The CMB as a detector of high-frequency gravitational waves

Camilo A. Garcia Cely
Alexander von Humboldt fellow

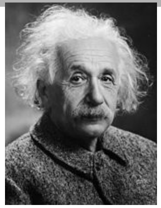
Quantum Universe Day

DESY

June 23, 2020

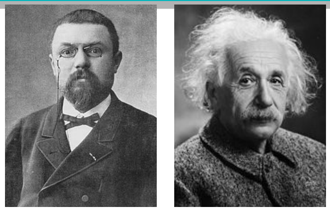
In collaboration with Valerie Domcke,
based on arXiv:2006.01161 [astro-ph.CO]

Gravitational Waves

- Predicted by Poincaré (1905).  
- Einstein provided a firm theoretical ground for them (1916).

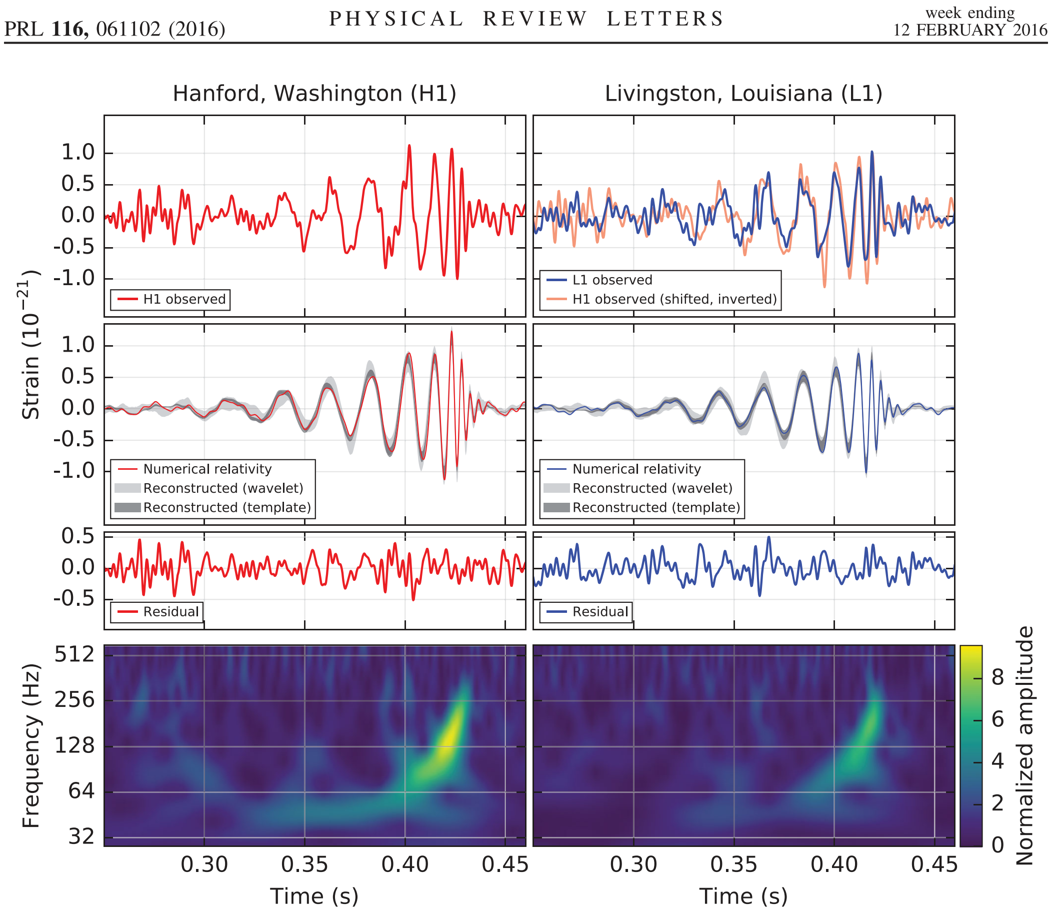
$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

Gravitational Waves



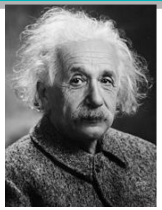
- Predicted by Poincaré (1905).
- Einstein provided a firm theoretical ground for them (1916).

$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$



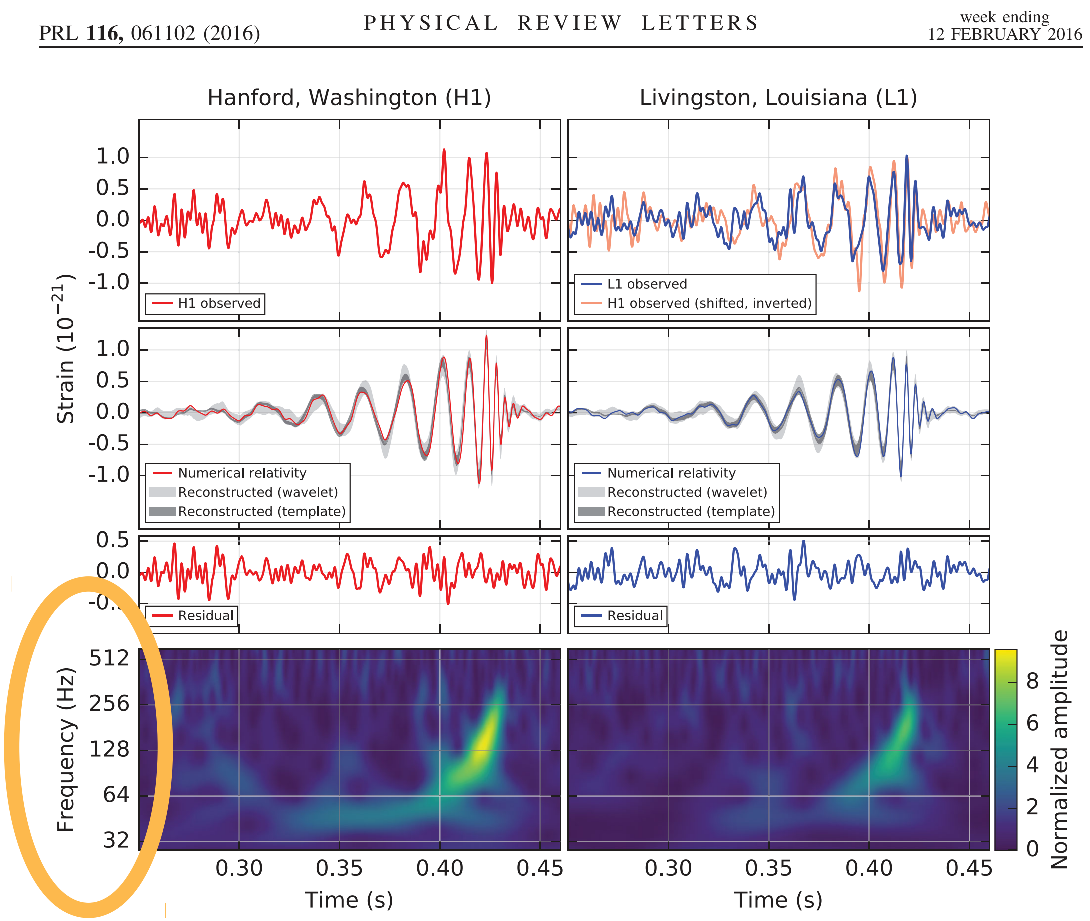
Terrestrial interferometers

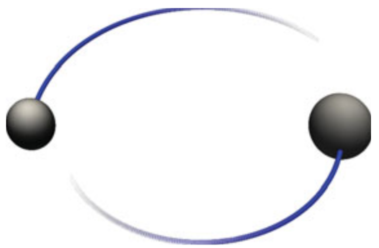
Gravitational Waves

- Predicted by Poincaré (1905).
- Einstein provided a firm theoretical ground for them (1916).

