M. Giovannini, PRD 70 123507 (2004); PRD 71 021301 (2005); PRD 73, 101302 (2006); PRD 74,063002(2006); CQG 23 4991 (2006); PMC Phys. A 1, 5 (2007); PRD 76 124017 (2007); PLB 659 (2008)

M. Giovannini and K. E. Kunze PRD 77 061301 (2008); PRD 77 063003 (2008); PRD 77 123001 (2008); PRD 78 023010 (2008)

CMB signatures of large-scale magnetic fields

Massimo Giovannini (INFN & CERN)

Paris, July 2008

A Magnetized Universe

- Large-scale magnetic fields (typical length-scales > 1 A.U.) $1 A.U. = 1.49\ 10^{13}\ cm$

- First speculations: early forties (Alfven) late forties (Fermi, Fermi & Chandrasekar) on cosmic ray physics $1\,\mu G = 0.1\ nT = 10^{-26}\ GeV^2$

-Today: magnetic fields measured with various techniques

Zeeman splitting of radio transitions

$$\Delta\nu_Z = \frac{e\overline{B}_\parallel}{2\pi m_e}$$

$$\Delta\nu_{Doppler} \simeq \left(\frac{v_{th}}{c}\right)\nu \gg \Delta\nu_{Zeeman} \simeq \frac{e\overline{B}_\parallel}{2\pi m_e}$$

Synchrotron emission

$$\varepsilon(\nu) = 10^{-23}\, n_{er0}\, L\, \xi(\gamma)\, (6.3\times 10^{18})^{(\gamma-1)/2} (B_\perp)^{(\gamma+1)/2}\, \nu^{(1-\gamma)/2}\ \ erg\ sec^{-1}\ cm^{-2}\ Hz^{-1}$$

Faraday rotation

$$\Delta\phi = \frac{f_e}{2}\left(\frac{\omega_p}{\omega}\right)^2 \omega_B\, \Delta z$$

$$\omega_p = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2} \qquad \omega_B = \frac{eB}{mc}$$

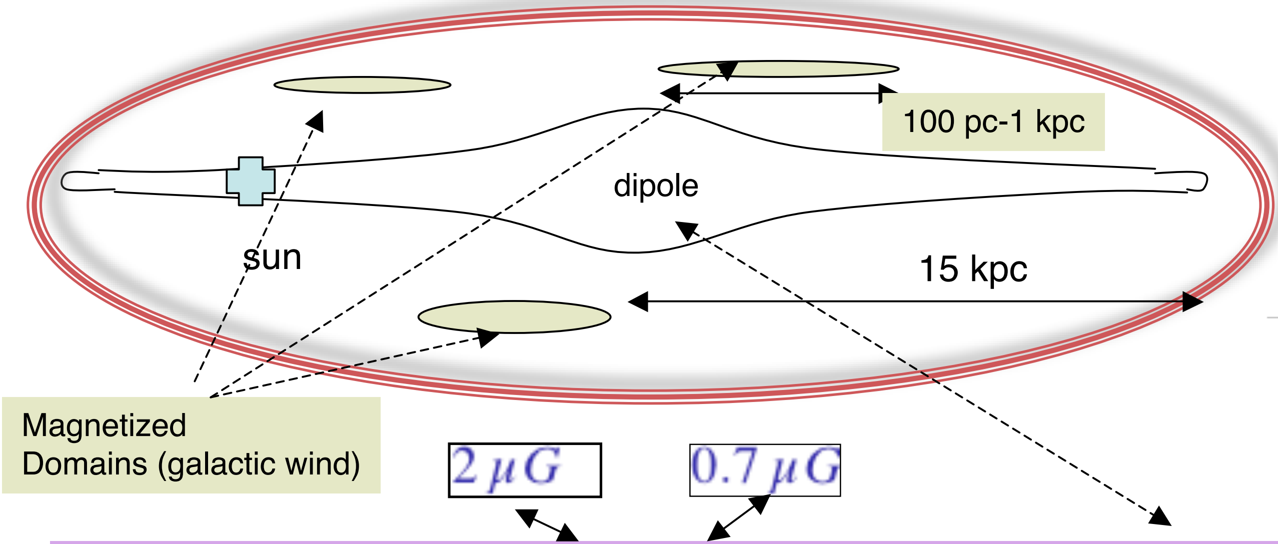
$$\phi = RM\,\lambda^2 + \phi_0$$

$$RM = \frac{\Delta\phi}{\Delta\lambda^2} = 811.9\int\left(\frac{n_e}{cm^{-3}}\right)\left(\frac{B_\parallel}{\mu G}\right) d\left(\frac{\ell}{kpc}\right)\ \frac{rad}{m^2}$$

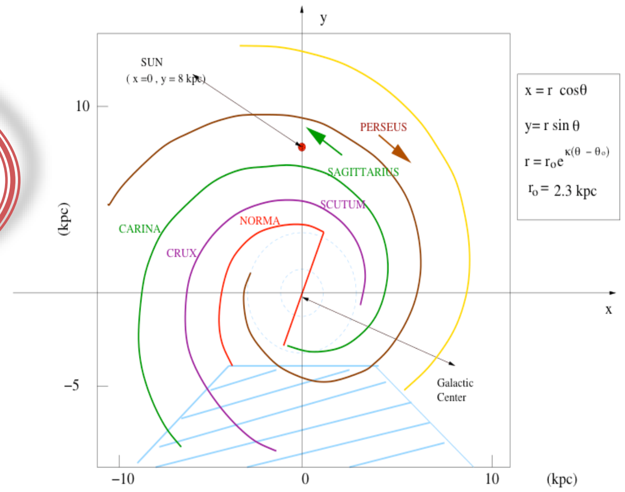
$$DM \propto \int n_e d\ell$$

$$\langle B_\parallel\rangle = \frac{RM}{DM}$$

Magnetized galaxies, clusters, and superclusters



SGP survey
Parkes



Milky way: toroidal field south/north hemisphere; dipoles (center) $10\, rad/m^2$

Local Group: Andromeda, Magellanic Clouds,… $2 - 7\,\mu G$ (elliptical galaxies: shorter scale)

Abell Clusters (like COMA): magnetic fields inside cluster (VLA+ROSAT) [Faraday RM]
Typical RM: $100\, rad/m^2$ $B \sim 0.5\,\mu G = 500\, n G$ $L \sim 50 - 100\, kpc$

Hercules / Perseus-Pisces $B_L \simeq 0.5 \mu G$

$n_e \simeq 10^{-6}\, cm^{-3}$ GRG $L \simeq 500\, kpc$

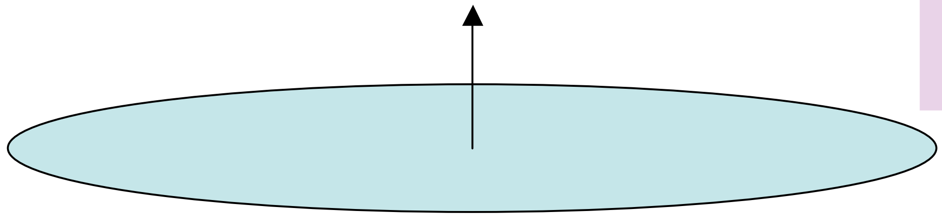
Faraday rotation should be reduced as $(z+1)^{-2}$

High redshift quasars (up to z ~ 3.7)

Kronberg, Bernet, Minati,Lilly
Short, Higdom arXiv. 07120435

Dynamo and compressional amplification

Galaxy:



Charged fluid (globally neutral)

$$\lambda_D \simeq \sqrt{\frac{T}{8\pi n_e e^2}}$$

Typical rotation period: $P \sim 3\times 10^8\ yrs$ age $T \sim 10^{10}\ yrs$

Dynamo instability:

$$\alpha = -\frac{\tau_0}{3}\langle \vec{v}\cdot\vec{\nabla}\times\vec{v}\rangle \quad \sim 9.1\times 10^6\ \frac{cm}{sec}$$

$$\frac{1}{4\pi\sigma} = 10^{25}\frac{cm^2}{sec}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}\times\vec{B}) + \frac{1}{4\pi\sigma}\nabla^2\vec{B}$$

Dynamo term — Diffusivity term

$$\frac{\partial <\vec{B}>}{\partial t} = \alpha\vec{\nabla}\times <\vec{B}> + \frac{1}{\sigma}\nabla^2 <\vec{B}>$$

$$1/k \sim L > kpc$$

Maximal and optimistic amplification: $e^{\Gamma t} \sim e^{T/P} \sim e^N \sim 10^{13}$

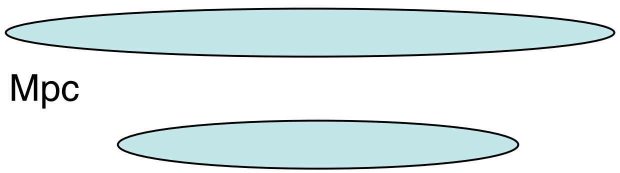
$B_i \sim 10^{-19}\ G$ Over L = 30 kpc

Clash: dynamo versus helicity conservation.
Brandenburg & Subramanian

$$\frac{d}{dt}\int_V d^3x \vec{A}\cdot\vec{B} = -\frac{1}{4\pi\sigma}\int_V d^3x \vec{B}\cdot\vec{\nabla}\times\vec{B} + O\left(\frac{1}{\sigma^2}\right)$$

Compressional amplification:

$$B_b = \left(\frac{\rho_b}{\rho_a}\right)^{2/3} B_a$$



Mpc

30 kpc

$$B_i \geq 10^{-23}\ G \quad over \quad L \sim Mpc$$

Primordial magnetogenesis

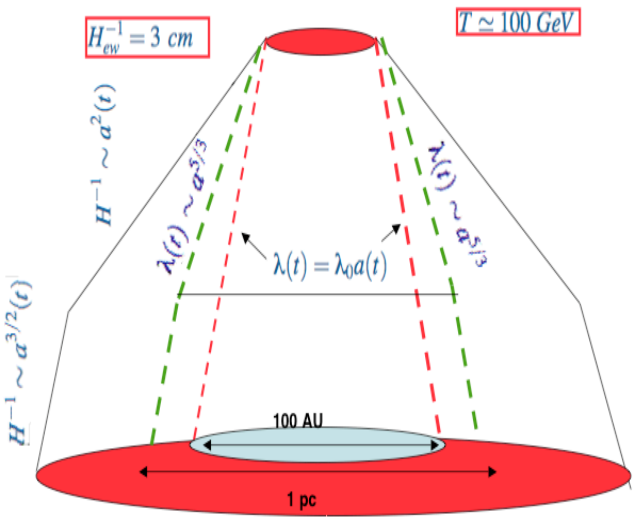
$B_{seed} > 10^{-23} G$ → Too optimistic $B \sim 10^{-2}\mathrm{nG}$

$B_{seed} > 10^{-18}\ G$ → $B \sim \mathrm{nG}$ Quasars?

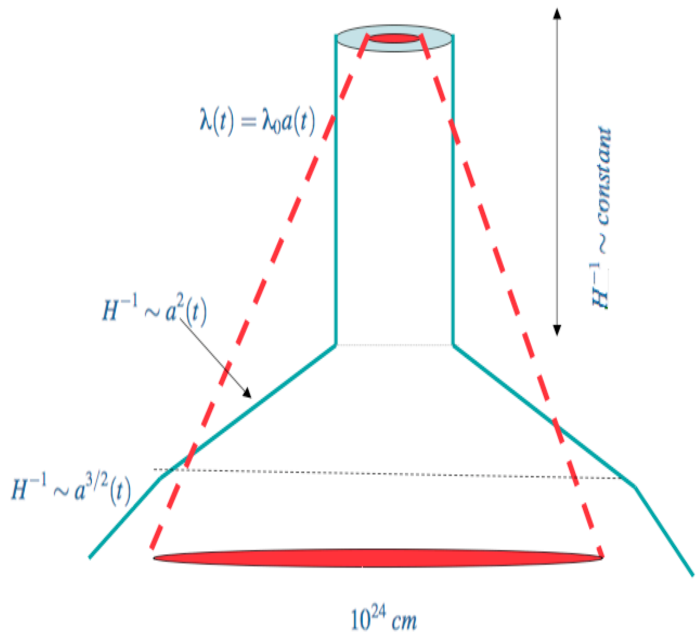
effective e-folds 30->25

More realistic [flux not exactly conserved, small-scale fields can grow large and swamp dynamo action]

