Magnetizing the Universe

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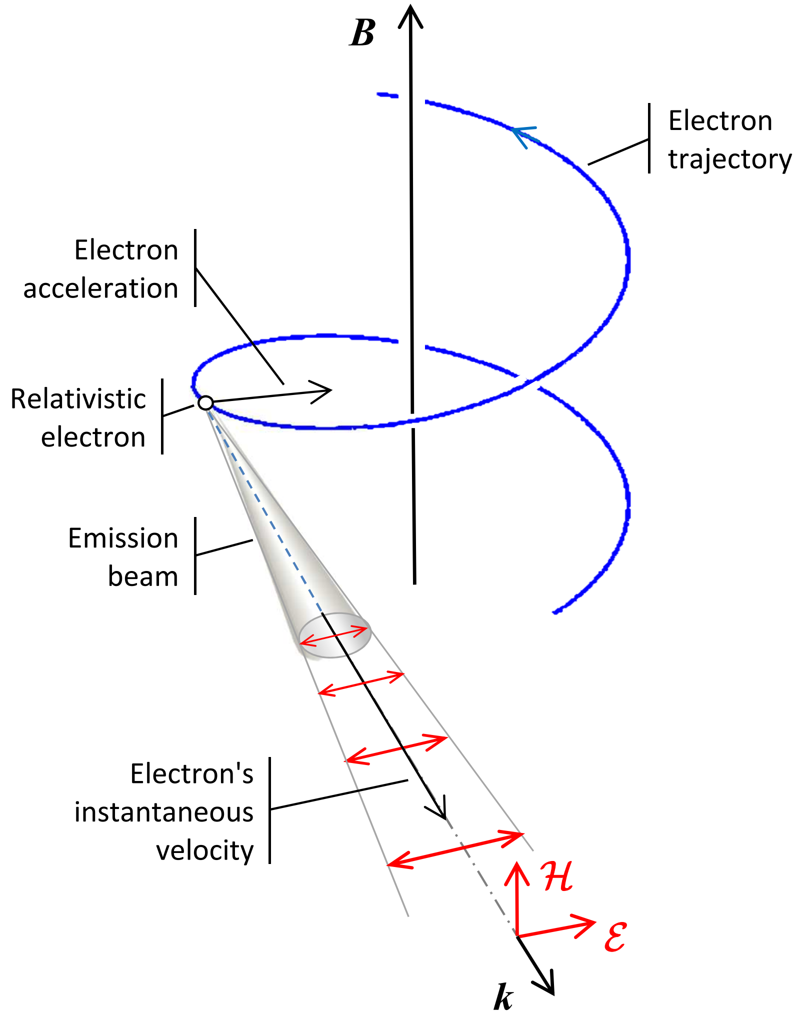
Summary

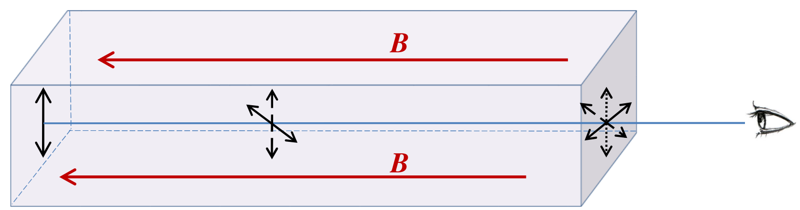
- The universe is magnetized: Planets, Stars, nearby and high Z Galaxies, Plasma in Galaxy clusters, Inter galactic medium in voids! How do such coherent magnetic fields arise?
- Cosmic Batteries and seed magnetic fields.
- Turbulence $\rightarrow$ Fluctuation dynamo in galaxies and clusters
- The large scale turbulent dynamos (LSDs): Stars/Galaxies
- Inflationary magnetogenesis? Caveats and constraints? Gravitational wave predictions.

K. Subramanian, From primordial seed magnetic fields to the galactic dynamo, Galaxies, Vol 7, Issue 2, p47, arXiv:1903.03744.

A. Shukurov and K. Subramanian, Astrophysical Magnetic fields: From Galaxies to the Early Universe, CUP, 2021.

Measuring B fields:Synchrotorn Radiation





Faraday Rotation gives $B_{\|}$

$$\Delta\phi = \lambda^2 \times RM = \lambda^2 \times K \int n_e \boldsymbol{B} \cdot \mathbf{dl}$$

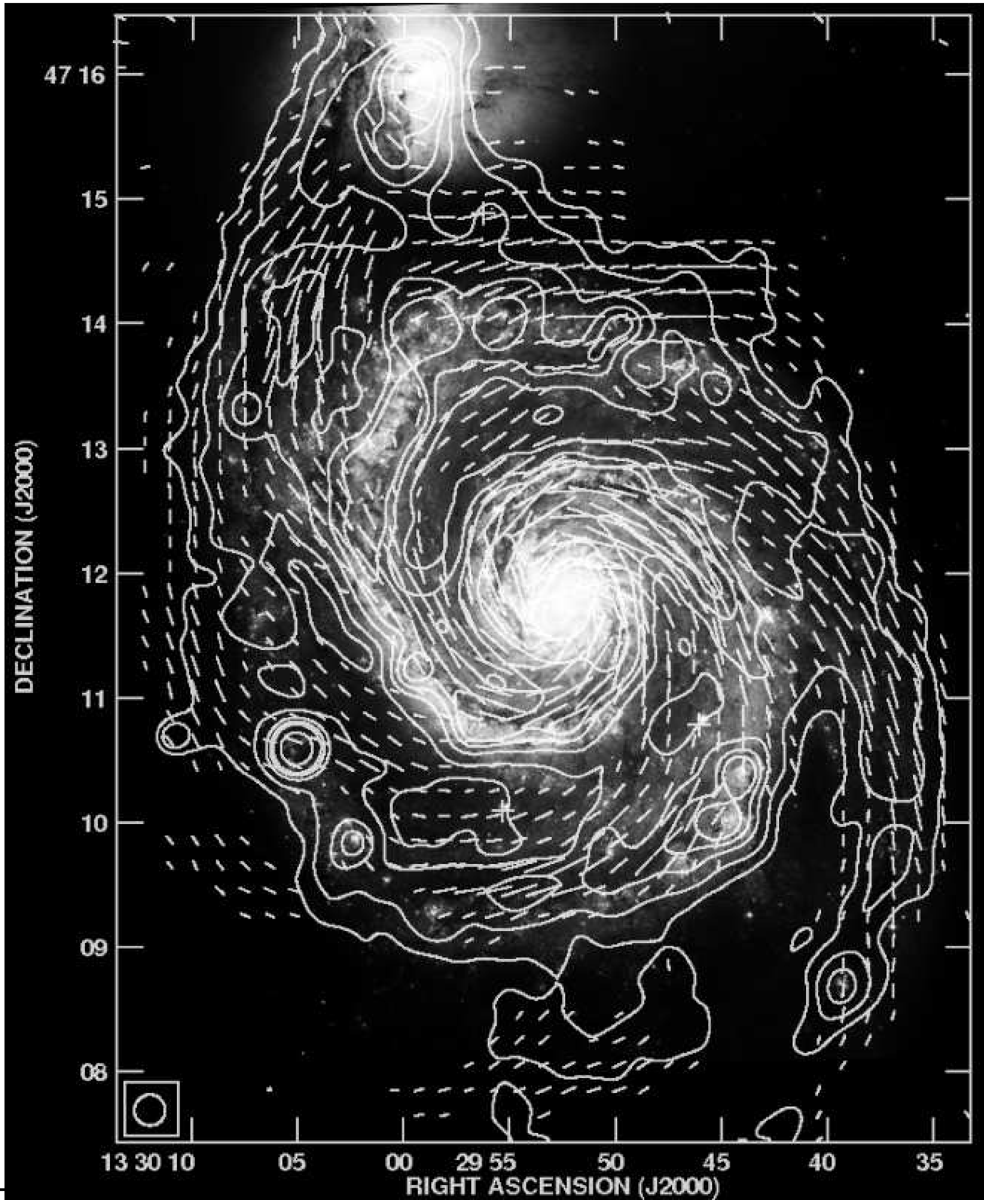
$$K = 0.81 \text{ rad m}^{-2} \, (\mu G)^{-1} \, (\text{pc})^{-1} \text{ cm}^{-3}$$

Synchrotron polarization gives $B_{\perp}$

$$\boldsymbol{E} \propto \hat{\boldsymbol{n}} \times [(\hat{\boldsymbol{n}} - \hat{\beta}) \times d\hat{\beta}/dt] \propto d\hat{\beta}/dt$$

Galactic Magnetic Fields: Observations

M51 at 6 cm (Fletcher and Beck)