$$\Box h_{\mu\nu} = -16\pi G T_{\mu\nu}$$

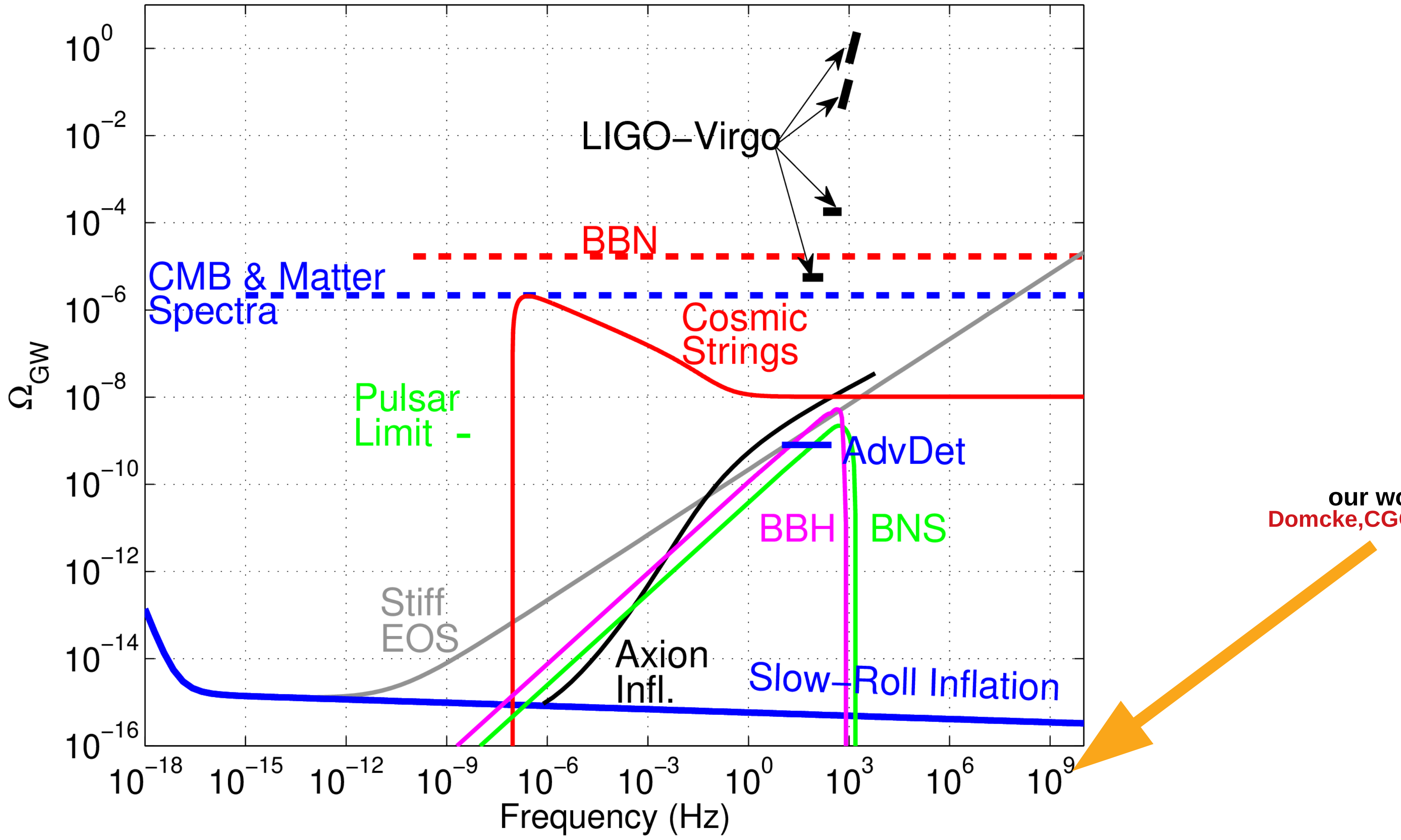




Terrestrial interferometers

Gravitational waves spectrum

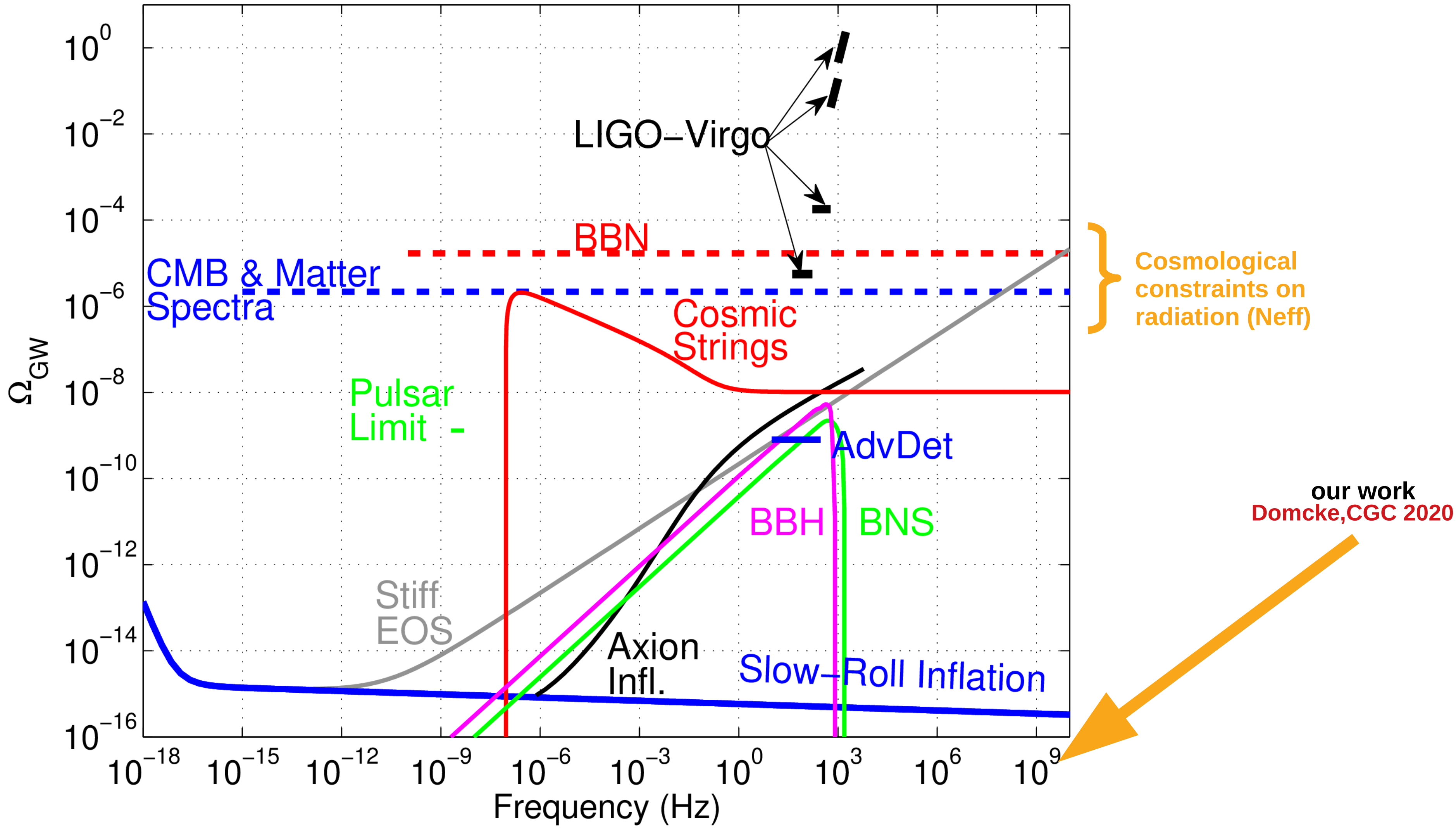
LIGO-VIRGO coll.'14



our work
Domcke,CGC 2020

Gravitational waves spectrum

LIGO-VIRGO coll.'14



Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

Terrestrial interferometers

Revisiting Gertsenhstein's ideas

SOVIET PHYSICS JETP VOLUME 14, NUMBER 1 JANUARY, 1962

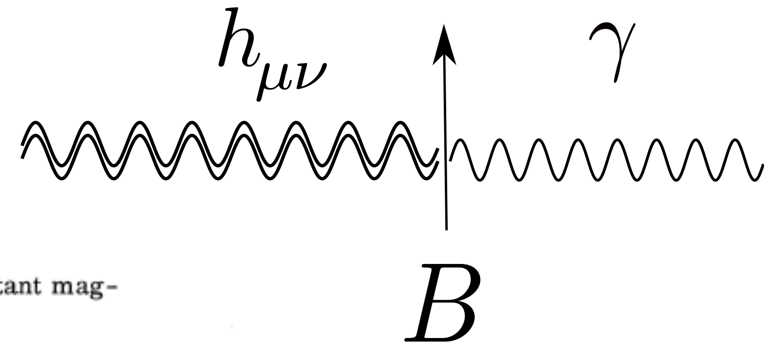
WAVE RESONANCE OF LIGHT AND GRAVITIONAL WAVES

M. E. GERTSENSHTEĬN

Submitted to JETP editor July 29, 1960

J. Exptl. Theoret. Phys. (U.S.S.R.) **41**, 113-114 (July, 1961)

The energy of gravitational waves excited during the propagation of light in a constant magnetic or electric field is estimated.



SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEĬN and V. I. PUSTOVOĬT

Submitted to JETP editor March 3, 1962

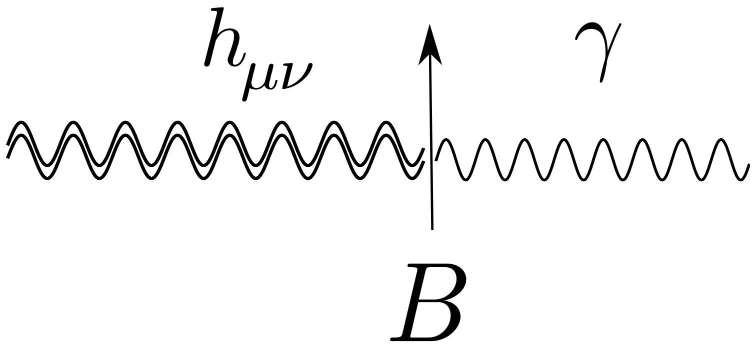
J. Exptl. Theoret. Phys. (U.S.S.R.) **43**, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.

Terrestrial interferometers

The Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process.
(Its rate does not involve ħ)

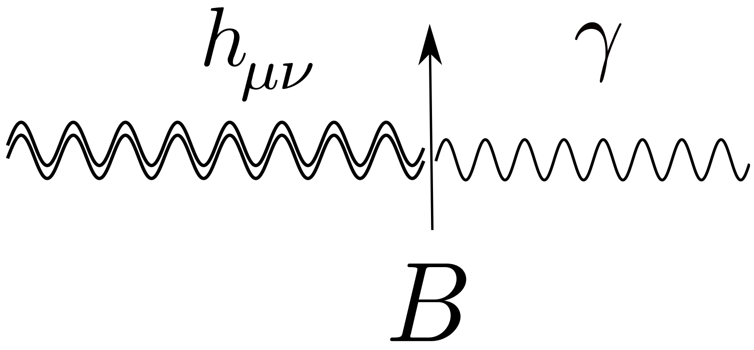


The Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process. (Its rate does not involve ħ)

- The process is *strictly* analagous to axion-photon conversion.

