pi}{(k\eta)^2}$$

this perturbation mode is well behaved during inflation

$$\frac{\rm Weyl}{\rm Ricci} \simeq \frac{k^2(\Phi+\Psi)}{\mathcal{H}^2} \simeq \Omega_\Pi \ll 1$$

Constraints for generation at inflation

$$S = -\int d^4x\,\sqrt{-g}\,\frac{f^2(\phi)}{4}F^{\mu\nu}F_{\mu\nu} \qquad f(\eta) = f_1\left(\frac{\eta}{\eta_1}\right)^{\gamma}$$

EM field does not affect the background
BUT it generates first order metric perturbations

but it is transferred to a constant mode in the radiation era (matching)

$$\Psi_{\rm rad} \propto \frac{\Omega_\Pi}{(k\eta_*)^2}$$

which spoils homogeneity and isotropy of the universe

$$\gamma = -2 \qquad \left.\frac{\rm Weyl}{\rm Ricci}\right|_{\rm rad} \sim \Omega_\Pi\left(\frac{\eta}{\eta_*}\right)^2$$

Conclusions

- the origin of MF observed in astrophysical objects is still unclear
- the lower bound on the MF amplitude in IGM by gamma-ray telescopes shows that MF are not only associated with collapsed objects
- this points towards very early generation: primordial, reionisation?
- primordial: causal generation mechanisms are disfavoured because they give rise to blue spectra, which suppresses the magnetic field amplitude at large scales
- charge separation and vorticity lead to too small fields
- EWPT, QCDPT do not explain the bound from gamma-ray telescopes
- generation at inflation by the most favoured mechanism leads to inhomogeneity in the universe and is excluded
- other inflationary mechanisms, reionisation?
- a combination of different mechanisms, operating at different epochs?