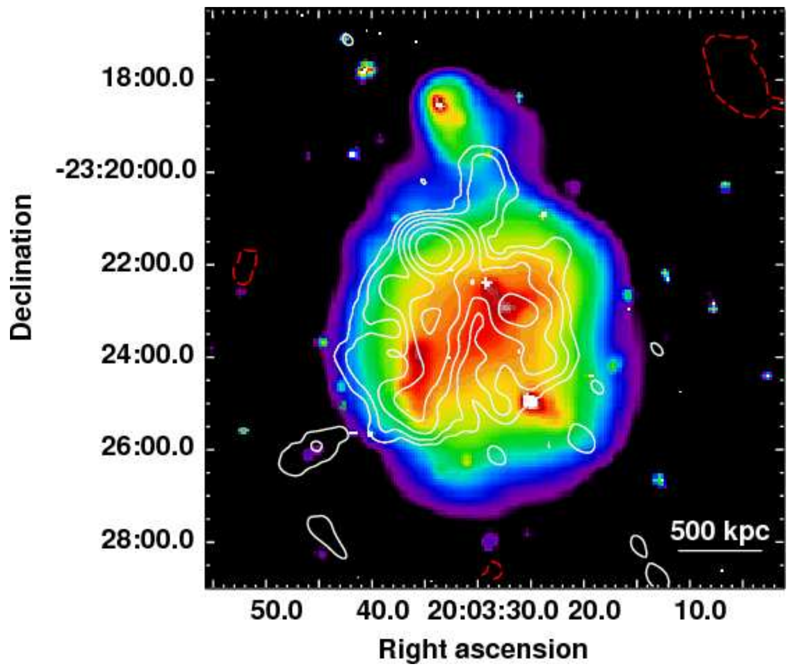


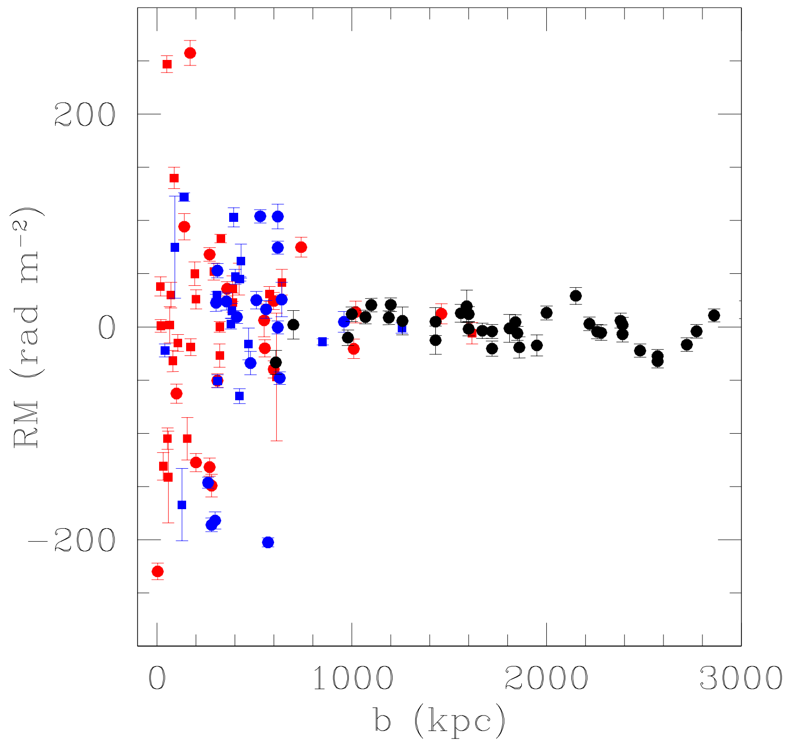
- **Galactic B fields via Synchrotron radiation: Intensity (B), polarization ($B_\perp$) and Faraday rotation ($B_\parallel$).**
- **Few μG mean Fields coherent on 10 kpc scales and larger random fields.**
- **Similar magnetic field strengths in younger galaxies at $z \sim 1$.** (Bernet et. al., 2008)

(1 pc is 3.26 light years)

Cluster Magnetic fields

Clarke et al., ApJ, 547, L111, 2001





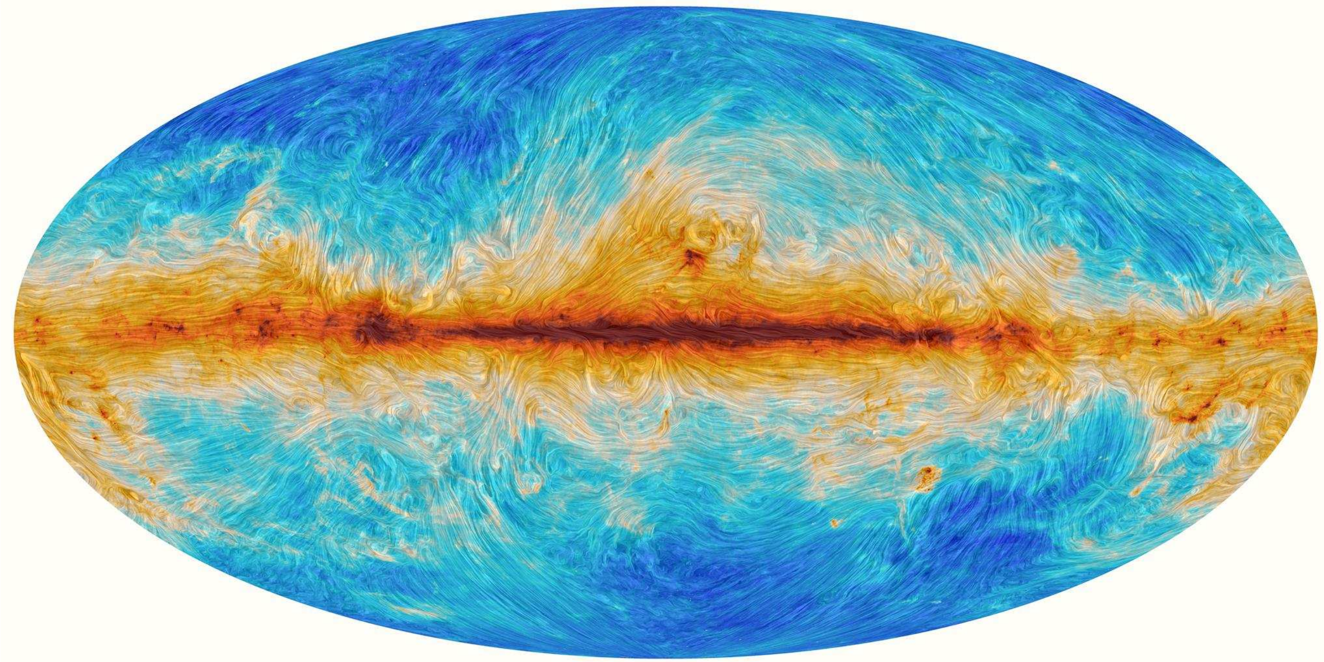
- **Chandra (X-Ray)-GMRT (235 Mhz): Giant radio halo in RXC J2003.5-2323**
- Giacintucci et al. A & A, 505, 45, 2009

- **Statistical RM study**
- $B \sim 5(l/10kpc)^{-1/2}\mu G$
- **embedded sources**
- **background sources**

Our Galaxy B seen by Planck

B from polarized emission (353 GHz) by elongated Dust grains (Planck)

(https://www.cosmos.esa.int/web/planck/picture-gallery)



- **Chandrasekhar-Fermi 1953 estimate of galactic B from dust polarization.**

Galactic Magnetic Fields: Observations

SOFIA Legacy Program, M51: Borlaff....KS..et. al, ApJ (2021)

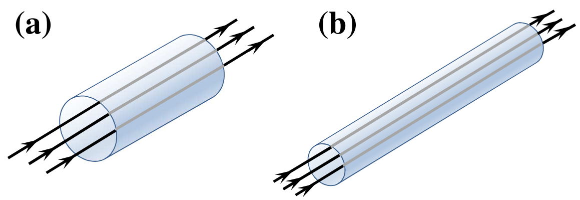
(FIR 145 μm)

(Radio 6 cm Fletcher et. al)

How do such large scale galactic fields arise? Mean field dynamo?

Maintaining magnetic fields

- Magnetic fields decay if not maintained: Lorentz force Driving motions, which are damped by Viscosity or become turbulent and then decay
- EM induction by Motions can maintain magnetic fields
  $\partial \mathrm{B}/\partial t = -c\nabla \times \mathbf{E}, \quad \boldsymbol{E} = -(\boldsymbol{V} \times \boldsymbol{B})/c + (\boldsymbol{J}/\sigma);$
  $(\partial \mathbf{B}/\partial t) = -c\nabla \times \mathbf{E} = \nabla \times (\mathbf{V} \times \mathbf{B} - \eta\nabla \times \mathbf{B})\,; \quad \eta = c^2/4\pi\sigma$
- The field back reacts on V via the Lorentz force $\mathrm{J} \times \mathrm{B}$
- If $\eta \to 0$, the flux $\Phi = \int_S \boldsymbol{B} \cdot d\mathrm{S}$ is 'frozen' $\to d\Phi/dt \to 0$.



$BA =$ constant and $\rho Al =$ constant $\to B/\rho \propto l$, and $A \propto 1/(\rho l)$

- Magnetic and Fluid Reynolds number: $R_m = vl/\eta$, $R_e = vl/\nu$.
  Galaxy, ionized: $R_m \sim 3 \times 10^{19}$, $R_e \sim 4.6 \times 10^7$, $l = 100\mathrm{pc}$, $v = 10\mathrm{kms}^{-1}$.
- Magnetic Field almost frozen to moving plasma. Need initial B field – "Battery". Need kinetic to magnetic energy conversion — dynamos

The first "seed" fields in the universe

- **Astrophysical Batteries using postive/negative charge asymmetry**
- **Biermann Batteries**: $\mathbf{E}_{Bier} = -\nabla p_e/en_e + \ldots$

$$(\partial \mathbf{B}/\partial t) = -c\nabla \times \mathbf{E}_{Bier} = -(ck/en_e)\nabla n_e \times \nabla T_e$$

  - **Re-Ionization fronts**: $B < 10^{-19}$ G (Subramanian, Narasimha, Chitre, MN, 1994; Gnedin, Ferrara and Zweibel, ApJ, 2000)
  - **Curved Structure formation Shocks** (Kulsrud et al, 1997)

- **Take curl, use Ampere, neglect Hall, inertial terms**

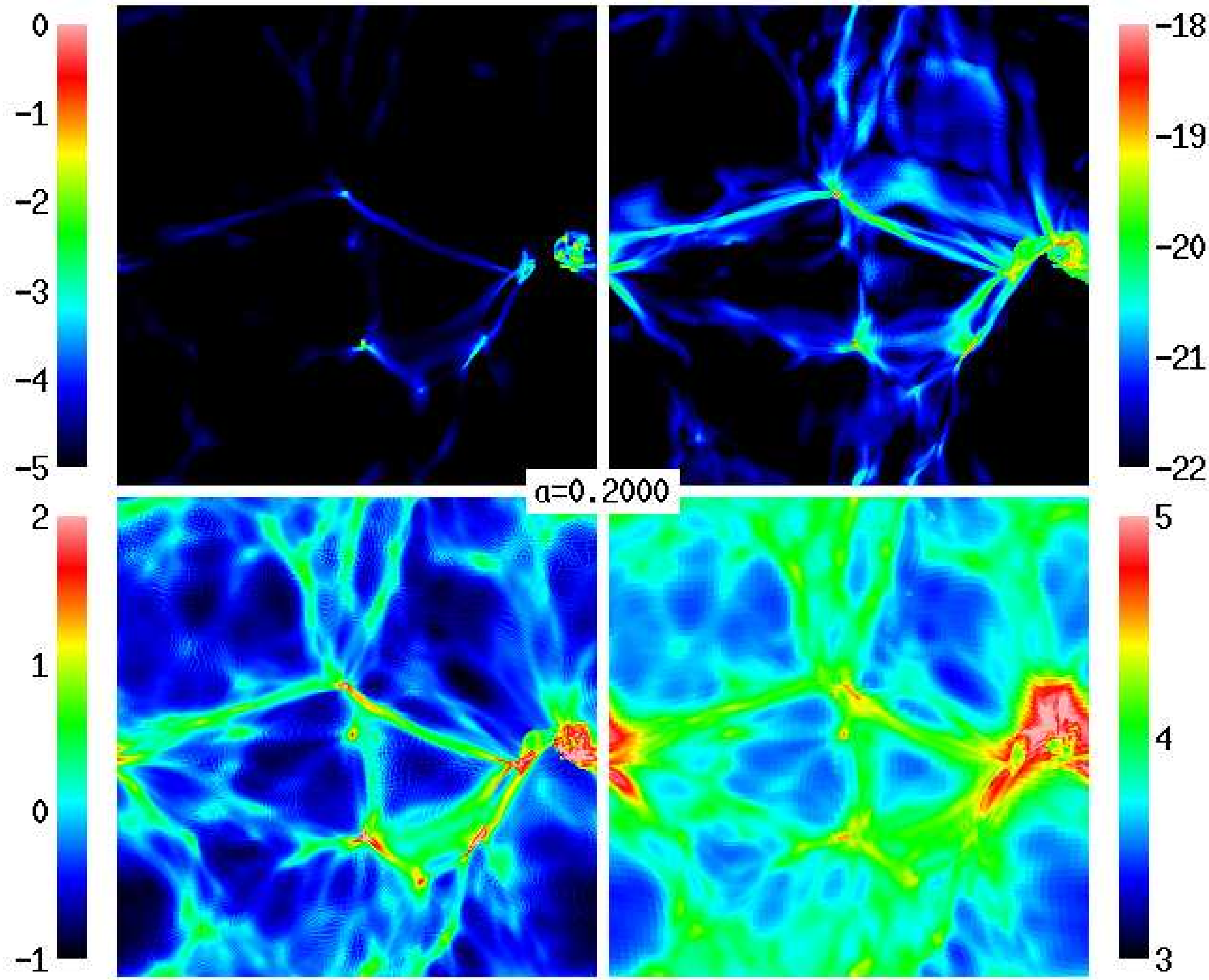
$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times [\boldsymbol{V} \times \boldsymbol{B} - \eta(\boldsymbol{\nabla} \times \boldsymbol{B})] - \frac{ck_{\rm B}}{e} \frac{\boldsymbol{\nabla} n_e}{n_e} \times \boldsymbol{\nabla} T.$$