Raffelt, Stodolsk '89

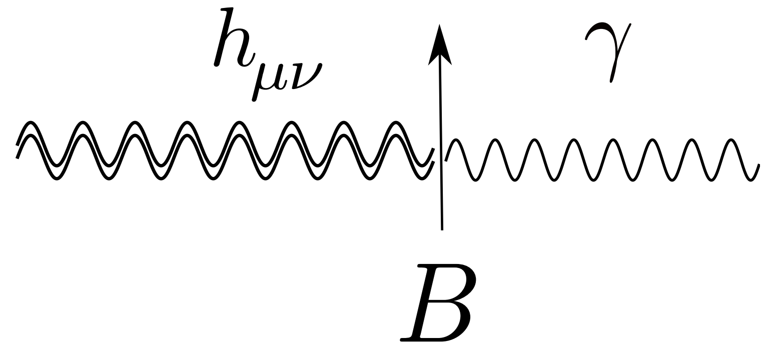


The Gertsenhstein Effect

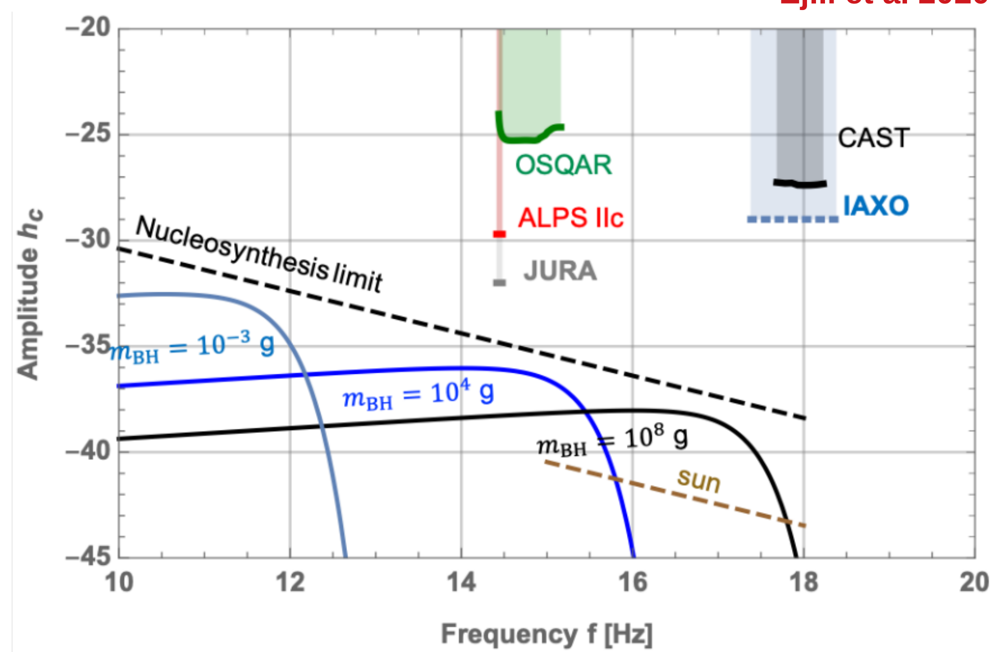
- The conversion of gravitational waves into electromagnetic waves is a classical process.
  (Its rate does not involve ħ)

- The process is *strictly* analagous to axion-photon conversion.

Raffelt, Stodolsk ‘89

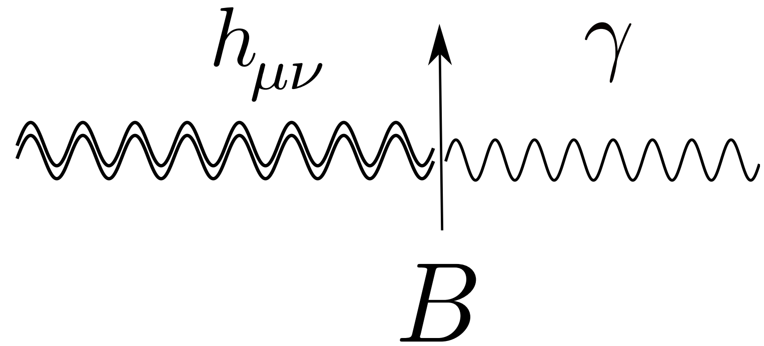


Ejlli et al 2020



The Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process.
  (Its rate does not involve ħ)

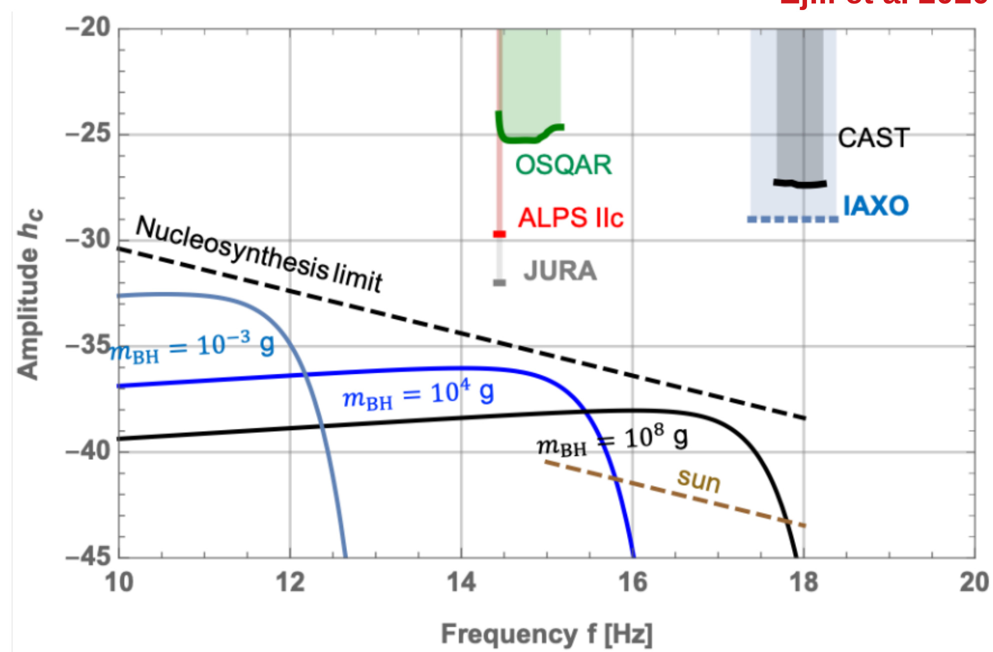


- The process is *strictly* analagous to axion-photon conversion.

Raffelt, Stodolsk '89

- Involving gravity, the conversion probability is extremely small. It may be compensated by a 'detector' of cosmological size.

Ejlli et al 2020



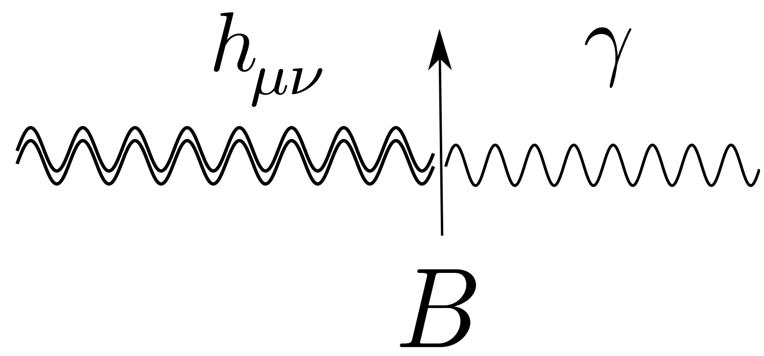
The Gertsenhstein Effect

- The conversion of gravitational waves into electromagnetic waves is a classical process.
  (Its rate does not involve ħ)

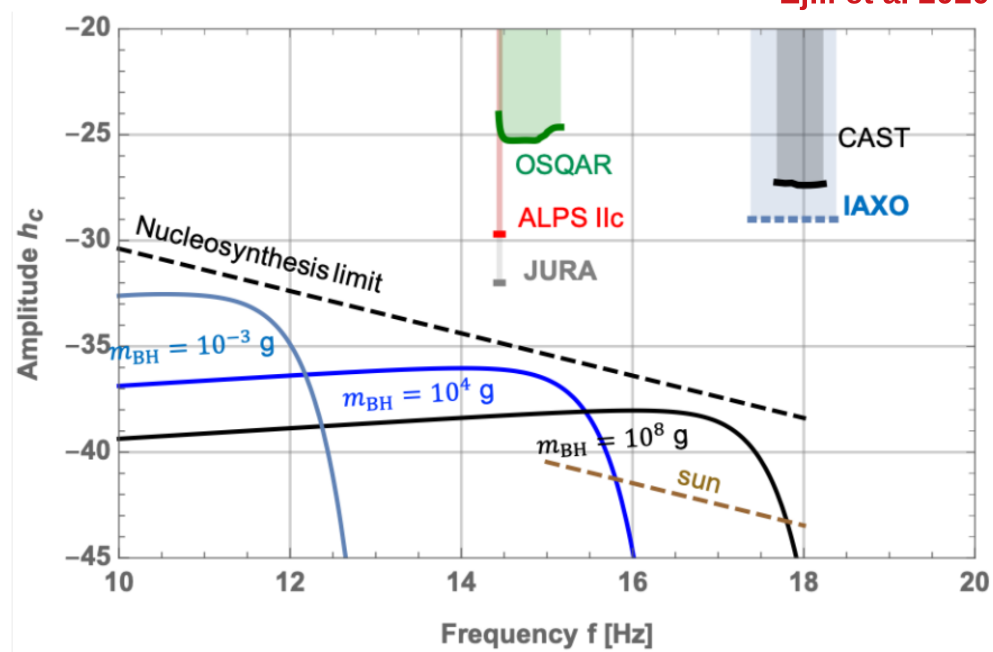
- The process is *strictly* analagous to axion-photon conversion.

Raffelt, Stodolsk '89

- Involving gravity, the conversion probability is extremely small. It may be compensated by a 'detector' of cosmological size.

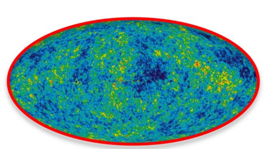


Ejlli et al 2020

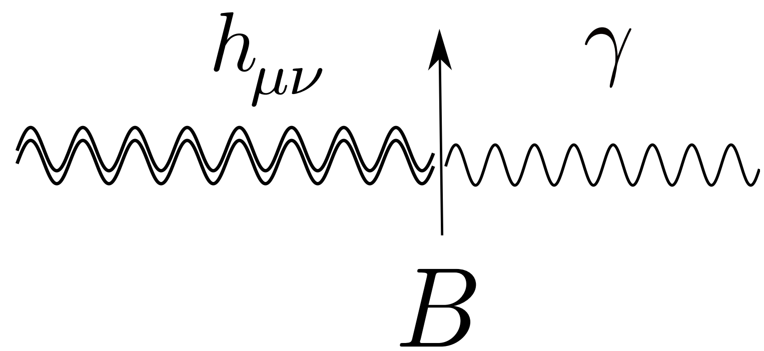


Distortions of the CMB?