CAUSAL mechanisms

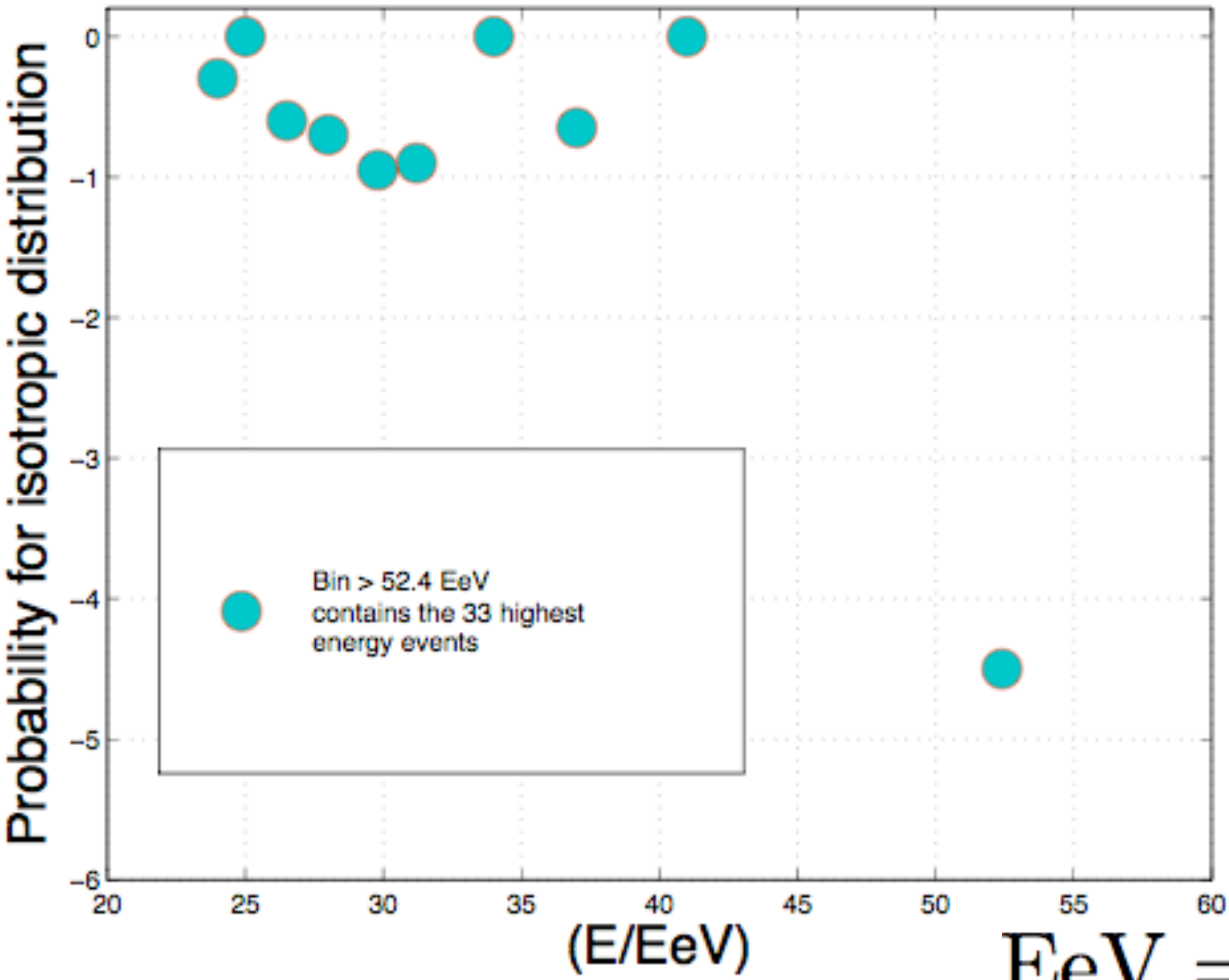


``Inflationary'' mechanisms



Auger

Cocoon~ 75 Mpc



$$\mathrm{EeV} = 10^{18}\,\mathrm{eV}$$

Magnetic fields and CMB physics :the past

1)SCATTERED results

2) Often unrealistic approximations;

Uniform magnetic field approximation
[magnetic field along a specific axis].
Simplified estimates
[not so realistic in diverse cases]

-- distorsion of the Planckian spectrum
-- shift of the polarization plane of CMB (Faraday rotation)
-- effects on primary anisotropies

Fully inhomogeneous magnetic fields : more realistic [mathematically less tractable]

Magnetic fields and CMB physics: two main assumptions

- Magnetic fields present prior to equality

- Spatial isotropy Unbroken -> Stochastic fields

1)

$$\langle B_i(\vec{k},\tau)B_j(\vec{p},\tau)\rangle = \frac{2\pi^2}{k^3}P_{ij}(k)\mathcal{P}_B(k)\delta^{(3)}(\vec{k}+\vec{p})$$

$$\mathcal{P}_{\rm B}(k) = A_{\rm B}\left(\frac{k}{k_{\rm L}}\right)^{n_{\rm B}-1}$$

Magnetic spectral index

Magnetic pivot scale

$$P_{ij}(k) = (\delta_{ij} - \hat{k}_i\hat{k}_j)$$

$$A_{\rm B} = \frac{(2\pi)^{n_{\rm B}-1}}{\Gamma\left(\frac{n_{\rm B}-1}{2}\right)}B_{\rm L}^2, \qquad n_{\rm B} > 1$$

$$A_{\rm B} = \frac{1-n_{\rm B}}{2}\left(\frac{k_0}{k_{\rm L}}\right)^{1-n_{\rm B}}B_{\rm L}^2, \qquad n_{\rm B} < 1$$

2) Universe expands

$$ds^2 = a^2(\tau)[d\tau^2 - d\vec{x}^2]$$

After neutrino decoupling

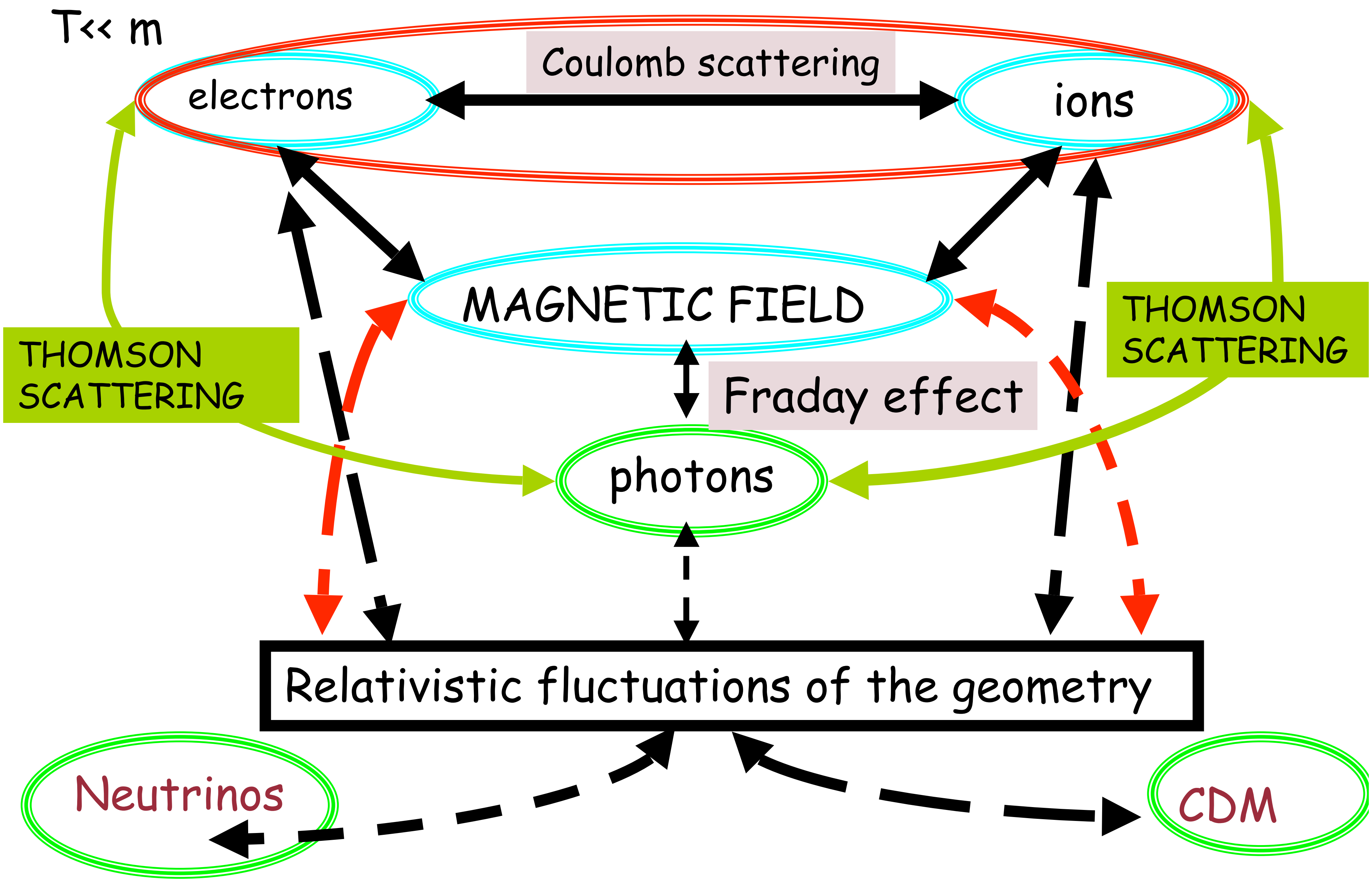
$$a(\tau) = a_{\rm eq}\left[\left(\frac{\tau}{\tau_1}\right)^2 + 2\left(\frac{\tau}{\tau_1}\right)\right]$$

$$\tau_{\rm eq} = (\sqrt{2}-1)\tau_1 = 120.658\left(\frac{h_0^2\Omega_{\rm M0}}{0.1326}\right)^{-1}\left(\frac{h_0^2\Omega_{\rm R0}}{4.15\times10^{-5}}\right)^{1/2}\ {\rm Mpc}.$$

$$\frac{a_0}{a_{\rm eq}} = 1 + z_{\rm eq} = 3195.17\left(\frac{h_0^2\Omega_{\rm M0}}{0.1326}\right)\left(\frac{h_0^2\Omega_{\rm R0}}{4.15\times10^{-5}}\right)^{-1}$$

Parameters: best fit 5 yr WMAP alone

Magnetized (cold) plasma



Plasma hierarchies

Plasma globally neutral ->

$$n_e = n_i = n_0 = \eta_{b0}\, n_{\gamma 0}$$

Plasma hierarchies controlled by PLASMA PARAMETER

$$g_{plasma} = \frac{1}{V_D n_0 x_e}$$
$$= 2.308 \times 10^{-7} \sqrt{x_e} \left(\frac{h_0^2 \Omega_{b0}}{0.02273} \right)^{1/2}$$

$$\eta_{b0} = 6.219 \times 10^{-10} \left(\frac{h_0^2 \Omega_{b0}}{0.02773} \right) \left(\frac{T_{\gamma 0}}{2.725} \right)^{-3}$$

$$V_D = \frac{4}{3}\pi\lambda_D^3 \longleftrightarrow \lambda_D = \sqrt{\frac{T}{8\pi e^2 n_0 x_e}}$$

1) $\frac{\lambda_D}{\lambda_{Coul}} = \frac{g_{plasma}}{48\pi} \ln \Lambda_C, \quad \Lambda_C = \frac{18\sqrt{2}}{g_{plasma}}$ Debye scale << Coulomb mean free path

2) $\frac{\Gamma_{Coul}}{\omega_{pe}} = \frac{\ln \Lambda_C}{24\sqrt{2\pi}} g_{plasma}, \quad \omega_{pe} = \sqrt{\frac{4\pi n_0 x_e}{m_e}}.$ Coulomb rate<< plasma freq.

3) $\sigma = \frac{\omega_{pe}^2}{4\pi\Gamma_{Coul}} = \frac{6\sqrt{2}}{\ln \Lambda_C} \frac{\omega_{pe}}{g_{plasma}}.$ Conductivity very large in units of pl. freq

4) $L_\sigma \simeq (4\pi\sigma H_{eq})^{-1}, \quad \sigma = \frac{T}{e^2 \ln \Lambda_C} \left(\frac{T}{m_e} \right)^{1/2},$

5) $r_{Be} \ll L \simeq r_H, \quad r_{Be} = \frac{v_\perp}{\omega_{Be}}, \quad v_\perp \simeq v_{th}$

Larmor radius much smaller Than inhomogeneity scale of the field

Charged species

Vlasov-Landau + curved space-time + relativistic inhomogeneities

$$\frac{\partial f_\pm}{\partial \tau} + v^i \frac{\partial f_\pm}{\partial x^i} \pm e(E^i + v_j B_k \epsilon^{j\,k\,i}) \frac{\partial f_\pm}{\partial q^i} + \frac{1}{2} h'_{ij} q^i \frac{\partial f_\pm}{\partial q^j} = \mathcal{C}_{\rm coll}.$$

$$\delta_s g_{ij}(\vec{x},\tau) = a^2(\tau) h_{ij}(\vec{x},\tau) \qquad h_{ij}(\vec{k},\tau) = [\hat{k}_i \hat{k}_j h(k,\tau) + 2\xi(k,\tau)(3\hat{k}_i \hat{k}_j - \delta_{ij})]$$

$$\vec{\nabla}\cdot\vec{E} = 4\pi e \int d^3v [f_+(\vec{x},\vec{v},\tau) - f_-(\vec{x},\vec{v},\tau)], \qquad \vec{\nabla}\cdot\vec{B} = 0,$$

$$\vec{\nabla}\times\vec{E} + \vec{B}' = 0, \qquad \vec{\nabla}\times\vec{B} - \vec{E}' = 4\pi e \int d^3v\, \vec{v}\, [f_+(\vec{x},\vec{v},\tau) - f_-(\vec{x},\vec{v},\tau)].$$

Early times before equality (initial conditions):
tight Thomson scattering, tight Coulomb scattering -> one fluid ->MHD

Around photon decoupling: photons separate from baryons

Around frequencies of the order of the plasma frequency :
electrons separate from ions (dispersive propagation of
electromagnetic signals) ->Faraday rotation