- **Fields generated from zero if ∇T not parallel to ∇n_e**

Need Dynamos to explain observed fields and maintain against decay

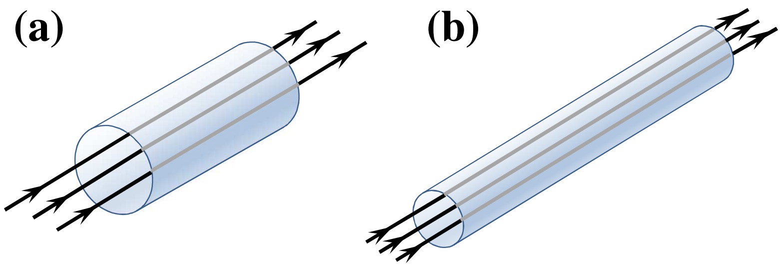
Magnetic fields from Reionization

HI, gas density, temperature and B field; Gnedin, Ferrara, Zweibel, 2000, ApJ



Flucutation/Small scale dynamo

- Turbulence common: Stars, galaxies, galaxy clusters: leads to Random Stretching + "Flux freezing" $\Rightarrow$ Growth of B



$BA =$ constant and $\rho A l =$ constant $\rightarrow B/\rho \propto l$, and $A \propto 1/(\rho l)$

- Cancellation (Eyink, 2011) and Resistance limits growth. (Stretching vs dissipation $\rightarrow v/l \sim \eta/l_B^2 \rightarrow l_B \sim l/R_{\mathrm{M}}^{1/2}$)

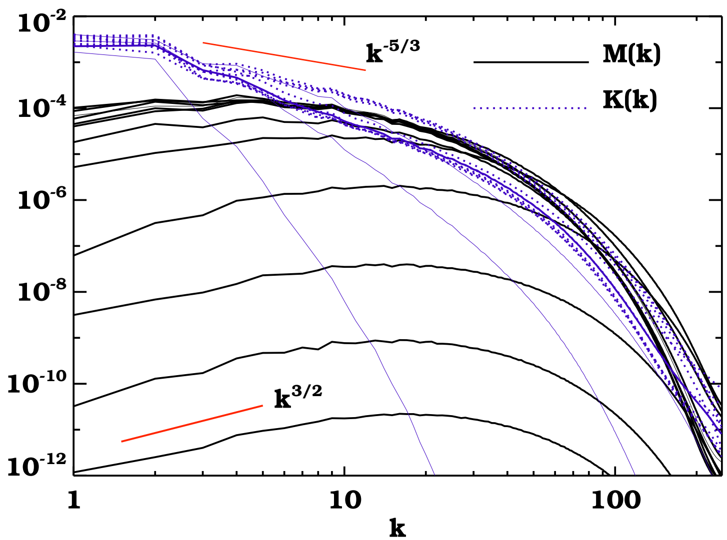
- Random B grows if $R_{\mathrm{M}} = vl/\eta > R_{crit} \sim 30 - 100$ (Kazantsev 1967)

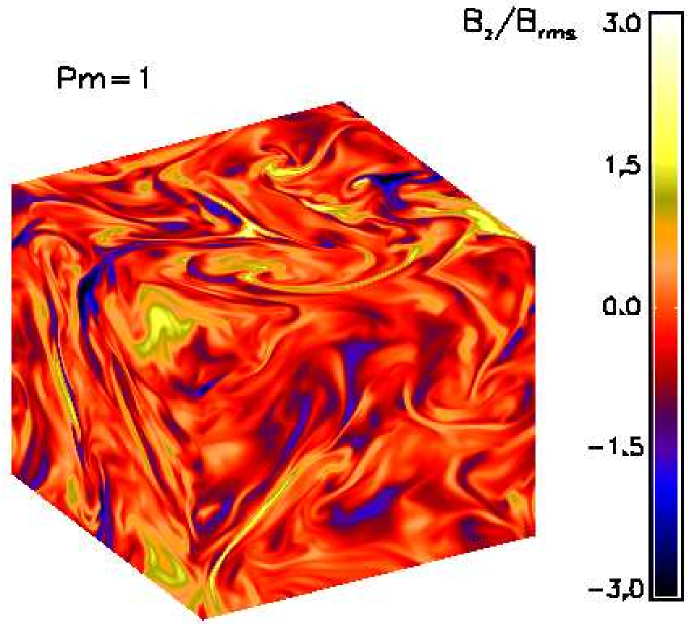
- Growth rate fast $\sim v/l$ (10^7 yr: Galaxies; 10^8 yr clusters).

- Field intermittent: Eddy scale l, to "resistive" scale $\sim l/R_m^{1/2} \ll l$

- How does it saturate? Important for young galaxy/cluster/IGM Faraday RM and mean field dynamos?

The fluctuation dynamo simulations

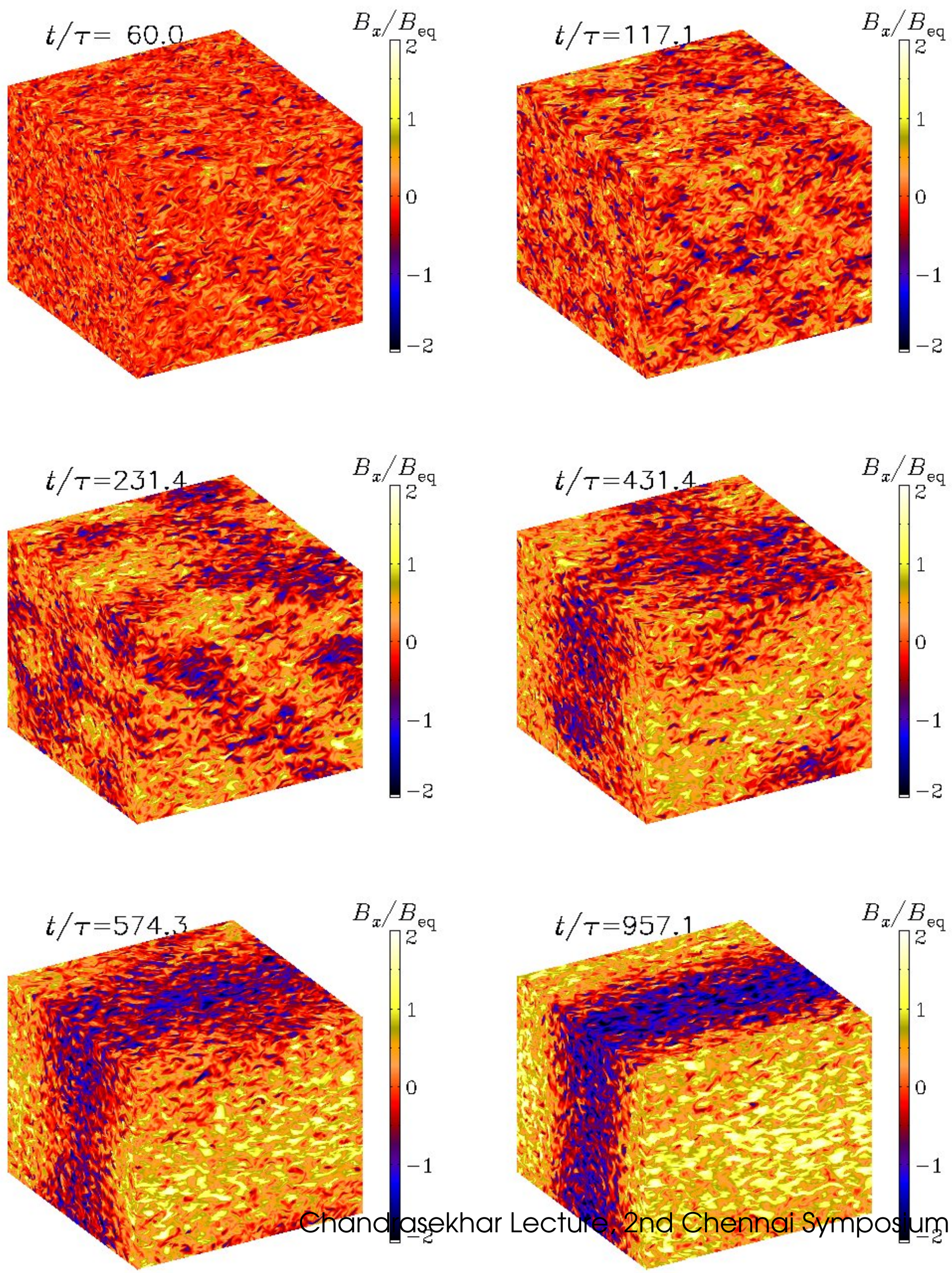




- Turbulence driven on scale of box. Random seed field amplified to Saturation. Field intermittent (Pallavi Bhat 2012).
- Renormalized η drives efective $R_{\rm M} \to R_{crit}$, $l_B \sim L/R_{crit}^{1/2}$ (KS, PRL, 99; 03).
- Or Reduced stretching BUT $l_B \sim L/R_{\rm M}^{1/2}$ (Schekochihin et al., ApJ, 04)

Closure models approximate and simulations limited to $R_m/R_{crit} \sim 20 - 30$.