Domcke,CGC 2020



- The conversion of gravitational waves into electromagnetic waves is a classical process.
  (Its rate does not involve ħ)

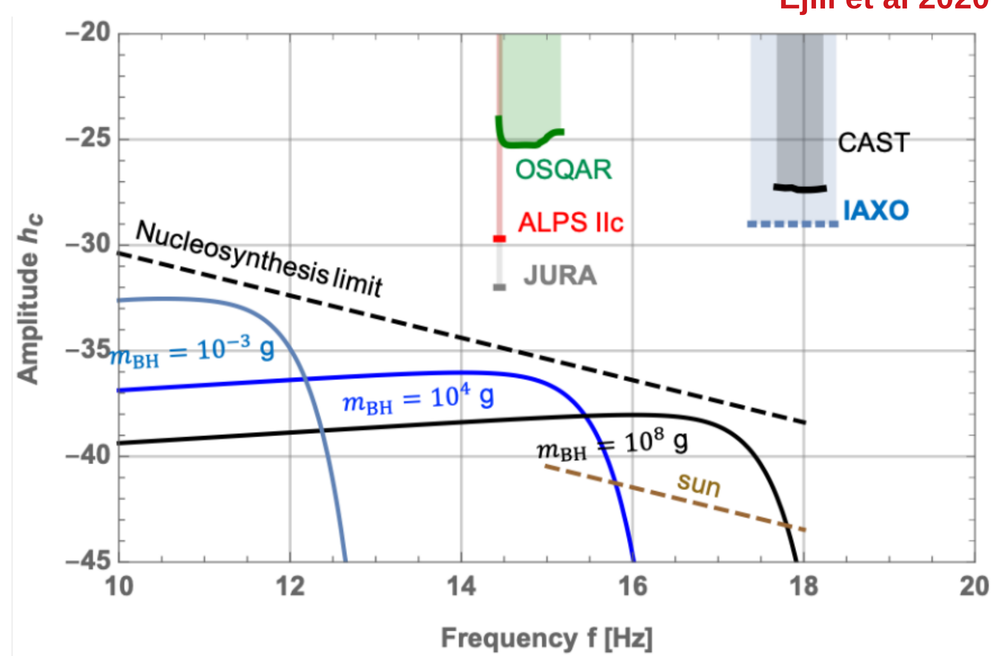


- The process is *strictly* analagous to axion-photon conversion.

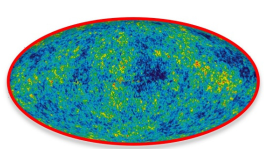
Raffelt, Stodolsk '89

- Involving gravity, the conversion probability is extremely small. It may be compensated by a 'detector' of cosmological size.

Ejlli et al 2020



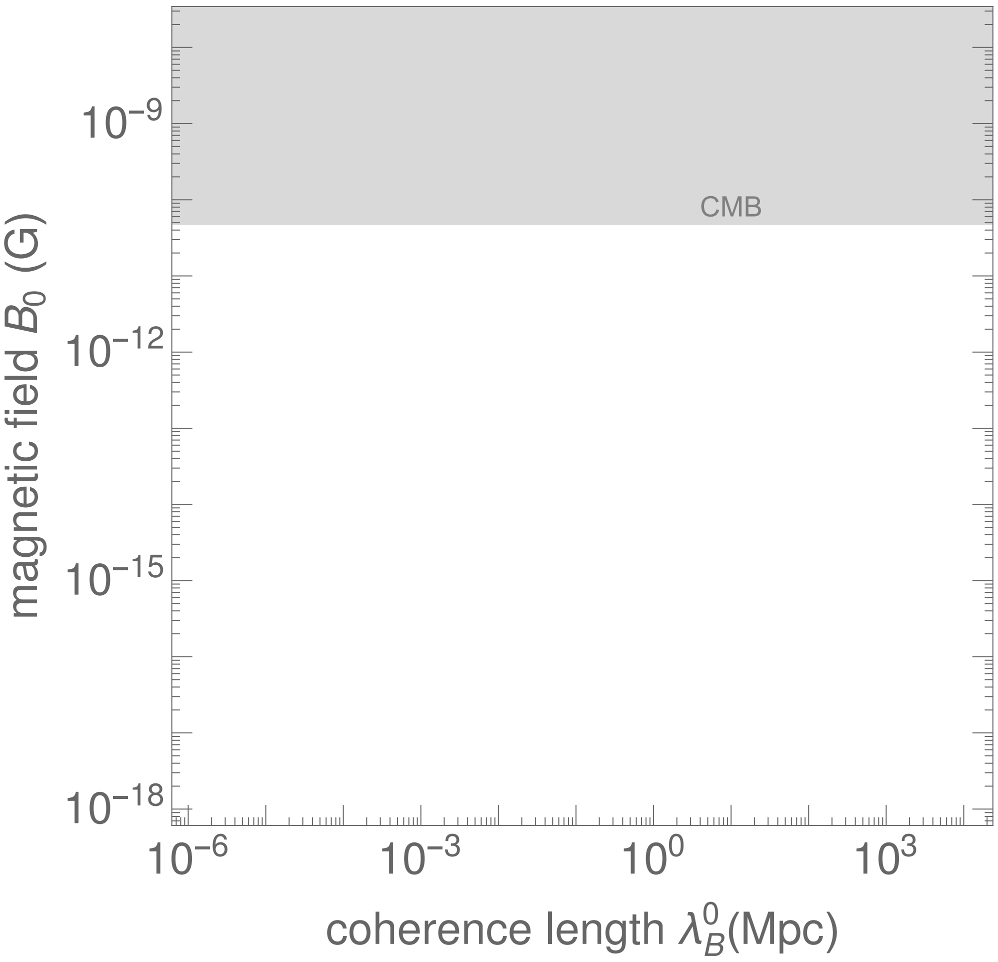
Distortions of the CMB?



Domcke, CGC 2020
Dolgov, Ejlli 2012
Pshirkov, Baskaran 2009
Chen 1995
…….

Cosmic Magnetic Fields in 2020

Domcke,CGC 2020



PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik[1,*] and Andrey Saveliev[2,3,†]

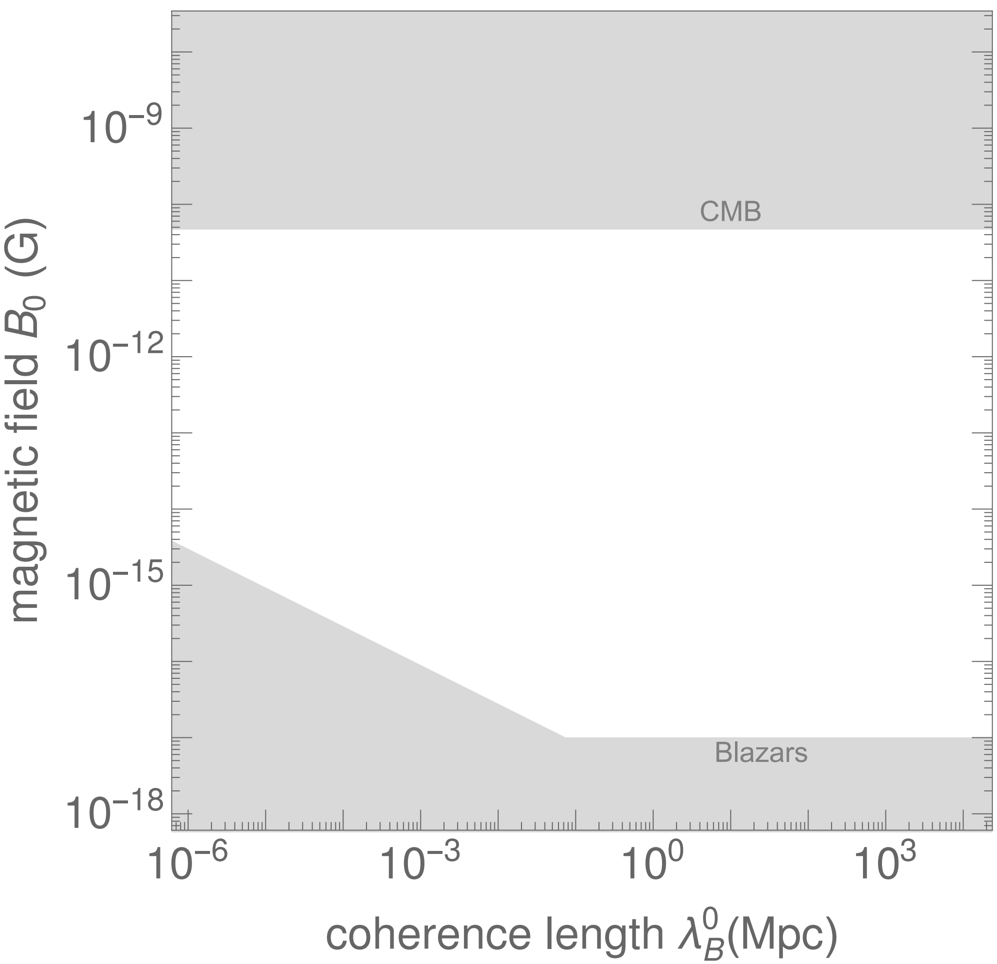
[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

(Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)

Primordial magnetic fields (PMFs), being present before the epoch of cosmic recombination, induce small-scale baryonic density fluctuations. These inhomogeneities lead to an inhomogeneous recombination process that alters the peaks and heights of the large-scale anisotropies of the cosmic microwave background (CMB) radiation. Utilizing numerical compressible MHD calculations and a Monte Carlo Markov chain analysis, which compares calculated CMB anisotropies with those observed by the *WMAP* and *Planck* satellites, we derive limits on the magnitude of putative PMFs. We find that the *total* remaining present day field, integrated over all scales, cannot exceed 47 pG for scale-invariant PMFs and 8.9 pG for PMFs with a violet Batchelor spectrum at 95% confidence level. These limits are more than one order of magnitude more stringent than any prior stated limits on PMFs from the CMB, which have not accounted for this effect.