Neutral species

CDM particles

$$\delta_c' = -\theta_c + \frac{h'}{2} \qquad \theta_c' + \mathcal{H}\theta_c = 0$$

$$\theta_c = \partial_i v_c^i, \qquad \delta_c = \frac{\delta\rho_c}{\rho_c}$$

Neutrinos

$$\mathcal{F}_\nu' + ik\mu\mathcal{F}_\nu = -4\xi' + 2\mu^2(h' + 6\xi')$$

Normalized (one-body) distribution

$$\delta_\nu' = -\frac{4}{3}\theta_\nu + \frac{2}{3}h',$$

$$\theta_\nu' = \frac{k^2}{4}\delta_\nu - k^2\sigma_\nu,$$

$$\sigma_\nu' = \frac{4}{15}\theta_\nu - \frac{3k}{10}\mathcal{F}_{\nu 3} - \frac{2}{15}(h' + 6\xi'),$$

$$R_\nu = \frac{r}{1+r}, \qquad r = \frac{7}{8}N_\nu\left(\frac{4}{11}\right)^{4/3} \equiv 0.681\left(\frac{N_\nu}{3}\right)$$

$\sigma_\nu = \mathcal{F}_{\nu 2}/2$ (anisotropic stress->Quadrupole)

Photons

Differential optical depth

$$\Delta_I' + ik\mu\Delta_I = -\left[\xi' - \frac{\mu^2}{2}(h' + 6\xi')\right] + \epsilon'\left[-\Delta_I + \Delta_{I0} + \mu v_b - \frac{1}{2}P_2(\mu)S_Q\right],$$

$$S_Q = \Delta_{I2} + \Delta_{Q0} + \Delta_{Q2}$$

$$v_b' + \mathcal{H}v_b + \frac{\epsilon'}{R_b}(3i\Delta_{I1} + v_b) + ik\frac{\Omega_B - 4\sigma_B}{4R_b} = 0$$

Lorentz force

$$R_b = \frac{3}{4}\frac{\rho_b}{\rho_\gamma} = \left(\frac{690.18}{1+z}\right)\left(\frac{\omega_{b0}}{0.02273}\right)$$

$$\Delta_Q' + ik\mu\Delta_Q = \epsilon'\left[-\Delta_Q + \frac{1}{2}(1 - P_2(\mu))S_Q\right] + \epsilon' F(\hat{n}, k)\Delta_U,$$

$$\Delta_U' + ik\mu\Delta_U = -\epsilon'\Delta_U - \epsilon' F(\hat{n}, k)\Delta_U,$$

Faraday rotation rate

Evolution of the geometry

$$\rho_t = \rho_e + \rho_i + \rho_\gamma + \rho_\nu + \rho_c + \rho_\Lambda$$

$$\mathcal{H}^2 = \frac{8\pi G}{3} a^2 \rho_t, \qquad \mathcal{H}^2 - \mathcal{H}' = 4\pi G a^2 (p_t + \rho_t),$$

$$p_t = \frac{\rho_\gamma}{3} + \frac{\rho_\nu}{3} - \rho_\Lambda$$

$$2\nabla^2\xi + \mathcal{H}h' = -8\pi G a^2 [\delta_s \rho_t + \delta\rho_B],$$

Hamiltonian constraint

$$\nabla^2 \xi' = 4\pi G a^2 \left\{ (p_t + \rho_t)\theta_t + \frac{\vec{\nabla} \cdot [\vec{J} \times \vec{B}]}{4\pi a^4 \sigma} \right\},$$

Momentum constraint

$$h'' + 2\mathcal{H}h' + 2\nabla^2\xi = 24\pi G a^2 [\delta p_t + \delta p_B],$$

Pressure

$$(h + 6\xi)'' + 2\mathcal{H}(h + 6\xi)' + 2\nabla^2\xi = 24\pi G a^2 [(p_\nu + \rho_\nu)\sigma_\nu + (p_\gamma + \rho_\gamma)\sigma_B],$$

Anisotropic stress

$$\nabla^2 \sigma_B = \frac{3}{16\pi a^4 \rho_\gamma} \vec{\nabla} \cdot [(\vec{\nabla} \times \vec{B}) \times \vec{B}] + \frac{\nabla^2 \Omega_B}{4}, \qquad \Omega_B(\vec{x}) = \frac{\delta\rho_B(\tau, \vec{x})}{\rho_\gamma(\tau)}$$

Magnetized adiabatic mode

Evolution from MG (2004,2006) MG+ KEK(2008)

$$
\begin{aligned}
\xi(k,\tau) &= -2C(k) + \left[\frac{4R_\nu+5}{6(4R_\nu+15)}C(k) + \frac{R_\gamma(4\sigma_{\rm B}(k) - R_\nu\Omega_{\rm B}(k))}{6(4R_\nu+15)}\right]k^2\tau^2, \\
h(k,\tau) &= -C(k)k^2\tau^2 - \frac{1}{36}\left[\frac{8R_\nu^2 - 14R_\nu - 75}{(2R_\nu+25)(4R_\nu+15)}C(k)\right. \\
&+ \left.\frac{R_\gamma(15-20R_\nu)}{10(4R_\nu+15)(2R_\nu+25)}(R_\nu\Omega_{\rm B}(k) - 4\sigma_{\rm B}(k))\right]k^4\tau^4, \\
\delta_\gamma(k,\tau) &= -R_\gamma\Omega_{\rm B}(k) - \frac{2}{3}\left[C(k) - \sigma_{\rm B}(k) + \frac{R_\nu}{4}\Omega_{\rm B}(k)\right]k^2\tau^2, \\
\delta_\nu(k,\tau) &= -R_\gamma\Omega_{\rm B}(k) - \frac{2}{3}\left[C(k) + \frac{R_\gamma}{4R_\nu}\Big(4\sigma_{\rm B}(k) - R_\nu\Omega_{\rm B}(k)\Big)\right]k^2\tau^2, \\
\delta_{\rm c}(k,\tau) &= -\frac{3}{4}R_\gamma\Omega_{\rm B}(k) - \frac{C(k)}{2}k^2\tau^2, \\
\delta_{\rm b}(k,\tau) &= -\frac{3}{4}R_\gamma\Omega_{\rm B}(k) - \frac{1}{2}\left[C(k) - \sigma_{\rm B}(k) + \frac{R_\nu}{4}\Omega_{\rm B}(k)\right]k^2\tau^2, \\
\theta_{\gamma{\rm b}}(k,\tau) &= \left[\frac{R_\nu}{4}\Omega_{\rm B}(k) - \sigma_{\rm B}\right]k^2\tau - \frac{1}{36}\left[2C(k) + \frac{R_\nu\Omega_{\rm B}(k) - 4\sigma_{\rm B}(k)}{2}\right]k^4\tau^3, \\
\theta_\nu(k,\tau) &= \left[\frac{R_\gamma}{R_\nu}\sigma_{\rm B}(k) - \frac{R_\gamma}{4}\Omega_{\rm B}(k)\right]k^2\tau - \frac{1}{36}\left[\frac{2(4R_\nu+23)}{4R_\nu+15}C(k)\right. \\
&+ \left.\frac{R_\gamma(4R_\nu+27)}{2R_\nu(4R_\nu+15)}(4\sigma_{\rm B}(k) - R_\nu\Omega_{\rm B}(k))\right]k^4\tau^3, \\
\theta_{\rm c}(k,\tau) &= 0, \\
\sigma_\nu(k,\tau) &= -\frac{R_\gamma}{R_\nu}\sigma_{\rm B}(k) + \left[\frac{4C(k)}{3(4R_\nu+15)} + \frac{R_\gamma(4\sigma_{\rm B}(k) - R_\nu\Omega_{\rm B})}{2R_\nu(4R_\nu+15)}\right]k^2\tau^2,
\end{aligned}
$$

Lambda CDM parameters

$$(\Omega_{b0},\, \Omega_{c0},\, \Omega_{\Lambda},\, h_0,\, n_s,\, \tau) = (0.0441,\, 0.214,\, 0.742,\, 0.719,\, 0.963,\, 0.087)$$

WAP 5-year alone

$$(\Omega_{b0},\, \Omega_{c0},\, \Omega_{\Lambda},\, h_0,\, n_s,\, \tau) = (0.042,\, 0.198,\, 0.76,\, 0.732,\, 0.958,\, 0.089).$$

WAP 3-year alone

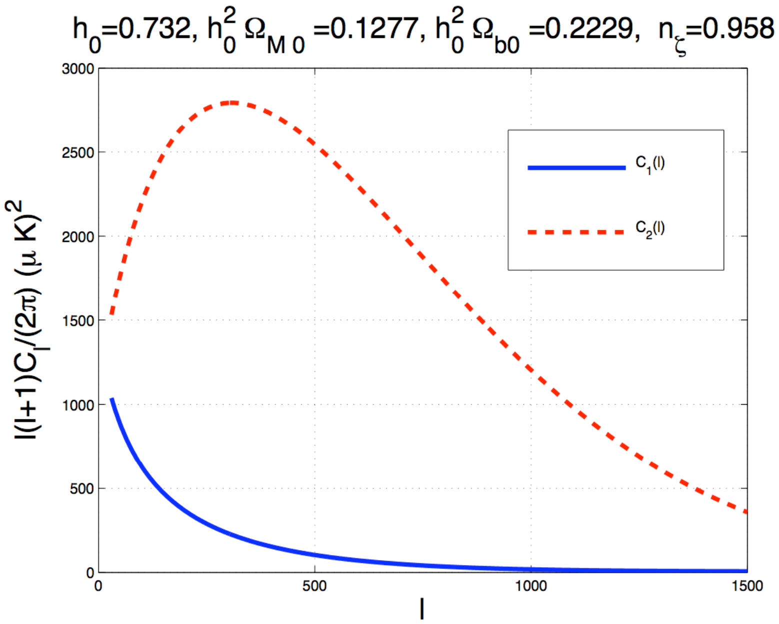
(WMAP + ACBAR +CBI + VSA+ HSTKP+ SDS+ SNLS+SNGS)

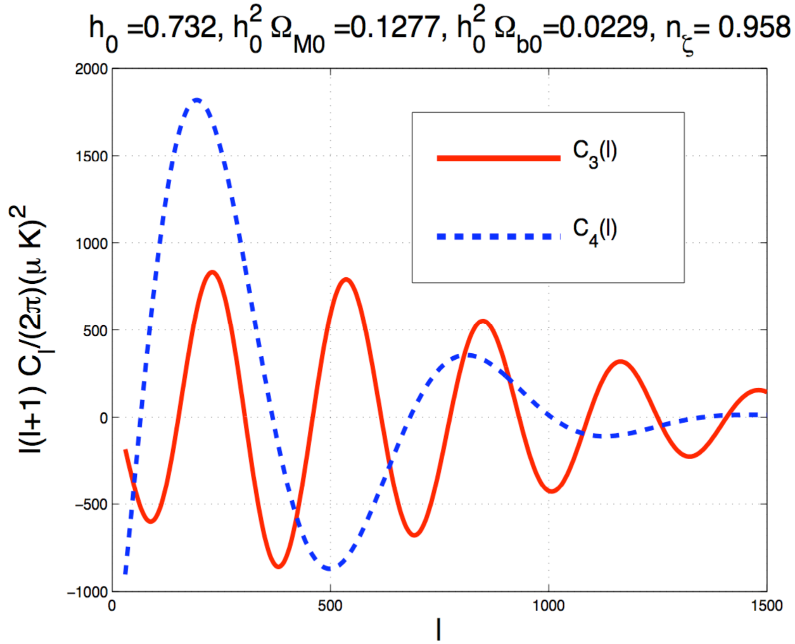
Bounds on magnetic fields? Old logic

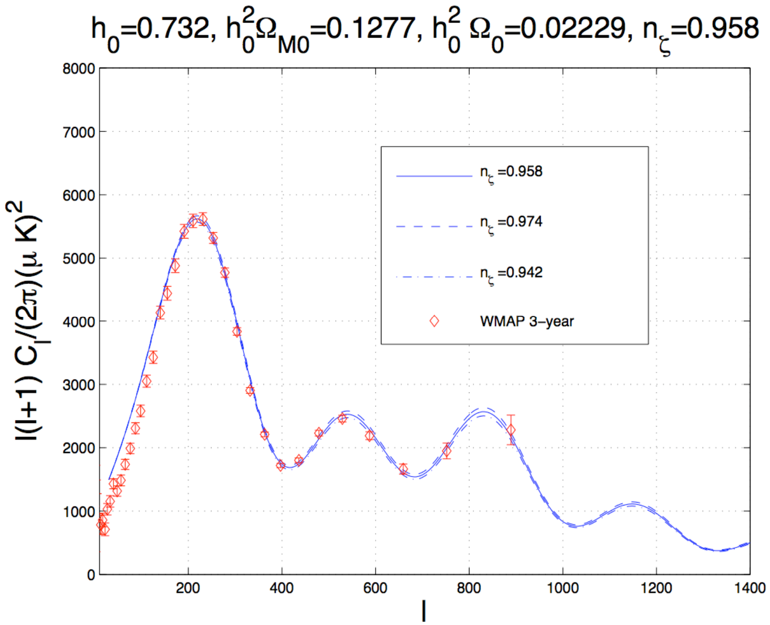
Add two new parameters: magnetic spectral index and magnetic field intensity and estimate the two parameters

