Gravitational Waves from Early-Universe Turbulent Sources

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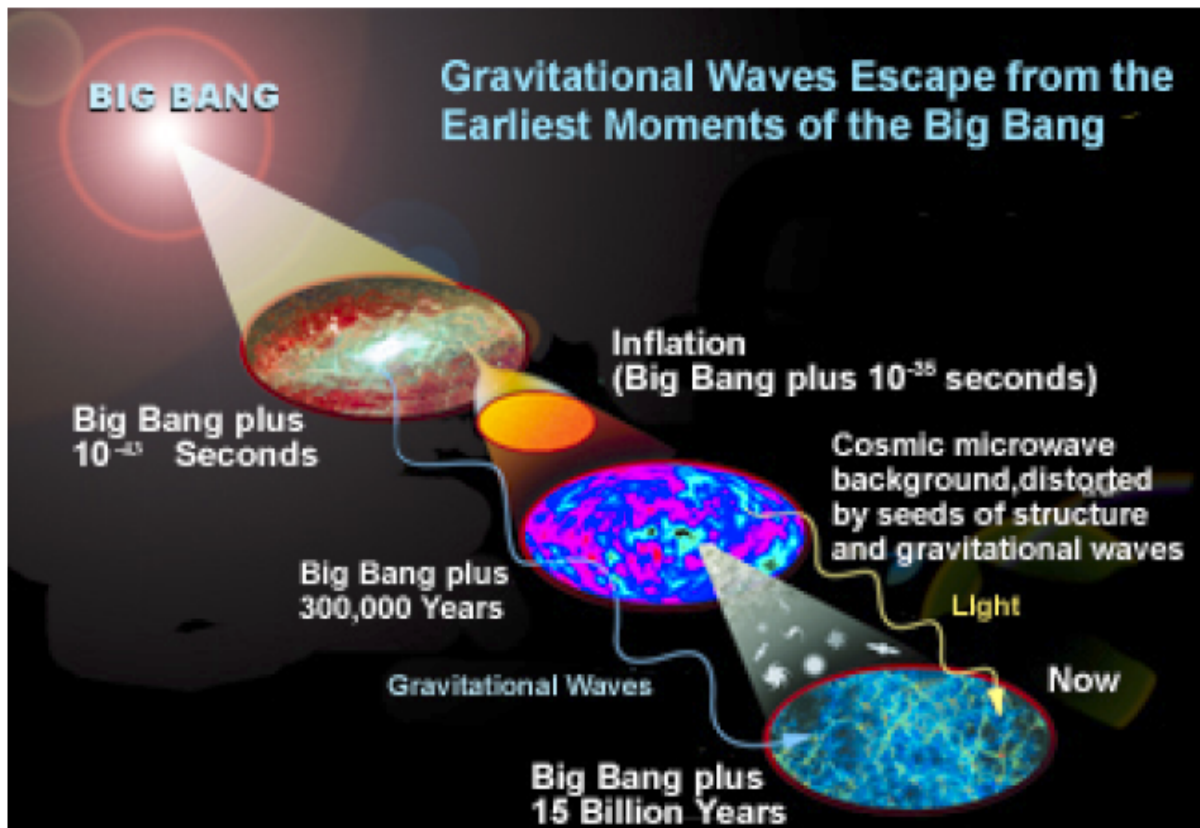
gravitational waves astronomy

- **Advantage**

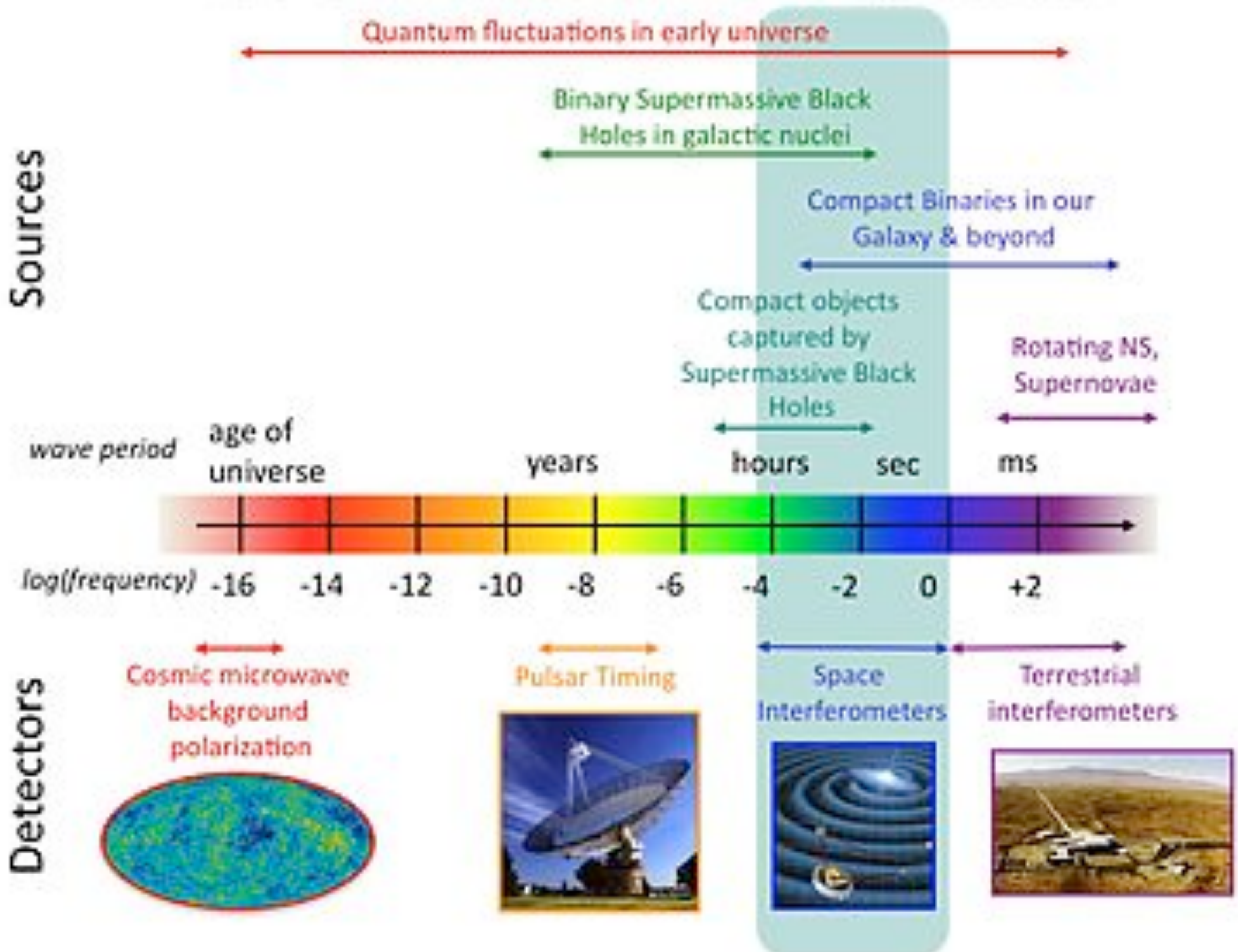
Connection with High Energy Physics – the best laboratory to test the energy scales EVEN near the Planck scale