Cosmic Magnetic Fields in 2020

Domcke,CGC 2020



PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik[1,*] and Andrey Saveliev[2,3,†]

[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

(Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)

Primordial magnetic fields (PMFs), being present before the epoch of cosmic recombination, induce small-scale baryonic density fluctuations. These inhomogeneities lead to an inhomogeneous recombination process that alters the peaks and heights of the large-scale anisotropies of the cosmic microwave background (CMB) radiation. Utilizing numerical compressible MHD calculations and a Monte Carlo Markov chain analysis, which compares calculated CMB anisotropies with those observed by the *WMAP* and *Planck* satellites, we derive limits on the magnitude of putative PMFs. We find that the *total* remaining present day field, integrated over all scales, cannot exceed 47 pG for scale-invariant PMFs and 8.9 pG for PMFs with a violet Batchelor spectrum at 95% confidence level. These limits are more than one order of magnitude more stringent than any prior stated limits on PMFs from the CMB, which have not accounted for this effect.

Science | Contents | News | Careers | Journals

SHARE

REPORT

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk

+ See all authors and affiliations

Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

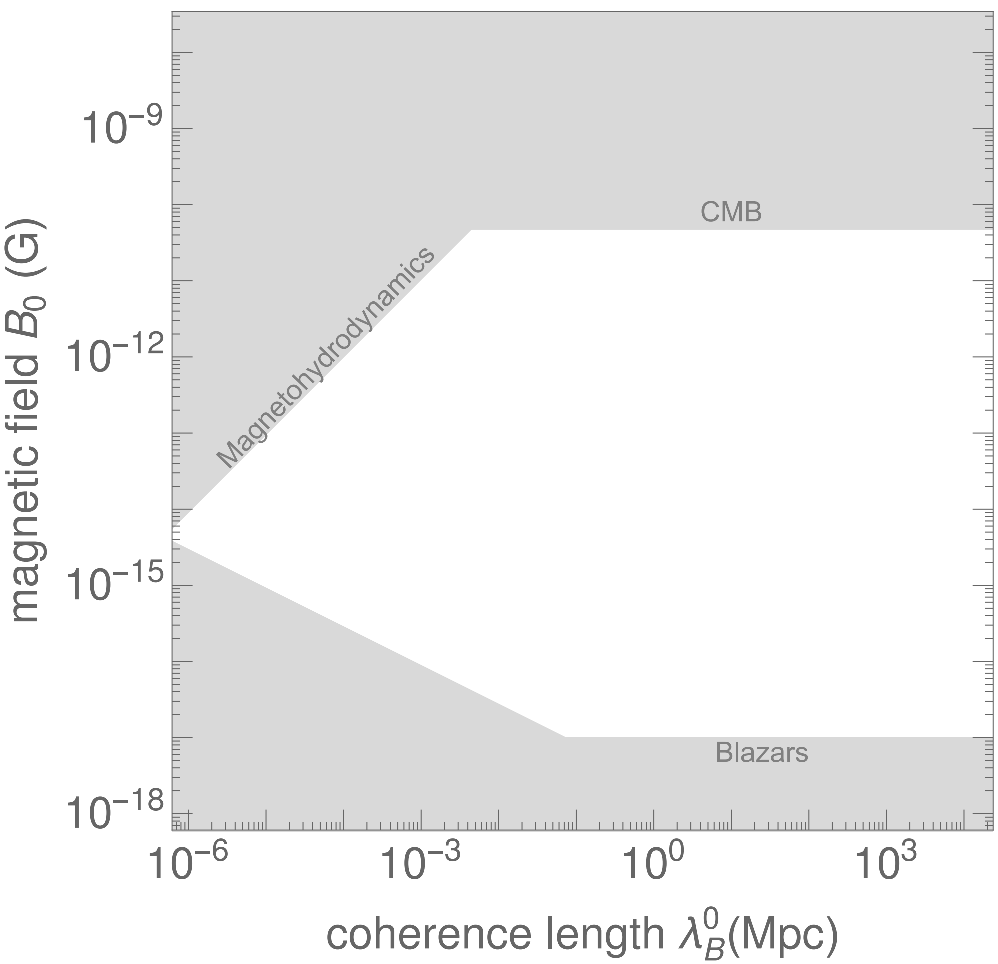
Article | Figures & Data | Info & Metrics | eLetters | PDF

Abstract

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera–electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

Cosmic Magnetic Fields in 2020

Domcke,CGC 2020



PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik[1,*] and Andrey Saveliev[2,3,†]

[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

(Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)

Primordial magnetic fields (PMFs), being present before the epoch of cosmic recombination, induce small-scale baryonic density fluctuations. These inhomogeneities lead to an inhomogeneous recombination process that alters the peaks and heights of the large-scale anisotropies of the cosmic microwave background (CMB) radiation. Utilizing numerical compressible MHD calculations and a Monte Carlo Markov chain analysis, which compares calculated CMB anisotropies with those observed by the *WMAP* and *Planck* satellites, we derive limits on the magnitude of putative PMFs. We find that the *total* remaining present day field, integrated over all scales, cannot exceed 47 pG for scale-invariant PMFs and 8.9 pG for PMFs with a violet Batchelor spectrum at 95% confidence level. These limits are more than one order of magnitude more stringent than any prior stated limits on PMFs from the CMB, which have not accounted for this effect.

Science   Contents   News   Careers   Journals

SHARE

REPORT

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk
+ See all authors and affiliations

Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

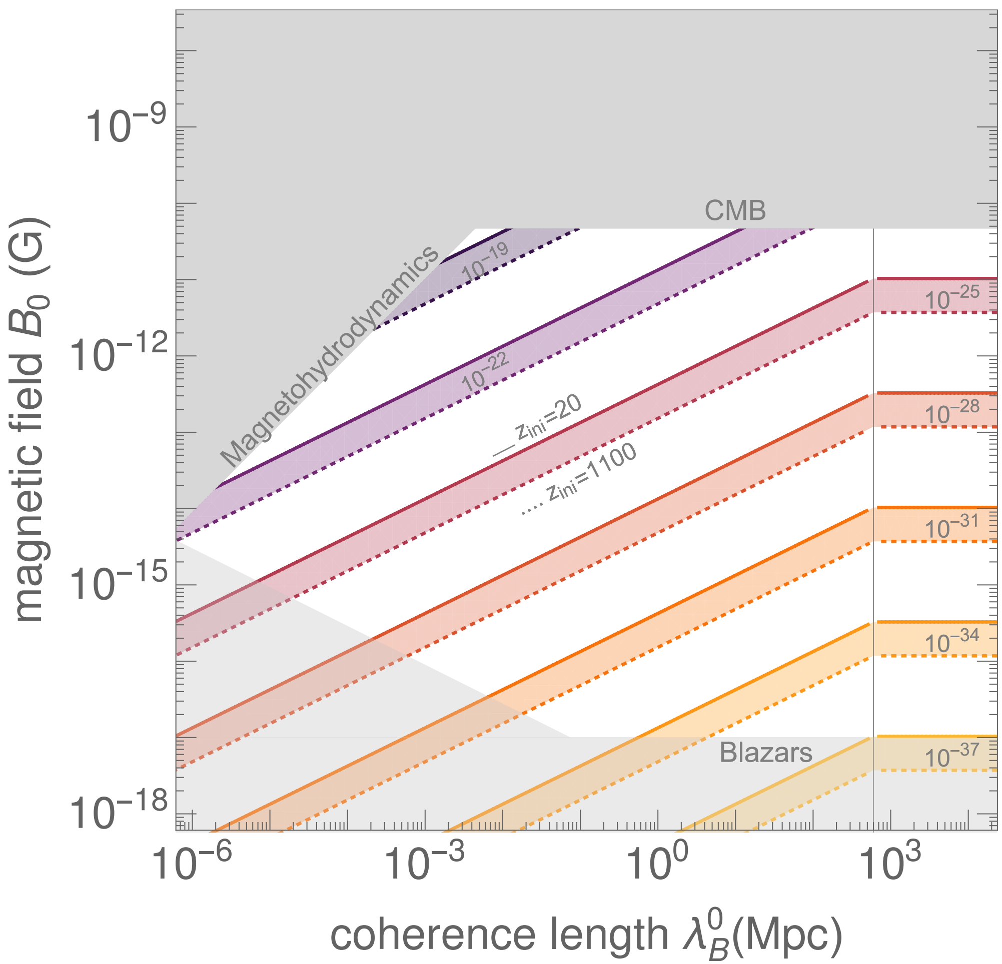
Article   Figures & Data   Info & Metrics   eLetters   PDF

Abstract

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera–electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

Cosmic Magnetic Fields in 2020

Domcke,CGC 2020



$$\mathcal{P} \equiv \int_{l.o.s.} \langle \Gamma_{g\leftrightarrow\gamma} \rangle dt$$

PHYSICAL REVIEW LETTERS **123,** 021301 (2019)

Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Background Radiation

Karsten Jedamzik[1,*] and Andrey Saveliev[2,3,†]

[1]*Laboratoire Univers et Particules de Montpellier, UMR5299-CNRS, Université de Montpellier, 34095 Montpellier, France*
[2]*Institute of Physics, Mathematics and Information Technology, Immanuel Kant Baltic Federal University, 236016 Kaliningrad, Russia*
[3]*Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, 119991 Moscow, Russia*

(Received 8 May 2018; revised manuscript received 13 September 2018; published 10 July 2019)

Primordial magnetic fields (PMFs), being present before the epoch of cosmic recombination, induce small-scale baryonic density fluctuations. These inhomogeneities lead to an inhomogeneous recombination process that alters the peaks and heights of the large-scale anisotropies of the cosmic microwave background (CMB) radiation. Utilizing numerical compressible MHD calculations and a Monte Carlo Markov chain analysis, which compares calculated CMB anisotropies with those observed by the *WMAP* and *Planck* satellites, we derive limits on the magnitude of putative PMFs. We find that the *total* remaining present day field, integrated over all scales, cannot exceed 47 pG for scale-invariant PMFs and 8.9 pG for PMFs with a violet Batchelor spectrum at 95% confidence level. These limits are more than one order of magnitude more stringent than any prior stated limits on PMFs from the CMB, which have not accounted for this effect.