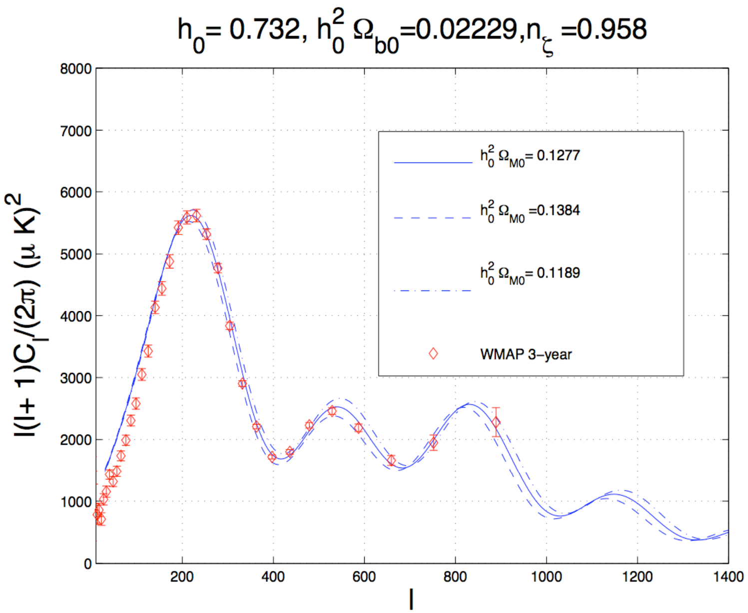
M-LambdaCDM (i.e. magnetized -LambdaCDM)

Temperature autocorrelations (semi-analytical)/a



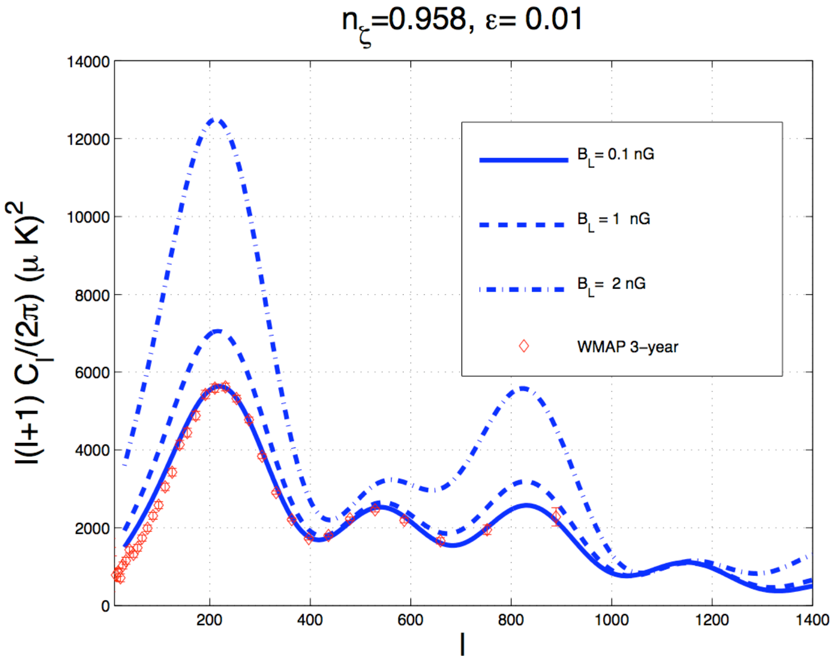


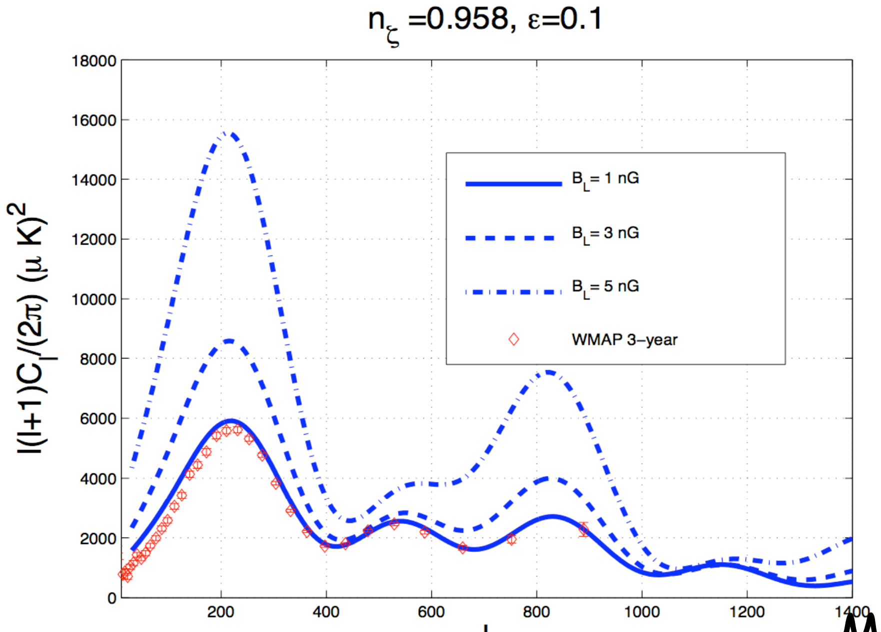




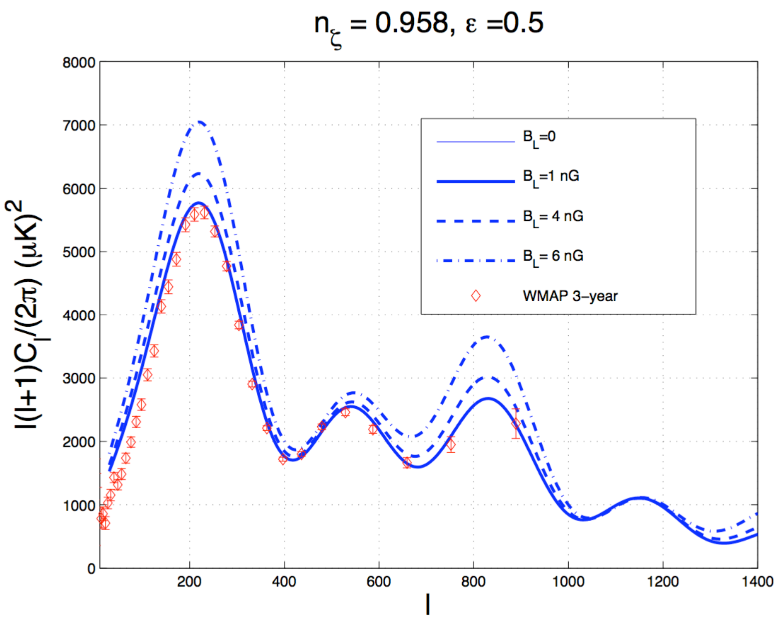
MG (2007)

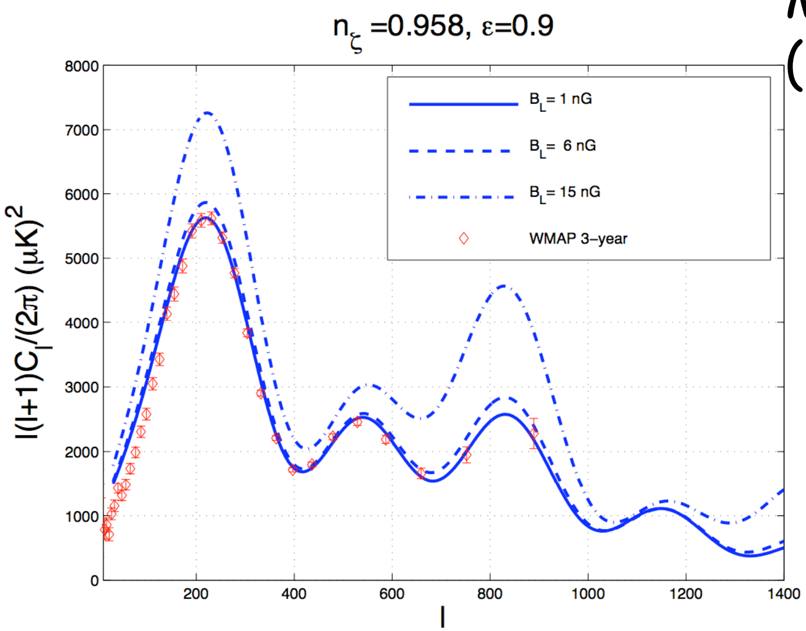
Temperature autocorrelations (semi-analytical)/b



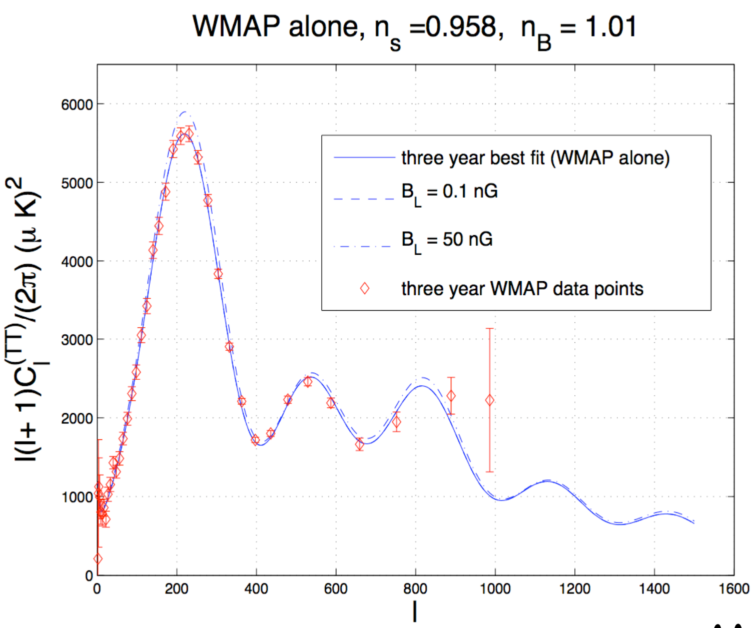


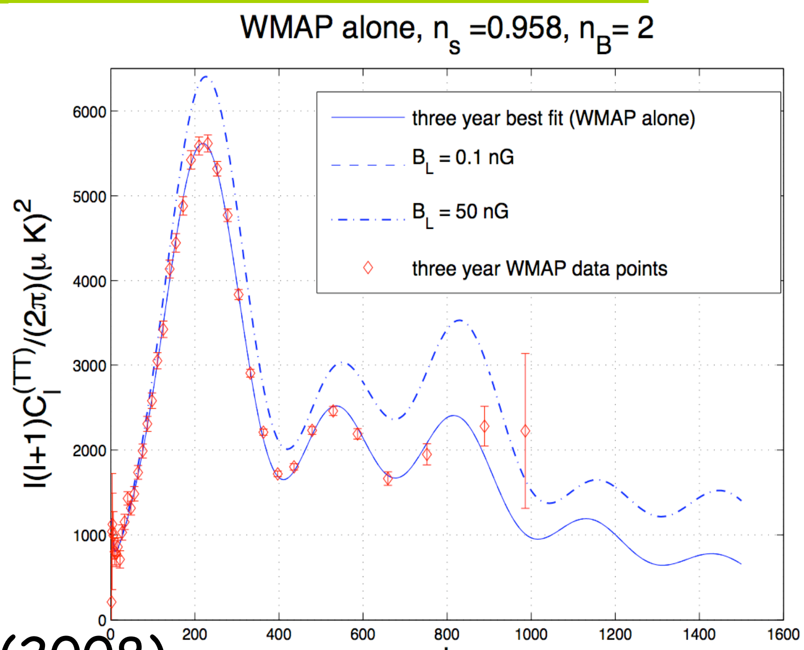
MG (2007)



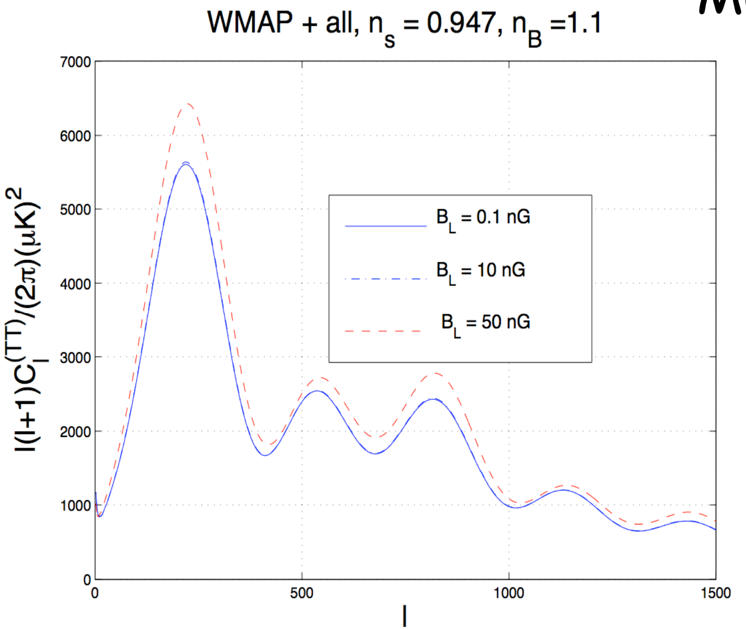


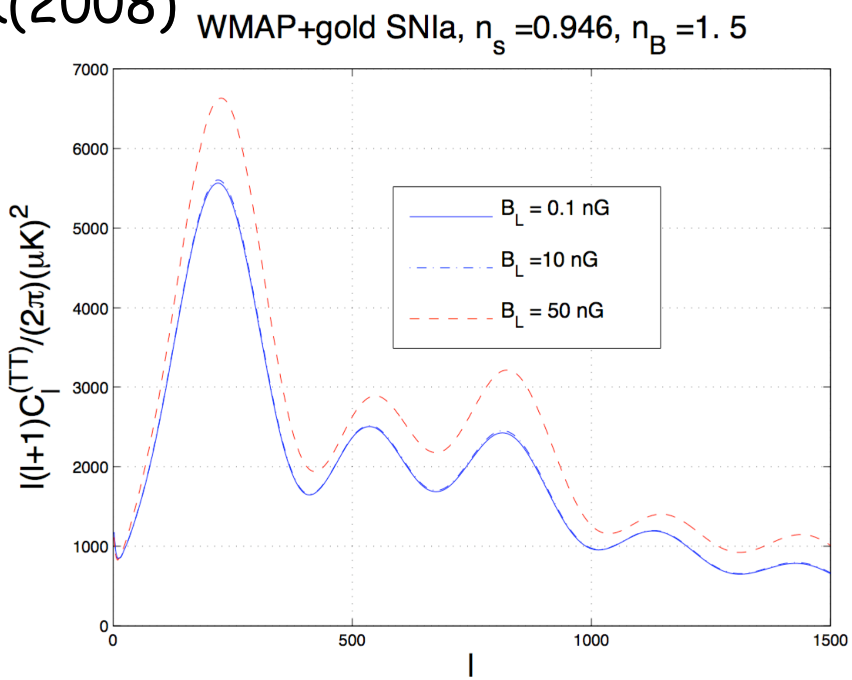
Temperature autocorrelations/fully numerical