Helically forced turbulent dynamos



- Remarkable change if turbulence is helical!
- Helical turbulence driven $1/15$ scale of box (Axel Brandenburg, 2001....2012).
- Rapid large-scale field growth in kinematic stage conserving magnetic helicity.
- Further Slow Growth on resistive timescale to Box scale! (dissipating small-scale helicity)

Turbulent Mean-Field Dynamo

- $\mathrm{V} = \overline{\mathrm{V}} + \mathrm{v}$, $\mathrm{B} = \overline{\mathrm{B}} + \mathrm{b}$: **Mean + Stochastic fields**
- **Mean satisfies DYNAMO equation, with** $\overline{\mathcal{E}} = \overline{\mathrm{v} \times \mathrm{b}}$:

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times \left(\overline{\mathbf{V}} \times \overline{\mathbf{B}} + \overline{\mathcal{E}} - \eta(\nabla \times \overline{\mathbf{B}}) \right);$$

- **The stochastic small-scale field satisfies:**

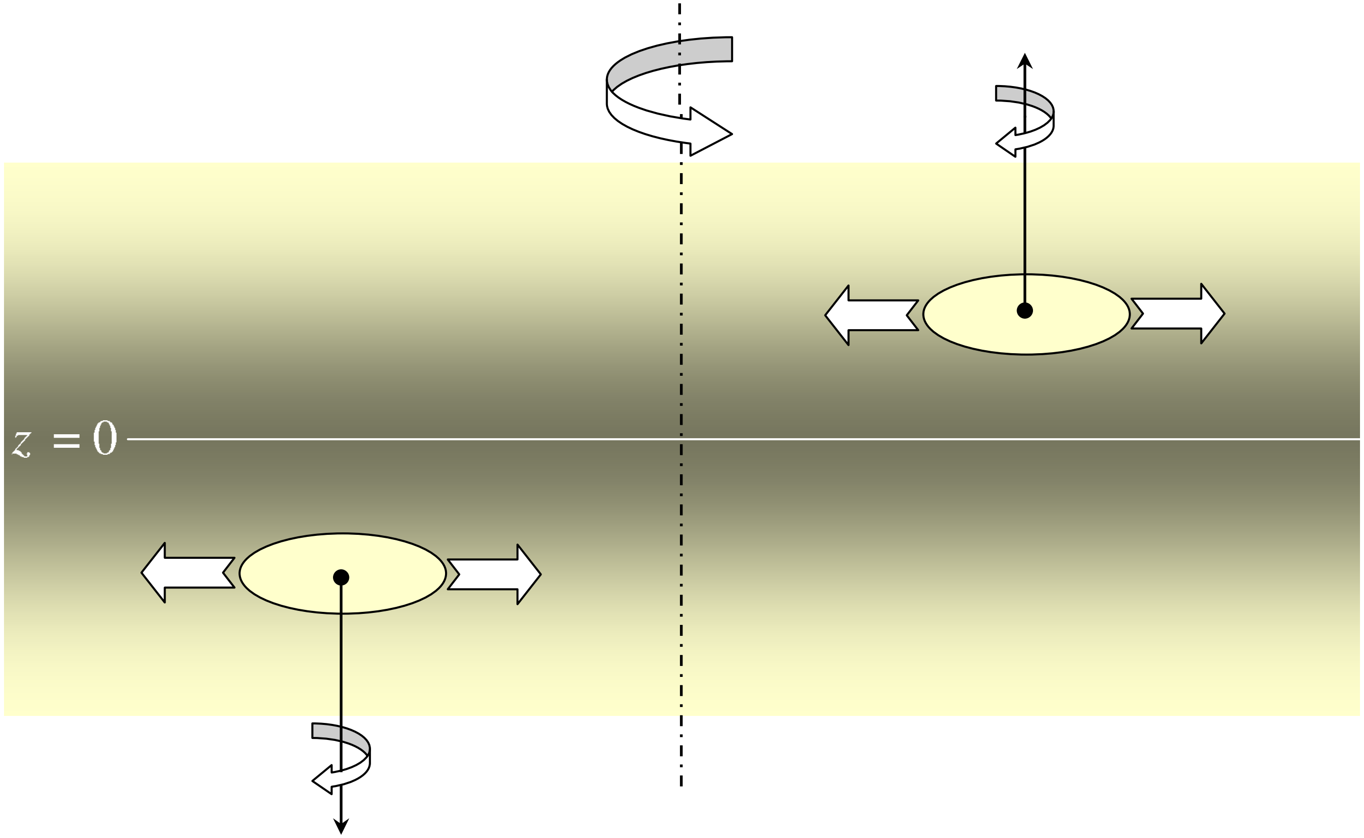
$$\frac{\partial \boldsymbol{b}}{\partial t} = \nabla \times (\overline{\boldsymbol{V}} \times \boldsymbol{b} + \boldsymbol{v} \times \overline{\boldsymbol{B}} - \eta \nabla \times \boldsymbol{b}) + \boldsymbol{G}$$

- **For short correlation times (τ), neglect G, also assume statistical isotropy of the random $\boldsymbol{v}$:**

$$\overline{\boldsymbol{\mathcal{E}}} = \overline{\boldsymbol{v} \times \int^t dt' (\partial \boldsymbol{b}/\partial t')} = \overline{\boldsymbol{v}(t) \times \int^t dt' [-\boldsymbol{v}(t') \cdot \nabla \overline{\boldsymbol{B}} + \overline{\boldsymbol{B}} \cdot \nabla \boldsymbol{v}(t')]}$$

$$\overline{\boldsymbol{\mathcal{E}}} = \alpha \overline{\boldsymbol{B}} - \eta_{\mathrm{t}} (\nabla \times \overline{\boldsymbol{B}}) \text{ with } \alpha \approx -\frac{1}{3}\tau \overline{\boldsymbol{v} \cdot (\nabla \times \boldsymbol{v})}, \quad \eta_{\mathrm{t}} \approx \frac{1}{3}\tau \overline{\boldsymbol{v}^2}$$

Helicity from rotation and stratification

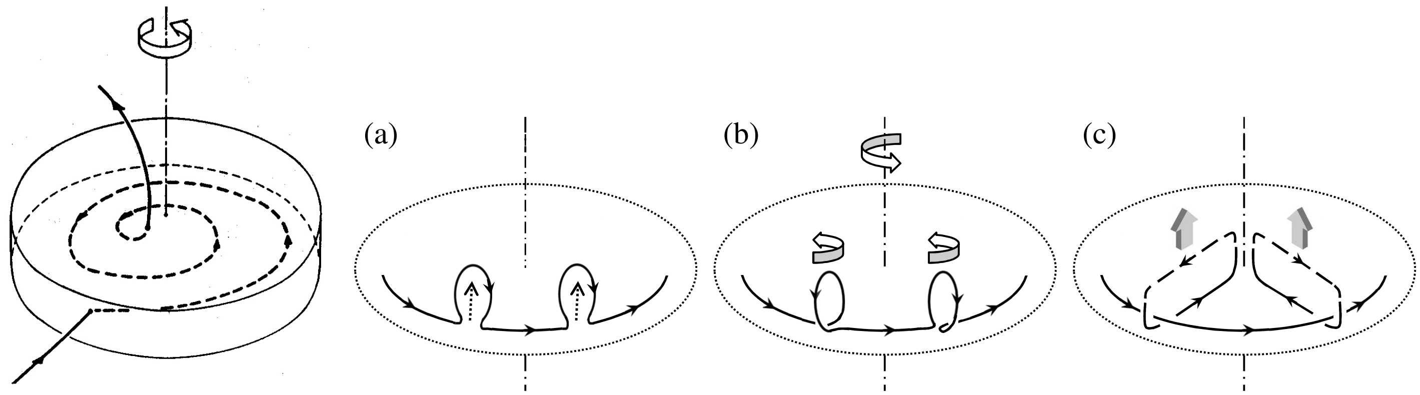


The turbulent galactic dynamo.

- $\partial\overline{\mathbf{B}}/\partial t = \nabla \times \left(\overline{\mathbf{V}} \times \overline{\mathbf{B}} + \alpha\overline{\mathbf{B}} - (\eta_t + \eta)(\nabla \times \overline{\mathbf{B}})\right)$;

  $\alpha \approx -\frac{1}{3}\tau\overline{\boldsymbol{v}\cdot\boldsymbol{\omega}} \approx -\frac{1}{3}v_{\rm turb}, \quad \eta_t \approx \frac{1}{3}\tau\overline{\boldsymbol{v}^2} \approx \frac{1}{3}l_{\rm turb}v_{\rm turb}$

- **Galactic differential rotation (shear) generates B_ϕ from B_r.** **Supernovae drive HELICAL turbulence** (**Due to Rotation + Stratification**) **Helical motions generate B_r from B_ϕ**



- **Exponential growth of $\overline{\mathbf{B}}$**, $t_{growth} \sim 10^8 - 10^9$ yr

- **Seen in DNS of SNe driven turbulence in local galactic patch** (Gressel + 2008; Gent, Shukurov + 2013; Bendre + 2013/15)

Helicity and dynamo quenching

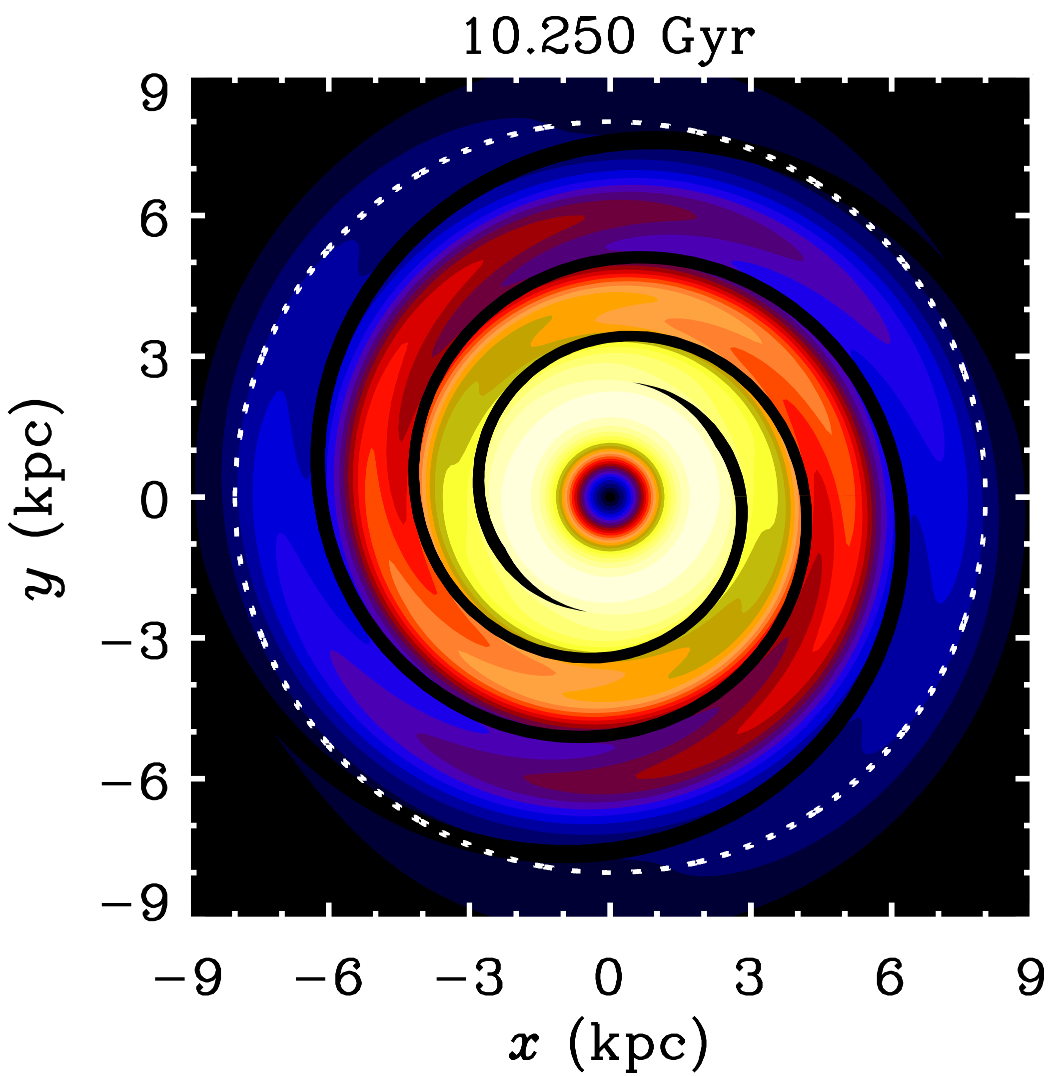
Anvar and Natasha Shukurov 2009

- Helical motions transfer helicity between WRITHE AND TWIST Helicities
- Lorentz force of small-scale twist Helicity grows to kill the dynamo
- Unless one has helicity fluxes. Simplest due to outflows!