Science   Contents ▾   News ▾   Careers ▾   Journals ▾

SHARE

REPORT

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

Andrii Neronov*, Ievgen Vovk
+ See all authors and affiliations

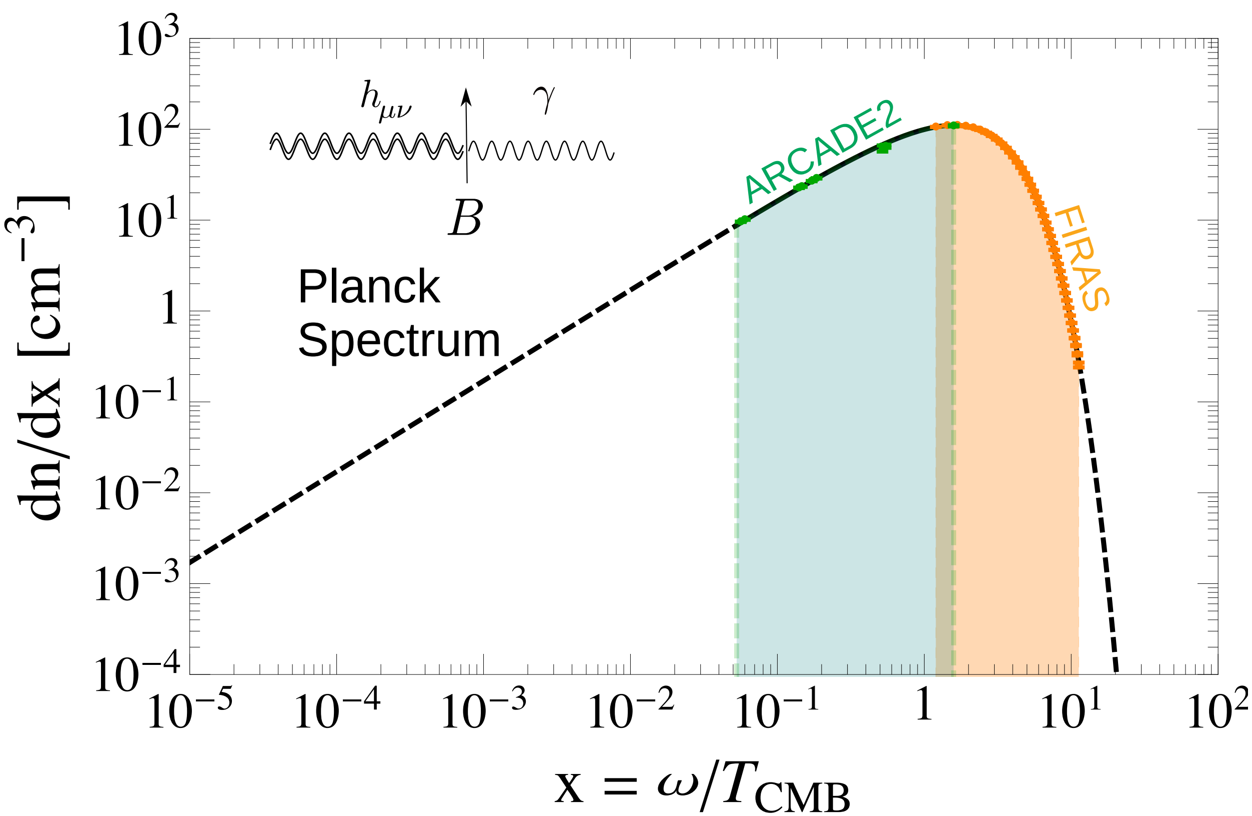
Science 02 Apr 2010:
Vol. 328, Issue 5974, pp. 73-75
DOI: 10.1126/science.1184192

Article   Figures & Data   Info & Metrics   eLetters   PDF

Abstract

Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \gtrsim 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera–electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, λ_B, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.

CMB distortions in 2020



Absolute **R**adiometer for **C**osmology, **A**strophysics, and **D**iffuse **E**mission

THE ASTROPHYSICAL JOURNAL

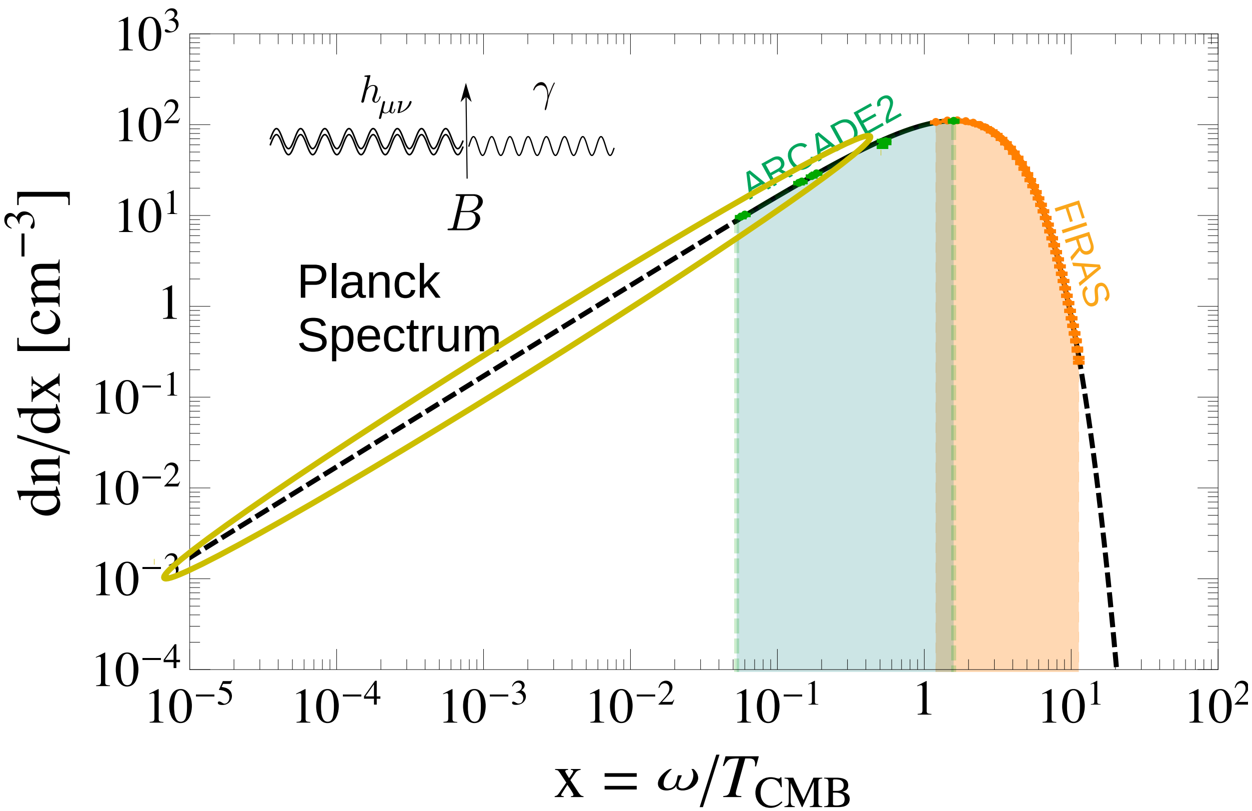
ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 • © 2011. The American Astronomical Society. All rights reserved.

The Astrophysical Journal, Volume 734, Number 1

CMB distortions in 2020



Absolute **R**adiometer for **C**osmology, **A**strophysics, and **D**iffuse **E**mission

THE ASTROPHYSICAL JOURNAL

ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

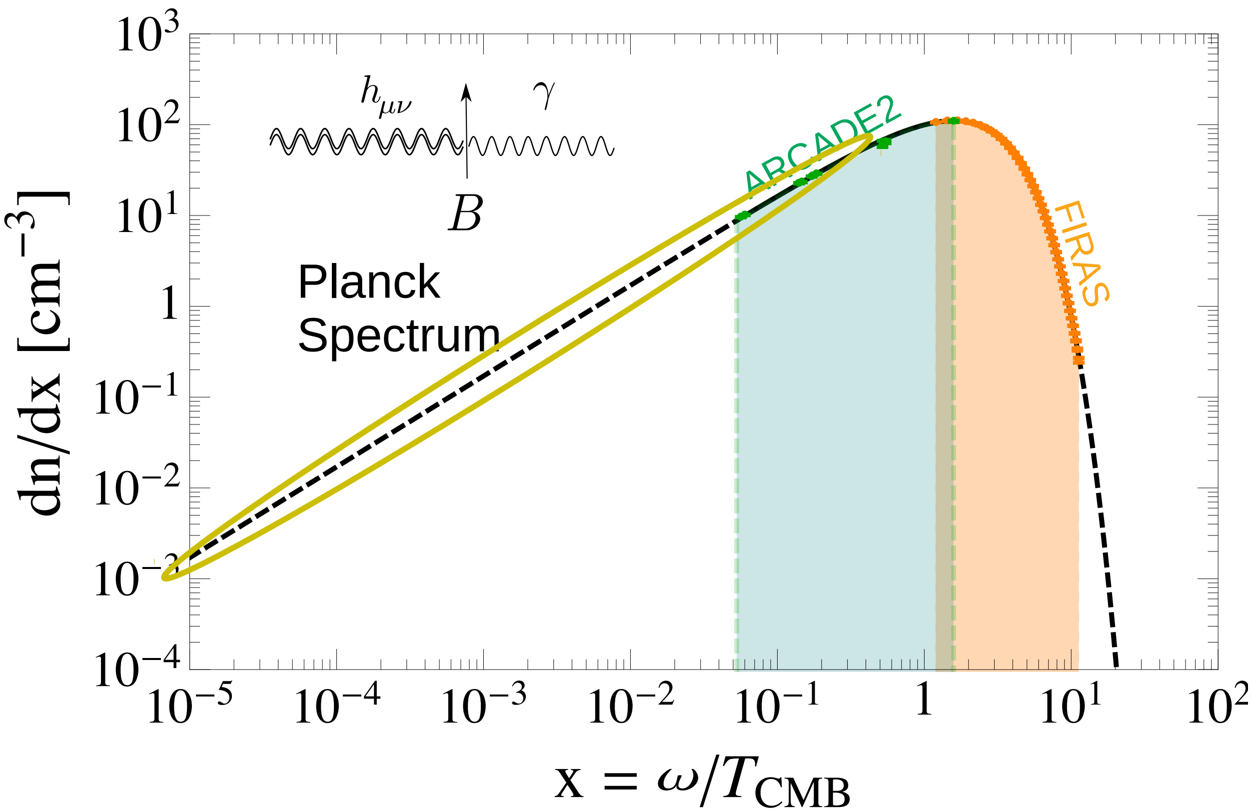
D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 •
The Astrophysical Journal, Volume 734, Number 1