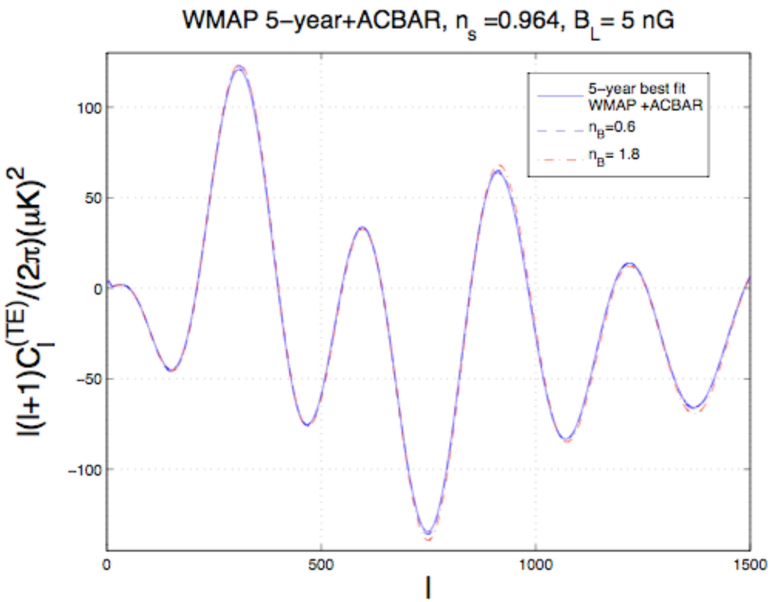


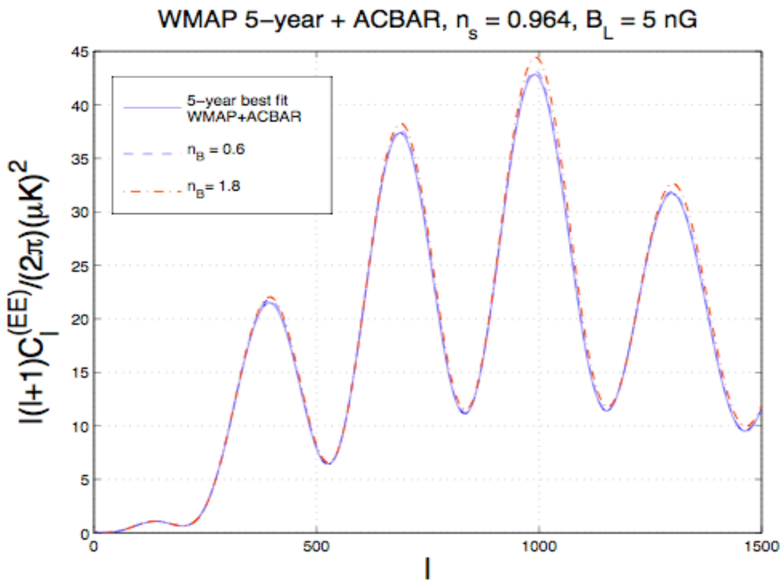
MG,KEK(2008)