- **Disadvantage**

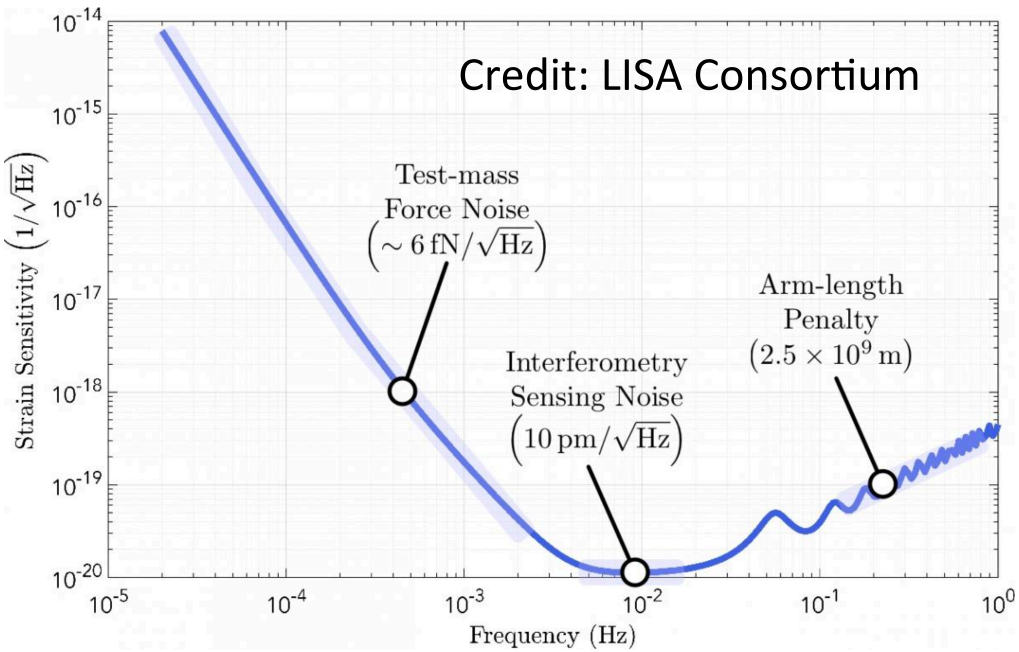
Direct detection is complicated



The Gravitational Wave Spectrum



LISA sensitivity & electroweak scale physics



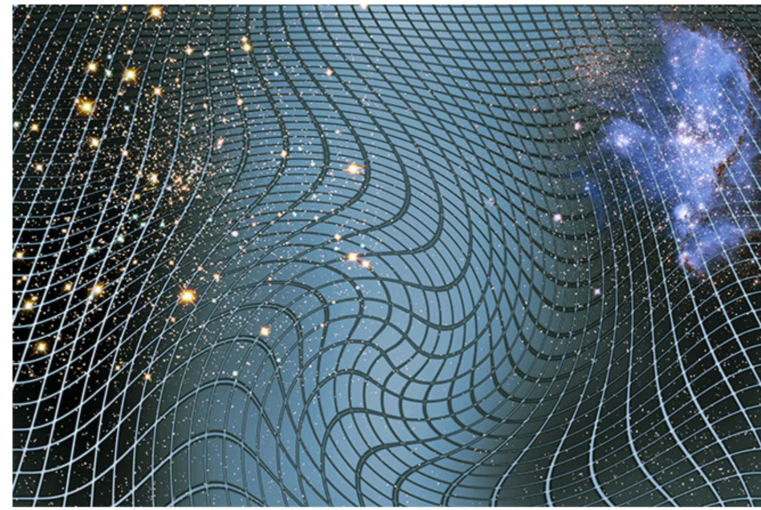
https://www.lisamission.org/multimedia/image/lisa-sensitivity

- **LISA's peak sensitivity corresponds to ~ 1/10 of Hubble horizon at 1 TeV energy scale**
- Hubble frequency f_0=10^{-4}Hz (T/1Tev)

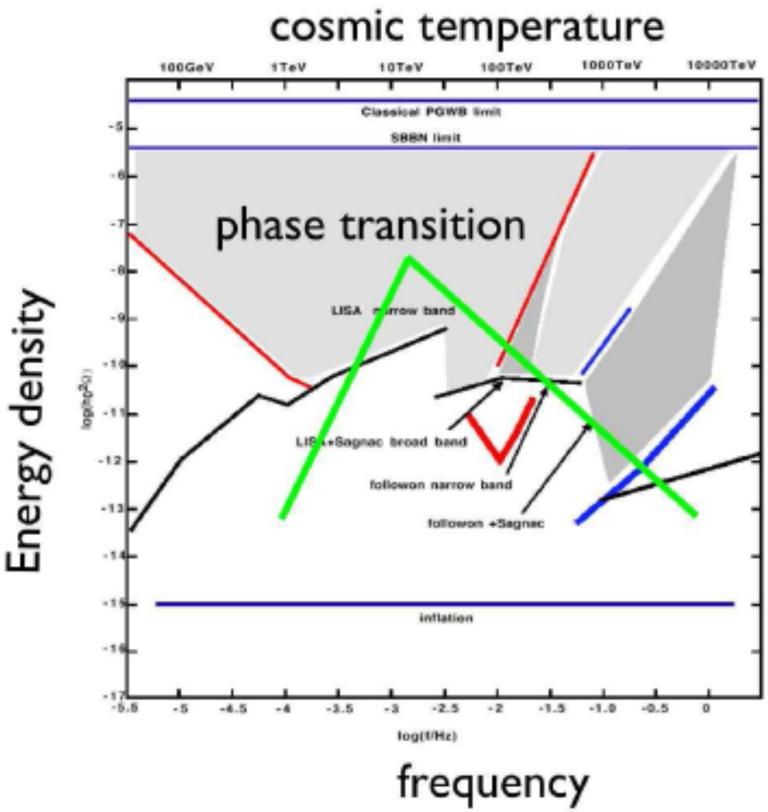
Large Hadron Collider (LHC) vs relic gravitational waves: Detecting New Physics?

relic gravitational waves signal - LISA

- The very early universe
  - Phase transitions
  - Turbulence
  - Seed magnetic fields
  - MHD turbulence



relic gravitational waves from phase transitions



C. Hogan, 2006

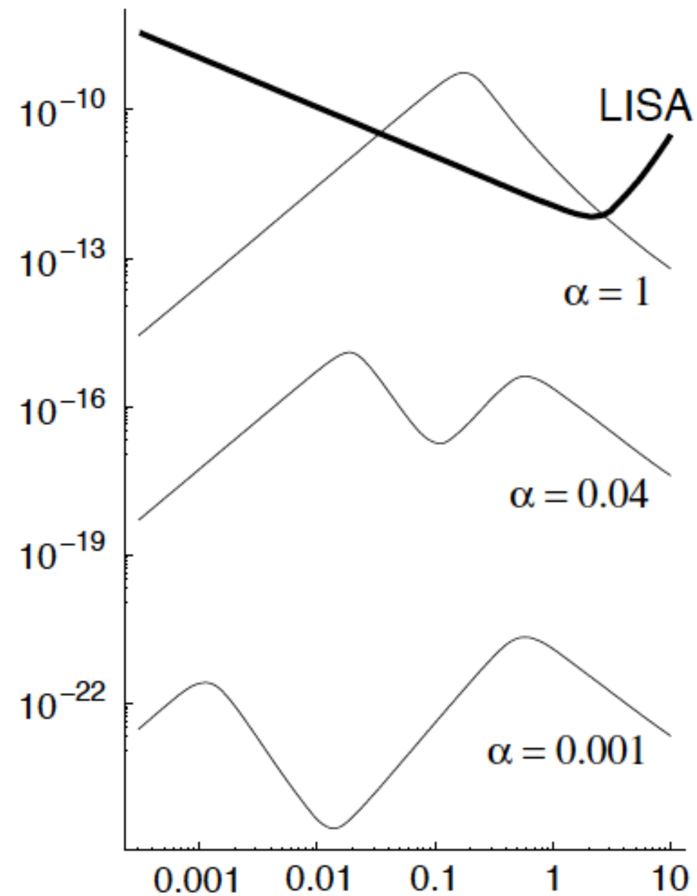
Pioneering works:

- Winicour 1973
- Hogan 1982, 1986
- Turner & Wilczek 1990
- Kosowsky et al. 1992
- Kosowsky & Turner 1993
- Kamionkowski et al. 1994

turbulence vs. gravitational waves

“Van Gogh's Turbulent Mind Captured Turbulence” credit Cosmos and Culture, 2015

- *Kosowsky, Mack, Kahniashvili, 2002*
- *Dolgov, Grasso, Nicolis, 2002*
- *Nicolis, 2004*
- *Kahniashvili, Gogoberidze, Ratra, 2005*



Nicolis 2004

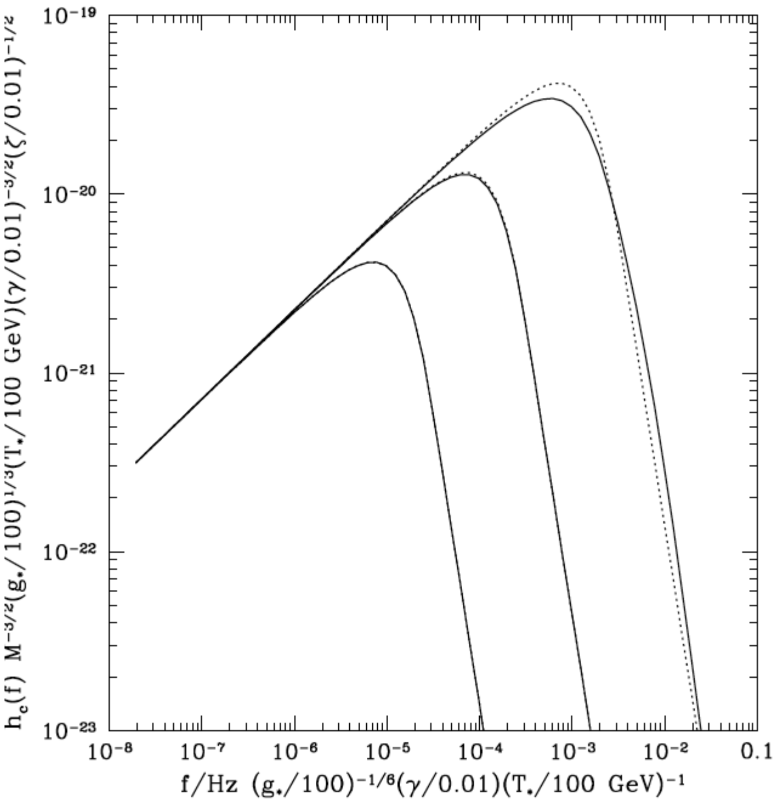
sound waves from turbulence

Aeroacoustic:
Sound waves generation by turbulence

$$\left(\frac{\partial^2}{\partial t^2} - c_s^2\nabla^2\right)\rho' = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j},$$

Lighthill, 1952
Proudman 1952

aeroacoustic approximation



$$\nabla^2 h_{ij}(\mathbf{x},t) - \frac{\partial^2}{\partial t^2} h_{ij}(\mathbf{x},t) = -16\pi G S_{ij}(\mathbf{x},t).$$

Gogoberidze, Kahniashvili, Kosowsky 2007

Parameters:

τ_T turbulence lasting time

k_0 stirring scale

$M = v_0/c$ - Mach number

$R^{3/4}=k_d/k_0$ - Reynolds number

$$\gamma H_*^{-1} = 2\pi/k_0, \qquad \zeta H_*^{-1} = \tau_T;$$

$$f = 1.65 \times 10^{-3}\,\mathrm{Hz} \left(\frac{\omega_*}{k_0}\right) \left(\frac{g_*}{100}\right)^{1/6} \left(\frac{\gamma}{0.01}\right)^{-1} \left(\frac{T_*}{100\,\mathrm{GeV}}\right),$$

$$h_c(f) = 1.28 \times 10^{-19} \left(\frac{100\,\mathrm{GeV}}{T_*}\right) \left(\frac{100}{g_*}\right)^{1/3} \left(\frac{\gamma}{0.01}\right)^{3/2} \left(\frac{\zeta}{0.01}\right)^{1/2} \left[k_0^3 \omega_*(f) H_{ijij}(\omega_*(f),\omega_*(f))\right]^{1/2}.$$

numerical simulations

- To account properly non-linear processes (MHD)
- Not be limited by the short duration of the phase transitions
- Two stages turbulence decay
  - Forced turbulence
  - Free decay
- The source is present till recombination (after the field is frozen in)
- Results – strongly initial conditions dependent

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2\right) h_{ij}^{\mathrm{TT}} = \frac{16\pi G}{a^3c^2} T_{ij}^{\mathrm{TT}},$$

Grishchuk 1974 $h_{ij}^{\mathrm{TT}} = a h_{ij}^{\mathrm{TT,phys}}$

$$\mathrm{d}t_{\mathrm{phys}} = a\mathrm{d}t$$

The MHD equations for an ultrarelativistic gas in a flat expanding universe [4, 20] are given by

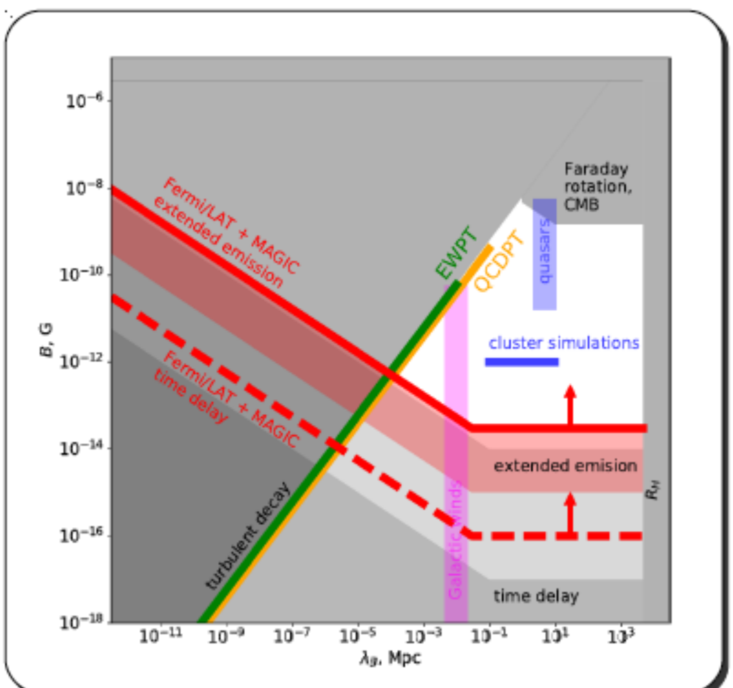
$$\frac{\partial \ln \rho}{\partial t} = -\frac{4}{3}(\nabla \cdot \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \ln \rho) + \frac{1}{\rho c^2}\left[\boldsymbol{u} \cdot (\boldsymbol{J} \times \boldsymbol{B}) + \eta \boldsymbol{J}^2\right], \quad (4)$$