Rayleigh-Jeans tail

- Largely unexplored, with upcoming advances in radio astronomy probing it in the near future.

CMB distortions in 2020



Absolute **R**adiometer for **C**osmology, **A**strophysics, and **D**iffuse **E**mission

THE ASTROPHYSICAL JOURNAL

ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 • © 2011. The American Astronomical Society. All rights reserved.

The Astrophysical Journal, Volume 734, Number 1

nature

Published: 01 March 2018

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

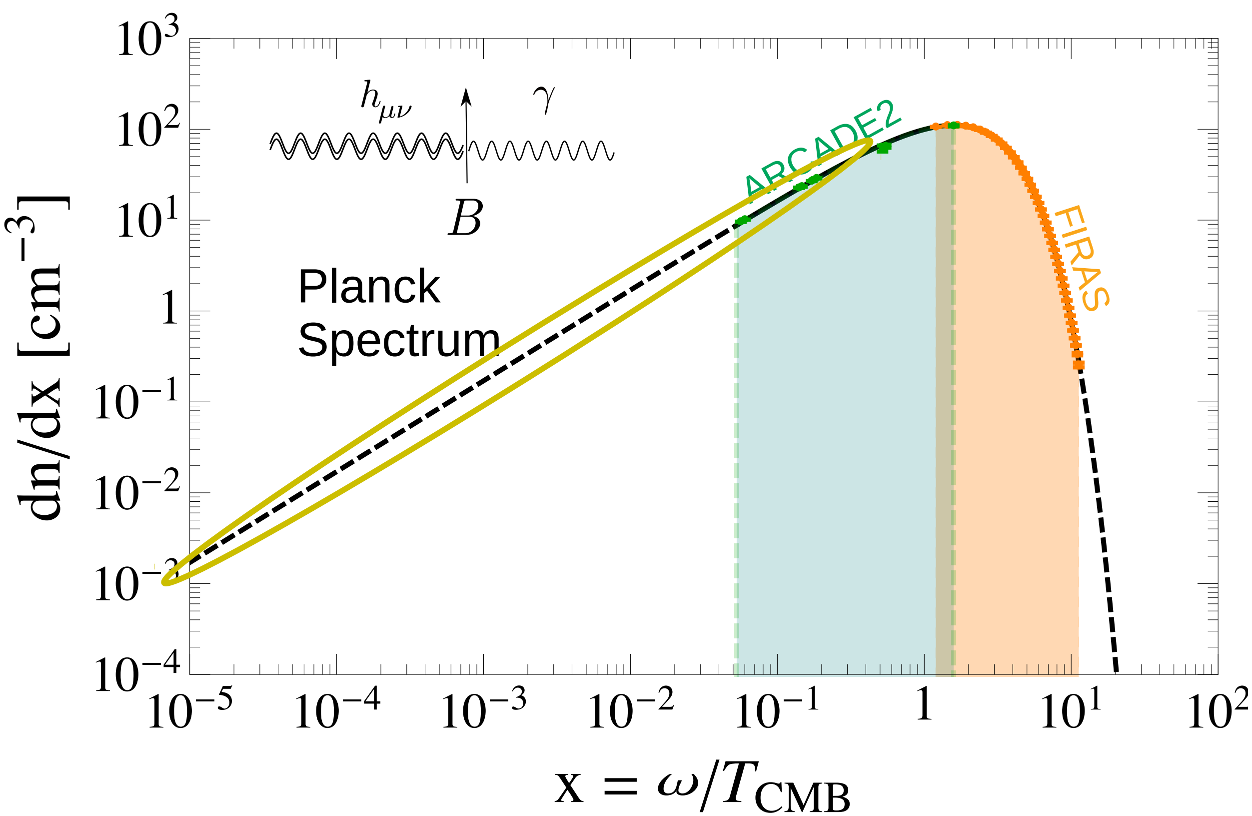
Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature

Rayleigh-Jeans tail

- Largely unexplored, with upcoming advances in radio astronomy probing it in the near future. (EDGES)

CMB distortions in 2020



Absolute **R**adiometer for **C**osmology, **A**strophysics, and **D**iffuse **E**mission

THE ASTROPHYSICAL JOURNAL

ARCADE 2 MEASUREMENT OF THE ABSOLUTE SKY BRIGHTNESS AT 3-90 GHz

D. J. Fixsen[1], A. Kogut[2], S. Levin[3], M. Limon[4], P. Lubin[5], P. Mirel[6], M. Seiffert[3], J. Singal[7], E. Wollack[2], T. Villela[8] +Show full author list

Published 2011 May 17 • © 2011. The American Astronomical Society. All rights reserved.

The Astrophysical Journal, Volume 734, Number 1

nature

Published: 01 March 2018

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

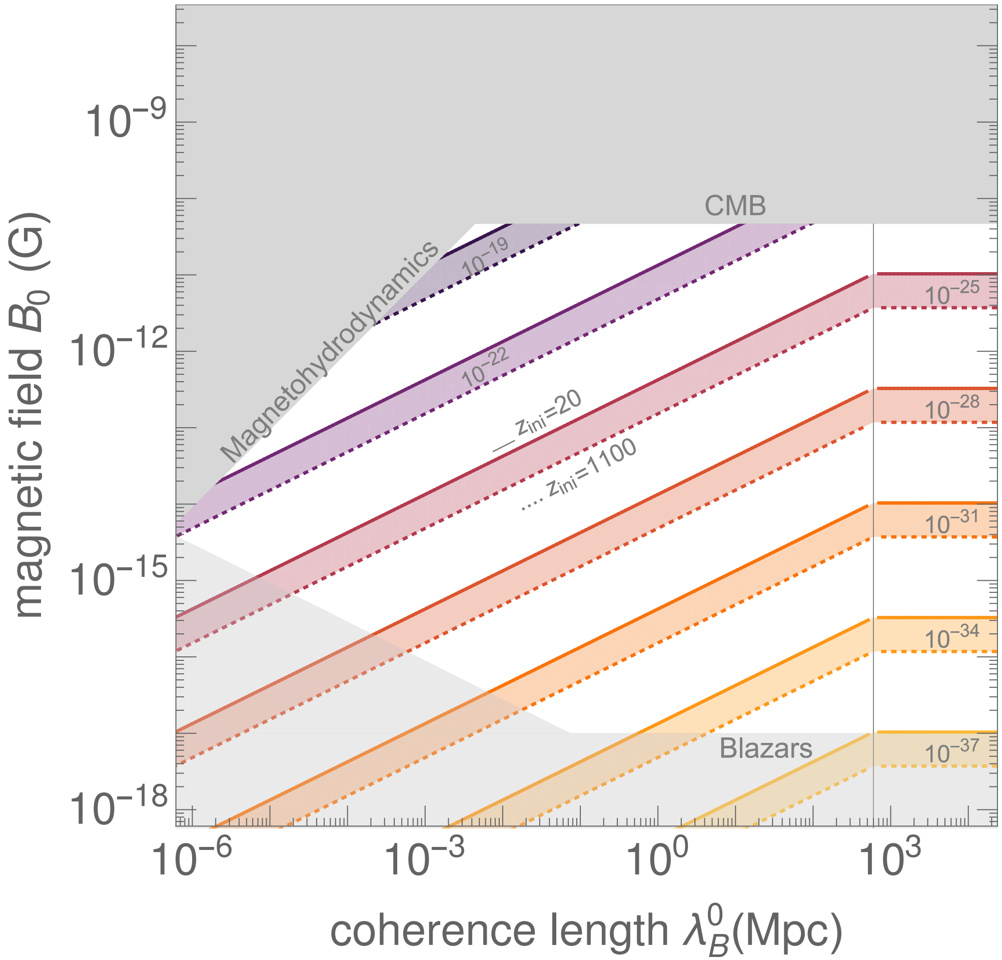
Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature

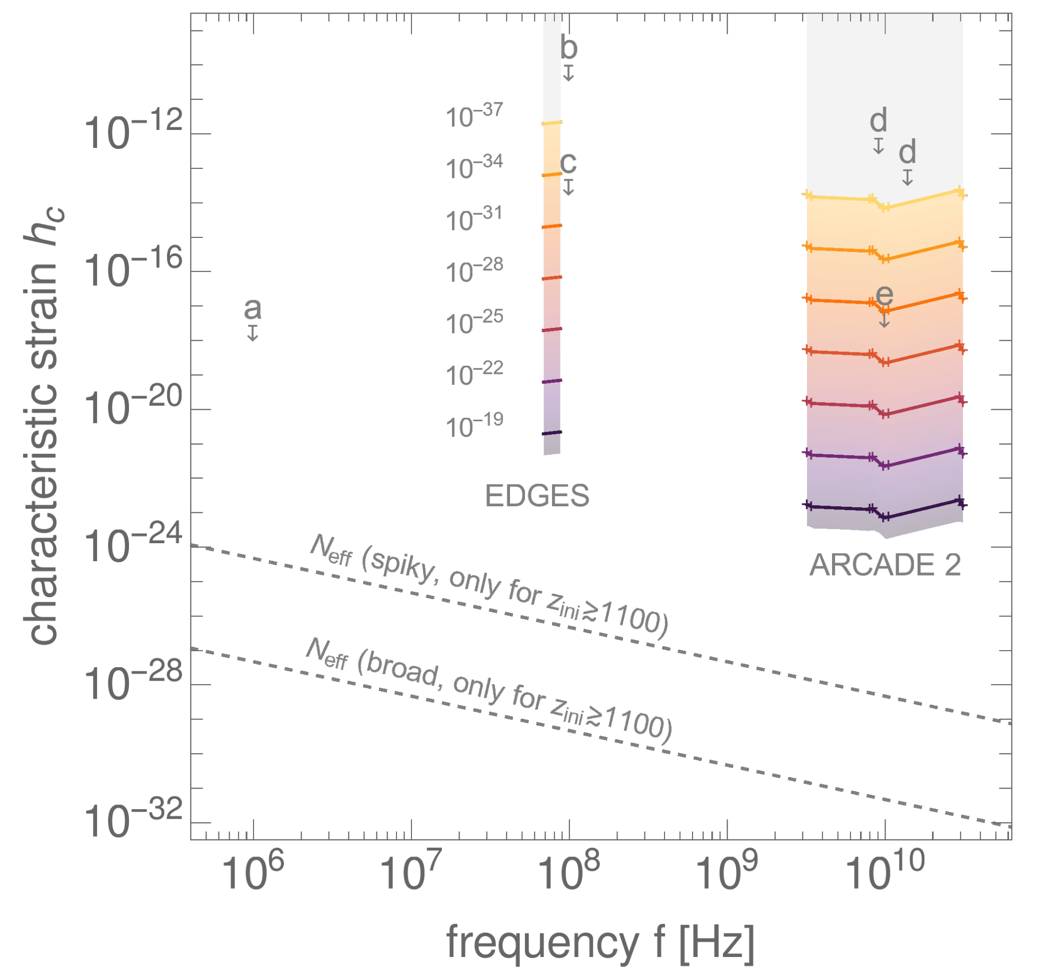
Rayleigh-Jeans tail

- Largely unexplored, with upcoming advances in radio astronomy probing it in the near future. (EDGES)
- They may conceivably push these bounds below the Neff constraint.

Upper bounds on stochastic gravitational waves

Domcke,CGC 2020



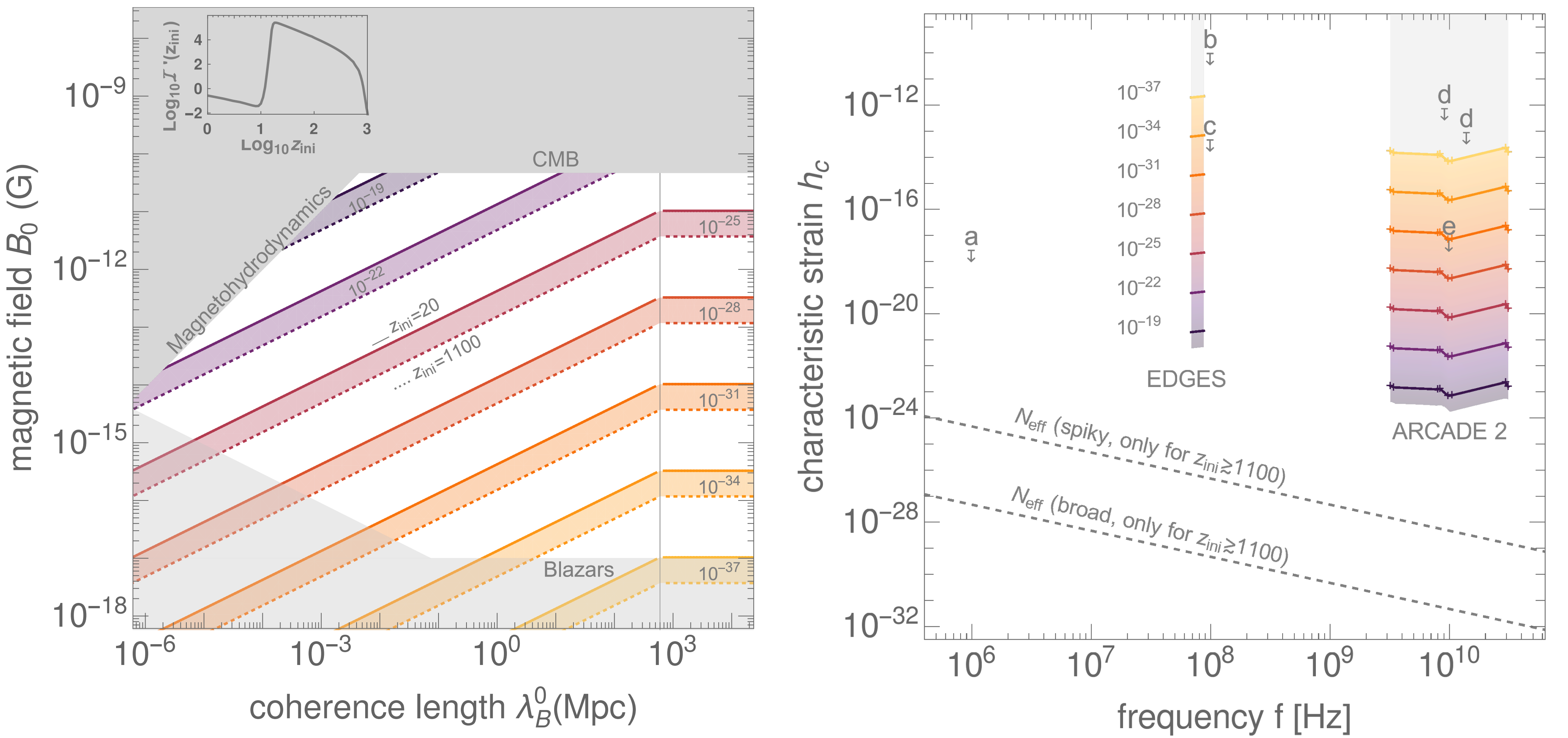


existing laboratory bounds from

a) superconducting parametric converter Reece et al '84
b) waveguide Cruise Ingley '06
c) 0.75 m interferometer Akutsu '08
d) magnon detector Ito, Soda '04
e) magnetic conversion detector Cruise et al '12

Upper bounds on stochastic gravitational waves

Domcke,CGC 2020



Conclusions

- The Gertsenshtein effect during the dark ages provides a powerful way to probe GWs in the MHz-GHz range from distortions of the Rayleigh-Jeans CMB tail.

- With upcoming advances in 21cm astronomy targeting precisely this frequency range with increasing accuracy, it becomes conceivable to push the limits derived from radio telescopes below the cosmological bound constraining the total energy in GWs.

Conclusions

- The Gertsenshtein effect during the dark ages provides a powerful way to probe GWs in the MHz-GHz range from distortions of the Rayleigh-Jeans CMB tail.

- With upcoming advances in 21cm astronomy targeting precisely this frequency range with increasing accuracy, it becomes conceivable to push the limits derived from radio telescopes below the cosmological bound constraining the total energy in GWs.

Thank you for your attention

Wave equation

$$\left(\Box + \omega_{\rm pl}^2/c^2\right) A_\lambda = -B\partial_\ell h_\lambda\,, \quad \Box h_\lambda = \kappa^2 B \partial_\ell A_\lambda\,,$$

Solution

$$\psi(t,\ell) \equiv \begin{pmatrix} \sqrt{\mu}\ A_\lambda \\ \frac{1}{\kappa}\, h_\lambda \end{pmatrix} = e^{-i\omega t} e^{iK\ell} \psi(0,0)\,,$$

$$K = \begin{pmatrix} \frac{\mu}{c}\sqrt{\omega^2 + \left(\frac{\kappa B}{1+\mu}\right)^2} & -i\frac{\sqrt{\mu}\,\kappa B}{1+\mu} \\ i\frac{\sqrt{\mu}\,\kappa B}{1+\mu} & \frac{1}{c}\sqrt{\omega^2 + \left(\frac{\kappa B}{1+\mu}\right)^2} \end{pmatrix}.$$

Conversion rate

$$\langle \Gamma_{g\leftrightarrow\gamma} \rangle = \frac{c\,|K_{12}|\ \ell_{\rm osc}}{2\Delta\ell}\,.$$

$$\ell_{\rm osc}^{-1} = \sqrt{\omega^2(1-\mu)^2/c^2 + \kappa^2 B^2}/2.$$

$$\mathcal{P} \equiv \int \langle \Gamma_{g\leftrightarrow\gamma}\rangle dt = \int^{z_{\rm ini}} \frac{\langle \Gamma_{g\leftrightarrow\gamma}\rangle}{(1+z)\,H} dz\,,$$

CMB distortions

$$\delta f_\gamma(\omega_0, T_0) = \left(f_g(\omega_{\rm ini}, T_{\rm ini}) - f_{\rm eq}\right)\mathcal{P} + \mathcal{O}(\mathcal{P}^2)\,,$$

$$\frac{\delta f_\gamma}{f_\gamma}(\omega_0, T_0) = \frac{\pi^4}{15}\left(\frac{T}{\omega}\right)^3 \mathcal{P}\,\frac{\Omega_{\rm GW}}{\Omega_\gamma} \quad \text{for } \omega \ll T$$

$$h_c = \left(\frac{3H_0^2}{4\pi^2}\Omega_{\rm GW} f^{-2}\right)^{1/2}.$$