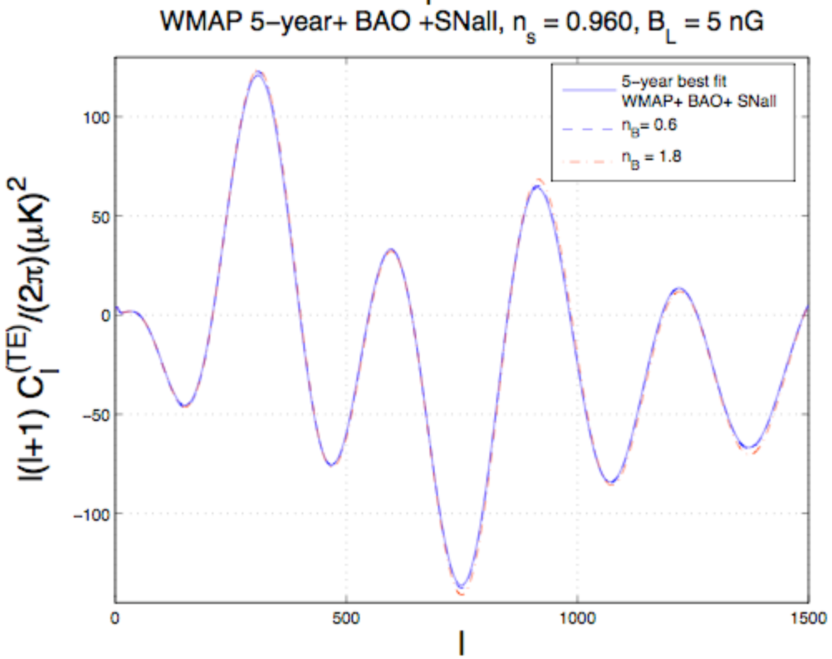


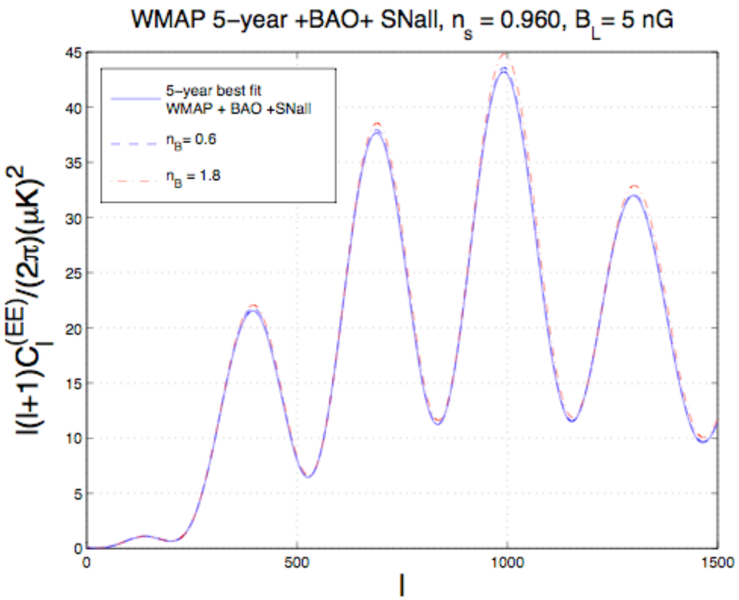


TE-EE correlations

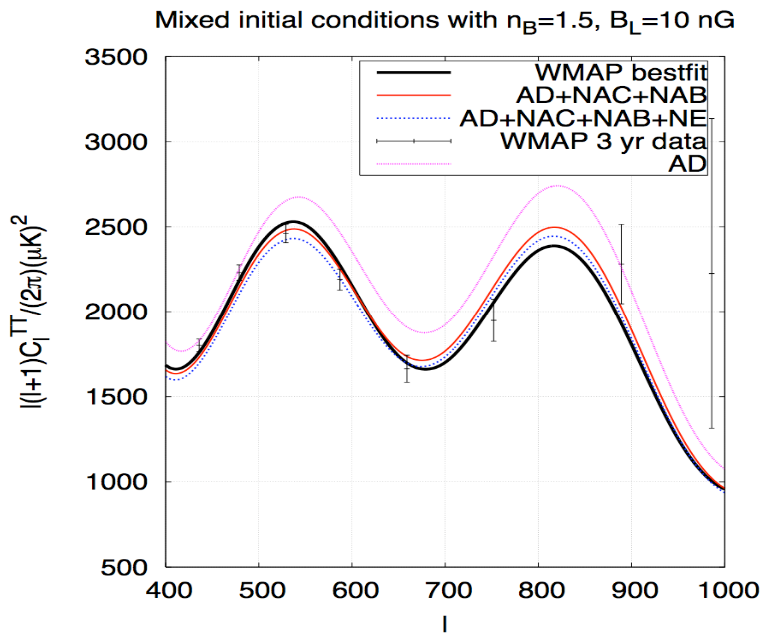


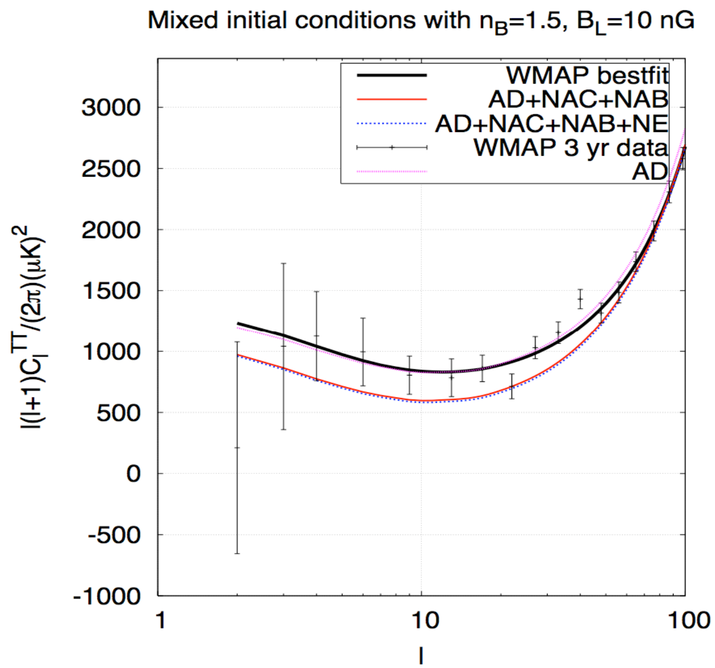


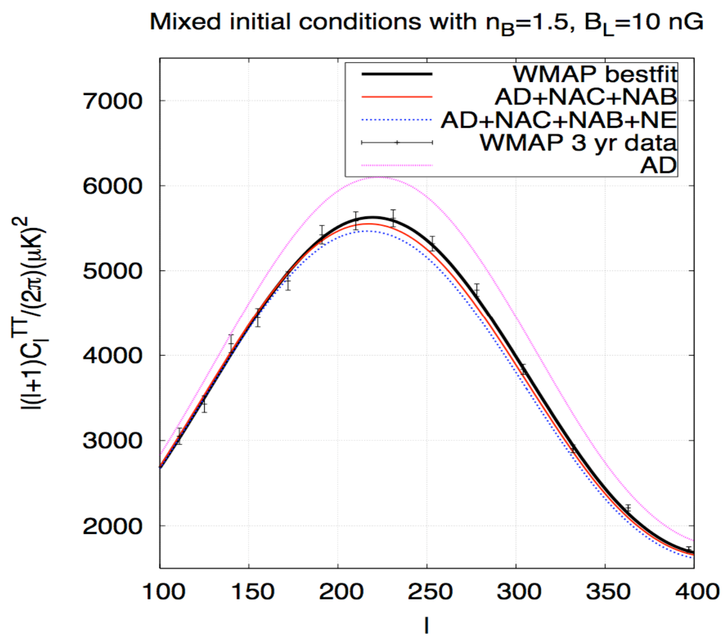


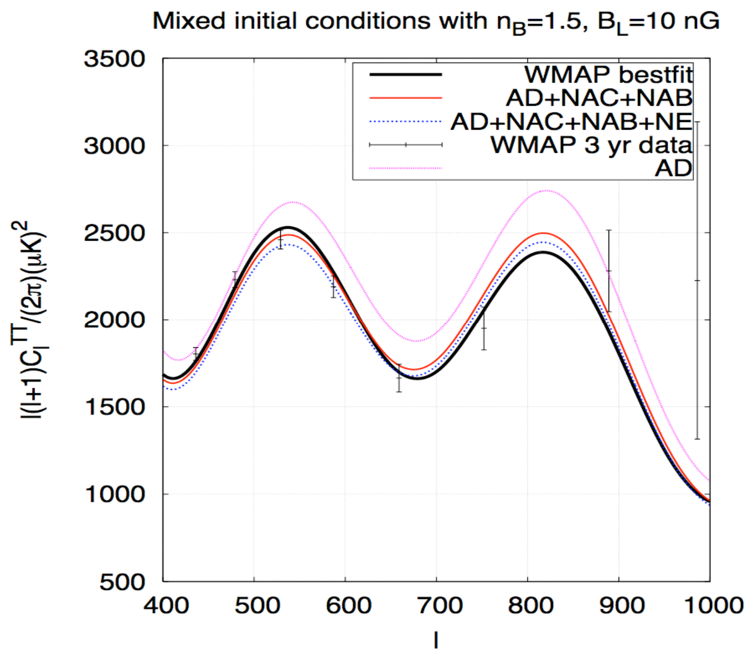


Non-adiabatic modes/1

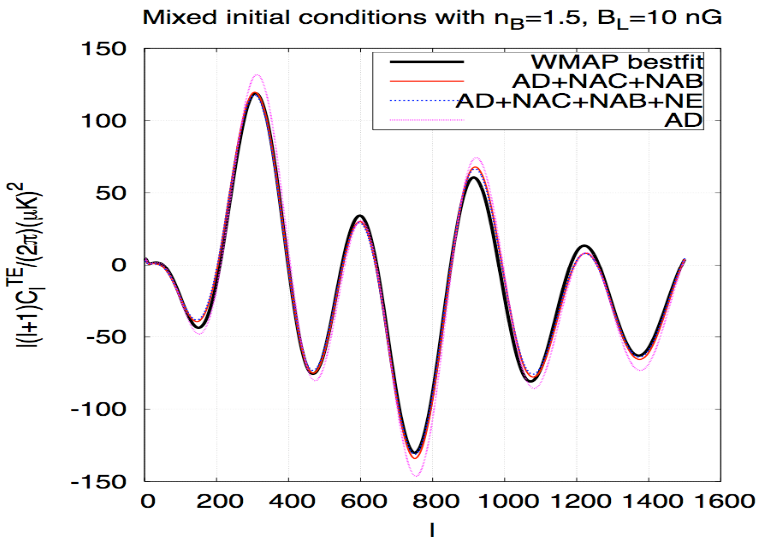


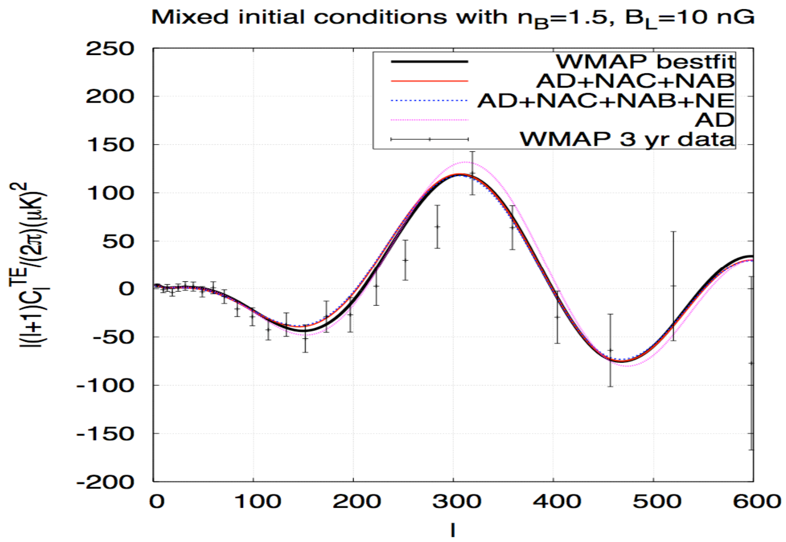


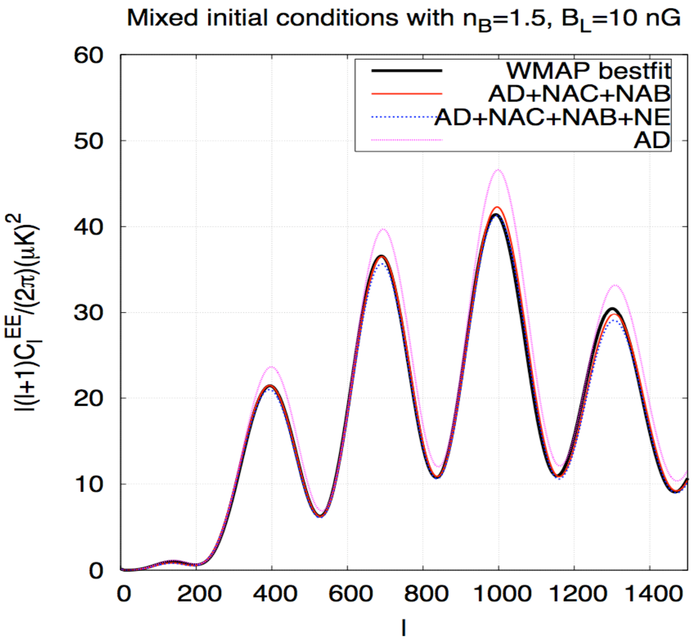


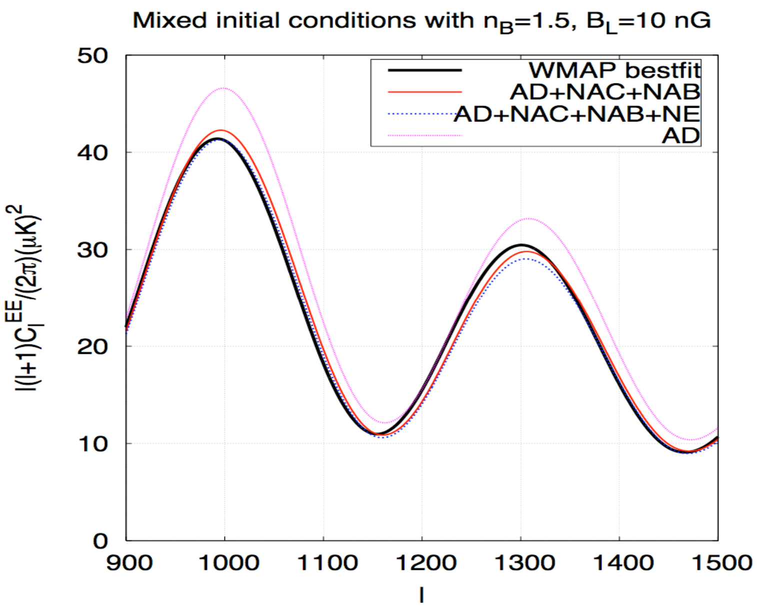


Non-adiabatic modes/2

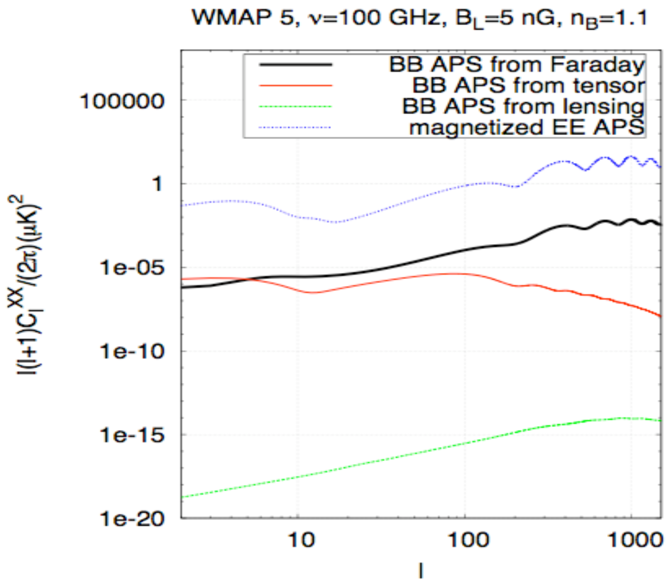


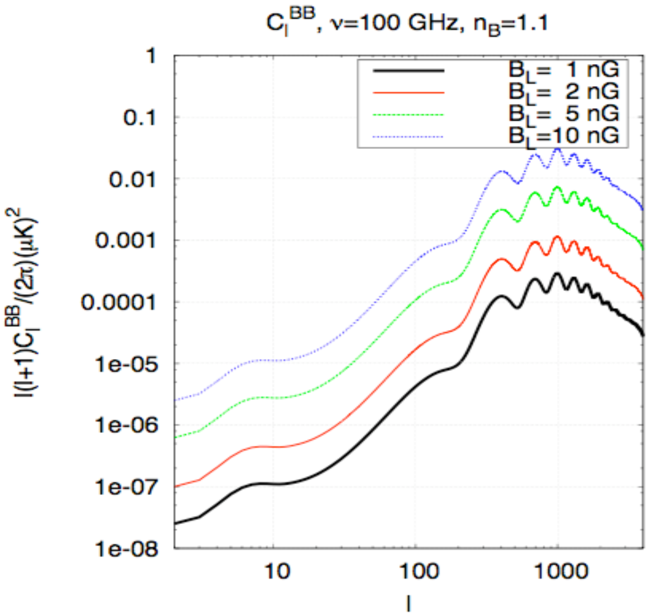




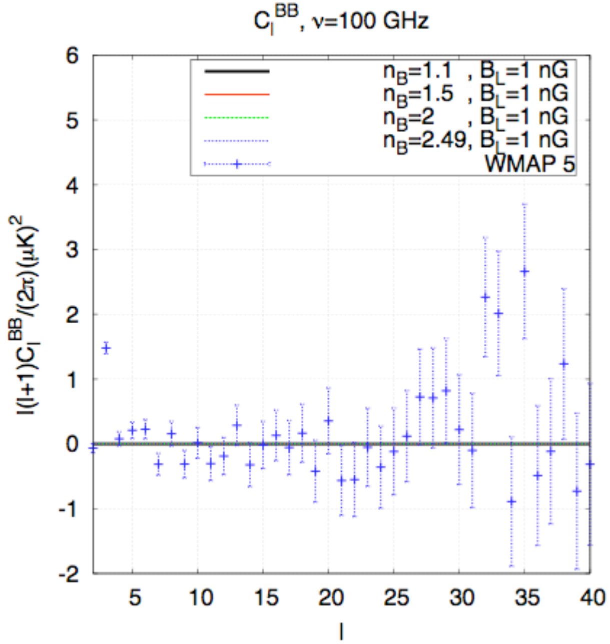


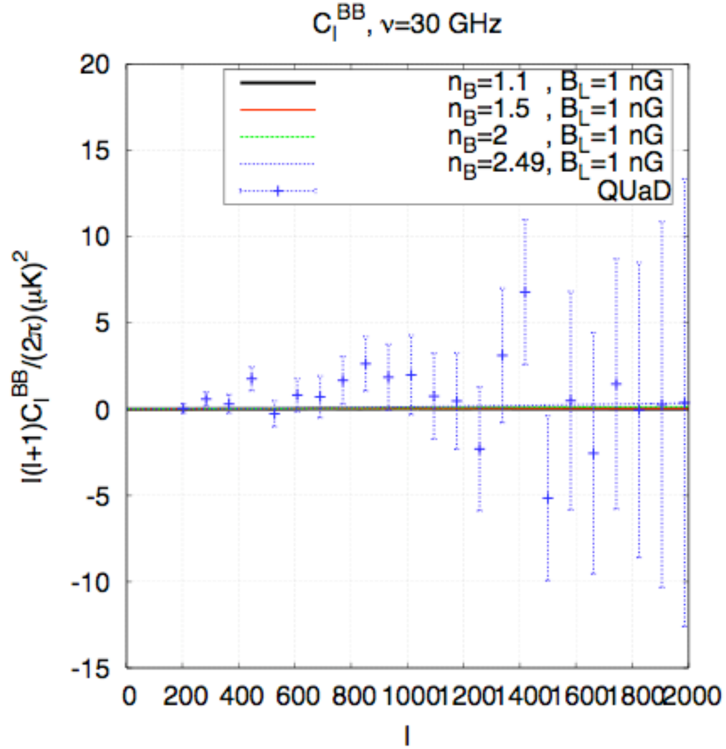
BB correlations/1



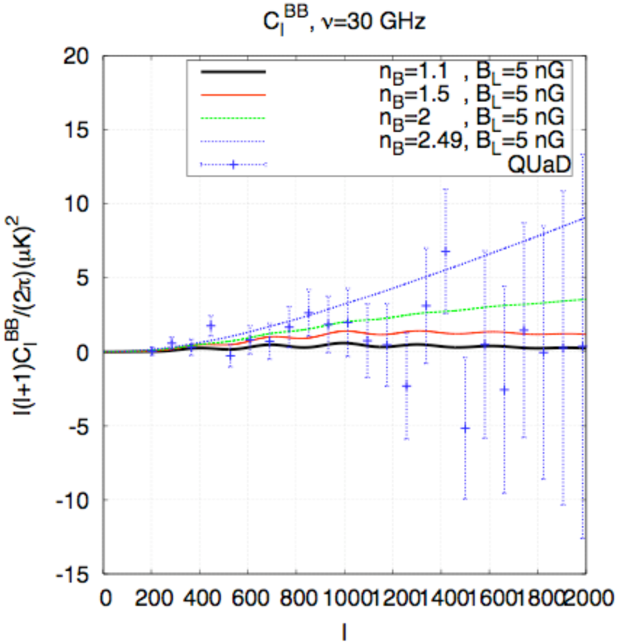