Galactic outflows and magnetic spiral

(Chamandy, Shukurov, Subramanian, MN, 2014)

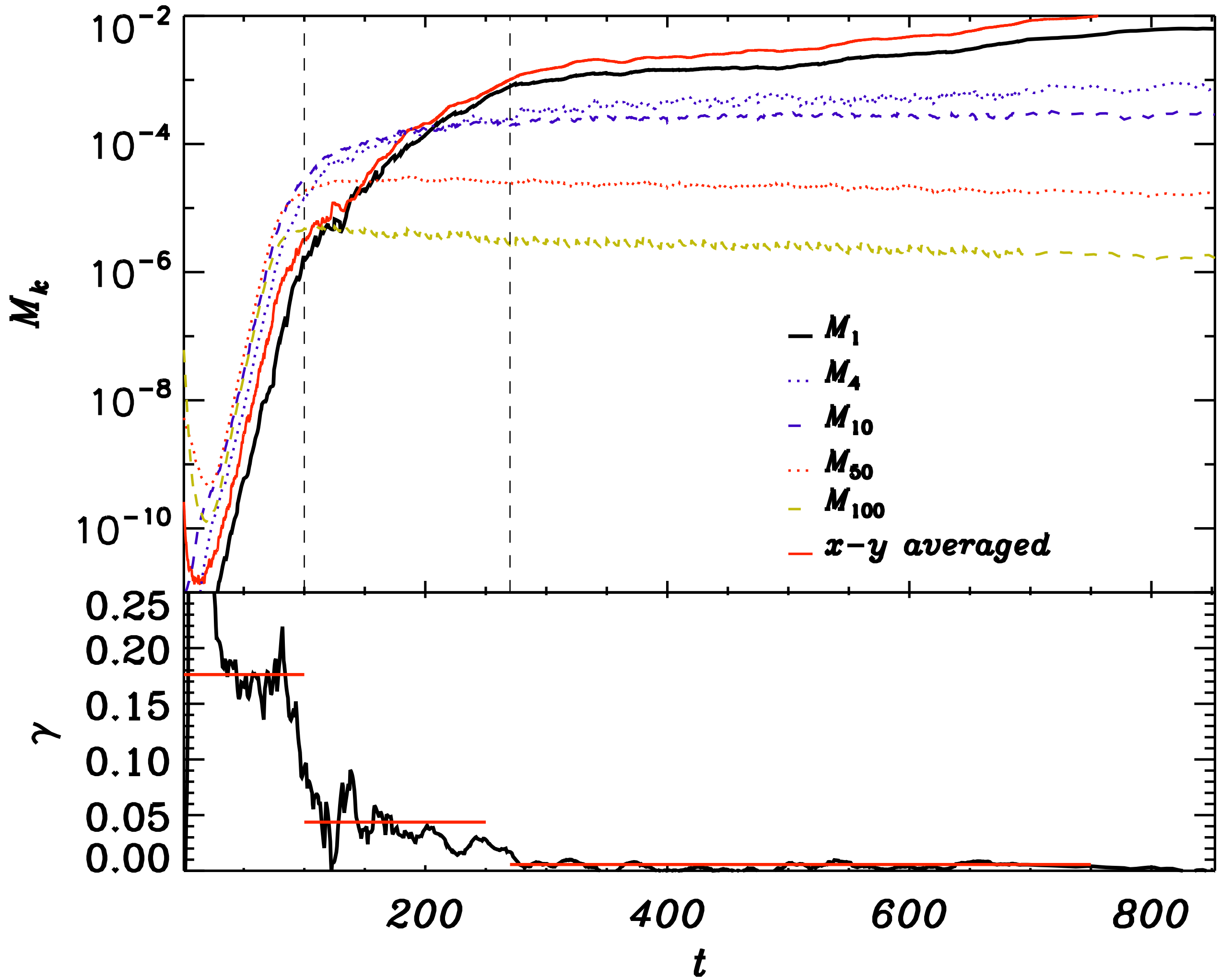
Winding up Spiral with enhanced $F_i^{\rm bulk}$ along spiral



Both dynamos (FD and LSD) unified?

Helical turbulence at $k = 4$ + **Uniform Shear** $S\tau = 0.38$, $R_m = 812$, $P_m = 10$.

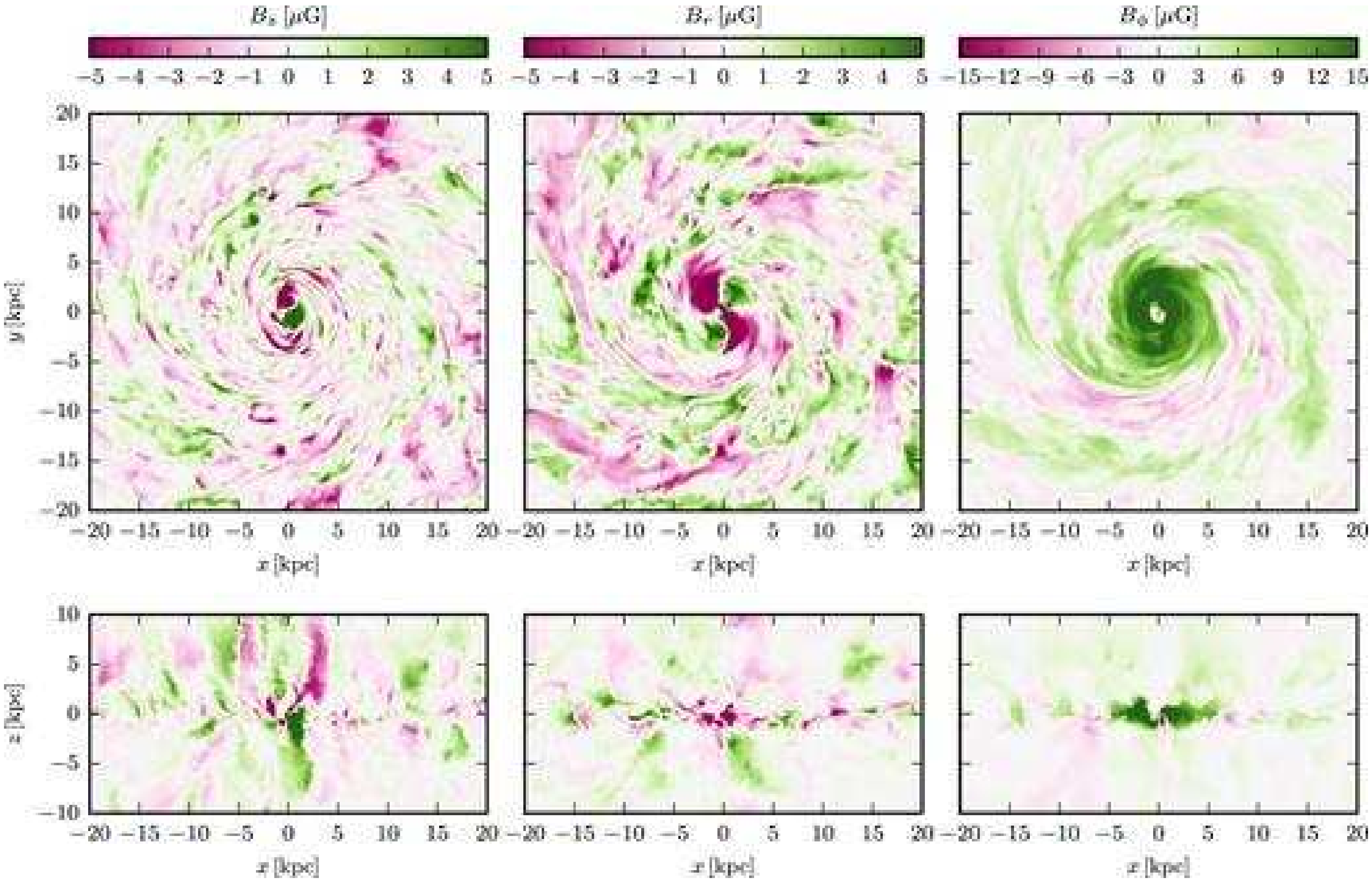
Signature of Two dynamos :-) **(Pallavi Bhat, KS, AB 2019)**