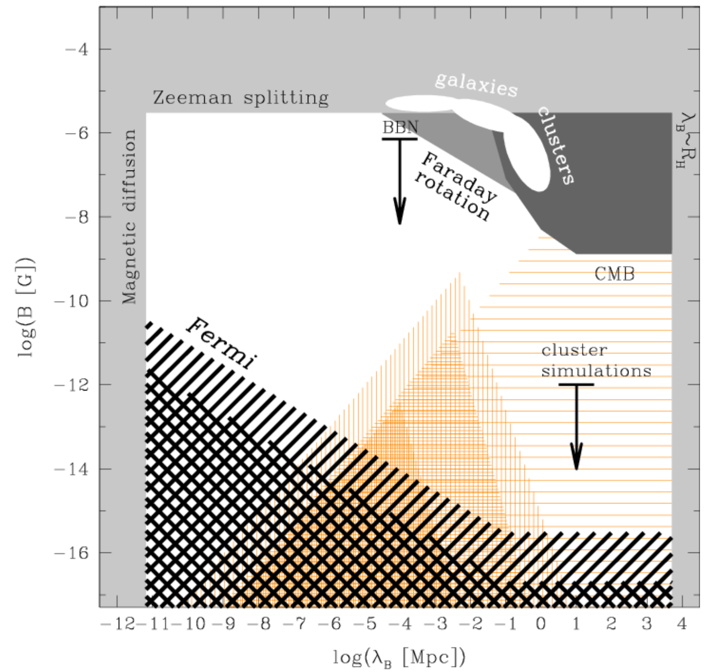
$$\frac{\partial \boldsymbol{u}}{\partial t} = -\boldsymbol{u} \cdot \nabla \boldsymbol{u} + \frac{\boldsymbol{u}}{3}(\nabla \cdot \boldsymbol{u} + \boldsymbol{u} \cdot \nabla \ln \rho) - \frac{\boldsymbol{u}}{\rho c^2}\left[\boldsymbol{u} \cdot (\boldsymbol{J} \times \boldsymbol{B}) + \eta \boldsymbol{J}^2\right] - \frac{c^2}{4}\nabla \ln \rho + \frac{3}{4\rho}\boldsymbol{J} \times \boldsymbol{B} + \frac{2}{\rho}\nabla \cdot (\rho \nu \mathbf{S}) + \boldsymbol{\mathcal{F}}, \quad (5)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u} \times \boldsymbol{B} - \eta \boldsymbol{J} + \boldsymbol{\mathcal{E}}), \quad (6)$$

why primordial MHD turbulence?

- Observations – lower limits of extragalactic magnetic fields in voids





Neronov & Vovk 2010

Vovk's courtesy 2018

primordial or astrophysical origin?

E ASTROPHYSICAL JOURNAL LETTERS, 727:L4 (4pp), 2011 January 20 doi:10.1088/2041-8205/727/1/L4

LOWER LIMIT ON THE STRENGTH AND FILLING FACTOR OF EXTRAGALACTIC MAGNETIC FIELDS

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ABSTRACT

High-energy photons from blazars can initiate electromagnetic pair cascades interacting with the extragalactic photon background. The charged component of such cascades is deflected and delayed by extragalactic magnetic fields (EGMFs), thereby reducing the observed point-like flux and potentially leading to multi-degree images in the GeV energy range. We calculate the fluence of 1ES 0229+200 as seen by *Fermi*-LAT for different EGMF profiles using a Monte Carlo simulation for the cascade development. The non-observation of 1ES 0229+200 by *Fermi*-LAT suggests that the EGMF fills at least 60% of space with fields stronger than $\mathcal{O}(10^{-16}$ to $10^{-15})$ G for lifetimes of TeV activity of $\mathcal{O}(10^2$ to $10^4)$ yr. Thus, the (non-)observation of GeV extensions around TeV blazars probes the EGMF in voids and puts strong constraints on the origin of EGMFs: either EGMFs were generated in a space filling manner (e.g., primordially) or EGMFs produced locally (e.g., by galaxies) have to be efficiently transported to fill a significant volume fraction as, e.g., by galactic outflows.

4. SUMMARY

We have calculated the fluence of 1ES 0229+200 as seen by *Fermi*-LAT using a Monte Carlo simulation for the cascade development. We have discussed the effect of different EGMF profiles on the resulting suppression of the point-like flux seen by *Fermi*-LAT. Since the electron cooling length is much smaller than the mean free path of the TeV photons, a sufficient suppression of the point-like flux requires that the EGMF fills a large fraction along the line of sight toward 1ES 0229+200, $f \gtrsim 0.6$. The lower limit on the magnetic field strength in this volume is $B \sim \mathcal{O}(10^{-15})$ G, assuming 1ES 0229+200 is stable at least for 10^4 yr, weakening by a factor of 10 for $\tau = 10^2$ yr. These limits put very stringent constraints on the origin of EGMFs. Either the seeds for EGMFs have to be produced by a volume filling process (e.g., primordial) or very efficient transport processes have to be present which redistribute magnetic fields that were generated locally (e.g., in galaxies) into filaments and voids with a significant volume filling factor.

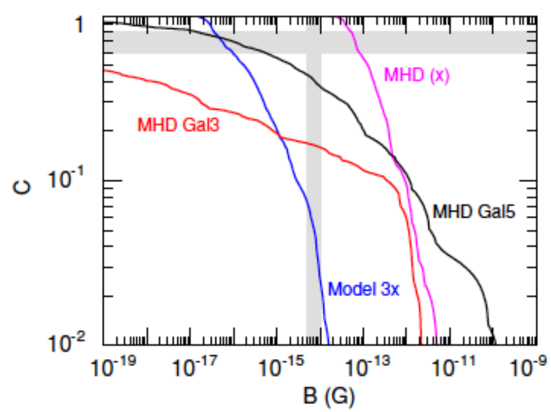
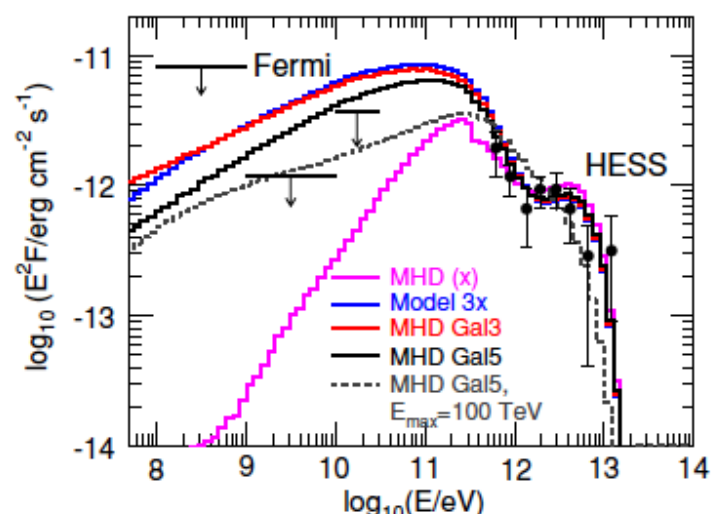