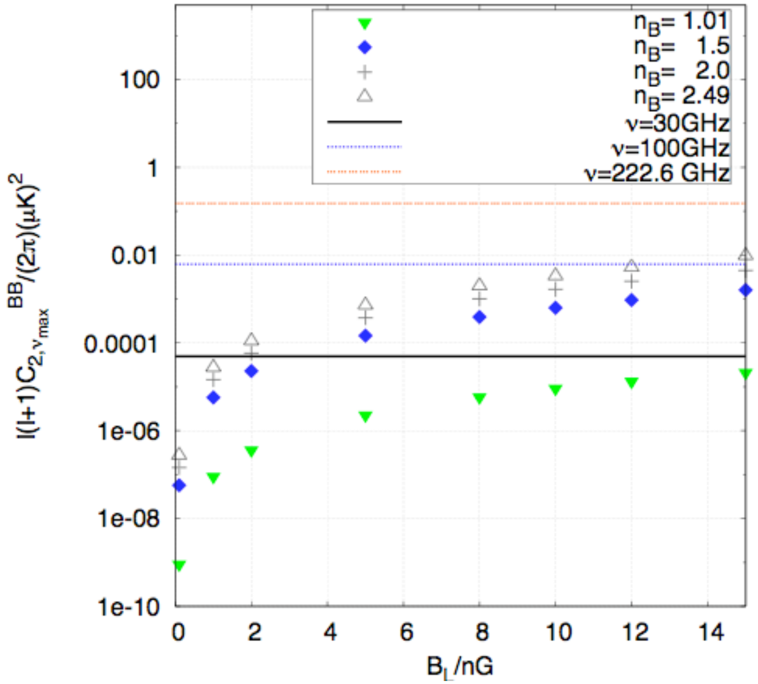
MG KEK 2008

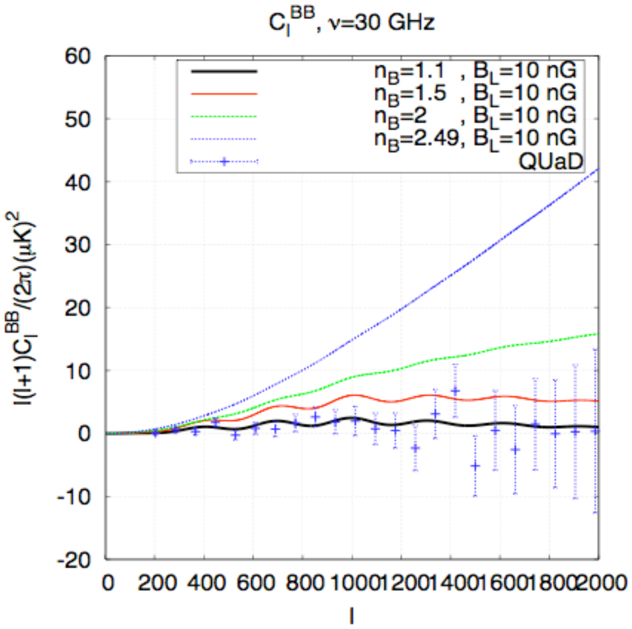


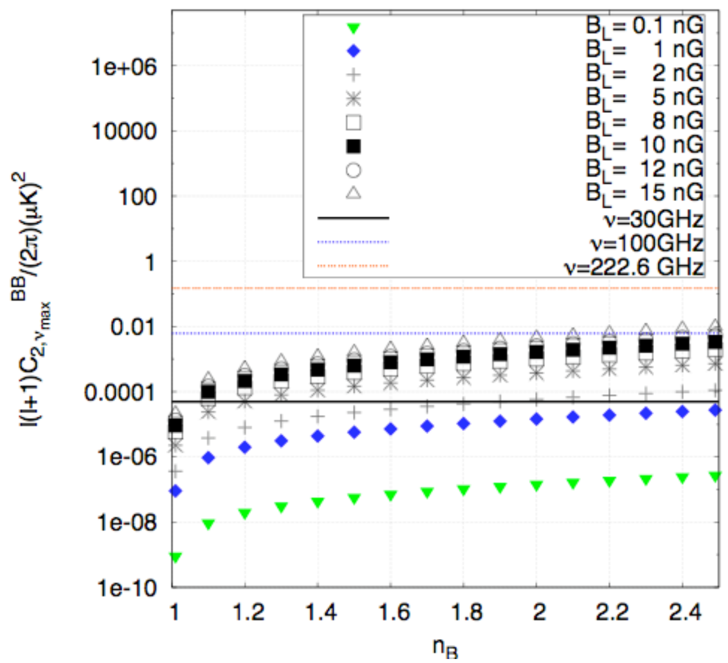


BB correlations/2

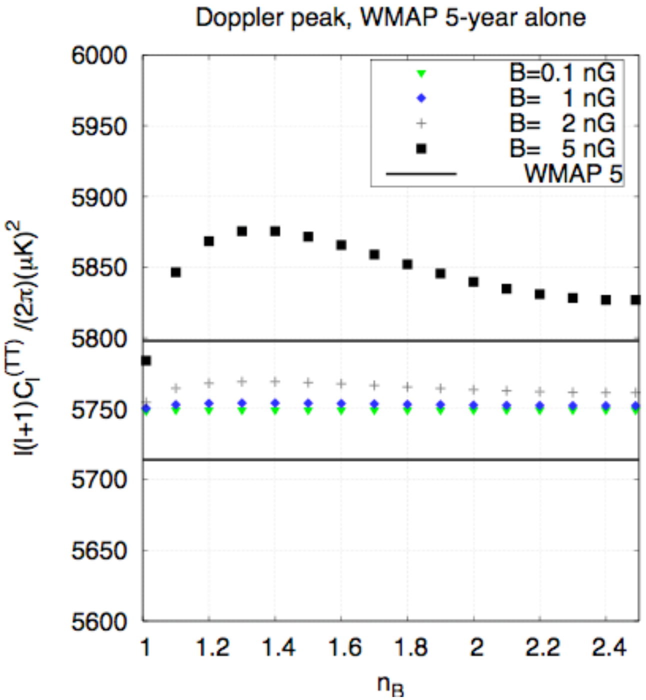


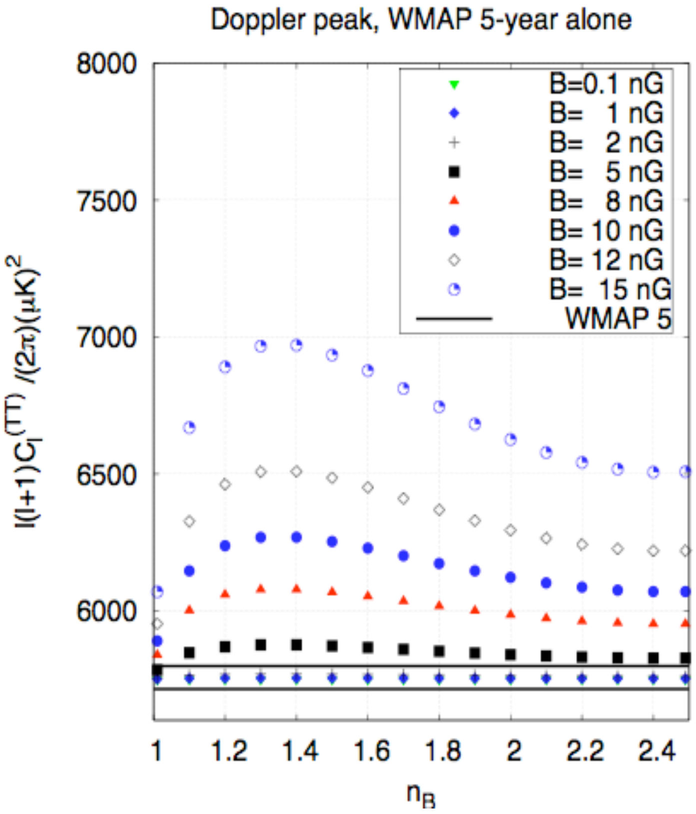






BB correlations/3



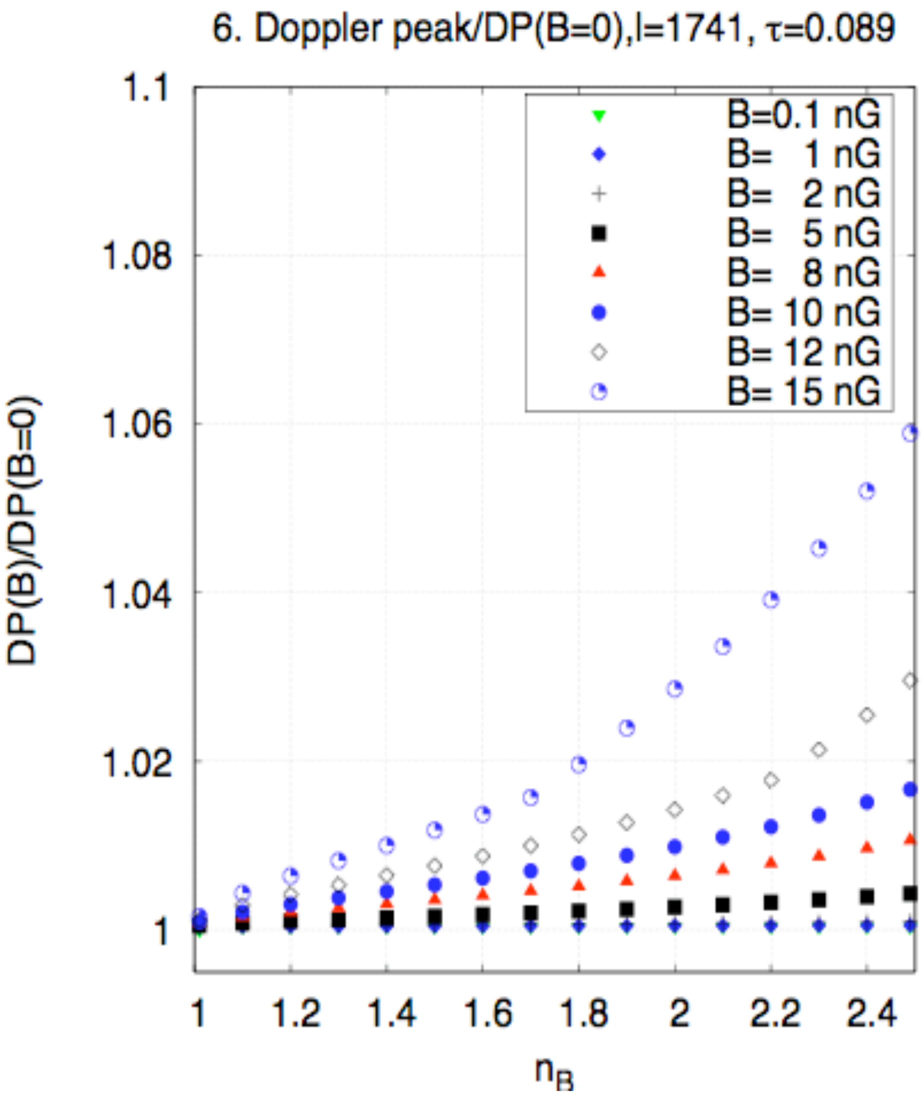


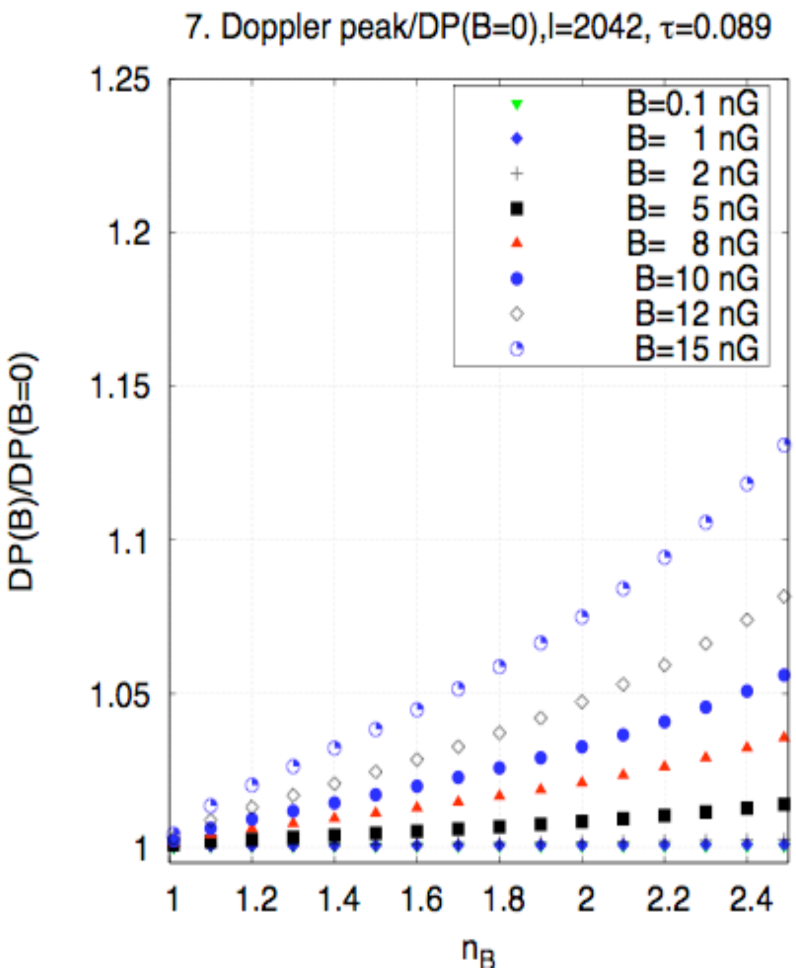
Smoking gun: frequency dependence of the signal

$$\mathcal{G}_\ell^{(\mathrm{T})} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{(\mathrm{TT})}, \qquad \mathcal{G}_\ell^{(\mathrm{E})} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{(\mathrm{EE})}, \qquad \mathcal{G}_\ell^{(\mathrm{B})} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{(\mathrm{BB})},$$