Growth rate: $\lambda = 0.175$, $\lambda = 0.036$, $\lambda = 0.004$

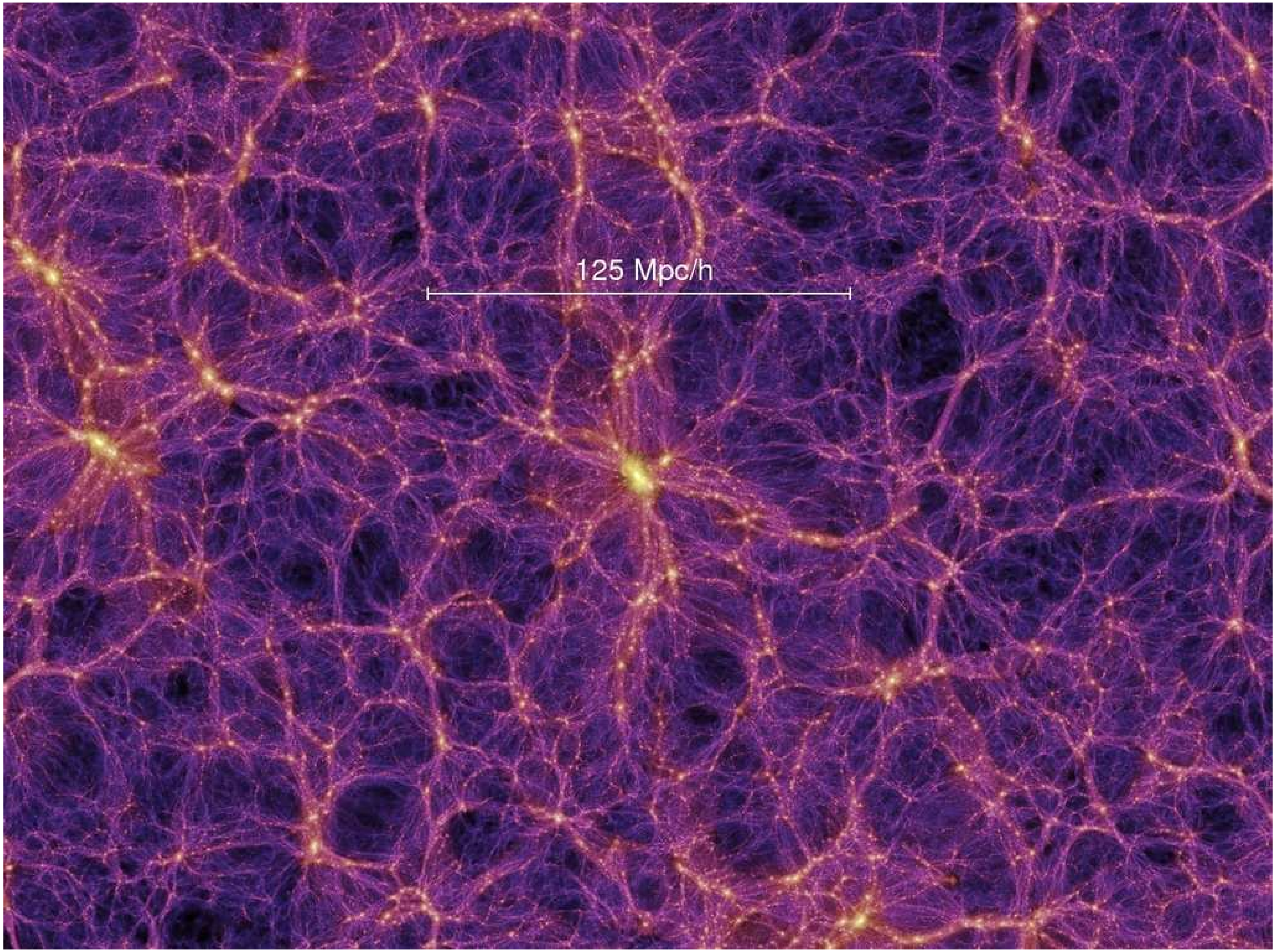
B fields in disk galaxy formation

Pakmor et al, MNRAS, 481, 4410 (2018)

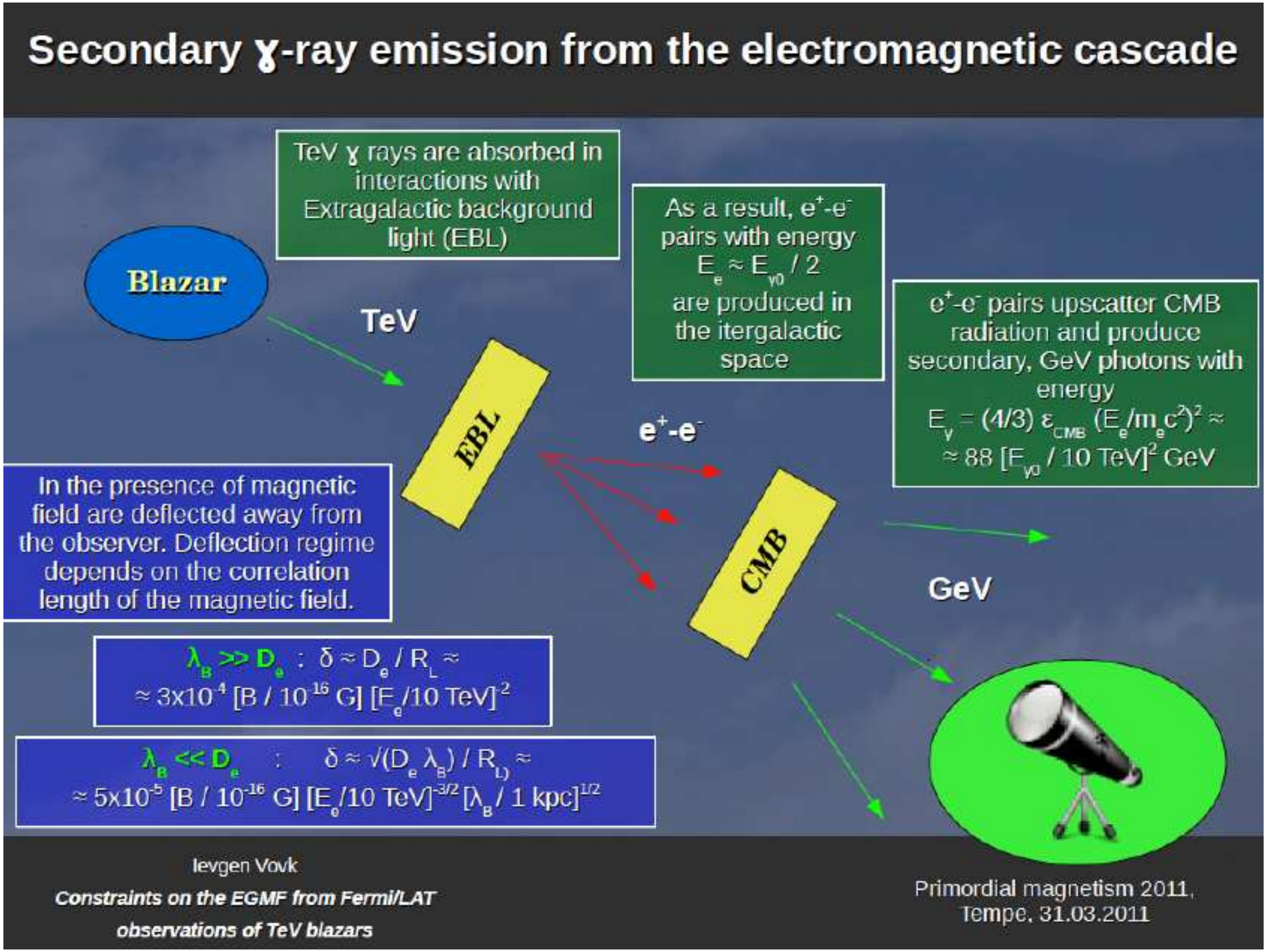


Structure formation: Millenium Simulation

The Cosmic web at Redshift $= 0$ or $t = 13.6$ Gyr



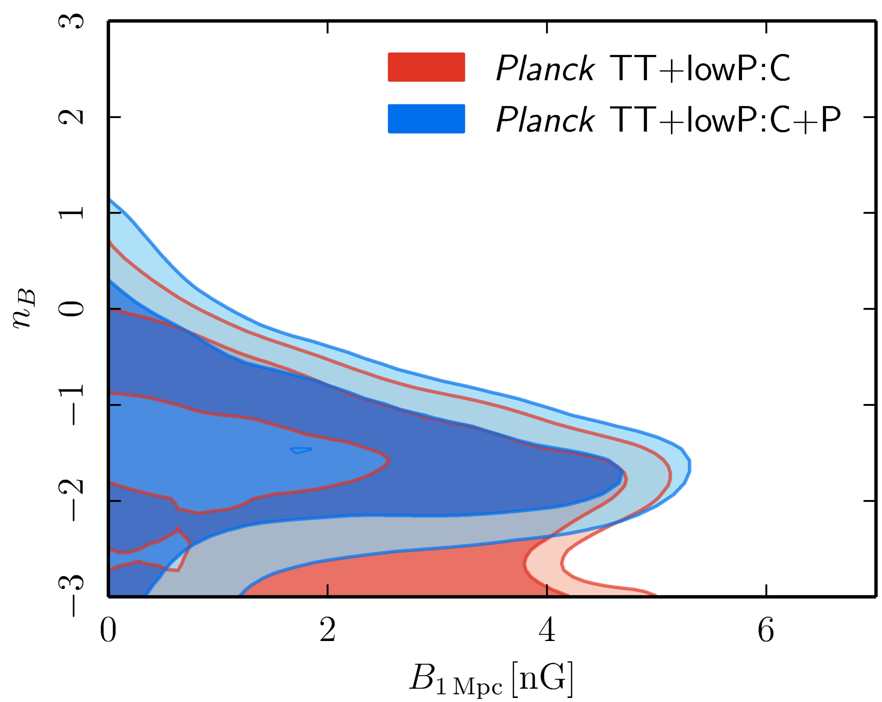
Gamma-Ray Constraints on void B



B in voids bigger than 10^{-16} Gauss!

Planck Constraints on primordial B & n_B

- **CMB signals from metric and velocity perturbations**
  Alfvén waves: (KS,JDB PRL,98; Durrer+98, TRS,KS, PRL, 01)
- **B field Dissipation $\rightarrow$ Ionization, Heating**
  (Sethi,KS MNRAS, 05,Kunze/Komantsu 15, Chluba+15)
  Ade et al. arXiv:1502.01594v1 (Paoletti)



- **Strong sub nano Gauss upper limit from CMB Non-Gaussianity**
  (TRS, KS, PRL, 2009; Trivedi, TRS, KS, PRL, 2012; Trivedi, KS, TRS, PRD, 2014)

Primordial fields origin during Inflation?