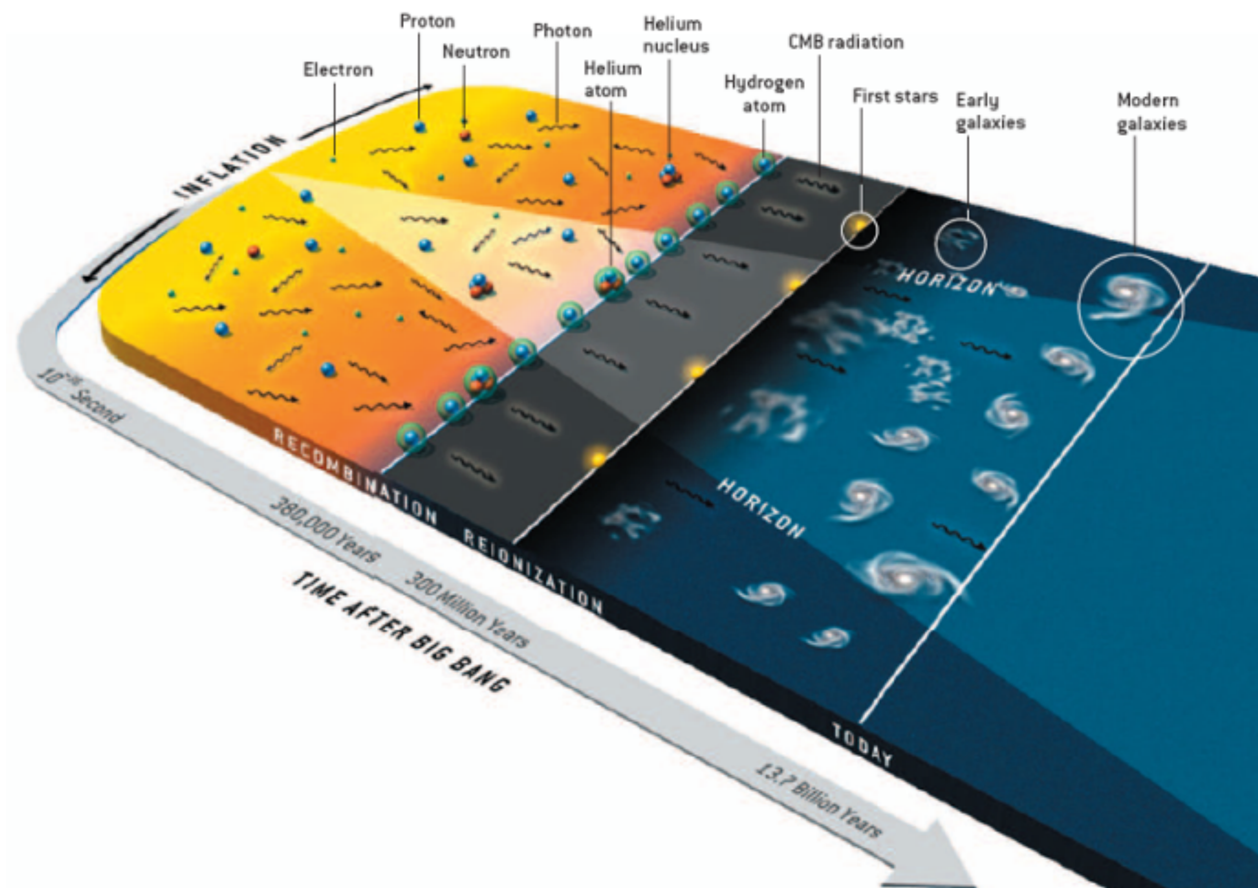
Figure 4. Cumulative volume filling factor $C(B)$ for the four different EGMF models found in MHD simulations.
(A color version of this figure is available in the online journal.)



magnetogenesis

F. Hoyle in Proc. ***"La structure et l'evolution de l'Universe"*** **(1958)**

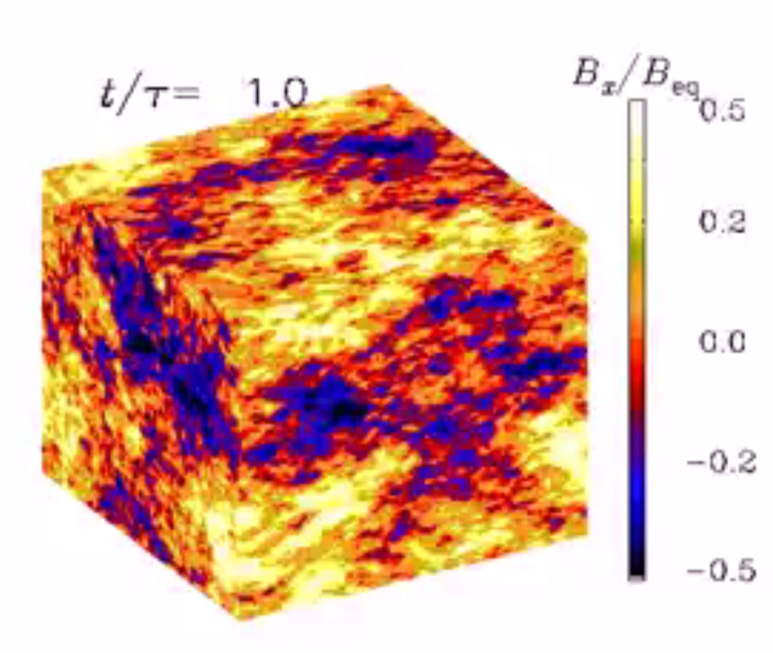
- inflation
- phase transitions
- supersymmetry
- string cosmology
- topological defects



MHD turbulence

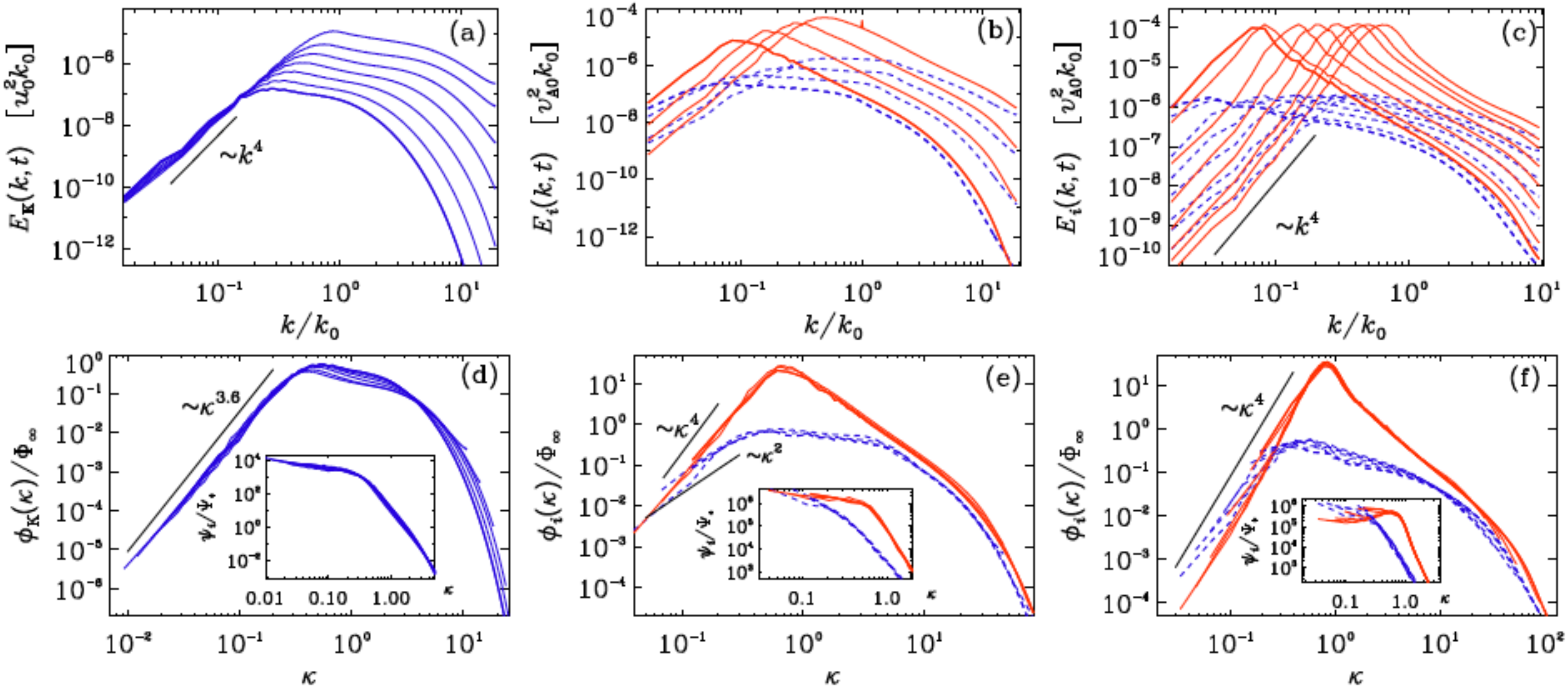
- Cosmic magnetic field origin – generation in the early universe
- Primordial magnetic fields – effects on phase transition physics
- Generation of turbulence
- MHD turbulence decay