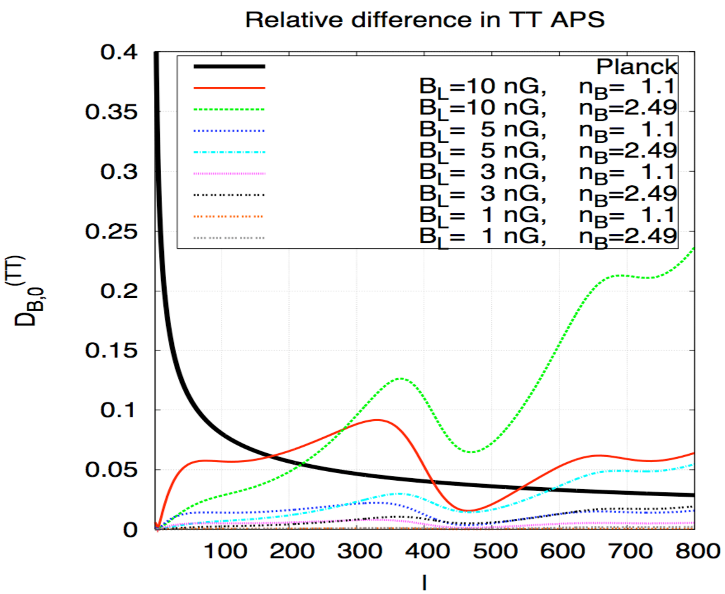
$$\mathcal{G}_\ell^{(\mathrm{T})}(\nu) = \tilde{\mathcal{G}}_\ell^{(\mathrm{T})}(\tilde{\nu}), \qquad \mathcal{G}_\ell^{(\mathrm{E})}(\nu) = \tilde{\mathcal{G}}_\ell^{(\mathrm{E})}(\tilde{\nu}), \qquad \nu^4 \mathcal{G}_\ell^{(\mathrm{B})}(\nu) = \tilde{\nu}^4 \tilde{\mathcal{G}}_\ell^{(\mathrm{B})}(\tilde{\nu}).$$

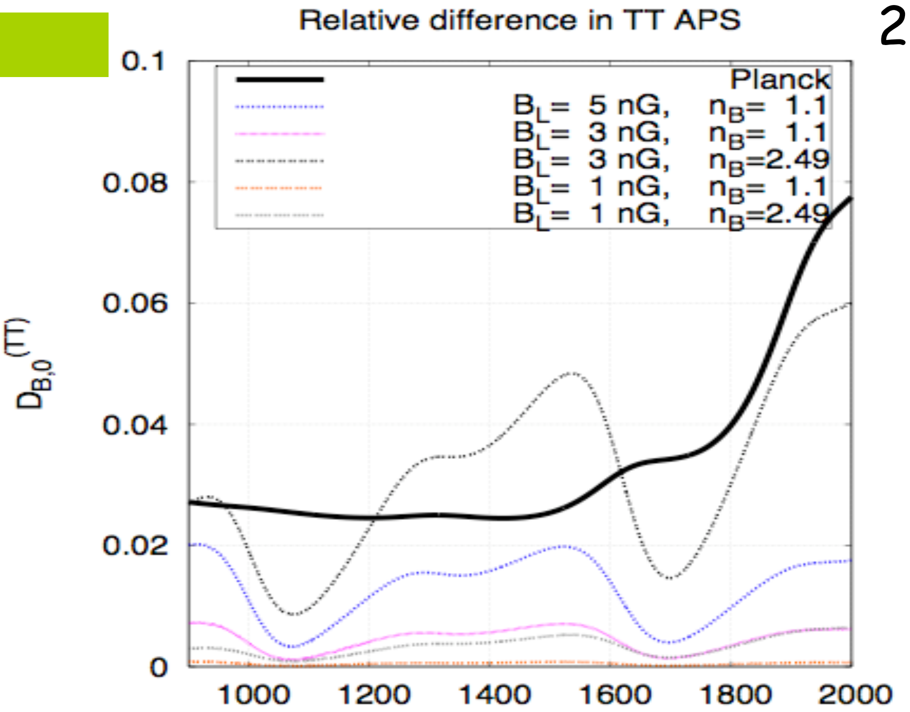
Larger acoustic peaks/1

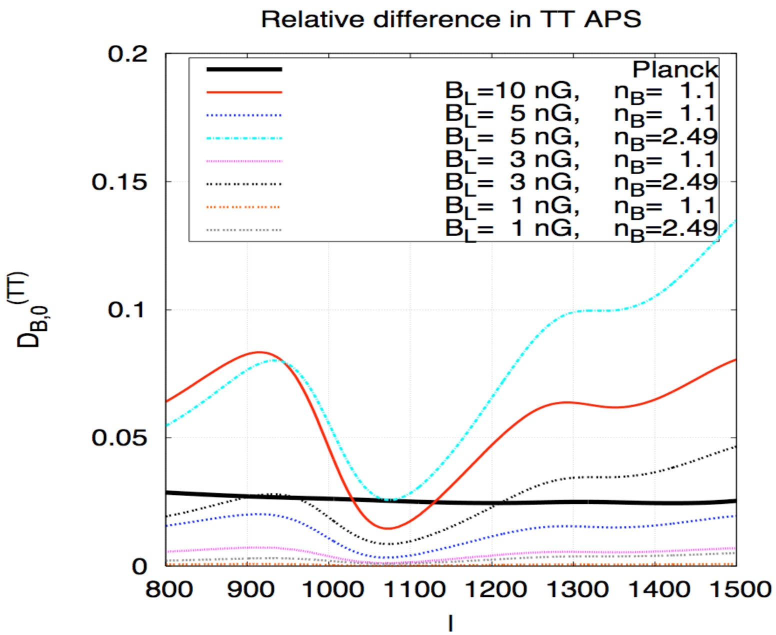


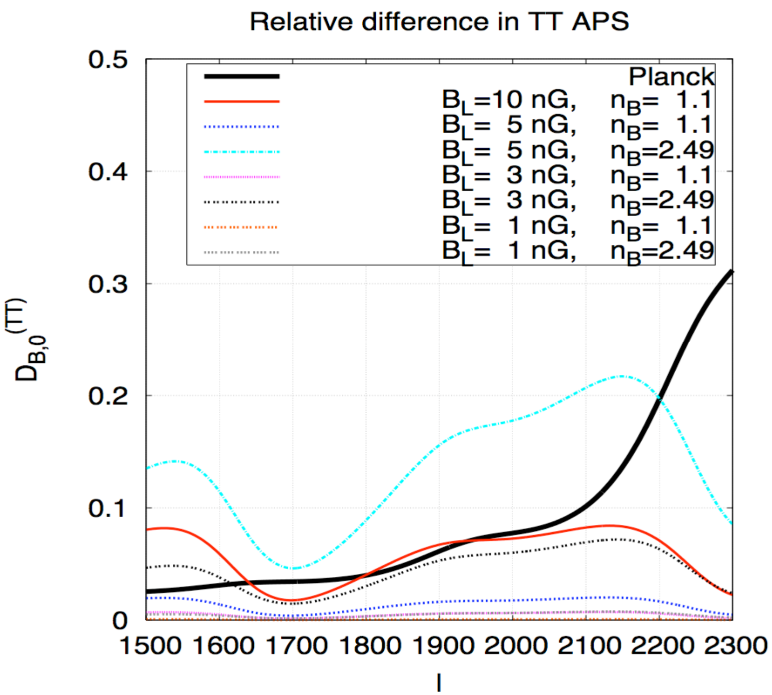


Planck and TT correlations

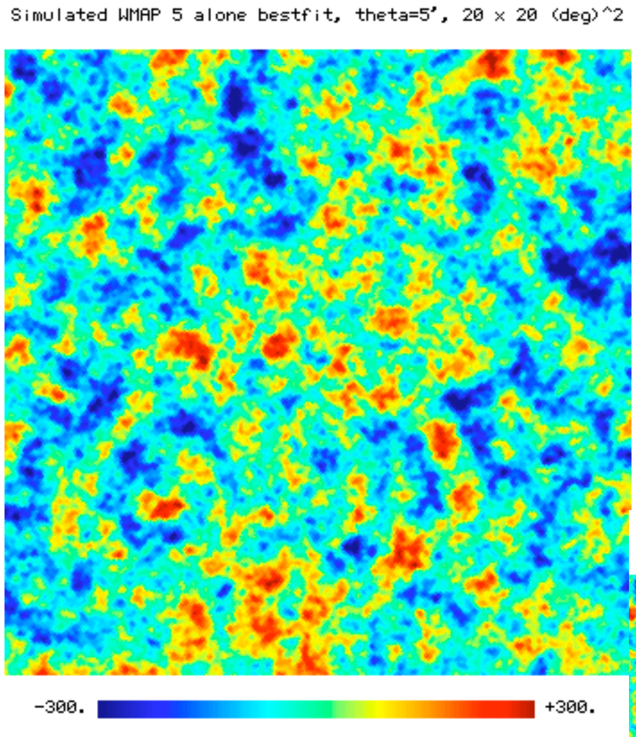


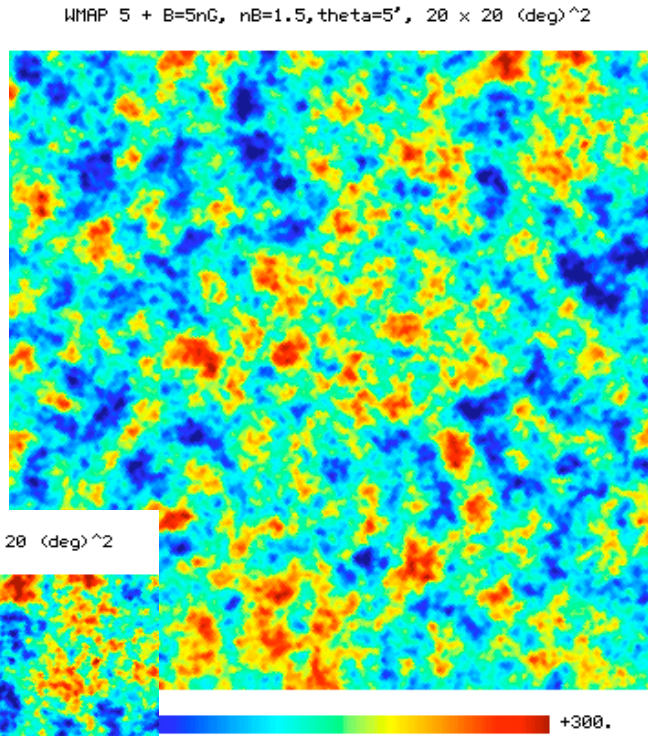


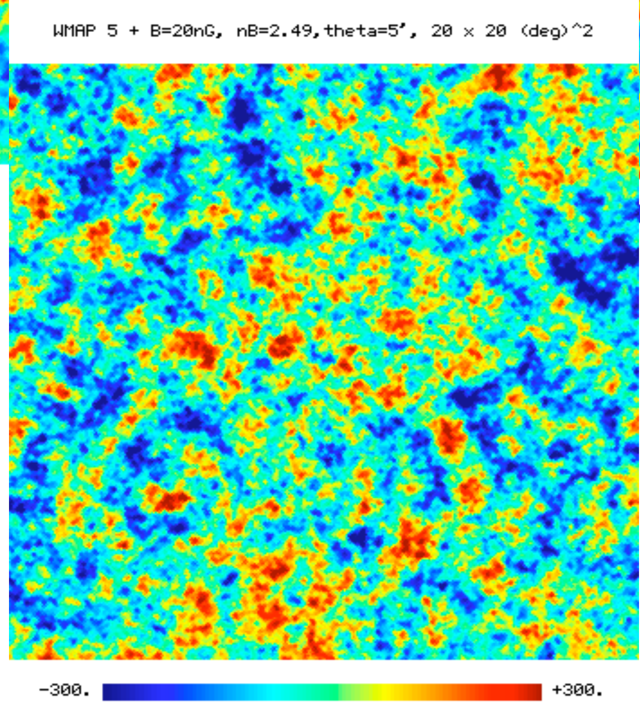




MAPS


Simulated WMAP 5 alone bestfit, theta=5', 20 x 20 (deg)^2
-300.
+300.


WMAP 5 + B=5nG, nB=1.5,theta=5', 20 x 20 (deg)^2
+300.


WMAP 5 + B=20nG, nB=2.49,theta=5', 20 x 20 (deg)^2
-300.
+300.

Summary

We have indirect indications of large-scale MF which must be O(0.1 nG) at high redshift

If they are there they must show up in CMB physics

Include magnetic fields in the treatment of CMB anisotropies
According to the same standards used in the absence of MF (2004-2008)

Interdisciplinary problem:
1) two-fluid description of magnetized plasmas - > Plasma Dynamics;
2) relativistic fluctuations of the geometry -> G R;
3) Astrophysical & cosmological implications -> CMB physics
Radio-astronomy, high-energy cosmic rays....

Novel results:- magnetized TT, TE, EE and BB angular power spectra
-MF included in the initial conditions AND in the dynamical equations;
-Magnetized CMB maps available
-Expected Planck data sensitive to MF O(0.001) nG

For the future : a lot of work...