(Turner and Widrow, 1988; Ratra 1992; Martin, Yokoyoma 2008, Subramanian 2010/16)

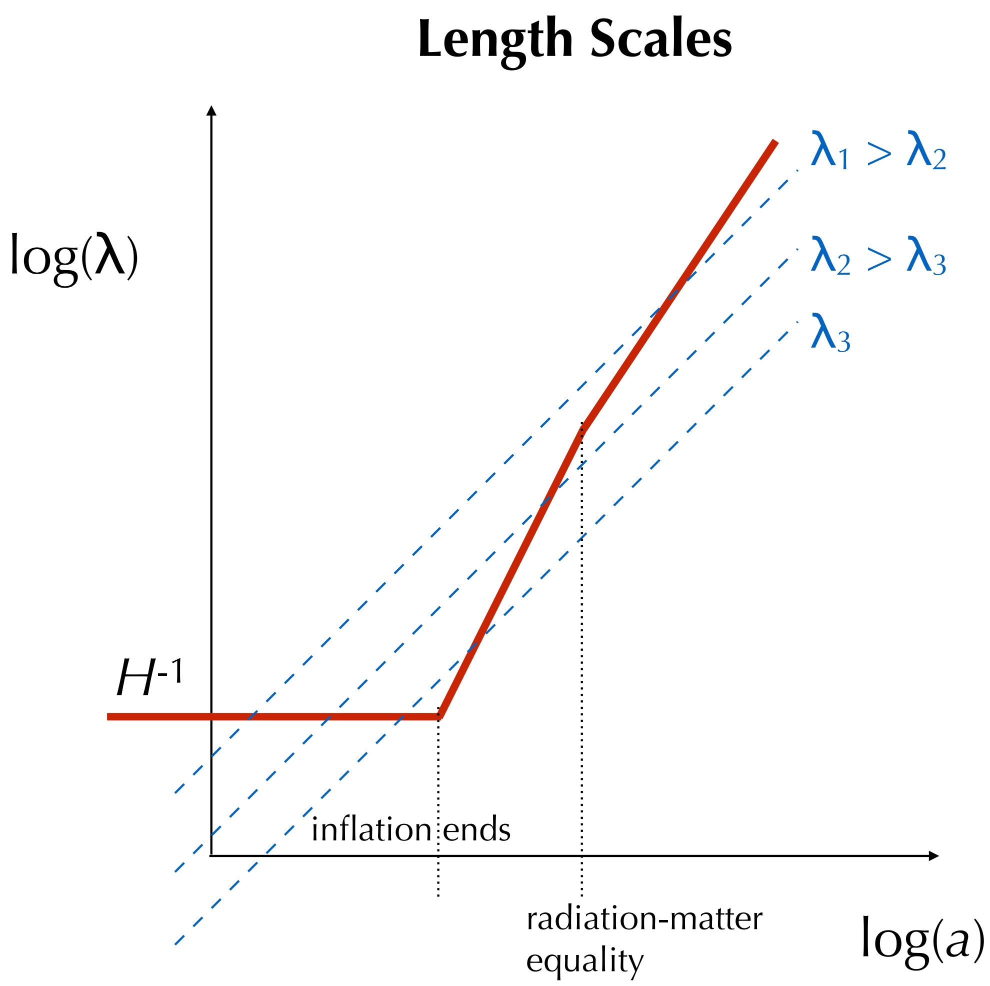
- **Rapid expansion $\rightarrow$ vacuum fluctuations amplified and stretched to long wavelength "classical" fluctuations**
- **Negligible charge density breaks flux freezing.**
- **BUT Need to break conformal invariance of ED (Couple to inflaton ϕ, higer dimensional scale factor $b(t)$, curvature R, axion θ ...)**

$$S = \int \sqrt{-g}\; d^4x\; b(t)[-f^2(\phi)\frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} - RA^2 + g\theta F_{\mu\nu}\tilde{F}^{\mu\nu}\;]$$

- **The mode function satisfies:** $\bar{A}'' + 2\frac{f'}{f}\bar{A}' + k^2\bar{A} = 0$
- **EM wave amplified from vacuum fluctuations**
- **After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in.**

Inflation and perturbations

Courtesy Prof. Aseem Paranjape



Consistent Inflationary Magnetogenesis?

Sharma, Sandhya, Seshadri, Subramanian, PRD, 2017; Sharma, Subramanian, Seshadri 2018

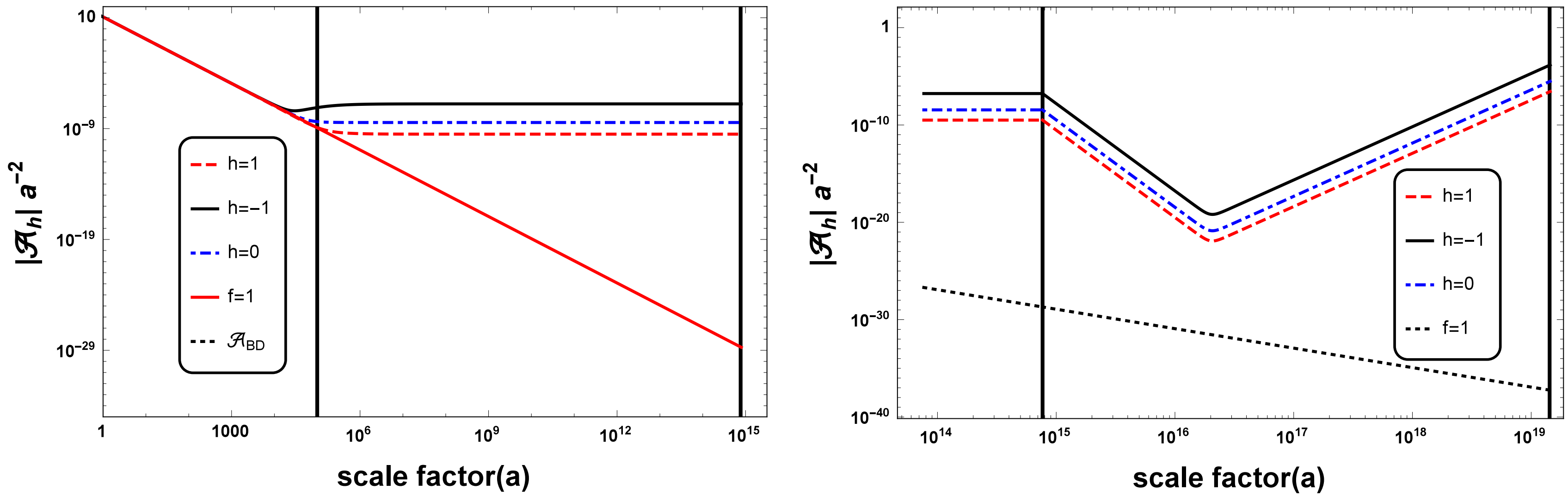
- Scale invariant magnetic spectrum when $f \propto a^2$ or $f \propto a^{-3}$

$$B_0 \sim 5 \times 10^{-10} \mathrm{G} \left(\frac{H}{10^{-4} M_{pl}} \right)$$

- Strong backreaction for $f \propto a^{-3}$ due to $\mathbf{E}$ field growth. For $f \propto a^2$, 'charge' $e_N = e/f^2$, can become very large/small. (Demozzi et al, 2009)
- Schwinger effect creates charge if electric field is large enough, and freezes $\mathbf{B}$ amplification? Kobayashi, Afshordi, 14
- Consider models with matter dominated epoch after inflation before reheating, where f decreases back to 1.
- For $k\eta \ll 1$, $\bar{A} = c_1 + c_2 \int d\tau / f^2$; for growing/decaying f, c_1/c_2 branch is growing mode
- When f transits from growth to decay, the dominant mode transits from c_1 to c_2 branch, spectrum transits to blue: $d\rho_B / d\ln k \propto k^4$

Consistent Inflationary Magnetogenesis

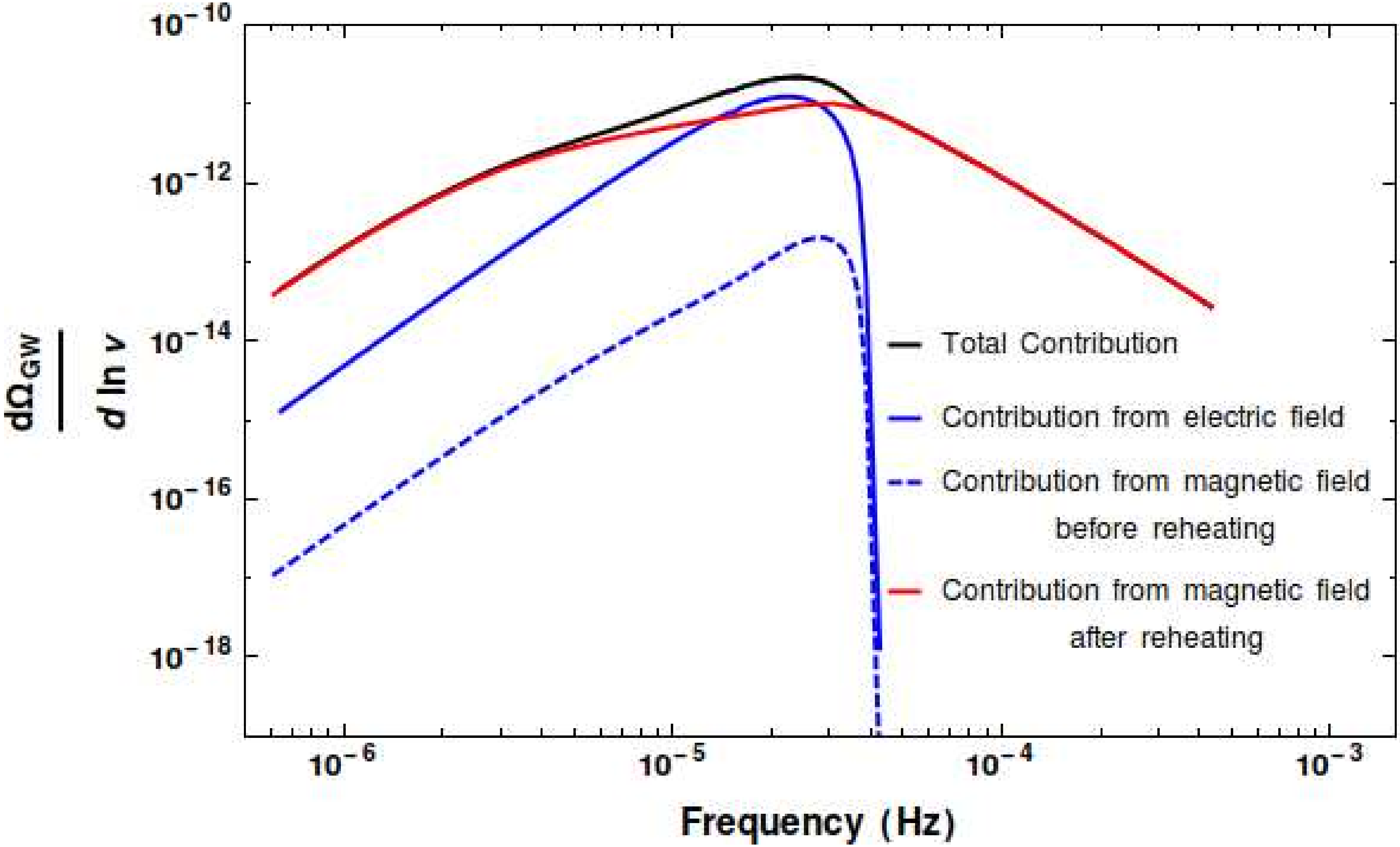
Sharma, SJ, TRS, KS, PRD, 96, 083511, 2017; Sharma, KS, TRS, PRD, 97, 083503, 2018



- **Require low scales of inflation and reheating to avoid back reaction**
- **Reheating at $T = 100$ GeV (EW), gives initial comoving $B \sim 6 \times 10^{-7}$G, $L_c \sim 3 \times 10^{15} cm$; and after turbulent decay including inverse transfer, $B \sim 7 \times 10^{-13}$G, $L_c \sim 0.2$ kpc**
- **Helical: Initially $B \sim 3.4 \times 10^{-7}$G, same L_c , decay with inverse cascade gives $B \sim 2.6 \times 10^{-11}$G, $L_c \sim 70$ kpc**