PENCIL CODE 3D compressible MHD



Brandenburg, Kahniashvili, Tevzadze, 2015

classes of turbulence



Brandenburg & Kahniashvili 2017

Brandenburg, et al. 2017

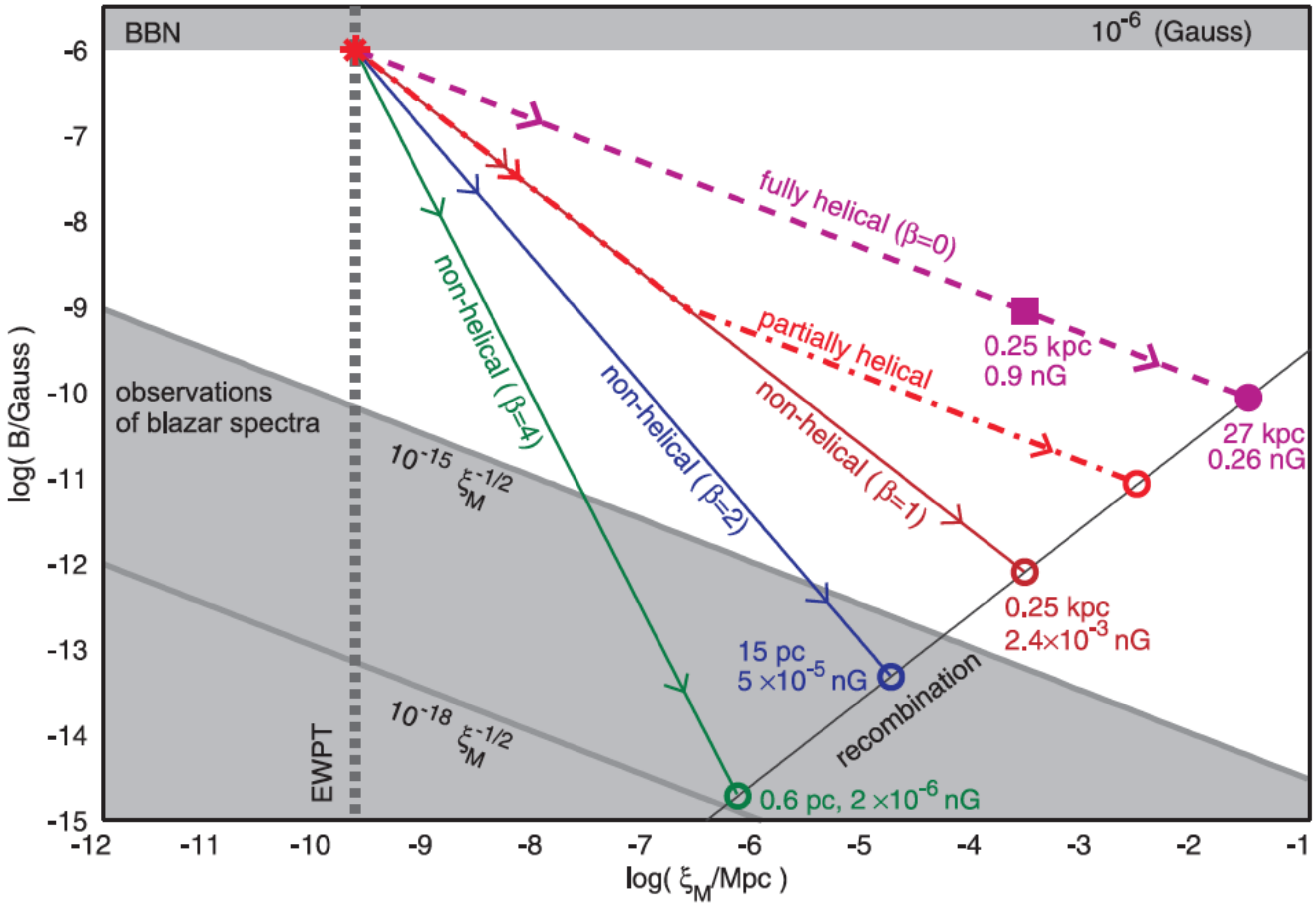
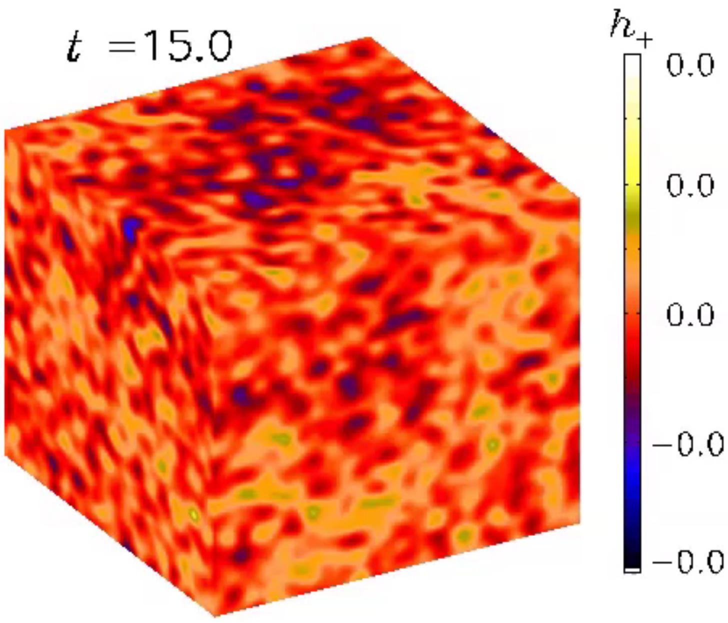
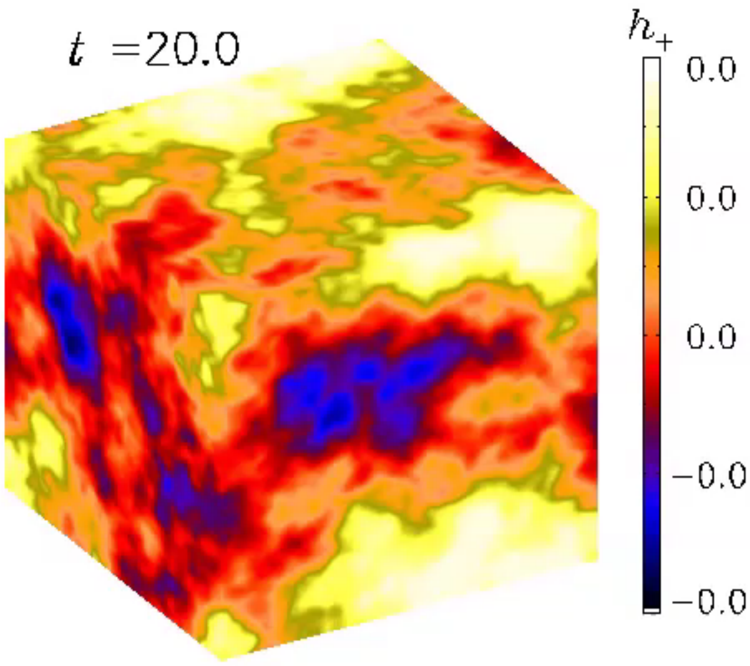