Gravitational Wave Predictions

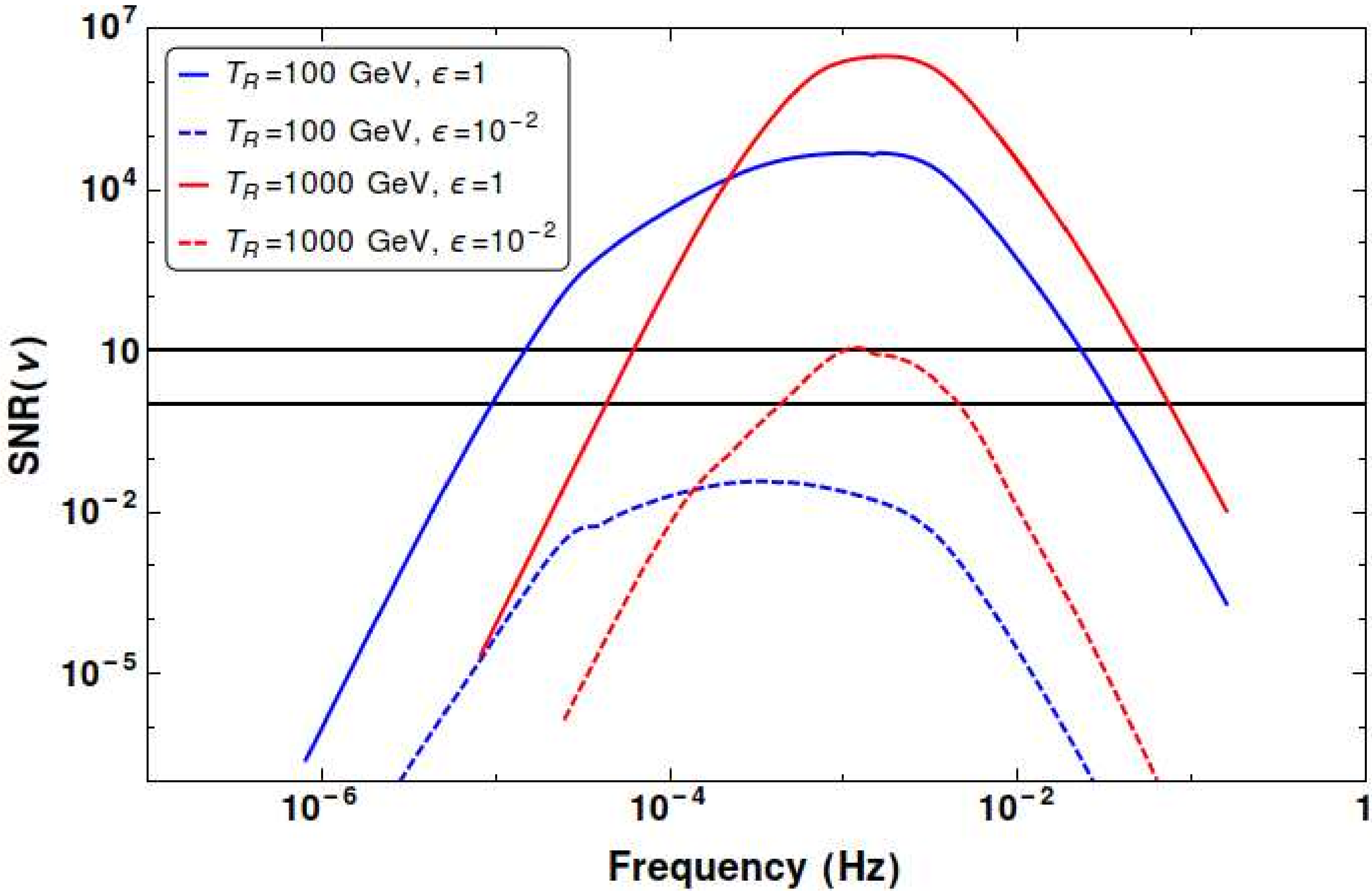
Sharma, KS, TRS, PRD, 101, 103526, 2020



Predictions for 1% in EM energy and $T_R = 100$ GeV

Gravitational Wave Predictions

Sharma, KS, TRS, PRD, 101, 103526, 2020



Predictions for higher T and LISA constraints

Where do we stand?

- Universe is Magnetized!
- Cosmic batteries can provide the first seed fields.
- Dynamos required to amplify/maintain fields.
- Field coherence when fluctuation dynamo saturates?
- For Large scale dynamos: Helicity Conservation? FD vs LSD?
- Primordial field required to explain B in Intergalactic voids? Inflationary magnetogenesis? Leads $\rightarrow$ blue spectrum?
- Traditional probes from radio, optical and infrared astronomy.
- New probes from γ-ray and GW Astronomy?

Optical/Infrared polarization probes B

Polarization: Optical and FIR

Both depend on aligned grains.
Orientation of E-vector of optical polarization is orthogonal to that of the emitted radiation.

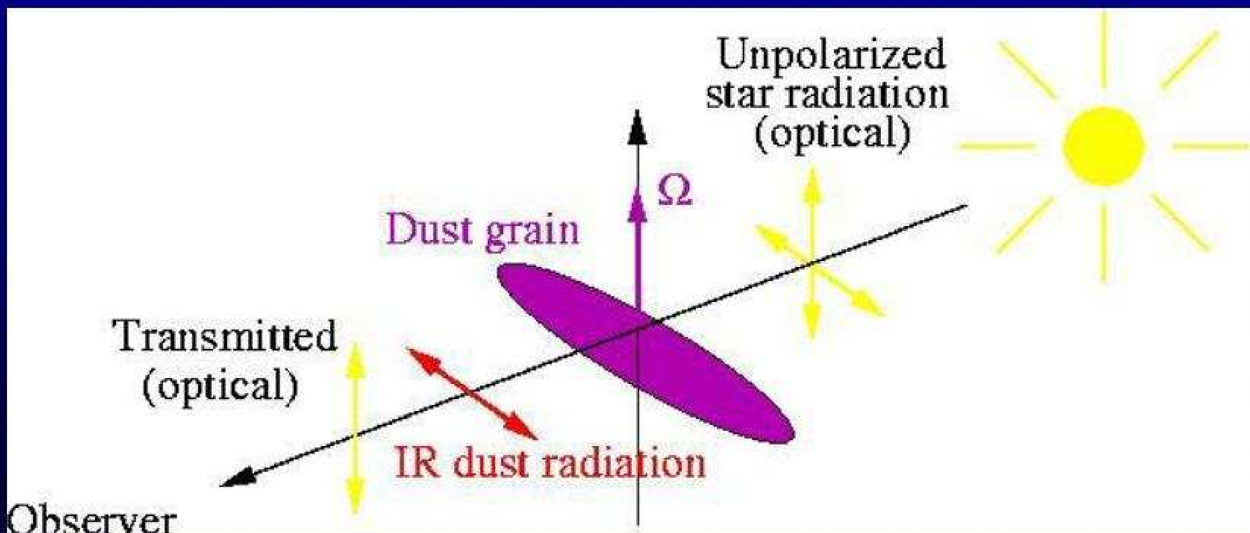
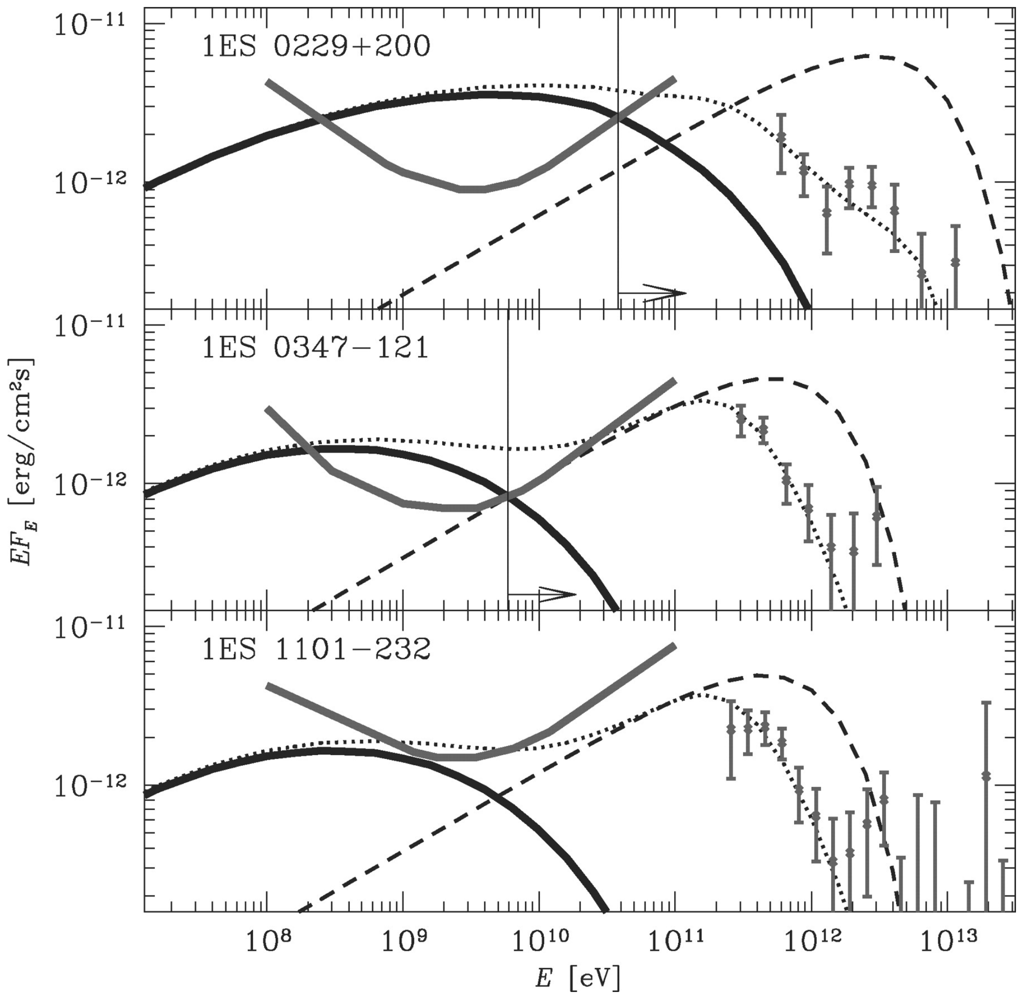


Figure from http://www.planck.fr/article263.html
Pontieu and Lagache

Gamma-Ray Constraints on B

Fig. 1 A comparison of models of cascade emission from TeV blazars (thick solid black curves) with Fermi upper limits (gray curves) and HESS data (gray data points).



Andrii Neronov, and Ievgen Vovk Science 2010;328:73-75