FIG. 11: Turbulent evolution of $B_{\rm rms}$ and $\xi_{\rm M}$ starting from their upper limits given by the BBN bound and the horizon scale at the EWPT for the fully helical case ($B_{\rm rms} \propto \xi_{\rm M}^{-1/2}$), the nonhelical case ($B_{\rm rms} \propto \xi_{\rm M}^{-1}$), and the fractionally helical case with $\epsilon_{{\rm M}\star} = 10^{-3}$. Circles indicate the final points at recombination for zero or partial initial magnetic helicity, the filled circle marks the fully helical case, and the filled square indicates the case with the initial kinetic helicity. The regimes excluded by observations of blazar spectra (upper line: limits claimed by Neronov and Vovk [59], based on the consideration of the expected cascade flux in the GeV band produced by the blazar TeV photons absorbed by the extragalactic background light, and assuming that the mean blazar TeV flux remains constant; bottom line corresponds to the limits obtained through accounting for the fact that the TeV flux activity is limited by the source observation period (few years) [60, 61] and BBN limits are marked in gray. The end of the evolution at recombination is denoted by the straight line given by the relation in Eq. (36), and the final values of $B_{\rm rms}$ and $\xi_{\rm M}$ are indicated for helical and nonhelical scenarios.

gravitational waves from turbulence

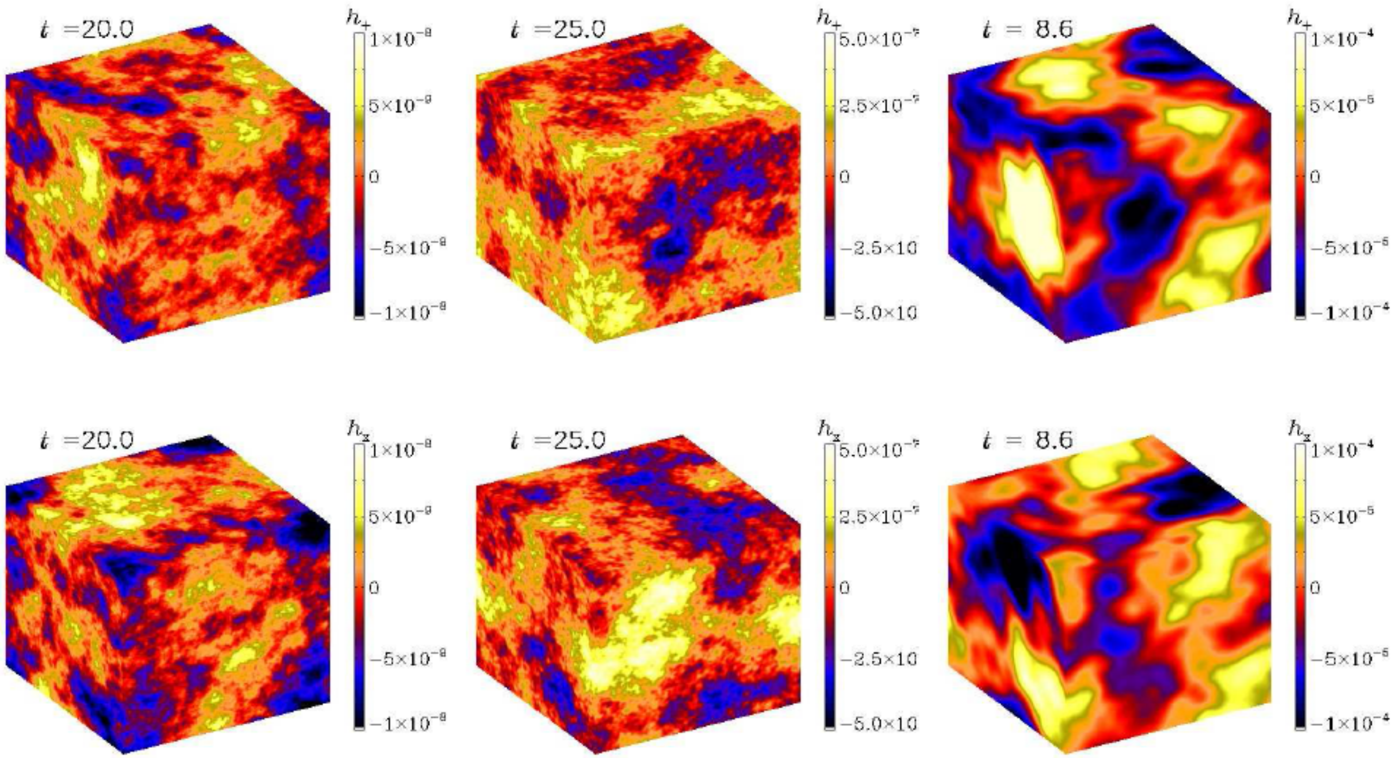


Acoustic turbulence



Vortical turbulence

gravitational waves: results



Roper Pol et al. 2019, 2020

$$\tilde{h}_+(\boldsymbol{k},t) = \tfrac{1}{2} e_{ij}^{+}(\boldsymbol{k})\, \tilde{h}_{ij}(\boldsymbol{k},t),$$
$$\tilde{h}_\times(\boldsymbol{k},t) = \tfrac{1}{2} e_{ij}^{\times}(\boldsymbol{k})\, \tilde{h}_{ij}(\boldsymbol{k},t).$$

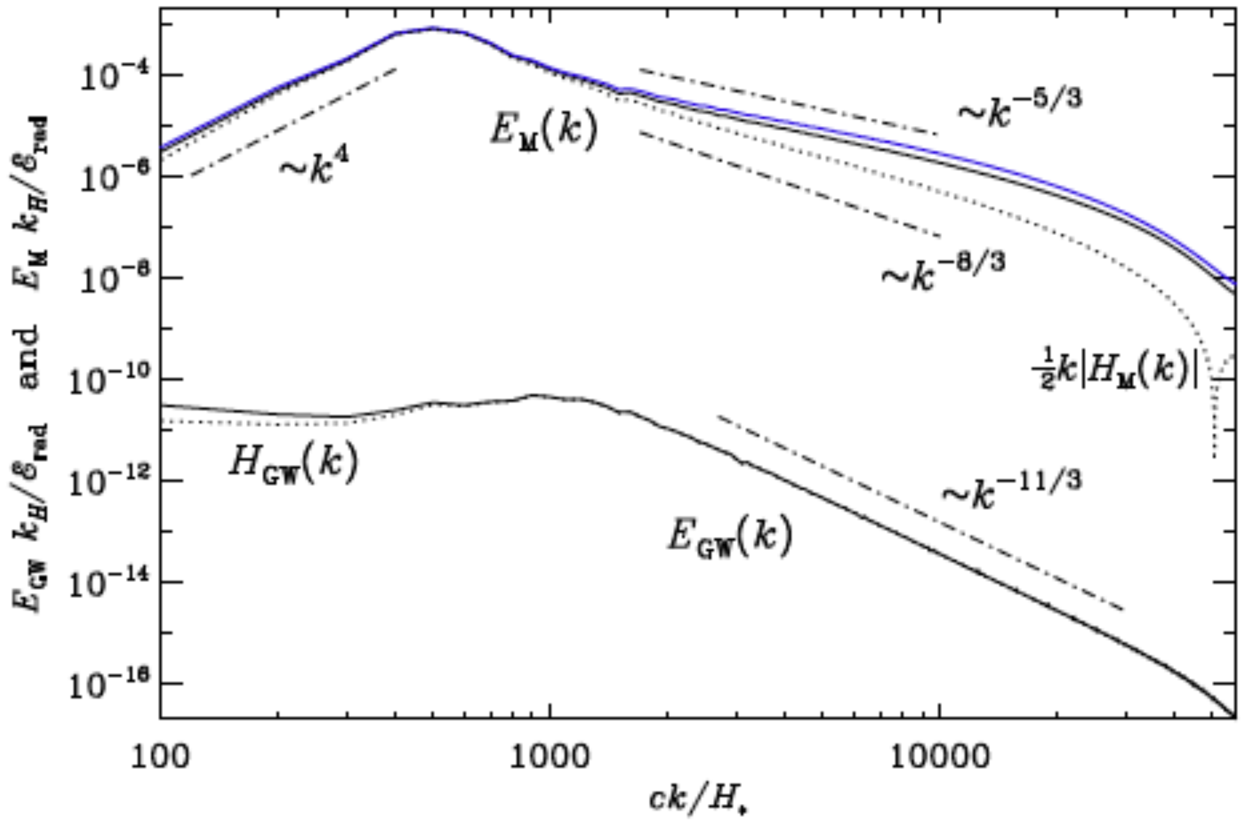


FIG. 1: The solid lines show magnetic and GW energy spectra for Run ini2 at $t = 1.1$, normalized to $\mathcal{E}_{\rm rad}/k_H$, where $k_H = H_*/c$ is the inverse horizon scale. The dotted lines show $\frac{1}{2}k|H_{\rm M}|$ and $H_{\rm GW}$, respectively. Both $H_{\rm M}$ and $H_{\rm GW}$ are positive, but $H_{\rm M}$ changes sign at high k.

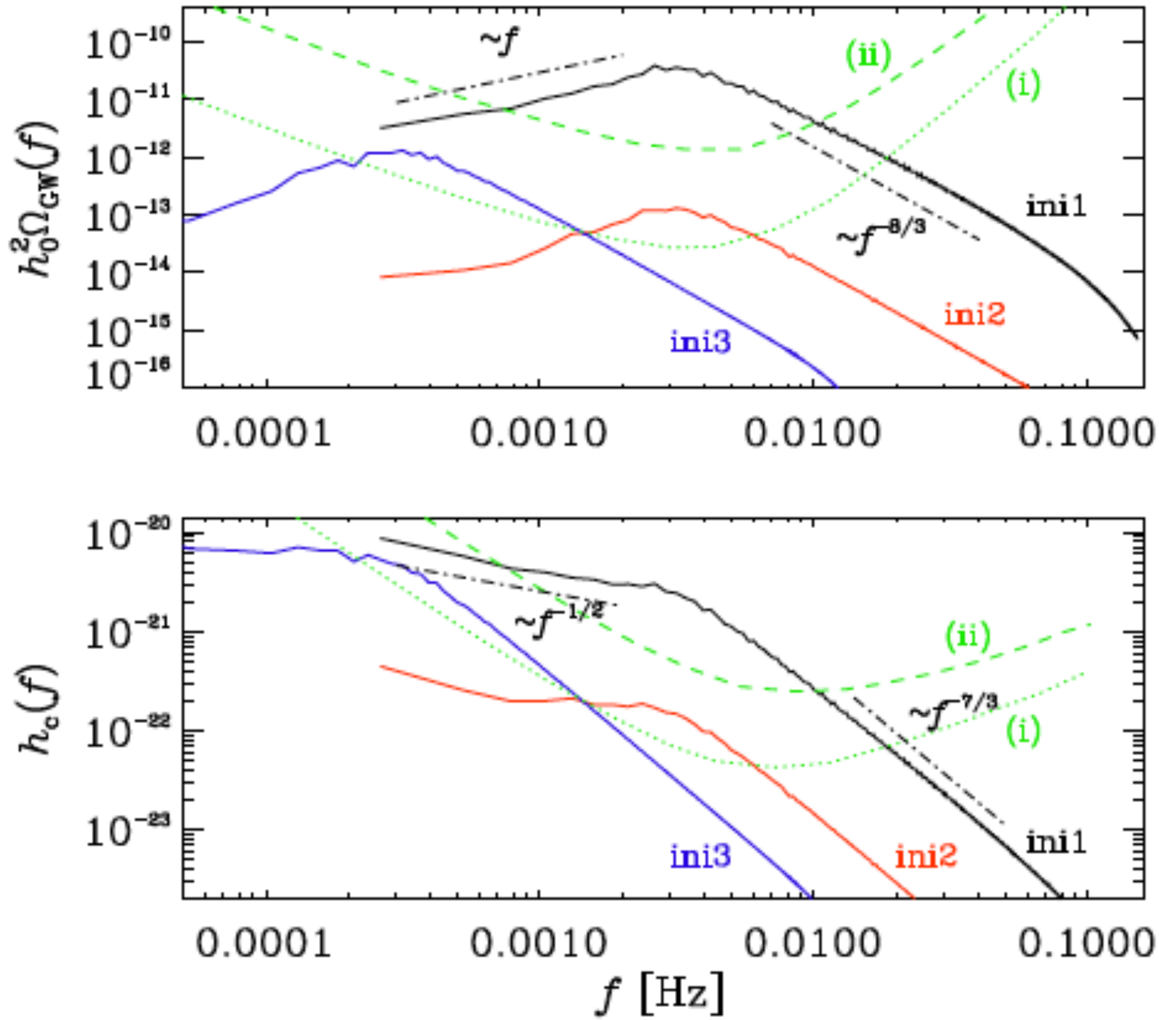


FIG. 2: Spectra of $h_0^2\Omega_{\rm GW}(f)$ and $h_c(f)$ along with the LISA sensitivity curves in (i) the 6-link configurations with 5×10^9 m arm length and (ii) the 4-link configurations with 2×10^9 m arm length after 5 years duration [30, 31]. The dash-dotted lines indicate the slopes 1 and $-8/3$ in the upper panel and $-1/2$ and $-7/3$ in the lower.

conclusions

- Primordial turbulence is potentially detectable by LISA
- Primordial magnetic fields can serve as seeds for the observed cosmic magnetic fields.
- Presence of primordial magnetic field makes the signal substantially stronger and allows it to spread over a wide range of frequencies.
- LISA mission offers a possibility to understand the physics of phase transitions (and possibly baryogenesis)
- Parity violating sources produce circularly polarized gravitational waves, and the polarization degree might be around 100% (for fully helical sources).

Thank you!